ABSTRACT BOOK

The 12th International Conference on Materials and Mechanisms of Superconductivity and High Temperature Superconductors

(M²S-2018)

August 19 - 24, 2018, Beijing, China

Organized by: National Lab for Superconductivity,

Institute of Physics, Chinese Academy of Sciences

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Scientific Presentation Time:

Plenary Talks: 40 mins (35 mins talk + 5 mins Q&A)
Invited Talks: 20 mins (15 mins talk + 5 mins Q&A)
Contributed Talks: 15 mins (12 mins talk + 3 mins Q&A)

Plenary talks

Pseudogap in cuprates, thermodynamic evidence for nematic phase transition

Y. Matsuda

Department of Physics, Kyoto University, Kyoto 606-8502, Japan

A long-standing controversial issue in the quest to understand the superconductivity in cuprates is the nature of the enigmatic pseudogap region of the phase diagram. Especially important is whether the pseudogap state is a distinct thermodynamic phase characterized by broken symmetries below the onset temperature T_{pg}.

Here we report torque-magnetometry measurements of anisotropic susceptibility [1] within the ab planes in orthorhombic YBCO with exceptionally high precision. The in-plane anisotropy along [100] direction (Cu-O-Cu direction) displays a significant increase with a distinct kink at T_{pg}, showing a remarkable scaling behavior with respect to T/T_{pg} in a wide doping range. The analysis reveals that the rotational symmetry breaking (nematicity) sets in at T_{pg} in the limit where the effect of orthorhombicity is eliminated [2].

We also performed the same measurements on simple tetragonal Hg1201 with single CuO_2 layer. Two-fold susceptibility anisotropy emerges spontaneously at T_{pg} , providing direct evidence of the broken rotational symmetry. These firmly establish that the nematic phase transition is universal in high-T_c cuprates. Surprisingly, unlike YBCO, the diagonal nematicity along [110] direction develops in Hg1201. Furthermore, the development of the diagonal nematicity is suppressed below the CDW order, implying that the nematicity competes with CDW [3].

In collaboration with Y. Sato, S. Kasahara, H. Murayama, Y. Kasahara (Kyoto Univ.), T. Shibauchi (Univ. of Tokyo), E.G. Moon (KAIST), T. Nishizaki (Kyushu Sangyo Univ.), T. Loew, J. Porra , B. Keimer (Max Planck), Y. Uchiyama (JASRI), A. Yamamoto (RIKEN), J. Cai, J. Freyermuth, and M. Greven (Univ. of Minnesota).

References

[1] S. Kasahara *et a*l. Nature **486**, 382 (2012).
[2] Y. Sato *et al*. Nature Phys. **13**, 1074 (2017).
[3] H. Murayama *et al*. arXiv:1805.00276.

High-temperature superconductivity in iron chalcogenides

Dunghai Lee

University of California, Berkeley, USA

Raising the superconducting transition temperature to a point where applications are practical is one of the most important challenges in science. In 1986 a family of superconducting materials, namely the copper-oxide superconductors, was discovered. To date, the highest transition temperature is ~140K. However, despite unprecedented research efforts, the precise cause of the high transition temperature is still controversial. In 2006 iron-based superconductors were discovered. To date, the highest superconducting transition temperature is found in FeSe-based compounds. These systems are made of entirely different materials, however, they share many common features with the copper-oxide superconductors. In particular, in 2012, a new interface high-temperature superconducting system was discovered in FeSe/$SrTiO_3$. In this talk, I shall explain the mechanism for strong Cooper pairing in this system and what it teaches us about finding even higher temperature superconductors.

What Makes Cuprate Superconductors so Amazing?

Ivan Božović[1,2]

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[2]*Applied Physics Department, Yale University, New Haven, CT 06520, USA*

When superconductivity was discovered, it presented a major puzzle that took four decades and many a failed attempt until it was finally solved by the BCS trio. Their theory then reigned unchallenged until the discovery of high-temperature superconductivity (HTS) in cuprates. Ever since, it has been debated whether essentially the same BCS picture applies to cuprates as well, or some qualitatively new physics is involved.

With this motivation, we have undertaken a very comprehensive experiment in which over 2,000 single-crystal LSCO films were grown by molecular beam epitaxy and studied over the course of 12 years. The key parameters of the normal and superconducting states — ρ, R_H, magnetoresistance, T_c, λ, ξ — have been measured precisely as a function of temperature T (down to 300 mK), magnetic field B (up to 90 T), doping, and in-plane azimuth angle ϕ. [1-3]

The key findings are as follows. (i) The superconducting phase stiffness is extremely low, comparable to T_c. (ii) The superfluid density $N_s(T)$ decreases linearly with T, up to T_c. (iii) T_c scales with N_{s0} linearly but with an offset, except very close to the dome edges where it scales as $\sqrt{N_{s0}}$. (iv) The superconducting state develops from an electronic nematic state that breaks the $\mathbf{C_4}$ symmetry of the underlying crystal lattice. (v) The electron fluid behaves as if it were comprised of two components, one Fermi-liquid (FL) like and the other showing ρ linear in T and B; with increased doping the later component diminishes and disappears, together with the nematicity, N_{s0}, and T_c.

The related results of other groups show that the above appears to be typical of HTS cuprates and independent on the details of the Fermi surface, the number of CuO_2 planes in the unit cell, the presence or absence of CuO chains, the density and the nature of dopants, the superconducting gap size, etc.

We conclude that HTS in cuprates involves some new physics, beyond the standard FL-BCS description. It seems to entail strong pairing, strong electron correlations, strong thermal phase fluctuations, and probably strong pair-breaking, intrinsic but T- and doping-dependent. Impurities and disorder are probably not essential, at least in the first cut.

These are just some broad conceptual constraints; much tighter ones are imposed by the particular surfaces in the (T,x,B,ϕ) space depicted by ρ, R_H, N_s, etc., which encode a wealth of incisive information about the physics of HTS, and may provide a new impetus to the theory — which in turn may lead to now discoveries.

References

[1] I. Božović, X. He, J. Wu and A. T. Bollinger, Nature 536**, 309 (2016).**
[2] J. Wu, A. T. Bollinger, X. He and I. Božović, Nature 547**, 432 (2017).**
[3] P. Girardo-Gallo *et al.,* Science 360 **(2018) in press.**

Superconducting Qubits Enable Quantum Control of Surface Wave Phonons

Andrew N. Cleland

Institute for Molecular Engineering and Argonne National Laboratory, University of Chicago, 5640 S Ellis Ave, Chicago IL 60637 USA

I report on a recent experiment using a superconducting qubit to both quantum-control and measure the 4 GHz fundamental mode of a surface acoustic wave (SAW) resonator. This experiment builds on prior work coupling superconducting qubits to SAW devices , here achieving full quantum control over the SAW mode and exceeding the control achieved over earlier bulk acoustic resonator-qubit experiments . The surface acoustic wave resonator was fabricated on bulk LiNbO3, a strong piezoelectric, combining a few-finger transducer with a pair of Bragg SAW mirrors. The structure was designed to have a single SAW mode centered at 4 GHz, with higher order modes outside the stop band of the mirror. A superconducting qubit (modified from the UC Santa Barbara gmon) was fabricated on a separate sapphire substrate, and the LiNbO3 chip with its SAW resonator was flip-chip bonded to the sapphire substrate, aligning the SAW transducer element to wiring on the qubit chip (Fig. 1). The qubit was inductively coupled to the SAW transducer through the 4 to 6 μm gap between the two chips, using a flux-controlled Josephson junction to provide variable coupling: The qubit could be completely isolated from the resonator, or coupled with up to about 6 MHz coupling strength. The qubit was characterized with the coupler off, showing good qubit T_1 and T_φ. With the variable coupler on, measurements of the qubit T_1 as a function of qubit frequency were used to measure the SAW electrical impedance, revealing the expected detailed structure of the transducer response. We then used the qubit to measure the SAW thermal phonon population, which was less than 0.02, as expected at the operating temperature of 7 mK; swap a single 4 GHz phonon in the SAW resonator and measure the phonon T_1 lifetime (148 ns); and swap a $|0\rangle+|1\rangle$ phonon state into the resonator and use it to measure the phonon T_2 lifetime (290 ns ≈2T_1); and finally use Wigner tomography to map the Wigner function of the phonon $|0\rangle,|1\rangle$ and $|0\rangle+|1\rangle$ states over the resonator phase space, showing good agreement with theoretical Wigner tomograms (Fig. 2).

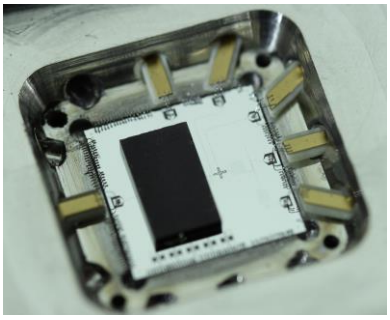

Fig. 1. *$LiNbO_3$ chip with SAW resonator (black), flip-chip coupled to 6mm by 6mm qubit chip (silver), wire bonded into a qubit mount*.

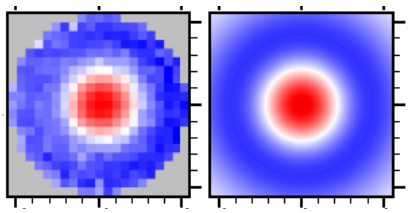

Fig. 2. *Wigner tomogram of the SAW resonator $|1\rangle$ phonon state, experiment (left) and theory (right). Horizontal axes are resonator phase space quadrature amplitude, extending from -1 to 1 (both horizontal and vertical) and color scale is $-2/\pi$ (center) to $+2/\pi$ (edge).*

M.V. Gustafsson et al., *Science* 346, 207-211, *2014; R. Manenti et al., Nature Comm., 8, 975 (2017); B.A. Moores et al., arXiv: 1711.05913 (2017)* A.D. O'Connell et al., *Nature* 464, 697-703 (2010); Y. Chu et al., *Science* 358, 199-202 (2017) Y. Chen et al, *Phys. Rev. Lett.* 113, 22052 (2014); M.R. Geller et al., *Phys. Rev. A* 92, 012320 (2015); C. Neill et al., *Nature Phys.* 12, 1037-1041 (2016)

Cooperative Interactions as a Route to High Temperature Superconductivity

Zhi-Xun Shen
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Scattering from high-temperature superconductors: new insights and perspectives

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We will summarize recent results and perspectives from neutron and resonant x-ray scattering experiments on cuprate superconductors, with a focus on the model compound $YBa_2Cu_3O_{6+x}$. Two sets of developments will be highlighted:

1. Charge density wave correlations and their interplay with superconductivity, including the response to biaxial and uniaxial strain, heterostructuring with other transition metal oxides (see the figure), and light illumination.

2. Spin correlations and their evolution over a wide range of doping levels, as well as high-precision measurements of their temperature-dependent lifetimes and their relationship to transport phenomena.

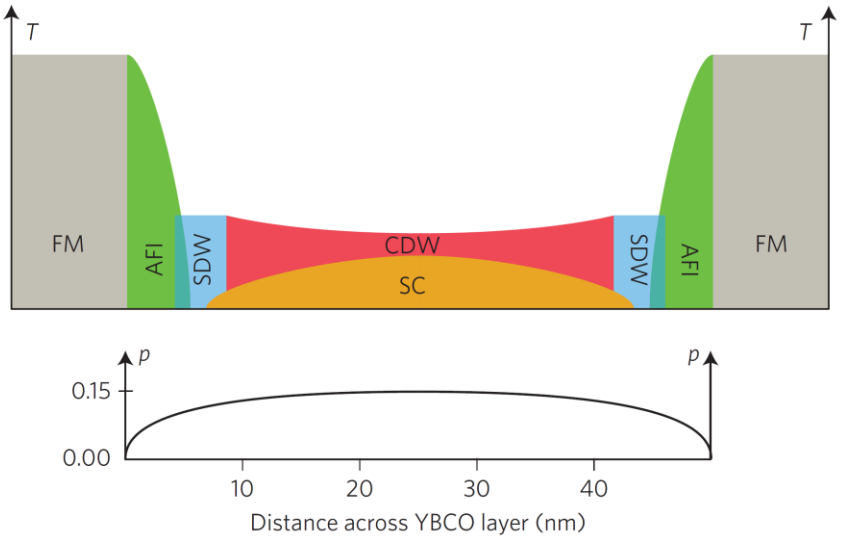

Fig. 1: *This schematic shows electronic ordering phenomena in a layer of the high-temperature superconductor $YBa_2Cu_3O_7$ (YBCO) between two ferromagnetic manganese-oxide layers as a function of temperature (T) and distance across the layer. FM = ferromagnetism, SC = superconductivity, AFI = antiferromagnetic insulator, SDW = spin density wave, CDW = charge density wave. The graph below shows the density of mobile charge carriers, p, as a function of distance. (reproduced from A. Frano et al., Nature Materials 15, 831 (2016)).*

Discovery and Exploration of the Cuprate Pair Density Wave State

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Cooper-pairs, if they have finite center-of-mass momentum $\boldsymbol{Q_P}$, can form a remarkable state in which the density of pairs modulates periodically in space at wavevector $\boldsymbol{Q_P}$. Intense theoretical interest has recently emerged in whether such a 'pair density wave' (PDW) state could, due to strong local electron-electron interactions, be another principal state in the phase diagram of underdoped cuprates. The most common model invoked is an eight unit-cell ($8a_0$) periodic modulation of the electron-pair condensate.

To search for a cuprate PDW at zero field, we developed a nanometer-resolution scanned Josephson tunneling microscopy (SJTM) to image Cooper-pair tunneling from a d-wave superconducting STM tip at millikelvin temperatures to the Cooper-pair condensate of underdoped $Bi_2Sr_2CaCu_2O_8$. The resulting images of the Cooper-pair condensate show clear pair-density modulations oriented along the Cu-O bond directions wavevectors $Q_P \approx (0.25,0);(0,0.25)2\pi/a_0$ [1].

Application of high magnetic fields in cuprates generates an exceptional electronic phase supporting exceptional quantum oscillations and an unidentified density wave state which may also be a PDW. To search for evidence of such a state at high fields, we visualize the modulations in the density of electronic states N(r) within the halo surrounding vortex cores. This revealed multiple signatures of a field-induced PDW, including two sets of N(r) modulations occurring at wavevectors $\boldsymbol{Q_P}$ and $\boldsymbol{2Q_P}$ both having predominantly s-symmetry form factors, the amplitude of the latter decaying twice as rapidly as the former. This is in detailed agreement with theory for a field-induced primary PDW that generates secondary CDWs within the vortex halo [2].

These data indicate that a PDW state exists in the superconducting and high-field pseudogap regimes of cuprates. Its order-parameter exhibits approximately eight CuO_2 unit-cell periodicity and predominantly d-symmetry form factor. We review the implications from these discoveries for the microscopic theory of the cuprate pseudogap phase.

References

[1] ***Nature 532,*** 343 (2016)

[2] **arXiv:1802.04673** & submitted ***Science*** (2018)

Quantum Criticality and Unconventional Superconductivity in Heavy Fermions

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Unconventional superconductivity (SC) often occurs near quantum critical points (QCPs) in antiferromagnetic (AF) heavy-fermion (HF) metals. The nature of the pairing symmetry of the first HF superconductor CeCu2Si2 [1], which is a prototype material for showing SC near a three-dimensional spin-density-wave QCP, has been the subject of recent controversy. While for many years this compound was considered to be a (single-band) d-wave superconductor [2], state-of-the-art measurements of the specific heat to temperatures as low as 30 mK on a high-quality S-type CeCu2Si2 single crystal revealed two-band SC with a fully developed gap at the lowest temperatures [3]. This led to claims of CeCu2Si2 being a two-band s-wave superconductor, with an either isotropic s++- [4, 5] or a loop-nodal s+-- [6, 7] state. To resolve this issue, a fully-gapped, effective two-band d-wave model was proposed [8], which was developed originally to explain weird properties of Fe-based superconductors by an orbital - selective pairing mechanism [9]. This 'd+d band-mixing Cooper pairing' model yields excellent fits to the temperature dependence of both the superfluid density, derived from the penetration depth [8], and the specific heat [3]. It also accounts for the sign change of the superconducting order parameter concluded from inelastic neutron-scattering data which occurs along the incommensurate nesting wave vector inside the dominating HF band [10]. Such a pairing model may be well applicable to a wider range of fully-gapped unconventional superconductors, including the case of a single CuO2 layer [11]. No SC has been detected down to 10 mK near the field-induced Kondo-destroying QCP in YbRh2Si2 [12]. However, recent results of magnetic and calorimetric low-field measurements on YbRh2Si2 reveal the onset of hybrid AF order ("A phase") dominated by the Yb-derived nuclear spins slightly above 2 mK as well as of HF SC at Tc = 2 mK [13]. The A phase was found to suppress the primary electronic AF order, which forms at TN = 70 mK, and to allow HF SC to develop. These results demonstrate a new way to approach the QCP in YbRh2Si2 and provide further support for unconventional SC near an AF QCP in a clean, stoichiometric HF metal being a robust phenomenon. Work performed in collaboration with G. M. Pang, M. Smidman, L. Jiao, J. L. Zhang, H. Q. Yuan, O. Stockert, H. S. Jeevan, P. Gegenwart, E. Schuberth, M. Tippmann, L. Steinke, M. Brando, A. Steppke, C. Krellner, E. M. Nica, R. Yu and Q. Si.

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Magic Angle Graphene: a New Platform for Strongly Correlated Physics

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The understanding of strongly-correlated quantum matter has challenged physicists for decades. Such difficulties have stimulated new research paradigms, such as ultra-cold atom lattices for simulating quantum materials. In this talk I will present a new platform to investigate strongly correlated physics, based on graphene moiré superlattices. In particular, I will show that when two graphene sheets are twisted by an angle close to the theoretically predicted 'magic angle', the resulting flat band structure near the Dirac point gives rise to a strongly-correlated electronic system. These flat bands exhibit half-filling insulating phases at zero magnetic field, which we show to be a Mott-like insulator arising from electrons localized in the moiré superlattice. Moreover, upon doping, we find electrically tunable superconductivity in this system, with many characteristics similar to high-temperature cuprates superconductivity. These unique properties of magic-angle twisted bilayer graphene open up a new playground for exotic many-body quantum phases in a 2D platform made of pure carbon and without magnetic field. The easy accessibility of the flat bands, the electrical tunability, and the bandwidth tunability though twist angle may pave the way towards more exotic correlated systems, such as quantum spin liquids.

The Pseudogap Critical Point of Cuprate Superconductors

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By suppressing superconductivity with a large magnetic field, we have investigated the metallic ground state of several cuprate superconductors in the $T = 0$ limit (YBCO, Bi2212, Bi2201, LSCO, Nd-LSCO, Eu-LSCO), via measurements of resistivity, Hall and Seebeck coefficients, thermal conductivity and specific heat. We observe a sharp transition at a critical doping p^* (red dot in Fig. 1), into the enigmatic pseudogap phase. The key signature is a drop in carrier density n from $n = 1 + p$ above p^* to $n = p$ below p^* [1,2], signalling a major transformation of the Fermi surface. At p^*, we observe the classic signatures of quantum criticality : the electrical resistivity is linear in T at low T, the electronic specific heat C_{el} shows a sharp peak at p^*, where it varies in temperature as $C_{el} \sim -T \log T$ [3]. Understanding the mechanisms responsible for these various signatures will help elucidate the nature of the pseudogap phase.

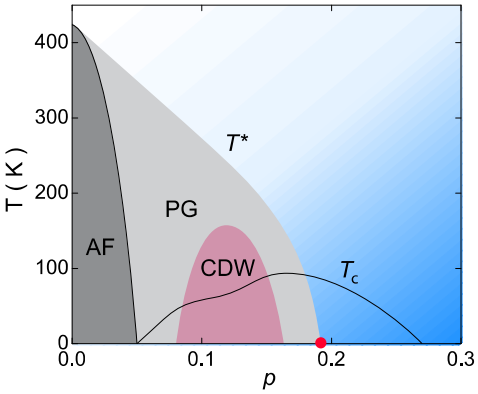

Fig. 1: *Schematic temperature-doping phase diagram of a hole-doped cuprate superconductor, once superconductivity has been removed by application of a large magnetic field. The zero-field critical temperature T_c is shown as a dotted line. The focus of this talk is the pseudogap (PG) phase (in grey), which ends at a critical doping p* (red dot). The phase of charge-density-wave (CDW) order (in burgundy) is peaked at p ~ 0.12 and it ends before p*.*

Work done in collaboration with: S.A.A. Afshar, P. Auban-Senzier, S. Badoux, J. Béard, S. Benhabib, D.A. Bonn, P. Bourgeois-Hope, C. Collignon, O. Cyr-Choinière, H. A. Dabkowska, D. Destraz, M. Dion, N. Doiron-Leyraud, M. Dragomir, P. Fournier, B.D. Gaulin, C. Girod, G. Grissonnanche, W.N. Hardy, J. Kačmarčík, T. Klein, T. Kurosawa, F. Laliberté, A. Legros, S.Y. Li, Z.Z. Li, R. Liang, S. Licciardello, Q. Ma, C. Marcenat, B. Michon, N. Momono, C. Proust, S. Pyon, H. Raffy, W. Tabis, H. Takagi, T. Takayama, S. Verret, B. Vignolle, D. Vignolles, S. Wiedmann, K. Yamada, and J.-S. Zhou.

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Progress on superconducting materials for high-field application in China

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Abstract: Practical superconducting material is currently one of the most important novel materials, and high-field superconducting magnet, like as fusion reactor, high-energy particle accelerator and nuclear magnetic resonance (NMR), is especially significant to practical application of superconducting materials. In this paper, we introduce the recent progress on a few of high-field superconducting materials at NIN and WST, including the Bi-2212, Nb_3Sn, and Nb_3Al strands. The result suggests that Bi-2212 is benefit of developing the superconducting magnets with a field up to 20 T~30 T, and Nb_3Sn could be used to make the superconducting magnets with a field of below 21.5 T. Because of outstanding strain-stress tolerance properties, Nb_3Al is a strong competitor for superconducting magnets application with a field at 10 T~15 T, comparing to Nb_3Sn superconductor.

Keywords: Bi-2212; Nb_3Sn; Nb_3Al; high-field application

Progress on Quantum Critical Metals

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Metallic quantum critical phenomena are believed to play a key role in many strongly correlated materials, including high temperature superconductors. Theoretically, the problem of quantum criticality in the presence of a Fermi surface has proven to be highly challenging. However, it has recently been realized that many models used to describe such systems are amenable to numerically exact solution by quantum Monte Carlo (QMC) techniques, without suffering from the fermion sign problem. I will review the status of the understanding of metallic quantum criticality, and the recent progress made by QMC simulations, focusing on the cases of spin density wave and Ising nematic criticality. The results obtained so far will be described, as well as their implications for superconductivity, non-Fermi liquid behavior, and transport in the vicinity of metallic quantum critical points. Some of the outstanding puzzles and future directions are highlighted.

Tunable Superconductivity and Phase Transitions by Field Effect Transistor

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Electric field is adopted to control physical performance via tuning the carrier density. Such controllability through an electrostatic doping greatly promotes the development of research and industry for semiconductors. However, conventional metal-insulator-semiconductor (MIS) FET can only sustain very limited carrier density. Consequently, researchers attempt to seek for FET with new gate dielectric, such as the electric double layer FET (EDL-FET) based on liquid ions. In this talk, we report high temperature superconductivity with an onset temperature above 40 K can be achieved in FeSe thin flake with Tc less than 10 K by tuning carrier with this EDL-FET technique [1]. We developed a novel FET device using solid ion conductor (SIC) as a gate dielectric. Based on this SIC-FET technique, we achieved an optimal Tc of 47 K in FeSe thin flakes. A superconductivity-insulating state transition is observed. Two new metastable structures of $Li_xFe_2Se_2$ are obtained due to the Li intercalation driven by electrical field [2]. A discrete superconducting phase diagram is observed in Li_xFeSe system [3]. Li ions can be driven in and out of the crystal based on the FET device using solid Li ion conductor as a gate dielectric, and many novel metastable structures can be obtained, and consequently a series of phase transitions take place in (Li,Fe)OHFeSe and MoS_2. Our works pave a way to access the metastable phase and control structural phase transformations as well as physical properties by the electric field.

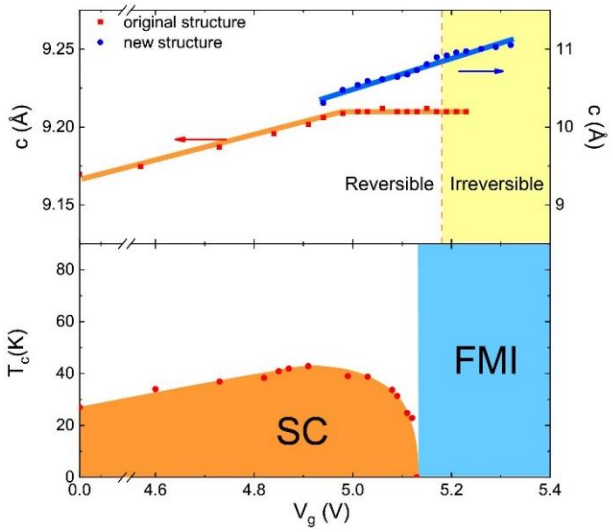

Fig. 1: *Phase diagram tuned by electric field with SIC-FET device in (Li,Fe)OHFeSe.*

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Invited and contributed talks

Collapse of superconductivity in cuprates via ultrafast quenching of phase coherence

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The possibility of driving phase transitions in low-density condensates through the loss of phase coherence alone has far-reaching implications for the study of quantum phases of matter. This has inspired the development of tools to control and explore the collective properties of condensate phases via phase fluctuations. Electrically gated oxide interfaces, ultracold Fermi atoms and cuprate superconductors, which are characterized by an intrinsically small phase stiffness, are paradigmatic examples where these tools are having a dramatic impact. Here we use light pulses shorter than the internal thermalization time to drive and probe the phase fragility of the Bi2Sr2CaCu2O8+δ cuprate superconductor, completely melting the superconducting condensate without affecting the pairing strength [1]. The resulting ultrafast dynamics of phase fluctuations and charge excitations are captured and disentangled by time-resolved photoemission spectroscopy. This work demonstrates the dominant role of phase coherence in the superconductor-to-normal state phase transition and offers a benchmark for non-equilibrium spectroscopic investigations of the cuprate phase diagram.

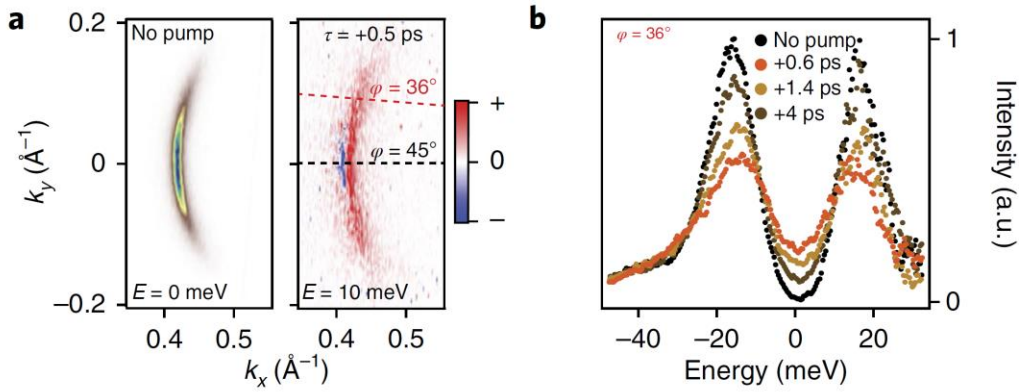

Fig. 1: *Ultrafast gap filling via enhancement of phase fluctuations.* ***a****, Equilibrium Fermi surface mapping (left panel) and differential (Pump on−Pump off) isoenergy contour mapping at 10 meV above the Fermi level E_F, 0.5 ps pump–probe delay (right panel). The integration energy range is 10 meV and kx is aligned along the Γ–Y direction. The dashed black and red lines in the right panel define the nodal and off-nodal cuts investigated in the present work.* ***b****, Off-nodal EDC at k = kF (φ = 36°) normalized to momentum-integrated nodal EDC (φ = 45°) at different pump–probe delays, F < FC fluence (FC ≈ 15 μ J cm^{-2}). EDCs have been deconvoluted from the energy resolution broadening.*

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The attraction between antiferromagnetic quantum vortices as origin of superconductivity in hole-doped cuprates

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We propose as key of superconductivity in hole-doped cuprates novel excitations of magnetic origin, characteristic of two-dimensions and of purely quantum nature: the antiferromagnetic spin vortices. The CuO planes of the cuprates are described in terms of a t-J model whose empty sites correspond to Zhang-Rice singlets. In this approach the charge pairing arises from a Kosterlitz-Thouless-like attraction between antiferromagnetic spin vortices centered on empty sites in different Nèel sublattices. This charge pairing induces also the spin pairing through the action of a gauge force generated by the no-double occupation constraint imposed in the t-J model. Superconductivity arises from coherence of pairs of excitations describing Zhang-Rice singlets and it is not of standard BCS type. We show that many experimental features of hole-doped cuprates can find a natural explanation in this formalism.

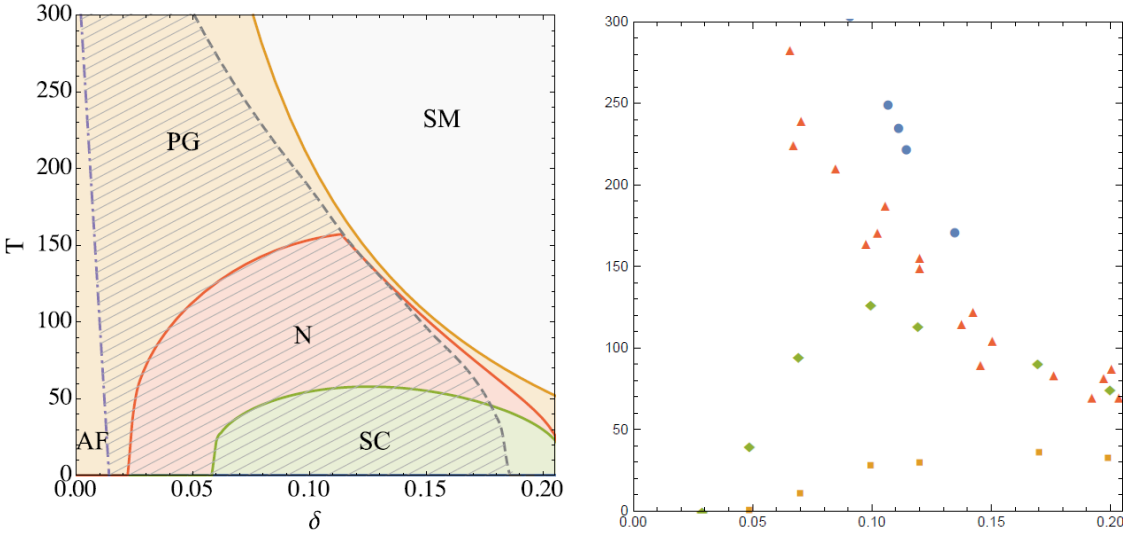

Fig. 1: *Left: theoretically derived phase diagram: charge pairing temperature (yellow line), spin pairing temperature (red line) , crossover small-large FS (dashed line), Tc (green line). Right: experimental data for Tc (yellow squares) and onset of Nernst signal (green diamonds) in LSCO,"low pseudogap" (red triangles) in LSCO and "high pseudogap" (blue circles) in YBCO.*

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Unusual superconducting gap in the cuprates: The Raman study on Bi2223

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The superconducting gap of the cuprates in the pseudo-gapped state is unusual. The maximum gap amplitude seems to increase with decreasing the doping level *p*, in spite of the decrease of the superconducting transition temperature T_c. This unusual behavior has been established in many mono- and bilayer cuprates, although its origin has not been well understood. Here we have extended our Raman study to the triple layer curpate $Bi_2Sr_2Ca_2Cu_3O_z$ (Bi2223) to investigate its gap energy size as well as its doping dependence[1]. Using four crystals with different doping levels, we found a double pair-breaking peak in the B_{1g} Raman spectrum which corresponds to the pair-breaking peak in the inner (IP)- and outer (OP)-CuO_2 plane. This implies that the doping levels of IP and OP are different, as was previously reported by NMR[2] and ARPES[3]. We first examined the doping dependence of the gap in each layer, and found that all the B_{1g} gap energies can be plotted on a single line (*p*) if we take into account the doping level of each layer. Although the gap energy is different in the IP and OP, the T_c values are the same in these layers, which indicates some interaction between the layers. The observed gap size was so large that it does not scale with T_c. Such a large gap could be an indication of a possible superconductivity at higher temperatures, as suggested by a precursor of superconductivity in the optical spectra of $YBa_2Cu_3O_y$[4, 5].

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High Temperature Superconductivity in Monolayer $Bi_2Sr_2CaCu_2O_{8+\delta}$

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The two-dimensional CuO_2 plane plays a fundamental role in the physics of cuprates. Indeed, cuprates (and all other families of high temperature superconductors) adopt a layered atomic structure. In $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), the weak van der Waals interaction between adjacent bismuth-oxygen layers makes the crystal easily cleavable, making atomically-thin Bi2212 an ideal system for investigating high temperature superconductivity in the two-dimensional limit. By fabricating samples in an inert atmosphere, we are able to obtain half-unit-cell-thick single crystals (referred to as monolayer) of Bi2212 samples and to probe the evolution of superconductivity as the dimensionality is reduced. We probe the electronic structure of monolayer Bi2212 with electronic transport measurements, as well as scanning tunneling microscopy (STM) and scanning tunneling spectroscopy (STS) techniques.

TBA

Alessandra Lanzara
Lawrence Berkeley National Lab, USA

The Superconducting Phase Diagram of High-T_c Cuprates

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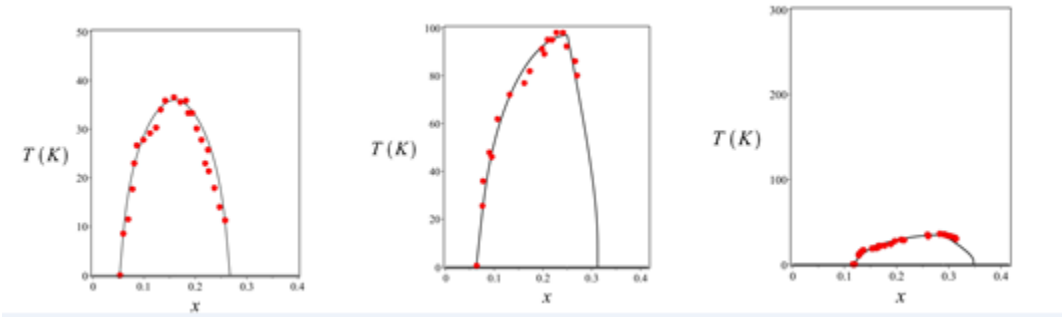
Understanding the mechanism of high-Tc superconductivity in the cuprate materials is, at the same time, one of the most fascinating and challenging problems in physics. Thirty years after the experimental discovery of superconductivity in such materials, we still do not have a theoretical framework that would allow us to describe, for instance, the details of the phase diagram of the cuprates. In this work, we address some basic issues of the superconducting part of such phase diagrams. We derive, in particular, analytic expressions for Tc(x), the critical temperature as a function of doping for such materials. These exhibit the well-known dome-shaped superconducting phases, which are in excellent agreement with the experimental data for materials such as LSCO, Bi2201 and Hg1201. Our results imply the optimal doping occurs when the oxygen sublattice of the CuO_2 planes is half-filled and the increase of the optimal temperature with the number of such planes can be simply understood as an enhancement of the relevant coupling parameter. Our starting point is a Dirac-BCS fermion theory, which is assumed to describe the dynamics of the active electron-holes in the cuprates, irrespective of the underlying microscopic mechanism responsible for the Cooper pair formation.



Phase diagrams of LSCO, Hg1201 and Bi2201. Solid line from our analytic expression arXiv 1805.08264

Stripes and Topological States in FeSe Film

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We report on low-temperature scanning tunneling microscopy studies of the multilayer FeSe films grown on $SrTiO_3$ by molecular beam epitaxy. We find a stripe-type charge ordering instability [1], which develops beneath the nematic state. The emergence of stripes indicates a magnetic fluctuation, competing with the ordinary collinear antiferromagnetic order in FeSe films. The existence of stripes in iron-based superconductor that resemble the stripe order in cuprates provides a platform to reveal the complex interactions between nematicity, magnetism and superconductivity in high-temperature superconductors. Besides that, a possible topological state is observed in the vicinity of the nematic edges [2], which might originate from the in-plane lattice expansion of the FeSe film.

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High resolution laser-ARPES on topological superconductivity on surface

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I would like to talk on topological superconductivity on the surface of an iron-based superconductor and topological surface states of bismuth selenide on niobium by using ultra-high-resolution angle-resolved photoemission spectroscopy(ARPES).

Topological superconductors are predicted to host exotic Majorana states that obey non-Abelian statistics and can be used to implement a topological quantum computer. Most of the proposed topological superconductors are realized in difficult-to-fabricate heterostructures at very low temperatures. By using high-resolution spin-resolved and angle-resolved photoelectron spectroscopy, we find that the iron-based superconductor $FeTe_{1-x}Se_x$ (x = 0.45; superconducting transition temperature Tc = 14.5 K) hosts Dirac-cone–type spin-helical surface states at the Fermi level; the surface states exhibit an s-wave superconducting gap below Tc. Our study shows that the surface states of $FeTe_{0.55}Se_{0.45}$ are topologically superconducting, providing a simple and possibly high-temperature platform for realizing Majorana states. [1]

A topological insulator film coupled to a simple isotropic *s*-wave superconductor substrate can foster helical pairing of the Dirac fermions associated with the topological surface states. Experimental realization of such a system is exceedingly difficult, but using a novel "flipchip" technique, we have prepared single-crystalline Bi2Se3 films with predetermined thicknesses in terms of quintuple layers (QLs) on top of Nb substrates fresh from *in-situ* cleavage. Our angle-resolved photoemission spectroscopy (ARPES) measurements of the film surface disclose superconducting gaps and coherence peaks of similar magnitude for both the topological surface states and bulk states. The ARPES spectral map as a function of temperature and film thickness up to 10 QLs reveals key characteristics relevant to the mechanism of coupling between the topological surface states and the superconducting Nb substrate; the effective coupling length is found to be much larger than the decay length of the topological surface states. [2]

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Topological superconductivity and Majorana bound state in Fe-based superconductors

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In this talk I will report our recent discoveries of topological superconductivity and Majorana bound state in Fe-based superconductors, mostly in Fe(Te, Se) single crystals. We have discovered a superconducting topological surface state of Fe(Te, Se) with Tc ~ 14.5K by using high-resolution ARPES. By using high-resolution STM on this material, we clearly observe a pristine Majorana bound state inside a vortex core, well separated from non-topological bound states away from zero energy due to the high ratio between the superconducting gap and the Fermi energy in this material. This observation offers a new, robust platform for realizing and manipulating Majorana bound states, which can be used for quantum computing, at a relatively high temperature. We have also found that most of Fe-based superconductors, including monolayer Fe(Te, Se)/STO, have similar topological electronic structures.

Topology meets High Tc Superconductivity in the $FeTe_{1-x}Se_x$ family.

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Low energy, laser-based ARPES with variable light polarization, including both linear and circularly polarized, is used to examine the Fe-based superconductor family, $FeTe_{1-x}Se_x$. At the center of the Brillouin zone we observe the presence of a Dirac cones with helical spin structure as expected for a topological surface state and as previously reported in the related $FeTe_{0.55}Se_{0.45}$.[1] These experimental studies are compared with theoretical studies that take account of the disordered local magnetic moments related to the paramagnetism observed in this system. Indeed including the magnetic contributions in the theoretical description is necessary to bring the chemical potential of the calculated electronic band structure into alignment with the experimental observations. In the bulk superconducting state for $FeTe_{0.7}Se_{0.3}$ the system appears to reflect the presence of some level of orbital selectivity in the pairing even though the system is in the tetragonal phase above and below the transition temperature T_c. At the same time the topological state appears to acquire mass at the superconducting transition. These observations are discussed in detail.

This work was carried out in collaboration with N. Zaki, J.D. Rameau, and G.D. Gu at BNL and M. Weinert in the Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin. The work at Brookhaven was supported in part by the U.S. DOE under Contract No. DE- SC0012704 and in part by the Center of Computational Design of Functional Strongly Correlated Materials and Theoretical Spectroscopy. The theoretical studies (MW) at UWM were supported by the National Science Foundation (No. DMR-1335215).

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Quantum Anomalous Vortex and Majorana Zero Mode in FeSeTe Superconductors

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The spin-orbit coupling (SOC) in FeSeTe produces a topological Dirac fermion surface state [1, 2], which has been detected by ARPES experiments [3] recently. The lightly electron doped surface state acquires a pairing gap below T_c by the natural proximity to the fully gapped bulk FeSeTe superconductor. On this premise, we demonstrate that the robust zero-bias conductance peaks observed originally in STM experiments [4] at the interstitial/excess Fe sites are indeed localized Majorana zero energy modes. We show that the local moments induced by the excess Fe and the SOC are able to generate superconducting vortices in the absence of an external magnetic field. We term such a spontaneous vortex a quantum anomalous vortex (QAV). The QAV nucleates around an excess Fe due to the coupling of the angular momentum and the local magnetization that lowers its energy compared to the energy of the vortex-free solution. We find that Majorana zero modes (MZM) emerge spontaneously from the topological surface state at the center of the QAV core without external magnetic fields. Moreover, the finite angular momentum Caroli-de Gennes states inside the QAV will be shown to be pushed to the energy of the bulk pairing gap. The latter significantly enhances the stability of the MZM. The obtained tunneling conductance in the QAV is in excellent agreement with the findings of the STM experiments [4]. The QAV thus provides a new and advantageous platform for the realization and manipulation of robust localized MZM.

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Topological Superconductivity on the Surface of Fe-Based Superconductors

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(Received 9 December 2015; revised manuscript received 19 May 2016; published 18 July 2016)

As one of the simplest systems for realizing Majorana fermions, the topological superconductor plays an important role in both condensed matter physics and quantum computations. Based on ab initio calculations and the analysis of an effective 8-band model with superconducting pairing, we demonstrate that the three-dimensional extended s-wave Fe-based superconductors such as $Fe_{1+y}Se_{0.5}Te_{0.5}$ have a metallic topologically nontrivial band structure, and exhibit a normal-topological-normal superconductivity phase transition on the (001) surface by tuning the bulk carrier doping level. In the topological superconductivity (TSC) phase, a Majorana zero mode is trapped at the end of a magnetic vortex line. We further show that the surface TSC phase only exists up to a certain bulk pairing gap, and there is a normal- topological phase transition driven by the temperature, which has not been discussed before. These results pave an effective way to realize the TSC and Majorana fermions in a large class of superconductors.

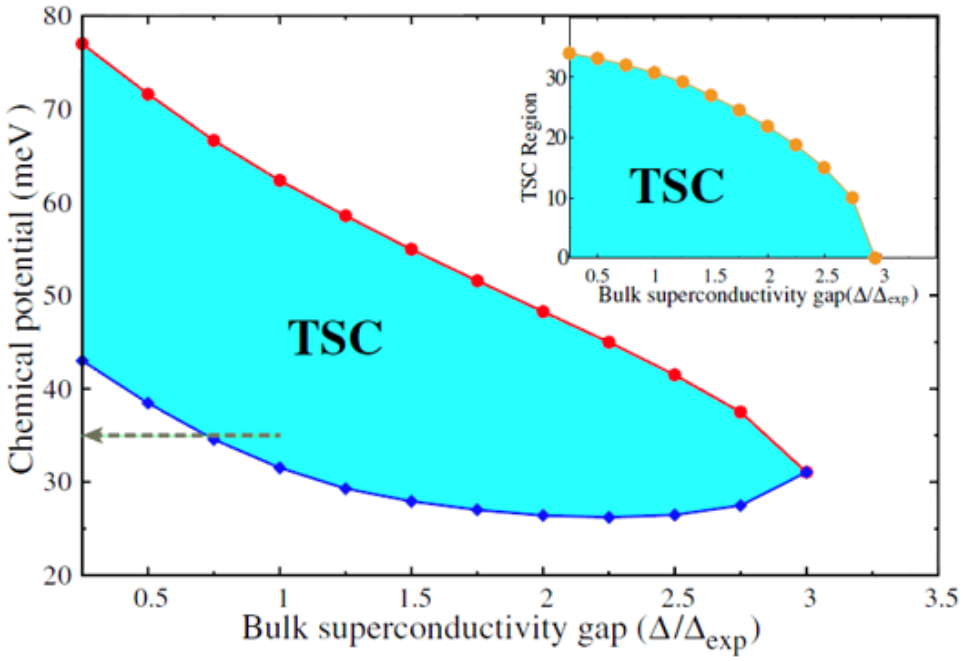

Fig. 1: TSC phase space vs bulk superconducting gap. The red and blue lines are the upper and lower phase boundaries of the TSC phase, respectively. The gray dash at μ=35 meV indicates a TSC at 0 K ($\Delta = \Delta_{exp}$) to NSC ($\Delta \sim 0$) phase transition with temperature increasing. The inset shows an evolution of the TSC region (red line minus blue line) with respect to the bulk pairing gap.

Two-dimensional superconductivity in few-layer stanene

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Two-dimensional superconductors exhibit rich quantum phenomena such as the Griffiths singularity and an extremely large in-plane critical magnetic field. Here we report the discovery of superconductivity in few layer stanene, which is unexpected because bulk gray tin is semi-metallic and non-superconductive [1]. We grow high quality stanene films on PbTe/Bi_2Te_3/Si(111) substrate via molecular beam epitaxy (Fig. 1 **a**). Superconductivity emerges in bilayer stanene and the transition temperature increases with the thickness of stanene (Fig. 1 **b**). We also modulate the superconducting properties by tuning the thickness of the PbTe layer (Fig. 1 **c**). Through transport and angle-resolved photoemission spectroscopy, we reveal the two-band nature of this superconductor. Our experimental studies are further supported by first-principles calculations, which suggest a topological non-trivial band structure.

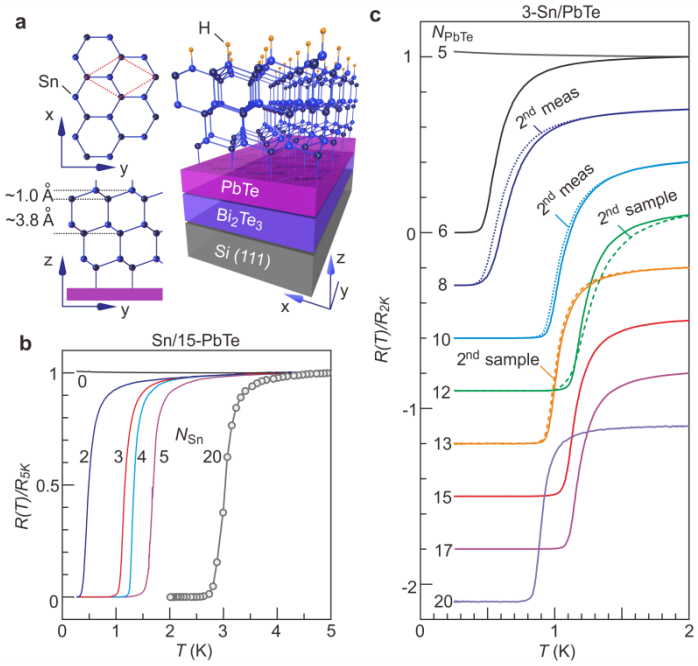

Fig. 1: *Superconductivity of few-layer stanene. (a) schematic illustration of the lattice structure of a trilayer stanene grown on top of PbTe/Bi_2Te_3/Si(111) substrate. The dangling bonds on the top layer of stanene are presumably saturated by hydrogen. (b) Normalized resistance of stanene samples as a function of temperature. The PbTe has a nominal thickness of 15 layers. (c) Normalized resistance of trilayer stanene grown on PbTe with different thicknesses. Dotted (dashed) curves indicate the data from the second cool-down (second sample).*

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Quantum phase transitions in gate-induced 2D superconductivity

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In the past decade, technological advances of materials fabrication have led to discoveries of a variety of highly crystalline two-dimensional (2D) superconductors at heterogeneous interfaces and in ultrathin films [1]. These systems are offering opportunities of searching for superconductivity at higher temperatures as well as investigating the physical properties of 2D superconductors, which are distinct from the conventional 2D superconductors with the amorphous or granular structure. Thus the new 2D superconductors could be a new plat form of physics of 2D superconductivity.

Among a variety of fabrication methds of 2D superconductors, ionic gating is a powerful tool. Gate-controlled electrostatic carrier doping with electric double layer transistors (EDLTs) has served to search for new superconductors an to establish T_c vs. carrier density phase diagrams in vairous gate-induced superconductivity. Furthurmore, it has been clarified that gate-induced sperconductivity is a new class of noncentrosymmetric 2D superconductors, which exhibits enhanced Pauli-limit due to the spin-valley locking, nonreciprocal superconducting transport, and quantum phase transitions [1].

Here we discuss the vortex phase diagram in crystalline 2D superconductors. In sharp contrast to the conventional amorphous 2D superconductors, the phase diagram is dominated by the quantum metallic state, owing to the strong quantum fluctuations [2, 3]. Furthermore, the 2nd harmonic resistance measurement on noncentrosymmetric MoS_2 revealed that the vortex dynamics in gated MoS_2 with in-plane broken inversion symmetry can be regarded as a quantum ratchet.

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Superconductivity in Topological Semimetals

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Topological semimetals have become one of most important topics in condensed matter physics. By using metallic tip to carry out hard point contact measurements, we detected the unconventional superconductivity at the contact on the surface of single crystalline and non-superconducting 3D Dirac semimetal Cd_3As_2 [1] with some signatures showing the possibility of topological superconductivity.[2] The hard point contact method has been demonstrated reliable in the study of topological metal Au_2Pb [3]. By using tip point contact method, we also discovered the unconventional superconductivity on Weyl semimetal TaAs.[4] Besides, by ultralow temperature transport measurements and STM studies, we observed unconventional quasi-1D superconductivity in time invariant type II Weyl semimetal $TaIrTe_4$ with minimum Weyl points. [5] The induced or detected superconductivity in topological semimetals pave a way to realize and detect topological superconductivity, which is expected to host Majorana fermions at the edge state and has attracted much attention.

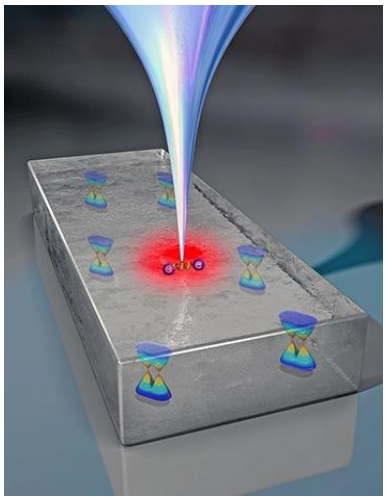

Fig. 1: *Unconventional superconductivity induced by hard tip on the surface of topological semimetal*

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[3] npj Quantum Materials 1, 16005 (2016)
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[5] arXiv:1805.10883

Superconductivity in Bi/Ni bi-layer system

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Coexistence of both Ising and Rashba type spin textures in monolayer $NbSe_2$

Shuyun Zhou

Department of Physics, Tsinghua University

The strong coupling between multiple degrees of freedom in transition metal dichalcogenides, e.g. spin-valley and spin-layer locking, not only leads to interesting electronic, spin and valley properties, but also affects correlated phenomena like superconductivity, e.g. Ising superconductivity as reported in monolayer $NbSe_2$. While the origin has been attributed to Ising paring – enhanced pairing between electrons with opposite out-of-plane spin components, so far direct experimental evidence on the three-dimensional spin texture has been missing. Here by using spin- and angle-resolved photoemission spectroscopy (ARPES), we show that both the out-of-plane Ising-type and in-plane Rashba-type spin polarizations are critical for a complete understanding of the spin physics and its impact on intriguing correlation phenomena in monolayer NbSe2.

Unconventional 2D Superconductors: The Out-Of-Equilibrium Response to A Laser Pulse

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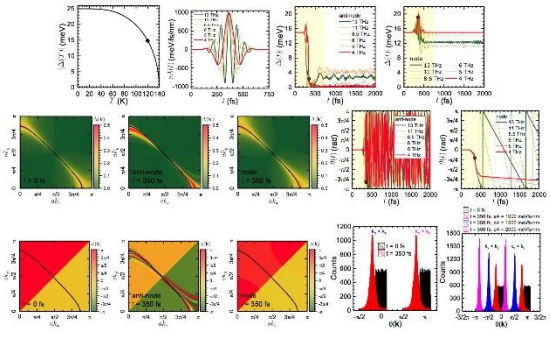
The dynamics of a 2D (un)conventional BCS superconductor, with a square-lattice tight-binding dispersion, driven out-of-equilibrium by a perpendicularly-impinging polarized laser pulse is analyzed in great detail on varying the temperature and the laser pulse characteristics (intensity, polarization, frequency) with respect to the maximum gap amplitude. The observed effects include: oscillations both in the amplitude and in the phase of the superconducting order parameter, suppression of the superconductivity, but also its enhancement with a strong dependence on all varying parameters and, in particular, on the polarization in plane of the applied vector potential and on the value of its intensity. The microscopic understanding of these effects is obtained by studying thoroughly the evolution of the amplitude and the phase of the momentum-dependent components of the gap (the complex pair amplitudes). This study opens up the possibility, for the d-wave case, to distinguish very clearly the behavior of the nodal and anti-nodal thermal and non-thermal excitations and explain some of the puzzling results of the current experimental scenario in the field. Moreover, by using a random initial value of the phase of the pair amplitude in momentum space has been demonstrated that it is possible to enhance the superconducting phase coherence through MID-IR excitations.



Figs. (1-3,1-5): *Relevant behaviors of gap amplitude Δ [vs temperature T (1,1)] and phase θ vs time t [(1,3-4), (2,4-5)], vector potential A vs t (1,2), pair amplitude modulus Λ and phase ϕ versus momentum* ***k*** *(2,1-3), (3,1-3), distribution of ϕ close to pulse maximum (t = 350 fs) for a random starting of value of ϕ at t = 0 (3,4) and different values of fluences of the applied electric field (3,5).*

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Nonreciprocal charge transport in noncentrosymmetric superconductors

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Nonlinear responses are an important subject both scientifically and from the viewpoint of applications. An example is the rectification by diode using pn-junction, i.e., nonlinear and directional I-V characteristics. We will discuss this nonlinear and nonreciprocal charge tarnsport in noncentrosymmetric superconductors such as the transition metal dichalcogenide MoS_2 [1] and superconductors with Rashba spin-orbit interaction, e.g., $SrTiO_3$ [2,3], in their resistive states. There are variety of physical mechanims for this nonreciprocal transport, i.e., the warping of energy dispersion, the mixing of singlet and triplet pairings, modified Bardeen-Stephan dissipation, and ratchet motion of vortices. Comparison with recent experiments will be also made.

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[3] S. Hoshino, R. Wakatsuki, K. Hamamoto, and N. Nagaosa, arXiv:1805.05735

Fit to Superconduct? – Cooper Pairing in Materials with reduced Symmetry

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The presence of inversion and time reversal symmetry is traditionally considered as the essential preconditions to form zero-momentum Cooper pairs (ZMCP) and constitutes the basis of Anderson's theorems. In this talk we will generalize these theorems introducing the concept of superconducting fitness to assess the stability of Cooper pairing states solely based on the normal state properties of the electronic system irrespective of the pairing interactions. This can be applied to complex materials involving several orbital, layer, sub-lattice or valley degrees of freedom. For this purpose, we define fitness functions as a simple theoretical tool. Several examples will be discussed to illustrate the application of the fitness concept. Moreover, we discuss the minimal symmetries required for two-dimensional superconductors to form ZMCPs and show that time reversal and inversion are not required, but that combinations of these symmetries with the mirror operation on the basal plane would be sufficient. This allows us to classify possible Cooper pairing states with their nodal structure. Using the fitness functions, we then provide possible structures of the gap functions. This discussion is likely relevant for some of the transition metal dichalcogenides. Our analysis can provide guidance to design superconductors with specific pairing symmetries and may allow to eliminate material features detrimental for a certain form of pairing.

Superconductivity with broken time reversal symmetry

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Center for Correlated Matter and Department of Physics, Zhejiang Uniersity

Unconventional superconductivity with additional symmetry breaking has been one of the most attractive topics in condensed matter physics during recent decades. Here we will present our recent studies on a few superconductors where the time reversal symmetry (TRS) is broken upon entering the superconducting state. $LaNiC_2$ and $LaNiGa_2$ display simple metallic behavior in the normal state and our measurements demonstrate the presence of two fully open superconducting gaps in these two compounds [1,2]. On the other hand, the muSR measurements provide evidence for TRS breaking below Tc [3,4]. These results allow us to propose a nonunitary triplet pairing state, which both breaks TRS and leads to nodeless two-gap superconductivity, and therefore accounts well for the seemingly contradictory experimental results of $LaNiC_2$ and $LaNiGa_2$ [1]. In addition, we have recently synthesized a few new noncentrosymmetric superconductors, which also break time reversal symmetry below T_c [5]. We performed various measurements to characterize the superconducting order parameter, and the possible pairing states will be discussed.

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Superconductivity in Weakly Correlated Noncentrosymmetric Systems

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Superconductivity in absence of inversion symmetry of the crystal structure (NCS SC) is basically controlled by a Rashba-like antisymmetric spin orbit coupling which splits the Fermi surface and removes the spin degeneracy of electrons. The Fermi surface splitting can originate a mixing of spin-singlet and spin-triplet states in the superconducting condensate. The presence of spin-triplet states is expected to be responsible for various uncommon features of the superconducting ground state. Experimentally, distinct deviations from the expectations of the BCS theory are found, in general, only in those systems where besides the missing of inversion symmetry strong correlations among electrons are present. Materials of this group are primarily based on Ce, Yb or U.

The present work intends to comprehensively map the much larger group of materials without substantial electronic correlations and classifying their superconducting properties with respect to broken symmetries. Recent experimental data on NCS SCs LaPtSi and HfRhGe, in the context of DFT derived results, indicate that the mere presence of a strong ASOC does not necessarily lead to unconventional behaviour

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Unconventional Superconductivity in Noncentrosymmetric Superconductors

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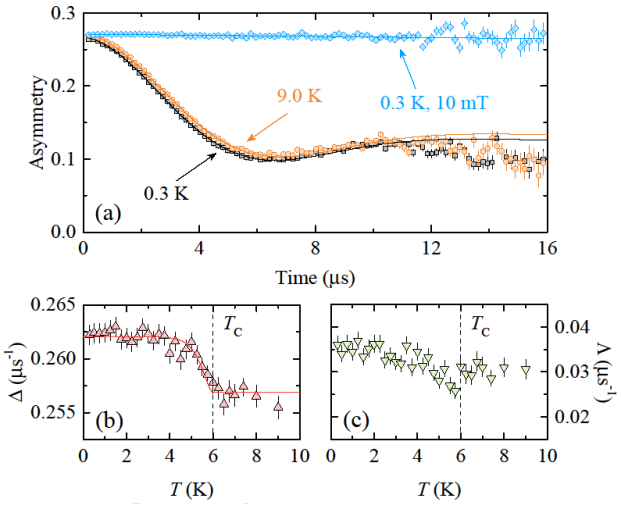
Recently, there has been a great deal of interest in noncentrosymmetric superconductors (NCS) due to the complex nature of their superconducting properties. The lack of inversion symmetry in these materials induces an antisymmetric spin-orbit coupling (ASOC), which causes mixed singlet-triplet superconducting ground state. This mixed pairing can lead noncentrosymmetric superconductors to display significantly different properties from conventional superconducting systems. However, despite intense theoretical and experimental efforts, the superconducting properties of NCS remain uncertain, a key question still remains unresolved regarding the role of ASOC and the pairing mechanism of NCS's.



signal below T_C in Δ (ZF-μSR) confirms TRSB in Re_6Hf.

In order to answer these questions, we systematically study two families of compounds having two different noncentrosymmetric crystal structure cubic *α-Mn*: Re_6X [X = Hf, Ti] and hexagonal: La_7X_3 [X= Ir, Rh] to understand the role of SOC and crystal structure of the pairing mechanism of NCS. Both the families contain heavy elements, in which SOC is usually expected to be strong, which in turn, can enhance the parity mixing ratio. Our experimental results confirm complex superconducting properties with time-reversal symmetry breaking (TRSB) observed in Re_6X [1,2], and La_7X_3 [3]. Interestingly, the emergence of identical results for all the members of Re_6X and La_7X_3 family of compounds suggests that ASOC seems essential to induce a TRS breaking in NCSs, but its strength is not a crucial condition.

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Theoretical Analysis of the Energy-, Momentum- and Temperature-Dependent Quasiparticle Self-Energies in BSCCO Superconductors

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A new methodology for the analysis of Angle-Resolved Photoemission Spectroscopy (ARPES) data taken for cuprate high-temperature superconductors [1] offers qualitatively new insight into the physics of these systems. It provides a consistent explanation of both EDCs and MDCs in terms of effective quasiparticles in a Nambu-Gor'kov framework whose self-energies result in the broadening and renormalization of an underlying bare band. Thus ARPES may now be used as a spectroscopy which allows the extraction of fully energy- and momentum-resolved single-particle self-energies. We focus on the evolution of these highly anisotropic quantities as functions of temperature. Both the real and imaginary parts of the self-energy are strong in the normal (anomalous metal) phase. As the pairing gap begins to develop at a temperature T_{pair}, which lies approximately 30 K above the temperature, T_C, of superconducting coherence, the self-energies show a strong temperature-dependence: the imaginary part falls dramatically as quasiparticle scattering is reduced, and the real part shows a concomitant strong peak. We consider the strength of this effect for quasiparticles in all parts of the Brillouin zone and discuss the connection between the two temperature scales and the nature of the paired states.

[1] Coherent organization of electronic correlations as a mechanism to enhance and stabilize high-T_C cuprate superconductivity, H. Li, X. Zhou, S. Parham, T. J. Reber, H. Berger, G. B. Arnold and D. S. Dessau, Nature Communications **9**, 26 (2017).

Genes of Unconventional High Temperature Superconductors

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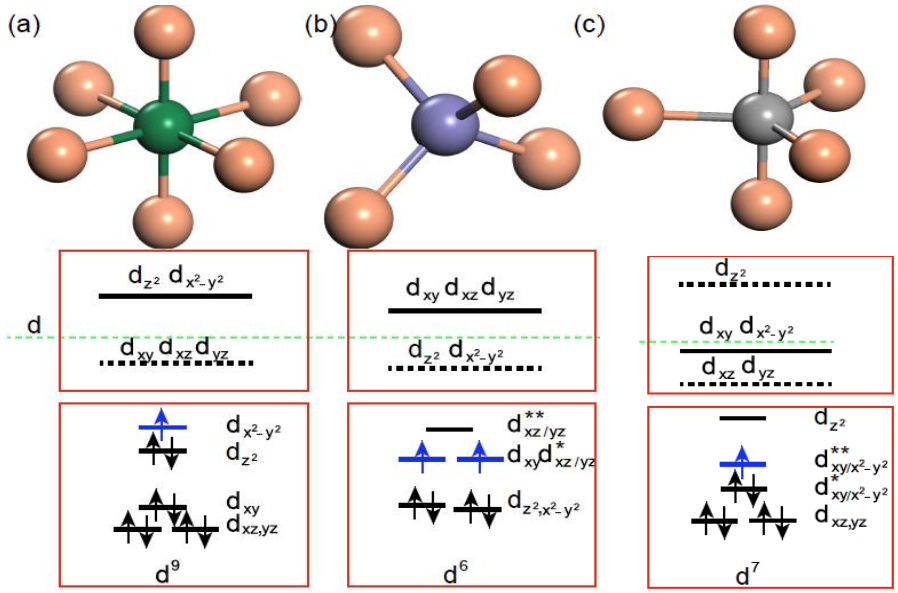
In the past, both cuprates and iron-based high temperature superconductors (High Tc) were discovered accidentally. Lacking of successful predictions on new high Tc is one of major obstacles to reach a consensus on unconventional high Tc mechanism. In this talk, we address the key question related to these two special materials: Why are Cu and Fe special? We answer this question by suggesting a common electronic gene behind these two families of materials. The common electronic gene explains their rareness as unconventional high Tc superconductors and can guide us to search for new high Tc materials. We extend this idea to predict possible unconventional high Tc superconductors. Verifying the prediction can convincingly establish high Tc superconducting mechanism and pave a way to design new high Tc superconductors.



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Mimicking Cuprates with Silver and Fluorine

Jakub Gawraczyński[1,2], Dominik Kurzydłowski[1,3], Wojciech Gadomski[2], Zoran Mazej[4], Giampiero Ruani[5] , Ilaria Bergenti[5], Tomasz Jaroń[1], Andrew Ozarowski[6], Stephen Hill[6,7], Piotr J. Leszczyński[1], Kamil Tokár[8], Mariana Derzsi[1], Paolo Barone[9], Krzysztof Wohlfeld[10], José Lorenzana*[11] and Wojciech Grochala*[1]

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Analogs of cuprates without cooper can pave the way to new quantum materials exhibiting exotic magnetic states and perhaps new high-T_c superconductors. Despite several attempts, materials that reproduce the key cuprate characteristics (spin-1/2, quasi 2D behavior, high superexchange constant) have not been found. A natural choice is to replace Cu d^9 by Ag d^9. As will be discussed, this requires replacing O by F to retain a positive charge transfer energy. AgF_2 (**Fig. 1**) results to be an excellent analog of parent cuprates. Density functional theory show remarkably similar electronic parameters in both materials. Furthermore, Raman scattering shows that the superexchange interaction reaches 70% of cuprates[1]. We argue that structures that reduce or eliminate the buckling of the AgF_2 planes could have an antiferromagnetic coupling that matches or surpasses the cuprates potentially leading to high-T_c superconductivity.

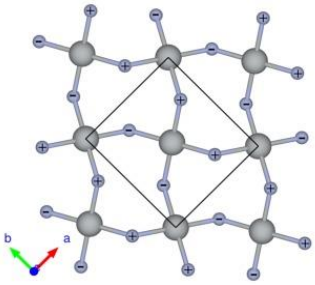

Fig. 1: *Schematic view of an* AgF_2 plane.

References

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Experimental tests of the AdS-CFT description of cuprate strange metals

S. Smit[1], L. Bawden[1], M. Berben[1], S.V. Ramankutty[1], Y. Huang[1], A. Krikun[2], M. Allan[2], K. Schalm[2], J. Zaanen[2], T. Kim[3], P. Dudin[3], E. van Heumen[1] and M.S. Golden[1]

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The strange metal phase found in the normal state of the cuprate high Tc superconductors is one the most enduring puzzles in condensed matter physics. Recently, a Dutch national research program has started up, with the key challenge being a broad-based experimental test of the efficacy of AdS-CFT based approaches to describe the strange metal state, with ARPES as one of the key experiments.
To generate experimental data free of complications due to both the bilayer splitting and diffraction replicas due to the super-modulation, floating-zone grown single CuO_2-layer, Pb-doped $Bi_2Sr_2CuO_6$ is the material of choice. High quality, high-resolution ARPES data have been recorded from made-to-measure single crystals over a wide energy range as a function of temperature, such as the data shown in the left-panel of the figure. The subsequent analysis centres on the energy and temperature dependence of the self-energy, resulting in data like those shown in the right-hand panel of the figure.

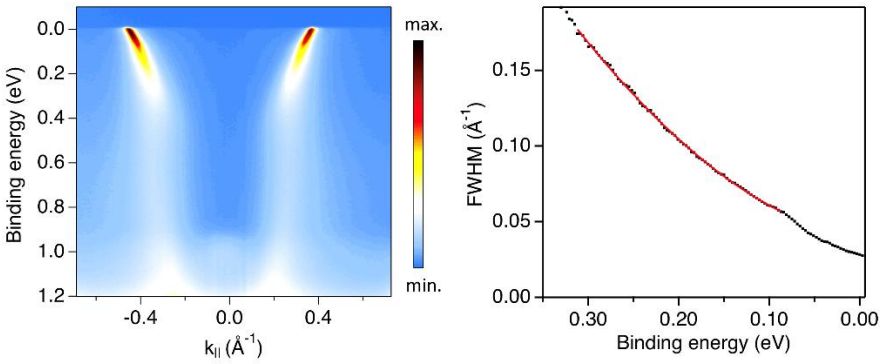

Fig. 1: ARPES data from single-layer (Pb,Bi)SrCuO-2201
Left panel: nodal cut recorded at 8K using a photon energy of 28eV.
Right-panel: exemplary self-energy data from MDC fits to the data (black) and self-energy fit (red).

The self-energy data in the right-hand panel can be fitted with a power law. In the case of these low T data, there is still significant phonon-related structure in the self-energy, so we start the fit at frequencies above this structure. As the right-panel shows, the power law works well (red line), and in this case, the frequency dependence shows an exponent of 1.7. In this talk, the doping, temperature and k-dependence of such exponents in the ARPES data will be presented and compared to predictions arising from holographic theoretical techniques.

Dark Fermion Theory and *Ab Initio* Studies on Cuprate Superconductors

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We study effective Hamiltonians for the cuprate superconductors derived from *ab initio* scheme called constrained GW formalism without adjustable parameters [1]. The Hamiltonian is solved and the phase diagram for *d*-wave superconducting ground state severely competing with the stripe state is obtained in quantitative agreement with the experimental phase diagram. This is in contrast to the simple Hubbard model results [2], where most of the doping concentration is governed by the stripe states over the superconducting state. A theory of doped Mott insulators is further presented in the light of recent understanding on the singular self-energy structure of the single-particle Green's function. The cancellation of the normal and anomalous self-energy contribution in the Green's function obtained in the cluster dynamical mean-field studies as well as in the machine learning analysis of the photoemission data is the evidence for the existence of the dark fermion. The dark fermion induces the high-temperature superconductivity in the anomalous part, while it generates Mott gap and pseudogap in the normal part [3,4]. Here, we elucidate that fractionalization of electrons, which is exactly hold in the Mott insulator in the atomic limit, more generally produces the emergent Mott-gap fermion and dark fermion in itinerant cases without any spontaneous symmetry breaking [5]. The two gaps are the consequences of the hybridization of these two fermions with bare electrons. The mechanism is discussed in terms of more general concept of gap physics, where comparison is made with that caused by conventional spontaneous symmetry breaking known over condensed matter and elementary particle physics including quantum chromodynamics. We further propose that the Mott-gap and dark fermions are the fermionic component of Frenkel- and Wannier-type excitons, respectively, which coexist in the doped Mott insulator. The Bose-Einstein condensation of the Frenkel-type excitons allowed without spontaneous symmetry breaking holds a key for understanding the unique pole structure and the pseudogap through the instantaneous hybridization between the quasiparticle and the dark fermion.

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Zero Energy States at a Normal--Cuprate-Superconductor Interface Probed by Shot Noise

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We report[1] measurements of the current noise generated in optimally doped x=0.15 Au-$La_{2-x}Sr_xCuO_4$ junctions. For high transmission junctions on (110) surface we observed split zero-bias conductance peaks (ZBCP), accompanied by enhanced shot noise. We attribute the enhanced noise to Cooper pair transport through the junctions. We observed no enhanced noise in low-transmission junctions on (110) surface or in any junction on (100) surface.

Current noise generated in a munt-channel junction due to both finite temperature and charge discreteness can be expressed as (Γ_n is the transmission of n's channel):

$$S_q = 2qI(1-\tilde{\Gamma})\coth\left(\frac{qV}{2k_BT}\right)+2k_BT\tilde{\Gamma}(G(0)+G(V)), \quad \tilde{\Gamma}=\frac{\sum\Gamma_n^2}{\sum\Gamma_n} \qquad (1)$$

In Fig.1 we show the noise[1] generated by a high-transmission junction; for comparison we plot by the dashed line the expectation for the noise S_e from Eq. (1) using $q=e$. We used $\tilde{\Gamma}\approx 0.4$ (corresponding to Fano factor $F=0.6$) to fit the *slope* of the data at large voltages at which the transmission is, presumably, constant. The data for this sample could be reasonably fit with temperature-independent $\tilde{\Gamma}$. At temperatures T=10.3 K and 7.3K the fit is good, it even reproduces the small maximum at V=0 due to enhanced thermal noise at ZBCP. At lower temperatures, and voltages below 1mV the experimental data lies above the expectation from Eq. (1), see inset in panel (b), with largest deviation at the lowest temperature of 2.7K. The observed enhanced noise coincides with the *maximal possible* noise S_e (shown in Fig.1 by the solid line) expected for charge-e carriers in the case $\tilde{\Gamma}=0$. Since both the temperature dependence of the noise at large voltages, and relatively small Fano are inconsistent with such a small $\tilde{\Gamma}$, we conclude that the noise in the zero-bias peak region at low temperatures must have charge $q=2e$ contribution.

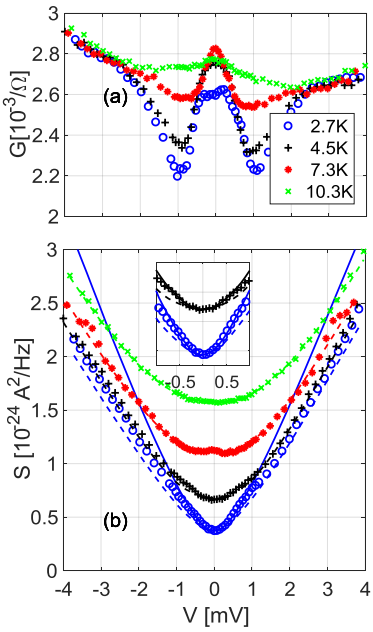

Fig. 1: *(a) Differential conductance of a high-transmission junction. The ZBCP and minima on its sides are suppressed with heating at temperatures much smaller than the bulk T_c. (b) Experimental results for the noise.*

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Electronic Self-Energies in Cuprates Beyond EDCs and MDCs – Self-Energy Conversion and Positive Feedback on the Pairing Interactions

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While it has long been recognized that the electronic interactions play the critical role in cuprate physics, we have to date only had approximate information about these interactions, with ARPES giving some of the most detailed and specific information. In particular, via the analysis of one-dimensional EDC and MDC cuts we have obtained information about the single particle self energies, though this information has remained approximate at best; MDCs have for example been favored near the node where the dispersion is large and gaps small, and EDCs have been favored near the antinode where the gaps are large. To solve this problem we have developed a new 2-dimensional ARPES analysis technique that fully encompasses both EDCs and MDCs, is automatically Kramers-Kronig self-consistent (i.e. is causal), and has orders of magnitude fewer parameters than fitting each EDC or MDC separately. With this we argue that not only the self-energies but also the electronic parameters (band energies, gaps, velocities, etc.) are more reliably extracted.

We apply this new technique to ARPES data on superstructure-free Pb-doped Bi2212 crystals, focusing on the antinodal regime where the pairing interactions and the self-energies are the most important. We quantitatively show how the "strange metal" diffusive interactions in the normal state are "undressed" or removed in the superconducting state in a novel way such that they are converted into a strongly renormalized coherent state, with stronger normal state correlations leading to stronger superconducting state renormalization. Further, we show that this conversion begins well above T_C at the onset of superconducting fluctuations and that it greatly increases the number of states that can pair. Therefore, there is positive feedback—the superconductive pairing creates the conversion that in turn strengthens the pairing. While such positive feedback could enhance a conventional pairing mechanism, it could also potentially sustain a fully electronic pairing mechanism.

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Effects of Reduction Annealing on Electron-Doped Cuprates Revealed by ARPES and Core-Level Spectroscopy

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It has been well known that reduction annealing is necessary to realize superconductivity in the electron-doped cuprates with the T' crystal structure, in addition to the Ce-atom substitution. Recently, however, improved annealing methods were shown to induce superconductivity in bulk crystals with Ce concentrations as low as ~ 5% and in thin films without Ce substitution. We have performed systematic studies of the effects of the new annealing methods using ARPES [1,2] and core-level spectroscopy [3], and found that the annealing dramatically suppresses antiferromagnetic correlations and increases the electron carrier concentration as well as Tc over a wide electron doping range. The result means that a significant amount of oxygen atoms are removed from the block layer and/or the CuO_2 plane, thereby providing the system with a large amount of electron carriers.

This work has been done in collaboration with M. Horio, C. Lin, T. Mizokawa, K. Horiba, H. Kumigashira, T. Anzai, M. Arita, H. Namatame, M. Taniguchi, S. Ideta, K. Tanaka, S. Shin, H. Wadati, A. Yasui, E. Ikenaga, Y. Krockenberger, H. Yamamoto, T. Adachi, and Y. Koike.

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Electron Number-Based Phase Diagram of $Pr_{1-x}LaCe_xCuO_{4-\delta}$ and Possible Absence of Disparity between Electron- and Hole-Doped Cuprate Phase Diagrams

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We performed annealing and angle resolved photoemission spectroscopy studies on electron-doped cuprate of $Pr_{1-x}LaCe_xCuO_{4-\delta}$ (PLCCO). It is found that the optimal annealing condition is dependent on the Ce content x. The electron number (*n*) is estimated from the experimentally obtained Fermi surface volume for *x*=0.10, 0.15 and 0.18 samples. It clearly shows a significant and annealing dependent deviation from the nominal *x*. In addition, we observe that the pseudo-gap at hot spots is also closely correlated with *n*; the pseudogap gradually closes as n increases. We established a new phase diagram of PLCCO as a function of *n*. Different from the *x*-based one, the new phase diagram shows similar antiferromagnetic and superconducting phases to those of hole doped ones. Our results raise a possibility for absence of disparity between the phase diagrams of electron- and hole-doped cuprates

From Mott to Not: Dirty d-wave state of overdoped cuprates

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I argue that recent measurements on both the superfluid density and the optical conductivity of high-quality LSCO films can be understood almost entirely within the theory of disordered BCS d-wave superconductors[1,2]. The large scattering rates deduced from experiments are shown to arise predominantly from weak scatterers, probably the Sr dopants out of the CuO2 plane, and correspond to significant suppression of T_c relative to a pure reference state with the same doping. Our results confirm the "conventional" viewpoint that the overdoped side of the cuprate phase diagram can be viewed as approaching the BCS weak-coupling description of the superconducting state, with significant many-body renormalization of the plasma frequency. They suggest that, while some of the decrease in T_c with overdoping may be due to weakening of the pairing, disorder plays an essential role. I discuss how a general picture of the overdoped cuprates may be obtained by comparing with other experiments and materials.

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Direct Observation of Multi-Band Physics in the Cuprate Superconductor $La_{2-x}Sr_xCuO_4$

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Whereas single-band theories have long been the dominating paradigm applied to cuprate superconductors [1], recent theoretical studies have highlighted the implications of orbital hybridization in the cuprates. Hybridization of the d_{x2-y2} band with the d_{z2} band increases with reducing apical oxygen height which in turn lowers the superconducting transition temperature [2,3].

In light of these theoretical predictions, we have performed angle-resolved photoemission spectroscopy (ARPES) studies on the cuprate $La_{2-x}Sr_xCuO_4$ (x = 0.23) [4,5]. By recording ARPES spectra down to ~ 2 eV below the Fermi level, not the only well-documented d_{x2-y2} band but also the d_{z2} band was successfully identified. We clearly observed a hybridization gap between those two bands along the antinodal (, 0) direction, which is the direct experimental evidence of the orbital hybridization [4]. This is in stark contrast with the nodal (,) direction where the opposite mirror symmetry between the d_{x2-y2} and d_{z2} band prohibits their hybridization. Indeed, we demonstrated by ARPES that this symmetry-protected band crossing represents the first example of two-dimensional type-II Dirac fermions (strongly tilted Dirac cone) [5]. Our results thus indicate that the multi-band nature in cuprates involves a wealth of physics: from high-temperature superconductivity to symmetry-protected band structures.

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Continuous doping of a cuprate surface: new insights from *in-situ* ARPES

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The cuprate superconductors distinguish themselves from the conventional superconductors in that a small variation in the carrier doping can significantly change the superconducting transition temperature ($\boldsymbol{T_c}$), giving rise to a superconducting dome where a pseudogap[1,2] emerges in the underdoped region and a Fermi liquid appears in the overdoped region. Thus a systematic study of the properties over a wide doping range is critical for understanding the superconducting mechanism. Here, we report a new technique to continuously dope the surface of $Bi_2Sr_2CaCu_2O_{8+x}$ through an ozone/vacuum annealing method. Using *in-situ* ARPES, we obtain precise quantities of energy gaps and the coherent spectral weight over a wide range of doping. We discover that the d-wave component of the quasiparticle gap is linearly proportional to the Nernst temperature that is the onset of superconducting vortices[3], strongly suggesting that the emergence of superconducting pairing is concomitant with the onset of free vortices, with direct implications for the onset of superconducting phase coherence at $\boldsymbol{T_c}$ and the nature of the pseudogap phenomena.

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Interplay between AF correlations and PG phase in electron-doped cuprates

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In recent years, various angle-resolved photoemission spectroscopy (ARPES) studies focused on electron-doped cuprate superconductors to explore the similarities and differences between the two sides of the cuprates phase diagram [1]. Contrary to the hole-doped counterpart, antiferromagnetic (AF) correlations in the electron-doped side are stronger, offering the unique opportunity to explore the close interplay between AF, superconductivity, and other underlying phases. Here we report an out-of-equilibrium study on the optimally-doped $Nd_{2-x}Ce_xCuO_4$ (NCCO, x=0.15) electron-doped cuprate superconductor. By exploiting time-resolved ARPES (TR-ARPES), we investigate the transient evolution of the AF-driven pseudogap (PG) by tracking the modifications of the low-energy electronic states upon a pump excitation. In particular, we can extract the temporal evolution of the PG at the hot-spot (blue circle in Fig.1a) as a function of the transient electronic temperature. The observed behavior qualitatively fits the temperature dependence of the spin correlation length as reported from neutron scattering measurements [2], suggesting the loss of long-range AF order as the main cause of the observed recovery of the spectral weight at the hot spots along the Fermi surface (Fig.1b). We will show that these experimental results can be indeed reproduced by allowing only a filling of the PG while maintaining the gap size. These results indicate the emergence of a true order parameter in the PG phase, and provide evidence for the primary role of long-range AF correlations in determining the PG phase transition in electron-doped cuprates.

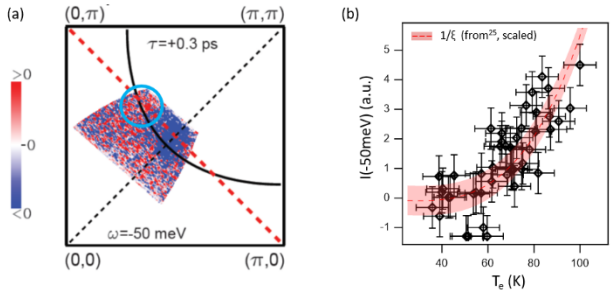

Fig. 1: (a) *Differential iso-energy contours map at τ=+0.3ps pump-probe delay at ω=-50meV, highlighting the increase of spectral weight at the hot-spot region (light blue circle).* (b) *Photoemission intensity at the hot-spot, as obtained by integrating in the blue circle displayed in (a), as a function of the electronic temperature (black circles). The red transparent shadow is the inverse of the spin correlation length ξ extracted from [2], appropriately scaled and offset.*

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Two Dome Structure in High Tc Iron-based Superconductors

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We reported a two dome structure in Tc-x relation of $LaFeAsO_{1-x}H_x$ (Iimura et al.Nat.Com.2012) and an AFM phase with different magnetic moment is located near the edge of each dome (Nat.Phys.2014)). Other 1111 systems such as Sm has a very broad dome ranging to x=~0.5 and the optimal Tc is >40K. We found two AFM phases with a different magnetic moment are located near the edge of a broad Tc dome in $SmFeAsO_{1-x}D_x$ using ^{154}Sm-substituted samples (Iimura et al. PNAS 2017). When high pressure was applied to La-1111 system, the two domes were merged into a single dome with the optimal Tc=52K (Takahashi et al. Sci.Rep. 2015). These results suggest the higher Tc>40K is realized by merging two dome structure. This idea was substantiated by the results on $SmFeAs_{1-y}P_yO_{1-x}H_x$ in which electron concentration are chemical pressure are independently tuned by x and y, respectively. When Tc>40K, one dome structure is seen, but two dome structure appears when Tc<40K (Matsuishi et al.PRB 2014).

Recently, two dome structure was reported in other system, $Li_{1-x}Fe_xOHFe_{1-y}Se$ (Sun et al.Nat.Com.2018) and $Li_x(NH_3)_yFeSe$ (shahi et al. PRB 2018). Both systems give two Tc domes when pressure is applied. The second Tc dome appearing at higher pressure has Tc>50K and T-dependence of in the normal state is linear (n=1). Such a situation is similar to $LaFeAsO_{1-x}H_x$. These findings suggest a global phase relation (Fig.1) would be present among Tc, electron concentration, local structure around Fe and AFM parent phases.

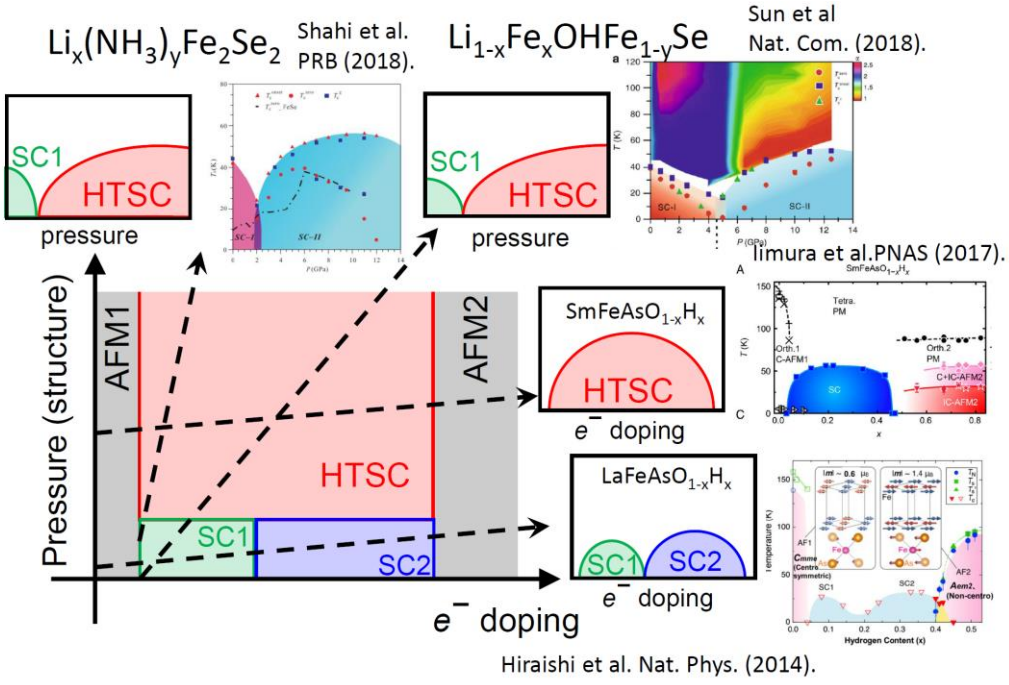

Fig.1. A speculative phase diagram explaining observed findings.

Superconductivity and nematicity in FeSe:

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Bulk FeSe is a special iron-based material in which superconductivity emerges inside a well-developed nematic phase. I will argue that the nematicity (spontaneous breaking of C4 lattice rotational symmetry) is the consequence of d-wave orbital order, which distinguishes between dxz and dyz orbitals. Recent STM and ARPES studies detected the shapes of hole and electron pockets in the nematic phase. The geometry of the pockets indicates that the sign of the orbital order is different between hole and electron pockets. I argue that this sign change cannot be reproduced if one solves for the orbital order within mean-field approximation, but it is reproduced once we include the renormalizations of the vertices in d-wave orbital channel. I next move to the superconducting state and analyze the gap anisotropy. I present the model for the nematic superconducting state, which takes into account the mixing between s-wave and d-wave pairing channels and the changes in the orbital spectral weight promoted by the sign-changing nematic order parameter. I show that nematicity gives rise to a cos2 variation of the pairing gap on the hole pocket, whose magnitude agrees with ARPES and STM data for experimentally-extracted Fermi surface parameters. I further argue that, dxz and dyz orbitals give nearly equal contributions to the pairing glue, i.e. nematic order alone accounts for the gap anisotropy, but has little effect on Tc. I compare our approach and the concept of orbital-selective pairing.

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Interface-Induced Superconductivity at Ambient Pressure in Undoped and Doped (FeAs)122 Single Crystals

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Non-bulk superconductivity has been detected in undoped single-crystalline $AeFe_2As_2$ (Ae122) with Ae = Ca, Ba, and Sr. Recently, superconductivity has been reversibly induced in undoped $CaFe_2As_2$ (Ca122) single crystals with T_c at ~25 K at ambient pressure and up to 30 K at 1.7 GPa. We found that Ca122 can be stabilized in two distinct tetragonal (T) phases: PI with a nonmagnetic collapsed tetragonal (cT) phase at low temperature and PII with an antiferromagnetic orthorhombic (O) phase at low temperature. Neither phase at ambient pressure is superconducting down to 2 K. However, systematic annealing for different time periods at 350 °C on the as-synthesized crystals reveals the emergence of superconductivity over a narrow time window. Detailed X-ray diffraction profile analyses further reveal mesoscopically stacked layers of the PI and the PII phases. The deduced interface density correlates well with the superconducting volume measured. The transport anomalies of the T-cT transition and the T-O transition are gradually suppressed over the superconductive region, presumably due to the interface interactions between the nonmagnetic metallic cT phase and the antiferromagnetic O phase. Our most recent STEM data display 8-20 nm domains in the superconducting Ca122 samples at 90 K. The results provide the most direct evidence to date for interface-enhanced superconductivity in undoped Ca122, consistent with the recent theoretical prediction. Similar results have recently also been obtained in Sr122 and Ba122, all pointing to the interfacial origin for the non-bulk superconductivity at ~ 20 K in the members of the Ae122 family.

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Electronic phase separation, charge transport and spin nematicity in iron selenide superconductors

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By developing the novel methods of hydrothermal ion-exchange [1] and ion-release [2], and matrix-assisted hydrothermal epitaxial growth (MAHEG) [3], we succeeded in synthesizing a series of big and high-quality single crystals of intercalated (Li, Fe)OHFeSe and prototypal FeSe, and thin films of (Li, Fe)OHFeSe, respectively.

We observed an evident drop in the magnetization at T_{afm} ~125 K, in the powder [4] and single crystal [5] samples of both non-superconducting and superconducting (T_c < ~38 K, cell parameter c < ~9.27 Å) (Li, Fe)OHFeSe. This indicates mesoscopic-to-macroscopic coexistence of an antiferromagnetic (AFM) state below T_{afm} with the normal or superconducting state. Such coexistence can be explained by electronic phase separation, similar to that in high-T_c cuprates and iron arsenides. A microscopic electronic phase separation was proposed for (Li, Fe)OHFeSe samples showing no magnetic drop at ~125 K. However, this static phase separation reaches vanishing point in high-T_c (~42 K) (Li, Fe)OHFeSe, as suggested by the occurrence of two-dimensional AFM spin fluctuations below nearly the same temperature as T_{afm} [1]. A complete phase diagram for (Li, Fe)OHFeSe was thus established [5].

In the (Li, Fe)OHFeSe film samples, we found that both the electron and hole carriers contribute to the charge transport [3], in contrast to the previous ARPES reports for the absence of hole Fermi pockets. Moreover, the values of electron and hole mobility, which become rather high and distinct from each other in high-T_c samples, tend to diverge prior to the superconducting transition.

In the binary FeSe single crystals, we identified a spin-nematic order below a characteristic temperature T_{sn} by in-plane angular-dependent magnetoresistance and magnetism measurements, and found a universal linear relationship between the T_c and T_{sn} [2].

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Interface Enhanced Superconductivity in Monolayer FeSe on MgO(001)

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Interface enhanced superconductivity over 50 K has been discovered in monolayer FeSe films grown on several TiO_2-terminated oxide substrates [1-4]. Whether such phenomenon exists in other oxide substrates remains an extremely interesting topic to investigate. We prepared monolayer FeSe films both on bulk MgO(001) substrates and on MgO bilayer epitaxial on $SrTiO_3$(001) substrates, and then investigated the superconducting properties by transport and scanning tunneling spectroscopy (STS) measurements in combination with scanning transmission electron microscopy characterization on the interface structures. The most important finding is that we observed a superconducting transition with onset temperature of 18 K in monolayer FeSe on bulk MgO(001) by transport [5] and a superconducting gap of 14-15 meV in monolayer FeSe/bilayer-MgO/$SrTiO_3$(001) by STS. We discussed the interface enhanced superconductivity in monolayer FeSe on MgO(001) from viewpoints of interface charge transfer and interface electron-phonon coupling as we learnt from monolayer FeSe on $SrTiO_3$ [4,6,7]. Our findings suggest that superconductivity enhancement in monolayer FeSe films on oxides substrates is rather general as long as charge transfer is allowed at the interface, thus points out an explicit direction for searching for new high temperature superconductivity by interface engineering.

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Exploration of layered superconducting materials via structural design

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Most layered superconducting materials contain superconductively active layers (SCALs). This structural feature allows us to design new superconductors in the same superconducting family. In this context, the essence of the structural design is to put new block layers into the SCALs so as to make a stable or metastable intergrowth compound. The new intergrowth material is then potentially superconducting.

In this talk, I will overview the recent development along this line, focusing on the exploration of iron-based superconductors via design [1]. The successful examples include (1) self-electron-doped $Ba_2Ti_2Fe_2As_4O$ [2], (2) self-hole-doped $AB_2Fe_4As_4X_2$ (A = K, Rb, Cs; B = Ca, rare earth; X = F, O) with double FeAs layers [3-7], (3) non-charge-doped ThFeAsN [5], and (4) self-electron-doped $Eu_3Bi_2S_4F_4$ [8]. Through these explorations, we find that the lattice match is crucial for stabilization of the intergrowth structure.

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Scanning SQUID-on-tip thermal imaging: Glimpse into dissipation in quantum systems down to atomic scale

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Energy dissipation is a fundamental process governing the dynamics of classical and quantum systems. Despite its vital importance, direct imaging and microscopy of dissipation in quantum systems is currently impossible because the existing thermal imaging methods lack the necessary sensitivity and are unsuitable for low temperature operation. We developed a scanning nanoSQUID with sub 50 nm diameter that resides at the apex of a sharp pipette [1] acting simultaneously as nanomagnetometer with single spin sensitivity and as nanothermometer providing cryogenic thermal imaging with four orders of magnitude improved thermal sensitivity of below 1 μK [2]. The non-contact non-invasive thermometry allows thermal imaging of minute energy dissipation down to the level equivalent to the fundamental Landauer limit for continuous readout of a single qubit. These advances enable observation of changes in dissipation due to single electron charging of a quantum dot and visualization and control of heat generated by electrons scattering off a single atomic defect in graphene [3], opening the door to direct imaging and spectroscopy of dissipation processes in quantum systems.

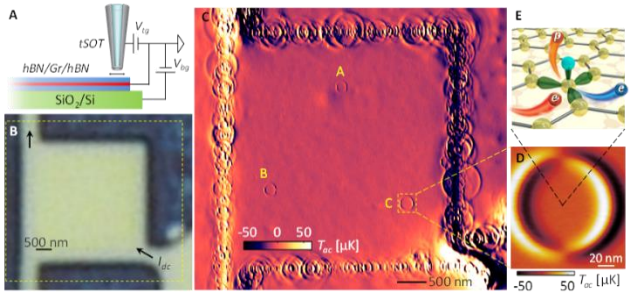

Fig. 1: *(A) Schematic measurement setup. (B) Optical image of the graphene device with 3 μA dc current driven through the constrictions. (C) Scanning ac nano-thermometry of the area outlined in (B) at 4.2 K. The sharp rings (D) reveal individual atomic defects in graphene (E) that mediate inelastic scattering of impinging electron (red) into phonon (orange) and lower energy electron (blue).*

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Practical low-Tc SQUID Systems for Geophysics Applications

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The sensitivity of low-Tc superconducting quantum interference device (SQUID) is independent of frequency and external magnetic field environment at low frequency range (< 100 Hz), thus playing an indispensable role in outdoor geophysics prospecting. To overcome the challenge of strong transient magnetic field change and radio-frequency interference, we develop practical SQUID systems utilizing homemade magnetometers and planar gradiometers, as well as readout electronics. These SQUID systems have been successfully used in two typical applications, the transient electromagnetic method (TEM) and the airborne full-tensor magnetic gradient prospecting (FTMG). In TEM detection, SQUID magnetometers measure the secondary eddy-current response of the ground to the pulsed primary transmitting field. The metalliferous minerals can be located by calculating the resistivity. Due to SQUID' high sensitivity, we obtained the accurate location of abnormality in metal mineral areas and it was in good agreement with drilling information. Furthermore, a low-resistivity abnormality at about 1000 m deep was identified in Inner Mongolia. On the other hand, FTMG is recognized as the 3rd generation aeromag technique, and low-Tc SQUID is widely regarded as the optimal sensor for this application. We build up the world's 2nd practical airborne FTMG system with multi-chips of planar gradiometers and observe several abnormal gradient signals during flying tests. The system resolution reaches 0.02 nT/m (0.01 ~ 5 Hz). By further optimization, our practical SQUID system will be applied to both the scientific research and the engineering applications in the near future.

Near-field Intermodulation Distortion Imaging for Superconducting Device Physics

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High frequency signal distortion can result from the nonlinear response of superconductors to microwave current. In this work, local points of signal distortion are sought out using a raster probe, producing a 2-dimensional whole-device image of the nonlinearity emphasizing nonlinear hotspots within the device [1]. This measurement technique will inform engineers about the limitations of the material in device applications and will give physicists insight into the intrinsic and extrinsic causes of nonlinearity. Two-dimensional intermodulation distortion (IMD) scans were made of the second and third order IMD for a number of microwave resonators patterned from YBa2Cu3O7 and Tl2Ba2CaCu2O8 thin films. Figure 1 shows the 3rd order IMD in a high-current section of two different YBa2Cu3O7 resonators that correspond (a) to the expected high current regions as well as (b) to defects [2]. Second and third order nonlinearity behave differently, and the test method [3] in this work identifies different physical mechanisms. Nonlinearity has long been known to be affected, for example, by the density of magnetic fluxons [4], and is seen in these measurements as a time relaxation of IMD upon the removal of an applied static magnetic field. Multiple nonlinear processes, including magnetic relaxation over the Bean-Livingston (BL) surface barrier [5], are observed in the relaxation of second order nonlinearity. However, BL is the only process that is observed in the relaxation of the third order nonlinearity.

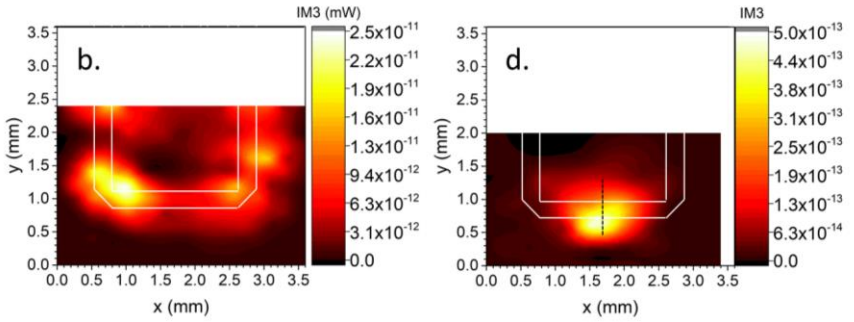

Fig. 1: *Scan of the IMD on 840 MHz $YBa_2Cu_3O_7$ resonators without (left) and with (right) a defect.*

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THz Emitters and Their Applications Using High-*T*c Superconducting Bi-2212 Mesa Structures for High Resolution and High Sensitivity Molecular Spectroscopy

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High-*T*c superconductors with highly 2D layered structures of CuO2 plane, which is responsible for the high-*T*c superconductivity, like a Bi2Sr2CaCu2O8+δ (Bi-2212) compound can generate rather intense THz electromagnetic waves after proper mesa structures were fabricated with certain dimensions and shapes [1]. The emission frequency spreads over a wide range of frequency domain from 0.3 THz to 2.4 THz [2] and the intensity can be up to 640 mW in case of three mesas synchronously operated [3]. The spectrum of THz radiation is sharp, a few tens of MHz due to synchronization of about a few thousands of intrinsic Josephson junctions in a stack along the c-axis. The mechanism of such a synchronized radiation from such many mesas can essentially be understood by the same as one on the LASER action, for example, CO2 gas LASER, *etc*. Because of sharp spectrum of the THz radiation, the peak intensity is extremely high, about 10^3-10^4 times stronger in the THz region than that of Hg lamp sources commonly used as a THz source. This means that it is possible to construct high sensitivity spectrometer using this high-*T*c superconducting device as a THz source.

This spectrometer is now designed and is planned to use for the various applications. One of the interesting applications is to selectively detect and analyze unknown organic compounds contained in lipids produced by algae as byproducts, such as Botryococcene oil from Botryococcus braunii, Squalene or Squalane from Aurantiochytrium, *etc*. This subject is very important for future health sciences in a long healthy human life society.

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In Situ Tailoring of Superconducting Junctions via Electro-Annealing

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We demonstrate the in situ engineering of superconducting nanocircuitry by targeted modulation of material properties through high applied current densities. We show that the sequential repetition of such customized electro-annealing in a niobium (Nb) nanoconstriction can broadly tune the superconducting critical temperature T_c and the normal-state resistance R_n in the targeted area. Once a sizable R_n is reached, clear magneto-resistance oscillations are detected along with a Fraunhofer-like field dependence of the critical current, indicating the formation of a weak link but with further adjustable characteristics [1]. Advanced Ginzburg-Landau simulations fully corroborate this picture, employing the detailed parametrization from the electrical characterization and high resolution electron microscope images of the region within the constriction where the material has undergone amorphization by electro-annealing.

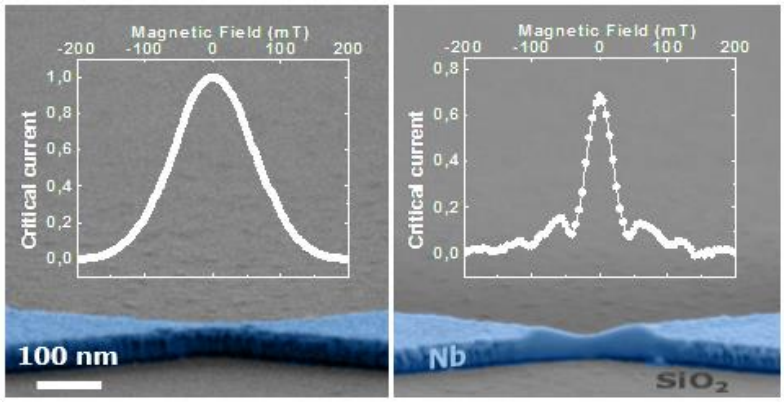

Fig. 1: *Amorphization by electro-annealing. (left) High-resolution SEM image of the constriction in the virgin state. (right) Constriction after several electro-annealing processes. The insets show the corresponding magnetic field dependence of the critical current of the junction.*

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Current-Induced Crossover of Flux Periodicity from *h/2e* to *h/e* in Superconducting Nb Nano-Ring

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The *h/2e* magnetic-flux periodicity observed in the magnetoresistance of superconducting rings has been considered as a hallmark for electronic pairing in superconductors, manifesting the existence of Cooper pairs. However, several theoretical works have shown that the existence of Cooper pairs does not necessarily imply an *h/2e* periodicity. For example, an *h/e* flux periodicity was predicted for s-wave nano-rings with size *smaller* than the coherence length, ξ_0 [1]. Here we report on a new observation of current-induced crossover from *h/2e* to *h/e* periodicity in a Nb nano-ring of size *larger* than ξ_0 by an order of magnitude. Our measurements show that as the bias current increases, the Little-Parks magnetoresistance oscillations switch to SQUID-like oscillations, both exhibiting *h/2e* periodicity [2]. However, upon further increasing the bias current, a more dramatic effect is observed: The *h/2e* periodicity disappears and *h/e* periodicity is observed over a large range of magnetic fields. This puzzling result may be interpreted as a sign of a normal-state behavior. Namely, the high bias current destroys superconductivity, and phase coherence of electrons in the Nb metallic ring results in Aharonov-Bohm magnetoresistance oscillation of period *h/e.* However, an interpretation based on supercurrent response may possibly apply if the high bias current switches the ring into a double-junction SQUID. These two possible interpretations will be discussed.

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Aharonov-Bohm *type* periodic magnetoconductance oscillations in planar and ballistic superconductor-quantum wells Josephson junctions

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It has been predicated that in the presence of a small perpendicular magnetic field, the magntoconductance oscillations (MCO) can be observed in planar and simply connected superconductor-semiconductor (S-Sm) junctions due to the interference effect of the Andreev reflected quasiparticles, interplay between quasiparticle cyclotron motion and the phase shift by the magnetic field. The MCO was found to be analogous to the Aharonov-Bohm type interference effect in a small ring [1,2].

Here, the first experimental observation of periodic MCO in planar and ballistic Josephson junctions at low prependicular magnetic fields $B < \pm$ 80 mT is reported [3]. The induced superconducting properties in $In_{0.25}Ga_{0.75}As$ quantum wells is discussed [4-6]. Furthermore, it is shown that at zero source-drain voltage V_{SD} bias, the differential conductance *dI/dV* of the junction drops in a step-like shape when *B* field is increased and as long as the quasiparticles are perfectly Andreev reflected at the Nb-$In_{0.75}Ga_{0.25}As$ interfaces. A hysteresis that is accompanied by oscillations of *dI/dV* is observed when *B* field is in reverse sweep direction (see Fig.1). It is found that the conductance oscillations are strongly temperature dependent but independent of *B* field sweep rates [3].

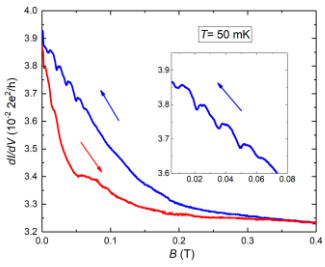

Fig. 1: ***The differential conductance oscillations in planar and ballistic Nb- $In_{0.75}Ga_{0.25}As$ -Nb Josephson junction:*** *the differential conductance (dI/dV) vs. applied B field perpendicular to the junction's plane at source-drain voltage V_{SD}= 0 and temperature T= 50 mK. Sweep directions are shown by arrows. Inset is the low dissipative part of the dI/dV in low B fields, clearly showing MCO.*

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ARPES view of the metal-insulator transitions in Sr_2IrO_4 and $Sr_3Ir_2O_7$

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Sr_2IrO_4 is a layered perovskite, structurally very similar to cuprates. One difference is that iridium is a *5d* transition metal, for which much smaller electronic correlations are *a priori* expected compared to cuprates, due to the much larger spatial extension of *5d* orbitals compared to *3d* ones. Nevertheless, Sr_2IrO_4 is an insulator, despite having an odd number of electrons in *5d* band, and orders antiferromagnetically below 240 K. This is believed to be the consequence of the large spin-orbit coupling, characteristic of this heavy element. It reshapes the electronic structure to form a non-degenerate half-filled band at the Fermi level, which is much more sensitive to electronic correlations than the original electronic structure. This new electronic structure also becomes very analogous to that of cuprates, so that theoreticians have proposed that doped compounds should be superconducting. Although no bulk systems have been found superconducting up to now, signs of superconductivity may have been observed recently in surface doped systems of Sr_2IrO_4.

We have grown a series of La and Rh doped samples of Sr_2IrO_4 and $Sr_3Ir_2O_7$ [1,2] and we will present the evolution of their properties through resistivity, magnetization and electronic structure (ARPES) measurements. We will discuss the similarities and differences between these two different ways to reach the metallic states and between the two different families.

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Interplay between Superconductivity and ferroelectricity in strontium titanate

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The large-gap semiconductor strontium titanate ($SrTiO_3$) becomes a metal upon removal of a tiny fraction of its oxygen atoms. The dilute metal has a sharp Fermi surface and is subject to a superconducting instability. Discovered half-a-century ago, the superconducting dome of strontium titanate remains doubly mysterious [1]: How can superconductivity persist when there is only one carrier for 10^5 atoms and the Fermi energy an order of magnitude smaller then than the Debye energy? What destroys this cooperative order as soon as carrier density exceeds 0.02 electrons per formula unit? A study of the parallel evolution of the Fermi surface topology and superconducting critical temperature provides hints [2].

On the other hand, substituting strontium with calcium stabilizes a long-range ferroelectric order in $Sr_{1-x}Ca_xTiO_3$. We find that in $Sr_{1-x}Ca_xTiO$ ferroelectricity coexists with metallicity and its superconducting instability in a narrow window of doping. As the carrier concentration is increased, the ferroelectric order is eventually destroyed by a quantum phase transition. This happens at a critical doping level at which the Friedel oscillations generated by neighboring dipoles interfere destructively. In the vicinity of this quantum phase transition, the superconducting critical temperature is enhanced [3]. We will discuss a possible link to ferroelectric quantum criticality [4,5].

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Novel Phase Emergence, Superconductivity and Quantum Criticality in Ferroelectric Materials

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By manipulating the lattice of incipient ferroelectric $SrTiO_3$ we are able to directly control the quantum criticality in this system. Pressure is the applied external field that couples to the lattice and its excitations - phonons. We use pressure to tune the strength of quantum critical fluctuations in this incipient ferroelectric, as well as the quantum paraelectric state to observe evolution of a novel phase emergent from the quantum critical point. We show that the quantum paraelectric state in $SrTiO_3$, which has been an enigma since its discovery nearly half a century ago, can be understood in terms of a coherent motion of polar and non-polar atoms in the $SrTiO_3$ lattice. The quantum coherent state essentially dissociates above a characteristic temperature, T*, which vanishes precisely at the ferroelectric quantum phase transition. Furthermore our experiments show that T_c in metallic SrTiO3 collapses rapidly with increasing pressure and hence with increasing frequency of the soft transverse optical polar phonon mode connected with the ferroelectric quantum critical point.

Superconductivity in strontium titanate under uniaxial strain near a quantum phase transition

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Suppression of weak ferromagnetism in low dimensional iridates by interfacial engineering of octahedral rotations

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Layered iridates, $Sr_{n+1}Ir_nO_{3n+1}$, have drawn great attention since they share remarkable similarities with high-T_c cuprates, including layered crystalline structure, (pseudo) spin ½ states, antiferromagnetic (AFM) Mott insulating ground state, Fermi arcs, and V shape energy gap, etc. Nonetheless, direct evidences of superconductivity such as zero resistivity and Meissner effect are still lacking up to date. The strong spin-orbit coupling in 5*d* iridates results in a canted AFM ground state with weak ferromagnetic moments in each IrO_2 plane. Here, we propose to suppress the weak ferromagnetism by suppressing the octahedral rotations in iridates, which may facilitate the Cooper pairing. Using a combination of reactive molecular beam epitaxy (MBE), *in situ* angle-resolved photoemission spectroscopy (ARPES) and first principle calculations, we investigate the evolution of octahedral rotations, electronic structure and magnetic ordering in epitaxial ultra-thin $SrIrO_3$ films grown on (001) $SrTiO_3$. Our experimental results and theoretical calculations show that octahedral rotations and weak ferromagnetic moments are fully suppressed in bilayer and single-layer $SrIrO_3$ films through interfacial clamping effects.

Superconducting Transition Temperature of 500 mK for La-doped $SrTiO_3$ Single Crystals with Oxygen Isotope (^{18}O) Substitution

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The strontium titanate, $SrTiO_3$ has been extensively as well as intensively studied due to its intriguing properties. It has been well known that for the electron-doped $SrTiO_3$ via oxygen vacancies, superconductivity appears around 300 mK [1], and for the insulating $SrTiO_3$, the quantum paraelectric state changes to a ferroelectric state when the normal oxygen (^{16}O) atoms are substituted with the oxygen isotope (^{18}O) ones [2]. In Ref. 3, a large lift of the critical temperature for superconductivity (T_C) upon the ^{18}O substitution has been reported, which indicates the ferroelectricity/ferroelectric instability is relevant to the superconductivity of the doped $SrTiO_3$. In this paper, we report a remarkable increase in T_C upon the ^{18}O substitution for the La-doped $SrTiO_3$ single crystals [4] prepared by the floating zone method. The resistivity is measured down to 100 mK in a cryostat equipped with a $^3He/^4He$ dilution refrigerator (dilution, Taiyo-Toyo Sanso Inc.). Figure 1 shows the T_C as a function of the carrier density (n) for the crystals of $Sr_{1-x}La_xTi^{16}O_3$ ($0 \le x \le 0.01$) and $Sr_{1-x}La_xTi(^{16}O_{1-z}{}^{18}O_z)_3$ ($z \sim 0.6$) with the ^{18}O substitution. In Fig. 1, the T_C's cited from Refs. 1 and 3 are also indicated. As shown in Fig. 1, the T_C for $Sr_{1-x}La_xTi^{16}O_3$ (red closed squares) reaches 0.4 K at $n \sim 6 \times 10^{19}$ [/cm^3], and for the enriched crystals, $Sr_{1-x}La_xTi(^{16}O_{1-z}{}^{18}O_z)_3$ ($z \sim 0.6$), it has been found that the T_C (blue closed squares) becomes as high as 0.5 K. We argue the enhancement of T_C with respect to the soft mode fluctuation near the ferroelectric quantum critical point (or line) [5]. It is also suggested from this study that the Sr/La alloying is a suitable way to lift the T_C despite of an inevitable cation disorder [6].

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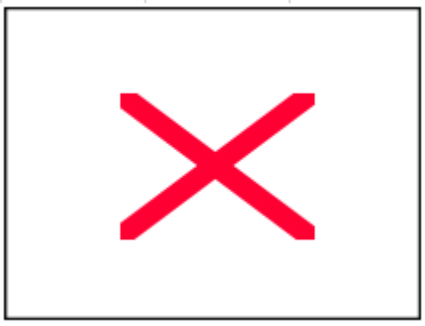

Fig. 1: *The critical temperature for the superconductivity (T_C) vs. carrier density (n) for the crystals of $SrTiO_{3-}$ (closed circles), $SrTi_{1-x}Nb_xO_3$ (crosses) [1], $SrTiO_{3-}$ ($^{18}O/^{16}O$ = 0 and ~ 0.35) (open and closed green circles) [3], and $Sr_{1-x}La_xTi(^{16}O_{1-z}{}^{18}O_z)_3$. (z = 0 and ~0.6) (red and blue closed squares)*.

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Evolution of the Magnetic and Phonon Excitations in High T_c Cuprates

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In high-T_c cuprates, superconductivity usually appears by suppressing the long-range antiferromagnetic order of the parent Mott insulators via doping charge carriers into their CuO_2 planes [1]. A spin-fluctuation-mediated pairing mechanism in unconventional superconductivity like cuprates was theoretically proposed [2] in analogy to the phonon-mediated pairing in conventional superconductors. However, the spin fluctuation across the phase diagram especially within the superconducting dome is still under intensive investigation.

By using resonant/non-resonant inelastic x-ray scattering (RIXS/IXS) [3,4], we measured the magnetic and phonon excitations in the high-T_c superconductor $(Bi,Pb)_2(Sr,La)_2CuO_{6+\delta}$, for a large doping range across the phase diagram. We unambiguously demonstrate the spin-flip character of magnetic excitations by the full polarization measurements. We find anisotropic damping of magnetic excitation in momentum space, faster in the nodal direction than in the antinodal direction. We compare the experimental results to numerically exact determinant quantum Monte Carlo (DQMC) calculations that provide the spin dynamical structure factor $S(q,\omega)$ of the three-band Hubbard model. The theory reproduces well the momentum and doping dependence of the dispersions and spectral weights of magnetic excitations. These results provide compelling evidence that paramagnons, although increasingly damped, persist across the superconducting dome of the cuprate phase diagram; this implies that long range antiferromagnetic correlations are quickly washed away, while short range magnetic interactions are little affected by doping [5]. Moreover, we will also discuss the evolution of low-energy phonons across the phase diagram and its implications on superconductivity.

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Two-dimensional topological and nodeless superconducting phases emerged from d-wave superconductors in proximity to antiferromagnets

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Motivated by the recent observations of nodeless superconductivity in the monolayer CuO_2 grown on the $Bi_2Sr_2CaCu_2O_{8+\delta}$ substrates[1], we study the two-dimensional superconducting (SC) phases described by the two-dimensional t-J model in proximity to an antiferromagnetic (AF) insulating layer. We found that[2] (i) the nodal d-wave SC state can be driven via a continuous transition into a nodeless d-wave pairing state by the proximity induced AF field. (ii) The energetically favorable pairing states in the strong field regime have extended s-wave symmetry and can be nodal or nodeless. (iii) Between the pure d-wave and s-wave paired phases, there emerge two topologically distinct SC phases with (s+id) symmetry, i.e., the weak and strong pairing phases, and the weak pairing phase is found to be a Z_2 topological superconductor protected by valley symmetry, exhibiting robust gapless non-chiral edge modes. These findings strongly suggest that the high-T_c superconductors in proximity to antiferromagnets can realize fully gapped symmetry protected topological SC.

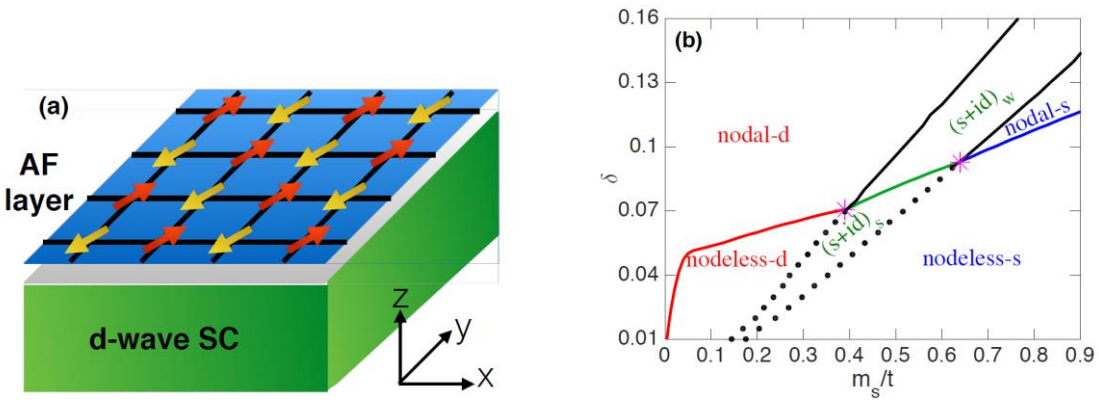

Fig. 1: (a) An antiferromagnetic insulating CuO_2 layer is grown on the optimal doped Bi-2212 copper oxide substrates. (b) The phase diagram of superconducting phases in terms of the AF field m_s and hole doping δ is derived with the relevant parameters for the cuprates: *J/t=0.3*, *t'/t=0.2* and *0.01<δ <0.16*. Continuous phase transitions are marked by solid lines, whereas discontinuous phase boundaries by dotted lines. Red, green and blue lines separate the weak pairing phases (upper region) from the strong pairing phases (lower region).

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Anomalous Excitation Spectra and Fractional Excitations in the two-dimensional Mott Insulator

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The low energy spin excitations in the high-Tc superconductor parent compound have been well described by spin-wave theory. However, the high-energy excitations are strongly damped near (π,0) point and exhibit a continuum. Similar phenomena have also been observed recently in a antiferromagnet $Cu(DCOO)_2 \cdot 4D_2O$(CFTD) [Nat.Phys.11,62 (2015)], which is considered as the best realization of the square-lattice Heisenberg model.

In this talk, I will present our recent work on spectral properties of the antiferromagnetic J1-J2 Heisenberg model, based on the extension of the electronic cluster perturbation theory to spin systems by using the mapping between spin-1/2 operators and hard-core bosons [1]. In the Neel phase (J2<0.4J1), in addition to the dominant magnon excitations, we obtain an obvious continuum coming from two-spinon excitations close to (π,0), which is consistent with the experiments. This result demonstrates that the magnonic spectrum in spin-1/2 Mott insulators does not rule out the existence of spinons. In the stripe phase (J2>0.6J1), similar continuua are also found, but their locations move to (π/2,π/2) and (π/2,π). In the intermediate phase (0.4J1<J2<0.6J1), the whole spectrum becomes a broad continuum, which is attributed to a Z2 RVB quantum spin liquid based on a variational-Monte-Carlo analysis. In addition, I will also show the coexistence of fractional spin excitations and magnons in the spectra of the Kitaev-Γ (off-diagonal) model, which is suggested to describe the spin-orbital Mott insulator α-RuCl3 [2,3].

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Phys. Rev. Lett. **118**, 107203 (2017)

Novel many-body quantum effect in doped Mott insulators/high-Tc cuprates

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In contrast to the Fermi statistics of a weakly interacting electron system, new sign structure can be identified in the doped Mott insulator as a strongly correlated electron system closely related to the high-Tc superconductors. By using exact diagonalization and density matrix renormalization group numerical methods, we show that such novel sign structure can be explicitly manifested by a persistent spin current pattern in a hole-doped ground state. Such anomaly persists for the odd numbers of holes, but the spin currents completely disappear for even numbers of holes, with the ground state exhibiting a d-wave symmetry. We construct the ground state wavefunctions for the one-hole and two-hole ground states, which reproduces the DMRG/ED results excellently by variational Monte Carlo calculations. Important implications to the high-Tc superconductivity and the pseudogap physics will be also discussed.

Static Spin Susceptibility in Magnetically Ordered States and Coexistent States of Superconductivity and Antiferromagnetism

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We point out that special care is needed when longitudinal magnetic susceptibility is computed in a magnetically ordered phase, especially in metals. We demonstrate this by studying static susceptibility in both a ferromagnetic and an antiferromagnetic state in the two-dimensional Hubbard model and that in a coexisting state of superconductivity and antiferromagnetism in the t-J model, using the random phase approximation (RPA). In contrast to the case in the disordered phase, a first derivative of the chemical potential (or the density) with respect to a magnetic field does not vanish in a magnetically ordered phase when the field is applied parallel to the magnetic moment. This effect is crucial and should be included when computing magnetic susceptibility in the ordered phase, otherwise an unphysical result would be obtained. In addition, consequently, the magnetic susceptibility becomes different when computed at a fixed density and a fixed chemical potential in the ordered phase. In particular, we cannot employ magnetic susceptibility at a fixed chemical potential to describe a system with a fixed density even if the chemical potential is tuned to reproduce the correct density. The above conclusions do not depend on the choice of models, dimensions, lattices, and approximations even beyond the RPA, as we can show based on the thermodynamic arguments. We also propose an experiment to directly test the present theory.

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The Stiffnessometer - a Magnetic-Field-Free Superconducting Stiffness Meter Reveals Two Critical Temperatures in LSCO

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A new method to measure the superconducting stiffness tensor $\bar{\rho}_s$, without subjecting the sample to magnetic field, is applied to $La_{1.875}Sr_{0.125}CuO_4$ (LSCO). The method is based on the London equation $\mathbf{J} = -\bar{\boldsymbol{\rho}}_s \mathbf{A}$, where $\mathbf{J}$ is the current density and $\mathbf{A}$ is the vector potential. Using rotor free $\mathbf{A}$ and measuring $\mathbf{J}$ via the magnetic moment of superconducting rings, we extract $\bar{\rho}_s$ at $T \to T_c$. The technique, named Stiffnessometer and presented in Ref. [1], is sensitive to very small stiffness, which translates to penetration depth on the order of a few millimeters. We apply this method to two different LSCO rings: one with the current running only in the CuO_2 planes, and another where the current must cross planes. We find different transition temperatures for the two rings, namely, there is a temperature range with two-dimensional stiffness.

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Percolative Superconductivity in the Cuprates

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The cuprate high-temperature superconductors are among the most intensively studied quantum materials, yet pivotal questions regarding their principal phases and the transitions between them remain unanswered. Motivated by insights that we gained from measurements of the simple-tetragonal compound $HgBa_2CuO_{4+\delta}$, we recently considered a percolation model for the normal state of the cuprates wherein 3*d* holes are gradually delocalized with increasing doping and temperature [1]. Within this picture, the spatial inhomogeneity of the localization gap is expected to cause a distribution of superconducting gaps as well, leading to superconducting percolation. This is indeed what we observe, using an experimental approach with unique sensitivity to superconducting correlations: nonlinear response. Upon measuring both nonlinear magnetization [2] and nonlinear conductivity [3] for a number of cuprates, we uncover that the superconducting precurser exhibits unusual yet robust exponential temperature dependence above T_c that can be captured by a simple percolation model. This observation is further confirmed by paraconductivity results for $HgBa_2CuO_{4+\delta}$ [4]. The inherent inhomogeneity responsible for the percolation of locally superconducting nanoscale regions appears to be rooted in self-organized structural instabilities and will need to be taken into account in the interpretation of a wide range of experimental results. We also will discuss our most recent efforts to extend nonlinear response measurements to other oxide superconductors.

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Probing pair-correlations and Coulomb energy of the superconducting state in the high Tc cuprates

M. K. Tran[1], J. Levallois[1], D. Pouliot[4], C. N. Presura[2], L. H. Greene[4], J. N. Eckstein[4], J. Uccelli[1], E. Giannini[1], G. D. Gu[3], A. J. Leggett[4,5] & D. van der Marel[1]

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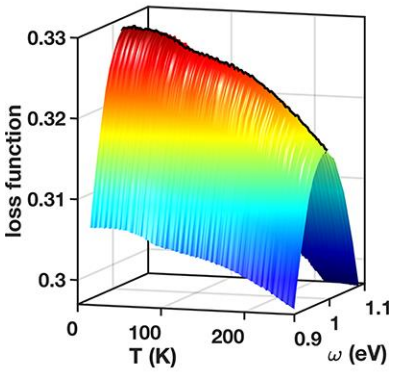
Several years ago, one of us [1] postulated that it is the saving of the Coulomb interaction energy of the conduction electrons, and specifically the part associated with long wavelengths and mid-infrared frequencies, which is the main driver of the superconducting transition in the cuprates (the "MIR scenario"). By virtue of a basic result from linear response theory the partial Coulomb energy associated with a given wave vector q is proportional to a thermally weighted integral of the electron energy loss function. To employ this "Coulomb energy" sumrule we measured the detailed temperature dependence of the loss function in a series of single crystals in the $Bi_2Sr_2CaCu_2O_{8-x}$ and $Bi_2Sr_2Ca_2Cu_3O_{10-x}$ with carrier concentrations ranging from strongly underdoped to strongly overdoped[2]. Our first observation is that, as the temperature drops through T_c, the loss function in the range up to 2 eV, and in particular the ab-plane plasmon peak, displays a change of temperature dependence as compared to the temperature dependence in the normal state. This effect at T_c depends strongly on doping, with a sign change for weak overdoping. The size of the observed change in Coulomb energy, using an extrapolation with reasonable assumptions about its q dependence, is about the same size as the condensation energy that has been measured in these compounds. Our results therefore lend support to the notion that the Coulomb energy is an important factor for stabilizing the superconducting phase. Because of the restriction to small momentum, our observations do not exclude a possible significant contribution to the condensation energy of the Coulomb energy associated with the region of q around (π, π).



Energy-temperature map of the energy loss function in the energy range of the plasmon peak of an underdoped cuprate sample measured with spectroscopic ellipsometry. The small bump in the temperature dependence around 80 Kelvin is caused by the phase transition into the superconducting state.

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Locating the missing superconducting electrons in overdoped cuprates

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Overdoped high-temperature cuprate superconductors have been widely believed to be described by the physics of d-wave BCS-like superconductivity. However, recent measurements indicate that as the doping is increased, the superfluid density decreases smoothly to zero rather than increasing as expected by BCS theory in the absence of disorder. Here, we combine time-domain THz spectroscopy with kHz range mutual inductance measurements on the same overdoped La2−xSrxCuO4 films to determine both the superfluid and the uncondensed carrier density as a function of doping. A significant fraction of the carriers remains uncondensed in a wide Drude-like peak even as T→0, which, when taken with the linear-in-temperature superfluid density, is inconsistent with existing theories for the role of disorder in suppressing the superfluid density in a d-wave superconductor. Our almost eight orders of magnitude in measurement frequency range gives us a unique look at the low frequency spectral weight distribution, which may suggest the presence of quantum phase fluctuations as the critical doping is approached.

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Antiferromagnetic Spin Gap Limits the Coherent Superconducting Gap in Cuprates

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Using inelastic neutron scattering, we have investigated the low-energy spin excitations in single crystals of $La_{2-x}Sr_xCuO_4$ with x = 0.17 and 0.21, bracketing the putative quantum critical point at x_c ~ 0.19. For the x = 0.21 sample in the normal state, we observe a peak in the magnetic spectral weight at ~ 20 meV and a strong drop off at lower energies, consistent with the behavior at x = 0.17. The presence of such energy-dependent structure demonstrates that the antiferromagnetic correlations, though weakening with doping, do not exhibit critical behavior. On cooling below the superconducting transition in each sample, the energy of the spin gap that develops, 8 meV, is in the regime of depressed spectral weight, with a small shift in spectral weight from below to above the gap. From a comparison with Raman scattering and Andreev reflection studies, we find that the coherent superconducting gap scale is equal to the spin gap. Motivated by this result, an inspection of the literature for cuprates with an observed spin gap indicates that the coherent superconducting gap is always equal to or smaller than the spin gap. We suggest that this is a consequence of the strong interaction between quasiparticles and antiferromagnetic spin excitations

Laser ARPES on Orbital Origin of Extremely Anisotropic Superconducting Gap in Nematic Phase of FeSe Superconductor

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National Lab for Superconductivity, Beijing National Laboratory for Condensed Matter Physics, and Institute of Physics, Chinese Academy of Sciences, Beijing, 100190, People's Republic of China

The iron-based superconductors are characterized by multiple-orbital physics where all the five Fe 3d orbitals get involved. The multiple-orbital nature gives rise to various novel phenomena like orbital-selective Mott transition, nematicity and orbital fluctuation that provide a new route for realizing superconductivity. The complexity of multiple-orbital also asks to disentangle the relationship between orbital, spin and nematicity, and to identify dominant orbital ingredients that dictate superconductivity. The bulk FeSe superconductor provides an ideal platform to address these issues because of its simple crystal structure and unique coexistence of superconductivity and nematicity. However, the orbital nature of the low energy electronic excitations and its relation to the superconducting gap remain controversial. In this talk, we will report direct observation of highly anisotropic Fermi surface and extremely anisotropic superconducting gap in the nematic state of FeSe superconductor by high resolution laser-based angle-resolved photoemission measurements. We find that the low energy excitations of the entire hole pocket at the Brillouin zone center are dominated by the single dxz orbital. The superconducting gap exhibits an anti-correlation relation with the dxz spectral weight near the Fermi level, i.e., the gap size minimum (maximum) corresponds to the maximum (minimum) of the dxz spectral weight along the Fermi surface. These observations provide new insights in understanding the orbital origin of the extremely anisotropic superconducting gap in FeSe superconductor and the relation between nematicity and superconductivity in the iron-based superconductors.

*Work done in collaboration with Defa Liu, Cong Li, Jianwei Huang, Bin Lei, Le Wang, Xianxin Wu, Bing Shen, Qiang Gao, Yuxiao Zhang, Xu Liu, Yong Hu, Yu Xu, Aiji Liang, Jing Liu, Ping Ai, Lin Zhao, Shaolong He, Li Yu, Guodong Liu, Yiyuan Mao, Xiaoli Dong, Xiaowen Jia, Fengfeng Zhang, Shenjin Zhang, Feng Yang, Zhimin Wang, Qinjun Peng, Youguo Shi, Jiangping Hu, Tao Xiang, Xianhui Chen, Zuyan Xu and Chuangtian Chen

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ARPES Study of Nematicity in FeSe

Ming Yi[1,2], Yan Zhang[3], Heike Pfau[4], Zirong Ye[3], Tong Chen[2], Pengcheng Dai[2,5], Robert J. Birgeneau[1], Donghui Lu[6]

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The origin of nematicity is an important issue for a comprehensive understanding of phase competition in iron-based superconductors and has strong implications on the mechanism of high temperature superconductivity. However, the strong coupling between the nematic order and spin density wave order makes it very challenging to disentangle the contribution from the orbital and magnetic degree of freedom in iron pnictides. FeSe, due to the lack of long range magnetic order, is an ideal system for isolating the contribution of nematicity to the fundamental physics of the iron-based superconductors. The nature of nematic electronic structure of FeSe has recently become a hotly debated issue due to conflicting reports on the magnitude of nematic splitting between d_{xz} and d_{yz} bands [1-9]. In this talk I will present our latest ARPES data taken on fully detwinned FeSe single crystals. The high quality single-domain data allow us to unambiguously identify the orbital character of the observed bands and confirm a momentum dependent nematic splitting between d_{xz} and d_{yz} bands that is consistent with the previous understanding of an electronically-driven nematic order in iron pnictide superconductors.

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Systematic ARPES of iron-based superconductors as a test for theories

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I will overview our recent results on iron-based superconductors [1-6]. Electronically driven nematic order is often considered as an essential ingredient of high-temperature superconductivity. Its elusive nature in iron-based superconductors resulted in a controversy not only as regards its origin but also as to the degree of its influence on the electronic structure even in the simplest representative materials FeSe and BaFe2As2. We use angle-resolved photoemission spectroscopy and density functional theory calculations to study the influence of the nematic order on the electronic structure of FeSe and BaFe2As2 and determine its exact energy and momentum scales. Together with the quasiparticle tight-binding fit and 3D gap functions determined experimentally our results provide a sufficient basis to test existing theories of superconductivity in iron-based superconductors.

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Pairing Mechanism of the FeSe-monolayer and related Systems: Dynamical Tuning of Pairing Cutoff Energy

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There are a group of FeSe systems: FeSe/SrTiO3 monolayer system (Tc~60-100K) and other heavily electron-doped iron selenide (**HEDIS**) compounds such as $A_xFe_{2-y}Se_2$ (A=K, Rb, Cs, Tl, etc.) (Tc~30-40K), $(Li_{1-x}Fe_xOH)FeSe$ (Tc~40K), etc. These systems have all very high Tc (30K -100K) despite having only the electron Fermi surfaces (FSs) but no hole FS.

Here we propose a unifying pairing mechanism [1] based on a new concept: dynamical tuning of pairing cutoff energy. With this mechanism, I show how the incipient band without a Fermi surface can participate pairing interaction through RG process and the system forms the s^{++}-wave state only with the electron pockets. In this way, the **HEDIS** system can achieve the maximum T_c, stored in the system, and yet avoid the detrimental impurity pair-breaking scattering. Our theory not only provides a unifying pairing mechanism for all **HEDIS** system, but also naturally explains the puzzling **double dome structure** of the phase diagram of T_c *versus* tuning parameter (doping, pressure, etc) [2, 3].

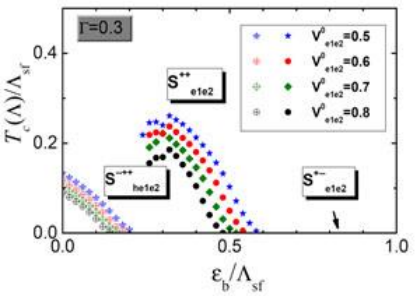

Fig.1(a): Theoretical phase diagram of T_c vs incipient band energy ε_b. [1].

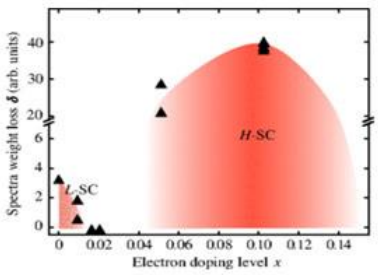

Fig.1(b): Experimental phase diagram of T_c vs electron doping (x) on FeSe thin film.[2].

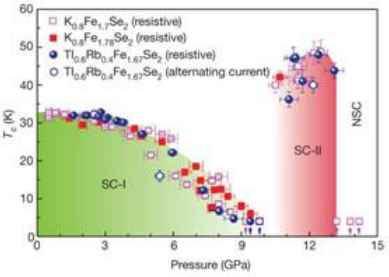

Fig.1(c): Experimental phase diagram of T_c vs pressure on various FeSe compounds[3].

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Extrinsic Photoelectron Energy Losses as the Origin of Replica Bands in Photoemission of FeSe on SrTiO3

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The replica bands observed in single-layer FeSe/STO by angle-resolved photoemission spectroscopy (ARPES) are widely regarded as a result of the FeSe electrons coupling with substrate phonons and used to explain the enhanced superconductivity in this system [1]. However, here we provide strong evidence that the replica bands are largely due to the energy loss process of the escaping photoelectron, resulted from the well-known strong coupling of external propagating electrons to Fuchs-Kliewer (FK) surface phonons in STO [2]. We calculate photoelectron energy loss in ARPES on single-layer FeSe/STO using the demonstrated successful semiclassical dielectric theory in describing low energy high-resolution electron energy loss spectroscopy (HREELS) of ionic insulators with the input of electron energy, measurement geometry and infrared optical phonons from experiment [2]. We reduce the loss probability by a factor 2 since the total path of electrons in HREELS is twice as long as in ARPES. Our calculation turns out to be able to reproduce the replica intensity and the other experimental features in detail very well without any fitting parameter [3]. This strongly suggests that the observed replica bands are mostly a result of extrinsic photoelectron energy loss and not a result of the electron phonon interaction of the Fe d electrons with the substrate phonons. Therefore, the mechanism of the strongly enhanced superconductivity in these monolayers remains an open question although other phonons than the FK types may still contribute.

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Antiferromagnetic Order in Epitaxial FeSe Films on $SrTiO_3$

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Single monolayer FeSe film grown on a Nb-doped $SrTiO_3$(001) substrate shows the highest superconducting transition temperature ($T_C \sim 100$ K) among the iron-based superconductors (iron pnictides), while the T_C value of bulk FeSe is only ~8 K. Although bulk FeSe does not show antiferromagnetic order, calculations suggest that the parent FeSe/SrTiO3 films are antiferromagnetic. Experimentally, because of a lack of a direct probe, the magnetic state of FeSe/$SrTiO_3$ films remains mysterious. In this talk, we will report the direct evidence of antiferromagnetic order in the parent FeSe/$SrTiO_3$ films by the magnetic exchange bias effect measurements. The magnetic blocking temperature was found to be ~140 K for a single monolayer film. The antiferromagnetic order disappears after electron doping [1]. Our findings provide important information for a comprehensive understanding of the novel properties of FeSe/ $SrTiO_3$ films.

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Interacting topological superconductor in one dimension

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Abstract: As a prototype of one-dimensional (1D) systems possessing Majorana zero modes at edges, Kitaev chain model has attracted a lot of attention since it was proposed. The pristine Kitaev chain is a non-interacting model and can be generalized to an interacting model. I shall talk about the exact solution to the (symmetric) interacting model, in the sense that all the eigenvalues and corresponding eigenstates are given. The solutions include topologically non-trivial phase at |U|<t and topologically trivial phase at |U|>t. The two phases are related by dualities. Quantum phase transitions in the model are studied with the help of the exact solution. The edge tunneling experiment is proposed to manifest the interacting effect in the topological phase.

Topological Nature of the Kondo Insulator SmB_6 – Dependency on the Crystallinity

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Samarium hexaboride (SmB_6), a well-known Kondo insulator, has recently received a great deal of attention as the first correlated topological phase [1]. Despite numerous experimental findings supportive of its topological nature, detailed spectroscopic properties still remain to be unraveled. Our recent tunneling spectroscopy [2, 3] based on planar junctions formed on stoichiometric SmB_6 single crystals grown by the flux method has not only found evidence for the existence of multiple surface Dirac cones, in agreement with a quantum oscillation study as well as theoretical predictions, but also revealed their intriguing topological nature affected by the inherent interaction of the surface states with bulk excitations, called spin excitons [4, 5]. We have extended this investigation into floating-zone grown crystals with different amount of crystalline disorders such as Sm deficiency. The tunneling conductance spectra show qualitatively similar features as in the stoichiometric flux grown crystals including the hybridization gap in the bulk. However, the conductance contributed from the surface states don't exhibit a similar distinct temperature evolution including the formation of coherent states at low temperature, suggesting that the detailed topological nature in SmB_6 varies depending on the crystallinity. Considering the robustness of the topological surface states as observed in weakly correlated band insulators such as Bi_2Se_3, this sensitiveness to disorder is seemingly counter-intuitive but could be understood by carefully looking into how the spin exciton excitations depend on the hybridization gap formation, which in turn requires translational invariance in the bulk.

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Topological superconductivity with spin-3/2 half-heusler compounds beyond spin triplet pairing

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Multi-component electronic systems are not rare in solid state physics due to the multi-orbital band structure and spin-orbit coupling. They exhibit richer structures of topological superconductivity beyond the conventional scenarios of spin singlet and triplet pairings. We generalize the ^{3}He-B type isotropic *p*-wave topological pairing to the four-component fermion systems, which are effectively described by spin-3/2 fermions. The p-wave triplet and f-wave septet pairings are identified as topologically non-trivial characterized by large topological indices and exhibiting high order Majorana-Dirac surface spectra. Recently, there has been experimental evidence of nodal spin-3/2 superconductivity in the half-Heusler compound YPtBi semi-metal with theoretically proposed p-wave septet pairing gap function. Zero energy Majorana flat bands on the (111)-surface and their signatures in the quasi-particle interference patterns are calculated. In addition, we also discuss how to realize the chiral Majorana modes by a “boundary of boundary” method starting with a degenerate Fermi surface without spin-orbit coupling. The$p \pm is$superconductors develop spontaneous magnetizations on the surfaces. Along the magnetic domain walls on the surface, the chiral Majorana modes propagate unidirectionally, which can be controlled by external magnetic fields.

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Superconductivity in Topological Materials:

Insights from Superconducting Density Functional Theory

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Superconductivity in doped topological or topological crystalline insulators is of great interest, since there have been several experimental studies suggesting that they are promising candidates of topological superconductors [1]. When we perform first-principles calculation for superconductivity in doped topological or topological crystalline insulators with heavy elements, we have to consider the following effects: First, the energy scale of the Fermi energy is usually very small, so that unconventional pairing mechanism such as the cooperation between plasmon and phonon can play a decisive role [2]. Second, we have to take account of the wave number dependence of the gap function to discuss anisotropic superconductivity. Third, the spin-orbit coupling can significantly affect the phonon frequencies, electron-phonon coupling and electronic structure [3].

Recently, we have performed a fully-nonempirical calculation considering these effects for doped SnTe (a topological crystalline insulator) and Bi_2Se_3 (a topological insulator) based on superconducting density functional theory [4,5]. For SnTe, we found that even-parity superconductivity always dominates over odd-parity superconductivity. The doping dependence of the superconducting transition temperature (T_c) agrees well with the experiment [6,7], where the relativistic effect and plasmon effect play a crucial role. We also found that the recent STM measurement of the gap function [8] is consistent with our calculation. On the other hand, for Bi_2Se_3, T_c for even-parity superconductivity mediated by phonon and plasmon is much lower than the experimental value of T_c [9].

This work was done in collaboration with T. Nomoto (Univ. Tokyo), M. Kawamura (Univ. Tokyo, ISSP), T. Koretsune (Tohoku Univ.), T. Machida (RIKEN), T. Hanaguri (RIKEN), M. Kriener (RIKEN) and Y. Taguchi (RIKEN).

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Helical Majorana edge mode in a superconducting antiferromagnetic quantum spin Hall insulator

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A two-dimensional time-reversal symmetric topological superconductor is a fully gapped system possessing a helical Majorana mode on the edge. This helical Majorana edge mode (HMEM), which is a Kramer's pair of two chiral Majorana edge modes in the opposite propagating directions, is robust under time-reversal symmetry protection. We propose a feasible setup and accessible measurement to provide the preliminary step of the HMEM realization by studying superconducting antiferromagnetic quantum spin Hall insulators. Since this antiferromagnetic topological insulator hosts a helical electron edge mode and preserves effective time-reversal symmetry, which is the combination of time-reversal symmetry and crystalline symmetry, the proximity effect of the conventional s-wave superconducting pairing can directly induce a single HMEM. We further show the HMEM leads to the observation of an e2/h conductance, and this quantized conductance survives even in the presence of small symmetry-breaking disorders.

Theory of Sr_2RuO_4: active/passive bands, spin-orbital coupling, and effect of uniaxial and biaxial strains

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We perform systematic theoretical study of the superconductivity in Sr_2RuO_4 by functional renormalization group based on singular-mode decomposition. In the complete three-orbital model in the absence of spin-orbital coupling, we find spin-fluctuations at small wave vector, arising from the γ band, drives p-wave pairing, primarily on this band. The resulting gap function develops deep minima along the Fermi surface. There are also spin-fluctuations at large wave vector, mainly from the α and β bands but are inactive for the p-wave pairing. With spin-orbital coupling, the γ band remains active, but inter-orbital proximity effect causes pairing on the α and β bands of amplitude about two-thirds of that on the γ band. Moreover, spin-orbital coupling causes steeper gap minima on the γ band, making the gap function there almost nodal. The calculated specific heat, NMR Knight shift and relaxation rate, thermal conductivity and superfluid density agree nicely with existing experiments. Finally, we study the effects of uniaxial and biaxial strains. The strain pushes the Fermi surface of the γ band closer and even beyond the van Hove singularity, causing enhancement of superconducting transition temperature initially, followed by a transition to the spin density wave order before the van Hove singularity is reached.

Uniaxial Pressure Studies of Unconventional Superconductivity

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I will describe the utility of uniaxial pressure as a probe of unconventional superconductors and proximate phases such as density waves. After discussing results obtained on Sr_2RuO_4 using novel piezo-activated controlled strain devices developed in our group [1,2], I will describe methods for studying heat capacity in our uniaxial pressure cells, and ways in which the design has been extended to allow their use in synchrotron, neutron scattering and muon spin rotation facilities. Finally I will describe new prototype cells that enable experiments under controlled stress conditions and consider the potential advantages of working, in future, with miniaturized samples and cells fabricated using focused ion beam techniques

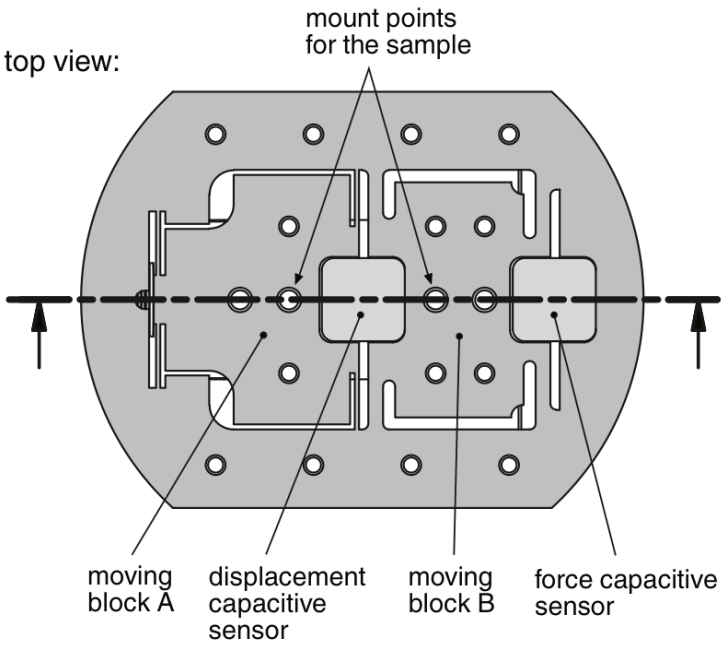

Fig. 1: *Schematic of a novel uniaxial pressure cell incorporating both displacement and force sensing, capable of working at constant stress under the application of appropriate feedback.*

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Josephson Coupling Enabled Mixed Pairing State in the Eutectic Phase of Ru-Sr_2RuO_4[†]

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Unconventional superconductivity marked by a non-*s*-wave pairing symmetry has been a frontier of condensed matter physics research. A crystal possessing an inversion symmetry can feature either an even parity, spin-singlet or odd-parity, spin-triplet pairing symmetry as requirement of the Fermi statistics of electron. A noncentrosymmetric material can in principle possess a pairing state mixing both the spin-singlet and spin-triplet pairings. In a mesoscopic superconductor with its size comparable with or smaller than the size of the Cooper pair wave packet, which makes the inversion symmetry for the pairing wave function poorly defined. A novel superconducting state mixing the two fundamentally different pairings is then allowed. However, such a pairing state can only be realized if appropriate effective interactions are present in the system to facilitate pairing in more than one channel. Here we report electrical transport measurements on single-crystal microdomains of *s*-wave superconductor Ru embedded in a bulk crystal of *p*-wave superconductor Sr_2RuO_4 which revealed a Josephson coupling between the Ru island and bulk Sr_2RuO_4, making the pairing in the *p*-wave channel coexisting with the *s*-wave pairing energetically favored within Ru microdomains. Our work suggests that the Ru/Sr_2RuO_4 can be used as a model system for the study of the unconventional superconductivity featuring a mixed pairing state.

[†]Work done in collaboration with Libin Wen, Wen Huang, Yanshen Yang, Wenjie Liu, Jian-Jian Ge, Mingliang Tian, Hui Xing, Shun Wang, and Zhi-Qiang Mao

Physical Properties of uniaxially strained Sr_2RuO_4 examined by ^{17}O NMR

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Sr_2RuO_4 is a correlated multiband system that undergoes a transition to a superconducting state at T_c=1.45 K. A longstanding question relates to order parameter symmetry, with many experiments interpreted as consistent with a chiral odd-parity state. Sr_2RuO_4 is also a superclean example of a Hund's metal, where interorbital interactions significantly impact the normal state properties. A feature which can be both studied and exploited is the proximity to a Lifshiftz point originating with the quasi-2D band of predominant Ru d_{xy} character. Recently, the Lifshitz point has been accessed by applying compressive uniaxial strain, which also revealed a remarkable increase of transition temperature, to 3.5 K, at the critical strain value ε_c. Here we report on ^{17}O NMR spectroscopy and relaxation measurements of the normal state while subject to *in situ* uniaxial strain. The results indicate a significant coupling of magnetic response between and the quasi-1D and bands, which could be interpreted in terms of the Hund's rule coupling, although spin-orbit coupling could also play a role. Studies of the superconducting state are underway, with spectra recorded near ε_c showing a drop in spin susceptibility upon lowering the temperature through the transition.

Spin-Triplet Superconductivity in the Ruthenate

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The superconducting symmetry of Sr_2RuO_4 has been widely recognized as spin-triplet, chiral *p*-wave, based on a number of experimental observations as well as theoretical examinations. Although there are unresolved issues to explain, such as the strong suppression of the upper critical field and the first–order transition for the in-plane magnetic fields, there does not seem to be an alternative spin-singlet scenario at present capable of explaining all the key experiments [1].

In this talk, some important facts to consider towards refining the proper spin-triplet scenario are presented, such as the multicomponent order parameter characteristics of the intrinsic "1.5-K phase" [2]. This talk also addresses the issue of topological superconductivity of Sr_2RuO_4 [3, 4]. Depending on the direction of the Cooper-pair *d*-vector, spinfull Dirac electron edge modes or spinless Majorana edge modes are expected.

This talk is mainly based on the collaborations and discussions with S. Kashiwaya, M. Sato, S. Yonezawa, Y. Yasui, M. Kunieda, M.S. Anwar, C. Hicks, A.P. Mackenzie, K. Lahabi, and J. Aarts.

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The symmetry of the superconducting order parameter of Sr_2RuO_4

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Despite the extensive effort, the pairing mechanism in the unconventional superconductor Sr_2RuO_4 is still unknown. The spin susceptibility is not affected by the superconducting transition suggesting odd-parity pairing [1,2]. In addition, muon-spin relaxation and polar Kerr rotation measurements have demonstrated the presence of broken time-reversal symmetry [3,4]. These experiments suggest a chiral *p*-wave order parameter in Sr_2RuO_4 [5].

Subsequent, specific heat, thermal conductivity and ultrasound attenuation measurements demonstrated the presence of low energy excitations related to nodal quasiparticles [6,7,8]. Furthermore, the interpretation of the thermal conductivity data suggests the presence of a vertical lines rather than horizontal lines nodes [7]. However, the presence of vertical nodes is incompatible with the chiral *p*-wave order parameter, implied by the muon-spin relaxation and polar Kerr rotation measurements [3,4].

Due to the coupling of the superconducting order parameter to the lattice strain, it is possible to get useful information about the symmetry of the order parameter using the ultrasound spectroscopy [9,10]. I will present systematic ultrasound study performed on single crystal of Sr_2RuO_4 in different acoustic modes. We observed a negative jump in transverse mode at T_c. From group theory and symmetry considerations, this result allows us to put strong constraints on the symmetry of the superconducting order parameter of Sr_2RuO_4 [11].

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The Density and Disorder Tuned Superconductor-Metal Transition in Two Dimensions

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Anomalous Metals – Failed Superconductors

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When a superconductor with a relatively high normal state (Drude) conductivity is tuned through a zero temperature superconductor to non-superconductor quantum phase transition, the proximate "normal" phase typically appears to be an anomalous metal – that is a state with zero temperature resistivity that is non-zero, but much smaller than the Drude resistance. In this and other ways, this state shows evidence of having very substantial superconducting correlations, but which fail to be become globally phase coherent even at T=0. Here we present an analysis of a model problem with establishes –as a point of principle – that such a quantum fluctuating "failed superconductor" is a possible quantum phase of matter.

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Gauge Theory of the Superconductor-Insulator Transition

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The standard model of particle physics is extraordinarily successful at explaining much of the physical realm. Yet, one of its most profound aspects, the mechanism of confinement, that binds quarks into hadrons and is supposedly mediated by chromo-electric strings in a condensate of magnetic monopoles [1-3], is not thoroughly understood and lacks direct experimental evidence. We demonstrate that the infinite-resistance superinsulating state [4-7], a mirror analogue of superconductivity, emerging at the insulating side of the superconductor-insulator transition (SIT) [8-12] is a condensed matter realization of the quark confinement. We reveal that the mechanism ensuring the infinite resistance of superinsulators is the binding of Cooper pairs into neutral "mesons" by electric strings and establish a mapping of quarks onto Cooper pairs in superinsulators. We derive the linear confinement of Cooper pairs in both two- and three dimensions, generalizing thus the concept of superinsulation onto 3D systems, and calculate the deconfinement temperature, which in 2D coincides with the Berezinskii-Kosterlitz-Thouless (BKT) transition temperature. We reveal a Cooper pair analogue of the asymptotic freedom effect [13] implying that systems smaller than the string scale appear in a quantum metallic state. We construct the phase diagram of the critical vicinity of the SIT and find the criterion for realizing either the direct SIT or the transition via an intermediate Bose metal phase. We unravel, finally, that this Bose metal phase is a topological insulator. Our findings offer a powerful laboratory for exploring fundamental implications of confinement, asymptotic freedom, and related quantum chromodynamics (QCD) phenomena via desktop experiments on superconductors.

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Thermal measurements at the SIT

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The superconductor-insulator transition (SIT) is a prototype of a quantum phase transition which is very versatile experimentally: varying a non-thermal tuning parameter such as disorder, thickness, composition, magnetic field or gate-voltage causes the system to switch from a superconductor to an insulator at zero temperature.

Unlike their classic counterparts, quantum phase transitions are governed by quantum fluctuations rather than thermal fluctuations. The direct experimental study of such fluctuations close to the SIT is rather challenging. So far research has mainly concentrated on dc resistivity based measurements such as transport and magnetoresistance and on global and local tunneling spectroscopy. These provide only limited information on the critical behavior through the transition.

In my talk I will describe thermal (specific heat and Nernst effect) experiments designed to measure direct signatures of quantum fluctuations and critical behavior close to the SIT. I will discuss the significance of the results and their contribution to understanding the electronic processes in the vicinity of the quantum phase transition.

Electronic structure in the pseudogap state of cuprates

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It is now commonly accepted that the physics of the strange metal state and superconductivity in the hole doped cuprates are governed by a quantum-critical point when the pseudogap transition temperature $T^*(x)$ goes to 0. The only robust phase transition observed in cuprates is the loop-current order transition. I will discuss calculations how modulations in this structure may give the anisotropic gap and the small fermi surface.

Singular Density Fluctuations in the Strange Metal Phase of $Bi_2Sr_2CaCu_2O_{8+x}$

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A central mystery in high-temperature superconductivity is the origin of the so-called strange metal (i.e., the anomalous conductor from which superconductivity emerges at low temperature). Measuring the dynamic charge response of the copper oxides, $\chi''(q, \omega)$, would directly reveal the collective properties of the strange metal, but it has never been possible to measure this quantity with meV resolution. Here, we present a measurement of $\chi''(q, \omega)$ for a cuprate, optimally doped $Bi_{2.1}Sr_{1.9}CaCu_2O_{8+x}$ (Tc = 91 K), using momentum-resolved inelastic electron scattering (M-EELS). In the medium energy range 0.1–2 eV relevant to the strange metal, the spectra are dominated by a featureless, temperature- and momentum-independent continuum persisting to the electronvolt energy scale. This continuum displays a simple power-law form, exhibiting q^2 behavior at low energy and q^2/ω^2 behavior at high energy (Fig. 1). Measurements of an overdoped crystal (Tc = 50 K) showed the emergence of a gap-like feature at low temperature, indicating deviation from power law form outside the strange-metal regime. Our study suggests the strange metal exhibits a new type of charge dynamics in which excitations are local to such a degree that space and time axes are decoupled [1].

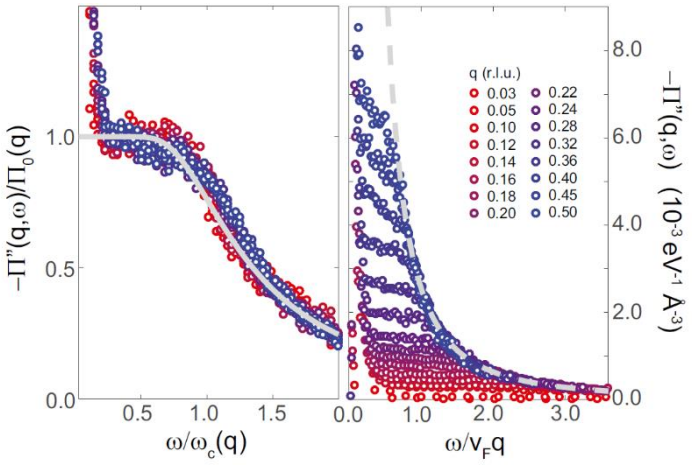

Fig. 1: *Scaling collapse of the density fluctuations in Bi2212 measured with M-EELS.*

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Signature of loop currents in superconducting cuprates and Other SC-$SrTiO_3$&Iridates

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Discovery of slow magnetic fluctuations and critical slowing down in the pseudogap phase of $YBa_2Cu_3O_y$

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The origin of the pseudogap region below a temperature T^* is at the heart of the mysteries of high-T_c cuprate superconductors. The predicted broken time-reversal and inversion symmetry due to ordered loop currents or other similar intra-unit-cell (IUC) magnetic order is consistent with five different classes of symmetry-sensitive experiments: polarised neutron diffraction, optical birefringence, dichroic ARPES, second harmonic generation, and polar Kerr effect. On the other hand, MuSR and NMR experiments do not see the static local fields expected for magnetic order, leaving room for scepticism. These probes have much longer time scales, however, over which local magnetic fields could be averaged by fluctuations. We have measured the dynamic muon relaxation rate in longitudinal applied field in single crystals of $YBa_2Cu_3O_y$, and have discovered fluctuating magnetic fields and fluctuation rates of the expected orders of magnitude, setting in consistently at temperatures $T_{mag} \approx T^*$. Equally important, we observe the critical slowing down of fluctuations at T_{mag} expected near time-reversal symmetry breaking transitions. Our discoveries remove any reasonable doubts about the existence of IUC magnetic order in the pseudogap phase.

No Evidence for Orbital Loop Currents in Charge Ordered $YBa_2Cu_3O_{6+x}$ from Polarized Neutron Diffraction

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It has been proposed that the pseudogap state of underdoped cuprate superconductors may be due to a transition to a phase which has circulating currents within each unit cell [1,2]. Here [3], we use polarized neutron diffraction to search for the corresponding orbital moments in two samples of underdoped $YBa_2Cu_3O_{6+x}$ with doping levels p=0.104 and 0.123. In contrast to some other reports [4] using polarized neutrons, but in agreement with nuclear magnetic resonance and muon spin rotation measurements, we find no evidence for the appearance of magnetic order below 300 K. Thus, our experiment suggests that such order is not an intrinsic property of high-quality cuprate superconductor single crystals. Our results provide an upper bound for a possible orbital loop moment which depends on the pattern of currents within the unit cell. For example, for the CC-θ_{II} pattern proposed by Varma [1,2], we find that the ordered moment per current loop is less than 0.013 $_B$ for p=0.104.

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Microscopic Analysis of ARPES Data in Superconductive State: Intrinsic Self-Energy and Pairing Interaction for Cuprates

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There is more information than the gap and relaxation rate in the ARPES data in superconductive state. The most complete and microscopic information may be obtained by analyzing the data in terms of the diagonal (normal) and off-diagonal (anomalous or pairing) self-energies. By performing the momentum distribution curve analysis on the ARPES intensity from the Bi2212 samples we demonstrate how the normal and pairing self-energies, $\Sigma(\theta,\omega)$ and $\phi(\theta,\omega)$, respectively, can indeed be extracted. The θ is the angle from the anti-nodal direction in the Brillioune zone and ω is the energy with respect to the chemical potential. This must be the tool of choice to discuss delicate and subtle issues in the cuprate phase diagram instead of some phenomenological expression both above and below *T*c. We then show that the extracted self-energies contain the contribution from the off-plane impurities. This serves as a flag for a successful extraction of the self-energy and also settles down the low energy kink in the ARPES dispersion as due to the off-plane impurity scatterings [1]. After subtracting the impurity part from the extracted self-energies we obtain the long-sought-after intrinsic self-energies. The θ and ω dependence of the intrinsic self-energies thus obtained may serve as one of the best ways to differentiate among proposals for the high *T*c superconductivity in cuprates [2].

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In collaboration with J. M. Bok, S. H. Hong, J. J. Bae, W. Zhang, J. He, Y. Zhang, L. Yu, C. M. Varma, and X. J. Zhou.

Phase Coherence Dominated Superconducting Transition in $Fe_{1+x}(Te,Se)$

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This talk will report our STM/S study on the iron-based superconductor $Fe_{1+x}(Te,Se)$. Earlier, we reported the discovery of a Majorana-like zero-energy mode localized at each interstitial Fe impurity sites. Further study has shown that these interstitial magnetic impurity atoms collectively destroy the superconducting condensate by decoherence, not by reduction of the pairing strength. This phenomenon is inconsistent with the Abrikosov-Gor'kov description of the effects of magnetic impurities on superconductivity. With a quantitative analyses of our STM/S results, we show that the linear reduction of T_c with increasing of the impurity concentration displayed by the magnetic susceptibility measurements could also be explained by the decoherence effect. In addition, we will show the results of the temperature dependent STS measurements to demonstrate that the interstitial Fe impurity atoms collectively drive a quantum phase transition from the coherence dominated superconducting state to an unknown quantum state.

Spectroscopic-Imaging STM Studies of Nematicity and Superconductivity in $FeSe_{1-x}S_x$

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Spontaneous breaking of lattice rotational symmetry in the electronic state, which is known as electronic nematicity, has been observed in various materials including unconventional superconductors such as cuprates and iron-based materials. In order to study the relationship between superconductivity and nematicity, we have performed spectroscopic-imaging STM on $FeSe_{1-x}S_x$. The parent material FeSe undergoes tetragonal-to-orthorhombic transition at 90 K, which is a manifestation of the electronic nematic order. Superconductivity sets in at lower temperature of 9 K. The electronic nematic order is suppressed with increasing sulfur content x and disappears above the nematic end point at $x \sim 0.17$ [1]. We have investigated the evolution of the band structure as a function of x by analyzing the quasiparticle interference (QPI) patterns (Fig. 1, top row). We have found that anisotropy of the in-plane band structure diminishes with increasing x but there is little change in the band structure at the nematic end point. Superconducting gap is hardly affected by sulfur doping in the nematic phase but suddenly becomes smaller above the nematic end point (Fig. 1, bottom row). This result indicates that there are two distinct superconducting pairing states depending on the presence or absence of nematicity [2].

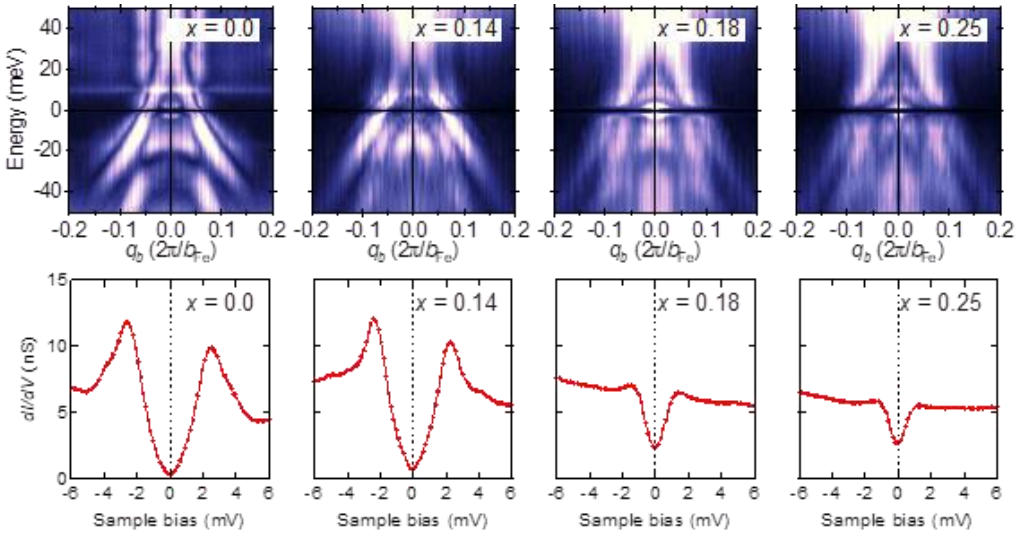

Fig. 1: *QPI patterns (top row) and superconducting gap spectra (bottom row) in* $FeSe_{1-x}S_x$.

This work has been done in collaboration with K. Iwaya, Y. Kohsaka, T. Machida, T. Watashige, S. Kasahara, T. Shibauchi and Y. Matsuda.

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Tuning superconductivity in $NbSe_2$ with uniaxial strain

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Ultra-Low Temperature Spectroscopic Imaging Studies of Vortices in the Topological Superconductor $FeTe_{0.6}Se_{0.4}$

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Detection of the Majorana fermion in a topological superconductor is one of the central issues in condensed matter physics. Although the Majorana fermion is expected to appear as a zero-bias peak (ZBP) in the single-electron spectrum in the vortex core, its experimental verification remains controversial [1,2]. Using a dilution refrigerator scanning tunneling microscope, we performed ultra-low temperature (~85 mK) spectroscopic imaging of the vortex cores in $FeTe_{0.6}Se_{0.4}$, which is one of the candidate materials of the topological superconductor. The tunneling spectra in the vortex cores consist of multiple peaks. Some vortices exhibit a ZBP in the spectra but others possess peaks only at finite energies. We found that vortices are not always stable but occasionally jump to another location. We focused on one of the vortices with the ZBP and examined the temporal evolution of its tunneling spectrum. As shown in Fig. 1(a), after the jump, the ZBP disappeared. Vortex imaging before and after the jump [Fig. 1(b), (c)] revealed that the shift of the vortex position was only ~2 nm. Such rather fragile nature of the ZBP provides a hint to understand the origin of the ZBP.

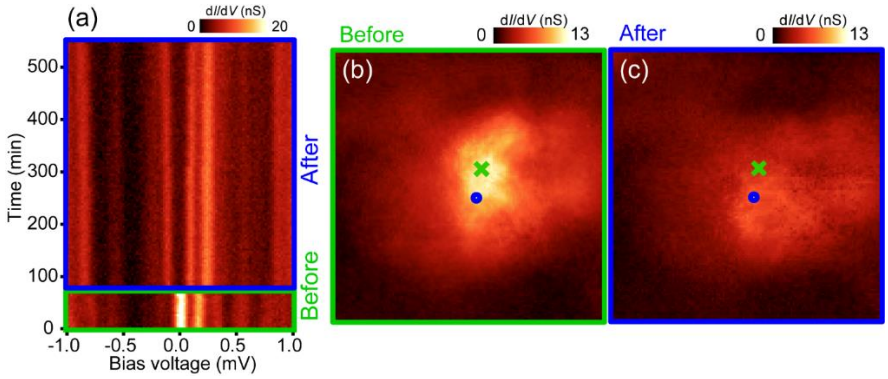

Fig. 1: *(a) Time dependence of the tunneling spectra taken at a vortex core. (b) and (c) The zero bias conductance maps on 16 nm x 16 nm field-of-view before (b) and after (c) the vortex jump. Green cross and blue circle indicate the highest intensity points before and after the jump, respectively.*

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Magnetism and the Absence of Superconductivity in $EuFe_{2-x}Ni_xAs_2$ Single Crystals

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Chemically-substituted $EuFe_2As_2$ is unique among the superconducting iron-based pnictides due to the coexistence of superconductivity and magnetic ordering. Interestingly, the substitution of Fe by Ni in $EuFe_2As_2$, although suppresses SDW, does not lead to the appearance of superconductivity [1, 2], in contrast to doping with other transition metals (e.g. Co, Ir). Finding the reason of the absence of superconductivity in $EuFe_{2-x}Ni_xAs_2$ could make a significant contribution to a better understanding of superconductivity in iron pnictides.

Single crystals of $EuFe_{2-x}Ni_xAs_2$ have been grown using Sn-flux method. The crystal structure monitored by means of x-ray diffraction and Ni-concentration determined using EDX spectroscopy have reveal solid solution formation in the compositional range of $0 \le x \le 0.4$. The physical properties of $EuFe_{2-x}Ni_xAs_2$ were studied by ac-susceptibility, magnetization, electrical resistivity and magnetoresistance measurements within the temperature range of 2-300 K and in magnetic fields up to 9 T. We have observed gradual suppression of the SDW order with increasing Ni-concentration. The SDW transition disappears for $x \ge 0.2$. The magnetic order of Eu^{2+} persists within the whole compositional range studied and reveals a change in character from antiferromagnetic to ferromagnetic with increasing Ni substitution. The previously reported spin-glass behavior [2] has not been observed. We have found no evidence for superconductivity in $EuFe_{2-x}Ni_xAs_2$ down to 55mK. The high-pressure resistivity measurements up to 2.5 GPa also showed no signs of superconductivity.

The theoretical calculations of the ground state electronic structure properties were performed using density functional theory. The calculated DOS and change of $N(E_F)$ vs. x will be presented.

The absence of superconductivity in Ni-doped $EuFe_2As_2$ is discussed in the light of the obtained experimental results and theoretical calculations in comparison to the related systems.

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Multigap Superconductivity in $RbCa_2Fe_4As_4F_2$ Investigated Using μSR

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The superconducting properties of the recently discovered double Fe_2As_2 layered high-T_c superconductor $RbCa_2Fe_4As_4F_2$ with $T_c \approx 30$ K have been investigated using magnetization, heat capacity, transverse-field (TF) and zero-field (ZF) muon-spin rotation/relaxation (μSR) measurements. Our low field magnetization measurements and heat capacity (C_p) reveal an onset of bulk superconductivity with $T_c \sim 30.0(4)$ K. Furthermore, the heat capacity exhibits a jump at T_c of $\Delta C_p/T_c$=94.6 (mJ/mole-K^2) and no clear effect of applied magnetic fields was observed on C_p(T) up to 9 T between 2 K and 5 K. Our analysis of the TF-μSR results shows that the temperature dependence of the magnetic penetration depth is better described by a two-gap model, either isotropic *s*+*s*-wave or *s*+*d*-wave than a single gap isotropic *s*-wave or *d*-wave model for the superconducting gap. The presence of two superconducting gaps in $RbCa_2Fe_4As_4F_2$ suggests a multiband nature of the superconductivity, which is consistent with the multigap superconductivity observed in other Fe-based superconductors, including $ACa_2Fe_4As_4F_2$ (A=K and Cs). Furthermore, from our TF-μSR study we have estimated an in-plane penetration depth λ_{ab} (0) =231.5(3) nm, superconducting carrier density $n_s = 7.45 \times 10^{26}$ m^{-3}, and carrier's effective-mass $m^* = 2.45me$. Our ZF μSR measurements do not reveal a clear sign of time reversal symmetry breaking at T_c, but the temperature dependent relaxation between 150 K and 1.2 K might indicate the presence of spin-fluctuations. The results of our present study have been compared with those reported for other Fe pnictide superconductors.

Extraordinary pinning efficiency of 1D artificial pinning centers with engineered interface in $YBa_2Cu_3O_{7-x}$ nanocomposite films

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Nanoscale c-axis aligned one-dimensional artificial pinning centers (1D-APCs) can provide strong correlated pinning and therefore reduces orientation-dependence of the critical current density J_c in $YBa_2Cu_3O_{7-x}$ (YBCO). A fundamental question arises on what determine the pinning efficiency of different 1D-APCs? In order to shed lights on this question, this work investigates the correlation between APC/YBCO interface and the pinning efficiency of 1D-APCs of $BaHfO_3$ (BHO) and $BaZrO_3$ (BZO) of comparable diameter of 5-6 nm. Intriguingly, a highly coherent BHO 1D-APC/YBCO interface was revealed even at high BHO doping level up to 6-vol.%, in contrast to a semi-coherent BZO 1D-APC/YBCO interface with a large number of dislocations. This difference is found to have a profound effect on the pining efficiency of the BHO and BZO 1D-APCs. Specifically, a record high pinning force density peak $F_{p,max}$~183.0 GNm^{-3} at $H_{max} > 9.0$ T and 65 K was obatined in the former, which is 440% higher than the best in the latter. Moreover, a ratio of the H_{max} to the accommodation field H^* that was determined based on the 1D-APC areal concentration using transmission electron microscopy is in the range of 2.5-3.5 in the former in contrast to the maximum of 0.6-0.7 in the latter, demonstrating the critical impact of the APC/YBCO interface on the pinning efficiency of 1D-APCs.

Keywords: Artificial pinning centers, nanocomposite, vortex pinning, J_c, interface

Acknowledgements
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Pinscape Spectroscopy: Solving the Inverse Problem in Vortex Pinning

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On the route to solving the vortex pinning problem, i.e. the effective immobilization of magnetic flux lines in type-II superconductors, most effort has been laid in accurately predicting macroscopic observables (e.g. critical current) from microscopic ingredients (e.g. defect density and strength). I shall discuss two recent examples that follow the opposite approach: by solving the inverse problem, microscopic pinning parameters are extracted from the experiment and pave the way for pinscape spectroscopy.

The first approach takes advantage of local probe techniques that can determine the displacement of a *single* vortex away from a local potential well when perturbed by a small ac force. We find that the in- and out-of-phase signals allow for a local reconstruction of the two-dimensional pinscape. A possible experimental realization involves local SQUID-on-tip experiments [1].

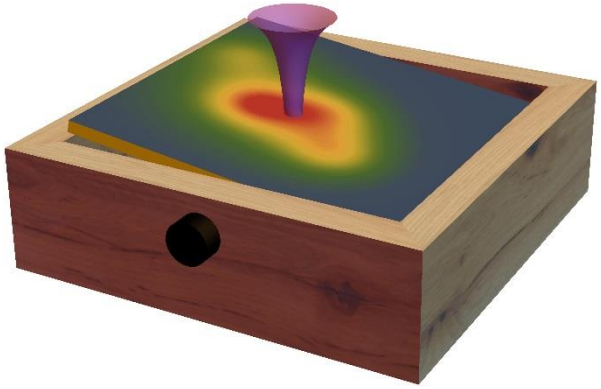

Figure: *Shaking a single vortex with an ac force allows to probe its local environment and to extract pinscape properties. As illustrated here, this approach is reminiscent of the ball in the maze game.*

The second approach is based on probing the *bulk* pinned vortex state [2-4]. In particular, the penetration length of an ac magnetic field as derived within the strong pinning framework [4] and evaluated from numerical simulations [3], allows the extraction of microscopic pinning parameters from bulk measurements. I shall illustrate this approach on the ample ac susceptibility data available for the clean superconductor $NbSe_2$ [5].

Both approaches provide quantitative access to the elementary constituents of vortex pinning, such as the well's pinning strength, and pave the way for further characterization experiments.

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Vortex Excitations in the Insulating State of an Oxide Interface

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In two-dimensional (2D) superconductors an insulating state can be induced either by applying a magnetic field, *H*, or by increasing disorder. Many scenarios have been put forth to explain the superconductor to insulator transition (SIT): dominating fermionic physics after the breaking of Cooper pairs, loss of phase coherence between superconducting islands embedded in a metallic or insulating matrix and localization of Cooper pairs with concomitant condensation of vortex-type excitations. The difficulty in characterizing the insulating state and its origin stems from the lack of a continuous mapping of the superconducting to insulating phase diagram in a single sample. Here we use the two-dimensional (2D) electron liquid formed at the interface between the two insulators (111) $SrTiO_3$ and $LaAlO_3$ to study the superconductor to insulator transition. This crystalline interface surprisingly exhibits very strong features previously observed only in amorphous systems. By use of electrostatic gating and magnetic fields, the sample is tuned from the metallic region, where supeconductivity is fully manifested, deep into the insulating state. Through examination of the field dependence of the sheet resistance and comparison of the response to fields in different orientations we identify a new magnetic field scale, $H_{pairing}$, where superconducting fluctuations are muted. Our findings show that vortex fluctuations excitations and Cooper pair localization are responsible for the observed SIT and that these excitations surprisingly persist deep into the insulating state.

Karman vortex streets generated by supercurrent flowing around pinning centers

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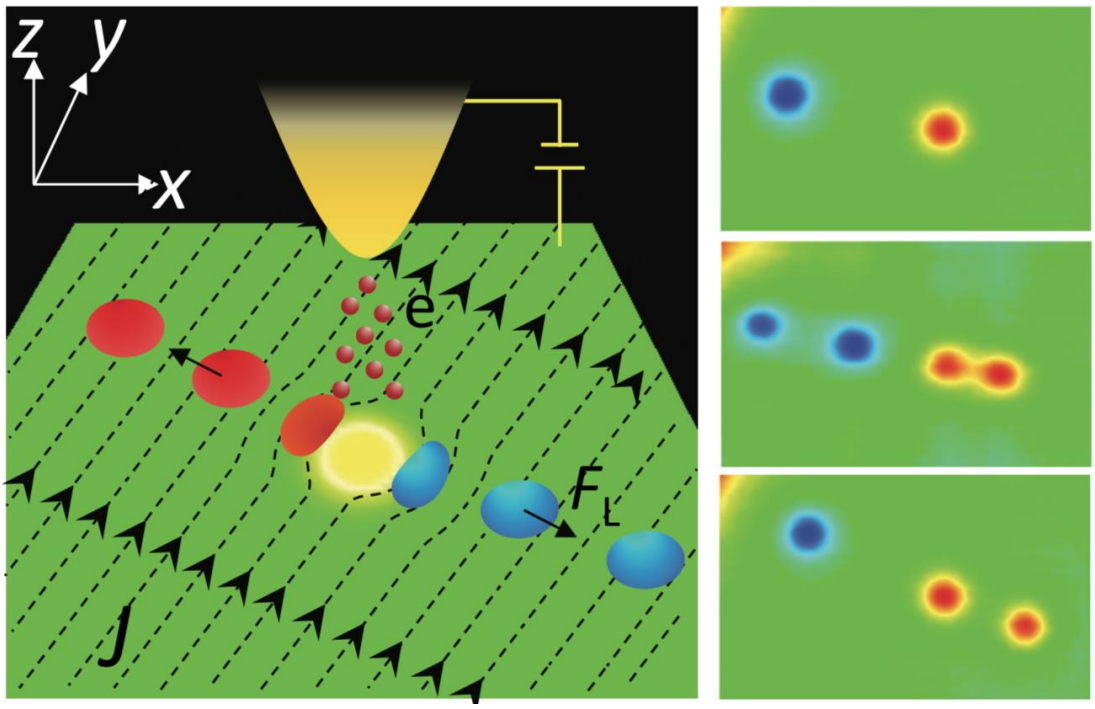
We report the controllable creation of single quantum vortices and antivortices at any desirable position inside a superconductor. We exploit for that the local heating effect of a scanning tunneling microscope (STM) tip: superconductivity is locally suppressed by the tip and vortex−antivortex pairs are generated in the form of the Karman vortex street when supercurrent J flows around the normal spot. The experimental results are well-explained by theoretical simulations based on the Ginzburg−Landau theory [1]. The Figure below presents schematics of the experiment (left panel) and the scanning Hall probe microscope images of vortices and antivortices (right panel) generated by current J flowing around the pinning center.



[1] Jun-Yi Ge, Vladimir N. Gladilin, Jacques Tempere, Jozef Devreese, and Victor V. Moshchalkov, *Nano Lett.*, *17* (8), pp 5003–5007, **2017**

Molecular Dynamics Simulation for Melting Transition of Vortex Lattice and Vortex Pinning in a Superconductor

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Vortex matter physics has been studied widely after the discovery of the cuprate high-Tc superconductors. The H-T phase diagram of the vortex structure in the high-Tc superconductor shows vortex lattice melting line. The vortex lattice melting is an ideal system for general melting transition because interaction between vortices is simple and well defined. So, Ooi et al. [1] studied melting transition of vortex lattice in a mesoscopic high-Tc superconducting square plate. They found that melting temperature oscillates with increasing number of vortices and when vortex number is a square number, the melting temperature shows maximum. This phenomenon is a kind of matching effect.

In order to analyze these phenomena, we use the molecular dynamics (MD) method for vortex dynamics. In molecular dynamics method, a vortex is treated as a point particle. Their motion is dissipative and the equation of motion is given as [2,3],

$$\eta \, d\boldsymbol{r}_i / dt = \boldsymbol{f}_{pi}^{imp} + \boldsymbol{f}_{vi} + \boldsymbol{f}_{fi} \ ,$$

Where $\boldsymbol{r}_i$ is the vortex position and $\boldsymbol{f}_{pi}^{imp}$ and $\boldsymbol{f}_{vi} = f_0 \sum_j K_1\left(r_{ij}/\lambda\right)\hat{\boldsymbol{r}}_{ij}$ are a pinning force from impurities and a vortex-vortex interaction, respectively. $\boldsymbol{f}_{fi}$ is a thermal fluctuation force. The vortex motion depends on temperature through the thermal fluctuation force and the vortex-vortex interaction force, where the penetration depth depends on temperature $\lambda = \lambda\left(T\right)$. In order to find the melting temperature, we calculate the standard deviation (SD) of vortex position during time development. In Fig. 1, we show example of temperature dependence of SD for vortices in a $3\lambda \times 3\lambda$ square superconducting plate.

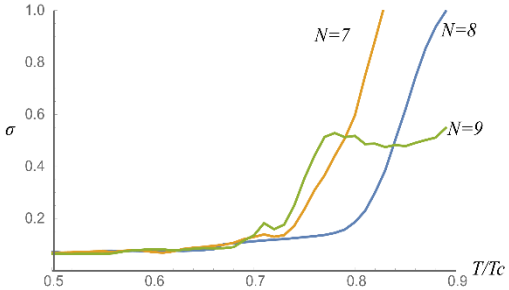

Fig. 1: *Temperature dependence of standard deviation of vortex positions.*

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Structural and Kinematic Studies of Metastable Vortex Lattice Phases in MgB_2

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The collective behavior of vortex matter exhibits similarities with skyrmions, soft matter systems such as liquid crystals, colloids, granular materials, and glasses. Specifically, the vortex lattice (VL) displays structure formation at the mesoscopic scale, metastable states, and low elastic moduli, making it an ideal two-dimensional model system.

Here we present small-angle neutron scattering (SANS) studies of the VL in MgB_2, as it is gradually driven from different metastable configurations towards the equilibrium state. The equilibrium phase diagram for MgB_2 consists of three hexagonal configurations, differing only in the VL orientation relative to the crystalline basal plane. Cooling or heating across the equilibrium phase boundaries leaves the VL in a metastable state, requiring significant vortex motion to achieve the equilibrium configuration [1]. Even in the presence of modest vortex motion some VL domains persist in the metastable orientation, excluding pinning as a cause for the metastability [2]. This implies a scenario where VL domain boundaries create energy barriers for rotation to the equilibrium orientation.

Using a stop-motion technique we have studied how the metastable VL returns to the equilibrium state under the influence of an AC magnetic field, allowing us to extract both structural and kinematic information. Following a supercooling across the intrinsically continuous equilibrium phase transition, the metastable VL return to the equilibrium state a discontinuous manner. This is in striking contrast to the superheated case, where the transition takes on a continuous nature. Further, the transition is independent of the distribution of vortices in different VL domains, providing further evidence that domain walls are central to stabilizing the metastable states.

From the kinematic studies we have determined the activation energy required to drive the VL to the equilibrium state. The activation is found to increase in the same manner as the transition progresses for both the supercooled and superheated VL, despite the different nature of the transition for the two cases. This suggest a work hardening of the VL, in analogy with Martensitic phase transitions.

We are grateful to J. Karpinski for providing the MgB_2 single crystal used for this work. We acknowledge useful discussions with E. M. Forgan, B. Janko, K. Newman, M. Pleimling, and U. C. Taüber, and assistance with the SANS experiments and data analysis from J. Archer, S. J. Kuhn, and A. Leishman. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Award No. DE-SC0005051. A portion of this research used resources at the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

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Magnetic correlations in iron-germanide superconductors

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The recently discovered iron-germanide superconductor YFe_2Ge_2 is of great interest because it is a new iron-based superconductor other than iron pnictides/chalcgenides [1]. Stoichiometric YFe_2Ge_2 does not exhibit long range magnetic order, but instead exhibits superconductivity below T_c~1.8 K. The nature of the magnetism and superconductivity in YFe_2Ge_2 remains unknown. Here, we report inelastic neutron scattering measurements of spin fluctuations in single crystalline YFe_2Ge_2. Our data reveal frustrated magnetic correlations, which naturally explain the absence of magnetic order in YFe_2Ge_2. The relationship between the spin fluctuation and pairing symmetry will be discussed.

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The competition between Charge Density Wave and Superconductivity in Pd_xHoTe_3

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HoTe3, a member of the rare-earth tritelluride (RTe3) family, and its Pd-intercalated compounds, PdxHoTe3, where superconductivity (SC) sets in as the charge-density wave (CDW) transition is suppressed by the intercalation of a small amount of Pd, are investigated using angle-resolved photoemission spectroscopy (ARPES) and electrical resistivity. Two incommensurate CDWs with perpendicular nesting vectors are observed in HoTe3 at low temperatures. With a slight Pd intercalation (x=0.01), the large CDW gap decreases and the small one increases. The momentum dependence of the gaps along the inner Fermi surface (FS) evolves from orthorhombicity to near tetragonality, manifesting the competition between two CDW orders. Both CDW gaps decrease with the emergence of SC upon further Pd intercalations, and eventually the CDW instabilities are suppressed, give rise to the maximal SC order. We discuss the interplay between multiple CDW orders, and the competition between CDW and SC in detail.There exist two domes of superconducting Tc in layered charge density wave (CDW) 2H-TaSe2−xSx single crystal alloys. Using ARPES, we study the electronic structure of the 2H-TaSe2 and observed the missing FSs at Brillouin Zone center. And the origin of the CDW in that material is discussed.

Recent progress on high throughput superconductivity research

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In this talk, I will present our recent achievements on high-throughput researches of superconducting materials.

To get the electronic phase diagram of cuprates in a more efficient way, we employed high-throughput synthesis technique to deposit the so-called combinatorial films, e.g. $La_{2-x}Ce_xCuO_4$ with x from 0.10 to 0.19 on a single substrate of 1 cm in length. That is, one sample can cover the regime from the optimally doped superconducting state to the heavily overdoped Fermi liquid state. On the basis of high efficiency screening techniques, a quantitative relation between the doping level and the superconducting transition temperature (T_c) was able to be identified for the first time in the electron-doped cuprates.

We also initiated a high throughput research on FeSe to establish the lattice-T_c library, by which we are able to fabricate film sample with gradient T_c from < 2 K to 12 K on centimeter substrate via single deposition, coming with ~ 1% expansion of the out-of-plane lattice and reduction of the in-plane lattice. In conjunction with transport and angular-resolved photoemission measurements on uniform FeSe films, we find that more conduction electrons benefit T_c, and the subsequent modification on selective orbital bands by the lattice modulation should have a significant effect on the conduction electrons. Apparently, a combination of high throughput and traditional experiments opens a promising avenue to elucidate the key ingredient to superconductivity.

An enlightened search for New Superconductors

Ivan Schuller
USCD, USA

A New Look at an Old Puzzle: ARPES on $Ba_{1-x}K_xBiO_3$

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The fact that T_c in perovskite bismuth oxides can exceed 30 K has been known since right around the discovery of the high-T_c cuprates. Yet for various reasons, the bismuthates were never studied to nearly the extent of cuprates. This is pity, because their phenomenology and underlying physics connect with a wide array of contemporary interests: not only unconventional/high-T_c superconductivity, but also metal-insulator and insulator-superconductor transitions, (bi)polarons, CDWs/charge-order, disordered systems, and so on. Recently we have succeeded in performing ARPES *in situ* on high-quality films of $Ba_{1-x}K_xBiO_3$ [1]. We revealed that the band structure of the insulating parent compound (x = 0) can be quite well captured by simple LDA. The gap opens in a predominantly oxygen-derived band, signaling the role of a negative charge transfer energy and supporting the notion that the ground state involving ordered BiO_6 breathing distortions is "bond disproportionated," as opposed to classically charge-ordered among the bismuth cations. Our latest experiments probe within the "under- to optimally-doped" region of the phase diagram. There we see a strongly dispersing metallic band forming a Fermi surface, despite an absence of peaks in the energy spectra that could be taken as the signatures of quasiparticles. We observe, moreover, two types of pseudogap-like behaviors: one extended over a broad energy scale and persisting above room temperature; the other set in a narrow region around E_F and opening in a well-defined temperature range above T_c. This latter "pseudogap" is revealed to be a signature of metal-insulator phase separation. I will discuss how our observations fit within a polaronic understanding of these materials. In particular, we view the transition to phase separation as the precipitation of ordered bipolaronic insulating regions out of a disordered polaronic liquid. Some possible implications for bipolaronic metallicity/superconductivity will also be discussed.

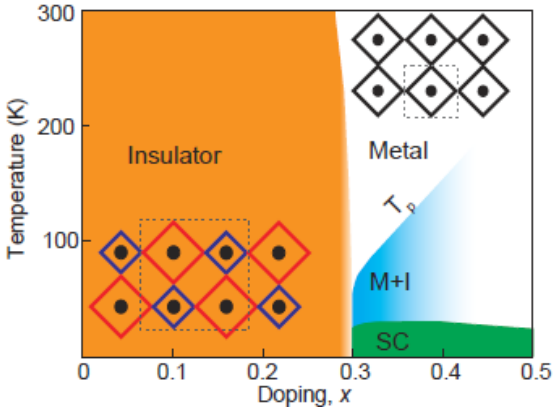

Fig. 1: *Qualitative phase diagram of $Ba_{1-x}K_xBiO_3$ showing the phase-separated region (M+I) revealed in ARPES experiments.*

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Themis Z: Opening the New Era for Superconductors

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As a powerful tool of studying the structure and properties of superconductors, transmission electron microscope (TEM) shows great application potential on the structural, elemental, and electronic analysis. Recently, Cs-corrected STEM has made breakthrough progress. On the basis of the large objective distance, the atomic resolution and best quality S/TEM image can be obtained in a short period of time, so as to carry out the two-dimensional characterization at sub-Ångström level and three-dimensional chemical analysis under nanometer scale. The powerful Velox™ software with Super-X™ technique, brand-new 4K Ceta16M™ CMOS camera, and enhanced piezo-stage enable Themis™ to achieve ultimate performance and extensive applications. For example, in Cuprate superconductors, though the functional role of the planes and chains has long been established, most probes integrate over both, which makes it difficult to distinguish the contribution of each. However, with the help of Cs- corrected S/TEM and electron energy loss spectroscopy, the charge transfer of holes from the chains to the planes as a function of oxygen content has been directly probed, and show that the change in orbital occupation of Cu is large in the chain layer but modest in CuO_2 planes, with holes in the planes doped primarily into the O 2*p* states. The result offers direct insight into the local electronic structure and charge transfers in this important high-temperature superconductor.

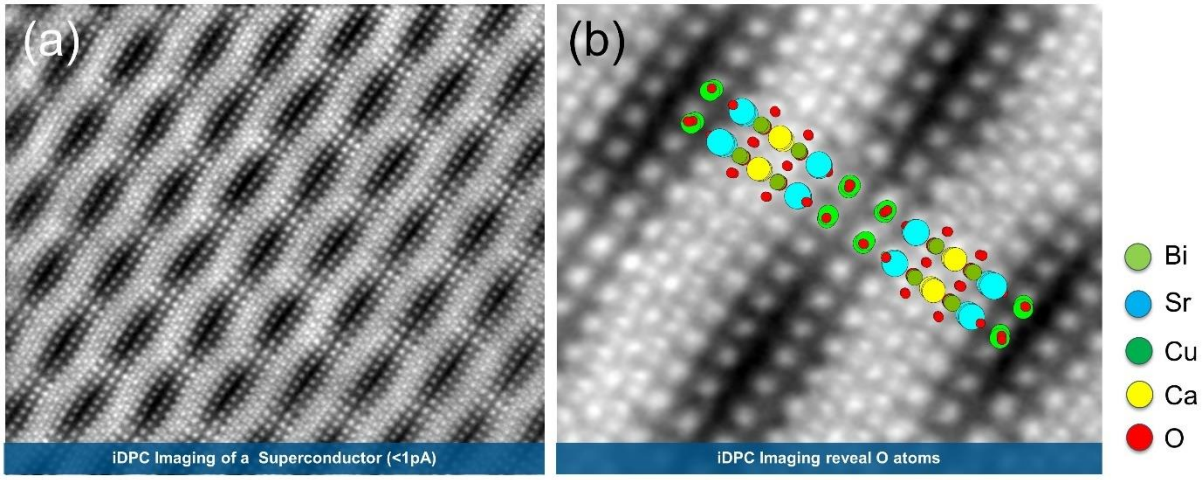

Fig. 1: *(a) iDPC image of BiSrCaCuO superconductors under STEM; (b) Oxygen atoms imaging in BiSrCaCuO superconductors*

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The So-called Nematic Phase is the Critical Regime of the Orbital/Structural Transition in the Fe-based Superonductors

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In our previous neutron scattering investigations on the structural and antiferromagnetic transitions in the 1111 [1], 122 [2], 11 [3] and 245 [4] families of the Fe-based superconductors, we have concluded that the close relation between the expansion (contraction) of the Fe pair distance with the antiferromagnetic (ferromagnetic) exchange interaction is due to the ordered pattern of the d_{xz} and d_{yz} orbital occupations. This orbital ordering picture is proposed as early as in 2018 [1], which is very similar to our previous investigations on transition metal oxides [5,6], and the orbital ordering was initially invoked by Goodenough to explain rich magnetic phases discovered by Wolland and Koehler in their classic neutron scattering study on manganites [7]. The orbital ordering, as manifested in the ordering of the two types of in-plane Fe bonds : the contracting and ferromagnetic bond and the expanding and antiferromagnetic bond, leads to the C2 symmetry breaking and consequently to the in-plane anisotropy in transport, thermal, and magnetic measurements, namely the so-called nematic propertie [8-10].

In the critical regime of the orbital transition, namely above the structural transition, dynamic orbital short-range order necessarily breaks the spin-space anisotropy through the usual spin-orbital coupling mechanism. We here demonstrate by measuring low-energy critical spin fluctuations in NaFeAs that in the so-called nematic phase spin space symmetry is indeed broken in spin-fluctuations [11]. The directional suppression of a dynamic spin fluctuation component above the structural transition has also been observed previously in our polarized neutron diffraction measurements of $Fe_{1.02}Te_{0.95}Se_{0.05}$ [12]. This dynamic spin-space symmetry breaking caused by dynamic orbital-order above the structural/orbital transition necessarily affects in-plane symmetry in transport, thermal, and magnetic properties through e.g. the electron-spin scattering.

Normal state physics in all Fe-based superconductors can thus be understood consistemently by the d_{xz}/d_{yz} orbital ordering picture. Understanding the unconventional Fe-based superconductivity should proceed basing on such a unified minimum physics model of the materials.

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Diverse Nematic States and Pairing Mechanisms in Fe-based and Cuprate Superconductors

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Electronic nematc states in strongly correlated electron systems exhibit very rich variety. In FeSe, the nematic state is given by the orbital polarization $n_{xz} \neq n_{yz}$ (B_{1g} symmetry) with sign-reversal in momentum space [1,2]. Surprisingly, in AFe_2As_2 (A=Cs,Rb), nematic order with B_{2g} symmetry has been reported recently. In cuprate superconductor YBCO, the nematic order with B_{1g} symmetry has been observed at the pseudogap temperature T^*, which is predicted to be the d-wave bond-order theoretically [3,4]. Interestingly, B_{2g} symmetric nematic order at $T=T^*$ has been reported in Hg-based compounds very recently. To understand such diverse nematic states, we perform systematic study based on the charge-density-wave (CDW) equation theory [2,4,5]. In this theory, both the orbital polarization and d-wave bond-order are given by the Aslamazov-Larkin vertex corrections.

In AFe_2As_2 (A=Cs,Rb), which is the heavily hole-doped Fe-based superconductors, we predict that the origin of B_{2g} nematicity is the bond-order with respect to xy-orbital hopping integrals [5]. That is, the nematiciy in this compound is given by the rotational-symmetry-breaking in the xy-orbital self-energy, which corresponds to the modification of the correlated hopping between the next-nearest-neighbor sites in real space. We also study the nematic bond-order in the presence of the hot-spot structure (or Fermi arc structure) based on the CDW equation theory, and find that the symmetry of bond-order changes from B_{1g} and B_{2g} when the hot-spot structure becomes prominent [6]. This result is significant to understand the rich variety of the nematicity in cuprate superconductors.

To summarize, diverse nematic orders discovered in various Fe-based and cuprate superconductors are naturally explained based on the CDW equation theory. We also discuss the pairing mechanism mediated by strong nematic fluctuations in these superconductors.

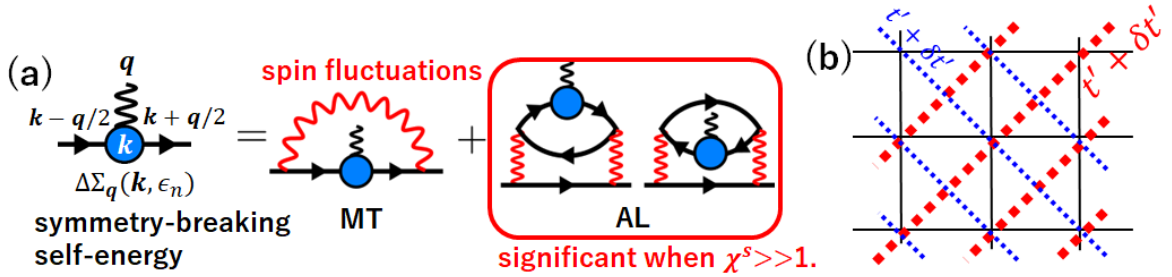

Fig. 1: *(a) CDW equation [2,4] and (b) predicted B_{2g} bond order (± t) in AFe_2As_2 and cuprates.*

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Origin of Nematicity in Iron-based Superconductors

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In iron-based superconductors, the structural transition from tetragonal to orthorhombic, and the antiferromagnetic transition from paramagnetic to the stripe spin-density-wave state occur simultaneously in some parent compounds such as the 122 family whereas they are separated by tens of Kelvins in some other compounds such as the 1111 family. Surprisingly, the FeSe parent compound has only the structural transition around 90 K but does not undergoes an antiferromagnetic transition at all. The origin of the nematic order which breaks the C4 rotational symmetry while keeps the translational symmetry remains elusive. Furthermore, whether the nematic order and nematic fluctuations help or suppress superconductivity is still under hot debate. Here using a combination of density functional theory and dynamical mean field theory with two-particle vertex correction, we compute the dynamical spin susceptibility of a large body of iron-based superconductors. Careful analysis of the dynamical spin susceptibility gives a natural explanation and a common origin of the nematicity in all the iron-based superconductors.

Orbital fluctuations driven nematic superconductivity: coexistence of orbital polarization and Cooper pairing

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Searching for novel unconventional superconducting (SC) compounds with high transition temperatures remains a huge challenge for condensed matter theorists and experimentalists. Motivated by recent discoveries of the superconducting phases in β-MNCl (M=Hf,Zr) with unexpectedly high transition temperatures and that in ironpnicitde compounds with anomalous two domes or with only one Fermi surface, we investigate the orbital-fluctuation-mediated superconducting phase diagrams of doped Kugel-Khomskii model. We find that due to the orbital exchange and orbital fluctuations, the ground states of the system may coexist inter-orbital or intra-orbital superconductivity and antiferro-orbital or ferro-orbital polarization or ordering in the presence of a antiferro-type (positive) or ferro-type (negative) superexchange coupling parameters, suggesting the possibility of nematic superconductors.

As shown in Fig.1(a), the SC phase transition from p-wave to d-wave is dependent on the total filling n and J. The antiferro-orbital order transition is second order with increasing J. If the next-nearest-neighbour super-exchange is considered, the interorbital s-wave should be favored around half filling with $J>0$. In Fig.1(b), the ferro-orbital order transition is first order and the system becomes orbital polarized absolutely with increasing J. Thus the SC phase is fully orbital selective with $J<0$. The doping concentration and superexchange interactions control the symmetry of the superconducting pairing. Our results may not only address the multiple superconductng phases in multiorbital compounds, but also explain the pairing origin in β-MNCl (M=Hf,Zr) compounds.

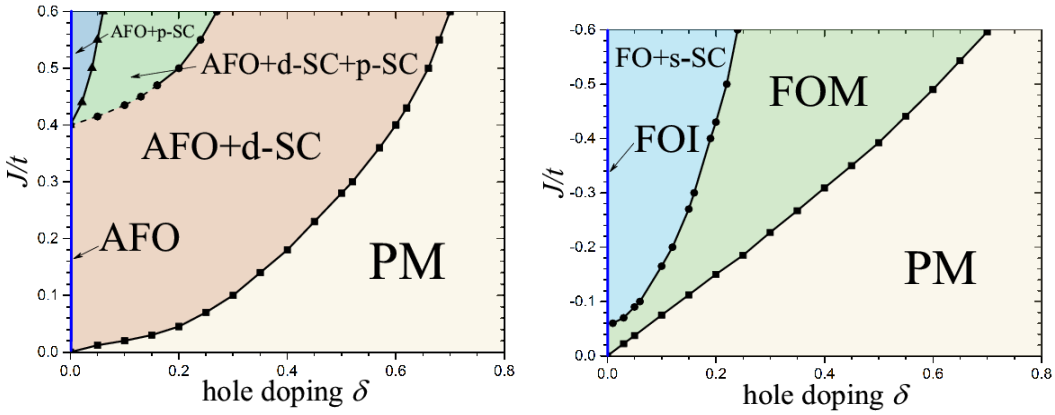

Fig.1 The phase diagrams as a function of super-exchange parameter *J* and filling *n* with square lattice for . Here AFO and FO denote antiferro-orbital order and ferro-orbital order. s-SC, d-SC and p-SC denote s-wave d-wave and p-wave SC orders, respectively.

Signatures of fluctuating nematic order in YBCO nanostructures

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The microscopic origin of superconductivity and the related phase diagram of High Critical Temperature Superconductors (HTS) is far from being fully understood. During the last few years Charge Density Wave (CDW) order has been ubiquitously observed in these materials unifying the behavior of the various HTS compound families [1]. Recently, transport measurements have been instrumental to detect signatures of CDW [2,3]. In this respect resistance noise measurements can be a powerful tool to understand the properties of these materials in the phase under study and to detect symmetry breaking orders [4,5]. Here we present resistance noise measurements performed on $YBa_2Cu_3O_{7-x}$ (YBCO) nano-structures, as a function of temperature and hole doping. Our measurements give clear indication that oxygen dynamics is the dominant mechanism responsible for the 1/f flicker noise [6]. The noise also shows unexpected strong two level fluctuators (TLFs) with distinct characteristic activation energies. These TLFs can be studied by performing cross-correlation noise measurements on YBCO X-bars Fig.1(a). The measurements show anti-correlation in the spectral phase, which points towards a symmetry breaking characteristic of fluctuations in a nematic ordered phase (e.g. CDW).

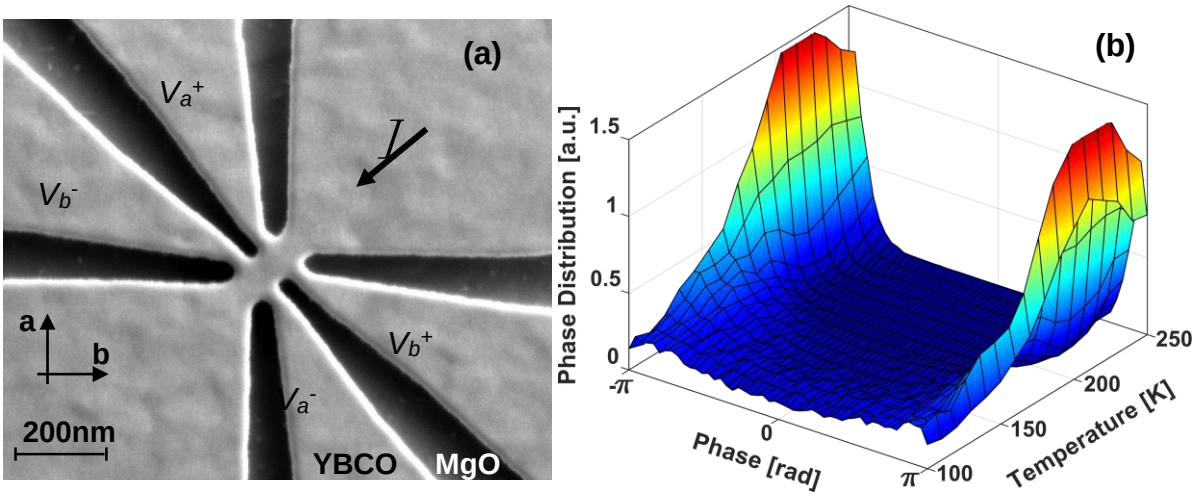

Fig. 1: (a) *SEM picture of a measured device. The current bias I flows along the [110] in-plane direction, the voltage is measured simultaneously along V_a^{+-} and V_b^{+-}. (b) Phase distribution of the cross-correlated spectra as function of temperature. The phase peaks around π for the temperature where the TLF are more pronounced as expected for anti-correlated noise, giving indication of nematic order.*

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Chirality Fluctuation and Electromagnetic Response in Nematic Superconductors

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Recently, "*nematic*" superconductivity accompanying the spontaneous breaking of the rotational symmetry has been reported in doped topological insulators, $M_xBi_2Se_3$ (M=Cu, Sr, Nb) [1,2]. The nematic state is a time-reversal-invariant pairing state in the E_u representation having two point nodes residing in the *xy* plane.

Here we propose that electromagnetic wave response in these compounds provides fingerprint spectroscopy of nematic superconductivity. Transverse electromagnetic waves resonate to long-lived massive bosonic ("*Higgs*") excitations that involve a coherent motion of macroscopic fractions of particles. In addition, their excitation spectra reflect the richness of the spontaneous symmetry breaking and pairing mechanism in superconducting states. Using quasiclassical Keldysh theory [3], we show the existence of two characteristic bosonic modes in nematic superconductors: nematicity and chirality fluctuation modes. The former is the pseudo Nambu-Goldstone boson associated with the broken rotation symmetry. The latter can be identified as the fluctuation of the orbital angular momentum of Cooper pairs. We find that the mass gap of the chirality mode closes at the critical doping rate, signaling the dynamical instability of the nematic state towards the chiral state with broken time reversal symmetry. We demonstrate that the spectral evolution of bosonic excitations can be clearly captured by the power absorption spectrum (Fig. 1). We further discuss the contributions of the fluctuation modes of competing A_{1u} and A_{2u} pairing to electromagnetic response.

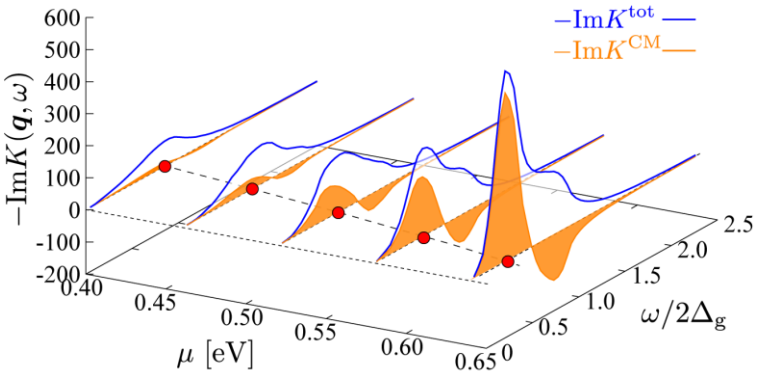

Fig. 1: *Power absorption spectra in nematic superconducting states. The shaded area represents the contributions of the chirality fluctuation mode.*

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Electronic structure and electronic order in lightly doped cuprates studied by STM

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Although the mechanism of superconductivity in the cuprates remains elusive, it is generally agreed that at the heart of the problem is the physics of doped Mott insulators. A crucial step for solving the high temperature superconductivity puzzle is to elucidate the electronic structure of the parent compound and the behaviour of doped charge carriers. In this talk we report recent scanning tunnelling microscopy studies of the atomic-scale electronic structure and electronic order in the parent and lightly doped cuprates. In the parent compound, the full electronic spectrum across the Mott–Hubbard gap, or more precisely the charge transfer gap, is uncovered by scanning tunnelling spectroscopy. The size of the charge transfer gap shows strong variations for different cuprate families, and an anti-correlation with the maximum transition temperature that can be achieved at optimal doping. Defect-induced charge carriers are found to create broad in-gap electronic states that are strongly localized in space. In lightly doped insulating Bi-2201 compound, we find that the main effect of charge doping is to induce a spectral weight transfer from the high energy Hubbard band to the low energy in-gap states. At sufficiently high doping, a sharp energy gap reminiscent of the pseudogap starts to form near the Fermi level, and is accompanied by the emergence of a checkerboard-like charge order. Our results demonstrate that the first ordered phase in the doped Mott insulator is a charge ordered insulator, which will gradually evolve into the superconducting state upon further doping. More recently, we observe a periodic modulation of both the superconducting coherence peak and gap depth in a severely underdoped Bi-2212, demonstrating the existence of a density wave order of Cooper pairing. The pair density wave order has the same spatial periodicity as the charge order, and the amplitudes of the two orders exhibit clear positive correlation. These results shed important new lights on the origin of and interplay between the charge order and Cooper pairing modulation in the cuprates.

Lattice Distortion Induced Effects on Electronic State in Bi-Sr-Ca-Cu-O Superconductors Determined by Scanning Tunneling Microscopy

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The nanoscale inhomogeneity of electronic state in copper oxide high-temperature superconductor has attracted a lot of attention in past studies. The lattice distortion is found to be one of the factors to tune the electronic inhomogeneity in Bi2Sr2CaCuO8+δ (Bi-2212). Here we apply scanning tunneling microscope to explore the effects of lattice distortion on electronic state for two types of samples in the Bi-Sr-Ca-Cu-O family tree, an optimally doped Bi-2212 and Bi2Sr2CuO6+δ (Bi2201). We determine the lattice distortion by a quantitative analysis of the atomic displacements in the structural supermodulation. In Bi-2212, a smooth modulation of the atomic displacement leads to a similarly modulated electronic spectrum and pesudogap amplitude. In Bi-2201, the lattice distortion is stronger than that in Bi-2212, which induce totally different effects on the electronic state: the spectrum has a very small averaged modulation along the periodic strucutre. A modeling is discussed to explain the different effects of lattice distortion on the electronic state.

Conventional aspects of vortex cores in a copper oxide high-T_C superconductor

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Superconductivity above liquid nitrogen temperature, considered impossible until it was observed in 1986, has been challenging the scientific community for over 30 years to explain its fundamental mechanism. High temperature superconductivity (HTS) was first found in an insulating oxide ceramic, very different from any superconducting material known at the time. Among the unusual features of HTS compounds is the electronic vortex core structure. The order parameter singularity at the vortex centre is responsible for a particular quasiparticle local density of states (LDOS) predicted by Caroli, de Gennes, and Matricon within the BCS theory framework. While this prediction was verified for low-temperature superconductors, it failed completely to explain the tunneling spectra measured at the vortex cores of HTS. We present a recent scanning tunneling spectroscopy study where we found that the tunneling current of $YBa_2Cu_3O_{7-}$ has two contributions: one from superconducting electrons and one from a non-superconducting LDOS. A detailed analysis of these data reveals that the superconducting condensate can be perfectly understood within a standard model [1], including the Caroli–de Gennes–Matricon vortex core states [2] which have remained undetected so far. We show that the tunneling spectra look unconventional because superconducting electrons are minority and we discuss the impact of these findings on the understanding of the pseudogap phase and presumed competition between superconductivity and charge order.

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Non-Fermi Liquid Scattering against Emergent Bose Liquid: Manifestations in the Kink and Other Exotic Quasiparticle Behaviors in the Normal-State Cuprate Superconductors

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The normal state of cuprate superconductors exhibits many exotic behaviors qualitatively different from the Fermi liquid, the foundation of condensed matter physics. Here we demonstrate that non-Fermi liquid behaviors emerge naturally from scattering against an emergent Bose liquid. Particularly, we find a finite zero-energy scattering rate at low-temperature limit that grows linearly with respect to temperature, against clean fermions' generic non-dissipative characteristics. Surprisingly, three other seemingly unrelated experimental observations are also produced, including the well-studied "kink' in the quasi-particle dispersion, as well as the puzzling correspondences between the normal and superconducting state. Our findings provide a general route for fermionic systems to generate non-Fermi liquid behavior, and suggest strongly that by room temperature the doped holes in the cuprates have already formed an emergent Bose liquid of tightly bound pairs, whose low-temperature condensation gives unconventional superconductivity.

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Electronic State in the Undoped (Ce-Free) Superconductor T'-$La_{1.8}Eu_{0.2}CuO_4$ Studied from Impurity Effects on Muon Spin Relaxation

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The high-T_c superconductivtiy in undoped (Ce-free) Ln_2CuO_4 (*Ln*: lanthanide elements) with the Nd_2CuO_4-type (so-called T'-type) structure has attracted great interest, because superconductivity emerges via the adequate reduction annealing without the substitution of Ce for *Ln*, namely, without extra electron doping [1-4]. Our studies of impurity effects on the superconducting (SC) transtion temperature, T_c, [5] and NMR [6] for SC undoped T'-$La_{1.8}Eu_{0.2}CuO_4$ (T'-LECO) have revealed that the superconductivity has *d*-wave symmetry and is mediated by the spin fluctuation. Our recent muon-spin-relaxation (μSR) measurements of a SC sample of T'-LECO with T_c = 15 K have revealed that the superconductivity coexists with a short-range magnetic order (SMO) [7].

Here, we report on the μSR study of impurity-free and impurity-substituted SC samples of T'-$La_{1.8}Eu_{0.2}Cu_{1-y}M_yO_4$ (*M* = Ni, Zn; *x* = 0, 0.005, 0.01) performed at the RIKEN-RAL Muon Facility. For the impurity-free SC sample of T'-LECO with T_c = 20 K, it has been found that phase separation into SC and SMO regions takes place clearly and that the volume fraction of the SMO region is smaller than that in the above SC sample of T'-LECO with T_c = 15 K [7], suggesting that the SMO region would disappear by the perfect removal of excess oxygen. For impurity-substituted SC samples, it has been found that no magnetic order is developed around *M* in the SC region and that the magnetic transition temperature in the SMO region increases and decreases by the Ni- and Zn-substitution, respectively. Accordingly, it has been concluded that the electronic state in the SC region is similar to that in the overdoped regime of hole-doped $La_{2-x}Sr_xCuO_4$ with the so-called T-type structure [8] and is understood as a strongly correlated itinerant electron system [9], while the SMO region is due to localized Cu spins induced by a very small amount of excess oxygen.

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Reduction and Electron-Doping Effects on the Cu-Spin Correlation in Electron-Doped High-T_c Cuprates $Pr_{2-x-y}La_yCe_xCuO_{4+d}$

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In electron-doped high-T_c cuprate superconductors with the so-called T' structure $RE_{2-x}Ce_xCuO_{4+d}$ (*RE*: rare earth), it has been believed that not only the electron doping into the parent Mott insulator but also the reduction annealing is essential for the superconductivity to appear. Formerly, it has been reported in thin films [1] and polycrystals [2] of the electron-doped cuprates that, through the appropriate reduction annealing, namely, the removal of excess oxygen, the superconductivity appears in a wide range of x including the parent compound of $x = 0$, which attracts considerable research attention. In order to clarify detailed effects of the reduction annealing and electron doping on the low-energy Cu-spin correlation, we have performed muon-spin-relaxation (uSR) measurements using single crystals of T'-cuprates $Pr_{2-x-y}La_yCe_xCuO_{4+d}$ (PLCCO).

Using the improved reduction annealing, namely, the protective, low-temperature, dynamic annealing [3,4], we have found for PLCCO with $x = 0.10$ and $y = 0.7$ that the reduction annealing brings about the increase in T_c and that after showing the maximum, T_c decreases with further annealing due to over-reduction [5]. The uSR measurements have revealed that an antiferromagnetic (AF) order is destroyed by the reduction annealing [4,6]. However, the AF Cu-spin correlation is developed at low temperatures for samples with high T_c values of ~ 27 K. For the electron-doping effects, the development of the AF Cu-spin correlation has been found to weaken with increasing x and almost disappears at the end point of the superconducting region of $x = 0.20$ in the phase diagram, which is consistent with the results of neutron scattering sensing the Cu-spin correlation of higher energy than that in uSR [7]. These results suggest that the developed AF Cu-spin correlation is in intimate relation with the appearance of superconductivity in the electron-doped cuprates.

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Orbital Selective Charge Quadrupole Density Wave in $FeSe_{1-x}S_x$ Charge Fluctuations in Iron Pnictides and Selenides

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Iron based superconductors present a new paradigm of multi-orbital superconductivity in proximity to nematic transition and spin density wave (SDW) order. Most compounds share a common phase diagram which in the underdoped region is marked by a tetragonal to orthorhombic phase structural transition at temperature T_S followed by a SDW transition at T_{SDW}, slightly below T_S. The orthorhombic distortion at T_S breaks C_4 rotational symmetry while the translational symmetry is broken due to doubling of the unit cell either at or above T_{SDW}. The systems provide exceptional setting to study coexistence and/or competition between charge quadrupole fluctuations, superconductivity, and density-wave phases.

We employ polarization-resolved resonant Raman spectroscopy to study phononic, electronic, inter-band and magnetic excitations in numerous families of the oxypnictide compounds. The Raman susceptibility shows critical quadrupole charge fluctuations across the entire phase diagram which we interpreted in terms of inter-orbital quadrupole excitations. We demonstrate that above the structural phase transition the quadrupolar fluctuations with long correlation times are precursor to the discrete four-fold symmetry breaking transition. This is manifested in the XY-symmetry collective fluctuations observed in dynamical Raman susceptibility and enhancement of the static Raman susceptibility. Below superconducting transition, these collective excitations undergo a metamorphosis into a coherent in-gap collective mode of extraordinary strength and at the same time serve as glue for non-conventional superconducting pairing [1-4].

In the most recent studies of $FeSe_{1-x}S_x$, the system which does not show long range magnetic order, we have discovered that a gap reminiscent to a mean-field order parameter opens in the spectra of XY symmetry below T_S. The data is interpreted as formation of the stripe-type quadrupole order. The interpretation provides explanation for the recently reported anisotropic electronic properties in the nematic phase as well as for the puzzling orbital selective superconductivity.

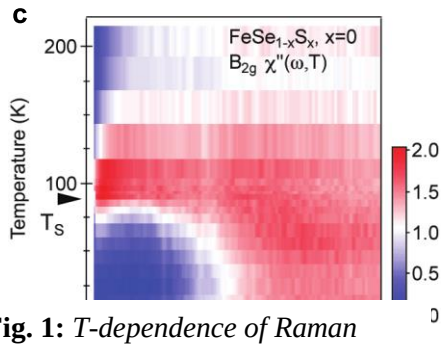

Fig. 1: *T-dependence of Raman res-ponse for FeSe [2]. Quadrupolar fluctuations and development of nematic gap are*

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In-situ doping control of iron-based superconductors via alkali-metal adsorption

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Alkali-metal adsorption on the surface of materials has been proved to be an effective method for in-situ electron-doping. Here, we studied the alkali-metal coated iron-based superconductors using angle-resolved photoemission spectroscopy (ARPES). Different families of iron-based superconductors show distinctive sensitivity to alkali-metal adsorption. While heavily electron doping can be achieved on the surface of FeSe with a band shift over 100meV, only a few meV band shift was observed in LiFeAs. Distinctive electronic phase diagrams have been delineated through a precise control of electron doping vis alkali-metal adsorption. In FeSe and $FeTe_{1-x}Se_x$, the superconductivity enhances in heavily electron doping regime of the phase diagram with a gap opening temperature over 25K. In 122-type of iron-based superconductors, when doping electrons, superconducting gap suppresses in $Ba_{1-x}K_xFe_2As_2$ and remains unchanged in $BaFe_2As_{2-x}P_x$. More intriguingly, the surface state of 122 iron-based superconductors is strongly suppressed by alkali-metal adsorption and hence the intensity of superconducting coherence peak increase significantly. Distinctive momentum distributions of superconducting gap were observed in $Ba_{1-x}K_xFe_2As_2$ and $BaFe_2As_{2-x}P_x$. Our results show that the alkali-metal adsorption not only is an effective method to control the electron doping of materials, but also turns on an intriguing interplay between the alkali-metal coated surface and bulk states, which could pave a new way for understanding the iron-based superconductors.

Electron Correlations and Multi-orbital Superconductivity in Iron Pnictides and Chalcogenides

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Identifying the key building blocks for the physics of the iron-based superconductors (FeSCs) remains a task in flux. The role of quantum fluctuations in the magnetic and nematic channels [1] has been addressed from early on. In more recent years, there has been a growing recognition that the underlying electron correlations manifest in an orbital-selective way [2,3], with an orbital-selective Mott phase anchoring this physics for the normal state. As a natural consequence for the superconducting state, an orbital-selective pairing has been advanced [4]. Most recently, the orbital-dependent superconductivity has been examined in the nematic state of FeSe [5,6]. I will summarize these issues and discuss their implications for the overall understanding of the FeSCs.

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Orbital Selectivity in the nematic and superconducting phases of Iron-based superconductors

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Unconventional superconductivity is usually found in correlated materials as a low temperature bridge between phases dominated by high- and low-energy scale of electronic interactions (e.g. Mott physics vs Fermi Liquid regime). The understanding of the nature and strength of correlations is key to unveil the nature of the pairing itself as well as its role as competitive/cooperative order with other ordered phases.
The multiorbital character of the electronic band structure close to the Fermi level complicates the analysis of correlation effects in Iron-based materials. Contrasting experimental evidences of weak and strong regime of electronic correlation polarized theoretical approaches around low-energy effective models [1] or, on the opposite side, strongly correlated approaches [2].
A deep understanding of the physics of iron-based material requires instead to combine these approaches to unveil the complex interplay between high and low energy scale of the interactions. From this analysis we find that the orbital selectivity emerges both in the nematic and in the superconducting phase as a main feature of the physics of iron based superconductors at every scale [3-5]. Such a result discloses a new scenario in which the key ingredient of the pairing itself comes from a new and unconventional cooperative interplay between low- and high-energy scale of electronic interactions [6].

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Spectral Evidence for Emergent Order in $Ba_{1-x}Na_xFe_2As_2$

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We report an angle-resolved photoemission spectroscopy study of the iron-based superconductor family, $Ba_{1-x}Na_xFe_2As_2$. This system harbors the recently discovered double-Q magnetic order appearing in a reentrant C4 phase deep within the underdoped regime of the phase diagram that is otherwise dominated by the coupled nematic phase and collinear antiferromagnetic order. From a detailed temperature-dependence study, we identify the electronic response to the nematic phase in an orbital-dependent band shift that strictly follows the rotational symmetry of the lattice and disappears when the system restores C4 symmetry in the low temperature phase. In addition, we observe a distinct electronic reconstruction that cannot be explained by the known electronic orders in the system, and is instead most compatible with the translation symmetry breaking of a theoretically predicted charge order that accompanies the double-Q magnetic order.

Hydrostatic pressure effect on critical current density and vortex dynamics in REBaCuO coated conductors derived by metallorganic deposition

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The present work introduces the in-situ hydrostatic pressure effect on the critical current density and vortex pinning in Y(Dy)$Ba_2Cu_3O_{7-\delta}$ coated conductors derived by metallic organic solution deposition. It is revealed that in-situ hydrostatic pressure enhances the critical current density at the applied conditions of high field and high temperature. In case of 80 K and 5 T, we observe a ten-fold increase in the critical current density and unvaried critical temperature under the pressure of 1.2 GPa, and the irreversibility line is shifted upwards as shown in Figure 1. The vortex dynamics are investigated through magnetic relaxation at different temperatures and fields under the in-situ pressure, showing that vortex creep rates are strongly suppressed due to applied pressure, and the pinning energy is significantly increased based on the collective creep theory. After releasing the pressure, the original superconducting properties are recovered. It is thus speculated that in-situ hydrostatic pressure exerted on the present coated conductor may enhance the pinning with existing extended-like defects, unlike what has been observed in $REBa_2Cu_3O_{7-\delta}$ melt-textured crystals, where the effect of pressure is believed to give rise to the point-like defects directly.

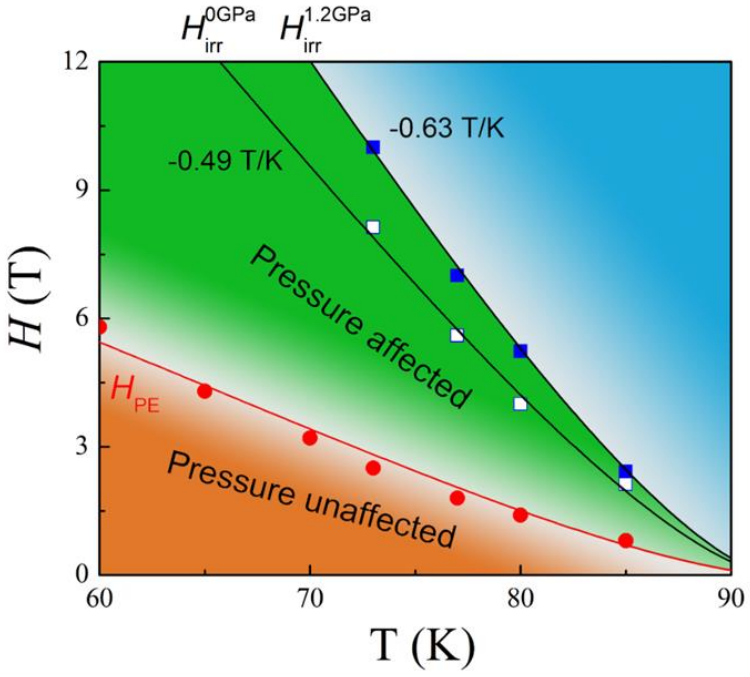

Fig.1: *H–T diagram showing the region where the in situ hydrostatic pressure effect is present with enhanced Jc and shifted the irreversibility line to higher temperatures and fields.*

Advances in high critical current nanocomposite $YBa_2Cu_3O_{7-x}$ coated conductors from chemical solutions

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High current superconducting wires for large scale power applications and magnets has been one of the most challenging achievements during all the HTS era which encompasses many materials science and engineering challenges. Coated conductors of $YBa_2Cu_3O_7$ (YBCO) have emerged as the most attractive opportunity to reach unique performances while reducing the cost/performance ratio continues to be a key objective at present. Chemical solution deposition (CSD) is a very competitive cost-effective technique which has been used to obtain nanocomposite films and CCs. In the recent years we have been able to demonstrate the unique potentiality of CSD techniques based on Ink Jet Printing deposition to achieve low cost, low anisotropy and high critical current coated conductors.

In this presentation, we will report on recent progress on the development of growth process of thick films and enhanced vortex pinning of CSD nanocomposite YBCO films, obtained from colloidal solutions where preformed oxide nanoparticles (NPs) stabilized in the YBCO precursor solutions are used. A thorough investigation correlating the pinning landscape with the defect microstructure has been pursuit through detailed angular dependent in-field critical currents and HRTEM/STEM analysis. We will show how these YBCO films can be properly tuned for Fault Current Limitation applications.

We will finally report that CSD films and nanocomposites can be obtained through a new growth approach based on the formation of a transient-liquid assisted growth (TLAG) enabling ultrafast growth rates, in the range of 100 nm/s, as demonstrated by in-situ synchrotron X-ray diffraction analysis of the growth process.

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FASTGRID and Excellence Program Severo Ochoa SEV2015-0496.

In-situ hydrostatic pressure induced giant enhancement of superconductivity, flux pinning, and J_c in Fe-based superconductors and YBCO coated conductors

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Pressure is well known to significantly raise the superconducting transition temperature, Tc, in both iron pnictides and cuprate based superconductors. Little work has been done, however, on how pressure can affect the flux pinning and critical current density in Fe-based superconductors. We demonstrate that the hydrostatic pressure up to 1.2 GPa can not only significantly increase T_c, but also significantly enhance the irreversibility field, H_{irr}, as well as the critical current density, J_c, at both low and high fields for doped and undoped doped $FeSe_{0.5}Te_{0.5}$, $NaFe_{0.97}Co_{0.03}As$, $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals and polycrystalline $Sr_4V_2O_6Fe_2As_2$ bulks. It was found that pressure can induce more point defects, which are mainly responsible for the Jc and flux pinning enhancement. By successfully employing the hydrostatic pressure effect, a remarkably significant enhancement of $\boldsymbol{J_c}$ by an order of magnitude can be achieved in $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes in both low and high fields. This is a promising technological step forward towards high-field applications, as the record high $\boldsymbol{J_c}$ values ($\sim 2 \times 10^5$ A/cm^2 at 4.2 K and 13 T, $\boldsymbol{P}$ = 1.1 GPa) obtained for $Sr_{0.6}K_{0.4}Fe_2As_2$ tape are superior to those of Nb_3Sn and other pnictide wires/tapes. Furthermore, we found that In-situ hydrostatic pressure induced giant enhancement of flux pinning and significant suppression of magnetic relaxation in YBCO coated conductors. The fundamental significance of the in-situ pressure induced significant enhancement of flux pinning or J_c is that there is still plenty of room to further improve the supercurrent carrying capability for both Fe-based superconductors and YBCO coated conductors.

This work is supported by Australian Research Council (ARC) through the ARC Centre of Excellence in Future Low-Energy Electronics Technologies (FLEET) and an ARC Professorial Future Fellowship project (FT130100778).

New experiments on the origin of the grain boundary problem in HTS cuprates

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Grain boundary weak links remain one of the principal obstacles to applications of both cuprates and Fe-based superconductors (FBS), because their avoidance requires strong texture to minimize the high angle grain boundary (GB) density. A recent magneto-optical (MO) imaging study of 6°[001] tilt Ca-doped $YbBa_2Cu_3O_{7-x}$ bicrystal films enabled reversible under- and over-doping of both the grains and the GBs and showed that both J_c^{GB} and J_c^{Grain} degrade on underdoping, the degradation expressed by J_c^{GB}/J_c^{Grain} being smaller in the underdoped state. A second striking result is the strong difference in J_c^{GB}/J_c^{Grain} (T) between a pure and a Ca-doped film, where the ratio increases much more strongly with increasing temperature $t = T/T_c$ for the Ca-doped than for pure films. We attribute this to very strong desegregation of Ca away from the channels between the grain boundary dislocations, leaving the channels with a higher T_c than the grains on either side. A parallel study of the effect of doping state in another system that allows both over- and under-doping (Bi-2212 multifilamentary wires with a significant biaxial texture ~15°) again shows that underdoping reduces the long-range transport J_c, as expected from the weaker vortex pinning of a more anisotropic, underdoped state. More curiously, hysteresis of the field-increasing, field-decreasing $J_c(H)$, a marked weak-link signature, is absent in all doping states, apparently violating the standard model of a weak-linked GB that it is underdoped with respect to the grains with a lower superfluid density and a Thomas-Fermi screening length comparable to the coherence length. These two contrasting materials, a quasi-ideal bicrystal, and an imperfectly but quite well-aligned biaxial polycrystalline array, emphasize that much still needs to be understood about grain boundaries in HTS materials. Fe-based superconductors too are finding similar challenges in their march to applications too.

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High Performance $Bi_2Sr_2CaCu_2O_x$ Round Wires

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Multifilamentary $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) wire made by powder-in-tube technique is the only high temperature superconductor made in the round shape preferred by magnet builders. The critical current density (J_c) of Bi-2212 round wire was improved significantly by the development of overpressure heat treatment in the past few years. Bi-2212 wire is commercially available in multiple architectures and kilometer pieces and has become a technical conductor for very high field NMR and accelerator magnets. We recently studied the effects of precursor powder, heat treatment condition, wire configuration, filament size and twisting on the superconducting properties and microstructure of the recent Bi-2212 wires. Short samples of recent wire showed J_c(4.2 K,15 T) = 6860 A/mm^2 and J_E(4.2 K, 15T and 30 T) = 1360 and 930 A/mm^2 with optimized overpressure processing. We believe that J_c of Bi-2212 wire is still not fully optimized, and it could be further improved by improved powder processing, wire manufacture process and the over-pressure heat treatment.

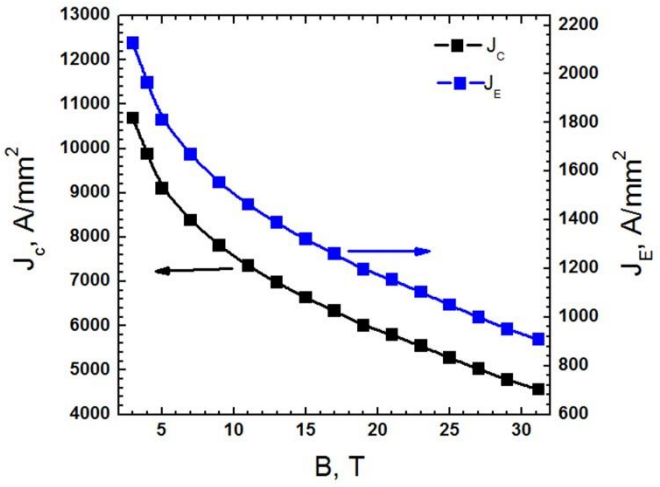

Fig. 1: *J_C(B) and J_E(B) measured in a 31.2 T magnet at the National High Magnetic Field Laboratory for a Bi-2212 wire with diameter of 0.8 mm and 55x18 filaments.*

We are grateful to our collaborators, Y. Kim, E. S. Bosque and D. V. Abraimov (NHMFL), T. Shen (LBNL), Y. Huang and H. Miao (B-OST), A. Xu and A. Hunt (nGimat), A. Otto (SMS), and S. Sengupta and R. Revur (MetaMateria). The work is supported by the US DOE Office of High Energy Physics under grant number DE-SC0010421, by the National Institute of General Medical Sciences of the NIH under Award Number R21GM111302, and by the NHMFL, which is supported by NSF under Award Numbers DMR-1157490 and DMR-1644779, and by the State of Florida, and is amplified by the U.S. Magnet Development Program (MDP).

Recent Progresses on BSCCO Wires and Applications at InnoST

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Innova Superconductor Technology Co., Ltd. (InnoST) has been developing the Bi-2223/Ag high temperature superconducting (HTS) wires since 2001. The present commercial HTS wires made by InnoST achieved critical current (Ic) up to 170A, and the highest Ic of short trial wires can be over 180A, at 77 K in self-field, respectively. As a certificated supplier to the International Thermonuclear Experimental Reactor (ITER), InnoST has finished 2km of low thermal conductivity HTS wires this year. The wire will be used in the current leads. To further improve the performance of the wires and broaden the product lines, several techniques have been developed and applied into the manufacturing processes. The hot isostatic pressing (HIP) sintering technique has been successfully introduced into trial wires to improve their density and Ic performance, and will soon be applied to commercial HTS wires. Besides, strengthened wires laminated with the reinforcing metals, with the critical tensile stress of over 250MPA (95% of Ic retention), and insulated wires with the DC breakdown voltage of over 1000V have been successfully developed to meet the requirements of various applications. Wires with higher critical tensile and breakdown voltage are being developed.

In the application areas, InnoST continues the long-termed specialty in HTS power cables and promotes a new frontier in the HTS railway traction transformers. InnoST emphasizes the efforts on pushing forward the adoption of HTS power applications in China, especially focuses on improving the power supply situations in the load centers in highly dense areas of large cities by using triaxial HTS cables. Since 2017, InnoST started to play a very important role in a key project on 6.6MVA HTS traction transformers that meet the railway standards, supported by Chinese Ministry of Science and Technology. The HTS wires made by InnoST will be used in this transformer. And the coils in transformer will be manufactured by InnoST.

In summary, InnoST is continuing its fruitful researches and developments in both BSCCO wires and its applications. InnoST will actively cooperate with other companies and research institutions in the fields of HTS wires manufacture and HTS applications to jointly exploit the enormous potential market of HTS technologies.

Crystal structure and properties of some novel superconductors

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In this talk, I will show some recent progresses on the exploration of superconducting materials. Firstly, new FeSe-intercalated phases have been prepared, including the orthorhombic phase at room temperature. They exhibit superconducting critical temperature at 45 K – 46.5 K, comparable to that of optimal Na-NH_3 co-intercalated FeSe, implying the superconductivity in this class of materials is not closely correlated to the nematicity. Secondly, a novel $CsFe_{4-\delta}Se_4$ compound has been obtained. The Cs-ordering induces a √2×√2×1 superstructure comparing to the structure of $CsFe_2Se_2$. It is proposed that the Fe vacancies (~8%) are responsible for the disappeared superconductivity. Third, I will present a novel CuAs-based superconductor. Its crystal structure is closely related to the FeAs-based superconductor. The parent phase shows the coexistence of possible CDW and superconductivity, and the former one is rapidly suppressed while the superconductivity is simultaneously enhanced with Ni doping. Finally, I will give a brief introduction to the 2D superconductivity in an Au based compound.

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Ionic-liquid-gating-assisted protonation: a new route for electron-doping and NMR studies in the iron-based and other superconductors

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Carrier doping is essential for tuning superconductivity and metal-insulator transitions. For bulk materials, doping is frequently achieved through chemical substitution at high temperatures. For thin films, various gating methods are also utilized to tuning the carrier density at low temperatures; however, gating voltage is required during measurements, which limits spectral spectroscopic studies.

Here I report our development of a protonation method in bulk materials [1], utilizing an ionic-liquid-gating-assisted method first reported in magnetic films [2]. After a long period of protonation, H^+ is successfully inserted into $FeSe_{1-x}S_x$ single crystals and induces multiple high-Tc phases due to electron doping effect. The maximal Tc is 42.5 K for H_y-$FeSe_{1-x}S_x$ ($x \leq 0.07$) and 18 K for FeS, which are enhanced by about four times after protonation. We also found proton implantation induces superconductivity in undoped $BaFe_2As_2$ and other quasi-2D, non-superconducting materials.

With this method, protons penetrate into samples over micrometers, and remain in the sample when the ionic-liquid-gating is removed. This enables spectroscopic studies, in particular high-sensitive proton NMR in material lack of NMR isotopes. With this, pairing symmetry and superfluid density are investigated in H_y-$FeSe_{1-x}S_x$. We believe that this electron doping method may be applied to a wide range of insulators, to tune metal-insulator transitions and unconventional superconductivity and allow for rich spectroscopy studies.

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Physical and Chemical Properties of Several New Intermetallic Superconductors

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Our work on the discovery of new superconductors in recent years has concentrated on materials with interesting chemical and crystallographic characteristics, and, in particular, on intermetallic compounds of the transition elements. I will describe some of that work in this talk and put it in context with previously known intermetallic superconductors. The work I will describe has primarily been done by students and postdoctoral fellows while in my research group - in particular by Elizabeth Carnicom, Fabian von Rohr, and Karoline Stolze, and also through our collaborations with professors Weiwei Xie at Louisiana State University, Tomasz Klimczuk at the Gdansk Technical University, (and Liling Sun and her group at the Institute of Physics in Beijing - they may discuss their work on HEAs separately.) and their graduate students and postdoctoral fellows.

My talk will concentrate on two superconducting materials systems. The first system is of interest due to its unusual crystallographic symmetry. In a non-centrosymmetric superconductor the standard superconducting state, where electrons with opposite momenta form pairs on the Fermi surface, is not possible. A few such materials are known; they display different degrees of influence of the lack of inversion symmetry on their superconducting properties. The effect of crystal structure chirality on the properties and applications of superconductors, on the other hand, is little discussed. I will describe our recent finding of two new non-centrosymmetric chiral superconductors $TaRh_2B_2$ and $NbRh_2B_2$. [1] The second superconducting system that I will discuss is based on high entropy alloys (HEA), one of which has simply a BCC structure (i.e. the Nb-Ta-Ti-Zr-Hf HEA) [2,3], and the second of which, made from combining both early and late transition elements, has a crystal structure of the CuAu type (i.e. the Sc-Zr-Nb-Rh-Pd HEA) [4].

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Superconductivity near pressure-induced instabilities

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Many complex materials display an interesting interplay between structural and electronic instabilities, which can be studied effectively under applied pressure. If a continuous structural phase transition is suppressed to low temperatures, as in the quasi-skutterudite system $(Sr/Ca)_3(Ir/Rh)_4Sn_{13}$ [1], low-energy vibrational excitations can arise that boost superconductivity and cause a linearly temperature dependent electrical resistivity. We report that the aperiodic high-pressure host-guest structure of elemental bismuth displays a similar phenomenology [2], suggesting significantly enhanced phonon spectral weight at low energies (Fig. 1).

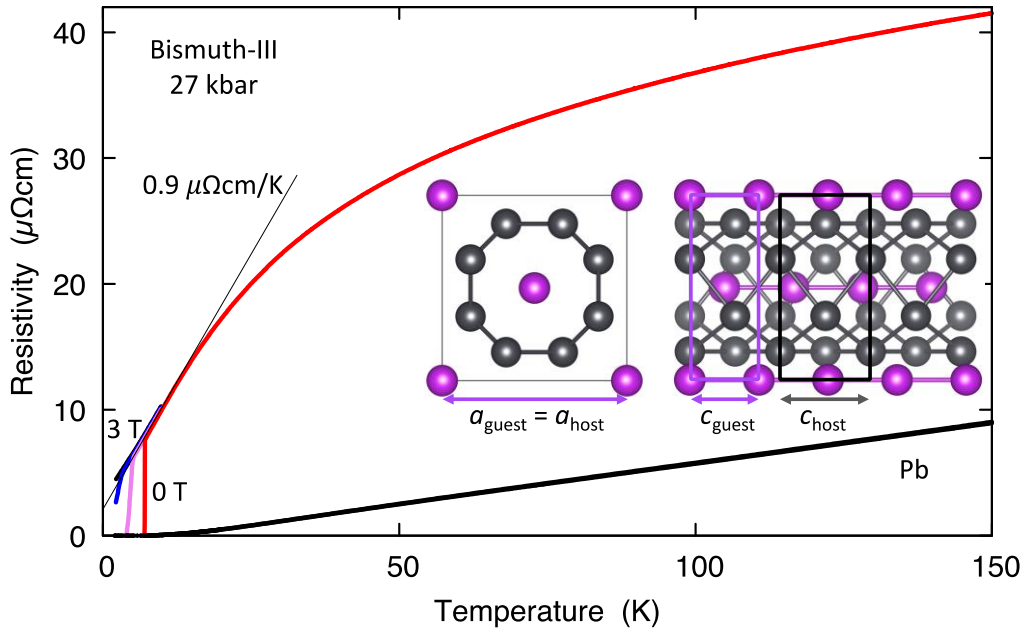

Fig. 1: *Temperature dependence of the resistivity of the aperiodic high pressure structure of bismuth, Bi-III, which displays type-II superconductivity below a normal state with anomalously strong electron-phonon scattering. The resistivity of the conventional strong-coupling superconductor lead, Pb, is given for comparison. The inset illustrates the aperiodic nature of Bi-III along the c-axis.*

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New type of superconductivity produced by electrostatic field and diffusion current in semiconductor

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We propose a new type of superconductivity independent on temperatures. The principal is that a diffusion current from the current source is supplied to a doped semiconductor (silicon) and an electrostatic field is applied to that semiconductor [1]. By this conduction, the electrostatic field is canceled with the Ohmic electric filed but the current is not zero because of the diffusion current, which derives from the gradient of carrier concentration. In theoretical approach, the unique electron concentration dependent on space is derived from the above mentioned device. Combining with the Poisson's equation, a novel electric field [2] and transient attractive interaction are obtained. The Coulomb repulsive interaction is also determined by Poisson's equation, but it does not appear on a macroscopic scale. Therefore two electrons approach each other up to extremely short distance (1Å), and thus the spin attractive interaction becomes substantially large. Estimating the combination energy (i.e., 10^{-18} J) prevents the electron pairs from the destruction due to room temperature heat. These pairs move uniformly, and Bose-Einstein condensation and a superconducting current are produced.

In the experiments, we confirmed both zero resistance and the Meissner effect. Moreover Nishio and his group at Mister Engineering produced another device, and we could confirm the replication of the experiments employing it.

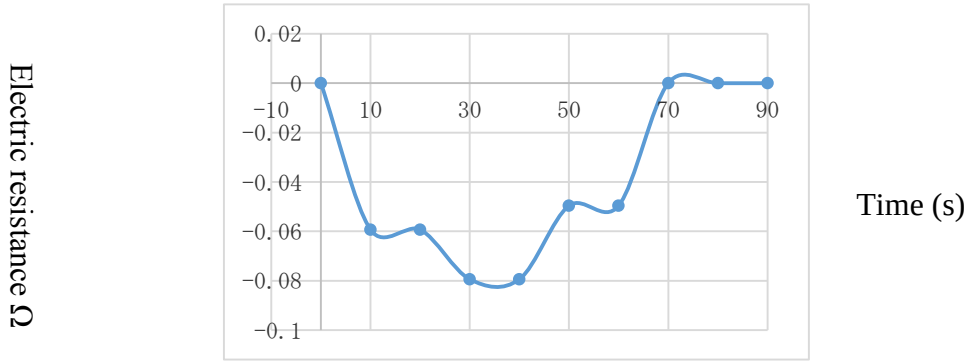

Fig. 1: . *Electrical resistance as a function of time. A negative electrical resistance was initially observed, which generally implies that energy is generated rather than consumed. In this study, this observation implies the existence of the new electric field which is described above. At 68.5 s, the electric resistance returns to approximately zero.*

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In-situ hydrostatic pressure induced significant suppression of magnetic relaxation and enhancement of flux pinning in $Fe_{1-x}Co_xSe_{0.5}Te_{0.5}$ Single Crystals

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Tsinghua Univ., China

We report the first study on the significant effect of in-situ hydrostatic pressure on the magnetic relaxation in $Fe_{1-x}Co_xSe_{0.5}Te_{0.5}$ single crystals. We find that vortex creep rates are significantly suppressed by pressure, and a crossover from elastic to plastic creep is observed. The pressure also induces vortex creep to move from the large bundle to the small bundle region. Our study indicates that in-situ hydrostatic pressure is very effective for not only significantly increasing the pinning energy and the critical current density, but also reducing the size of flux bundles to suppress the decrease in current density from vortex motion.

Abstract: No definitive evidence of spacetime supersymmetry (SUSY) that transmutes fermions into bosons and vice versa has been revealed in nature so far. Moreover, whether spacetime SUSY in two and higher spatial dimensions can occur or emerge in generic microscopic models remains open. Here, we introduce a lattice realization of a single Dirac cone with attractive Hubbard interactions that preserves both time-reversal and chiral symmetries. By performing numerically-exact sign-problem-free determinant quantum Monte Carlo simulations [1,2], we show that the interacting single Dirac fermion in 2+1 dimensions features a superconducting quantum critical point (QCP). More remarkably, we demonstrate that the N=2 spacetime SUSY in 2+1D emerges at the superconducting QCP by showing that the fermions and bosons have identical anomalous dimensions 1/3, a hallmark of the emergent SUSY [3]. To the best of our knowledge, this is the first numerical observation of emergent 2+1D spacetime SUSY in quantum microscopic models. We further show some experimental signatures which can be measured to test such emergent SUSY in candidate systems such as the surface of 3D topological insulators.

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Machine Learning Emergence from Quantum Matter Data

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In recent years, enormous data sets have begun to appear in real-space visualizations (scanning probes) and reciprocal-space visualizations (scattering probes) of electronic quantum matter. Increasing volume and variety of such data present new challenges and opportunities that are ripe for a new approach: machine learning. However, the scientific questions in the field of electronic quantum matter require fundamentally new approaches to data science for two reasons: (1) quantum mechanical imaging of electronic behavior is probabilistic, (2) inference from data should be subject to fundamental laws governing microscopic interactions. In this talk, I will review the aspects of machine learning that are appealing for dealing with quantum complexity and present how we implemented a machine learning approach to analysis of scanning tunneling spectroscopy data.

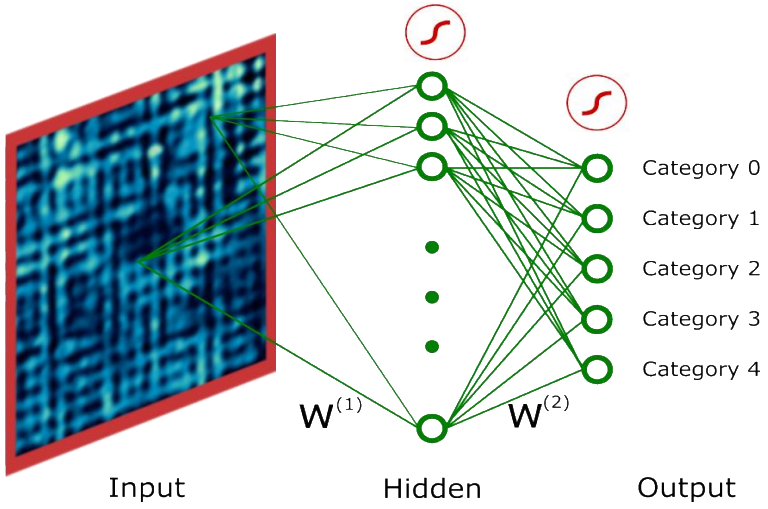

Fig. 1: *Artificial Neural Network Architecture*

References can also be given in the abstract [1]. Abstract text is allowed to flow around the graph.

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The Superconductor-Insulator transition and the Bose-Metal state

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In our 1999 paper [1] we stated "A Bose insulator (BI) phase is characterized by an extra order parameter, viz. the charge density. It is like a charge density wave but built out of Cooper pairs. . . . This implies a possible existence of a disordered phase where both the order parameters are zero at T=0. We consider this to be a Bose metal phase."

We will discuss a current version of the Bose metal phase [2] in which it arises out of a Fermi liquid of composite vortices. These are bosonic vortices bound to the Cooper pair liquid via a unit flux of an emergent gauge field a, whose curl equals the Cooper pair density.

Since Cooper pairs 'see' a vortex as a unit of flux and vice versa, and because both particles are mutual bosons, it follows that in a mean-field description, the groundstate involves bosons at $\nu = 1$. Bosons at $\nu = 1$ map onto a composite fermion metal in which the Pauli principle is operative. This substantially stabilizes the mean-field ground state. Thus, in this approach a composite fermion metal provides an effective description for a self-dual Superconductor-Insulator with a finite T = 0 resistance.

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The Long-Range Singlet Proximity Effect

for the Josephson System with Ferromagnet Nanowire

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A possible explanation for the long-range proximity effect observed in single-crystalline cobalt nanowires sandwiched between two superconducting tungsten electrodes [1] is proposed. We propose a singlet mechanism of the long-range proximity effect in superconductor-ferromagnet structures. Our approach is based on a simple physical picture the effective masses in majority and minority spin subbands are different [2,3]. We also consider the Fermi-surface anisotropy [2]. The derived Eilenberger-like equations allowed us to obtain a renormalized exchange interaction that is completely compensated for some crystallographic directions under certain conditions. Indeed, this feature can lead to a compensation of the total momentum of the Cooper pair in a ferromagnet. It is easy to understand within the simple picture of the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) pairing mechanism [4,5] with total momentum **q** of the pair (**q** is much less than the Fermi momentum $\mathbf{k}_F$). In ferromagnet the momentum **q** is obtained from the condition $(\mathbf{k}_F + \mathbf{q}/2)^2/2m_\uparrow - h = (-\mathbf{k}_F + \mathbf{q}/2)^2/2m_\downarrow + h$, where h is an exchange field. It follows immediately that $\mathbf{q}\mathbf{k}_F/2M \approx h - \eta k_F^2/2M$, where $M = 2m_\uparrow m_\downarrow/(m_\downarrow + m_\uparrow)$ and mismatch parameter $\eta = (m_\uparrow - m_\downarrow/(m_\downarrow + m_\uparrow)$. Thus the total momentum of the FFLO-like pair completely vanishes at $\eta = h/E_F \sim 0.1$, where E_F is the Fermi energy. It leads to a long-range spatial extent of the induced superconductivity in a ferromagnetic nanowire.

Note that, in the isotropic case [3], only a sole mismatch parameter η is possible. The energy dispersion anisotropy leads to the appearance of a set of points for which a long-range Josephson effect is possible [2]. In this case, the region of parameters where the long-range effect is noticeable is sufficiently broad. In contrast to previous theoretical works [6,7], we also focus on a case of spin-singlet proximity effect with three-dimensional nanowire observed in the experiment [1].

The work was supported by the subsidy of the Ministry of Science and Higher Education of the Russian Federation (Grant No. 3.2166.2017) allocated to Kazan Federal University for performing the project part of the state assignment in the area of scientific activities. The authors are grateful Prof. I.M. Eremin and Prof. A.M. Kadigrobov for valuable discussions. M.V.A. is also thankful to the RFBR (Grant No. 16-02-01016) for partial support.

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Uniaxial Pressure Control of Competing Orders in a High Temperature Superconductor

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External control of electronic phases in correlated-electron materials is a long-standing challenge of condensed-matter research. Layered cuprates exhibit antiferromagnetic, charge-density-wave (CDW), and high-temperature superconducting ground states which can be tuned by doping and external magnetic fields. However, disorder generated by lattice defects and randomly pinned magnetic vortices greatly complicates the interpretation of these experiments. Here, we report a high-resolution inelastic x-ray scattering study of the high-temperature superconductor YBa2Cu3O6.67 under uniaxial stress, and show that a three-dimensional long-range-ordered CDW state can be induced by pressure along the *a*-axis, in the absence of magnetic fields. The amplitude of the CDW is strongly suppressed below the superconducting transition temperature, indicating strong thermodynamic competition with superconductivity. We also show that the transition is driven by the complete softening of an optical phonon mode. The results provide new insights into the anomalous normal-state properties of high-temperature superconductors an illustrate the potential of uniaxial-pressure control of competing orders in quantum materials [1].

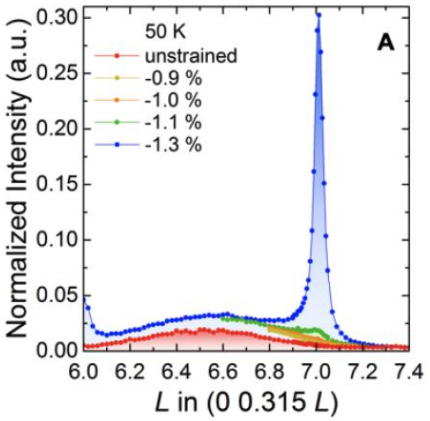

Fig. 1: *a-axis compression (ε_{xx}) dependence of the quasi-elastic intensity of $YBa_2Cu_3O_{6.6}$ measured by inelastic x-ray scattering at T= 50 K along the (0 0.315 L) direction*.

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Interplay between charge order and superconductivity in cuprate superconductors

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One of the central issues in the recent study of cuprate superconductors is the interplay of charge order with superconductivity [1,2]. Here [3] the interplay of charge order with superconductivity in cuprate superconductors is studied based on the kinetic-energy-driven superconducting mechanism by taking into account the intertwining between the pseudogap and superconducting gap [4,5]. It is shown that the appearance of the Fermi pockets is closely associated with the emergence of the pseudogap [3]. However, the distribution of the spectral weight of the superconducting-state quasiparticle spectrum on the Fermi arc, or equivalently the front side of the Fermi pocket, and back side of Fermi pocket is extremely anisotropic, where the most part of the spectral weight is located around the tips of the Fermi arcs, which in this case coincide with the hot spots on the electron Fermi surface. In particular, as charge order in the normal-state [6], this electron Fermi surface instability drives charge order in the superconducting-state, with the charge-order wave vector that is well consistent with the wave vector connecting the hot spots on the straight Fermi arcs [3]. Furthermore, this charge-order state is doping dependent, with the charge-order wave vector that decreases in magnitude with the increase of doping. Although there is a coexistence of charge order and superconductivity, this charge order antagonizes superconductivity. The results from the superconducting-state dynamical charge structure factor indicate the existence of a quantitative connection between the low-energy electronic structure and collective response of the electron density. The theory also shows that the pseudogap and charge order have a root in common, they and superconductivity are a natural consequence of the strong electron correlation [3].

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Intertwined order in cuprates and black hole hair.

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The non-Fermi-liquid "strange metals" found in cuprates are in all likelihood densely many body entangled states of matter that can only be reliably addressed by a quantum computer [1]. The confusing "intertwined order" in underdoped cuprates may then be viewed as some generalized BCS-type instability departing from the entangled metallic state. It appears that the AdS/CFT duality discovered in string theory may reveal ubiquitous principles associated with such genuine quantum matter [2]. This maps the quantum matter problem on a dual gravitational description involving black hole physics in one higher dimension. Remarkably, resting on highly general effective field principles on the gravitational side the most salient features of the intertwined order roll out naturally in terms of highly fanciful black hole hair [3,4].

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Theory of Resonant Inelastic X-Ray Scattering in Cuprate Superconductors

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Resonant inelastic x-ray scattering (RIXS) experiments tuned for Cu K edge have provided a lot of new insights about spin dynamics in spin-flip channel as well as charge dynamics in non-spin-flip channel in cuprate superconductors. The two channels are selected predominately by the polarization dependence of incident photon. Not only such polarization dependence but also incident-photon energy dependence of the RIXS spectrum gives us useful information on the electronic states of the cuprates. Firstly, we investigate the incident-photon energy dependence by using the exact diagonalization technique for a single-band Hubbard model [1]. Depending on the value of core-hole Coulomb interaction in the intermediate state, RIXS for non-spin-flip channel shows either an incident-photon energy dependent fluorescence-like or incident-photon energy independent Raman-like behavior for hole doping. Next we focus on a recent RIXS experiment for a stripe-ordered cuprate that exhibits an anomalous spin excitations along the (0,0)-(,0) direction [2]. The stripe order in the ground states is realized in a four-leg *t*-*t'*-*J* ladder system. Investigating the dynamical spin structure factors of a 24 4 *t*-*t'*-*J* ladder by using dynamical density-matrix renormalization group, we find that spin excitations are strongly influenced by the stripe order along the (0,0)-(,0) direction in hole doping, resulting in two branches that form a discontinuous behavior in the dispersion [3]. This is similar to the RIXS data. We also discuss contrasting behaviors in RIXS between hole- and electron-doped cuprates as well as high-energy charge dynamics seen by O K-edge RIXS [4].

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Charge order and scaling between the superfluid density and the critical temperature T_c in cuprate superconductors

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A universal linear relation between the critical temperature T_c and the low temperature superfluid density $\rho_{sc}(0)$ with increasing carrier density in underdoped cuprate superconductors was discovered almost thirty year ago [1]. Typical values of $\rho_{sc}(0)$ are one to two orders of magnitude lower than conventional superconductors while T_c is one order of magnitude higher, pointing to an unconventional mechanism of superconductivity which fluctuations of the superconducting (SC) order parameter are important. Another universal property is the presence of nonuniform incommensurate charge order (CO) distributions in the underdoped region. We simulate the observed CO structure by a phase separation approach controlled by the Cahn-Hilliard time-dependent non-linear differential equation based on the Ginzburg-Landau (GL) free energy. The GL potential (V_{GL}) is adjusted to provide the λ_{CO} charge oscillations and its fluctuations yields the energy scale for SC pair formation. The SC correlations above T_c, CO granular structure with small charge amplitudes and the local gaps suggest an electronic granular superconductivity with long range order driven by Josephson coupling $E_J(T)$. Accordingly, we perform SC calculations keeping always the CO constant what gives a disordered granular superconductor. The local E_J and ρ_{sc} are proportional and both quantities are in the calculations of $\rho_{sc}(0)$ and T_c . More recently, a similar scaling linear relation was found in overdoped $La_{2-x}Sr_xCuO_4$ (LSCO) films [2]. Based on experiments indicating charge inhomogeneity, we perform calculations with very small charge variations and reproduced the experimental results to overdoped LSCO. In conclusion the underdoped and overdoped $\underline{\rho_{sc}(0)-T_c}$ relation and their unusual properties imply that all cuprates are nanoscale granular superconductors with T_c driven by Josephson coupling.

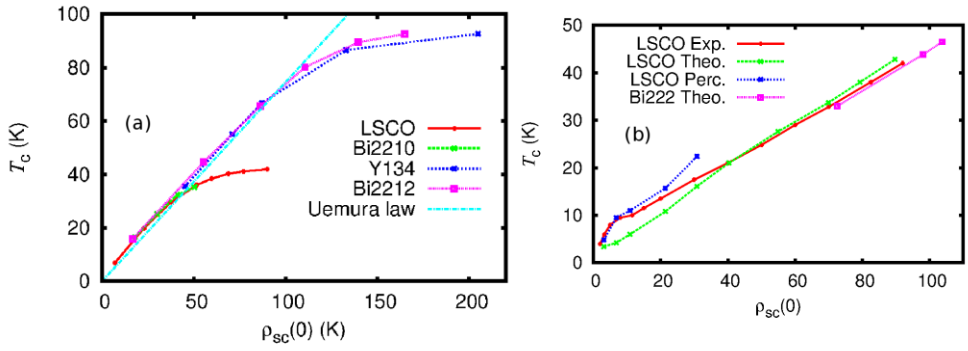

Fig. 1: [a] Our theoretical calculation $\underline{\rho_{sc}(0)-T_c}$ to underdoped cuprates with Uemura law[1].[b] Similar calculations to overdoped with the measurements of [2].

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Dimensional Crossover of Charge-Density Wave Correlations in the Cuprates

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Short-range charge-density wave correlations are ubiquitous in underdoped cuprates. They are largely confined to the copper-oxygen planes, where they appear along both crystallographic axes, and typically oscillate out of phase from one unit cell to the next in the *c* direction. Subsequently, it was found that a considerably longer-range charge-density wave order develops in $YBa_2Cu_3O_{6+x}$ (YBCO) above a sharply defined crossover magnetic field. This order is more three-dimensional, unidirectional in the planes, and is in-phase along the *c* axis. We show [1] that such behavior is a consequence of the bilayer structure of YBCO and the conflicting ordering tendencies induced by the disorder potential and the Coulomb interaction. The magnetic field acts to tip the scales from the former to the latter by providing vortices that act as strong nucleation centers for halos of longer-range order, while the weak anisotropy induced by the chain layers suffices to orient the halos in the planes. We base our conclusions on analytic large-*N* analysis and Monte Carlo simulations of a nonlinear sigma model of competing superconducting and charge-density wave orders.

Recently, motivated by signatures of nematicity in YBCO, we have augmented our model by interactions, which act to promote fourfold rotational symmetry breaking. We find that such symmetry breaking by the charge-density wave correlations coincides with the onset of the longer-range order. Moreover, the additional terms make the onset significantly sharper, closely resembling the experimental observations. Finally, we also discuss the implication of the model to other members of the cuprate family and present preliminary results concerning the relation between the charge-density wave correlations and measurements of quantum oscillations in these systems.

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Hund's metal compressibility and its correlation with Tc in Iron-based superconductors

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Metallic phases with Hund's correlations ("Hund's metals") are presently the focus of intensive research, in particular in relation to unconventional Fe-based superconductors.
Recent experiments validate this emerging theoretical picture of a metallic phase with evidences of large local paramagnetic moments, large and orbital-selective mass renormalizations and orbitally-selective pairing in the superconducting state.
Further theoretical insight shows that Hund's coupling can also enhance the electronic compressibility[1] altering the quasiparticle interactions in some regimes, thus potentially renormalizing the pairing strength. This is shown to correlate with experimental high-Tc superconductivity in Fe-based pnictides[1] and FeSe[2].

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The electronic structure of 112 iron pnictide superconductors probed by ARPES

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The studies of iron-pnictides have shown that the multi-orbital low energy electronic states formed in the FeAs layer are moderately correlated due to finite Hund's coupling and on-site Coulomb interaction. However, so far, only little is known about the influence of the spacer layer on the low energy electronic states of the FeAs layer. Using angle-resolved photoemission spectroscopy, supported with DFT calculations, we determined the electronic structure of 112 Fe-pnictide $Ca_{1-x}La_xFeAs_2$ which has a metallic spacer layer between FeAs planes from which the superconductivity originates. Our studies reveal that, comparing to other superconducting iron-pnictides with insulating spacer layers the electron-electron correlations are not weakened by the metallic spacer layers. Furthermore, due to spin-orbit coupling the electronic structure of each CaAs layer is topologically non-trivial. These results indicate that below superconducting transition temperature $Ca_{1-x}La_xFeAs_2$ could be an alternating combination of a quantum spin Hall insulator and a superconductor.

Quantum oscillations studies of superconducting $FeSe_{1-x}S_x$ tuned by chemical and applied pressure across the nematic phase transition

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Understanding the electronic behaviour of competing electronic normal states that help stabilize the superconductivity is essential for solving the pairing mechanism of in iron-based superconductors. Among them, the nematic electronic state and its associated nematic fluctuations emerges as a potential candidate for pairing but often its role is intertwined with other electronic orders, making it difficult to assess its importance. I will present the evolution of the Fermi surfaces and electronic interactions across the nematic phase transition in single crystals of $FeSe_{1-x}S_x$ using Shubnikov-de Haas oscillations in high magnetic fields up to 45 T in the low temperature regime. I will compare the effect of the chemical and applied hydrostatic pressure on the low-energy electronic structure and discuss the role of Lifshitz transitions and the changes in electronic correlations across the nematic phase transition. These results can shed light on the interplay between competing electronic orders in $FeSe_{1-x}S_x$ which can be finely tuned by combing chemical and applied pressure.

This work was mainly supported by EPSRC (EP/I004475/1, EP/I017836/1, EP/M020517/1). A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1157490 and the State of Florida. A.I.C. acknowledges an EPSRC Career Acceleration Fellowship (EP/I004475/1).

Manifestation of the multiband nature in the BCS-BEC crossover of $FeSe_{1-x}S_x$

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Weak coupling Bardeen-Cooper-Schrieffer (BCS) pairing and strong coupling Bose-Einstein condensation (BEC) are connected continuously through the BCS-BEC crossover regime [1]. The ratio between the superconducting gap Δ and the Fermi energy ε_F is regarded as a pairing strength tuning parameter of the BCS-BEC crossover. The iron-based superconductor FeSe shows Δ/ε_F = 0.3 ~ 1.0, which suggests it is in the BCS-BEC crossover regime [2]. We explore the BCS-BEC crossover in the isovalent substituted system, $FeSe_{1-x}S_x$, by using laser-excited angle-resolved photoemission spectroscopy, and find that a hole band around the Γ point in the Brillouin zone shows a systematic change from a downward convex to an upward convex in the superconducting state as x increases. Whereas the pseudogap is absent above T_c for x = 0, 0.13, it is observed for x = 0.21. This systematic band change and the existence of the pseudogap should be regarded as the evidence that $FeSe_{1-x}S_x$ can be controlled from a BCS region to a BEC region by increasing x. The pseudogap accompanied by the BEC-like band dispersion has never been observed in other candidates of the BCS-BEC crossover, for example, $Fe_{1+y}Se_xTe_{1-x}$ [3]. The estimated value of Δ/ε_F decreases as the system goes to the BEC region, in contrast to the expectation from the single-band calculation. This contrasting behavior should demonstrate the importance of the multiband nature for the BCS-BEC crossover in $FeSe_{1-x}S_x$.

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Discovery of a strain-stabilized charge density wave in LiFeAs

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In a number of high T_C superconductors, small orthorhombic distortions of the lattice structure result in surprisingly large symmetry breaking of the electronic states and macroscopic properties, an effect often referred to as nematicity. This nematicity has been studied extensively on materials with an orthorhombic crystal structure, where the lattice symmetry is already reduced from four-fold (C_4) to two-fold (C_2). To directly study the impact of symmetry breaking lattice distortions on the electronic states, we image at the atomic scale the influence of strain-tuned lattice distortions on the correlated electronic states in the iron-based superconductor LiFeAs, a material which in its ground state is tetragonal, with C_4 symmetry. Our experiments uncover a new strain-stabilized nematic phase that exhibits a unidirectional charge density wave (CDW) in LiFeAs, an electronic state which not only breaks rotational symmetry but also reduces translational symmetry. We follow the evolution of the superconducting gap from the unstrained material with C_4 symmetry through the new nematic phase with C_2 symmetry and CDW order to a state where superconductivity is completely suppressed.

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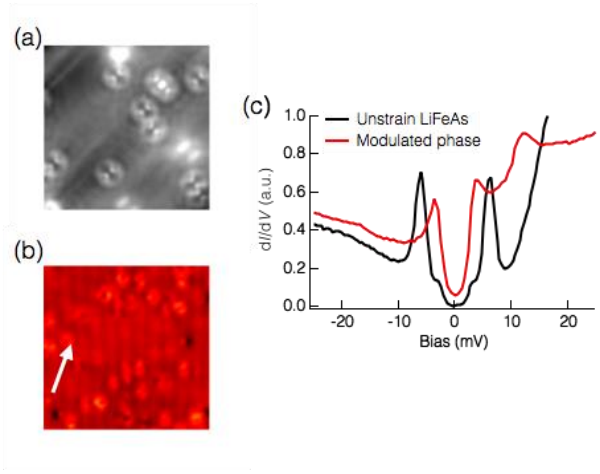

Fig. 1. (a) STM Topographic image (17×17 nm^2) of unstrained LiFeAs. (b) Topographic image (30×30 nm^2) taken from the modulated phase of strained LiFeAs. The strain direction is along [110], as indicated by the white arrow. (c) Point differential conductance (dI/dV) spectra taken from the defect-free areas of the (black) unstrained sample and (red) the modulated phase of strained LiFeAs.

Fermi Surfaces and Spin Resonances in High-T_c Iron Selenide by Lifshitz Transition

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The electron Fermi surface pockets that are characteristic of iron-selenide high-temperature superconductors are accounted for by an extended Hubbard model over the square lattice of iron atoms that includes the principal $3d_{xz}$ and $3d_{yz}$ orbitals. Perfect nesting between electron-type and hole-type Fermi surfaces at the center and at the corner of the one-iron Brillouin zone is revealed at half filling, in the absence of next-nearest neighbor intra-orbital hopping. It results in hidden magnetic order in the presence of magnetic frustration. After including the effects of spin-fluctuation exchange, we find that the Fermi surface undergoes a Lifshitz transition to electron/hole pockets centered at the corner of the two-iron Brillouin zone for moderate to strong on-site Coulomb repulsion[1]. A rigid shift of the renormalized band structure by sufficiently strong electron doping yields electron pockets alone[2], in agreement with angle-resolved photoemission spectroscopy (ARPES) on iron-selenide high-temperature superconductors. A spin-wave analysis of the hidden-magnetic-order state, which is valid at the limit of strong on-site Coulomb repulsion[2], finds a "floating ring" of low-energy spin excitations centered at the "checkerboard" wavenumber (π,π). (See Fig. 1.) This prediction is consistent with recent observations of low-energy spin resonances in intercalated iron-selenide high-temperature superconductors by inelastic neutron scattering[3].

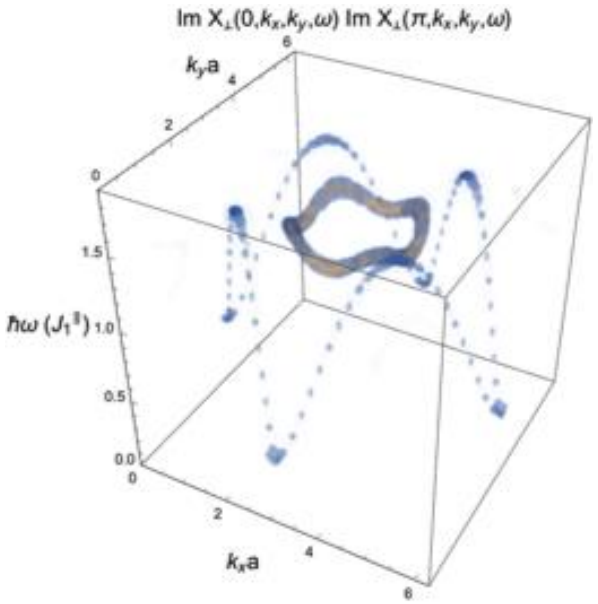

Fig. 1: *Low-energy spin resonances predicted by the hidden-magnetic-order state of the extended Hubbard model in the limit of strong on-site Coulomb repulsion (ref. [1]).*

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Latest Progress in THEVA's HTS Wire Fabrication and Applications

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An overview on recent improvements of coated conductors (CC) manufactured using the all E-beam PVD pilot production line at THEVA will be given.

Due to a continuous optimization of equipment as well as processes, the critical current of the wires has been enhanced continuously beyond 500 A/cm at high yield production conditions and even up to 650 A/cm have been demonstrated on production length.

In addition to the critical current, for technical HTS wire a number of additional requirements must be met to render it useful for application in electrical devices. Metallic stabilization and wire integrity is a necessity for almost all applications and considerable cost factor in production. Mostly electroplating is employed - an costly chemical process which increases the risk of wire damage and yields inhomogeneous thickness distribution towards the tape edges. The latter is a real drawback for the use in coils.

We developed and established a very efficient PVD metallization process at low cost and with extremely good uniformity and material yield. Further mechanical requirements are stress, strain and bending tolerance as well as delamination strength which were measured using several types of the stabilization. A recently developed joining technique for long-length CCs is discussed in terms of resistance and mechanical properties for various joint configurations.

Such HTS wire is very robust and has been utilized in several large scale reference applications. The most prominent example is the worldwide first real-size 3.6 MW wind turbine generator developed within the European EcoSwing consortium, which is currently installed on a windmill platform at the Danish coast. Other examples are high current (20 kA) busbars for electrolysis and cables for power distribution and large magnets. An overview on the wire requirements and the current state of these applications will be presented.

Recent progress in the development of Fe-based superconducting wires and tapes

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The high upper critical field and low anisotropy of iron-based superconductors (IBS) make them being particularly attractive for high-field applications, especially for the construction of next-generation nuclear magnetic resonance (NMR) spectrometers, particle accelerators and ultra-high-field magnets.

Recently, the development of IBS superconducting wires at the IEECAS has progressed rapidly resulting in improving the transport critical current density (J_c) and mechanical properties, such as: i) We found the synergy effect of high core density and high degree texture in the IBS wire was the key to achieve higher Jc. As a result, superior J_c of 1.5×10^5 A/cm^2 (I_c = 437 A) at 4.2 K and 10 T and 5.5×10^4 A/cm^2 at 4.2 K and 27 T has been reached in Ba-122 tapes, as shown in figure 1. ii) Transport J_c values of latest 100-meter 122 IBS wires have been further improved, larger than 2×10^4 A/cm^2 (4.2 K, 10 T). iii) High strength multifilamentary 122 conductors for low ac loss use are being developed. Finally, the outlook will be given with the directions of a future work to make high performance IBS wires readily available for high-field magnet applications.

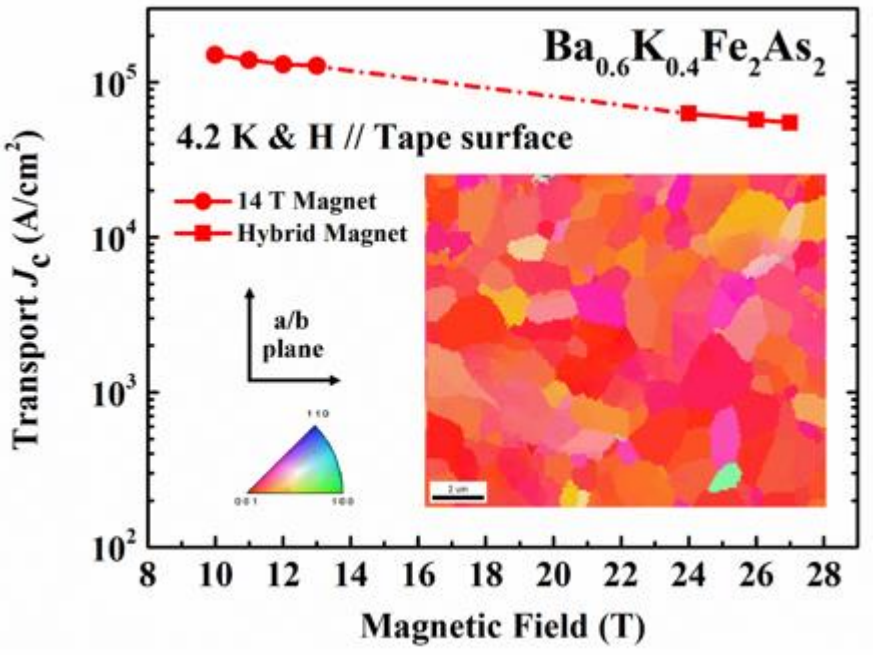

Fig. 1: *Magnetic field dependence of transport J_c for textured Ba-122 tape at 4.2 K.*

Annealing Effect and Superconductivity in $FeSe_xTe_{1-x}$ Superconductors

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In the family of iron-based superconductors (IBSs), the layered iron-chalcogenides $Fe_{1+y}Se_xTe_{1-x}$ have the simplest structure, and some exotic features, such as significant pressure effect, and excess Fe at the interstitial site, such unique features make it an ideal candidate to understand the superconducting mechanism in IBSs. The presence of excess Fe is almost unavoidable, which hinders the appearance of bulk superconductivity and causes strong controversies in fundamental properties. In this talk, we will discuss the annealing effect, magneto-transport properties and phase diagram of $FeSe_xTe_{1-x}$ superconductors, which can be summarized as follows: (1) Intrinsic magneto-transport properties were investigated on postannealing high-quality $FeTe_{0.6}Se_{0.4}$ single crystals, in which a temperature dependent linear MR was firstly discovered, suggesting the possible existence of Dirac fermions [1]. (2) Whole doping phase diagram of $FeSe_xTe_{1-x}$ ($0 \le x \le 1$) was firstly established via thin films fabricated by using PLD method, which is helpful for understanding the superconducting mechanism of $Fe_{1+y}Se_xTe_{1-x}$ system [2]. (3) The behavior of upper critical field $H_{c2}(T)$ of $Fe_{1+y}Se_xTe_{1-x}$ and pure FeSe single crystals were investigated by measuring the resistivity in high magnetic fields. The effect of excess Fe or disorders on the orbital or Pauli paramagnetic pair breaking are systematically analyzed. (4) Based on the results of high pressure electric transport measurement of FeSe crystal, the evolution of intrinsic electronic state in both low-T_c and high-T_c phase with pressure will be discussed via mobility spectrum analysis.

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Fundamentally Different Behaviors between Superconductor and Conventional Conductor in a Lenz's Law Experiment

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One of the experiments to demonstrate the Lenz's Law is to analyze the interacting force between a magnet and a conductive cylinder. During the experiment, the experimenter moves the magnet along the axis of the cylinder and measure the magnitude and direction of the interacting force between the magnet and the cylinder. By way of analyzing the force at different movement stage of the magnet with the assistance of the Faraday's Law of Electromagnetic Induction, the correctness of Lenz's Law is verified. Using conductive cylinders with different conductivity (for example, using a copper cylinder and an aluminum cylinder with identical dimensions) in this experiment and making comparisons of experimental results can help better understand the conclusion. One of the characteristic features in this experiment is that when the magnet moves close to the cylinder, the cylinder will try to repel the magnet and after the magnet passes the center point of the cylinder, the cylinder will try to drag the magnet. In short, the cylinder always tries to refuse the motion of the magnet in this experiment.

Recently, we used a superconducting coil as the replacement of a conductive cylinder to perform this experiment. We observed that the interaction behavior between the superconducting coil and the magnet is fundamentally different from that in the experiment with a conventional conductive cylinder. The experimental results indicate that after the magnet passes the center of superconducting coil, the magnet no longer experiences a dragging force, instead it encounters a pushing force. This result makes the well recognized statement of "the cylinder always tries to refuse the motion of the magnet" invalid. In this presentation, we will introduce the details of our experiment and give an explanation for the origin of this new discovered phenomenon.

In-Plane Anisotropy of the Critical Current in Ba-122 Single Crystals

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The influence of the electronic nematicity or anisotropy on the superconducting properties is among the current challenges for the understanding of superconductivity in the iron-based superconductors. An in-plane anisotropy of the resistivity was reported for Cobalt[1,2] and Ruthenium[3] doped Ba-122 single crystals. We utilized scanning Hall-probe microscopy to visualize J_c (Fig.1) of twinned and detwinned $Ba(Fe_{1-x}Co_x)_2As_2$ (x=5%–8%) crystals to compare the electronic normal state properties with superconducting properties. We find that the electronic in-plane anisotropy continues into the superconducting state. The observed correlation between the electronic and the J_c anisotropy agrees qualitatively with basic models, however, the J_c-anisotropy is larger than predicted from the resistivity data. Furthermore, our measurements show that the maximum of J_c at the orthorhombic/tetragonal phase boundary does not vanish when the crystals are detwinned. This shows that twin boundaries are not responsible for the large J_c, suggesting an exotic pinning mechanism.

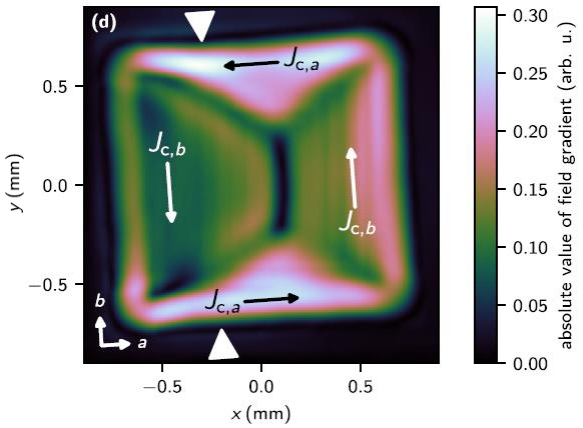

Fig. 1: *In J_c-anisotropy of* $Ba(Fe0.95Co_{0.05})_2As_2$ *at 5 K.*

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Anomalous Enhancement of Critical Current Density due to Novel Planar Defects in $CaKFe_4As_4$

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$CaKFe_4As_4$ is a newly found iron-based superconductor with T_c~36 K, which has a unique crystal structure similar to $BaFe_2As_2$ with ordered alternate occupation of Ba site by Ca and K. Thus, physical properties of $CaKFe_4As_4$ including behavior of critical current density (J_c) is expected to be similar to related compounds $(Ba,K)Fe_2As_2$ and $(Ca,Na)Fe_2As_2$. Figure 1(a) shows J_c as a function of magnetic field parallel to the *c*-axis. J_c at 2 K under self-field is ~1.7 MA/cm^2, which is roughly half the value for optimally doped $(Ba,K)Fe_2As_2$ [2]. When the magnetic field is applied parallel to the *ab*-plane, there are two components of J_c, one parallel to the *ab*-plane (J_{c2}) and another parallel to the *c*-axis (J_{c3}). We need to measure two *M-H* hysteresis curves for a rectangular sample to extract J_{c2} and J_{c3}. Figure 1(b) shows thus determined magnetic field dependence of J_{c2} for H // *ab*-plane. What is striking here is that J_{c2} is weakly temperature dependent and is larger than the in-plane J_c for H//*c*-axis. In addition, J_{c2} shows maxima at around H = 10 kOe. Extensive TEM observations on $CaKFe_4As_4$ clarified the presence of novel planar defects nearly parallel to the *ab*-plane. Considering the average separation of the planar defects of ~500 A, it is reasonable to explain the anomalous enhancement of J_{c2} at ~10 kOe is due to geometrical matching of vortex lattice to the defect structure.

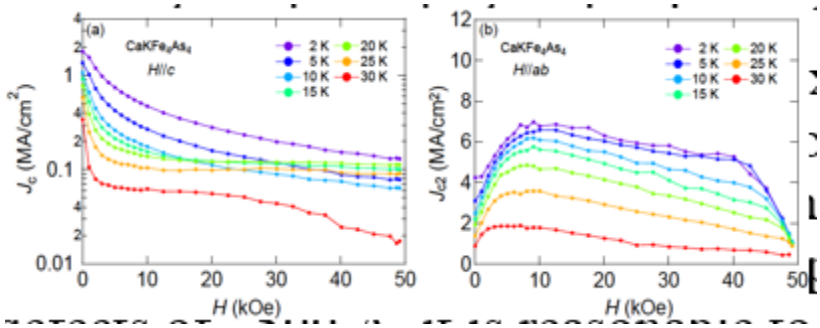

Fig. 1: *(a) Critical current density as a function of magnetic field applied parallel to (a) c-axis (log scale) and (b) ab-plane (linear scale).*

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Revisit of heavy fermion quantum critical superconductivity

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Unconventional superconductivity was first discovered in 1979 in the heavy fermion compound $CeCu_2Si_2$. For over three decades, its superconducting gap is believed to be of *d* wave as evidenced in the power-law temperature dependence of the nuclear magnetic resonance spin-lattice relaxation rate below T_c. However, a number of recent experiments observed two nodeless gaps, causing heated debates concerning its detailed gap structure. Here we propose a phenomenological model taking into account two coexisting electron and hole Fermi surfaces and the intra- and interband quantum critical pair interactions [1]. Our analysis suggests that a strong inter-band pair scattering may yield a nodeless $s^{\pm}$ wave gap, in contrast to the prevailing *d* wave scenario but in good agreement with latest experiments. The appearance of the $s^{\pm}$ wave may be associated with the orbital characters of the electron and hole Fermi surfaces. As the electron Fermi surface is suppressed with increasing pressure, our theory predicts a crossover from the nodeless $s^{\pm}$ wave to nodal *s* wave governed by the hole Fermi surface. Our work implies that it is important to revisit our current understanding also in other heavy fermion superconductors.

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Superconductivity in $YbRh_2Si_2$; electrical transport and noise experiments

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We report electrical transport measurements on the putative heavy fermion superconductor $YbRh_2Si_2$ [1]. Measurements were made on two high quality single crystal samples, over the temperature range 1 K to 0.6 mK. We clearly identify a superconducting state. There is evidence for strong anisotropy of the superconductivity in this material. With modest in-plane magnetic fields (above 4 mT), applied perpendicular to the c-axis, we observe "re-entrance" of the normal state resistance at the lowest temperature. This is attributed to the interplay between superconductivity and electro-nuclear magnetism. The influence of in-plane magnetic fields up to 70 mT, through the quantum-critical field, has also been investigated. We discuss the prospect of tuning the magnetism by choice of Yb isotope in enriched samples, coupled to studies at ultralow temperatures of electric transport at the field-tuned quantum critical point. Furthermore a superconducting transition has been detected in a focussed-ion-beam machined sample. This opens the way to improved studies of anisotropy in superconducting transport, and its likely intrinsic origin.

The rather low superconducting transition temperatures found in $YbRh_2Si_2$ requires the use of sensitive ultra-low dissipation measurement techniques. An experimental set-up with SQUID-based detection was employed in which samples were contacted via ultrasonically bonded aluminium wire. This has enabled measurements of Nyquist noise, which showed that on cooling below around 12 mK (sample I), there is a clear transition from normal metal into a state in which the resistance gradually decreases with decreasing temperature. With the same set-up, the detection of persistent currents demonstrated the transition to a zero-resistance phase-coherent superconducting state of the current loop including the aluminium-$YbRh_2Si_2$ contact region. This transition occurred at 3.6 mK (sample I) and 6.0 mK (sample II). Subsequently a SQUID-based impedance measurement technique was applied to sample II. This unambiguously identified a superconducting transition in the ab plane, occurring at 6 mK in zero magnetic field. These measurements also provide evidence for anisotropy in electrical transport, between 6 mK and 11 mK, and are consistent with the noise measurements. The field dependence of these features demonstrate heavy fermion superconductivity.

We propose that superconductivity coexists with magnetic order in this system, and that quantum criticality plays no role in the superconductivity observed so-far. However we observe a very weakly field dependent feature in the electrical response of the sample, at around 2 mK, which we identify with the magnetic transition proposed in [1]. The nature of the superconducting order; the pairing symmetry; the possibilities of multiple superconducting phases, quantum critical superconductivity and distinct phases at the interface between an s-wave superconductor and $YbRh_2Si_2$ will be discussed.

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Interplay between Superconductivity and Magnetism in Heavy Fermion Compounds Ce_3PdIn_{11} and Ce_3PtIn_{11}

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Superconductivity (SC) emerging in some heavy-fermion compounds at the verge of magnetic instability continues to be one of the most intriguing yet still unsolved central problems of modern condensed matter physics. In our on-going research we address the issue of the coexistence of SC and long-range antiferromagnetic (AFM) ordering in crystalline materials bearing multiple inequivalent lattices of localized magnetic moments [1]. The specific systems of our interest are Ce_3PdIn_{11} and Ce_3PtIn_{11}, which possess two Kondo sublattices in their crystal structure [2]. In both indides, heavy-fermion SC sets in within an AFM state, and their phase diagrams indicate the presence of quantum critical points induced by hydrostatic pressure or/and external magnetic field [3,4]. In my talk, I shall report on our experimental results, and discuss possible interdependence of the two cooperative phenomena occurring despite their formal separation in the reciprocal space.

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Attractive superconducting potential due to valence fluctuations in Heavy fermion superconductors

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Electron-phonon coupling is, so far, the only realizable source of attractive potential for conventional (s-wave) superconductivity in condensed matter systems. In two prototypical heavy-fermion superconductors, $CeCoIn_5$, and $CeCu_2Si_2$, recent experiments have suggested the presence of conventional superconductivity in a small parameter space, where decades of studies suggested unconventional pairings. Interestingly, the materials have insufficient electron-phonon coupling strength to cause such conventional pairing. Here we present a theory of superconductivity from valence fluctuations between conduction and localized bands which is ubiquitous in heavy-fermion materials. We find that when we account of multiple valence fluctuations, there is a solution for robust conventional superconductivity with typical s-wave pairing symmetry. The results are consistent with recent experimental observations of nodeless, conventional superconductivity in these materials.

Kohn-Luttinger superconductivity and the role of Lifshitz transitions in ferromagnetic superconductors: the paradigm of URhGe

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We develop a microscopic theory of the re-entrant superconductivity in the ferromagnetic superconductor URhGe in a transverse magnetic field, based on the Kohn-Luttinger mechanism of superconductivity and the interplay of Lifshitz Fermi surface transitions in a magnetic field, associated with two bands.

The theory, within a strong coupling approach, provide an excellent agreement with experimental results on (i) the increase of the effective mass (ii) the re-entrance of the superconductivity as a function of external field (iii) the weakly first order of the re-entrant superconducting transition (iv) the dependence of the critical temperature Tc as a function of the magnetic field in the ferromagnetic region and (v) the Sommerfeld coefficient and the quadratic coefficient of the resistivity. The theory can be extended to other ferromagnetic superconductors when the topology of the Fermi surface is taken into account.

Ferromagnetic fluctuations and Superconductivity of UCoGe under Pressure

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Uranium-based ferromagnetic (FM) superconductors have attracted much attention because of the variety of the unusual features including the coexistence of ferromagnetism and superconductivity [1]. UCoGe is a member of the FM superconductors, and we have shown that the Ising-type FM fluctuations are essential for the superconductivity [2, 3]. UCoGe is a unique system in which the SC phase remains in the hydrostatic pressure region where the FM state is suppressed [4, 5].

We have performed ^{59}Co NMR and nuclear quadrupole resonance (NQR) to reveal how the FM fluctuations are evolved under pressure from the microscopic point of view. We revealed that the FM fluctuations at the superconducting (SC) transition temperature T_{SC} are enhanced around the critical pressure P_c and start to decrease at higher pressure.
Since T_{SC} is also enhanced around P_c, this result is also consistent with the idea that the superconductivity is mediated by the FM fluctuations.

We also report the nuclear spin-lattice relaxation rate $1/T_1$ in the SC state at the PM side. This result gives us information about the SC gap structure, as well as how the FM and SC states coexist at ambient pressure.

NMR measurements have also performed in the SC state at the paramagnetic (PM) side, and it was found that the decrease of the Knight shift below T_{SC} is much smaller than the total spin part in the field perpendicular to the easy axis. This is a microscopic indication of the spin-triplet superconductivity in the PM side.

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Optical Melting of the Transverse Josephson Plasmon in Bilayer and Trilayer Cuprates

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Using ultra-short laser pulses to drive quantum materials out of equilibrium is an emergent technique for dynamical materials control. Selectively driving low-energy excitations using femtosecond laser pulses can achieve novel quantum phases inaccessible at equilibrium.
Combining dynamical light control with ultra-broadband transient optical spectroscopy, we are able to probe the dynamics of lattice vibrations and electronic excitations over the whole far-infrared region, revealing the physics behind the transient quantum phases. In this talk, I will present our recent work on light-induced transient superconductivity in bilayer and trilayer cuprates [1-3].

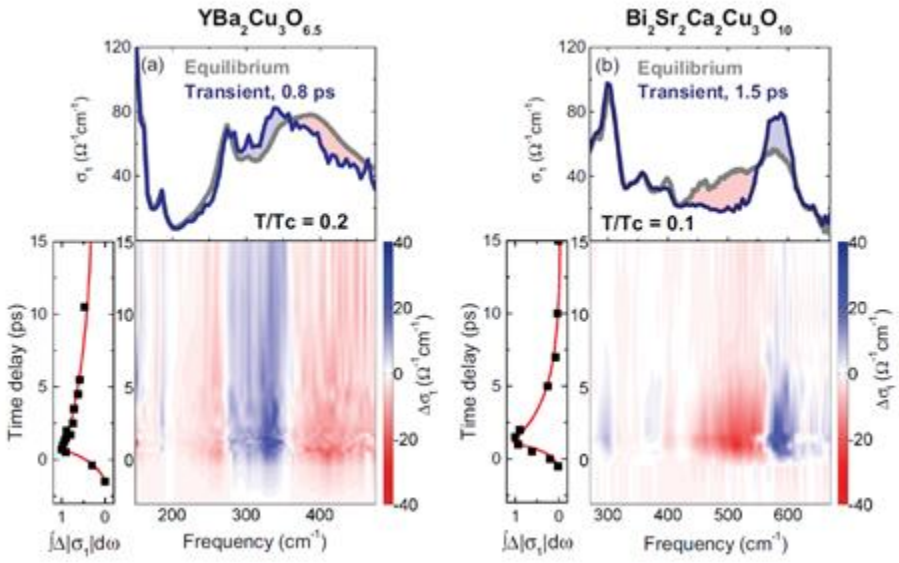

Fig. 1: *Dynamical redistribution of interlayer coherence in bilayer and trilayer cuprates [3].*

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Photo-induced new collective modes and metastable states in cuprate superconductors

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We present near and mid-infrared pump c-axis terahertz probe measurement on hole and electron doped 214 superconducting single crystals ($La_{1.905}Ba_{0.095}CuO_4$ with Tc=32 K and $Pr_{0.88}LaCe_{0.12}CuO_4$ with Tc=22 K). The measurement reveals that the pump-induced change occurs predominantly at the Josephson plasma edge position below Tc. Upon excitation by the intense near- or mid-infrared pulses, the superconducting state is disturbed and incoherent quasiparticle excitations develop in frequency regime above the static plasma edge. However, within very short time delay we observe the reappearance of a very sharp Josephson plasma edge at frequency lower than the static Josephson plasma edge and the emergence of a new light-induced edge at higher energy. Then the effect keeps almost unchanged up to the longest measurement time delay 210 ps. The results suggest that the intense pump drives the system from a superconducting state with a uniform Josephson coupling to a new metastable superconducting phase with modulated Josephson coupling strengths.

Theory of Higgs Spectroscopy of Superconductorsin non-equilibrium

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Time-resolved pump-probe experiments recently attracted great interest, since they allow to detecting hidden states and they provide new information on the underlying dynamics in solids in real time. With the observation of a Higgs mode in superconductors it is now possible to investigate the superconducting order parameter, and thus the ground state, directly. We have established a theory for superconductors in non-equilibrium after a quantum quench, for example in a THz pump-probe experiment. Using various methods we have developed an approach to calculate the optical response and the ARPES spectrum of conventional and unconventional superconductors in a time-resolved experiment. By comparison with analytical calculations we now have a microscopic understanding of the Higgs mode in superconductors.

Recently, we have extended our theory for 2-band superconductors and calculate the Leggett mode in non-equilibrium. We find the unique case that amplitude and phase oscillations are coupled resulting in new dispersion of the Leggett mode [1]. Furthermore, we generalized our theory to tailored quantum quenches which can excite all possible symmetries of Higgs oscillations. In analogy to phonon spectroscopy, these oscillations allow for a complete characterization of the superconducting gap function. Simulations for realistic laser pulses reveal spectroscopic information of these Higgs oscillations in the optical conductivity. By exemplary calculating the non-equilibrium response of *s*- and *d*-wave superconductors [2] we show, that such non-equilibrium Higgs spectroscopy opens a unique approach to distinguish between different symmetries of the condensate, even for new and unknown superconductors [3].

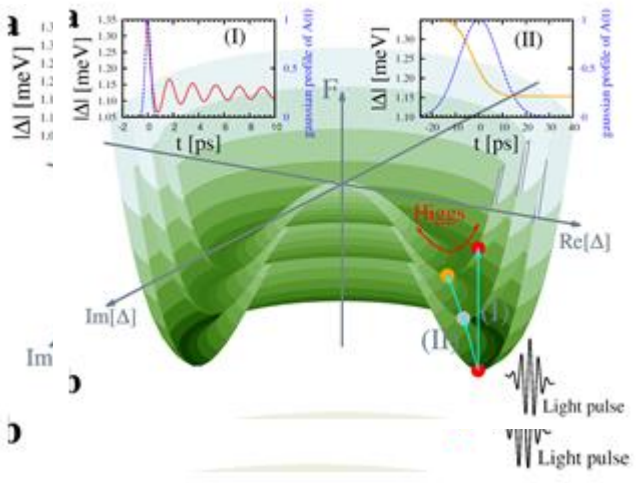

Fig. 1: *Mexican hat potential of the Free Energy in non-equilibrium as a function of time delay. Only in the non-adiabatic case (I), using a THz pulse with short pulse duration, Higgs oscillations can be generated.*

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TBD

Thomas Peter Devereaux, Stanford Univ., USA

Tunneling Probe of Fluctuating Superconductivity in Disordered Thin Film

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Disordered thin films close to the superconducting-insulating phase transition (SIT) hold the key to understanding quantum phase transition in strongly correlated materials. The SIT is governed by superconducting quantum fluctuations, which can be revealed for example by tunneling measurements. These experiments detect a spectral gap, accompanied by suppressed coherence peaks, on both sides of the transition. We describe the insulating side in terms of a fluctuating superconducting field with finite-range correlations. We perform a controlled diagrammatic resummation and derive analytic expressions for the tunneling differential conductance. We find that short-range superconducting fluctuations suppress the coherence peaks, even in the presence of long-range correlations. Our approach offers a quantitative description of existing measurements on disordered thin films and accounts for tunneling spectra with suppressed coherence. [1]

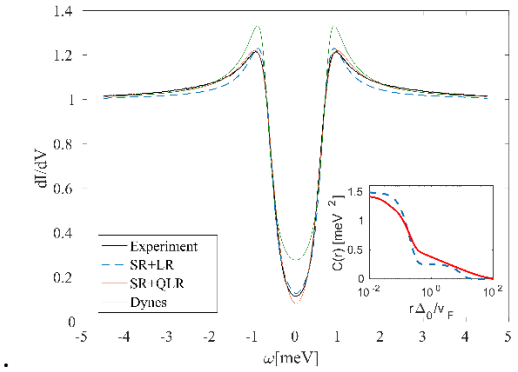

Fig. 1: *Comparison between our theoretical predictions and tunneling measurements performed on an insulating thin film close to the SIT by Ref. [2]. The best theoretical fit corresponds to a sum of short range (SR) and quasi-long-range (QLR) fluctuations.* **Inset:** *Superconducting correlations extrapolated from the data. Here* $C(r-r') = \langle \Delta^*(r)\Delta(r) \rangle$*, where* $\Delta(r)$ *is the local pairing gap.*

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Universal *T*-linear Resistivity and Planckian Limit in Overdoped Cuprates

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The perfectly linear temperature dependence of the electrical resistivity observed as $T \rightarrow 0$ in a variety of metals close to a quantum critical point (QCP) is a major puzzle of condensed matter physics [1-3]. In cuprates, a *T*-linear resistivity as $T \rightarrow 0$ has been observed in few families once superconductivity is suppressed by a magnetic field. On the electron-doped side, *T*-linear resistivity is seen just above the QCP where AF order ends [4]. On the hole-doped side, however, the doping values where *T*-linear is observed are very far from the QCP where long-range AF order ends. Instead, these values are close to the critical doping where the pseudogap phase ends [5]. Several questions must be answered. Is T-linear resistivity generic in cuprates? Is there a common mechanism linking cuprates to the other metals where $\rho \sim T$ as $T \rightarrow 0$? We measured the low-temperature resistivity of the bi-layer cuprate $Bi_2Sr_2CaCu_2O_{8+\delta}$ and found that it exhibits a *T*-linear dependence with the same slope as in the other hole-doped cuprates. It has been proposed that T-linear resistivity may be associated with the scattering rate $1 / \tau$ reaching the Planckian limit, i.e. $\hbar / \tau = k_B T$ [6, 7]. We show that the Planckian limit is obeyed in all cuprates where a pure *T*-linear resistivity has so far been observed.

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Phase Diagram of Underdoped Cuprates in a Magnetic Field: A Unified Perspective

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In the underdoped pseudogap regime of cuprate superconductors, the upper critical magnetic field (H_{c2}), a measure of the strength of superconductivity, has been difficult to access because of their high zero-field transition temperatures T_c^0. Thus the values of H_{c2} or the extent of superconducting phase with vortices, a type of topological excitations, and the role of charge orders that are present at high H, remain under debate. We present a study [1] of underdoped La-214 cuprates with a "striped" charge order and a low T_c^0, which opens a much larger energy scale window to explore the vortex phases compared to previous studies of any underdoped cuprate. By combining linear and nonlinear transport techniques sensitive to vortex matter, we determine the T-H phase diagram, directly detect H_{c2}, and probe deep into the normal state. Our results demonstrate a key role of disorder in the behavior of vortex matter as T goes to 0, while H_{c2} does not seem very sensitive to the details of the charge orders. We discuss the important implications for other cuprates, such as YBCO. The agreement between our transport results in a magnetic field and a variety of spectroscopic data in H=0 obtained on other cuprate families provides a unified perspective on the strength of pairing correlations in the cuprate pseudogap regime.

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The Essence of the High-T_c Cuprates

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We have performed a thorough experimental study of HgBa2CuO4+δ, which in many respects is a model cuprate compound. From the comparison with data for other cuprates we are able to separate universal underlying behavior from compound-specific features. The most remarkable finding is the existence of an underlying Fermi-liquid scattering rate [1] that remains essentially unchanged across the phase diagram [2,3]. Guided by established universalities, and by the knowledge that the cuprates are inherently inhomogeneous, we propose a simple model in which exactly one localized hole per planar copper-oxygen unit is delocalized and becomes itinerant with increasing doping and temperature [4]. The model is percolative in nature, with parameters that are nearly compound- and doping-independent and experimentally constrained. It comprehensively captures pivotal unconventional experimental results, including the temperature and doping dependence of the pseudogap phenomenon, the strange-metal linear temperature dependence of the planar resistivity, and the doping dependence of the superfluid density.

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Using high magnetic fields to reveal critical behavior near optimum doping in high-temperature superconductivity

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We measure the electronic specific heat in a series of Ba122 high-temperature superconductors. High magnetic fields are used to suppress the superconducting state, providing a direct experimental determination of the density of electronic states that take part in superconductivity in these samples. We find that this density of states is greatly enhanced as one approaches optimum doping, evidencing increased electronic correlations in more strongly superconducting samples. Indeed, the data extrapolate to imply a divergence precisely at optimum doping.

Thermodynamic signatures of quantum criticality in cuprates

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Recent measurements of electrical transport in cuprates at high magnetic field have revealed new signatures of the critical point p^* where the pseudogap phase ends at $T = 0$. In the absence of superconductivity, the carrier density drops abruptly from $n \sim 1+p$ above p^* to $n \sim p$ below p^* [1,2] and at p^* the electrical resistivity exhibits a linear temperature dependence at $T \to 0$ [2,3]. A fundamental question then arises: Is this drop in carrier density caused by a quantum phase transition? Is p^* a quantum critical point?

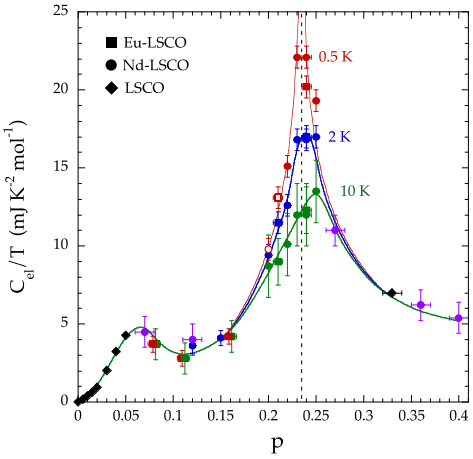

Fig. 1: Doping dependence of C_{el}/T

Here we report on low-temperature measurements of the specific heat C in the cuprate superconductors Eu-LSCO and Nd-LSCO for dopings across $p^* = 0.23$. We obtain the electronic specific heat in the normal state, C_{el}, as a function of temperature from $T = 0.5$ K to 10 K and doping from $p = 0.07$ to 0.40, by applying a magnetic field up to 18 T. We observe two properties: 1) as a function of doping, C_{el}/T shows a huge peak at p^* (**Fig. 1**); 2) at p^*, C_{el}/T varies as $\log(1/T)$. Theses are the classic signatures of a quantum critical point, as observed in heavy-fermion metals [4] and iron-based superconductors [5] where their antiferromagnetic phase ends. This shows that the pseudogap phase of hole-doped cuprates ends at a quantum critical point, the nature of which now remains to be elucidated.

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Pressure Induced Reemergence of High-T_c Superconductivity in Heavily Electron Doped FeSe Materials

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β-FeSe is a bulk superconductor with relatively low T_c = 9 K at ambient pressure. Interestingly, high-T_c superconductivity can be achieved in various heavily electron doped (HED) FeSe-derived materials, including $A_xFe_{2-y}Se_2$, $A_x(NH_3)_yFe_2Se_2$ (A = Alkaline metal), (Li,Fe)OHFeSe, and monolayer FeSe/$SrTiO_3$. In addition, a second high-T_c superconducting (SC-II) phase was reported in the pressurized $A_xFe_{2-y}Se_2$. In order to shed more light on this intriguing issue, we recently performed detailed magneto-transport measurements on several HED FeSe-based materials under hydrostatic pressures above 10 GPa. We have not only observed the emgernence of SC-II phase above a critical pressure P_c, but also provided important normal-state information for a better understanding of the SC-II phase. As seen in Fig. 1, the SC-II phase emerges above P_c = 5 GPa in (Li,Fe)OHFeSe, and the normal state evolves from a Fermi-liquid for $P < P_c$ to a non-Fermi-liquid for $P > P_c$ [1]. We have also achieved the highest T_c = 55 K in the SC-II phase of $Li_x(NH_3)_yFe_2Se_2$ [2]. In this talk, I will present the detailed hig-pressure results on several HED FeSe materials.

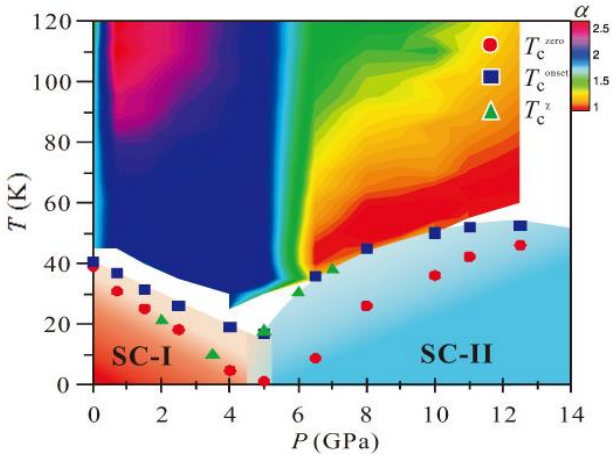

Fig. 1: *T-P phase diagram of $(Li_{0.84}Fe_{0.16})OHFe_{0.98}Se$ single crystal.*

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Acknowledgements

I am grateful for the close collaborations with J. P. Sun, P. Shahi, B. S. Wang, X. L. Dong, Z. X. Zhao, H. C. Lei, Y. Uwatoko, D. J. Singh, and G. M. Zhang. This work is supported by the CAS, NSF, and MOST of China.

Discrete superconducting phases in FeSe-derived superconductors

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A general feature of unconventional superconductors is the existence of a superconducting dome in the phase diagram as a function of carrier concentration. For the simplest iron-based superconductor FeSe (with transition temperature Tc ~ 8 K), its Tc can be greatly enhanced by doping electrons via many routes, even up to 65 K in monolayer FeSe/$SrTiO_3$. However, a clear phase diagram with carrier concentration for FeSe-derived superconductors is still lacking. Here, we report the observation of a series of discrete superconducting phases in FeSe thin flakes by continuously tuning carrier concentration through the intercalation of Li and Na ions with a solid ionic gating technique. Such discrete superconducting phases are robust against the substitution of Se by 20% S, but are vulnerable to the substitution of Fe by 2% Cu, highlighting the importance of the iron site being intact. A complete superconducting phase diagram for FeSe-derivatives is given, which is distinct from other unconventional superconductors.

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Recent Progress in 1144- and 122-type Fe-based Superconductors

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Fe-based superconductors (*Ae*,*A*)Fe_2As_2 (122-type) or *Ae*AFe_4As_4 (1144-type) forms depending on the combination of alkali metal (*A* = K, Rb, Cs) and alkaline-earth metal/Eu (*Ae* = Ca, Sr, Eu) [1-3]。 In order to expand material variation, we focused on (La,Na)Fe_2As_2 ((La,Na)122) which includes trivalent La^{3+} and monovalent Na^+ [4] as a parent compound of new 122- and 1144-type superconductors. As shown in Fig. 1 (a), new 1144-type family of (La,Na)*A*Fe_4As_4 (*A* = Rb, Cs) were crystalized by an alternate stacking of (La,Na)Fe_2As_2 and *A*Fe_2As_2 units along *c*-axis direction [5]. Superconducting transitions were observed at 25.5 K and 24.0 K for *A* = Rb and Cs, respectively.

$(La_{0.5-x}Na_{0.5+x})Fe_2As_2$ is an interesting system in the sense that either electrons ($-0.5 \le x < 0$) or holes ($0 < x \le 0.5$) can be doped into the Fe_2As_2 layers, simply by changing *x*. We have synthesized the hole-doping side of (La,Na)122 samples and constructed phase diagram as shown in Fig. 1 (b). Anti-ferromagnetic order was suppressed by hole doping and superconductivity emerged for $0.15 \le x \le 0.35$ with the highest T_c = 27.0 K [6]。 Now, we are trying to synthesize electron-doped samples ($x < 0$) which cannot be obtained via a conventional method by using high-pressure synthesis technique.

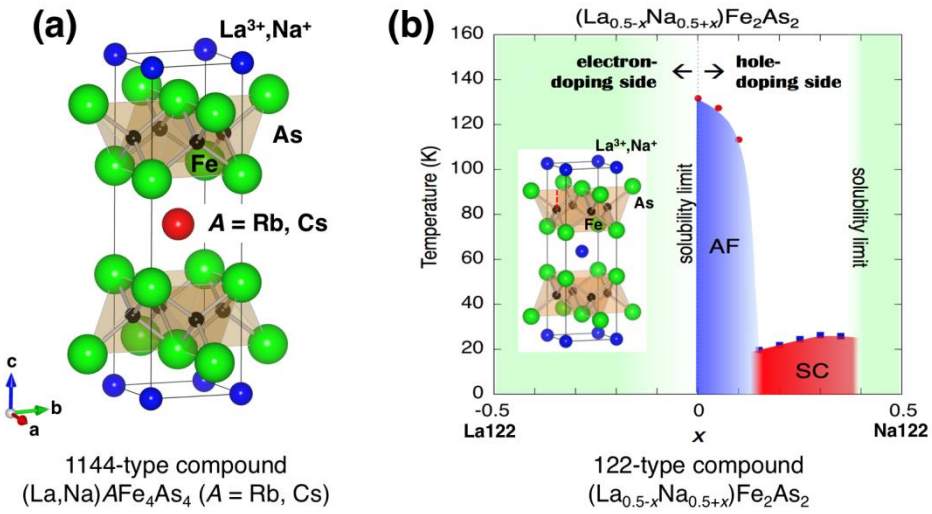

Fig. 1: (a) Crystal structure of *1144-type compound (La,Na)*AFe_4As_4 *(A = Rb, Cs).* (b) Crystal structure *and phase diagram (x ≥ 0) of 122-type compound* $(La_{0.5-x}Na_{0.5+x})Fe_2As_2$.

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Enhanced anisotropy and transport properties of heavily electron doped $Li_x(NH_3)_yFe_2(Se, Te)_2$ single crystals

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We grow $Li_x(NH_3)_yFe_2Se_2$ (LiFeSe-122) and $Li_x(NH_3)_yFe_2Te_{1.2}Se_{0.8}$ (LiFeTeSe-122) single crystals successfully and carry out a comprehensive study on their transport properties. After intercalation of Li-NH_3, the superconductivity transition temperature T_c is enhanced to about 44 K and 21 K for LiFeSe-122 and LiFeTeSe-122, respectively. Our results show the enhanced electronic anisotropy in both normal and superconducting states for both crystals when compared to Fe(Te, Se). However, the electronic anisotropy remarkably decreases with substitution of Se by Te. In LiFeSe-122, the dominant electron-type carriers with rather high concentration confirms its heavily electron doped (HED) feature, while a crossover from the electron- to hole-type carriers with increasing temperature is observed in LiFeTeSe-122. Moreover, possibly due to the anisotropic relaxation time τ and the change of carrier concentration with temperature, LiFeSe-122 shows anomalous transport properties in normal state, implying the exotic Fermi surface topology. Our current observations in LiFeSe-122 single crystals without materials complexity suggest that the superconductivity in HED FeSe-based SCs is mainly determined by electron doping level and the suppression of hole pockets would closely related to the giant enhancement of T_c to 40 - 50 K. Moreover, once above the threshold value (0.05 e/Fe), the T_c seems insensitive to the carrier concentration and strong anisotropy of τ, i.e., insensitive to the size and shape of electron pockets.

Electrochemical control of hysteretic current-voltage characteristics in Fe(Te,Se) superconductors

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Intrinsic Josephson junction (IJJ) is naturally formed in the layered supercondcutors with weak inter-layer coupling (*c*-axis coherence length, ξ_c, smaller than the layer distance, *d*,) [1], which is of great importance in the application because it can be applied as the sources of THz radiation, closing the famous "THz gap" [2]. Until now, the study of IJJ is focused on cuprate superconductors, mainly in $Bi_2Sr_2CaCu_2O_x$ (BSCCO) because of its large anisotropy ($\gamma > 100$). The discovery of iron-based superconductors (IBSs) gives out another system to probe the IJJ. Recently, the IJJ has been found in some special IBSs with long layer distance such as the $(V_2Sr_4O_6)Fe_2As_2$ [3]. On the other hand, the hysteretic *c*-axis current-voltage (*I-V*) curves, which is a common feature of underdamped Josephson junctions, is observed unexpectedly in $FeTe_{1-x}Se_x$ IBSs [4] with a very small anisotropy ($\gamma < 2$) [5]. Thus, it is crucial to confirm that if the hysteretic *I-V* behavior is coming from the IJJ of $FeTe_{1-x}Se_x$ or extrinsic influnces like the excess Fe in the interstitial positions of the Te/Se layers [6].

In this report, we studied this issue by measuring the *I-V* curves in sample with different amount of excess Fe. Single crystal was fabricated to a narrow *c*-axis-bridge junction by focused ion beam (FIB), and the amount of excess Fe was tuned by *in situ* eletrochemically deintercalating method [7]. Details about this method is shown schematically in Fig. 1. We found out that the superconducting transition temperature, T_c, is enhanced with the increase of the electrochemical reaction time, which confirms that the excess Fe is effectively removed. In the meantime, the hysteresis in the *I-V* curves expands and survives up to higher temperatures. This results confirm that the hysteretic *I-V* behavior also exsits in $FeTe_{1-x}Se_x$ free from excess Fe, indicating the IJJ in this system.

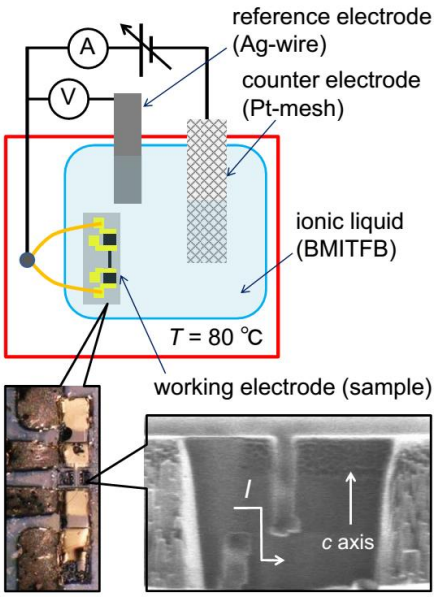

Fig. 1. Schematic of the *in situ* electrochemical method applied to $FeTe_{1-x}Se_x$ single

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Superconductivity in Akali-Metal- and Organic-Molecule-Intercalated FeSe: Comparison with Single-Layer FeSe Films

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The simple layered compound FeSe has attracted great interest, because the superconducting transition temperature, T_c, dramatically increases from 8 K to ~45 K through the co-intercalation of alkali or alkali-earth metal and ammonia or organic molecules such as ethylenediamine ($C_2H_8N_2$) [1-3] and hexamethylenediamine ($C_6H_{16}N_2$) [4-6] between FeSe layers. Recently, we have succeeded in the synthesis of alkali-metal- and 2-phenethylamine-interclated $A_x(C_8H_{11}N_2)Fe_{1-z}Se$ (A = Li, Na) with T_c = 39 – 44 K and the largest interlayer spacing d of 19 Å among those of the FeSe-based intercalation superconductors [7]. It has been concluded that the relationship between T_c and d in the FeSe-based intercalation superconductors is not domic but T_c is saturated at ~45 K for d > 9Å, which is explained in terms of the paring mediated by the spin fluctuation [8]. This saturated value of T_c is comparable to not onset T_c values due to the superconducting fluctuation but mean T_c values of single-layer FeSe films obtained from resistive measurements [9]. This is reasonable, because the single-layer FeSe films may be regarded as a kind of FeSe-based intercalation compound with infinite d values. Accordingly, it is concluded that the electronic structure of the single-layer FeSe films is very similar to that of the FeSe-based intercalation superconductors with large d values.

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Scanning probe microscopy of vortices in tilted magnetic fields

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Quite often, macroscopic experiments in single crystalline superconductors address vortex properties as a function of the angle between the magnetic field and the crystal lattice. However, the behavior of single vortices is largely unknown because there are few real space imaging experiments at tilted magnetic fields. Here I will discuss this problem by presenting recent real space observation experiments of vortices in three systems with a layered structure but very different in-plane vs out-of-plane anisotropy, the isotropic system Bi2Pd, the anisotropic superconductor 2H-$NbSe_2$ and the quasi-two dimensional material $Bi_2Sr_2CaCu_2O_8$[1-3]. In Bi_2Pd, I will show that vortices bend close to the surface and exit at an angle and that the intervortex interaction has a relevant long range Coulomb like component. In 2H-NbSe2, I will show that in-plane magnetic fields leads to striking patterns on the surface that strongly change when modifying the in-plane angle of the magnetic field. By comparing to theory, I will show that the sixfold gap anisotropy is present over the whole Fermi surface. In Bi2Sr2CaCu2O8, the anisotropy is so strong that Cooper pair currents can only circulate either fully within or perpendicular to the layers. Thus, tilted magnetic fields lead to a configuration of mutually perpendicular circular currents inside the superconductor, consisting of intertwined lattices of Josephson and pancake vortices. I will show how to trigger vortex motion channeled along the Josephson vortices and motion across Josephson vortices, and how such motion is mediated by the attractive interaction between pancake vortices that decorate Josephson vortices.

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Strong Pinning Theory

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Strong pinning allows for a quantitative assessment of vortex pinning in type II superconductors. It is defined through a precise criterion involving the (negative) curvature of the pinning potential of individual pins, the so-called Labusch criterion, and applies to the case of a dilute density of strong pins. After its first inception by Labusch and by Larkin and Ovchinnikov in the 70-ies of last century, further progress has been made recently in developing a more complete theory of strong pinning, its connection to weak collective pinning, and an intriguing relation to the Landau theory of phase transitions. New results include a force-density diagram delineating various regions characterized by one- and three-dimensional weak and strong pinning, including the evolution of the critical current density through these regimes [1], the determination of the current-voltage characteristic exhibiting an excess-current characteristic [2], the quantitative assessment of the Campbell length and its relation to the critical current density [3], and the effect of thermal fluctuations leading to thermal depinning and strong creep. Experiments support various aspects of these theoretical considerations.

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AC dynamic reorganization and critical phase transition in vortex matter

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In a variety of complex systems, among witch vortex matter is a prototype, glassy behavoir and metastable configurations give rise to striking history effects closely connected with a rich dynamics where plasticity plays a key role. Superconducting materials with randomly distributed weak pinning centers are an ideal playground for research. In these systems, the stable vortex phase at low temperature and low magnetic fields is an ordered dislocation free Bragg Glass (BG). With increasing field and/or temperature, the system undergoes an order-disorder transition to a strongly pinned disordered phase, whose fingerprint is a sudden increase in the effective pining, known as the Peak Effect (PE) anomaly. It is well known that a field-cooled vortex lattice (VL) remains trapped below the PE in a more strongly pinned disordered configuration; with the help of high dc currents or large shaking magnetic fields the system can reach the stable ordered BG, free of dislocations, which has lower effective pinning. In this framework, the existence of a transitional region between the ordered and the disordered phases remained a controversial issues for more than a decade.

In this talk I will briefly review the main results obtained in the last years by our group supporting the existence of a narrow in-between transitional region between the ordered and the disordered phases, where the application of shaking AC fields gives rise to bulk VL configurations with intermediate dislocation densities correlated with intermediate effective pinning [1]. Numerical simulations [2] suggested that these "intermediate" configurations are originated from a VL reorganization driven by the oscillatory dynamics. We present new experimental results [3] that show clear evidence of this dynamic reordering. Moreover, unambiguous signature of criticality suggests that this reorganization is closely connected with a dynamic phase transition (Fig. 1).

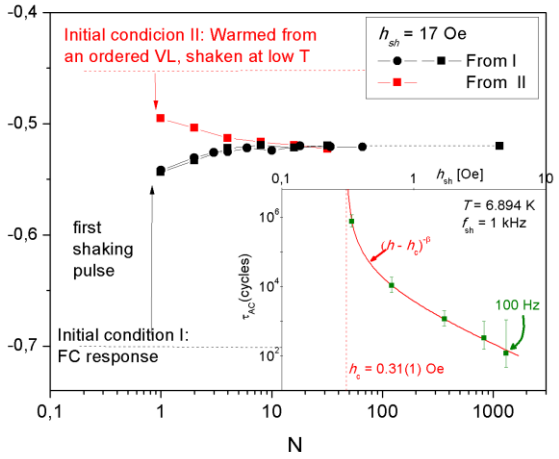

Fig.1: *Evolution of the linear susceptibility after applying N shaking cycles, starting from different conditions. After a transient number of cycles (τ_{AC}) the response converges to a stationary state.* **Inset***: τ_{AC} diverges when the shaking amplitude h_{sh} approaches h_c.*

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Bose-glass vortex phase in heavy ion irradiated BaK122 iron based superconductors

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Localization of Abrikosov vortices on random line defects results in a distinct Bose-glass phase. This correlated disorder landscape, produced in high-T_c cuprates by heavy ion irradiation, offers most efficient pinning, hence high critical currents. Replication of the same method in iron-based superconductors encounters the difficulty: areal density of produced traces is below expected from the number of impinging ions. This indicates recrystallization of target material during irradiation at ambient conditions. Side effect of this process is generation of point defects and depression of the critical temperature, T_c [1].

Here, we report improvement of the process by irradiating samples cooled to 80 K. Direct TEM imaging of wedge – sliced samples of optimally doped BaK122 crystal confirmed that low-temperature irradiation with 1.5 GeV U^{238} ions leads to formation of continuous amorphous traces with concentration matching the number of ions impacted the sample.

Resistive transition exhibits small decrease of T_c, with the rate, $\Delta T_c/\Delta\rho_{xx}$, of an order of magnitude lower than in the case of point defects produced by electron irradiation [1].

To determine unidirectional nature of the produced defects, samples were irradiated at 45° angle away from the c-axis. Local magnetization was measured using Hall-array technique. Gradient of the magnetic induction on the surface of a bar shaped sample is proportional to the current, while the average value gives magnetic field. Hysteresis loops recorded at various directions of the applied field show larger width of the loop measured for $H_{applied}$ aligned with the direction of irradiation indicating localization of vortices on columnar defects. Magnetic relaxation was measured and analyzed following modified Maley method [2]. The energy barrier controlling flux creep rate as a function of current density was determined in three magnetic field directions: parallel and perpendicular to the columnar tracks and along c-axis. Power law diverging barrier $U \propto J^{-\mu}$ with $\mu \approx 0.5$ was found for two latter configurations. In contrast, for $H_{applied}$ parallel to the traces, in the Bose-glass phase, two distinct flux creep regimes were detected: high-T - low-J, characterized by the logarithmically divergent barrier, and low-T - high-J with $\mu=1$, expected for the Bose-glass with flux creep by half-loop nucleation in the space between columnar defects.

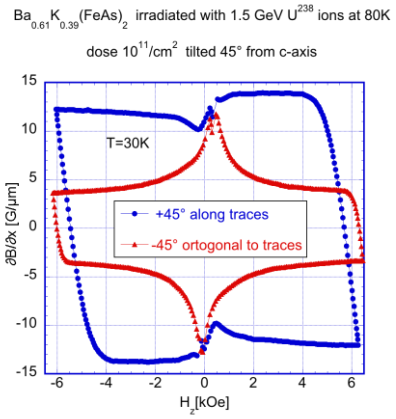

***Fig 1**. Magnetic hysteresis loops recorded on low temperature irradiated sample for two equivalent directions +45 °and -45 °in respect to c-axis.*

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Nucleation of Fractional Vortices in a Superconducting Bilayer

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Two-band superconductors have internal degrees of freedom in a quantum phase. It has been shown in theory [1] that a soliton-shaped phase difference wave can be excited and it emerges accompanied by fractional quantum vortices in two-band superconductors. However, experimental evidence of a soliton has not reported yet as far as we know. Thus, we attempt to create a fractional vortex and observe it as a soliton, using double-layered superconducting films as two-band superconductors. We designed and fabricated artificial two-band superconductors based on ultra-thin films of a Nb/AlO/Nb layered structure, where a 20 nm thick Nb layer corresponds to a one-band superconductor and the upper Nb layer has holes, as shown in Fig. 1. Magnetic images of vortices were obtained by scanning superconducting quantum interference device microscopy after a sample was cooled to 4.2 K in magnetic fields of a few microtesla. Figure 2 shows magnetic images of vortices in the B field [2]. Clearly, one vortex in the middle part has the higher magnetic flux density in comparison with others. The others have only half of the magnetic flux density that it has. Integrals of the magnetic flux density approximate to Φ_0 in the former and to $0.5\Phi_0$ in the latter. It indicates that the latter vortices are fractional vortices created in an artificial two-band superconductor. Its implication in a soliton will be discussed in the presentation. This work was partially supported by JSPS KAKENHI Grant Number JP 16K06275 and TIA collaborative research program Kakehashi.

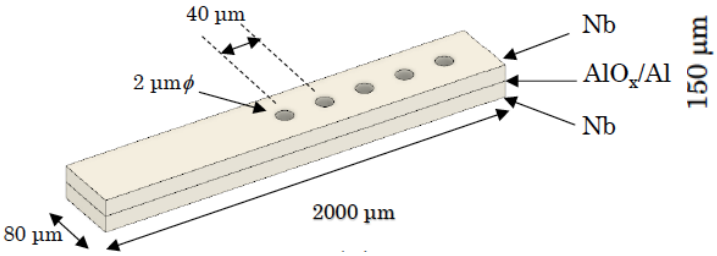

Fig. 1: *Schematic of a Nb/AlO/Nb film.*

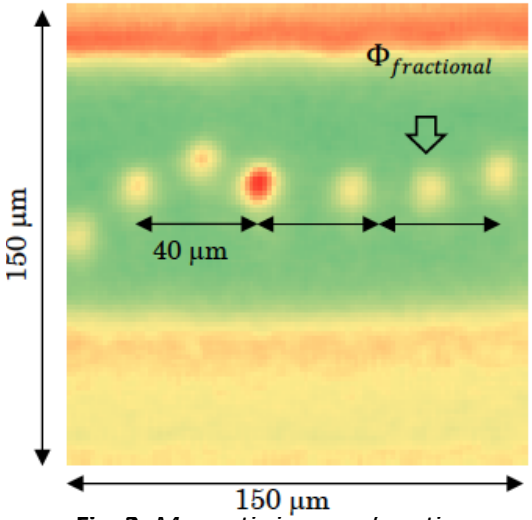

Fig. 2: *Magnetic image of vortices.*

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Flux Creep in Strong Pinning Theory

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Vortices in type II superconductors define a soft matter system that is prone to thermal fluctuations. We study vortex pinning and creep in type-II superconductors produced by a low density of strong defects. Extending the strong pinning theory to account for thermal effects, we calculate the current-voltage characteristic and thus provide the first quantitative treatment of vortex creep. We describe the thermally assisted flux flow regime found at small driving currents, which is characterised by a constant activation barrier. We show that thermal fluctuations produce a downward shift of the depinning current but preserve the overall shape of the excess-current characteristic typical of a strong pinning material. Contrary to expectations, our result implies that thermal creep persists far beyond the critical force, providing new insights into the distinctly different scenarios for the depinning process.

Strain effects on superconductivity in Ce*M*In$_5$ (*M* = Co, Rh, Ir) investigated by thermal expansion

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The thermal expansion is a directional thermodynamic probe that allows investigation of the multidimensional entropy landscape near a quantum critical point (QCP) where a quantum phase transition is tuned to absolute zero by a control parameter such as pressure, magnetic field, or composition]1]. An important issue is how the approach to a QCP upon reduction of the temperature is affected by additional phases occurring nearby. Superconductivity near quantum criticality is one of the prime examples that has been observed in many different material classes. We previously reported on the identification of a quantum critical line in the (*p*, *B*) phase diagram of CeCoIn$_5$ employing measurements of the volume thermal-expansion coefficient [2].

Here, we report on a comprehensive study of the anisotropic thermal-expansion coefficients α_i of Ce*M*In$_5$ (*M* = Co, Rh or Ir) for different directions *i* = *a*, *c*. The coefficients α_i are directly related to the entropy derivatives with respect to uniaxial stress σ_i, *i.e.*, $\alpha_i = \partial\varepsilon_i/\partial T = \partial S/\partial\sigma_i$, where ε_i and σ_i are strain and stress, respectively, along the principal crystallographic axes of the tetragonal 115 structure. In the Ce*T*In$_5$ materials class, the superconducting transition temperature T_c taken at ambient pressure varies linearly with the *c*/*a* ratio [3]. However, there are important differences: While in CeIrIn$_5$ both elongation of *c* and reduction of *a* lead to a large *c*/*a* ratio, in CeCoIn$_5$ a weak decrease of *c* is overcompensated by a strong decrease of *a* [4]. Thus in both cases T_c increases with the *c*/*a* ratio. This feature underlines that the $T_c \sim c/a$ relation is insufficient for a complete characterization. We will present a detailed phase diagram of the occurrence of superconductivity and magnetic order in the (*a*,*c*) coordinate space.

In this space, the maximum superconducting critical temperatures $T_{c,\max}$ – determined as a function of hydrostatic pressure *p* for different samples – follow a line of decreasing *c* and increasing *a.* This line is roughly perpendicular to the line of hydrostatic pressure, and therefore corresponds to a pure shear strain in the (*a*,*c*) plane. Interpreting the $T_{c,\max}(a,c)$ line as the locus of the underlying line of QCPs indicates that the distance from the QCP at low but finite temperature does not change along this line despite the fact that $T_{c,\max}$ changes appreciably.

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$CeRhIn_5$ in an Applied Magnetic Field

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$CeRhIn_5$ is a prototypical example of a system where superconductivity emerges from an antiferromagnetic quantum critical point. I will detail our recent work where we have investigated the parent antiferromagnetic state in an applied magnetic field to better understand the magnetism that gives rise to superconductivity. We illustrate that the exchange interactions in heavy fermions can be strongly field dependent, and show that this physics may be understood as a consequence of the changing crystal field levels with an applied field. Since crystal field splitting in 4*f* materials is typically of order 10 meV we expect that field dependent exchange interactions are a general phenomenon. Combined with the presence of magnetic frustration in $CeRhIn_5$, this field dependent exchange interaction leads to so-called ANNNI (axial next nearest neighbor Ising) physics. A consequence of this is that the magnetism is modulated in real space, with intertwined orders resulting in potentially reduced dimensional electronic states. We find precisely such a state when the magnetic field exceeds 30 T along the c-axis of the crystal. The electronic degrees of freedom dramatically break the fourfold symmetry of the lattice, with only a minor perturbing in-plane field component, suggesting an XY electronic nematic state.

Unidirectional Superconductivity in the Three-dimensional Metal $CeIrIn_5$

M.D. Bachmann[1,2], T. Meng[3], C. Putzke[1], T. Helm[1], Y.-S. Li[1,2], K.A. Modic[1], M. Nicklas[1], M. König[1], A.P. Mackenzie[1,2], F. Arnold[1], E. Hassinger[1], R.D. McDonald[4], L.E. Winter[4], E.D. Bauer[4], F. Ronning[4], and P.J.W. Moll[1]

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The superconducting transition of the heavy-fermion $CeIrIn_5$ is clearly evidenced by a textbook-like specific heat anomaly and the sharp onset of diamagnetism at T_c~400mK. At the same time, high purity single crystal consistently show a transition to a zero-resistance state at substantially higher temperatures, up to T_c*~1.2K. To investigate this phenomenon on the m-scale, we have fabricated transport devices from high purity single crystals using Focused Ion Beam (FIB) machining. The normal state transport properties of the devices quantitatively reproduce the measurements on macroscopic crystals. Pronounced Shubnikov-de Haas oscillations are observed in the microstructures, and the frequencies agree quantitatively with the well-studied de Haas-van Alphen spectrum of macroscopic crystals.

The superconducting state that unfolds in transport around T_c*, however, appears highly unusual. The material consistently transitions to a robust, zero resistance state at high temperatures around T_c*, *however only for currents along the crystallographic c-direction*. The in-plane transport follows the typical T^2 temperature dependence of the Fermi liquid without even the slightest anomaly at T_c*. Only at significantly lower temperatures, at the T_c~400mK observed by magnetic measurements, the material fully exhibits zero resistance along all directions.

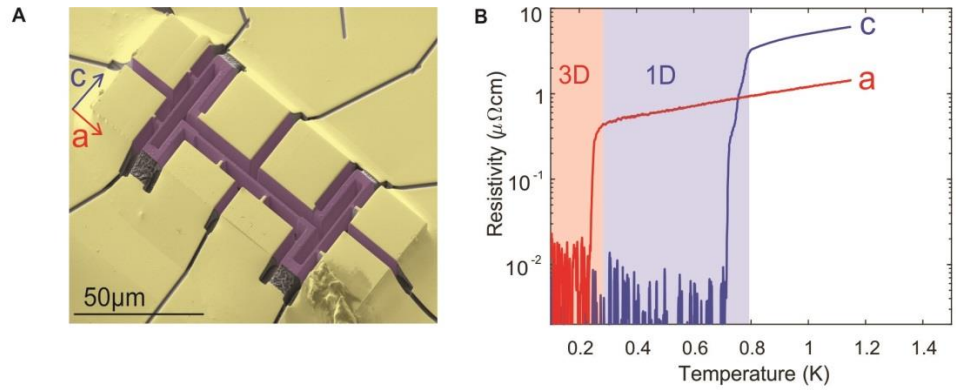

Figure 1: A) single crystal microstructure of $CeIrIn_5$, designed to probe the transport anisotropy. The device features four-probe measurements along the a-direction and the c-direction (x2) B) Resistance measured in the structure shown in A.

Impurity effects on SDW order in FFLO phase of CeCoIn5

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Clarifying the genuine picture on the high field and low temperature (HFLT) superconducting (SC) phase of CeCoIn5 is a longstanding issue. This phase includes a long-range spin-density-wave (SDW) order [1], while the NMR [2] and doping experiments [3] have shown the presence of an FFLO order, i.e., a one-dimensional spatially modulation of the SC condensate *parallel to* the applied magnetic field. In contrast to the NMR experiment, however, the presence of the SDW order has not been clarified in the doping experiment [3]. In the previous theory [4] explaining the doping experiment, the SDW order has been assumed to remain localized around the nodal planes formed by the FFLO modulation in the doped samples. However, it is known that this SDW order is of an electronic origin, and hence, there is no reason why the impurity effect on the SDW order obeys the same ensemble as that on the FFLO modulation of the SC order.

This time, the theory in Ref.[4] is extended, with no essential change of the results there, to consider the impurity effects on the two couplings between the intertwined orders [5] in the HFLT phase. First, it is found that the coupling between the SDW and the d-wave SC orders is rapidly weakened by quite a small amount of impurities and reduces to that in the limit with no FFLO modulation. That is, it is argued that, in the doped samples showing quite a broad heat capacity jump at the second order transition, the SDW order is present only in a narrow corner in higher fields and lower temperatures than the range examined in the doping experiments [3]. Second, the staggered triplet order, which is argued to have been detected in the recent thermal conductivity measurement [5], is predicted to be absent anywhere in the HFLT phase of the doped samples [3]. These results should be verified by various experiments including NMR and thermal conductivity measurements.

Based on the present theory, it is understood that the drastic difference in the experimental phase diagram following from the NMR results done by two groups [2,6] should be ascribed to a sample quality. Further, based on the present result, it is anticipated that the HFLT phase in the Nd-doped material [7] does not include the FFLO modulation but consists just of the SDW, a staggerd triplet SC and the uniform d-wave SC orders.

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Pressure Dependent Critical Current in Quantum Critical Superconductors

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Emergent quantum phases, such as high-T_c superconductivity, are often observed near the zero-temperature quantum phase transition. The role of quantum critical point (QCP) in unconventional superconductivity, however, has yet to be explored in depth because QCP is typically inaccessible without destroying superconductivity [1, 2]. Generally, the critical current I_c is studied for the practical application of superconductors because I_c sets the current limit below which the zero-resistance SC state remains. Recently, I_c has been proposed as an experimental technique to probe the role of QCP in unconventional superconductors because it is determined by fundamental SC properties [3]. Here, we present a novel approach to reveal the relationship between the SC coupling strength and quantum criticality via the pressure (P) evolution of I_c in quantum critical superconductors $CeRhIn_5$ and $CeRhSn_{0.22}In_{4.78}$. Since external pressure does not create new pinning sites, evolution of $I_c(P,T)$ is not dominated by flux pinning property, but is rather associated with the pressure evolution of SC coupling strength. A sharp peak in I_c is observed at the QCPs for both samples and the shape of SC dome is described by $I_c(P,T)$. In contrast, dc conductivity σ_{dc} at T_c onset shows a minimum value at P_c (QCP), suggesting that I_c and σ_{dc} are anti-correlated in the quantum critical superconductors. These results indicate that the pressure evolution of I_c is determined mainly by quantum critical fluctuations and the peak in I_c is a direct link to the hidden QCP.

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Non-Fermi-liquid behaviors and quantum critical points in iron-based superconductors

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Superconductivity in iron-based superconductors is closely related to both antiferromagnetic (AF) and nematic orders. Theoretically, it has been proposed that the quantum critical points (QCPs) of both orders may result in non-Fermi-liquid behaviors in the normal-states. However, the presence of superconductivity makes it hard to study them in details. In this talk, I will show our recent results on two non-superconducting systems of iron pnictides. In $Ba(Fe_{0.97}Cr_{0.03})_2(As_{1-x}P_x)_2$ where the superconductivity in $BaFe_2(As_{1-x}P_x)_2$ is fully suppressed by 3% Cr doping, an AF QCP is observed but no nematic QCP presents. In $Ba(Fe_{1-x}Cu_x)_2As_2$, we find no AF QCP but a possible nematic QCP. By comparing the normal-state properties of these two systems, we find that non-Fermi-liquid behaviors are most likely associated with the AF QCP. The nematic QCP seems to have much less significant effects on the normal-state properties.

Phase diagram of unconventional superconductors: common threads revealed by multiple tuning

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I will discuss a comprehensive study of the superconducting (SC) properties and phase diagrams using multiple tunings (such as disorder, pressure or magnetic field in addition to doping and vice versa) across several families of unconventional superconductors, including copper-oxides, heavy-fermions, organics, iron-pnictides, iron-chalcogenides, and oxybismuthides. All families possess two SC domes, with lower and higher superconducting transition temperatures Tc, both unconventional but with distinct SC and normal states properties. The lower Tc dome arises with or without a quantum critical point (QCP), and not always associated with a non-Fermi liquid (NFL) background. On the other hand, the higher-Tc dome stems from a NFL or strange metal phase, without an apparent intervening phase transition or a QCP. The two domes appear either fully separated in the phase diagram, or merged into one, or arise independently owing to their respective normal state characteristics. Furthermore, the results suggest an intimate link between NFL physics and higher-Tc superconductivity.

A Local Quantum Phase Transition in YFe_2Al_{10}

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It is now well accepted that the suppression of ordered states, such as magnetism, can give rise to a novel state with highly anomalous metallic characteristics. It remains a challenge to understand the role of the quantum critical fluctuations associated with the T=0 phase transition in inducing this new state, and if there is feedback between the fluctuations and the essential properties of the quasiparticles in the non-Fermi liquid electronic state. A lack of detailed experimental results on suitable QC systems has slowed progress towards this understanding. The quasi-two dimensional metal YFe_2Al_{10} is a very promising system, comprised of layers of nearly square nets of Fe atoms. Despite the strong divergence of the susceptibility, $\chi(T) \sim T^{-1.4}$ there is no evidence for magnetic order above 0.02 K. Inelastic neutron scattering measurements find that the scattering has no indication of incipient magnetic order, rather there is no measureable wave vector dependence, beyond that of the form factor. However, the scattering displays a strong energy divergence, and the Kramers-Kronig analysis indicates that it is these quantum critical excitations that are responsible for the divergence in the magnetic susceptibility. The scattering is also temperature independent, evidence that the imaginary part of the dynamical susceptibility $\chi''(E,T)$ displays E/T scaling, where the absence of any characteristic energy scale beyond temperature is the hallmark of quantum critical systems. The quantum critical fluctuations are very strong in YFe_2Al_{10}, signaling that it is very close to a T=0 phase transition. The neutron scattering measurements reveal that the critical fluctuations are completely local, with each moment fluctuating incoherently, each with the same spectrum of excitations. These findings rule out the possibility that YFe_2Al_{10} is near magnetic ordering, and instead it seems likely that the phase transition corresponds to a purely electronic phase transition, possibly an orbital selective Mott transition, where localized magnetic moments first emerge.

Magnetic interactions and possible quantum paraelectricity in spin liquid candidate $H_3LiIr_2O_6$

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$H_3LiIr_2O_6$ was recently identified to be a candidate of quantum spin liquid []. It has similar structure to the "Kitaev materials" A_2IrO_3 (A=Li, Na), where the Ir honeycomb lattice was proposed to host a pseudo-spin-1/2 Kitaev spin liquid. However, the A_2IrO_3 materials have magnetic long-range orders at low temperature due to various interactions beyond the exactly solvable Kitaev model, while $H_3LiIr_2O_6$ shows no sign of magnetic order in experiments. In this talk we will report our first-principle calculations of the structure and magnetic interactions of $H_3LiIr_2O_6$. We found that the magnetic interactions detrimental to spin liquid are relative small in $H_3LiIr_2O_6$ compared to other "Kitaev materials", but this alone would not place this material in the spin liquid phase (see Fig. 1). We further studied the position and dynamics of H atoms, and found that the H atoms form "hydrogen bonds" between O atoms of different IrO3 layers (see Fig. 1). Similar to many other hydrogen bonds, each H atom has two classical ground state positions away from the O-H-O bond center. We propose that the quantum tunneling of H atoms, or the fluctuation of the electric dipoles of the O-H-O bonds, causes additional frustration in the Ir pseudo-spin interactions and pushes $H_3LiIr_2O_6$ into the Kitaev quantum spin liquid phase.

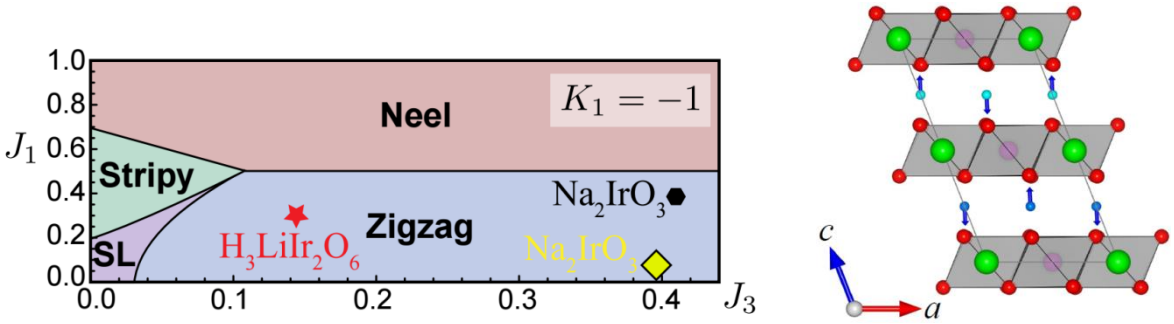

Fig. 1: *Left: Phase diagram of Kitaev-J_1-J_3 model [Winter et al Phys. Rev. B 93, 214431 (2016)], the red 5-pointed star indicates the model parameters of $H_3LiIr_2O_6$ according to our calculation. Right: Structure of H_3LiIrO_6. The small blue circles are H atoms, red circles are O atoms.*

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Magnetic (AF SDW) transition in the normal state of iron- and copper-based HTSC

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The detailed analysis of in-plane magnetoresistive measurements on doped pnictide (selenide) single crystals and single-crystalline films demonstrates that superconducting (SC) transition in their conducting planes, is preceded by dielectric in nature, (dynamic) magnetic phase transition from the spin-disordered state to the spin-density-wave (AF SDW) state [1] (similar picture is in cuprates [2], see Fig.1). The dielectric and superconducting parts of the in-plane resistive transition are separated by a Bloch-Gruneisen curve (dashed curve) [1,2]. The intersection points correspond to the onset temperature of SC transition *Tc(H)*. As a result, at *T* < *Tc(H)*, two order parameters are present in the system: SC and SDW-dielectric one.

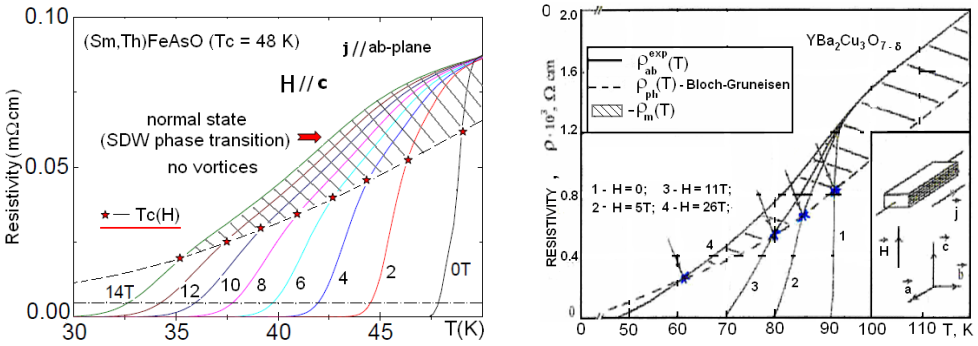

Fig. 1: *Magnetic (AF SDW) 2D-phase transition in the normal state of iron- and copper-based HTSC .*

The theory for such a picture is presented on the basis of the Keldysh-Kopaev model of metal-insulator transition. Thermodynamics of such transition is analogous to that of superconducting transition, and electron energy spectrum is the same as in superconductor. Such approach being extended to systems with coexistence of dielectric (e-h) and superconducting (e-e) pairings leads to partial dielectrization of the Fermi surface [3]. The corresponding dielectric (SDW) gap is highly anisotropic since it is only formed at symmetrical parts of the Fermi surface, and its magnitude is large compared with that of SC gap. The analytical expression is derived for in-plane resistivity as a function of H at given T. It indicates that upper critical magnetic field $H_{c2}(0)$ in iron-based HTSC at H || c is only near 20 T rather than 70-80 T claimed in literature. The similar picture is discussed for sulfur hydrides at high pressure. It is demonstrated that the onset of resistive transition at 203 K in them can be of magnetic nature rather than SC one, while onset of SC transition is only of the order of 40 K [4]. The study of possibility of such a proposal is now in progress (see e.g. [5]).

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Umklapp Scattering as the Origin of T-linear Resistivity in the Normal State of High-T_c Curpate Superconductors

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The high-temperature normal state of the unconventional cuprate superconductors has resistivity linear in temperature T, which persists to values well beyond the Mott-Ioffe-Regel upper bound. At low-temperature, within the pseudogap phase, the resistivity is instead quadratic in T, as would be expected from Fermi liquid theory. Developing an understanding of these normal phases of the cuprates is crucial to explain the unconventional superconductivity. We present a simple explanation for this behavior [1], based on the theoretical analysis presented in [2], in terms of umklapp scattering of electrons. This fits within the general picture emerging from functional renormalization group calculations that spurred the Yang-Rice-Zhang ansatz: umklapp scattering is at the heart of the behavior in the normal phase.

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Two fluid model for diamagnetic susceptibility and Nernst effect in high Tc Superconductors

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There exist very strong signals of diamagnetic susceptibility and Nernst effect in high Tc superconductors. They are most apparent in the underdoped regime, where a pseudogap is evident. In this talk, I will present a simple two-fluid model, in which the system is composed of fermionic and bosonic degrees of freedom. While the former are Bogoliubov-like quasiparticles, the latter are finite momentum fermion pairs. We show that these pairs contribute to a large diamagnetic signal and Nernst coefficient. We find a large diamagnetic response for a range of temperatures much higher than the transition temperature Tc. In particular, we report semiquantitative agreement with the measured diamagnetic susceptibility onset temperatures, over the entire range of hole dopings [1]. At the lower critical doping of the superconducting dome, where Tc vanishes and the pseudogap onset temperature remains large, the onset temperature for both diamagnetic and Nernst coefficients tends to zero.

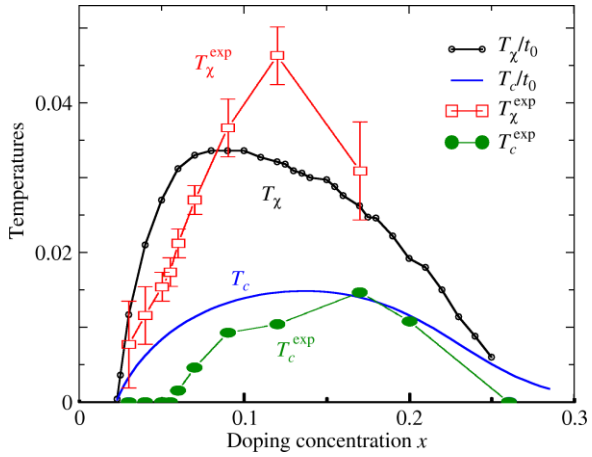

Fig. 1: Semiquantiative agreement between theory and experiment: Doping dependence of the calculated diamagnetic susceptibility onset temperature T_χ (black) and T_c (blue), along with corresponding experimental data for T_χ (red squares) and T_c (green discs). For both cases, the maximum of T_χ is skewed towards the underdoped regime.

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Superconductivity and Competing Phases in High T_c Cuprates

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Efforts to understand the microscopic origin of superconductivity in the cuprates are dependent on our knowledge of the normal state. In the underdoped cuprates, both incommensurate charge density wave (CDW) order and the pseduogap phase are known to exist in the same part of the phase diagram as superconductivity. It has been conjectured that fluctuations in either, or both of these may be a contributing factor towards the high temperature superconductivity. An increase in effective mass suggestive of a quantum critical point has been observed close to optimal doping [1] which is also close the end point of the CDW and pseudogap phases. Alongside this, a sharp decrease in the Hall coefficient (R_H) in the high field ($T\rightarrow0$) limit, has been linked to the endpoint of the pseudogap phase [2].

Here I will review our experiments to investigate the approach to optimal T_c from both the underdoped and overdoped sides of the phase diagram. On the underdoped side we can continuously increase T_c by applying hydrostatic pressure. Our results for $YBa_2Cu_4O_8$ (Y124) show that the effective mass measured by quantum oscillations decreases [3] as optimal T_c is approached, in sharp contrast to the doping studies $YBa_2Cu_3O_{7-}$ (Y123), suggesting that any quantum critical behaviour is not generically linked to the maximum T_c. Measurements of the R_H of underdoped Y123 (p=0.11), show a very slow suppression [4] of the CDW transition with pressure which contrasts sharply with the linear increase in T_c (with pressure). This suggests that the CDW formation does not suppress Tc significantly.

Measurements of the R_H of the single layer cuprate $Tl_2Ba_2CuO_{6+}$ (Tl2201) are used to investigate how R_H in the $T\rightarrow0$ limit evolves in the overdoped so-called strange metal phase of cuprates. We find that R_H is enhanced above the value expected from the number of doped holes over much of the overdoped part of the phase diagram and that this enhancement correlates with the emergence of the anomalous linear-in-T term in the longitudinal resistivity. This may suggest that cuprates are described by a holographic model of quantum criticality over much of the phase diagram.

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Anomalous Transport Properties of Electron-Doped $La_{2-x}Ce_xCuO_4$

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We report new measurements of resistivity, Hall Effect and thermopower in $La_{2-x}Ce_xCuO_4$ for $0.19 \geq x \geq 0.08$ as a function of temperature and magnetic field. The major results are:
1) Transport evidence for a Fermi surface reconstruction is found at low temperatures at a critical doping of 0.14 [1].
2) The normal state magnetoresistance exhibits an anomalous linear-in-H behavior at the same doping and temperature where a linear-in-T resistivity was previously observed for $H>H_{c2}$ [2].
3) The normal state Seebeck coefficient, S/T, exhibits a low temperature –logT dependence at the same doping where linear-in-T resistivity is found
4) The normal state resistivity from 80 K to 300 K follows an anomalous $A(x)T^2$ behavior at zero field for all doping(x), with smooth variation even through the critical doping 0.14.
We will discuss these results in comparison to conventional Fermi liquid transport. We conclude that conventional Fermi liquid theory cannot explain any of these results [3].

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The c-axis resistance mystery in high temperature superconductor: insights from scanning noise spectroscopy

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I will present novel insight into the long-standing mystery of c-axis transport in the cuprates. While these materials behave perfectly metallic in the *ab* – plane, they are insulating in the *c*-axis, with ratios between the resistivities exceeding 10^5. This has early been identified as a key open question and has been connected to the mechanism of high-temperature superconductivity. Here, I will report data from a novel scanning noise spectroscopy instrument we build to understand how electrons tunnel between different layers. Our results show surprising deviations from Poissonian noise expected from uncorrelated electrons. In my presentation, I will show how these novel observations connect to the mystery of c-axis transport in the high-temperature superconductors and shed new light onto this issue.

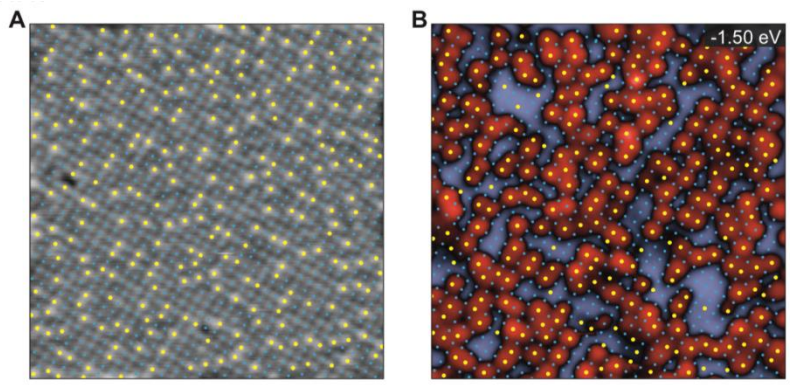

Fig. 1: *Spectroscopic-imaging STM data from a high-temperature superconducting sample.*

Infrared Study of Antiferromagnetic Correlations and Electron-Phonon Coupling in Hole-Doped Iron Arsenide Superconductors

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We present a detailed infrared spectroscopy study of a series of hole-doped $Ba_{1-x}K_xFe_2As_2$ (BKFA) and $Ba_{1-x}Na_xFe_2As_2$ (BNFA) single crystals with a special focus on two particular aspects. Firstly, we show that the competition with superconductivity is much stronger in the so-called tetragonal antiferromagnetic (t-AF) state than in the stripe-like, orthorhombic (o-AF) state. In the t-AF state, we observe a dramatic suppression of the superconducting condensate density that in addition to the competition for the electronic states near the Fermi-level seems to involve a severe reduction of the SC pairing strength.

In the second part of the talk, we focus on the evolution of the Fano-effect of the Fe-As stretching mode. We show that it exhibits a very characteristic temperature and doping dependence that provides evidence that the electron-phonon interaction is strongly enhanced by the antiferromagnetic spin fluctuations. We also discuss the evidence that this enhanced electron-phonon coupling is involved in the SC pairing mechanism.

Orbital Selective Physics in Iron-based Superconductor KFe_2As_2

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KFe_2As_2 is a heavily holed iron-based superconductor. It is reported that there is an incoherence to coherence crossover, resembling that observed in heavy fermion systems. We have measurements the optical and magnetic responses of KFe_2As_2 by far-infrared and magnetic torque measurements. Indeed an incoherence to coherence crossover is observed which demonstrates itself as the emergence of a Drude peak in the low temperature in the optical conductivity. Spectrum weight analysis shows that the emergent Drude weight comes from the spectrum weight transfer from high energy bound states. Theoretical calculation suggests that the crossover possibly comes from the delocalization of electrons in the d_{xy} orbital. The similarity between the phenomena observed in KFe_2As_2 and those in heavy fermion systems are being discussed.

Fingerprints of Cooper Pairing in Iron-Based Superconductors

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Results of Raman scattering experiments on $Ba_{1-x}K_xFe_2As_2$ ($0.22 \le x \le 0.7$) and $CaKFe_4As_4$ will be presented with the main focus placed on electronic excitations in the superconducting state below T_c. In all materials a redistribution of spectral weight from low to high energies is observed upon crossing T_c. The gap magnitudes derived from the Raman spectra are in approximate agreement with the results from other methods, in particular photoemission spectroscopy and specific heat measurements. The gaps on the individual bands are almost isotropic but there is substantial variation between the bands. The smallest gap is observed on the outer hole band and has a magnitude between 1 and 2 in units of k_BT_c. The gaps on the electron and inner hole bands reach values of up to $8k_BT_c$ thus indicating strong coupling. Inside the large gaps narrow lines having a nearly resolution-limited width are found for $Ba_{1-x}K_xFe_2As_2$ in the range $0.35 \le x \le 0.48$. The spectra in $CaKFe_4As_4$ are very similar to those of $Ba_{0.65}K_{0.35}Fe_2As_2$. Possible explanations of the in-gap modes include a nematic resonance, Leggett oscillations between the condensates on the electron and hole bands, and Bardasis-Schrieffer (BS) excitons resulting from phase oscillations of the gap in the presence of anisotropic pairing interactions $V_{\mathbf{k},\mathbf{k}'}$. It is shown that the experiments are in full agreement with the theoretical predictions for BS modes.

Further support for this view comes from studies of the relative pairing strength in different channels using functional renormalization group and spin fluctuation theory. Both approaches predict the same ground state and hierarchy of pairing channels, the relative pairing strengths and the related eigenvectors. The theoretical results reproduce the experiments qualitatively and suggest that spin fluctuations are an important if not the leading interaction in the pnictides.

Optical properties of the electronic nematic phase in FeSe

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FeSe undergoes a structural tetragonal-to-orthorhombic transition below 90 K, which breaks the four-fold rotational symmetry of the tetragonal phase, without any subsequent onset of magnetic ordering. The substantial anisotropy of the transport properties in the broken symmetry state is ascribed to an electronic nematic phase. FeSe thus provides an opportunity to address the impact of nematicity on its intrinsic physical properties without the limitations of the reconstruction of the Fermi surface due to the SDW collective state in the orthorhombic phase, typical for several other iron-based superconductors. We describe results of reflectivity measurements over a broad spectral range that probe the optical response to variable uniaxial stress, detwinning the specimen and acting as an external symmetry breaking field, and as a function of temperature across the structural transition [1]. We extract the optical conductivity through Kramers-Kronig transformation. Our data reveal an astonishing anisotropy of the optical response in the mid-infrared-to-visible spectral range, which bears testimony of an important polarization of the underlying electronic structure in agreement with ARPES results. Our findings at high energy scales support models for the nematic phase based on an orbital-ordering mechanism, supplemented by orbital selective band renormalization. The far-infrared response of the charge dynamics moreover allows establishing the link to the dc resistivity. The dc limit of the optical conductivity indeed agrees with the measured transport properties, deploying an anisotropy typical of hole-doped iron-based materials. Our optical results at energies close to the Fermi level furthermore emphasize scenarios based on scattering by anisotropic spin-fluctuation, shedding new light on the origin of nematicity in FeSe.

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Ultrafast Quasiparticle Dynamics and Electron-Phonon Coupling in $(Li_{0.84}Fe_{0.16})OHFe_{0.98}Se$

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Distinctive superconducting behaviors between bulk and monolayer FeSe make it challenging to obtain a unified picture of all FeSe-based superconductors. Here, we investigate the ultrafast quasiparticle dynamics of an intercalated superconductor $(Li_{1-x}Fe_x)OHFe_{1-y}Se$, which is a bulk crystal but shares a similar electronic structure with single-layer FeSe on $SrTiO_3$. We obtain the electron-phonon coupling (EPC) constant λ (0.23 ± 0.03), which well bridges that of bulk FeSe crystal and single-layer FeSe/$SrTiO_3$ [1]. Moreover, we find that such a positive correlation between λ and superconducting T_c holds among all known FeSe-based superconductors, even in line with reported FeAs-based superconductors. Our observation indicates possible universal role of EPC in the superconductivity of all known categories of iron-based superconductors, which is a critical step towards achieving a unified superconducting mechanism for all iron-based superconductors.

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opological spin-triplet superconducting states revealed by NMR

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A topological superconductor is analogous to a topological insulator (TI) in that the superconducting gap function has a nontrivial topological invariant. Although a great success has been achieved in the study of TIs, progress in establishing bulk topological superconductivity with time reversal symmetry has been slow until recently [1].

In this talk, I will present some of our results in the quest of topological superconductivity in doped topological insulators $Cu_xBi_2Se_3$ [1] and Sr_x Bi_2Se_3, as well as in strongly-correlated superconductors $(K,Rb)_2Cr_3As_3$ [2].

In $Cu_{0.3}Bi_2Se_3$, our ^{77}Se nuclear magnetic resonance (NMR) measurements indicate that spin rotation symmetry is spontaneously broken in the hexagonal plane below the superconducting transition temperature Tc=3.4 K (Fig.1) [1]. This is the first evidence for such symmetry breaking found in any superconductors. Our results not only establish spin-triplet (odd parity) superconductivity in this compound, but also show that it is a topological superconductor belonging to DIII class. I will also discuss our most recent effort to obtain single crystals of $Cu_xBi_2Se_3$ with various doping contents and different properties.

In $Rb_2Cr_3As_3$ (T_c=4.8 K), we found strong ferromagnetic spin fluctuations in the normal state and point nodes in the superconducting gap [2], which suggest that this compound may be a solid-state analogue of superfluid ^3He.

This work was done in collaboration with K. Matano, M. Kriener, K. Segawa, Y. Ando, J. Yang (IOP), G.H. Cao (Zhejiang U), Y.G. Shi (IOP), Zheng Li (IOP) and C.-J. Zhang (USTC).

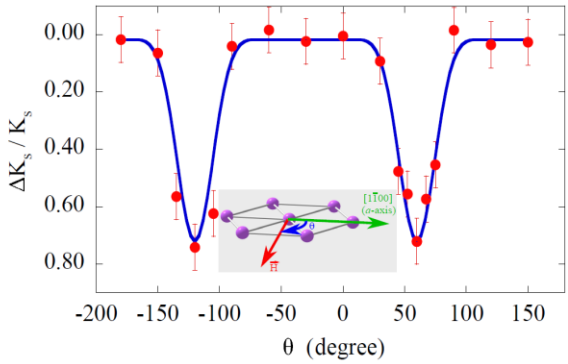

Fig. 1: *The Knight shift reduction below Tc as a function of the angle between the in-plane magnetic field and the a-axis in $Cu_xBi_2Se_3$*

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Evidence of Nematic Superconductivity in Doped Bi_2Se_3 and Bi_2Te_3/FeTeSe Heterostructures

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Topological superconductor is a timely and frontier topic in condensed matter physics. In superconducting state, an order parameter will be established with the basic or subsidiary symmetry of the crystalline lattice. Here we report the direct evidence of nematic superconductivity in Bi_2Te_3 thin film on top of an iron-based superconductor $FeTe_{0.55}Se_{0.45}$. Firstly, we report the observation of the discrete Caroli-de Gennes-Matricon (CdGM) states[1] which were predicted in 1964 as low energy excitations within vortex cores of type-II superconductors. In the quantum limit, the energy levels of these states were predicted to be discrete with the basic levels at $\pm \mu\Delta^2/E_F$ (μ = 1/2, 3/2, 5/2,…) with Δ the superconducting energy gap and E_F the Fermi energy. Here we report the clear observation of these discrete energy levels of CdGM states in $FeTe_{0.55}Se_{0.45}$.

In Sr doped Bi_2Se_3, we find that the c-axis resistivity exhibits a two fold symmetry when a magnetic field is rotated within the ab-planes, indicating the nematic superconductivity[2]. Furthermore, we show the systematic study of scanning tunneling microscope/spectroscopy on the possible topological superconductor $Sr_xBi_2Se_3$. We find that the surface Dirac electrons will simultaneously condense into the superconducting state when the energy is smaller than the bulk superconducting gap[3]. In order to explore the superconductivity with possible odd parity, we deposit Bi_2Te_3 thin film on the $FeTe_{0.55}Se_{0.45}$ substrate and get the proximity induced superconductivity. By using the quasiparticle interference technique, we demonstrate clear evidence of twofold symmetry of the superconducting gap. The gap minimum is along one of the main crystalline axis following the so-called Δ_{4y} notation. This is also accompanied by the elongated vortex shape mapped out by the density of states within the superconducting gap. Our results reveal the direct evidence of superconductivity with two-fold symmetry in Bi_2Te_3 thin film. This result is also consistent very well with the prediction of odd-parity superconductivity in this hereo-structure[4].

Collaborated with Huan Yang, Minyang Chen, Xiaoyu Chen, Xiyu Zhu, Zengyi Du, Enyu Wang et al.

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Nematic superconductivity in $Cu_xBi_2Se_3$ studied by scanning tunneling spectroscopy

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$Cu_xBi_2Se_3$ hosts both topological surface states and bulk superconductivity. It has been identified recently as a topological superconductor (TSC) with an extraordinary nematic, i. e. C_2-symmetric, superconducting state and odd-parity pairing. Here, using scanning tunneling microscopy (STM), we directly examine the response of the superconductivity of $Cu_xBi_2Se_3$ to magnetic field. Under out-of-plane fields ($B_\perp$), we discover elongated magnetic vortices hosting zero-bias conductance peaks consistent with the Majorana bound states expected in a TSC. Under in-plane fields ($B_{//}$), the average superconducting gap exhibits two-fold symmetry with field orientation, the long C_2 symmetry axes are pinned to the dihedral mirror planes under $B_{//}$=0.5 T but slightly rotate under $B_{//}$=1.0 T. Moreover, a nodeless Δ_{4x} gap structure is semi-quantitatively determined for the first time. Our data paint a microscopic picture of the nematic superconductivity in $Cu_xBi_2Se_3$ and pose strong constraints on theory. [1] I will also present our recent data on the robust zero-bias conductance peak in the vortex of an iron based superconductor.

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Nematic Superconducting Gap in the Topological Superconductor $Cu_xBi_2Se_3$

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Doped Bi_2Se_3 systems with ion intercalations have been extensively studied as a leading candidate for topological superconductivity [1]. More recently, it has been proposed that this class of materials can host novel superconductivity with rotational-symmetry breaking in the gap *amplitude* of the order parameter [2]. Such superconductivity has been termed as "nematic superconductivity", in an analogy to the nematic liquid-crystal phases exhibiting spontaneous rotational-symmetry breaking without losing fluidity.

In this study, we measured the specific heat of the Cu-doped topological insulator $Cu_xBi_2Se_3$ (x ~ 0.3) under accurate magnetic-field-direction control [3]. Here, as shown in Fig. 1, we observed clear two-fold-symmetric behavior in the in-plane field angle dependence of the specific heat, as well as in the upper critical field. Considering the trigonal symmetry of the lattice, the observed two-fold behavior in bulk quantities indicates rotational symmetry breaking in the superconducting gap *amplitude*, namely the realization of the nematic superconductivity. In addition, according to the theories [2], the nematic superconductivity in this compound actually belongs to a class of topological superconductivity. Thus, our results also provide thermodynamic evidence for topological superconductivity in this compound.

This work has been performed under collaboration with K. Tajiri, S. Nakata, Y. Maeno (Kyoto Univ., Japan), Y. Nagai (Japan Atomic Energy Agency, Japan), Z. Wang, Y. Ando (Univ. Köln, Germany), and K. Segawa (Kyoto Sango Univ., Japan).

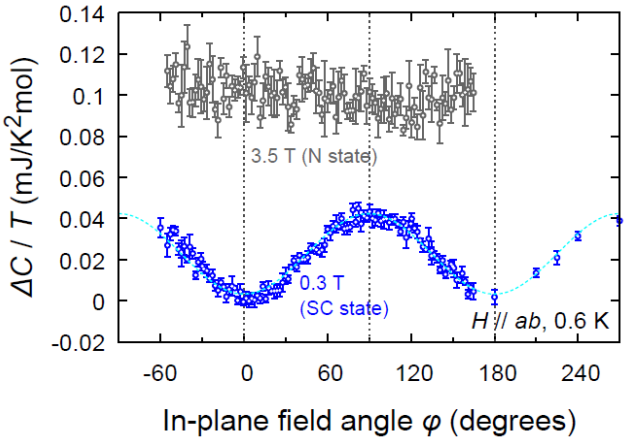

Fig. 1: *In-plane field angle dependence of the specific heat of single-crystalline $Cu_xBi_2Se_3$ (x ~ 0.3) in the superconducting (0.3 T) and normal (3.5 T) states [3].*

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Nematic superconductivity in doped topological insulators

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If the topological insulator Bi_2Se_3 is doped with electrons, superconductivity with $T_c \approx 3-4K$ emerges for a low density of carriers ($n \approx 10^{20} cm^{-3}$) and with a small ratio of the superconducting coherence length and Fermi wavelength: $\xi/\lambda_F \approx 2\cdots 4$. These values make fluctuations of the superconducting order parameter increasingly important, to the extend that the T_c-value is surprisingly large. Strong spin-orbit interaction led to the proposal of an odd-parity pairing state. This begs the question of the nature of the transition in an unconventional superconductor with strong pairing fluctuations. We show that for a multi-component order parameter, these fluctuations give rise to a nematic phase at $T_{nem} > T_c$. Below Tc several experiments demonstrated a rotational symmetry breaking where the Cooper pair wave function is locked to the lattice. Our theory shows that this rotational symmetry breaking, as vestige of the superconducting state, already occurs above T_c. The nematic phase is characterized by vanishing off-diagonal long-range order, yet with anisotropic superconducting fluctuations. It can be identified through direction-dependent para-conductivity, lattice softening, and an enhanced Raman response in the E_g symmetry channel. In addition, nematic order partially avoids the usual fluctuation suppression of T_c.

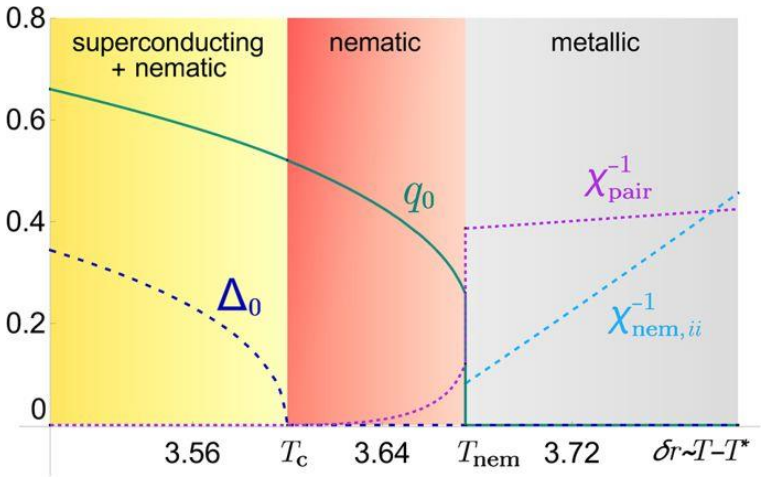

Figure 1: Temperature dependence of the nematic (q_0) and the superconducting (Δ_0) order parameters, together with the pair susceptibility and the nematic susceptibility of the system.

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Nematic superconductivity in topological materials

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Topological insulators have generated a wide research interest, because they offer access to novel quantum states with unprecedented properties. Most interestingly, the concept of topological insulators can be transferred to superconductors, where the superconducting gap plays the role of the band gap of the insulator. Here we focus on recent developments in the family of intercalated Bi_2Se_3-based crystals, such as $Cu_xBi_2Se_3$ and $Sr_xBi_2Se_3$, where field-angle dependent measurements of the transport, thermal and magnetic properties reveal spontaneously broken rotational symmetry in the macroscopic superconducting properties, for instance in the upper critical field [1,2]. This unusual property can be explained by recent theoretical models for topological superconductors in terms of nematic superconductivity associated with a two-component superconducting order parameter (E_u representation) [3]. The experimental results provide solid evidence for unconventional superconductivity with an odd-parity spin-polarized triplet Cooper-pair state (Δ_4-pairing).

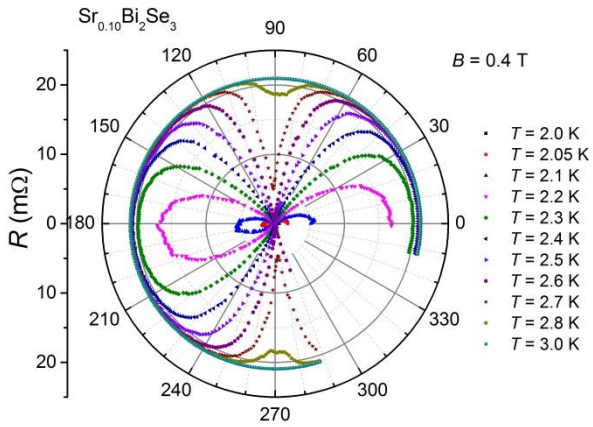

Fig. 1: *Polar plot of the resistance of $Sr_{0.10}Bi_2Se_3$ in a field of 0.4 T at temperatures as indicated. The field is applied in the trigonal basal plane. The rotational symmetry is broken and a clear two-fold symmetry remains.*

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Electron-Phonon Coupling in Compressed H-rich Solids

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The predictions in 2014 of very high T_c in compressed H_2S (80K) [1] and H_3S (200K) [2] based on modern computational implementation of Eliashberg theory of an electron-phonon coupled Fermi liquid was too exciting initially to take seriously. The rapidly following discovery [3] of T_c=200K in H3S in the range 160-200 GPa pressure made these predictions a reality, and has accelerated the computational study of compressed H-rich solids. While the predictions seem generally to be realistic (only a few confirmed, most untested) and detailed understanding of the high Tc is improving, certain areas require more study.

One area to be discussed is the effect of strong EPC on the narrow peak in the density of states in H_3S [4] and its impact on physical properties. Using the EPW code, we have obtained the EPC self-energy corrections to the band energies, and derived a zone-averaged complex self energy $\Sigma(\omega)$ from which the electron interacting spectral density can be obtained, and its impact explored. A primary consequence is that the spectral density $A(\omega)$ contains a peak at the Fermi energy narrowed from the density of states $N(\varepsilon)$ by a factor proportional to $1+\lambda$, i.e. the peak at low temperature is *narrowed rather than broadened* by strong EPC.

Another effort is to gain a more complete understanding of el-ph matrix elements, since these must increase under pressure as much as the phonon frequencies do, to maintain strong coupling and thereby high Tc. We focus on select classes of hydrides, viz. binary hexahydrides *M*H6, for which certain members have been predicted to have Tc > 100K. The light mass of H allows separation of frequencies into those assignable to H and to the metal atom *M*. The dominance of H vibrations focuses attention on the scattering of Fermi surface electrons by H vibrations, which can be related to the electronic structure.

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Raising superconducting transition temperature by lifting the σ-bonding bands to the Fermi level

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Raising superconducting transition temperature (T_c) is an important task of fundamental research of superconductivity. It is also a prerequisite for the large scale application of superconductors. In the absence of microscopic mechanism of high-T_c superconductivity, the conventional approach for raising T_c is either to apply high pressure on a material which has potential to become superconducting or to push it close to an antiferromagnetic or other quantum instability point by doping. Here we introduce another approach that can be used in the search of new superconductors: it is to raise T_c by lifting the σ-bonding bands to the Fermi level, namely by metalizing σ-bonding elections. This approach can increase the probability of finding a new high-Tc superconductor because the coupling of σ-bonding electrons with phonons is generally strong and the superconducting transition induced by this interaction can happen at relatively high temperature. After elucidating the underlying mechanism, we discuss a number of schemes to metalize σ-bonding electrons, and present our recent prediction for the crystal and electronic structures of two potentially high-Tc superconductors Li_2B_3C and $Li_3B_4C_2$ with Tc higher than 50 K, based on the first-principles electronic structure calculations in the framework of the Eliashberg equations.

Superconductivity and Magnetism in all-Carbon π-electron Systems

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Superconductors and magnets in which the electronically-active components are molecules rather than atoms often consist of π-electron open-shell molecular units as the main component of the electronic conduction and spin network, respectively. Current best-in-class materials are the all-carbon π-electron fullerides – these show the highest known superconducting critical temperature, T_c at 38 K coupled with a record upper critical magnetic field, H_{c2} in excess of 90 T [1,2]. The dominance of strong electron correlations in defining their behavior poses significant challenges for understanding the highly robust superconducting response to both temperature and magnetic field in these highly correlated molecular systems. Here I will attempt to trace the development of this field of science to date with emphasis on its current status and future prospects. Issues pertaining to other all-carbon -electron systems such as the polyaromatic hydrocarbons will be also addressed - here alkali metal phenacenes were shown to provide the first example of a 3D quantum spin-liquid state to 50 mK arising purely from π-electrons (Fig. 1), while, at the same time, harboring orbitally entangled states, prerequisites of the emergence of quantum magnetism and exotic superconductivity [3,4].

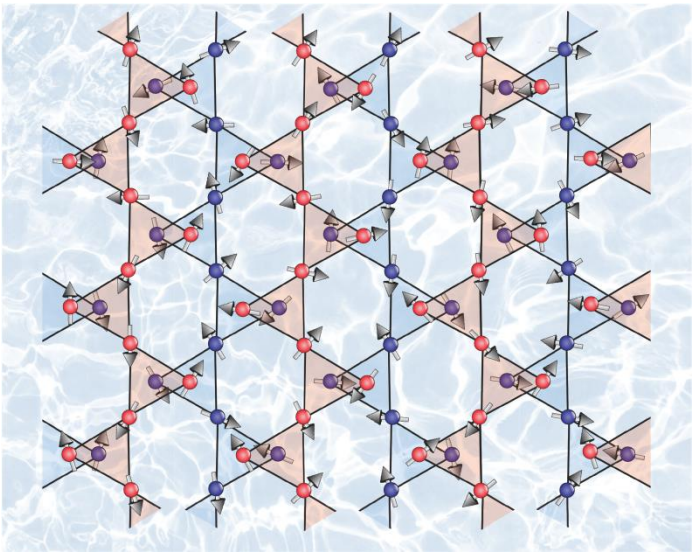

Fig. 1: *Schematic structural depiction of the candidate quantum spin liquid Mott insulating phase, $Cs(C_{14}H_{10})$ ($C_{14}H_{10}$ = phenanthrene) [3].*

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Formation of High-T_c Phase of Sulfur Hydride by Low-Temperature Compression

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By compression of hydrogen sulfide, the record for the superconducting critical temperature, T_c was elevated up to 203 K, using high-pressure treatment under 150 GPa with guide of theoretical predictions [1,2]. The material has two superconducting phases. One of the phases, called the "low-T_c phase", exhibiting T_c ~ 60 K at 150 GPa is obtained by compression exceeding 100 GPa at a low temperature around 200 K. The second phase, called the "high-T_c phase", exhibiting T_c ~ 200 K at 150 GPa, appears upon annealing the low-T_c phase at room temperature. Several theoretical groups proposed the crystal structures and the value of T_c in some sulfur hydrides H*x*S*y* under pressures [3-6]. According to the results of their theoretical calculation, it is considered that H_2S dissociates into H_3S and elemental sulfur through other stoichiometric compounds H*x*S*y*, and the H_3S which has cubic structure shows the high-T_c over 200 K [2-6]. Recently, the direct synthesis of H_3S from the mixture of H_2 and S has been reported from several groups [7,8], however, their transport properties and the formation process of superconducting phases of H_3S from H_2S were not experimentally clarified yet. Here we report our recent results of synchrotron x-ray diffraction with electrical resistance measurements on this formation process in sulfur hydride including the direct synthesis. Our results suggest that H_2S dissociates into H_3S and elemental sulfur under high pressure through metastable phases, and the high-T_c phase corresponds to theoretically predicted cubic-symmetric H_3S [9,10]. This work was supported by JSPS KAKENHI Grant Number 26000006.

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Potential high-T_c superconducting ternary hydrides at high pressure

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Search for high-temperature superconducting materials has been an important topic in the field of condensed matter physics. As the lightest element, hydrogen was predicted to be of very high-temperature superconductivity if it can be metallized. However, hydrogen still do not become metallic at the pressure achieved in experiment. In 2004, Ashcroft[1] proposed that the hydrogen-rich materials might become high-temperature superconductors at much lower pressures than that of hydrogen. This has stimulated extensive studies mainly on binary hydrides. Many hydrides are predicted to be superconductors with high T_c. Encouragingly, H_3S compressed from H_2S was observed to be a superconductor with a remarkably high T_c of 203 K, where the sulfur atoms form a very high-symmetry body centered cubic structure with the hdyrogen atoms located at the octahedral sites. Moreover, many other hydrogen-rich hydrides with high T_cs are predicted to be stable with the high-symmetry structures. For example, both CaH_6[2] and YH_6[3] take the same high-symmetry *Im*-3*m* structure and are predicted to have T_cs of 235 and 264 K at 150 and 120 GPa, respectively. GaH_3 is predicted to be stable with a *Pm*-3*n* sturcutre, which is also estimated to be a superconductor with a T_c of about 100 K at 120 GPa.[4] Unitl now, only a few studies have been taken on ternary hydrides.

Here, we take an extensive exploration on the ternary hydrides to search for the high-temperature superconductors with high-symmetry structures by using the particle swarm optimization technique implemented in the CALYPSO code[5,6]. It is found that both $CaYH_{12}$ and $GaScH_6$ can be stable in the high-symmetry strucutres at cetain pressure range. Moreover, electron phonon calculations revealed that $CaYH_{12}$ and $GaScH_6$ are potential high-temperature superconductors with T_c of 258 and 76 K at 200 GPa, respectively. Thus, high-symmetry structure plays a very important role in getting high values of T_c in hydrogen-rich materials.

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Single-orbital realization of high temperature s± superconductivity in the square-octagon lattice

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The remarkable s± superconductivity (SC) is well known in the iron-based superconductors, which are of multi-orbital characteristic. Here we propose a single-orbital realization of this intriguing pairing state with high superconducting critical temperature Tc in the square-octagon lattice, which is hosted by a few real materials. Owing to the perfect Fermi surface nesting at half-filling, arbitrarily weak Hubbard-interaction drives long-range spin-density wave (SDW) with Neel antiferromagnetic order. Such SDW order persists into the doped regime for finite Hubbard U, but with its wave-vector shifting linearly with doping concentration, leading into incommensurate SDW state. When such SDW order is killed by further doping or parameter-tuning, strong short-ranged spin fluctuations mediate unconventional SC with rich pairing phase-diagram. The largest portion of the phase-diagram is occupied by the s± SC, with high Tc. Moreover, we talk about possible pairing symmetry and magnetism in the related lattices.

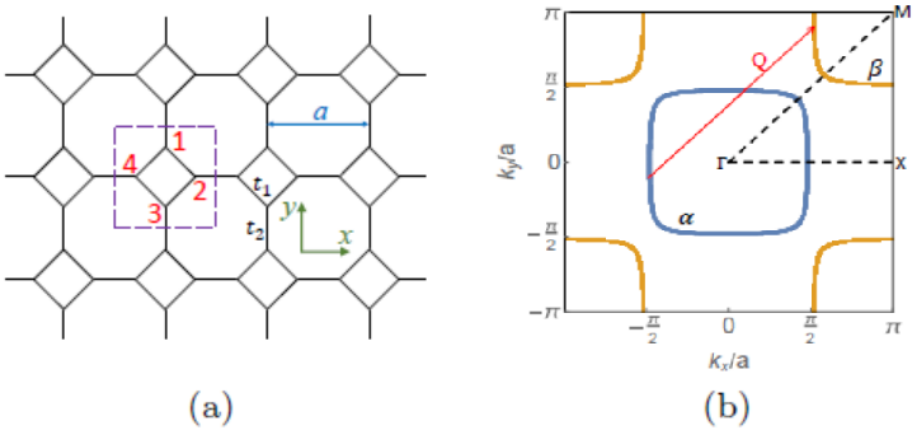

Fig. 1: (a) *Square-octagon lattice with hoppings t_1 and t_2.* (b) *Fermi surface for the undoped case.*

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Molecular orbital approach to electron phonon and pairing interactions in skipped valence and negative charge transfer gap Oxides

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In high oxidation state oxides like the trivalent Nickel oxides, tetravalent Co and Fe oxides as well as the parent superconductors BaBiO3 and SrBiO3 and High Tc hole doped cuprates, the cation electron affinity in the formal valence could end up larger than the O 2- ionization potential leading to a so called negative charge transfer gap. If the charge transfer energy is strongly negative, then we should really adopt starting electronic configurations such as Ni2+ rather than 3 + or Bi 3+ rather than 4+ with compensation holes in the O 2p valence band for charge neutrality. If in addition the lowest energy cation ionization states are strongly hybridized with the valence O 2p states the low energy scale electronic structure and be well described by a molecular orbital type of approach (1,2). This is a new approach to the Wannier function description (3) but with explicit inclusion of the O states which provides a natural path to inclusion of the electron phonon coupling, charge density wave formation, potential bipolaron formation and paring interactions in superconductors. We discuss recent developments in this approach and show that the effective electron phonon coupling involving these molecular like orbitals is much stronger than that estimated from density function approaches. We also show that this leads to Peierls like charge density wave like ground states and we describe how the electron phonon coupling involving the hopping integrals rather than the on-site energies evolves into a large effective attractive interaction between low energy scale electrons. The main contributors to this ongoing research are Arash Khazraie, Shadi Balandeh, Kateryna Foyevtsova, Ilya Elfimov, Oliver Yau Chuen Yam, Mona Berciu, and Steve Johnston.

1)Arash Khazraie,_ Kateryna Foyevtsova, Ilya El_mov, and George A. Sawatzky
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Thermodynamics of cuprate, hydride and all superconductors

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The physics of the complex phase diagram of the HTS cuprates is discussed in the light of thermodynamic measurements of the electronic specific heat. New data is presented for the system $YBa_2Cu_4O_8$ as being the canonical exemplar of an underdoped cuprate dominated by the presence of a pseudogap. We have also begun investigating $YSr_2Cu_3O_y$ where, due to the lattice compression resulting from substitution of Ba by Sr, the exchange interaction energy is some 60% higher than in the parent compound. The relative effects of J on the pseudogap and superconducting parameters are compared. We also explore the important role of superfluid density in fluctuations, as well as in the magnitude of the critical temperature and the critical current. In particular this work suggests that the record $T_c \approx 203$ K in sulphur hydride is already depressed some 10 K below its mean-field value due to amplitude fluctuations and fluctuations will play a greater, and ultimately restrictive, role in any new hydride systems with higher T_c values. Finally we demonstrate the universal role of superfluid density in the critical current density for all superconductors, irrespective of type, symmetry or material.

Ground-state order in the underdoped region of the 2D Hubbard model

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Wigner Electronic Crystallization as an Example of Local Field Influence on Superconducting Transition

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The BCS theory of superconductivity does not treat an inter-electron interaction perturbatively, and as a result we were able to establish that a new ground state - the superconducting state - of the system appears, and the properties of this new state are quite different from a normal metal. This is a common situation for a strongly interacting system - interactions between electrons lead to a formation of a new state of matter. In the standard theory the superconductivity occurs due to the quasiparticle attraction. Usually, it is connected to the electron-phonon interaction (*EPI*). In case of an isotropic and homogeneous system a weak (quasi)-particle interaction described by an effective potential $V_{eff}(\boldsymbol{q},\omega)$ ($\boldsymbol{q}$ is the momentum and ω is the frequency) in the leading approximation looks like as for two external (test) charges (e) embedded into the medium of a positive charged background via the total longitudinal dielectric function $\varepsilon_{tot}(\boldsymbol{q},\omega)$. Without vertex corrections we have the textbook expression $V_{eff}(\boldsymbol{q},\omega)=4\pi e^2/q^2\varepsilon_{tot}(\boldsymbol{q},\omega)=V_C(\boldsymbol{q})+W_{EPI}(\boldsymbol{q})+4\pi e^2/q^2\varepsilon_{el}(\boldsymbol{q},\omega)$, where $V_C(q)=4\pi e^2/q^2$ is a bare Coulomb interaction, $W_{EPI}(\boldsymbol{q})$ is a contribution due to vibrating ions, which gives the quasi-particle attraction, and the last term is connected to the electronic gas polarization effects. Whether this term helps to the superconductivity depends on the sign of the static electronic dielectric function $\varepsilon_{el}(\boldsymbol{q},0)$ (if it is negative, it can give an additional attraction) [1]. One of simple system with $\varepsilon_{el}(\boldsymbol{q},0)$ negative at any momentum $\boldsymbol{q}$ is the Wigner electron crystal (see, [2,1]).

It is known that in the case of the total localization the superconducting state cannot exist. Below we will consider the case of the partial localized case, when some part of electrons is localized into a Wigner crystal and the others are the itinerant (free) charges. This additional attraction can lead to an enhancement of the critical temperature of the superconducting transition T_c and to a nonmonotonical dependence of T_c on the localized fraction of the electron gas.

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Pairing origin of the pseudogap as observed in ARPES measurement in the underdoped cuprates

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We show that electron pairing is indispensable for the development of the leading edge gap as observed in ARPES measurement in the underdoped cuprates, even though clear evidence for the violation of the particle-hole symmetry is found in the electron spectrum. To support this assertion, we studied the electron spectrum under the scattering of diffusive antiferromagnetic(AF) spin fluctuation, which is thought to be a major candidate for a competing order in the competing order scenario of the pseudogap phenomena. We find that the Fermi level crossing in the anti-nodal region can only be avoided when the M=(π, 0) point is pushed above the Fermi level in this scenario. We argue that the same conclusion holds in all competing order scenarios that preserve the U(1) charge conservation. The inconsistency between this prediction and the ARPES observation implies that a competing order in the particle-hole channel alone is not sufficient to explain the pseudogap as observed in ARPES measurement. We also find that the electron system always forms a single large Fermi surface under the scattering of short-ranged dynamical spin fluctuation, rather than forming small Fermi pockets as predicted by the AF band folding picture. The AF shadow band is smeared out in energy as a result of the dispersion in the scattered quasiparticle state and the diffusion in spin fluctuation energy. Nevertheless, we find that the AF band folding effect is important for the understanding of the quasiparticle dynamics in the pseudogap phase, especially, of the origin of the high energy hump structure in the anti-nodal region and the signature of particle-hole asymmetry in the electron spectrum. It may even provide the driving force of the pseudogap phenomena, since the strong dressing of the anti-nodal quasiparticle by the AF spin fluctuation will greatly reduce the kinetic energy penalty for electron pairing in this region.

Interplay Between Superconductivity and Pseudogap in Cuprates

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Although high-T_c superconductivity has been discovered more than 29 years, the mechanism of superconductivity is not yet understood and raises fundamental questions [1]. My talk will be focus on the link betwen superconductivity and the pseudogap phase, its origin remains mysterious.

Our Raman spectroscopy study of a slightly underdoped single crystal of $HgBa_2Ca_2Cu_3O_8$ (Hg-1223) allowed us to observe that the superconducting pair-breaking peak is associated with a dip on its higher-energy side, disappearing together at T_c. This result reveals a key aspect of the unconventional pairing mechanism : spectral weight lost in the dip is transferred to the pair-breaking peak at lower energies. This conclusion is supported by cellular dynamical mean-field theory (CMDFT) on the Hubbard model, which is able to reproduce all the main features of the Raman response and explain the peak-dip behavior in terms of a nontrivial relationship between the superconductivity and the pseudogap [2]. We confirmed this result on others compounds revealing his universality.

We tracked this structure with doping on $Bi_2Sr_2CaCu_2O_8$ [3]; the pseudogap survives in the overdoped region and then disappears abruptly above p ~ 0.225. This disappearance coincides with a change of Fermi surface toplogy - Lifshitz transition - as revelead by our Raman and ARPES combined study [4]. This confirmed that the pseudogap cannot exist with an electron-like Fermi surface.

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BCS-like Pseudogap and Novel Isotope Effects in High-T_c Cuprate Superconductors

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We study the Cooper pairing of charge carriers without superconductivity in the normal state of high-T_c cuprates and the formation of a BCS-like pseudogap below a characteristic temperature T^*. The relevant charge carriers in these high-T_c materials are assumed to be polarons which are bound into bosonic Cooper pairs above T_c followed by condensing into a Bose superfluid at the superconducting transition temperature T_c. We determine the pseudogap formation temperature T^*, the T_c and novel isotope effects on T^* and T_c in various cuprate superconductors, from the underdoped to the overdoped regime. Our results for T^* and T_c, isotope shifts $\Delta T^*$and ΔT_c and isotope exponents α_{T^*} and α_{T_c} in high-T_c cuprates are in good agreement with the existing well-established experimental data. We argue that the polaronic effects and related pseudogap disappear in heavily overdoped cuprates (with $T^*= T_c$) and the isotope effects on T_c in these systems just like in conventional metals are positive ormay become even negative.

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In-plane Anisotropy of the Pseudogap Temperature in Underdoped Ultrathin $YBa_2Cu_3O_{7-\delta}$ Thin Films

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The microscopic origin of the properties of High T_c Superconductors (HTS) remains elusive 30 years after their discovery. Various symmetry breaking electronic ordering, such as charge density waves and nematicity, have been revealed in the underdoped region of the phase diagram, where the pseudogap dominates the normal state properties. The correlation lengths of these phenomena are in the nm-range; the study of HTS nanodevices can be instrumental for understanding the intertwining of the various orders and the superconducting state.

We have developed a fabrication method to obtain nanowires from untwinned $YBa_2Cu_3O_{7-\delta}$ films, which allows one to study transport properties as a function of hole doping and device dimensions. With this approach heavily underdoped nanowires keep the physical properties of the as-grown films[1].

Transport measurements of underdoped devices have revealed a remarkable in plane anisotropy of the pseudogap, see fig. 1. As the thickness is reduced to 10 nm, the pseudogap features gradually disappear at φ=90° (b-axis). This "unconventional" behavior of the pseudogap is most prominent at the 1/8 hole doping which points towards a common critical doping for the various nanoscale electronic orders in HTS.

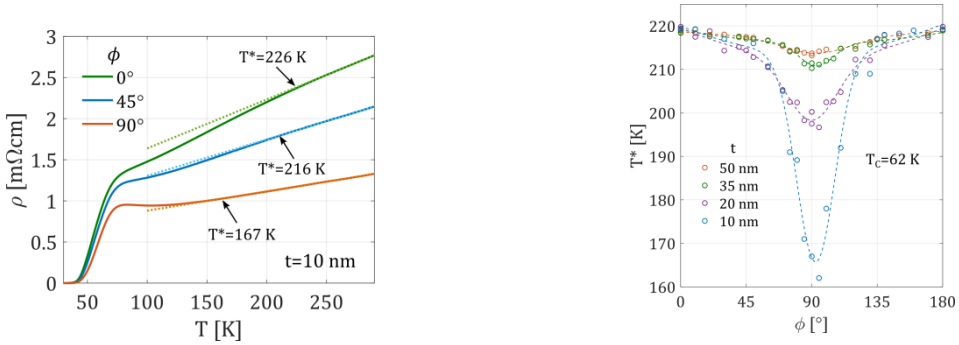

Fig. 1: *Left: Resistivity vs. temperature of 10nm thick devices oriented along the a-axis(ϕ=0°), diagonal(ϕ=45°) and b-axis(ϕ=90°). The extracted pseudogap temperature T* is given for each device. Right: Full in-plane angular dependence of T* for devices of different thickness ranging from 10-50 nm. Notice the suppression of T* along the b-axis.*

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Exotic Z2 Symmetry Breaking Transitions : theory of pseudo-gap transitions

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The Landau paradigm of phase transitions is one of the backbones in critical phenomena. With a Z_2 symmetry, it describes the Ising universality class whose central charge is one half (c = 1/2) in two spatial dimensions (2D). Recent experiments in strongly correlated systems, however, suggest intriguing possibilities beyond the Landau paradigm. We uncover an exotic universality class of a Z_2 symmetry breaking transition with c=1. It is shown that fractionalization of discrete symmetry order parameters may realize the exotic class. In addition to novel critical exponents, we find that the onset of an order parameter may be super-linear in contrast to the sub-linear onset of the Ising class. We argue that a super-linear onset of a Z_2 order parameter without breaking a bigger symmetry than Z_2 is evidence of exotic phenomena, and our results are applied to recent experiments in phase transitions at pseudo-gap temperatures.

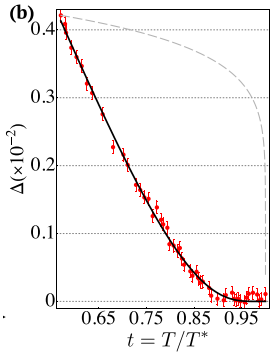

Fig. 1: *Order parameter onset of the proposed exotic Z2 transition. Data (red dots) fitting of the magneto-torque experiment [2] is presented. The dashed line is a typical onset of the Ising class.*

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Mode-coupling Model of Cuprate Pseudogap: Insights from New First-principles Results

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Response of the nematicity and superconductivity of FeSe to in-plane anisotropic strain

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By affixing thin single crystals of FeSe to rigid sample carriers and then applying uniaxial stress to the carrier, we apply in-plane uniaxial strains of up to ~0.3% to FeSe. Above the structural transition temperature T_s, anisotropic strain drives partial polarisation of the nematic order [1, 2], however at large strains the induced nematicity appears to saturate, and one can start to discern the intrinsic elastoresistivity of a single nematic domain. Below T_s, the extrinsic contribution to the resistivity from structural domain walls can be resolved, and by sweeping the strain at low temperature these domain walls can be annealed out of the sample. For strains below ~0.2%, the dependence of the critical temperature of the superconductivity on anisotropic strain is modest, but resolvable.

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Local orthorhombic lattice distortions in the paramagnetic tetragonal phase of superconducting $NaFe_{1-x}Ni_xAs$ Pengcheng Dai

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We use neutron scattering to measure the doping and temperature dependence of magnetic and nematic orders throughout the phase diagram of $NaFe_{1-x}Ni_xAs$. We find that while both static antiferromagnetic and nematic orders compete with superconductivity, the onset temperatures for these two orders remain well-separated approaching the putative quantum critical points. Using the high resolution provided by neutron Larmor diffraction, we find local orthorhombic distortions persist well above the tetragonal-to-orthorhombic structural transition temperature Ts in underdoped samples and extend well into the overdoped regime that exhibits neither magnetic nor structural phase transitions. These unexpected local orthorhombic distortions display Curie-Weiss temperature dependence and become suppressed below Tc, suggesting they result from a large nematic susceptibility near optimal superconductivity. Our results account for observations of rotational symmetry breaking above Ts in the tetragonal phase of iron pnictides, and attest to the presence of significant nematic fluctuations near optimal superconductivity.

Site-selective NMR evidence for spin nematic state in FeSe superconductors

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In FeSe superconductor, lattice rotational symmetry is spontaneously broken in a 'nematic' phase below T_{nem} ~ 90 K. Due to the absence of magnetic ordering, the origin of the nematic phase is under strong debate. Here, by measuring the splitting of both ^{57}Fe and ^{77}Se NMR spectra in ^{57}Fe enriched FeSe single crystal below T_{nem}, we revealed a remarkable in-plane anisotropy in local spin susceptibility, which only becomes substantial below T_{sn} ~ 75 K rather than immediately below T_{nem}. This result indicates that such spin anisotropy is beyond simple spin-orbital coupling to orbital order[1], suggesting a spin nematic state as that in LaOFeAs[2]. In addition, a prominent involvement of $3d_{xy}$ orbital to orbital order is also suggested by the present result, which is beyond previously proposed two-orbital model[1]. The present result brings crucial understanding on the nature of the electronic nematicity in FeSe.

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Nematic fluctuations and superconductivity in Iron-based Superconductors

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The most important aspect of the iron-based superconductors may be that they open a new landscape in which to study mechanisms of unconventional pairing that lead to high-T_c superconductivity. The high transition temperatures in both cuprates and iron pnictides cannot be explained theoretically by the conventional electron-phonon pairing mechanism, and thus there is almost complete consensus that the superconductivity of both systems has an unconventional origin. One of the key questions on the iron-based superconductivity is the relationship between the electronic nematicity and high-T_c superconductivity. Here I will discuss the nematic phases and their fluctuations in the phase diagrams of iron-based superconductors. In $BaFe_2As_2$-based superconductors, we find several pieces of evidence for the presence of the quantum critical point (QCP) of the antiferromagnetically ordered phase, where several anomalous properties have been observed [1]. However, the ordered phase also involves electronic nematicity, whose impact on the superconductivity is hard to be distinguished from that of magnetism. In contrast, one can tune nonmagnetic nematic QCP in FeSe-based superconductors [2]. The comparisons between phase diagrams of these two systems [1-4], the relationship between nematicity and superconductivity will be discussed.

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Evidence of nematic electronic state and nodal superconducting gap along [110] direction in $RbFe_2As_2$

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Unconventional superconductivity often intertwines with various forms of order, such as the "nematic" order which breaks the rotational symmetry of the lattice. Investigation of these ordered phases sheds crucial light on the superconductivity itself. Here we report a low-temperature scanning tunneling microscopy (STM) study on $RbFe_2As_2$, a heavily hole-doped Fe-based superconductor (FeSC). We observe significant symmetry breaking in its electronic structure and magnetic vortex which differentiates the (π, π) and (π, -π) directions. It is thus a novel nematic state, distinct from the nematicity of undoped/lightly-doped FeSCs which breaks the (π, 0) / (0, π) equivalence. Moreover, we observe a clear "V"-shaped superconducting gap which can be well fitted with a nodal gap function. The gap is found to be suppressed on surface Rb vacancies and at step edges, and particularly strong at the [110]-oriented edges, which is possibly due to a d_{x2-y2} like pairing component with nodes along diagonal directions. Our results highlight the intimate connection between nematicity and superconducting pairing, and promote a universal understanding of them [1].

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Singular magnetic anisotropy in the nematic phase of FeSe

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FeSe is one of simplest, yet one of the most enigmatic superconductors. Its superconducting phase emerges from a nematic but non-magnetic ground state, which is unprecedented in iron-based superconductors and thus stands as a puzzle. Here, using nuclear magnetic resonance in mechanically detwinned single crystals, we show that the in-plane anisotropy of both the uniform spin susceptibility χ_{spin} and the spin-lattice relaxation rate $1/T_1$ is opposite to that in the nematic state of iron pnictides such as LaFeAsO and $BaFe_2As_2$. This observation challenges the current understanding of magnetic correlations in FeSe ant it places stringent constraints on the origin of spin-space anisotropy as well as on the structure of the spin-fluctuation spectrum as a function of energy and momentum.

Topological superconductor and Majorana fermions in the vortex

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Majorana fermion (MF) whose antiparticle is itself has been predicted in condensed matter systems. MFs can be used in fault-tolerant quantum computation relying on their non-Abelian braiding statistics, therefore, lots of efforts have been made to find them. Signatures of the MFs have been reported as zero energy modes in various systems. As predicted, MF in the vortex of topological superconductor appears as a zero energy mode with a cone like spatial distribution. Also, MF can induce spin selective Andreev reflection (SSAR), a novel magnetic property which can be used to detect the MFs. Here, I will show you that the $Bi_2Te_3/NbSe_2$ hetero-structure is an artificial topological superconductor and all the three features are observed for the MFs inside the vortices on the $Bi_2Te_3/NbSe_2$. Especially, by using spin-polarized scanning tunneling microscopy/spectroscopy (STM/STS), we observed the spin dependent tunneling effect, which is a direct evidence for the SSAR from MFs, and fully supported by theoretical analyses. More importantly, all evidences are self-consistent. Our work provides definitive evidences of MFs and will stimulate the MFs research on their novel physical properties, hence a step towards their statistics and application in quantum computing.

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Spectroscopic evidence of two distinct chiral topological superconducting phases in a heterostructure of a superconductor and a quantum anomalous Hall insulator

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The quantum anomalous Hall insulator (QAHI) exhibits conducting quantum Hall edge states even in zero field. If superconductivity (SC) is introduced by the proximity effect, two different topological superconducting phases with one or two chiral Majorana edge modes with Chern numbers N = 1 and 2 were predicted [1]. Recent experiments on a SC / QAHI heterostructure revealed integer and half-integer quantized plateaus in the conductance over a deposited SC strip as evidence of these superconducting QAHI states [2]. We provide spectroscopic evidence for a superconducting QAHI state using point contacts at the edge of a SC / QAHI heterostructure with clear fingerprints of two topological superconducting phases. The phase with N=1 occurs in a narrow field regime during the magnetization reversal just before the QAHI enters its trivial insulating state.

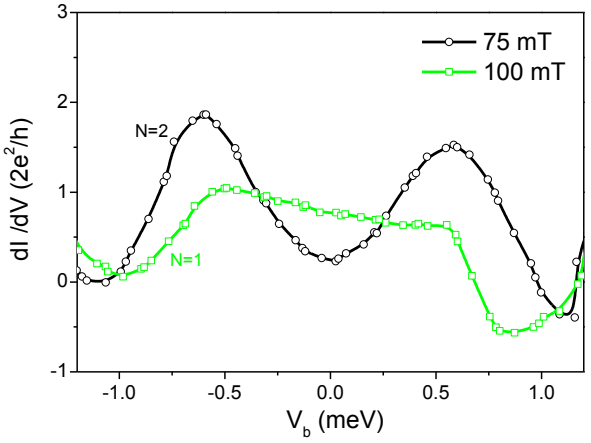

Fig. 1: *Differential conductance of an edge point contact of a* $(Cr_{0.12}Bi_{0.26}Sb_{0.62})_2Te_3$ */ superconductor heterostructure at 15 mK. A dip surrounded by two coherence-like peaks mark the N = 2 topological superconducting state (75mT), while the flat plateau is attributed to the N = 1 state (100mT).*

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Topological Larkin-Ovchinnikov phase and Majorana zero mode chain in bilayer superconducting topological insulator films

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We theoretically study bilayer superconducting topological insulator film, in which superconductivity exists for both top and bottom surface states. We show that an in-plane magnetic field can drive the system into Larkin-Ovchinnikov (LO) phase, where electrons are paired with finite momenta. The Larkin-Ovchinnikov phase is topologically non-trivial and characterized by a Z2 topological invariant, leading to a Majorana zero mode chain along the edge perpendicular to in-plane magnetic fields.

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Quantization of Chiral Majorana Fermions: Quantum Transport and Interference

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In a quantum anomalous Hall insulator coupled to an s-wave superconductor, the surface Dirac fermion at the interface forms a p_x+ip_y superconductor, which accommodates one-dimensional chiral Majorana fermion modes propagating along the edges when the topological order is carefully controlled. Experimental signatures of this mode is captured by the magneto-electric transport measurements in a hybrid system of a quantum anomalous Hall insulator [Cr-doped $(Bi,Sb)_2Te_3$] thin film partially capped by a superconductor layer (Nb). The external magnetic field serves as a "knob" to tune the system into different topological regimes that allow the degenerate and non-degenerate propagation of Majorana edge modes. This tuning was signified as quantized conductance transitions among e^2/h, $0.5e^2/h$, and 0 as the external magnetic field was swept, which correspond to the topological superconducting phases with Chern numbers of 2, 1, and 0. This phase transition was recently further investigated by the edge tunneling spectra, which show the interference signature of the chiral Majorana fermions. When the Chern number is odd, the single chiral Majorana fermion contributes to a tunneling conductance quantized to $2e^2/h$. Otherwise conductance dips appear, which is attributed to the destructive interference of the degenerate Majorana fermions.

Spotting the Elusive Majorana in Atomic Chains Under the Microscope

Ali Yazdani

Princeton University

Ettore Majorana famously considered that there may be fermions in nature that are their own antiparticle — and then he mysteriously disappeared just after proposing the idea in 1938. In recent years, we have learned how to engineer materials that harbor quasiparticles that behave similar to fermions Majorana had envisioned. In particular, there has been a focus on one-dimensional topological superconductors that harbor Majorana zero modes (MZMs) that can potentially be used to make fault-tolerant topological quantum computation possible. Recently, we have proposed and implemented a platform for realization of topological superconductivity and MZMs in chains of magnetic atoms on the surface of a superconductor [1,2]. In this talk, I will describe this platform and the series of experiments we have performed to establish the presence of these exotic quasiparticles using spectroscopic mapping with the STM.[2-4] These include a recent study of the unique spin signature of MZM.[4] Finally, if there is time I will describe some ongoing experiments on realization of MZMs in a platform based on chiral quantum spin Hall edge states.

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Majorana Multiplexing

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Time-quasiperiodic Majoranas are generalizations of Floquet Majoranas in time-quasiperiodic
superconducting systems. We show that in a system driven at *d* mutually irrational frequencies, there are up to 2^d types of such Majoranas, coexisting despite spatial overlap and lack of time-translational invariance. Although the quasienergy spectrum is dense in such systems, the time-quasiperiodic Majoranas can be stable and robust against resonances due to localization in the periodic-drives induced synthetic dimensions. This is demonstrated in a time-quasiperiodic Kitaev chain driven at two frequencies. We further relate the existence of multiple Majoranas in a time-quasiperiodic system to the time quasicrystal phase introduced recently. These time-quasiperiodic Majoranas open a new possibility for braiding which will be pursued in the future.

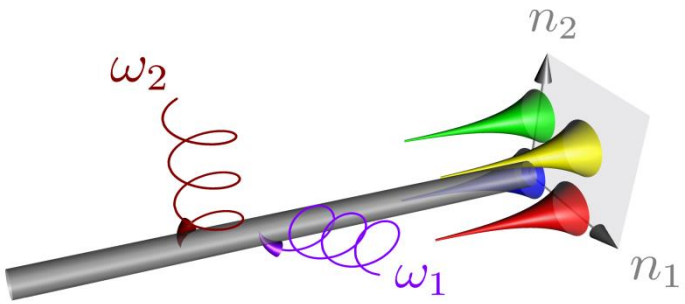

Fig. 1: *Schematic representation of time-quasiperiodic Majoranas localized at the end of a 1D topological superconductor (in grey) driven at two frequencies ω 1 and ω 2 . These Majoranas are localized in both real space and the two synthetic dimensions with coordinates n_1 and n_2 .*

The nature of correlations in the insulating states of twisted bilayer graphene

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Unexpected insulating states have been recently observed upon doping a graphene bilayer with a small twist angle [1]. The stacking misorientation creates a moire pattern with a superlattice modulation corresponding to thousands of atoms per unit cell. The insulating states arise when the charge per moire cell is ±2 with respect to the charge neutrality point and are believed to be due to electronic correlations [1]. Superconductivity, most probably unconventional, emerges from the insulating state with two holes per moire cell [2]. Understanding the nature of the insulating state is key to uncover the origin of the superconductivity.

In order to clarify the nature of the correlations which produce the insulating behavior we have compared the experimental observations with the properties of Mott insulating states [3]. Specifically we have focused on a two-orbital Hubbard model on a honeycomb lattice. We show that the theoretical expectations from local correlations are not compatible with the experimental properties of the insulating states with temperature and magnetic field. Even if the interactions are restricted to those electrons which are on the same site, correlations between the electrons in different sites appear. We argue that the inclusion of these non-local correlations in the description can reverse the predictions for the magnetic and temperature dependencies. These non-local correlations also have consequences for the critical interactions and could produce pseudogap physics.

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Wigner Crystallization in lieu of Mottness in Twisted Bilayer Graphene

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A new chapter in graphene and superconductivity research unfolded recently by the surprising discovery that sheets of graphene, when twisted at certain angles, provide a perfect playground for studying strong-correlation physics, including superconductivity. Although, the electronic properties of each graphene-layer can essentially be described by non-interacting physics, in a twisted bilayer graphene the kinetic energy of the electrons is heavily quenched, causing the interactions to dominate, and thus exhibiting a metal-insulator transition. Current experimental and theoretical works argue for such a transition to be of Mott character; however we point to some key aspects of the experiments that render Mottness contentious. We envisage an alternative possibility for this correlated insulator, namely Wigner crystallization, a crystal formed with localized electrons. In light of this possibility, we discuss the current experiments. We also argue that the observed superconductivity originates by melting (doping) this Wigner crystal.

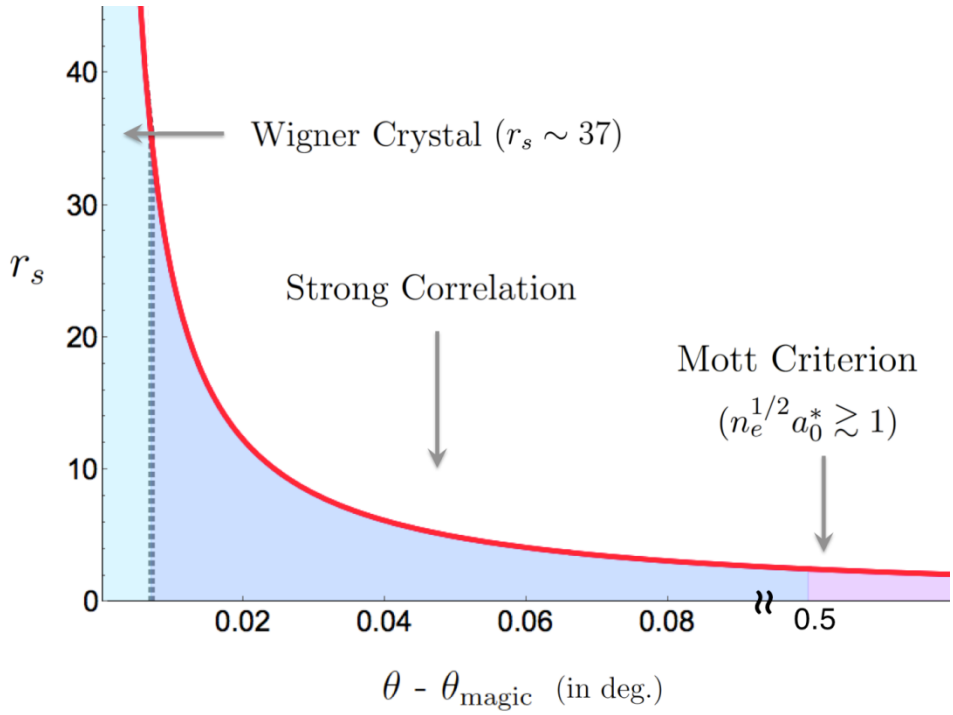

Fig. 1: *We plot the dimensionless density as a function of twist angle. Close to the magic angle r_s is very large, paving way for Wigner crystallization. Using Mott criterion one can see that Mott physics arises significantly away from the Magic angle.*

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Superconducting graphene

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Graphene is a single-atomic carbon sheet with hexagonal lattice, exhibiting a variety of amazing properties absent in and/or superior to the mother material, graphite. Graphene has a stronger tensile strength than steel while it is lighter than paper, being waterproofed, transparent, and flexible against bending, and has thermal conductivity higher than copper. The most spectacular property of graphene is the involved ballistic electron with very high mobility forming the Dirac-cone state. However, even this wonder material lacks only one but very important property essential for making this material a real wonder material. That is superconductivity. No or very few reports have been made on the emergence of superconductivity in graphene or graphene compounds.

In this talk, we report the first success of fabrication of superconducting bilayer graphene and the characterization of electronic states by angle-resolved photoemission spectroscopy (ARPES) [1] and 4-point-probe (4PP) method [2]. Figure 1 shows a schematic view of Ca-intercalated bilayer graphene (C6CaC6) which we fabricated with several well-controlled steps. Figure 2 shows the band structure near the Fermi level at the point for C6LiC6 and C6CaC6, where we clearly see a free-electron-like parabolic band (called interlayer band) only in C6CaC6, while and * bands are commonly seen in both samples. Figure 3 shows the temperature dependence of resistivity for C6CaC6, which clearly shows that the superconducting transition takes place at around 4 K. We did not observe such transition in pristine or Li-intercalated bilayer graphene. These results indicate that the interlayer band is essential for the occurrence of superconduct in intercalated graphene.

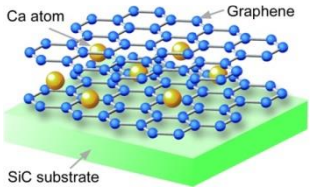

Fig. 1: *Schematic view of Ca-intercalated bilayer graphene*

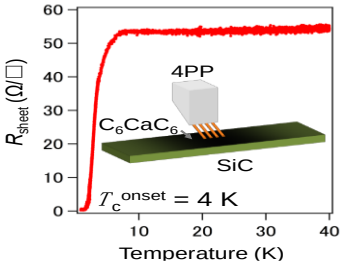

Fig. 3: *Temperature dependence of resistivity for C6CaC6*

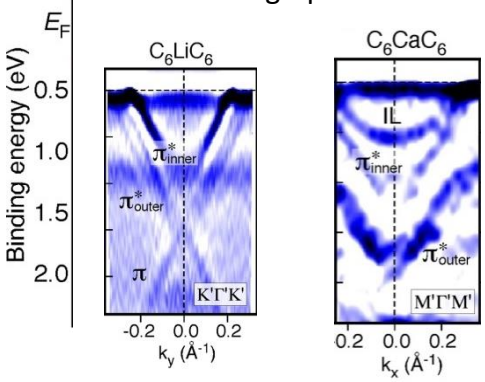

Fig. 2: *Band structure near EF around Γ point for C6LiC6 (left) and C6CaC6 (right)*

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Hubbard Model, Unconventional Superconductivity and Density Waves in Twisted Bilayer Graphene

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We study the twisted bilayer graphene where unconventional superconducting and correlated insulating phases are recently discovered at the filling of n=2 electrons per supercell. In the strong-coupling point of view, we obtained the effective tight-binding model and hence Hubbard model for the lowest four minibands, by constructing the maximally-localized Wannier orbitals which preserve required symmetries. In the weak-coupling point of view, we study electronic ordering instabilities at n=2, motivated by the Fermi surface nesting and the proximity to Van Hove singularity. We find d/p-wave superconductivity and charge/spin density wave emerge as the two types of leading instabilities driven by Coulomb repulsion. The density wave state has a gapped energy spectrum at n=2 and yields a single doubly-degenerate pocket upon doping to n>2. The intertwinement of density wave and superconductivity, and the quasiparticle spectrum in the density wave state are consistent with experimental observations.

Chiral SDW and d + id Superconductivity in the Magic-angle Twisted Bilayer-graphene

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We model the newly synthesized magic-angle twisted bilayer-graphene superconductor with two $p_{x,y}$-like Wannier orbitals on the superstructure honeycomb lattice, where the hopping integrals are constructed via the Slater-Koster formulism. The characteristics exhibited in this simple model are well consistent with both the rigorous calculations and experiment observations. Then, with repulsive Hubbard interactions turning on, we performed random-phase-approximation (RPA) based calculations to identify the electron instabilities. As a result, we find chiral d + id topological superconductivity bordering the correlated insulating state near half-filling, identified as noncoplanar chiral spin-density wave ordered state, featuring quantum anomalous Hall effect. The phase-diagram obtained in our approach is qualitatively consistent with experiments.

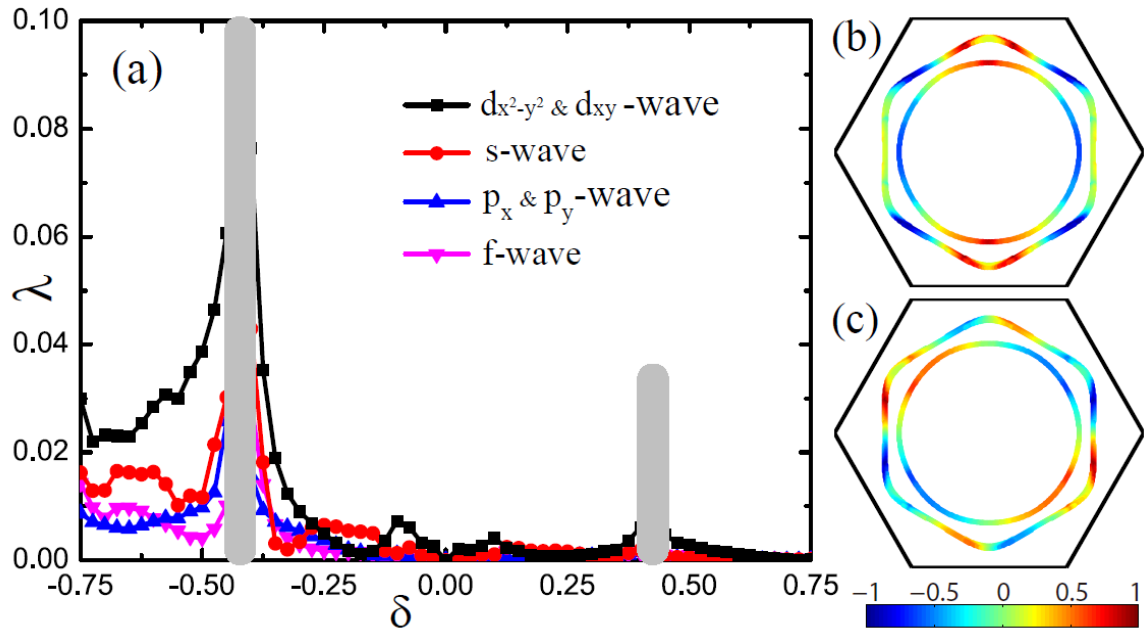

Fig. 1: *(a) The filling dependence of the largest eigenvalues λ for all pairing symmetries, which can also be taken as the phase diagram. The vertical bold grey lines indicate the SDW regime. (b) and (c) are the gap form factors of $d_{x^2-y^2}$ and d_{xy}-wave symmetries near half- filling , respectively.*

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Effects of Electron-Electron Interactions in Twisted Bilayer Graphene at Magic Angle: Spin-Density-Waves and Conductivity

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We theoretically study the effects of electron-electron interaction and possible ground states of twisted bilayer graphene (tBLG) at the so called first magic angle θ_c(~1-2 ?)[1]. Recently it has been shown that the bilayer graphene at this angle possess a number of very intriguing properties, such as Mott insulating states and superconductivity[2,3]. It is known that for angles $\theta>\theta_c$ the tBLG has a Dirac spectrum with renormalized Fermi velocities. Below θ_c no more Dirac cones exist, and the system has 4 almost degenerate flat bands. Each of these bands, are doubly degenerate on electron spin. In our study, starting from tight-binding model with screened Coulomb interaction, we introduce multicomponent exciton-plus-SDW order parameter of the form: $\Delta_{nia}^{mjb} = V\left(r_n^{ia} - r_m^{jb}\right)\langle d_{nia\uparrow}^{+} d_{mjb\downarrow}\rangle$ (1)
Optimization of such an order parameter using mean-filed scheme allows us to calculate the electronic spec-trum and the dc conductivity. The latter cor-relates very well with recent expe-rimental obse-rvations [3].

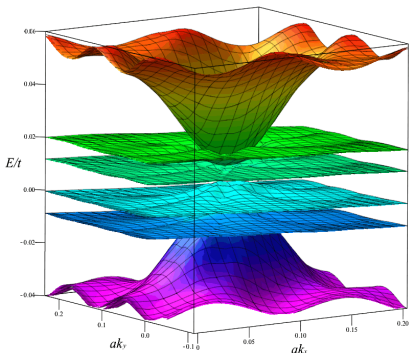

Fig. 1. Low-energy spectrum of tBLG.

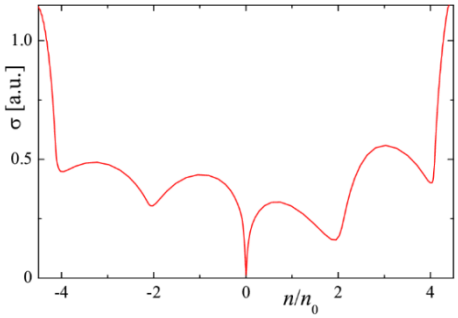

Fig. 2. DC conductivity of tBLG along the bilayer (cf. with Fig2a in [3]). SDW order.

Note, that if we keep only on-site terms in (1), we never obtain sat-llite deeps experi-mentally observed at doping level[2,3] $n/n_0=\pm2$, where n_0 is the maximum number of electron per unit cell occupied flat bands. We show that the central deep in the dependence of conductivity on doping is due to on-site terms in multi-component order parameter, in agreement with recent theoretical studies [4]. We show also that satellite deeps in conductivity are due to the formation exciton-plus-SDW ground state of tBLG. The excitons couple charge carriers living in different layers. Such kind of excitons were recently predicted by our group for bilayers with $\theta>\theta_c$ [5]. This work is partially supported by Russian Foundation for Basic Research project No. 17-02-00323, JSPS-RFBR grant No. 17-52-50023.

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Dynamics of the Meissner Effect: How Superconductors Expel Magnetic Fields

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The Meissner effect presents us with a fundamental puzzle that has surprisingly not been noticed before: *how is the mechanical momentum of the supercurrent that expels the magnetic field compensated, so that momentum conservation is not violated?*
The only possible answer is, the body as a whole has to acquire equal and opposite momentum to the one developed by the supercurrent. In a cylindrical geometry, the supercurrent has mechanical angular momentum *parallel* to the applied magnetic field, hence the body has to acquire angular momentum *antiparallel* to the applied field. How does that happen?
The Faraday electric field that develops in the process of magnetic field expulsion transmits angular momentum to the body in the wrong direction, *parallel* to the magnetic field, of magnitude that is many orders of magnitude too large. How does the body manage to ignore this enormous Faraday torque and rotate in the opposite direction?
Any momentum transfer between electrons and the body as a whole has to occur without entropy generation since the transition is thermodynamically reversible. This excludes scattering processes involving impurities or phonons, that generate entropy.
The theory of hole superconductivity [1] explains this puzzle [2]. The explanation relies on the facts that within this theory (a) normal metals becoming superconducting expel electrons from the interior to the surface [3], and (b) the normal state charge carriers are necessarily holes [4].
The conventional theory of superconductivity does not have those physical ingredients, hence we argue that it cannot explain this puzzle. Therefore we argue that superconducting materials described by the conventional theory of superconductivity would either (i) not expel magnetic fields or (ii) violate momentum conservation. Consequently, they don't exist.
The alternative theory of hole superconductivity explains superconductivity as arising through pairing of hole carriers driven by lowering of kinetic energy [5], predicts that superconductors have inhomogeneous macroscopic charge distribution with more negative charge near the surface and more positive charge in the interior [3], and that a spin current flows near the surface in the absence of applied fields [6]. It also provides guidelines for the search for new and better superconducting materials.

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Recent development in spin superconductor

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We propose the concept of the spin superconductor (SSC), a counterpart to the charge superconductor. We carry out theoretical study to show the existence of a spin superconductor in a ferromagnetic graphene, in which the spin-polarized electron-hole excitons play the roles of the `Cooper' pairs. We present a BCS-type theory and the Laudau-Ginzburg theory for the SSC. With the ``London-type equations" of the super-spin-current density, we show the existence of an electric ``Meissner effect" against a spatial varying electric field. We further study a SSC/normal conductor/SSC junction and predict a spin-current Josephson effect. Recent experimental results showing spin superconductor in canted antiferromagnetic Cr2O3 via nonlocal spin transport will be reported.

Bulk Topological Superconductors, Gap Structure, and Effect of Electron Scattering

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Doped topological insulators such as Bi_2Se_3 represent to date the most promising basis for the realization of bulk topological superconductors. Such topological superconductors may serve as platform for quantum computing utilizing the non-Abelian braiding statistics of Majorana zero modes. Here, we present studies of the thermodynamic, magneto-transport and structural characteristics of $Nb_xBi_2Se_3$ and $Sr_xBi_2Se_3$. The results of specific heat and magnetization measurements show that superconductivity in these materials is a bulk property. Both display a surprisingly large two-fold in-plane asymmetry of the superconducting state, which is not expected considering their trigonal crystal structure. Synchrotron x-ray diffraction shows no distortions from the ideal crystal structure, Fig. 1 [1]. The results can be accounted for in a model of a topological odd-parity nematic superconducting E_u state. Indeed, the low-temperature variation of the penetration depth and the robustness against electron scattering give evidence for the nematic nodal $_{4x}$ gap structure.

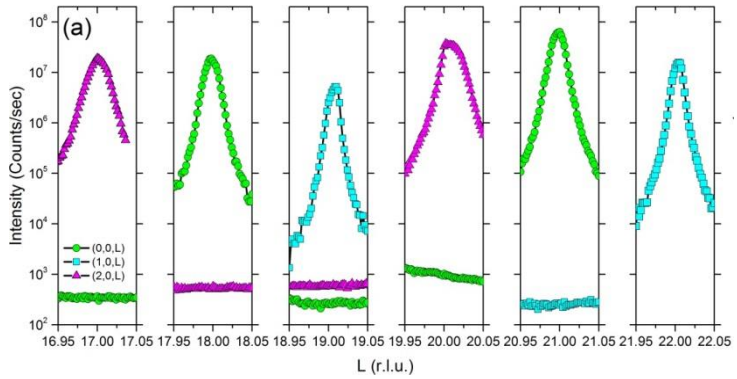

Fig. 1: Scans centered at (h,k,l) for multiple values of l on a $Sr_{0.1}Bi_2Se_3$ crystal. Multiple values of h are shown; h = 0 (green circles), h = 1 (blue squares), h = 2 (pink triangles). The trigonal structure enforces extinction unless 2h+k+l = 3n , where n is an integer. The allowed peaks show approximately 5 orders of magnitude more intensity than at l values that are not allowed, showing that any distortions away from an ideal trigonal crystal structure are exceedingly small.

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Quasiparticle interference and strong electron-boson coupling in Sr2RuO4

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The single-layered ruthenate Sr2RuO4 has attracted a great deal of interest as a spin-triplet superconductor with an order parameter that may potentially break time reversal invariance and host half-quantized vortices with Majorana zero modes. While the actual nature of the superconducting state is still a matter of controversy, it has long been believed that it is condensed from a metallic state that is well described by a conventional Fermi liquid. In this talk I will show high resolution Fourier transform scanning tunneling spectroscopy (FT-STS) measurements on Sr2RuO4. We use a combination of FT-STS and momentum resolved electron energy loss spectroscopy (M-EELS) to probe interaction effects in the normal state of Sr2RuO4. Our high-resolution data show signatures of the β-band with a distinctly quasi-one-dimensional (1D) character. The band dispersion reveals surprisingly strong interaction effects that dramatically renormalize the Fermi velocity, suggesting that the normal state of Sr2RuO4 is that of a `correlated metal' where correlations are strengthened by the quasi 1D nature of the bands. In addition we observe kinks at energies of approximately 10meV, 38meV and 70meV are observed. I will discuss
comparisons with M-EELS data, which show that the two higher energy features arise from coupling with collective modes. As time permits I will also show preliminary STM data below Tc. The strong correlation effects and the kinks in the quasi 1D bands may have important implications for the superconducting state.

Reformulating Supercurrent Generation in Superconductors

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Recent developments in condensed matter physics theory point to a necessity for reformulating supercurrent generation mechanism in superconductors. The first impetus comes from a misfit that exists between the experimentally observed ac Josephson effect and the Josephson's prediction [1,2]. Actually, there is a significant difference in boundary conditions between the Josephson's derivation and the experiment. The Josephson's derivation assumes a simple appearance of a dc voltage across the Josephson junction; however, a dc voltage does not appear by a simple application of a dc voltage; instead, when a dc voltage is applied, a dc Josephson effect takes over, resulting in a zero voltage across the junction. In the experimental situation where a finite voltage exists, there also exist a radiation field and a dc current flow. If the ac frequency is obtained in this situation with carefully taking into account the gauge invariance, an extra contribution for the ac frequency arises. By including this extra contribution, there are two contributions; one from the chemical potential difference between the leads connected to the junction, and the other from the electric field in the non-superconducting region between the two superconductors in the junction. Their contributions are equal due to the balance between the voltage and chemical potential difference. By taking into account the two contributions and also the fact that $\dot{\varphi}$=2eV/$\hbar$ is observed experimentally, the charge on the charge carriers is $q = -e$ [1,2]. This indicates that the electron pairing is not the true cause of the supercurrent generation, although the pairing energy gap formation temperature is the superconducting transition temperature for many superconductors (but not for cuprates).

We show that the supercurrent generation can be attributed to the occurrence of spin-twisting circular motion of electrons. For the superconductors where Tc is calculated by BCS theory,

such a motion arises if the Rashaba interaction is included in the presence of magnetic field; it modifies the electron pairing from the original BCS one to the pairing of spin-twisting cyclotron motion states in the region where the magnetic field is present [3]. For cuprate superconductors, the spin-twisting loop current motion is realized as the spin-vortex-induced loop current (SVILC) [4]; Tc for the cuprate superconductor is given as the stabilization temperature of the SVLCs [5]. The common feature of the above two cases is that the energy minimizing wave function becomes multi-valued function with respect to electron coordinates due to the spin-twisting circular motion. In this case, the legitimate single-valued ground state wave function is given as a product of the energy minimizing multi-valued wave function and a U(1) phase factor that compensates the multi-valuedness of the former. This phase factor provides a U(1) instanton. Then, the persistent current generation, flux quantization, and voltage quantization are explained as topological effects of this U(1) instanton [6].

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Pair density wave as the mother state of the pseuo-gap in Cuprates.

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Four years ago, we proposed that a fluctuating pair density wave (PDW) can explain many of the phenomenology associated with the pseudogap physics in underdoped Cuprates. [1] The PDW order is a superconductor with a finite period, ie, the Cooper pairs have finite wave-vector P and –P. While fluctuations destroy the long range order of the PDW, a charge density (CDW) with wave-vector Q=2P can be stabilized, in agreement with experimental observations. A recent scanning tunneling microscopy (STM) experiment [2] reports the observation of CDW with period of approximately 8a in the halo region surrounding the vortex core, in striking contrast to the approximately period 4a CDW that are commonly observed in the cuprates. This striking observation is consistent with a period 8a PDW co-existing with the d-wave superconductor, thus provides strong support for the presence of the PDW. Inspired by this work, we study a model where a bi-directional pair density wave (PDW) with approximately period 8a is at play. We explore the possibility that the PDW is the primary order, the so called “mother state” that persists with strong phase fluctuations to high temperature and high magnetic field and lies behind the pseudogap phenomenology. We study the charge density wave structures near the vortex core in this model. We emphasize the importance of the phase winding of the d-wave order parameter. The PDW can be pinned by the vortex core due to this winding and become static. Furthermore, the period 8 CDW inherits the properties of this winding, which gives rise to a special feature of the Fourier transform peak, namely, it is split in certain directions. There are also a line of zeros in the inverse Fourier transform of filtered data. We propose that these are key experimental signatures that can distinguish between the PDW-driven scenario from the more mundane option that the period 8 CDW is primary. Finally we attempt to place the STM experiment in the broader context of pseudogap physics of underdoped cuprates and relate this observation to the unusual properties of X ray scattering data on CDW carried out to very high magnetic field.

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Evolution of pair density waves from superconducting to pseudogap phases in copper oxide superconductors

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One of the most puzzling problems of high temperature superconductors lies on the relation between the low temperature superconducting (SC) phase and its higher temperature pseudogap phase when superconductivity disappears. Here we present a renormalized mean-field theory to treat the strongly-correlated t-t'-J model for cuprates. We found a particular kind of incommensurate unidirectional pair density wave (PDW) solution that involves modulation of pairing order, the charge density and also the form factor. This state with all three orders intertwined can have an additional uniform pairing order at low temperatures and shows two d-wave like SC gaps. When we extend the calculation to finite temperatures, this PDW solution is evolved into a state without this uniform pairing order and one of the two gaps closes and becomes Fermi arcs with a finite density of states. The temperature and doping dependence of these gaps and arcs, as well as several other spectra anomalies, are in very good agreement with experiments. Possible experiments to identify these PDW states are discussed. This could provide a new step towards understanding of the high temperature superconductor.

Pair Density Waves and Intertwined Orders in High T_c Superconductors

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I will argue that the orders that are found in the phase diagrams of high temperature superconductors naturally arise with the same strength and should better regarded as intertwined rather than competing. I illustrate this concept in the context of the orders that are present in the pair-density-wave state and the phase diagrams that result from this analysis. [1,2]

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Atomic-Scale Andreev Reflection

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Andreev reflection (AR) is a fundamental particle-hole conversion process that governs current transmission across superconductor/normal-conductor (S/N) interfaces. By virtue of its dependence on spin, momentum and time-reversal invariance, AR can be used to study a host of basic properties, ranging from the spin polarization of itinerant ferromagnets to the pairing symmetry of unconventional superconductors. Traditionally, the spatial resolution of AR measurements is limited by the need for high-transparency S/N contact, in order that the transmission probability of AR outweighs that of quasiparticle tunneling. Recent studies using quantum point contacts have achieved AR through just a few Landauer conductance channels. In this talk, I will report on progress of extending AR measurements into the non-contact regime, by exploiting the resonant nature of AR for *d*-wave pairing symmetry, and towards demonstrating atomic-scale AR via both scanning topography and conductance spectroscopy.

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Magnetic-field Induced Pair Density Wave State in the Cuprate Vortex Halo

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When very high magnetic fields suppress the superconductivity in underdoped cuprates, an exceptional new electronic phase appears. It supports remarkable and unexplained quantum oscillations and exhibits an unidentified density wave (DW) state. Although generally referred to as a 'charge' density wave (CDW) because of the observed charge density modulations, theory indicates that this could actually be the far more elusive electron-pair density wave state (PDW). To search for evidence of a field-induced PDW in cuprates, we visualize the modulations in the density of electronic states $N(r)$ within the halo surrounding $Bi_2Sr_2CaCu_2O_8$ vortex cores. This reveals multiple signatures of a field-induced PDW, including two sets of $N(r)$ modulations occurring at wavevectors Q_P and $2Q_P$, both having predominantly *s*-symmetry form factors, the amplitude of the latter decaying twice as rapidly as the former, along with induced energy-gap modulations at Q_P. Such a microscopic phenomenology is in detailed agreement with theory for a field-induced primary PDW that generates secondary CDWs within the vortex halo. These data indicate that the fundamental state generated by increasing magnetic fields from the underdoped cuprate superconducting phase is actually a PDW with approximately eight CuO_2 unit-cell periodicity (=8a_0) and predominantly *d*-symmetry form factor.

Numerical evidence of fluctuating stripes in high-T_c cuprate superconductors

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Upon doping, Mott insulators often exhibit symmetry breaking where charge carriers and their spins organize into patterns known as stripes. For high-T_c superconducting cuprates, stripes are widely suspected to exist in a fluctuating form. Here, we present numerically exact determinant quantum Monte Carlo calculations that demonstrate dynamical stripe correlations in the three-band Hubbard model, which represents the local electronic structure of the Cu-O plane. Our results, which are robust to varying parameters, cluster size, and boundary condition, strongly support the interpretation of a variety of experimental observations in terms of the physics of fluctuating stripes, including the hourglass magnetic dispersion and the Yamada plot of incommensurability vs. hole doping. These findings provide a novel perspective on the intertwined orders emerging from the cuprates' normal state.

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Spin-orbit coupling and preferred magnetic excitations in iron-based superconductors

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In this talk, I will present our inelastic neutron scattering (INS) efforts to determine low-energy spin excitations in a variety of iron-based superconductors, in which spin-orbit coupling leads to anisotropic response in spin space. In BaFe(2)As(2) and FeSe(1-x)S(x) regardless of whether long-range magnetic order is present at low temperatures, we show that the magnetic excitations are preferentially polarized along the c-axis, and that the anisotropy gradually diminishes upon sulfur doping in the latter towards the nematic critical point. In Sr(1-x)Na(x)Fe2As2, we find the first spectroscopic evidence that the itinerant charge carriers actually "prefer" to be assisted by c-axis polarized magnetic excitations in their formation of superconducting Cooper pairs. Between this material's orthorhombic and tetragonal magnetic phases, our data indicate that the main spectral difference occurs only at low energies, where the c-axis response is strongly suppressed in the tetragonal phase in accordance with the associated reorientation of the ordered moments. Despite this suppression and the prominence of the remaining in-plane response, only the weak c-axis response exhibits a spin resonant mode in the superconducting state. Our results not only explain naturally why the superconductivity competes strongly with the tetragonal magnetic phase, but also provide a fresh view on how to make a good superconductor out of a magnetic "Hund's metal".

Spin-space Anisotropy in FeAs Based Superconductors

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We resume inelastic neutron-scattering experiments on magnetic correlations in Co and Na doped $BaFe_2As_2$ using neutron polarization analysis [1-5]. Spin orbit coupling implies an anisotropy in spin space, which remains effective from the parent material [1] to under and optimum doping [2,4] and even in overdoped compounds [3]. In contrast to a simple guess, the softer magnetic directions in pure $BaFe_2As_2$ do not correspond to the layered character of the crystal structure, but the orbital ordering associated with magnetic ordering in FeAs materials causes the in-plane direction perpendicular to the propagation vector to become the hard magnetic axis. The soft magnetic axes are in-plane parallel to the propagation vector and out of plane. These two magnetic soft axes perfectly agree with the spin-reorientation occurring in hole-doped $BaFe_2As_2$.

In Co optimum-doped $BaFe_2As_2$ the same two soft directions appear as the polarization of an extra low-energy spin-resonance mode (SRM) [2,4]. This low-energy mode exhibits a pronounced 3-dimensional character but remains poorly understood; it appears below the much broader isotropic SRM. Applying a magnetic field in the superconducting state the isotropic SRM exhibits a splitting into two chiral components that can be visualized by polarized neutron scattering. This observation strongly supports its triplet character. In contrast the lower mode seems not to split in a similar way.

In Co underdoped $BaFe_2As_2$ the sizeable ordered moment seems to imply a rather different constellation of SRM's. In the longitudinal excitations a large gap opens with the antiferromagnetic ordering which seems to suppress SRM's in the longitudinal channel [4]. There is no isotropic SRM in Co underdoped $BaFe_2As_2$, but two anisotropic modes appear in the two spin polarizations transversal to the static order.

In Na-doped $BaFe_2As_2$ the spin-reorientation transition allows for further insight to the character of the anisotropic SRM's. In a superconducting compound with rotated magnetic order the anisotropy of the SRM's is not following the spin rotation. Near the full suppression of magnetic order, where magnetism is particularly soft, a very strong extra SRM occurs that seems to compensate for the suppression of ordered moment in the superconducting phase.

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Momentum and Doping Dependence of the Band Renormalization and Scattering Rates in Iron-based Superconductors Determined by ARPES

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Unconventional/high temperature superconductivity (SC) is believed to occur in correlated systems. A prerequisite for the understanding of the mechanism of superconductivity is the understanding of the electronic structure in the normal state. While in the single-band cuprates the starting point for the description of correlation effects in the normal state is the Mott-Hubbard model, in the multi-band iron-based superconductors, besides the onsite Coulomb interaction, also Hund's exchange interaction has to be taken into account. Using angle-resolved photoemission spectroscopy we have studied the momentum dependence of the band renormalization and the energy dependent scattering rates of charge carriers in various transition metal pnictides and iron chalcogenides as a function of the doping concentration. In this way we obtain information on the location of the hot spots on the Fermi surface determining antiferromagnetism and superconductivity as well as on the location of the cold spots determining the normal state transport properties. The aim is to obtain a microscopic understanding of the electronic structure of these systems in the normal and in the superconducting state. The experimental results are compared with current models such as quantum critical scenarios, spin-Fermion models, and DFT+DMFT calculations of Hund's metal behavior.

Theory of Normal State and Supercondctivity in Iron Pnictides and Chalcogenides

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Iron pxictides and chalcogenides are Hund's metals. Materials which are strongly correlated, but their correlations derive from the Hund's coupling J, rather than their Hubbard U. Using LDA+DMFT and simple models, we will describe their normal state properties as well as the implications for the superconductivity, and show that a value $2\Delta_{max}/k_BT_c$ close to twice the BCS value emerges from the theory. We will contrast this behavior with those of other correlated superconductors such as the cuprates and the bismuthates.

Magnetic-field Induced Pair Density Wave State in the Intrinsic Charge Dynamics in High-Tc AFeAs(O,F) Superconductors

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Odd and even modes of neutron spin resonance in $CaKFe_4As_4$

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In unconventional superconductors, the neutron spin resonance, which is argued to be a spin-1 collective mode of particle-hole excitations in the superconducting state, is a crucial evidence for spin fluctuation mediated superconductivity in the proximity of an antiferromagnetic (AF) instability [1]. In iron pnictides/chalcogenides, the spin resonance is theoretically predicted to arise from sign-reversed s−wave (s±) Cooper-pairing between nesting hole-electron or electron-electron pockets [2]. Although the resonance energy is proportional to T_c [3], the spin resonance peak is unexpected much broader in energy distribution and more dispersive both in-plane and along L direction due to the complex multi-orbital nature [4].

By using inelastic neutron scattering, we have studied the neutron spin resonance in the first bilayer iron-based superconductor $CaKFe_4As_4$. In contrast to its quasi-two-dimensional electron structure, three strongly L-dependent modes of spin resonance are found below T_c = 35 K. The energies of each mode are below and linearly scale with the total superconducting gaps summed on the nesting hole and electron pockets, essentially in agreement with the results in cuprate and heavy fermion superconductors. This observation supports the sign-reversed Cooper-pairing mechanism under multiple pairing channels, and resolves the long-standing puzzles concerning the broadening and dispersive spin resonance peak in iron pnictides. More importantly, the triple resonant modes can be classified into odd and even symmetries with respect to the distance of Fe-Fe planes within the Fe-As bilayer unit. Therefore, our results closely resemble those in the bilayer cuprate $YBa_2Cu_3O_{6+y}$ system with non-degenerate spin excitations, suggesting that iron-based superconductors share a common nature with cuprate high-T_c superconductors [5].

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Scanning Tunneling Spectroscopy of Interface Superconductivity

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Interface superconductivity has recently been a subject of numerous studies for the condensed matter physics community. In this talk, I would focus on our atomic-scale design, preparation, characterization and control of interface supercnductors by combining the strengths of molecular beam epitaxy and scanning tunneling microscopy. We succeed to prepare cooper oxide monolayer films (the key building layers of cuprate superconductors) on the BiO surfaces of the cleaved $Bi_2Sr_2CaCu_2O_{8+x}$ crystals, and reveal that the superconducting gap is nodeless, rather than the nodal *d*-wave pairing scenario that is generally believed to occur in cuprate superconductors [1]. A modulation doping model is proposed to explain the observed superconductivity, and supported by our recent observation of interface superconductivity in monolayer $SnSe_2$ film grown on graphitized SiC(0001) substrates, where the two-dimensional electron gas, formed at the interface due to charge transfer from graphene to $SnSe_2$, is found to solely contribute to the density of sates at the Fermi level [2].

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Scanning tunneling microscopic observation of the enhancement of T_c and critical field in epitaxial islands grown on $SrTiO_3$ substrate

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Recent experimental and theoretical studies on a single-layer FeSe film grown on $SrTiO_3$ [1] have revealed the interface enhanced superconductivity, which opens up a pathway to promote the superconducting transition temperature. To investigate the role of $SrTiO_3$ substrate in epitaxial superconducting film, here, we grew several conventional superconductors onto $SrTiO_3$ substrate by molecular beam epitaxy. By employing scanning tunneling microscope and spectroscopic measurements, the enhanced Tc is found for these epitaxial islands, deduced by fitting the temperature dependence of the gap values using the BCS formula. The observed interfacial charge injection and enhanced electron-phonon coupling are responsible for the Tc enhancement. Moreover, the critical field exhibits a tremendous increase due to the suppression of the vortex formation. Therefore, the coexistence of enhanced superconductivity and high critical field of conventional superconductor islands, demonstrates a feasible and effective route to improve the superconductivity by growing conventional superconductor islands on perovskite-type titanium oxide substrates.

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Superconductivity at the $LaAlO_3/SrTiO_3$ interface and related systems

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Possible Unconventional Superconducting Pairing Mechanism of Two-Dimensional Electron Gas at $LaAlO_3/SrTiO_3$ Interface

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The heterointerfaces between transition metal oxides have attracted a lot of attention due to uniquely diverse physical phenomena [1,2]. The most typical case is the interface between two band insulators, $LaAlO_3$ and $SrTiO_3$ (LAO/STO). The high mobility two dimensional electron gas (2DEG) is formed and a vast variety of fascinating properties such as superconductivity[3,4], ferromagnetism[5,6], and their coexistence[7,8] are observed at the interface. Over the last decade, LAO/STO interface has been widely studied, but a lot of questions remain unanswered, such as the paring mechanism of its superconductivity.

In this report, the superconductivity of LAO/STO samples is demonstrated based on the transport measurements. With decreasing backgate voltage (V_G), the superconducting transition temperature and critical current increases firstly then decreases, a dome-shaped superconducting region is formed. Here we investigated the V_G dependence of perpendicular critical field, and the results revealed that the perpendicular critical field increases monotonically as V_G decreases. This unconventional trend indicates that the Cooper pair potential is stronger in underdoped region, which is analogous to high-T_c cuprates.

Besides, at LAO/STO(110) interface, we found that a peak of magnetoresistance emerges around zero magnetic field. Further investigation showed that the emergence of peak is associated to the sweep direction of magnetic field, when the magnetic field sweep from positive to negative value, the peak appears at the negative direction closing to zero magnetic field. And the intensity of peak is dependent of the magnetic field sweep rate and temperature, larger sweep rate and lower temperature lead to higher peak intensity. These results may be attributed to ferromagnetism, while the interface was still superconducting. Hence, we observed the coexistence of superconductivity and ferromagnetism at LAO/STO(110) interface.

For LAO/STO system, the coexistence of superconductivity and ferromagnetism is always a great concern. There are two different understandings, one is the coexistence of superconductivity and ferromagnetism exist in the form of phase separation; Another is that the coexistence is originated from the same electronic contribution. We are currently working on the associated phase sensitive experiments, in order to confirm the coexistence, and to further clarify the pairing mechanism of the superconductivity at the LAO/STO system. The latest results will be reported at the conference.

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Manipulating electronic structure of novel correlated materials by tailoring superlattices

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Recently, a number of novel phenomena at complex quantum materials' interfaces have been discovered. Charge confinement/deconfinement in multiple valence heterostructures, coupling of structural instabilities, and continuity of the electric displacement field at interfaces have been applied as the guiding principles to manipulating electronic structure of novel correlated materials through building superlattices.

Following these principles, we successfully fabricated a series of $[(SrIrO_3)_m/(SrTiO_3)]_n/SrTiO_3(100)$ superlattices using the layer-by-layer oxide molecular beam epitaxy. In this series of superlattices, the metal-insulator transition (MIT) is introduced by tuning the thickness of SrIrO3 interlayer. Besides, the emergent interfacial magnetism by such an artificial dimensionality control of iridates is realized. The mechanism of this MIT has been then investigated by in-situ angle-resolved photoemission spectroscopy (ARPES). Our results could provide a comprehensive understanding of the phase transition in this spin-orbit Mott insulator.

Moreover, using ARPES, we studied the electronic structure evolution of $(PbSe)_{1.16}(TiSe_2)_m$ superlattices (m=1, 2), which are naturally occurring van der Waals heterostructures (VDWHs), and discovered several striking charge transfer effects. When the thickness of the TiSe2 layers is halved from m=2 to m=1, the amount of charge transferred increases unexpectedly by more than 250%. This is accompanied by a dramatic drop in the electron-phonon interaction strength far beyond the prediction by first-principles calculations and, consequently, superconductivity only exists in the m=2 compound with strong electron-phonon interaction. These findings of anomalous charge effects lay a foundation for further understanding and tuning VDWHs based on the manipulation of superlattices.

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Robust Zero Resistance in Superconducting High Entropy Alloys against Pressure up to 190 GPa

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High entropy alloys (HEAs) are a new class of materials that are composed of multiple transition metal elements in equimolar or near equimolar ratios. The diverse elements in HEAs are arranged randomly on the crystallographic positions in a simple lattice, and thus have been referred to as a metallic glass on an ordered lattice. By applying this concept, many HEAs have been found in disordered solid solution phases with body-centered cubic, hexagonal closest-packed and face-centered cubic crystal structures. In many respects, HEAs display novel properties, including ultrahigh fracture toughness at cryogenic temperatures, excellent specific strength, and superior mechanical performance at high temperatures. In addition to their promising mechanical properties, some HEAs also exhibit interesting electronic properties, for example, HEAs were found to display superconductivity. In this talk, we will report the observation of extraordinarily robust zero-resistance superconductivity in the pressurized high entropy alloys. The transition to superconductivity of $(TaNb)_{0.67}(HfZrTi)_{0.33}$ HEA icreases from an initial temperature of 7.7 K at ambient pressure to 10 K at ~ 60 GPa, and then slowly decreases to 9 K by 190.6 GPa, a pressure that falls within that of the outer core of the earth. We infer that the continuous existence of the zero-resistance superconductivity from one atmosphere up to such a high pressure requires a special combination of electronic and mechanical characteristics. This high entropy alloy superconductor thus may have a bright future for applications under extreme conditions, and also poses a challenge for understanding the underlying quantum physics [1].

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The Multi-gap Superconductivity, Pressure and Substitution Effect in $TlNi_2(Se,S)_2$

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After our first discovery of multi-band superconductivity (SC)[1] with T_C = 3.7 K in $TlNi_2Se_2$ crystals, we successfully grew a series of $TlNi_2Se_{2-x}S_x$ ($0.0 \le x \le 2.0$)[2], and $TlCo_{2-x}Ni_xSe_2$ ($0.0 \le x \le 2.0$) single crystals. Measurements of resistivity, specific heat, and susceptibility were carried out for these crystals. It was found that all the $TlNi_2Se_{2-x}S_x$ ($0.0 \le x \le 2.0$) compounds exhibit SC with T_C =1.9~3.7 K, and they appear to involve heavy electrons with an effective mass m^* = (13~25) m_b, as inferred from the normal-state electronic specific heat and the upper critical field, H_{C2}(T). In the mixed state of the $TlNi_2Se_{2-x}S_x$ system, the field dependence of the residual specific heat coefficient, γ_0 (H), changes from $H^{0.5}$ (for x = 0) to a linear H behavior. We also found that the T_C value changes with the disorder degree induced by the partial substitution of S for Se, characterized by the residual resistivity ratio (RRR). As well as, we checked the pressure dependence of T_C in $TlNi_2Se_{2-x}S_x$ via the ac susceptibility method[3]. The pressure-temperature phase diagram exhibits two unexpected features: (a) a sudden collapse of the SC state at moderate pressure and (b) a dome-shaped pressure dependence of T_C for $TlNi_2SeS$ (half-substitution). For the Co-doped $TlCo_{2-x}Ni_xSe_2$ system, it was found that with the Ni partial substitution for Co, it changes from an incommensurate AFM (x=0) to a commensurate AFM ($x \le 1.60$), then becomes a superconductor ($1.80 < x \le 2.0$) with the Neel temperature T_N = 0 K. The phase diagram T-x was constructed for $TlCo_{2-x}Ni_xSe_2$ system, indicating the SC in $TlNi_2Se_2$ being close to a new AFM. The temperature dependence of the penetration depth, λ(T), determined[6] very recently by the small-angle neutron scattering technique, indicates that this material has an unconventional gap structure with nodes, although the low-temperature thermal conductivity[4], the STM data[5], as well as the results of ARPES measurements[6] on $TlNi_2Se_2$ crystals suggested that SC exhibits a multi-gap nodeless SC weak electronic Coulomb correlation. These results may provide a different view for the understanding on the SC in Fe-based compounds, and cuprates.

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Unconventional Superconductivity and Electronic Correlations in Pr-based "Cage Compounds"

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Unconventional types of superconductivity (SC) have been observed in two classes of Pr-based "cage compounds," PrT_4X_{12} (T = Fe, Ru, Os, Pt; X = P, As, Sb, Ge) "filled skutterudites" [1] and PrT_2X_{20} (T = Ti, V, Ni, Pt, Pd; X = Zn, Cd, Al) "1-2-20" compounds [2]. The localized 4*f*-electron states of the Pr "guest" ions that reside within the "atomic cages" in these compounds hybridize with the ligand states of the surrounding ions that comprise the "atomic cages" and can lead to strong electronic correlations. For example, the "filled skutterudite" compounds $PrOs_4Sb_{12}$ [3] and $PrPt_4Ge_{12}$ [4] exhibit unconventional SC, with SCing critical temperatures (T_c's) of 1.86 K and 7.9 K, respectively. The SC arises from multiple bands, appears to have gap nodes, and breaks time reversal symmetry; both compounds are nonmagnetic with Pr^{3+} singlet crystalline electric field ground states. The "1-2-20" compounds $PrTi_2Al_{20}$ and PrV_2Al_{20} have been reported to display unconventional SC with T_c's of 0.2 K and 0.05 K, respectively. The SC coexists with ferroquadrupolar (FQ) order (T_{FQ} = 2 K) in $PrTi_2Al_{20}$ and antiferroquadrupolar (AFQ) order (T_{AFQ} = 0.6 K) in PrV_2Al_{20}. In this talk, we review recent experiments in which Ce and Eu substitutions for Pr have been used to probe the unconventional SC and electronic correlations in the filled skutterudite compound $PrPt_4Ge_{12}$ by means of electrical resistivity, magnetic susceptibility, and specific heat measurements as a function of Ce and Eu substituent composition x, temperature T and magnetic field H. Experiments on the $Pr_{1-x}Ce_xPt_4Ge_{12}$ system reveal a depression of T_c with x with positive curvature that is reminiscent of pair weakening interactions or the interplay between SC and the Kondo effect with a large Kondo temperature $T_K >> T_c$ [5]. Specific heat measurements [6] indicate that SC develops in at least two bands, and the SCing order parameter has nodes on one Fermi pocket and remains fully gapped on the other. Both the nodal and nodeless gaps decrease with increasing Ce concentration with a rate of suppression that is larger for the nodal gap. Experiments on the $Pr_{1-x}Eu_xPt_4Ge_{12}$ system reveal a depression of T_c with x with negative curvature indicative of SCing electron pairbreaking by divalent Eu ions which carry localized magnetic moments of 7 μ_B [7]. The specific heat measurements [8] reveal the presence of short range AFM correlations between Eu ions under the SCing dome for $x \leq 0.5$ and long-range AFM order for $x \geq 0.5$. SC and AFM most likely coexist for $0.3 \leq x \leq 0.6$. The SCing gap has line nodes for $0 \leq x \leq 0.1$ and is isotropic for $0.15 \leq x \leq 0.5$.

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Superconductivity in Novel Hexagonal BaPtAs with an Ordered Honeycomb Network

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Alkaline-earth platinum pnictides exhibit a variety of hexagonal structures that are characterized by honeycomb networks, such as $CaPt_xP_{2-x}$, SrPtAs, and BaPtSb with an AlB_2-(*P*6/*mmm*, D_{6h}^1, No. 191), a KZnAs- (*P*6$_3$/*mmc*, D_{6h}^4, No. 194), and a SrPtSb-type (*P*-6*m*2, D_{3h}^1, No. 187) structures, respectively. SrPtAs exhibits superconductivity at 2.4 K, as we reported [1]. Superconductors with honeycomb networks have attracted interest since the theoretical predictions of exotic superconductivity in SrPtAs, such as a singlet-triplet mixed state [2], a chiral *d*-wave state [3], and an *f*-wave state [4]. In order to explore the exotic superconducting states, we have developed novel compounds with honeycomb networks.

BaPtAs has been known to crystallize in the cubic LaIrSi-type structure (*P*2$_1$3, T^4, No. 198). We discovered novel hexagonal structures of BaPtAs with ordered PtAs honeycomb networks, namely, SrPtSb- (*P*-6*m*2, D_{3h}^1, No. 187) and YPtAs-type (*P*6$_3$/*mmc*, D_{6h}^4, No. 194) structures [5]. Both phases exhibited superconductivity at 2.8 and 2.1-3.0 K, respectively [5]. Inversion symmetry is broken in the SrPtSb-type, whereas it is preserved in the YPtAs-type. Our discovery provides opportunities not only for the experimental examination of the predicted superconductivity but also for further studies on exotic states that result from the strong spin-orbit interaction of Pt under broken inversion symmetry.

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Stabilization of $Sr_3Al_2O_6$ Templates for Ex-situ Synthesis of Superconducting Freestanding $SrTiO_3$ Membranes

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A generic synthetic approach has recently been developed for the fabrication of freestanding perovskite oxide membranes, which involves the epitaxial growth of a water-soluble sacrificial layer [1]. Here, utilizing an ultrathin capping layer of $SrTiO_3$, we show that this sacrificial layer can be stabilized in air and therefore become transferrable 'templates' for *ex situ* epitaxial growth of various oxides using other techniques, such as MBE. We also find that the stabilization of the 'templates' depend on the thickness of the capping layer. Following this path, first freestanding superconducting $SrTiO_3$ membrane was synthesized. This study paves the way to the synthesis of an expanded variety of freestanding oxide membranes in an *ex situ* manner.

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Engineering the Mott State of Cuprates for High-Temperature Superconductivity

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Recent synchrotron (RIXS and ARPES) experiments on La-based cuprates will be presented [1-4]. The talk is taking basis on the recent identification of the dz2 band in overdoped $La_{2-x}Sr_xCuO_4$ (LSCO) [1]. Implications on superconductivity and pseudogap physics from of the resulting the Fermi surface structure (in- and out-of-plane) and orbital hybridization will be discussed. Topological aspects of the LSCO is being touch briefly [3]. Finally, the engineering of this electronic structure let us to find that the magnetic exchange interaction in La_2CuO_4 films can be tuned through strain [4]. We noticed that films with the largest exchange interaction also has the highest superconducting transition T_c upon doping – consistent with a magnetic pairing scenario.

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Toward a first-principles description of stronger correlations: Stripe and magnetic phases in cupates to topological materials

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I will discuss how advanced density functionals are enabling new insights into the electronic structure, phase diagrams and magnetism of a wide variety of materials that have until now been considered to be so strongly correlated as to lie outside the scope of the first-principles density-functional theory framework. A spectacular example is provided by the cuprate high-Tc superconductors in which the first-principles computations have failed to correctly predict the half-filled parent compounds to be insulators. The recently constructed strongly-constrained-and-appropriately-normed (SCAN) functional, in sharp contrast, not only reproduces the insulating character and magnetism of the half-filled cuprates, but also captures the transition to the metallic state with doping without invoking any free parameters such as the Hubbard U.[1] A first-principles description of the competing stripe and magnetic phases in the cuprates also then becomes possible. I will also comment on the opportunities for a new generation of predictive modeling in correlated materials more generally, including the topological phases of quantum matter, which are of intense current interest [2].

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Spontaneous symmetry breaking of *d*-wave superconductivity in t-J model: unbiased finite sizes tensor network studies

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We study the t-t'-J model on the square lattice by using an unbiased finite size numerical method, Grassmann Multi-scale Entanglement Renormalization Ansatz (GMERA). Within grand canonical ensemble, the ground state shows a spontaneous symmetry breaking of *d*-wave superconducting state in the intermediate doping region for sufficiently large system size. Moreover, in superconducting states, we find evidence of coexistence of charge density wave and spin density wave. The next nearest neighboring hopping t' term may significantly affect superconductivity in the system. In particular, the hole-doping case for negative t' may enhance the superconductivity while the electron-doping case for positive t' may suppress the superconductivity. All these main results agree qualitatively with experimental facts.

Finite-temperature charge dynamics and the melting of the Mott insulator

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We propose a slave-fermion (holon-doublon) formulation to describe the two-dimensional Mott-insulating state. We benchmark its predictions against state-of-the-art quantum Monte Carlo simulations, finding quantitative agreement. Qualitatively, the short-ranged spin fluctuations at finite temperatures are sufficient to induce holon-doublon bound states, and renormalize the charge sector to form the Hubbard bands. The Mott (single-particle) gap is understood as the holon-doublon gap renormalized downwards by these spin (particle-hole) fluctuations. With increasing temperature, the Mott gap closes while the holon-doublon gap remains finite, causing a pseudogap regime to appear naturally during the process of melting the Mott insulator.

Superconductivity in Doped Mott Insulators From a Dynamical Mean-Field Perspective

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The first-order transition from metal to Mott insulator as a function of interaction strength in two-dimensions is well described by cluster generalizations of dynamical mean-field theory [1] applied to the Hubbard model. It was shown, using that method with a continuous-time quantum Monte Carlo solver [2], that an extension of the first-order Mott transition appears when the insulator is doped [3]. In this talk we show that this transition controls much of the phase diagram of the high-Tc cuprates. It leads to a temperature T*, near half-filling, below which density of states is lost [4]. This is the so-called pseudogap regime. The T* line as a function of doping has a slope and an intercept that depend on interaction strength and band structure in ways that are consistent with experiments [5]. In addition, the remnant of the first-order Mott transition away from half-filling also controls the high-temperature superconducting phase, [6] determining whether the condensation energy comes mainly from potential or kinetic energy. This is analogous to what happens at half-filling where, even when the Mott transition is pre-empted by an ordered antiferromagnetic phase, it determines the origin of condensation energy in that ordered phase [7]. The superfluid stiffness is highly non-BCS [8,9] and controls the value of the superconducting transition temperature in the pseudogap regime. Coexistence with other phases is more detrimental to superfluid stiffness than it is to the superconducting order parameter [9].

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Do all underdoped Mott insulators have a pseudogap in two dimensions?

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The doped Mott insulator is broadly considered as a starting point for the understanding of the high T_c cuprate superconductors. In particular, the mysterious pseudogap state in the underdoped regime has long been conjectured as a hallmark of cuprates being in proximity to the Mottness, although its exact nature is yet fully revealed due to strong coupling. In this work, we investigate different underdoped Mott insulators of the Hubbard model to clarify the relationship between pseudogap and Mottness in two dimensions. We find that although pseudogap arises from strong-coupling physics, its occurrence and particle-hole asymmetry can be surprisingly sensitive to non-interacting band parameters. Consequently, a two-dimensional underdoped Mott insulator does not necessarily possess a pseudogap, even with the presence of strong magnetic correlations.
An example of magnetically unfrustrated doped Mott insulator without extended pseudogap region is proposed. We also propose a simple equation to capture the particle-hole asymmetry of the doped Hubbard model on square lattice.

Related reference:

Pseudogap and Fermi-Surface Topology in the Two-Dimensional Hubbard Model
W. Wu, M. Scheurer, S. Chatterjee, S. Sachdev, A. Georges, and M. Ferrero
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Commensurate to Incommensurate Transition of the Cuprate CDW

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The strong electronic correlations within the cuprates give rise to an array of unconventional phases beyond high temperature superconductivity. Multiple broken symmetries, including translational, rotational, time-reversal, and inversion, are observed, and yet the underlying organization of the ground state remains unknown. Emerging views contend this complex phase diagram is controlled by a quantum critical point (QCP) lying beneath the superconducting dome, tuned by doped hole concentration, and signified by abrupt change in the Fermi surface topology. Here we use scanning tunneling microscopy (STM) to study $(Bi,Pb)_2(Sr,La)_2CuO_{6+d}$, in which the symmetry-breaking density wave (DW) state persists on both sides of the QCP[1], and can be used to track the fingerprint of dominant electronic interactions. First, we discover a commensurate to incommensurate transition of the DW wavevector that is coincident with the Fermi surface transition. Second, we find that the wavevector on the overdoped side of the transition evolves more rapidly with doping than the fermiology, providing evidence for persistent effects of strong correlations.

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The spin susceptibility of charge-ordered $YBa_2Cu_3O_y$

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Some of the most important breakthroughs in the understanding of high-T_c cuprates have been achieved by applying magnetic fields [1-5]. Magnetic fields, particularly intense ones, eradicate superconductivity and allow one to observe the normal state down to low temperatures. This strategy has been remarkably succesful in the cuprates in revealing electronic ordering that is otherwise hampered by the onset of superconductivity.

In this talk, I shall present three different sets of results concerning the uniform spin susceptibility χ_{spin} of the CuO_2 planes in charge-ordered $YBa_2Cu_3O_y$ [6-8], all obtained from ^{17}O nuclear magnetic resonance (NMR) measurements in high magnetic fields.

At T=2 K, the observed saturation of χ_{spin} above field values ranging from 20 to 40 T (depending on exact doping) is consistent with the low $H_{c2}(T=0)$ values claimed previously [9] and with the interpretation that the CDW reduces H_{c2} in $YBa_2Cu_3O_y$. See ref. [6].

The characteristic field H_{sat} at which $\chi_{spin}(H)$ (and the specific heat) saturates shows an inflection near the onset of the long range 3D CDW order, suggesting that superconductivity and CDW are two mutually exclusive orders that eventually establish a form of cooperation (possibly a pair-density wave) in order to coexist at low T. See ref. [7].

Using fields greater than H_{c2}, we have been able to observe the T dependence of χ_{spin} from room T down to ~2 K. Specifically, χ_{spin} can be described by the sum of a residual term and of thermally activated contributions. The doping dependence of the different terms invites a two-component description of the pseudogap state in which singlet correlations and the associated quantum spin-gap coexist with fermionic excitations. These latter appear to be partially gapped out when CDW correlations are present. See ref. [8].

Work performed with R. Zhou, I. Vinograd, M. Hirata, T. Wu, H. Mayaffre and S. Krämer (LNCMI Grenoble), A.P. Reyes and P.L. Kuhns (NHMFL, Tallahassee), W.N. Hardy, R. Liang and D.A. Bonn (UBC Vancouver), T. Loew, J. Porras and B. Keimer (MPI Stuttgart)

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Charge Density Wave Order and Nematicity in Cuprate Superconductors Probed via Resonant X-Ray Scattering.

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In underdoped cuprate superconductors, a rich competition occurs between superconductivity and charge density wave (CDW) order. Whether rotational symmetry-breaking (nematicity) occurs intrinsically and generically or as a consequence of other orders is under debate. Here, we employ resonant x-ray scattering in stripe-ordered superconductors $(La,M)_2CuO_4$ to probe the relationship between electronic nematicity of the Cu 3*d* orbitals, structure of the $(La,M)_2O_2$ layers, and CDW order. We find distinct temperature dependences for the structure of the $(La,M)_2O_2$ layers and the electronic nematicity of the CuO_2 planes, with only the latter being enhanced by the onset of CDW order. These results identify electronic nematicity as an order parameter that is distinct from a purely structural order parameter in underdoped striped cuprates.

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Study of Charge Dynamics and CDW in high-T_c cuprates via Resonant Inelastic X-ray Scattering

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Spin excitations and charge order in superconducting cuprates studied by resonant inelastic x-ray scattering

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Resonant inelastic x-rays scattering (RIXS), performed at the L_3 edge of Cu, is an ideal spectroscopy for the study of magnetic and charge excitations and orders of cuprate high Tc superconductors. In fact, RIXS can be used to determine the spin excitation dispersion and damping over a large part of the reciprocal space. And the elastic peak carries the information about charge density waves.

We have exploited the superior sensitivity of the ERIXS instrument of the beam line ID32 of the ESRF to take a deeper look at the spin excitations and CDW phenomenonon. We have studied the magnon and paramagnon dispersion in different families [1], with a particular focus on the single layer Bi2201 for the doping dependence of the excitation energies and damping [2]. These results confirm the importance of longer range hopping integrals for superconductivity in cuprates and that spin excitations preserve most of their properties upon hole doping. Moreover, we have re-examined the temperature dependence of CDW in the 123 family [3], with surprising results that, combined with the discovery of charge order in overdoped Bi2201 [4] and with the observation of high temperature CDW in LBCO [5], are going to stimulate a revision of the current understanding of the CDW phenomenon in cuprates.

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Charge-Density-Wave Order and Pseudogap in Single Layered $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ Superconductor

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High temperature superconductivity appears in the cuprates when a spin order is destroyed, while the role of charge is less known [1]. Recently, charge density wave (CDW) was found below the superconducting dome in bi-layer $YBa_2Cu_3O_y$ superconductor when a high magnetic field is applied perpendicular to the CuO_2 plane, which was suggested to arise from incipient CDW in the vortex cores that becomes overlapped [2]. In this presentation, we report our recent results of ^{63}Cu-nuclear magnetic resonance (NMR) study that discovered a long-range CDW order in single-layered $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ superconductors [3]. In contrast to the result of $YBa_2Cu_3O_y$, the CDW in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ sets in above the superconducting dome, under an in-plane field H >10 T that does not create vortex cores in the plane. From the systematic measurements of the NMR spectrum and nuclear-spin lattice relaxation rate ($1/T_1$), we find that the doping dependence of the CDW onset temperature T_{CDW} scales with the pseudogap temperature T^*, which suggests that the T^* is a high-temperature fingerprint of the CDW. Furthermore, in high magnetic field, the T_{CDW} smoothly takes over the spin order temperature T_N beyond a critical doping level at which superconductivity starts to emerge as shown in Fig.1. These results provide new insights into the relationship between spin order, CDW and the pseudogap, and their connections to high-temperature superconductivity.

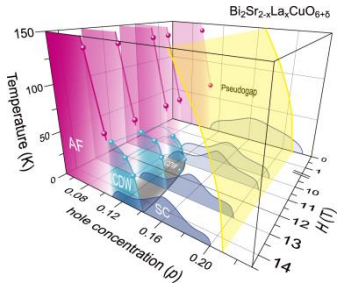

Fig. 1: *Hole concentration (p)- and H-dependence of T*, T_N, T_c, and T_{CDW} for $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$.*

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Universal Phonon Broadening near the Charge Order Q-vector in Bilayer Cuprate $Bi_2Sr_2CaCu_2O_{8+y}$

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In this talk, we will report the observation of a persistent low-energy phonon broadening around $q_B \sim 0.28$ reciprocal lattice units along the Cu-O bond direction in the high-T_c cuprate $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212). We will show that such broadening exists both inside and outside the conventional charge density wave (CDW) phase, via temperature dependent measurements in both underdoped and heavily overdoped samples. Combining inelastic hard x-ray scattering, diffuse scattering, angle-resolved photoemission spectroscopy, and resonant soft x-ray scattering at the Cu L_3-edge, we did not observe the presence of a CDW in the heavily overdoped Bi-2212 similar to that observed in the underdoped systems. Finally, we will discuss the origin of such anisotropic low-energy phonon broadening, and its potential precursory role to the CDW phase in the underdoped region.

Intertwined and vestigial electronic phases in hole doped $Sr_{1-x}Na_xFe_2As_2$

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Hole-doped $ReFe_2As_2$ (Re = Ba, Sr, Ca) exhibit much richer phase diagrams than the corresponding electron-doped systems. In particular, the phase diagram of Na-doped $BaFe_2As_2$ exhibits a small pocket of a double-Q reentrant C4 magnetic phase [1], as well as another yet unidentified magnetic phase [2]. In strong analogy with the charge order observed in underdoped cuprates [3], these additional phases strongly compete with the emerging superconducting order [2,4].

Here we present a detailed phase diagram of the Na-doped $SrFe_2As_2$ system using thermodynamic probes (heat capacity, thermal expansion and magnetization). The double-Q C4 reentrant phase is much more stable in this system, and our data demonstrates that the phase diagram of Na-doped $SrFe_2As_2$ exhibits even more complexity than the K- and Na-doped $BaFe_2As_2$ counterparts.

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Intertwined Orders and Magnetic Degeneracy in Iron-Based Superconductors

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Recent experiments in iron-based materials have challenged our understanding of the magnetic properties of these systems. Besides the usual orthorhombic stripe magnetic phase, different types of magnetic order that preserve tetragonal symmetry (hence called C_4 orders) have been observed in a hole-doped, electron-doped, and undoped pressurized compounds, usually in the region of the phase diagram where the superconducting transition temperature is maximum. In this talk, a theoretical model will be presented that attributes this behavior to an emergent magnetic degeneracy arising from the impact of the spin-orbit-coupling on the putative magnetic quantum critical point. A unified picture will be discussed in which a rich landscape of composite vestigial orders emerges from this magnetic degeneracy, intertwining the magnetically ordered states with unique $\mathbf{Q}$=0 electronic states that preserve the translational symmetry of the system while breaking other symmetries of the two-iron unit cell by condensing unusual types of orbital order.

Changing Nature of Superconductivity in FeS under Pressure

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Among iron chalcogenide superconductors, FeS can be viewed as a simple, highly compressed relative of FeSe without nematic phase and with smaller electronic correlations. However, under pressure, the superconductivity of stoichiometric FeS disappears and reappears, forming two domes. We perform electronic structure and spin fluctuation theory calculations for tetragonal FeS in order to analyze the nature of the superconducting order parameter. In random phase approximation we find a gap function with *d* wave symmetry at ambient pressure, in agreement with several reports of a nodal superconducting order parameter in FeS. Our calculations show that as function of pressure, the superconducting pairing strength decreases until at 4.6 GPa, a Lifshitz transition happens in the electronic structure. Due to a weakening of the (π,π) nesting of the d_{xy} orbital, the pairing symmetry changes to sign changing *s* wave, and the pairing strength increases to a new maximum at 5.5 GPa. Thus, the occurrence of two domes in the superconducting transition temperature can be linked to the occurrence of a Lifshitz transition in pressurized FeS.

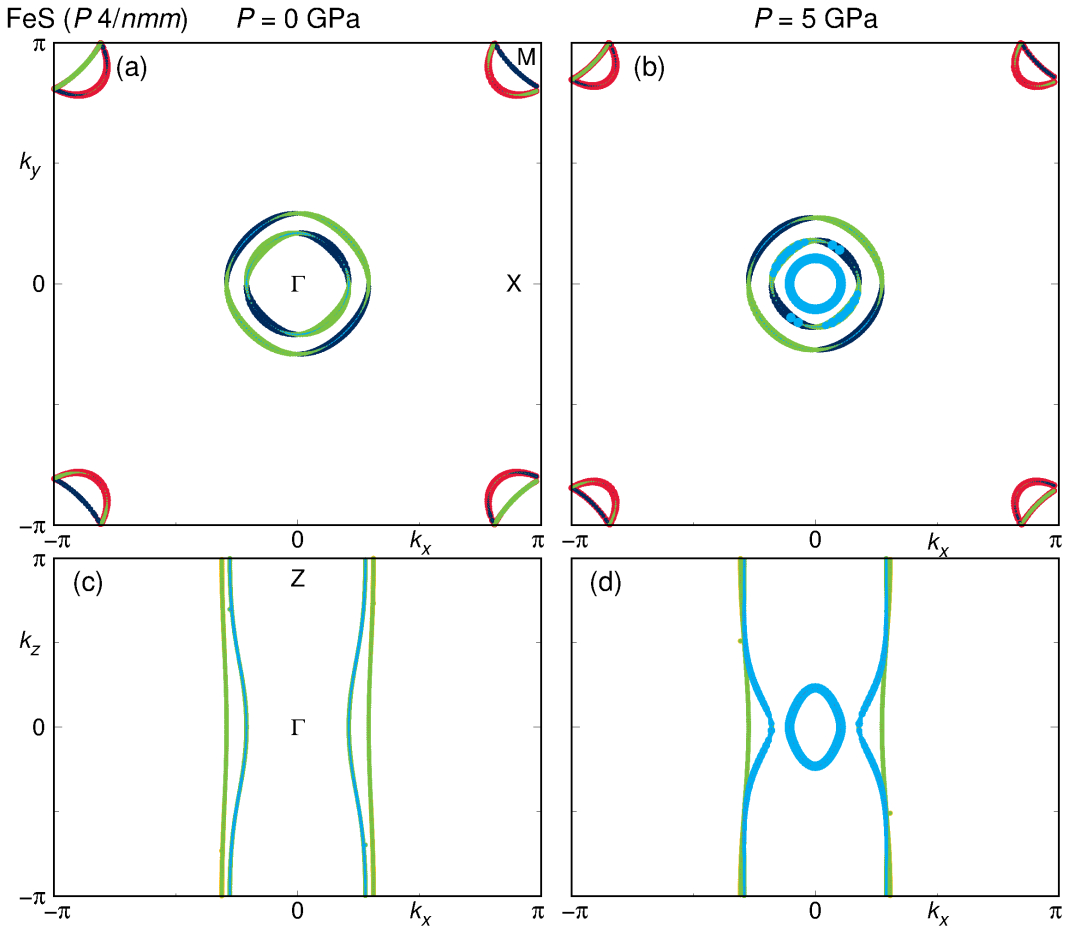

Fig. 1: *Fermi surfaces of FeS at two different pressures, showing a Lifshitz transition.*

Microwave Surface Impedance and Complex Conductivity of $Ba(Fe_{0.926}Co_{0.074})_2As_2$ Single Crystals

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The paper compares the experimental results on the response of pnictide single crystal $Ba(Fe_{0.926}Co_{0.074})_2As_2$ obtained in frequency X-band (9.4 GHz) with the results obtained earlier in two frequency ranges, namely, 10-15 MHz and Ka-band (39.3 GHz) [1,2]. It is shown that the penetration depth λ at $T<T_c/2$ varies in accordance with the power law T^n where n = 2.8 $\pm$0.1 over the entire frequency range. Measured in the X-band, Fe-pnictide's surface impedance $Z_s=R_s+iX_s$ allowed us to find a complex conductivity $\sigma_1-i\sigma_2$ in the temperature range from 2 to 25 K. An amazing feature of the behavior of quasiparticle conductivity σ_1, manifested in the growth of σ_1 with decreasing $T<T_c$, found in the Ka band, is confirmed in the X-band. This fact can be explained by the strong temperature dependence of the quasiparticle scattering rate τ^{-1} in the s-state. The temperature dependence of the τ^{-1} in the X-band is constructed and compared with the analogous dependence in the Ka-band [3]. It is shown to what temperature, when it is lowered, one can use a simplified expression valid for $\omega\tau<<1$ to find τ. In addition, experiments confirm that for a bulk sample with a thickness greater than the penetration depth, there is no unusual feature in the temperature dependence of losses in the cavity near Tc, which appears in a resonator with very thin films at a perpendicular orientation of the film with respect to the microwave magnetic field of the resonator [4].

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Frustrated Superconductivity close to the Lifshitz Transition in $Ba_{1-x}K_xFe_2As_2$

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In systems having a complex band structure near the Fermi level, frustrated pairing interactions may result in an *s*+i*s'* or an *s*+i*d* superconducting (SC) states with broken time reversal symmetry (BTRS). The experimental observation of a frustrated BTRS SC state is challenging as it appears in a narrow doping range only, presumably close to topological changes of the Fermi surface [1] and the related spontaneous magnetic fields might be very weak in such a state.[2,3] Here, we investigate the magnetic properties of the SC state for the hole doped $Ba_{1-x}K_xFe_2As_2$ system using the muon spin relaxation (μSR) technique. We observed spontaneous magnetic fields at $T^* \leq T_c$ in a narrow doping range of about $0.7 < x < 0.85$, where T_c is the superconducting transition temperature (Fig.1). The magnitude and the direction of the spontaneous internal fields are consistent with theoretical predictions for an anisotropic multiband *s*+i*s'* state.[3] A detailed specific heat study points to a scenario where the BTRS dome appears close to a Lifshitz transition(s). Our results provide strong evidence for the realization of a frustrated superconducting state in these multiband superconductors.

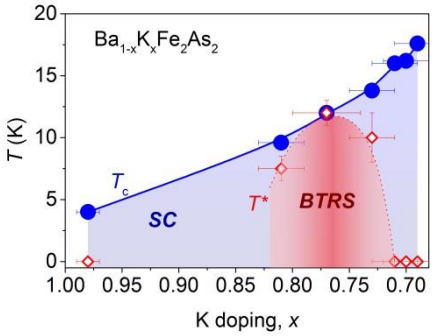

Fig. 1: *The phase diagram of the hole overdoped* $Ba_{1-x}K_xFe_2As_2$ *system (T^* is the onset temperature of the appearance of spontaneous magnetic fields, and T_c is the superconducting transition temperature).*

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Phase diagram of single-crystalline $Eu(Fe_{1-x}Co_x)_2As_2$ ($0 \leq x \leq 0.24$) grown by transition metal arsenide flux

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Interplay of magnetism and superconductivity (SC) has been a focus of interest in condensed matter physics over several decades. $EuFe_2As_2$ is a potential platform to investigate interactions between structural, magnetic, electronic effects and coexistence of magnetism and SC at similar temperatures. However, there are obvious inconsistencies in the reported phase diagrams of $Eu(Fe_{1-x}Co_x)_2As_2$ crystals grown by different methods. For transition metal arsenide (TMA)-flux-grown crystals, even the existence of SC is open for dispute. Here we re-examine the phase diagram of single-crystalline $Eu(Fe_{1-x}Co_x)_2As_2$ grown by TMA flux. It is found that the lattice parameter *c* shrinks linearly with Co doping. With Co doping, the spin-density-wave (SDW) order of Fe is quickly suppressed, being detected only up to x = 0.08. The magnetic ordering temperature of the Eu^{2+} sublattice (T_{Eu}) shows a systematic evolution with Co doping, first goes down and reaches a minimum at x = 0.08, then increases continuously up to x = 0.24. A new magnetic feature is observed at temperatures below T_{Eu}. Over the whole composition range investigated, no signature of SC is observed above 1.8 K.

Anomalous Magnetic Moments as Evidence of Chiral Superconductivity in Bi/Ni Bilayer

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There have been continuous efforts in searching for unconventional superconductivity over the past five decades. But there still lacks of a common agreement on the existence of chiral superconductivity with broken time reversal symmetry (TRS) and spontaneous magnetization. Bi/Ni epitaxial bilayer is a potential unconventional superconductor with broken TRS, for that it demonstrates superconductivity and ferromagnetism simultaneously at low temperatures [1,2]. In this talk, I will present our phase-sensitive investigation on Bi/Ni [3]. We employ a specially designed superconducting quantum interference device (SQUID) constructed in situ on the Bi/Ni bilayer, to detect the orbital magnetic moment which is expected if the TRS is broken. An anomalous hysteretic magnetic response has been observed in the superconducting state, providing the evidence for the existence of chiral superconducting domains in the material.

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Doping-Induced Enhancement of the Superconducting T_c in the Crystalline Topological Insulator Tin Telluride

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SnTe is a simple semiconductor which recently regained much interest since it was identified as a topological crystalline insulator [1]. Due to unintentionally self-doped Se vacancies it also superconducts below critical transition temperatures of T_c < ~300 mK [2]. Interestingly In-doping was found to enhance T_c of $Sn_{1-x}In_xTe$ by one order of magnitude [3-6], and the question what mechanism is responsible for the strong enhancement triggered many experimental and theoretical works. When it was experimentally demonstrated that the topologically nontrivial surface state survives against the doping [7], the system was considered as a candidate material for realizing topological superconductivity attracting even more attention. However, one drawback of this system is that In doping also induces a structural phase transition from cubic to tetragonal which destroys the superconductivity around x ~ 0.5.

In this talk we will report that we overcame this shortcoming and successfully synthesized the whole solid solution $Sn_{1-x}In_xTe$ by employing a high-pressure growth method allowing to map out the full phase diagram, see Fig. 1. We found a sudden and unexpected strong suppression of the superconducting T_c in a narrow doping range around x = 0.58. Only for a slightly higher x ~ 0.6 the maximum T_c in $Sn_{1-x}In_xTe$ is realized. Moreover, codoping with Se at the Te site further enhances T_c for higher x [8].

The resulting complex phase diagram and the doping effect of In and Se on the band structure of this system will be discussed as well as possible mechanisms which may explain the observed enhancement of T_c.

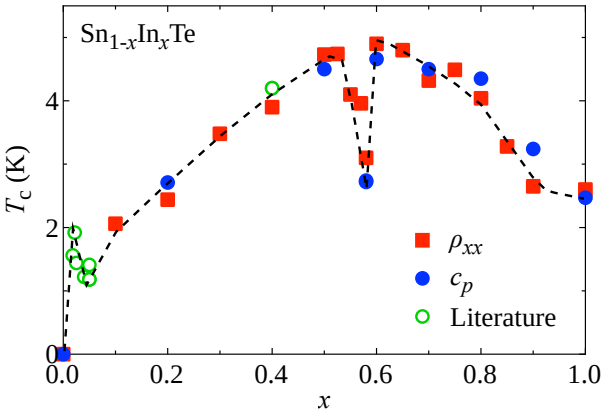

Fig. 1: *Superconducting phase diagram T_c vs x of $Sn_{1-x}In_xTe$. Red squares represent the temperatures at which the resistance has dropped to zero, blue filled circles the onset temperatures of the superconducting transition in specific-heat data. Green open circles are taken from Refs. 4 and 6. The dashed line is a guide to the eyes. (Fig. adopted from Ref. 8.)*

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Exploring superconductivity in layered topological materials

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To explore superconductivity in topological insulators (TIs) and topological semimetals (TSMs) has been a hot research spot in recent years because the Majorana bound states in topological superconductors are critical to implement non-abelian quantum computing. Applying high pressure has been proved to be an effective way to tune TIs and TSMs into superconducting state and thus topological superconductivity could be induced by this way. Unfortunately, most topological materials will experience structural phase transitions before entering superconducting state under high pressure, and thus it is very suspicious whether the topological nature could be kept after the structural phase transitions. Here we report the study on tuning one member of the transition-metal dipnictides, i.e. $NbAs_2$, into superconducting state by applying high pressure without observing any structural phase transitions. Superconductivity with Tc of 2.6 K is observed in $NbAs_2$ for a pressure range between 12.8 and 27.9 GPa. Using high-pressure X-ray diffraction and Raman scattering, we confirm that there is no structural phase transition up to the maximum experimental pressure of 29.8 GPa. Thus the topological surface state should remain undisturbed in the superconducting state. The revolution of Fermi surface and the topological band structure with pressure supports the conclusion. We also report a new topological semimetal $TaInSe_2$ with Weyl-type nodal line and a coexistence of charge density wave and superconductivity in this compound is discovered.

Rotational Symmetry Breaking in a Trigonal Superconductor Nb-doped Bi3Se3

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The search for unconventional superconductivity has been focused on materials with strong spin-orbit coupling and unique crystal lattices. Doped bismuth selenide (Bi2Se3) is a strong candidate given the topological insulator nature of the parent compound and its triangular lattice. The coupling between the physical properties in the superconducting state and its underlying crystal symmetry is a crucial test for unconventional superconductivity. In this paper, we report direct evidence that the superconducting magnetic response couples strongly to the underlying trigonal crystal symmetry in the recently discovered superconductor with trigonal crystal structure, niobium (Nb)-doped bismuth selenide [1]. As a result, the in-plane magnetic torque signal vanishes at every 60o. More importantly, the superconducting hysteresis loop amplitude is enhanced along one preferred direction spontaneously breaking the rotational symmetry [2]. This observation indicates the presence of nematic order in the superconducting ground state of Nb-doped Bi2Se3.

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The fourth superconducting gap: intrinsic Bogoliubov Fermi surfaces

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A hallmark of unconventional superconductivity is a nodal gap. In the absence of disorder or a magnetic field, it is commonly believed that only point or line nodes are allowed. We demonstrate [1] that for an even-parity nodal superconducting state which spontaneously breaks time-reversal symmetry, as is believed to occur in URu_2Si_2 [2], the low-energy excitation spectrum generally does not belong to either of these categories; instead it has *intrinsic* Fermi surfaces of Bogoliubov quasiparticles. This effect arises from the strong spin-orbit coupling, which produces interband pairing potentials; these in turn generate an effective magnetic-field-like term, which "inflates" the point or line nodes into spheroids or tori, respectively. These Fermi surfaces can be energeticaly stable, and are topologically protected by particle-hole and inversion symmetries; "accidental" Fermi surfaces can also persist when inversion is weakly broken [3]. The crucial ingredient in our theory is that more than one band is involved in the pairing; since all candidate materials for even-parity superconductivity with broken time-reversal symmetry are multiband systems (e.g. URu_2Si_2 [2], YPtBi [3,4], SrPtAs [5]), we expect Bogoliubov Fermi surfaces to be ubiquitous.

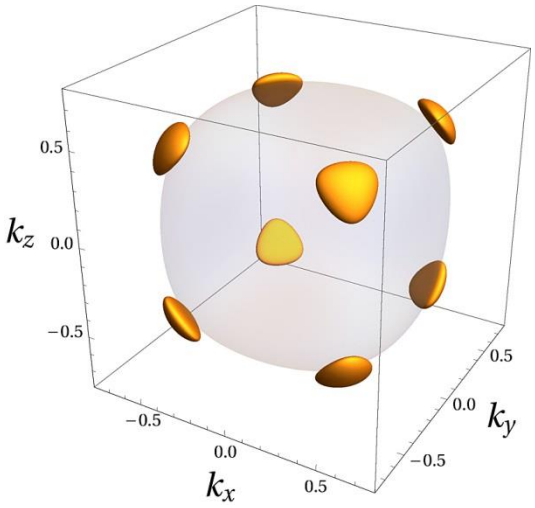

Fig. 1: *Bogoliubov Fermi surfaces (solid gold) and normal-state Fermi surface (transparent).*

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Z_4Topological Crystalline Superconductivity in UCoGe under pressure

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Superconductivity with emergent topologically nontrivial properties, namely topological superconductivity (TSC), has attracted great attention in these days [1]. Recent studies have revealed that the presence of crystalline symmetries enriches topological structures in SCs [2]. Among them, TSC enriched by nonsymmorphic (NSM) crystalline symmetries is dubbed topological NSM crystalline superconductivity (TNCS), and takes much interest because of the novel topological structures represented by *Möbius*- or *hourglass*-shaped surface states unique to NSM systems [3-5]. Interestingly, some of TNCS are classified into Z_4 topological phases, which do not appear in the conventional topological periodic table [1]. However, material realization of such Z_4TNCS has been lacking, to the best of our knowledge.
Here, we propose that the paramagnetic superconducting phase of UCoGe under pressure [6] is a promising candidate of TNCS with nontrivial Z_4 indices. We clarify that the glide topological invariants on the Brillouin-zone faces are determined from Fermi-surface topology, and demonstrate the topological invariants take nontrivial values for Fermi surfaces of UCoGe previously obtained by ab-initio calculations [7]. We check our predictions by tight-binding model calculations, and illustrate the 4π-periodic surface states.

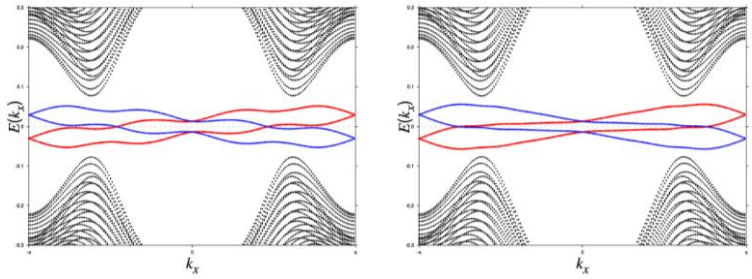

Fig. 1: *4π-periodic surface states of Z_4 TNCS.*

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Edge currents as a probe of the strongly spin-polarized topological noncentrosymmetric superconductors

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Recently the influence of antisymmetric spin-orbit coupling has been studied in novel topological superconductors such as half-Heuslers and artificial hetero-structures. We investigate the effect of Rashba and/or Dresselhaus spin-orbit couplings on the band structure and topological properties of a two-dimensional noncentrosymetric superconductor. For this goal, the topological helical edge modes are analyzed for different spin-orbit couplings as well as for several superconducting pairing symmetries. To explore the transport properties, we examine the response of the spin-polarized edge states to an exchange field in a superconductor-ferromagnet heterostructure. The broken chiral symmetry causes the uni-directional currents at opposite edges [1].

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Unconventional superconductivity in Cr-based materials

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The discovery of superconductivity in CrAs has stimulated considerable research interest in Cr-based materals. In this talk, I will show the quantum criticality and possible unconventional superconductivity in CrAs and $CrAs_{1-x}P_x$ from transport and thermodynamic measurements, and experimental evidence of line-nodes in superconducting gap function of in $K_2Cr_3As_3$ from specific heat measurements, as well as the exploration of new superconductors in Cr-based materials. Work done in collaboration with W. Wu, J. G. Cheng, Y.T. Shao, F. K. Lin, Y. G. Shi and J. P. Hu.

Discovery of several new superconductors in Cr/Mo related compounds with quasi-one-dimensional crystal structure

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The strongly correlated electrons in the transition metal compounds often exhibit various intriguing physical phenomena at low temperatures, and the most fascinating one is the coherent electron pairing for exotic superconductivity. From the early 1970's, there were a large number of molybdenum chalcogenide superconductors $M_xMo_6X_8$ and $M_2Mo_6X_6$ (X = S, Se, or Te) discovered, also known as the Chevrel phases. And in 2015, a new family of chromium arsenide based quasi-one-dimensional superconductors $A_2Cr_3As_3$ (A = K, Rb or Cs) were reported with spin-triplet electron pairing suggested. Is there some common underlying origin for the occurrence of superconductivity in these group VIB transition metal compounds? Here we talk about our discovery of superconductivity in several Cr/Mo related compounds that contain similar quasi-one-dimensional chain structures, which include the 133-type ACr_3As_3 (A = K, Rb) superconductors, the 233-type $Na_2Cr_3As_3$ superconductor with a T_c at 8.6 K, and the first MoAs-based $A_2Mo_3As_3$ (A = K, Rb, Cs) superconductors with higher T_c above 10 K. The similarity and difference between these Cr/Mo related superconductors will be discussed.

Possible high-T_c superconductivity in Ruddlesden-Popper compounds: incipient-narrow bands originating from "hidden-ladders"

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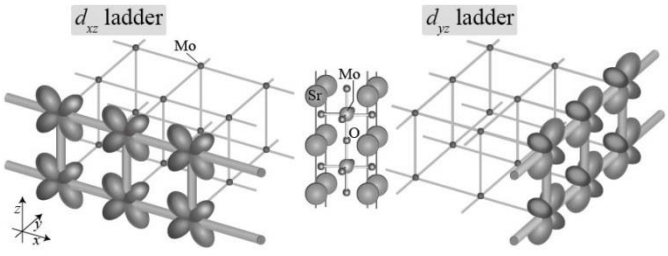
An ideal situation for realizing high-T_c superconductivity is to have light electron mass and strong pairing interaction at the same time, but usually the two are not compatible with each other. In ref.[1], the present author proposed a way to circumvent this problem ; in a system consisting of wide and narrow bands, light effective mass and strong pairing interaction is simultaneously realized when the Fermi level sits in the vicinity of, but does not intersect, the narrow band. The two-leg Hubbard ladder with diagonal nearest neighbor hoppings, a model for the ladder-type cuprates, was studied as a system in which such a situation is realized, where a possible occurrence of extremely high T_c was suggested. Here, we extend this study, and show that this high-T_c mechanism works in a variety of systems that consist of wide and narrow (or flat) bands, such as the diamond lattice [2] and the three-leg ladder. We apply the fluctuation exchange approximation to the Hubbard model on these lattices, and show that superconductivity is strongly enhanced when the Fermi level sits close to the narrow band [3]. This shows the generality of the mechanism of high-T_c superconductivity originating from wide and incipient narrow bands.

In reality, ladder-type cuprates are notorious for being unable to control carrier doping and thus the Fermi level. As a way to realize the above mentioned situation in actual materials, we introduce a concept of "hidden ladder" electronic structure in the bilayer Ruddlesden-Popper compounds, where anisotropic *d*-orbitals of the transition metal give rise to inherent ladder-like electronic structures (figure) [4]. Namely, considering the case in which t_{2g} orbitals form the bands crossing (or lie near) the Fermi level, an electron in the $d_{xz/yz}$ orbital selectively hops in the *x*/*y* direction as well as in the *z* direction normal to the bilayer. This means that the $d_{xz/yz}$ orbital form a ladder with *x*/*y* and *z* directions being the leg and rung directions, respectively. We propose that $Sr_3Mo_2O_7$ and $Sr_3Cr_2O_7$ are candidates for the hidden ladder materials where the Fermi level sits in the vicinity of the narrow-band edge without large amount of carrier doping. Based on this electronic structure, we discuss a



possible occurrence of high-T_c superconductivity in these materials.

Figure: schematic image of hidden ladders in bilayer RP compounds

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Temperature and angular dependence of the upper critical field in $K_2Cr_3As_3$

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We report measurements of the upper critical field H_{c2} as functions of temperature T, polar angle θ (of the field direction with respect to the crystallographic c axis), and azimuthal angle ϕ (of the field direction relative to the a axis within the ab plane) for the Cr-based superconductor $K_2Cr_3As_3$ with a quasi-one-dimensional and noncentrosymmetric crystal structure[1]. We confirm that the anisotropy in H_{c2}(T) becomes inverse with decreasing temperature. At low temperatures, H_{c2}(θ) data are featured by two maxima at θ = 0 (H || c) and π/2 (H⊥c), which can be quantitatively understood only if uniaxial effective-mass anisotropy and absence of Pauli paramagnetic effect for H⊥c are taken simultaneously into consideration. The in-plane H_{c2}(ϕ) profile shows a unique threefold modulation especially at low temperatures. Overall, the characteristics of the H_{c2}(θ, ϕ, T) data mostly resemble those of the heavy-fermion superconductor UPt_3, and we argue in favor of a dominant spin-triplet superconductivity with odd parity in $K_2Cr_3As_3$.

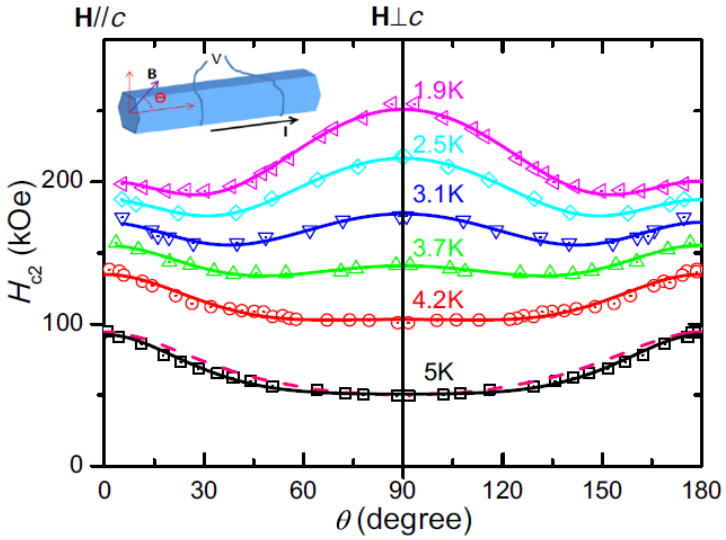

Fig. 1: *The out-of-plane $H_{c2}(\vartheta)$ (in symbols) at various temperatures for $K_2Cr_3As_3$, which are well fitted quantitatively (in solid lines) with uniaxial effective-mass anisotropy and absence of Pauli paramagnetic effect for H⊥c.*

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Ferromagnetic *p*-wave Superconductors: Progress and Open Questions

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The first discovery of an intrinsic bulk ferromagnetic superconductor dates back from 2000, in the strongly correlated uranium-based system UGe_2 under pressure [1]. Soon after, URhGe [2] and later UCoGe [3], have been found to present also homogeneous coexistence of ferromagnetism and superconductivity, at ambient pressure. We will expose the progress done on the understanding of these singular materials, thanks to successful confrontation of experiments [4,5] and theoretical predictions [6]. Remarkably, in these systems, identification of the pairing mechanism [4] is much ahead of that of the precise order parameter symmetry. Further insight has been gained by stress experiments, which revealed a strong boost of the critical temperature T_{sc} and of the upper critical field H_{c2} [5] (see Fig. 1): it is shown to arise from the intrinsic "two gaps" nature of the (non-unitary) p-wave state. This situation will be compared to the opposite case of UBe_{13}, where recent pressure measurements up to 5.6 GPa strongly support an old proposal [7] of a *p*-wave state with admixture of A_{1u} and E_u representations, but where the nature of the pairing mechanism is still completely unknown.

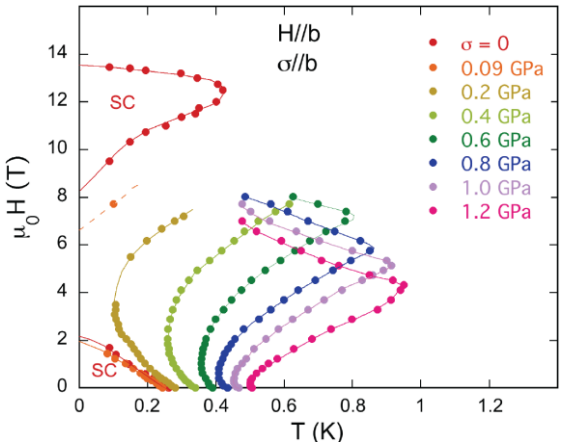

Fig. 1: *Upper critical field of URhGe, under stress applied along the b-axis [5]*

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Preformed Pairs and BEC-BCS Crossover in Organic superconductors situated near Mott localization

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Owing to the flexible lattices of organic materials, electron correlation in them is easily and precisely controllable by pressure [1]. Here, we report on our NMR and transport investigations that reveal (i) preformed Cooper pairs persisting up to twice as high as T_c on the verge of the band-width-controlled Mott transition and (ii) a pressure-induced BEC-BCS crossover in a doped spin-liquid candidate.

(i) The NMR experiments that were carried out for half-filled band systems, κ-(BEDT-TTF)$_2$X, with a range of pressures and magnetic fields show that the pseudogap-like behavior observed above T_c arises from the preformed Cooper pairs intertwined with antiferromagnetic fluctuations [2], not being accompanied by complexities of competing orders as observed in cuprate superconductors. The conventional amplitude fluctuations due to low dimensionality are ruled out by investigating three materials of different superconducting anisotropy. Concomitantly, paraconductivity above T_c is largely enhanced in excess of the conventional Aslamasov-Larkin and Maki-Thompson contributions as the system approaches the Mott localization by pressure variation.

(ii) The nonstoichiometric compound, κ-(BEDT-TTF)$_4$Hg$_{2.89}$Br$_8$ (κ-HgBr), with a neraly triangular lattice is regarded as a 11% hole-doped Mott insulator although the nonstoichiometry is uncontrollable [3]. The spin susceptibility is nearly perfectly scaled to that of a spin liquid Mott insulator, κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, whereas the two systems are distinctive in the charge sector (a metal versus an insulator) [4, 5]. This is a clear indication of spin-charge separation and substantiates the realization of a doped spin liquid in κ-HgBr. The Hall coefficient and resistivity behaviors of κ-HgBr signify a sharp crossover or quatum phase transition from a non-Fermi liquid with a small carrier density to a Fermi liquid with a large carrier density at approximately 0.5 GPa, where T_c forms a maximum, ~7 K. The pressure evolution of cohrenece length deduced from upper critical field suggests that superconductivity crosses over from BEC-like to BCS-like one at around 0.5 GPa as pressure is increased.

The work presented here was conducted in collaboration with T. Furukawa, M. Matsumoto, H. Oike, J. Ibuka, Y. Suzuki, Y. Seki, M. Urai, K. Miyagawa and H. Taniguchi.

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Thermodynamic studies on iron-chalcogenides Fe(Se,S) in the BCS-BEC crossover

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The BCS-BEC (Bardeen-Cooper-Schrieffer--Bose-Einstein condensate) crossover is one of the most fundamental frameworks treating the ground states of interacting fermions, connecting the BCS limit of weakly-coupled fermion pairs represented by most metallic superconductivity, and BEC limit of tightly-bound pairs with bosonic characters [1]. Recently the iron-chalcogenide FeSe is found to exhibit large ratio of superconducting gap and Fermi energy E_F, and giant superconducting fluctuation above the superconducting transition temperature, both of which suggest that this material is located in the BCS-BEC crossover regime [2,3]. However, the thermodynamic properties of the superconducting states in FeSe are basically described by weak-coupling BCS limit possibly due to the multiband nature of this material, where the specific heat exhibits a sharp jump of mean-field type transition at the superconducting transition temperature T_c, and there is no discernible signature of fluctuations above T_c. To investigate the evolution of the thermodynamic properties with the change of multiband character, we perform high-resolution specific heat measurements using home-built relaxation calorimeters on S-substituted FeSe, where the tetragonal-to-orthorhombic structural transition in FeSe is suppressed with increasing S concentration[4]. In the orthorhombic phase, the specific heat shows a clear jump at T_c, but in the tetragonal regime it abruptly changes to a kink-like feature with small increase of specific heat toward T_c. The evolution of specific heat with S concentration is discussed based on BCS-BEC crossover physics.

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Tuning across the BCS-BEC crossover in the multiband superconductor $Fe_{1+y}Se_xTe_{1-x}$: An ARPES study

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The crossover from Bardeen-Cooper-Schrieffer (BCS) superconductivity to Bose-Einstein condensation (BEC) is difficult to realize in quantum materials because, unlike in ultracold atoms, one cannot tune the pairing interaction. We realize the BCS-BEC crossover in a nearly compensated semimetal $Fe_{1+y}Se_xTe_{1-x}$ by tuning the Fermi energy, ε_F, via chemical doping, which permits us to systematically change Δ/ε_F from 0.16 to 0.50, where Δ is the (SC) gap. We use angle-resolved photoemission spectroscopy to measure the Fermi energy, the SC gap and characteristic changes in the SC state electronic dispersion as the system evolves from a BCS to a BEC regime. Our results raise important questions about the crossover in multiband superconductors which go beyond those addressed in the context of cold atoms.

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Dimensionality-Induced BCS-BEC Crossover

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The BCS-BEC crossover [1] is an exciting phenomenon in Fermionic systems, which connects the condensation of weakly bound pairs within the Bardeen-Cooper-Schrieffer (BCS) framework to the Bose-Einstein condensation (BEC) of strongly bound pairs. In ultracold Fermi gases, the Feshbach resonance has made it possible to experimentally realize the BCS-BEC crossover by tuning the attractive interaction strength. In superconductors, on the other hand, the BCS-BEC crossover has rarely been observed so far because the attractive interaction is usually very weak.

Recently, several experiments have suggested a surprising possibility that a relatively strong attractive interaction may be present in the iron selenide (FeSe), one of the iron-based superconductors [2, 3]. Consequently, if we can tune a bit the interaction strength, the BCS-BEC crossover will be realized in FeSe. However, in contrast to ultracold Fermi gases, it is generally difficult to control the strength of the attractive interaction in superconductors. Therefore, another idea to invoke the BCS-BEC crossover in FeSe is required.

In this study, we suggest an idea that the BCS-BEC crossover may be caused by changing the dimensionality, for example, by inserting some insulating layers. By applying the T-matrix approximation to an attractive Hubbard model of a layered system, we calculate the pair-condensation, or superconducting-transition, temperature T_c and the pair-formation temperature T^*. We found that the BCS-BEC crossover can be realized when the inter-layer hopping t_{out} is changed (Fig. 1).

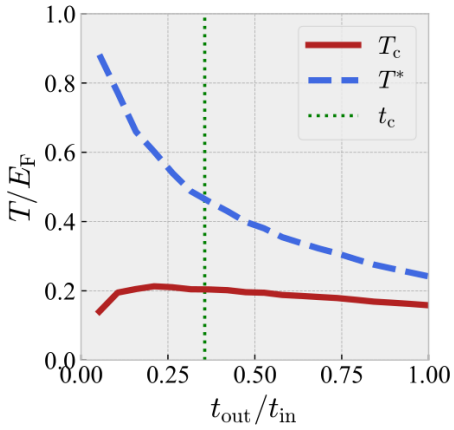

Fig. 1: *The pair-condensation temperature T_c (red solid line) and the pair-formation temperature T^* (blue dashed line) as a function of the inter-layer hopping t_{out}. Roughly speaking, the BCS-BEC crossover is realized when t_{out} passes over the bound-state-formation threshold t_c (green dotted line).*

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Weak Coupling Instability to Finite Momentum Superconductivity in the BCS to BEC Crossover

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We consider electrons in two dimensions with attractive local interaction and a microscopic π-junction type pair-hopping, deriving the Ginzburg-Landau (GL) theory to study the BCS to BEC crossover. The corresponding GL free energy includes up to sixth order derivatives of the order parameter giving rise to an intricate phase diagram. For arbitrarily weak pair-hopping there is a transition through a Lifshitz point from a homogeneous superconducting
state to a finite momentum (Fulde-Ferrell type) superconducting state. At stronger pair-hopping, the corresponding transition is bicritical with a discontinuous change from zero to finite pair momentum. At the intersection of these two types of transitions, there is a multicritical ``super-Lifshitz'' point with extra soft fluctuations, $\omega \sim q^6$, and distinct mean-field exponents. For large pair momentum the Fulde-Ferrell state may be unstable to a spatially modulated Larkin-Ovchinnikov (Pair-density wave) state. The weak coupling instability suggests a route to finite momentum superconductivity without spin-population imbalance, and we discuss the possible relevance to the cuprate superconductors.

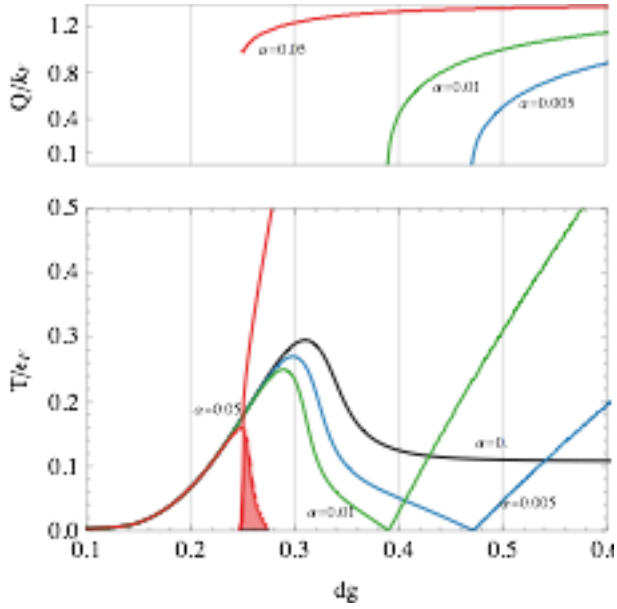

Fig. 1: *Critical temperature and pair-momentum,Q, for different relevant strengths, α, of pair-hopping. For small α the transition to a finite momentum (Fulde-Ferrell) state is continuous in Q and goes trough a zero temperature Lifshitz point. For greater α the momentum jumps at a finite temperature bicritical point..*

Gate-controlled low carrier density 2D superconductors toward BCS-BEC crossover

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Electrical control of two-dimensional (2D) superconductivity has been attracting more and more interests as represented by $SrTiO_3$, and very recently, gate-tunable superconductivity in magic angle-twisted bilayer graphene caused a significant excitement [1]. In this presentation, we demonstrate that the gate-control of electrochemical intercalation processes offers a new opportunity to approach low carrier-density 2D superconductors. Associated with the enhancement of critical temperature T_c in lightly doped region of layered nitrides (ZrNCl and HfNCl), the system approaches a crossover region from the Bardeen-Cooper-Schrieffer (BCS) limit to the Bose-Einstein condensation (BEC) limit. This result sheds new light on the investigation of 2D superconductors.

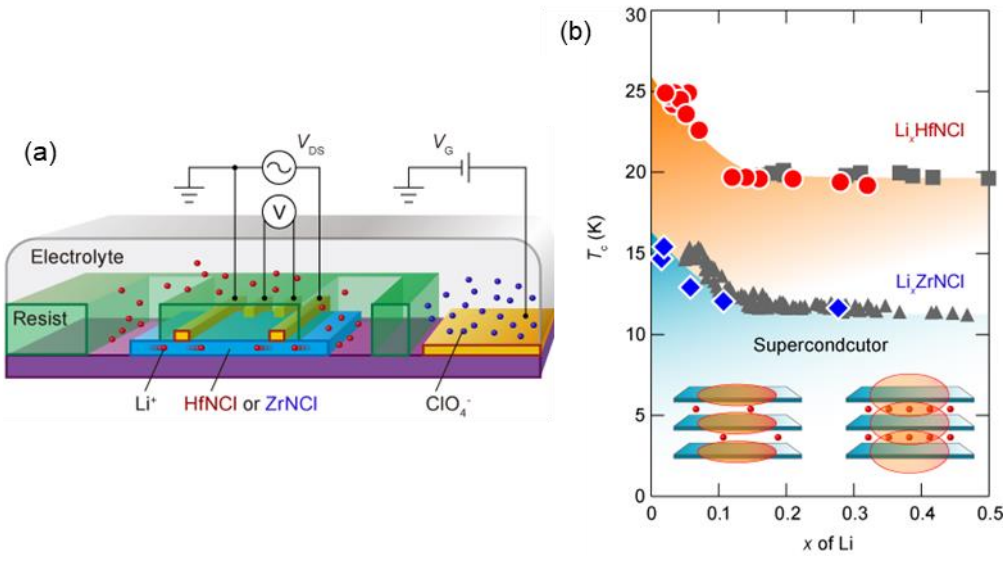

Fig. 1: *(a) Schematic of the device for intercalation. Lithium ions are intercalated to the crystal driven by a gate voltage V_G. (b) Phase diagram of layered nitrides. Red circles and blue diamonds indicate T_c obtained in our study, whereas gray squares and triangles are data taken from previous studies [2,3].*

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Robust Dynamical Charge Density Waves in High-T_c Superconducting Cuprates

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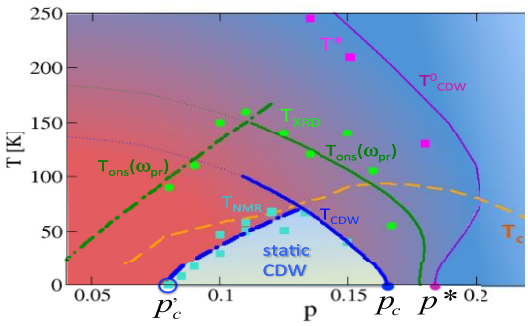

Fig. 1: (*From [1]) Summary YBCO phase diagram. Increasing reddish hue corresponds to more well-defined CDW amplitude*

There is increasing consensus that charge modulations are a common occurrence in all families of high temperature superconducting cuprates. According to an old proposal [1] recently revised and extended [2], charge density waves (CDW) arise from a quantum critical point around optimal doping, but, due to the near two-dimensionality of the CuO_2 planes and competition with superconductivity, the quantum charge fluctuations usually stay dynamical without forming a long-ranged CDW. These dynamical fluctuations could in fact provide a possible mechanism for the Marginal Fermi Liquid behavior of these systems and (contribute to) the high superconducting Tc. Commensuration, pinning and/or surface effects make the CDW more static and its presence was since long confirmed in the *underdoped* region by inelastic neutron scattering, STM, or NMR. On the other hand, at higher doping and temperature, where the short-range fluctuating character of the CDW is more pronounced, Resonant Inelastic X-ray Scattering (RIXS) is most suitable to investigate the presence and the character of CDW fluctuations and it provides a clear evidence that strong, quite long-ranged CO fluctuations extend even in the overdoped region of Bi2201 cuprates [3]. The important role of a van Hove singularity in driving CDW in the overdoped regime of this class of cuprates indicates that CDW occur as an instability of a metallic Fermi liquid state with no influence of long-ranged spin excitations and `Mottness'. RIXS has also recently allowed a re-examination of the temperature dependence of CDW in the 123 family [4], with surprising results that will stimulate a revision of the current understanding of the CDW phenomenon in cuprates.

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A NON-EQUILIBRIUM APPROACH TO THE OPTICAL SPECTROSCOPY OF CUPRATES SUPERCONDUCTORS

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Non-equilibrium spectroscopies of high temperature superconductors have evolved in the last two decades from avant-garde studies to a crucial tool for understanding the physics of high temperature superconductors. In particular, the possibility of obtaining both spectral and temporal information simultaneously leads to insights that are complementary (and in some instances beyond to) those attainable by conventional equilibrium experiments. This presentation is focused on the still unresolved problem of the origin of the pseudo-gap in cuprates, one of the major open issues about copper-oxides based superconductors. Indeed, the ubiquitous phenomenology of the pseudo-gap, occupying a wide region of the phase diagram, is not understood yet. Its comprehension could provide clue information about the microscopic mechanisms of these materials and their phase diagram. We investigate the pseudo-gap with non-equilibrium approach, that allows to disentangle the intertwined degrees of freedom (carrier, lattice. long range order) by their timescale.

Unconventional high field superconductivity in the underdoped copper-oxide Tc superconductors

Suchitra Sebastian
University of Cambridge

We explore the nature of superconductivity in the underdoped high Tc superconductors by studying the electrical resistivity over a broad range of magnetic field and temperature. We find strikingly unconventional behaviour characteristic of strong pairing in the underdoped cuprates, in contrast to the overdoped cuprates.

Scanning noise spectroscopy on a cuprate high temperature superconductor

Doohee Cho[1], Koen M. Bastiaans[1], Tjerk Benschop[1], Damianos Chatzopoulos[1], Irene Battisti[1], Maarten Leeuwenhoek[1], Jan Zaanen[1], Milan P. Allan[1]

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Valuable information about dynamics in electric charge transport cannot be accessed by conventional time-averaged spectroscopy techniques. An example is the granularity of charge that leads to current fluctuations; so called shot noise. Correlations can lead to deviations from Poissonian noise which are smeared out in the averaged current value. In mesoscopic systems, noise-spectroscopy measurements have been widely used to investigate the dynamics of strongly correlated phenomena. Here, we present a newly developed noise spectroscopy technique, for which we combined a Scanning Tunneling Microscope (STM) with a novel MHz amplifier to bring noise-spectroscopy measurements to the atomic scale. We demonstrate the Poissonian tunneling process on Au(111) surface. In addition, we observe unexpected non-Poissonian tunneling process on a cuprate high temperature superconductor with atomic resolution. This provides us a new way to unveil electronic properties hidden in the time-averaged transport measurements on exotic quantum materials.

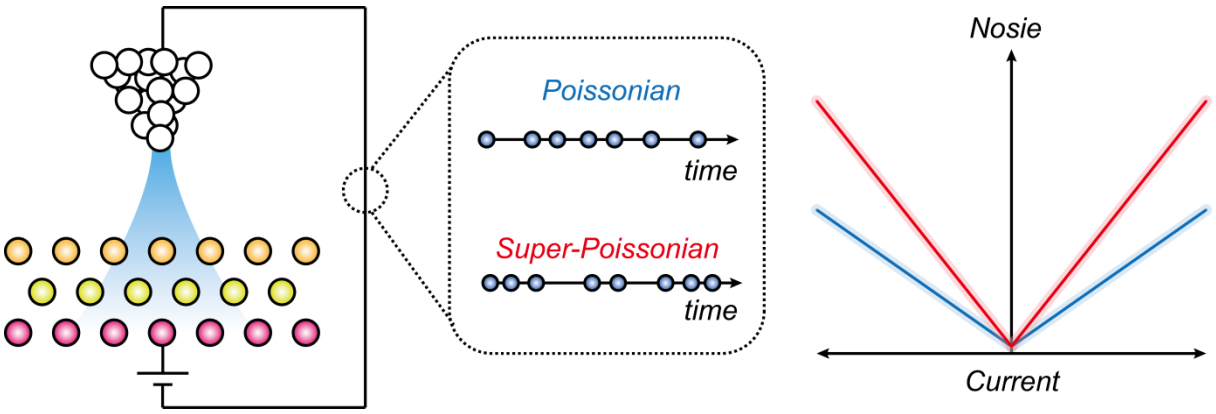

Fig. 1: *Schematics of (super)-poissonian tunneling process and their noise spectra.*

NMR study of CDW order in $YBa_2Cu_3O_y$ under hydrostatic pressure

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We address the question whether the enhancement of superconducting T_c with the application of hydrostatic pressure is due to the suppression of a competing charge-density-wave ordered (CDW) phase as proposed by Cyr-Choinière et al. [1]. Using a BeCu clamp cell and Daphne oil as the pressure medium we apply 1.9 GPa (19 kbar) to a very clean $YBa_2Cu_3O_y$ single crystal with an oxygen concentration y = 6.56 (p = 0.109) and increase its Tc from 60.5 K at 0 GPa to 66.5 K.

We have performed ^{17}O-NMR measurements under hydrostatic pressure and studied its effect on the 2D short-ranged CDW as well as the 3D long-ranged CDW in high magnetic fields. Since hydrostatic pressure enhances T_c and the critical field H_{c2} the main effect is a higher onset field towards the long-range CDW order which emerges when CDW patches inside and around vortex cores start to overlap [2]. Neither CDW phase appears to be strongly affected by the applied pressure. This is confirmed by the fact that a negative sign of the hall effect in $YBa_2Cu_3O_{7-\delta}$ (p=0.11) [3] as well as Quantum Oscillations in $YBa_2Cu_4O_8$ [4] persist under moderate pressures. On the other hand these results are in conflict with different X-ray diffraction studies that find a complete suppression of charge order at 10 to 15 kbar [5-6].

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Orbitals and Nematicity in La-1111 Single Crystals

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While there is broad consensus that superconductivity in Fe based superconductors is due to an unconventional, most likely electronic pairing, many important aspects of the normal and superconducting state are still unexplored. In particular, the role of orbital degrees of freedom for the normal state electronic properties, nematicity, and pairing is discussed very controversial. In my talk I will present results on a series of large high quality La-1111 single crystals which have been grown for the first time using a method based on anomalous solid state reaction. We have reexamined the phase diagram and studied magnetism and nematic order by means of NMR and strain dependent transport measurements. The possible formation of polaron-like structures will be discussed and evidence for an unusual state with suppressed long range order and soft nematic fluctuations will be presented.

Symmetry-breaking phenomena in iron-based superconductors

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The anomalous normal state of high T_c copper oxide superconductors remains a mysterious state of matter. It has been attributed to several mechanisms such as a precursor pairing, a novel form of spin/charge ordering, electron nematicity, and so on. To gain further insights into the relationship between the high T_c superconductivity and these possible symmetry breaking phenomena, the exploration of normal states in other high T_c superconductors, namely iron-based superconductors, is highly desired.

Here we provide the evidences of symmetry-broken electronic states via angle-resolved photoemission spectroscopy (ARPES) in superconducting $BaFe_2As_2$ and FeSe families. Our results reveal an indication of composition-dependent orbital ordering in the isovalent $BaFe_2(As_{1-x}P_x)_2$ system [1], appearing as the inequivalent energy shifts in the *zx* and *yz* iron 3*d* orbitals that breaks the fourfold rotational symmetry of iron square lattice. They persist above the nonmagnetic superconducting dome to the optimally doping, and disappears in the overdoped regime concomitantly with the pseudogap [2]. It thus shows a notable similarity with the anomalous normal states in cuprates. Similar type of *zx* / *yz* orbital ordering, but with the sign change in momentum sapce, is also observed in FeSe [3]. In contrast to these rotational symmetry broken state, a recent result on hole-doped $(Ba,K)Fe_2As_2$ system provides the clear signatures of antiferroic instability existing in the wide doping region including the optimally doping[4]. The nature of these ubiquitous symmetry breaking phenomena in iron-based superconductors will be discussed.

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Orbital selectivity and nematicity in iron pnictides and chalcogenides

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I will first briefly review our recent study on the orbital selectivity in iron-based superconductors by using the U(1) slave-spin method. Then I will focus on the interplay between orbital selectivity and nematicity in FeSe. I show that a finite nematic order helps to stabilize an orbital selective Mott phase. Moreover, when the d- and s-wave bond nematic orders are combined with the ferro-orbital order, there exists a surprisingly large orbital selectivity between the xz and yz orbitals even though the associated band splitting is relatively small. These results explain the seemingly unusual observation of strong orbital selectivity in the nematic phase of FeSe, and uncover new clues on the nature of the nematic order, and set the stage to elucidate the interplay between superconductivity and nematicity in iron-based superconductors.

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Abrupt Change of the Superconducting Gap Structure at the Nematic Critical Point of $FeSe_{1-x}S_x$

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The emergence of the nematic electronic state that breaks rotational symmetry is one of the most striking properties of the iron-based superconductors. Recent experiments on FeSe, in which superconductivity coexists with a non-magnetic nematic order, have revealed highly exotic electronic properties, including its extremely small Fermi-surface pockets, superconductivity at the verge of BCS-BEC crossover, and highly anisotropic superconducting gap even in the tiny Fermi pockets [1]. $FeSe_{1-x}S_x$, in which the nematicity can be tuned by isoelectronic sulfur substitution, offers a fascinating opportunity to clarify the direct relationship between the nematicity and superconductivity [2].

Here, we measure thermal conductivity and specific heat of $FeSe_{1-x}S_x$ to reveal how the superconducting gap evolves with nematicity. Two findings are highlighted [3]. First, superconducting gap is highly anisotropic in the whole nematic regime and the tetragonal regime, indicating strongly anisotropic pairing interaction in the whole superconducting regime. Second, more surprisingly, the superconducting gap structure in the nematic and the tetragonal regimes are essentially different, demonstrating a dramatic change of the pairing interaction at the nematic quantum critical point. Our observation provides direct evidence that the orbital-dependent nature of the critical nematic fluctuations has a strong impact on the superconducting pairing interaction.

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Theory of the supercyclotron resonance and Hall response in anomalous 2d metals

Sean Hartnoll
Luca Delacretaz

Abstract:

Weakly disordered superconducting films can be driven into an anomalous low temperature resistive state upon applying a magnetic field. Recent experiments on weakly disordered amorphous InO_x have established that both the Hall resistivity and the frequency of a cyclotron-like resonance in the anomalous metal are highly suppressed relative to the values expected for a conventional metal. We show that both of these observations can be understood from the flux flow dynamics of vortices in a superconductor with significant vortex pinning. Results for flux flow transport are obtained using a systematic hydrodynamic expansion, controlled by the diluteness of mobile vortices at low temperatures. Hydrodynamic transport coefficients are related to microscopics through Kubo formulae for the longitudinal and Hall vortex conductivities, as well as a `vorto-electric' conductivity.

Unconventional superconducting phases in hole doped two dimensional transition metal dichalcogenides

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Monolayers of transition-metal dichalcogenides (TMDCs) are two-dimensional materials whose low energy sector consists of two inequivalent valleys. The valence bands have a large spin splitting due to lack of inversion symmetry and strong spin-orbit coupling. Furthermore the spin is polarized up in one valley and down in the other (in directions perpendicular to the two-dimensional crystal). We focus on lightly hole-doped systems where the Fermi surface consists of two disconnected circles with opposite spins. For both proximity induced and intrinsic local attractive interaction induced superconductivity, a fully gapped intervalley pairing state is favored in this system, which is an equal superposition of the singlet and the m=0 triplet for the lack of centrosymmetry. Consequently a ferromagnetically ordered magnetic-adatom chain placed on a monolayer TMD superconductor provides a platform to realize one-dimensional topological superconducting state characterized by the presence of Majorana zero modes at its ends. The topological superconducting phase is affected not only by the adatom spacing and the direction of the magnetic moment, but also by the orientation of the chain relative to the crystal.

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Mott Jahn-Teller insulating state in single layer $1TNbSe_2$

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We study the structural, electronic and vibrational properties of single-layer $1TNbSe_2$ from first principles. Within the generalized gradient approximation, the 1T polytype is highly unstable with respect to the 2H. The DFT+U method improves the stability of the 1T phase, explaining its detection in experiments. A charge density wave occurs with a $\sqrt{13}\times\sqrt{13}$ R30° periodicity, in agreement with STM data. At U=0, the David-star reconstruction displays a flat band below the Fermi level with a marked d_{z2-r2} orbital character of the central Nb. The Hubbard interaction induces a magnetic Mott insulating state. Magnetism distorts the lattice around the central Nb atom in the star, reduces the hybridization between the central Nb d_{z2-r2} orbital and the neighboring Se p-states and lifts in energy the empty d_{z2-r2} flat band becoming non-bonding. This cooperative Jahn-Teller and correlation effect amplifies the Mott gap.
Our results are relevant for the broad class of correlated insulator in the presence of a strong Jahn-Teller effect.

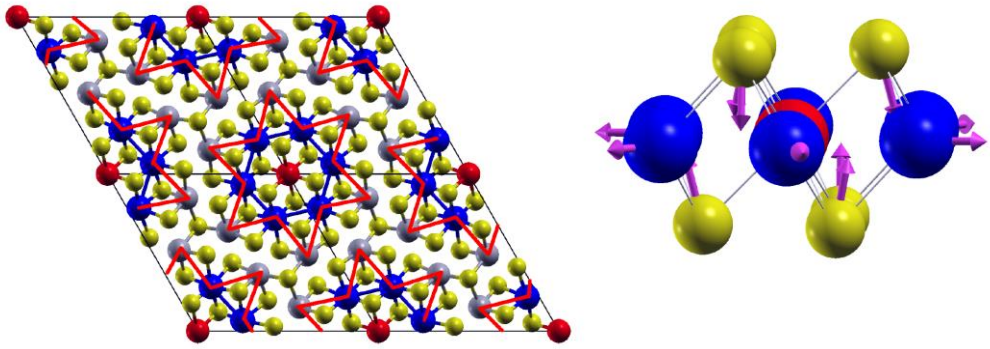

Fig. 1: Left, $\sqrt{13}\times\sqrt{13}$ R30° charge density wave reconstruction in single layer 1TNbSe2. Right, Jahn-Teller distortion inducing an insulating state on top of the $\sqrt{13}\times\sqrt{13}$ R30° David-star reconstruction. Yellow spheres are Se atoms, red is the central Nb atom in the star, and blue are the Nb atoms nearest to the central one forming a $\sqrt{7}\times\sqrt{7}$ cluster.

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Chiral and disordered polaron textures, metastability and carrier duality in systems with competing orders

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Photoexcited metastable states created under different non-equilibrium conditions in correlated electron materials exhibit various complex charge-ordered textures. 1T-TaS_2, which shares much of the physics with high-temperature superconductors, but on a triangular lattice, shows new metastable complex vortex charge-ordered structures[1] and an amorphous glassy state[2] that can be observed in fine detail by scanning tunneling microscopy (STM). The observed near-degenerate states are reached by fine control of non-equilibrium conditions under which they are created. Remarkably, the quantum glass exhibits dual localized/itinerant character. Such a duality has been a long-standing puzzle of the textured normal state of cuprates and other oxides, and known from the 2-component optical response, the dichotomy observed in STM/transport/ARPES measurements and other related anomalies in transport properties. Here we attribute the dual behavior to a Fano-like interference between localized states jammed in the process of avalanche multiplication, and itinerant carriers in a highly dispersive band forming the equilibrium Fermi surface. An analogy can be drawn between this k-space duality and the interplay of nodal and antinodal quasiparticles in cuprates. Modelling of the observed self-organized textures with fractionally charged metastable states can be understood to be the result of localization of a portion of the photoexcited electrons subject to competing Coulomb correlations and screening arising from the lattice deformations. The metastability of the emergent states is caused by topological protection of non-trivial defects, revealing a mechanism for creating metastable functional states in photoexcited strongly correlated electron systems.

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Transport study of superconducting-normal (SN) junctions at the surface of ionic gated MoS_2

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Molybdenum disulfide (MoS_2) is a layered material similar to graphene that can be thinned down to a few atomic layers. Along with the superior electronic and optical properties that are promising for ultrathin electronic devices, applying strong field effect on MoS_2 can dope this intrinsic semiconductor to be a superconductor [1-3]. In this work, we focus on the electrical transport properties at the superconducting-normal (SN) interface in ionic gated MoS_2. We show the results of two different device structures: (1) By partially covering MoS_2 with a hexagonal boron nitride (*h*-BN) flake to isolate MoS_2 from ionic media, an SN junction could be configured at the top surface of MoS_2. The magnetoresistance at the SN interface shows a non-monotonic behavior, signifying the Andreev reflection as a function of the energy barrier height, the superconducting gap and the electron energy [4]. (2) The differential conductance between a normal metal contact and superconducting MoS_2 exhibits a clear suppression at low bias voltages. This behavior can be nicely fitted by the Blonder-Tinkham-Klapwijk (BTK) model [5], which describes the crossover from metallic to tunneling behavior of a SN micro-constriction contact. From the fitting, valuable information could be obtained about the gate induced superconductivity in MoS_2, such as the superconducting gap, potential barrier etc.

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Orbital Degeneracy, Mott-Jahn-Teller Insulators, and Strongly Correlated Superconductivity in Molecular Conductors, especially Fullerides

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Orbital-related effects, generally quenched in broad-band solids, recover an important role for molecular conductors near a Mott transition, where electron correlations lead to dramatic quasi-particle band narrowing. I will review our model of alkali fullerides [1] as an instructive example where orbital degeneracy-driven dynamic Jahn-Teller distortions lead to superconductivity from metallization of a low-spin Mott insulator [2], a mechanism at the same time correlation- and phonon-related. I will show how comparison of calculated and experimental IR spectra provides spectroscopic evidence for this mechanism. [3] Finally if time permits I will briefly discuss other models such as those speculatively suggested in connection with doped polycyclic aromatic hydrocarbons, [4] where once again degeneracy may allow Coulomb correlations to favor superconductivity rather than suppressing it.

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Crossover from impurity-controlled to granular superconductivity in $(TMTSF)_2ClO_4$

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The organic superconductor $(TMTSF)_2ClO_4$ is an archetypal quasi-1D non-*s*-wave superconductor [1,2]. It also exhibits an order-disorder transition, due to ClO_4 tetrahedral anions orientation at T_{AO} = 24 K, that can be controlled by the cooling rate across T_{AO} [2]. Thus, this compound provides a rare opportunity to precisely study how non-*s*-wave superconductivity evolves with disorder.

In this study, we performed simultaneous measurements of the *c*-axis resistivity and AC susceptibility of $(TMTSF)_2ClO_4$ single crystals, under precise control of the cooling rate across T_{AO}. The measurements were performed below 1 K, using a dedicated compact susceptometer [3]. Higher cooling rates increase the residual resistance and reduce T_c (Fig. 1), as expected for the destruction of non-*s*-wave superconductivity by non-magnetic impurities [2]. However, when the disordered volume fraction increases, the critical temperatures derived from resistivity and from susceptibility deviate from each other, while superconducting shielding is incomplete and dissipation finite. All these features indicate that superconductivity becomes inhomogeneous at high disorder [4].

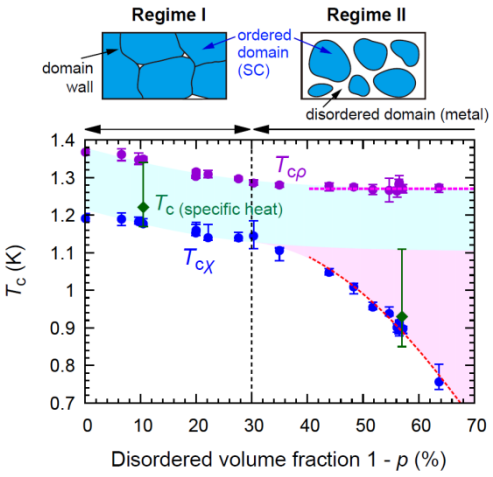

Fig. 1: *Evolution of the critical temperatures derived from resistivity ($T_{c\rho}$) and from susceptibility ($T_{c\chi}$) with the disordered volume fraction, proportional to the cooling rate.*

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Discovery of superconductivity in poly-*p*-phenylene oligomers

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Organic compounds are always promising candidates of superconductors with high transition temperatures T_c's. Here we will talk about our recent discovery of superconductivity in polyparaphenylene oligomers. We will show that doping C-C bond connecting molecules – *p*-terphenyl [1] or *p*-quaterphenyl [2] by potassium can bring about superconductivity above 120 K at atmosphere pressure, which is comparable to the highest T_c in cuprates. Superconductivity has also been found in other oligomers with short or long chain lengths [3,4], together with a phenyl molecule [5]. The easy processability, light weight, durability of plastics, and environmental friendliness of these new superconductors have great potential for the fine-tuning of electrical properties. This discovery opens a window for exploring high temperature superconductivity in chain link organic molecules.

This work was done in collaboration with Ren-Shu Wang, Kai Zhang, Jia-Feng Yan, Ge Huang, Yun Gao, Zhong-Bing Huang, Guo-Hua Zhong, and Hai-Qing Lin.

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Confined Superconductivity and Ferromagnetism in Boron Doped Diamond.

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Diamond is an interesting material for both, science and applications. Its importance increased even more after the discovery of superconductivity upon boron doping in 2004. It opened novel possibilities for fundamental research of superconductivity in doped insulators and in the presence of tunable disorder. Particularly, in its polycrystalline form, it represents a complex system in which the intragranular, as well as intergranular effects in superconducting condensate can be observed locally and compared to its bulk properties. In our experiments, we studied polycrystalline boron doped diamond prepared by chemical vapor deposition under various conditions. Our observations revealed *i.a.* signs of ferromagnetism coexisting with superconductivity [1] and breaking of the global phase coherence of the superconducting condensate [2]. The apt combination of experiments studying bulk properties with local investigations at the nanoscale enabled us to test and interpret these nonintuitive findings.

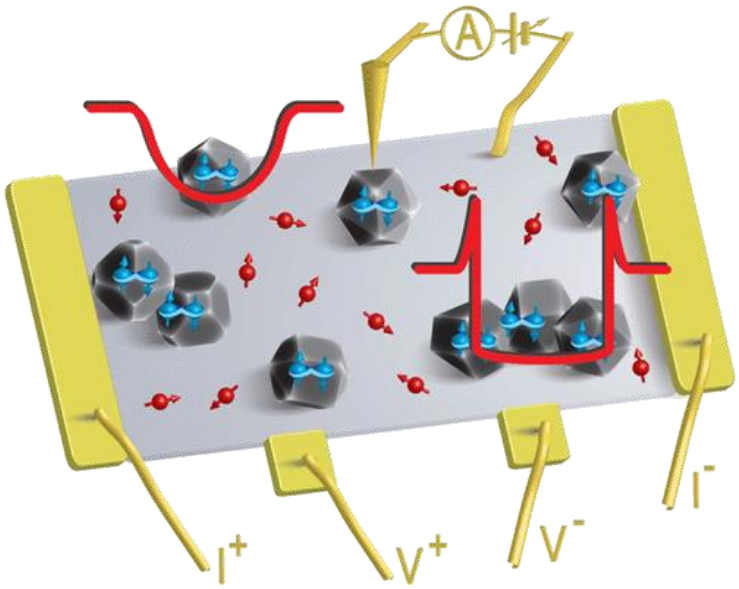

Fig. 1: *In polycrystalline boron doped diamond, a phase-coherent superconducting condensate is present. In isolated nanograins, however, localized Cooper pairs were observed.*

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Interplay between electron-phonon and electron-electron interactions in electron doped aromatic carbon materials viewed from electrical transport probe

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A Mott physics on unconventional superconductors, such as cuprates, Fe pnictides, and organic conductors is now claimed for electron-doped aromtatic hydrocarbon such as antracene, tetracene, pentacene, and expanded C_{60} [1-4] as well as even in graphene [5]. Electron-electron (e-e) correlations are thought to be the very important origin of its high Tc superconductivity. On the other hand, the highest superconductivity surpassing the cuprates recently found in H_2S under high pressure gives the discussion back to the electron-phonon (e-ph) mediated superconductivity for achieving high T_c. Although, relatively high T_c in superconductivity was once claimed for simple aromatic hydrocarbons with electron carrier filling into their bands by alkali-metal insersion, the real electronics states have not yet been understood so far. This is partly beause important scientific discussions have been made based on only limited magnetic and optical probes. The Fermi surface of A_3C_{60} (A=alkali metals: K, Rb, Cs) superconductors with expanded cell ($V_{cell}(C_{60}^{3-})$) provides an intriguing research platform for both e-e and e-ph interactions. However, being different from other unconventional superconductors, electrical transport measurements had been very difficult in expanded A_3C_{60} and they are made only for K_3C_{60} and Rb_3C_{60} with small cell size far apart from the Mott boundary. Here, we give experimental results that accurate electrical resistivity (ρ(T,P)) can be achieved for a variety A_3C_{60} with expanded $V_{cell}(C_{60}^{3-})$ near the Mott boundary under various temperature (T) and pressure (P). Electrical transport was carefully measured as a function of T and P, straddling the phase boundary between the Mott insulator and the metallic/superconducting phase. In this presentation, a new phase diagram is proposed, which unambiguously shows an unprecedented new metallic state existing in the universal T-$V_{cell}(C_{60}^{3-})$ phase diagram. The new metallic states shows an exotic antiferromagnetic metallic state, which can be recognized to be metallic in the electrical transport ρ(T) and antiferromagnetic from the viewpoint of magnetic susceptibility χ(T). The new phase is interpreted to be generated by interplay between e-ph interactions via dynamic Jahn Teller phonons and relatively large e-e correlations, showing a strong T-evolution of ρ(*T*). This intriguing relation can systematically be observed for A_3C_{60} with a variety of cell volume controlled by chemical (stoichiometric composition of A_3C_{60}) and physical pressure. The new electronic phase is considered to have a common physics among many materials having large freedom of entropy.

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New Superconductors Tuned at High Pressures

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Discovery of a New Cuprate with Unusual Features: Significance for High-T_c Physics

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The new cuprate, $Ba_2CuO_{3+\delta}$ (or Ba_2CuO_{4-y}), has oxygen deficient K_2NiF_4 structure and T_c of 73 K. High-T_c superconductivity of this cuprate emerges from unprecedented environments; (1) strongly hole-overdoped, (2) the shortest apical-O distance among the known cuprates, and (3) oxygen-deficient Cu-O planes. The estimated hole density $p = 2\delta$ is 0.6 ± 0.2/Cu, well beyond the T_c-dome of ordinary cuprates, and the apical-O distance is 1.862 Å, shorter than the in-plane Cu-O bond length 2.0015 Å.

The features (1) and (2) suggest that this cuprate may be a multi-band high-T_c superconductor with possible pairing symmetry different from the ordinary *d*-wave. The most intriguing is (1); this cuprate contains a large amount of O vacancies ($y = 0.7 \pm 0.1$) in its Cu-O plane. Although the exact O-depleted plane structure remains to be determined, the vacancies should order, organizing a new structure other than the CuO_2 plane that sustains high-T_c superconductivity.

Onset of the photo-excited transient superconductivity and Nernst effect at the emergence of local phase coherence of preformed pairs

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In recent series of optical conductivity measurements after ultrafast laser photo-excitations in high-T_c cuprates and K_3C_{60} systems, Cavalleri and co-workers found a signature similar to superconducting gapping in transient responses well above T_c, reaching up to 300 – 400 K [1,2]. In 2000 – 2010, Ong and co-workers observed Nernst effect [3] and diamagnetic susceptibility [4] which develop in the underdoped region of cuprates well above T_c. In this presentation, resorting to a plot of T_c versus the superfluid density [5], and T_c versus the effective Fermi temperature T_F [5,6], we point out that the onset of the transient gapping of optical conductivity, Nernst effect and diamagnetic susceptibility occurs at the emergence of local phase coherence of preformed pairs in the normal state well above T_c.

Since 1988, we performed Muon Spin Relaxation measurements of the superfluid density n_s/m^* in high T_c cuprate and many other unconventional superconductors [4], and presented a nearly linear relation between T_c and n_s/m^* at $T \rightarrow 0$, and T_c vs T_F obtained from n_s/m^*. The superfluid density corresponds to the gapped Drude spectral weight in optical conductivity. From n_s/m^* one can derive a "hypothetical BEC energy scale" T_{BEC} by calculating Bose-Einstein condensation temperature of ideal non-interacting Bose gas having boson density of $n_s/2$ and mass $2m^*$. T_{BEC} represents the temperature at which the thermal wave length of bosons becomes comparable to the interboson distance. For the situation with dominant pre-formed pairs in the normal state of underdoped cuprates, superconductivity should have occurred at T_{BEC} if there were no competing states.

The actual T_c in cuprates and other unconventional superconductors is reduced from T_{BEC} at least by a factor of 4-5 due to competition of superconducting (SC) and antiferromagnetic (AF) order. In strongly underdoped region of cuprates, however, we demonstrate that T_{BEC} derived from MuSR agrees well with the onset temperature of Nernst effect and the diamagnetic susceptibility, and T_{BEC} derived from the transient gapped spectral weight of optical responses agrees well with the onset temperature of the gapped optical responses. This observation can be extended to the cases in K_3C_{60}, organic BEDT superconductors, as well as URu_2Si_2. These results suggest that the "superconductivity-like" responses in Nernst, diamagnetic and transient optical conductivity measurements emerge when local, dynamic and short-ranged phase coherence develop among pre-formed pairs. We also discuss the role of the magnetic resonance mode which controls T_c in the competition of the SC and AF orders, resorting to an analogy with rotons in superfluid ^{4}He [6] and noticing a transient loss of the 400 cm^{-1} mode responses in photo-excited optical conductivity [7].

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Direct Observation of Symmetry-Distinct States with Nontrivial Doping Evolution in a High-Tc Cuprate Family by Polarization-Dependent ARPES

Rui-Hua He[1], M. Hashimoto[2], K. Tanaka[3], S.-K. Mo[4], A. Sorini[2], T. Sasagawa[5], M. Fujita[6], T. Adachi[6], M. Enoki[6], S. Iikubo[6], Yu He[2], M. Yi[2], N. Mannella[2], Hong Yao[2], W. Meevasana[2], T. P. Devereaux[2], Y. Koike[6], K. Yamada[6], Z. Hussain[4], Z.-X. Shen[2]

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Current understanding of high-temperature superconductivity in cuprates largely builds upon a simplified description of the low-energy electronic structure as a single band formed by states of in-plane d_{x2-y2} symmetry. Recent experiments in La-based cuprates (La214), however, revealed signs for a possible breakdown of this description and key relevance of some states of c-axis symmetry as the hole doping increases above ~20%. Direct observation of these symmetry-distinct states in the energy-momentum space and study of their doping evolution would provide an important basis for understanding these results. Here we use polarization-dependent angle-resolved photoemission spectroscopy to identify states of predominantly c-axis symmetry near the Fermi level in La214. Above ~20% doping, these states reside in the same band as the d_{x2-y2}-symmetry states. Below ~20%, a notable difference is observed in their band dispersions as both symmetry states start to be influenced by similar pseudogap phenomena. Our finding highlights a nontrivial doping evolution of the c-axis-symmetry states in La214 yet to be captured by a more complete description of its electronic structure, and warrants systematic studies of these states in other cuprate families using a similar approach.

POSTERS

Crystal growth and superconductivity in $CaBi_2$

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$CaBi_2$ single crystals were grown by self-flux method [1]. The energy-dispersive spectroscopy (EDS) yielded a Ca:Bi ratio of 1:2, and the powder X-ray diffraction confirmed the $ZrSi_2$–type crystal structure of the samples. The crystals were studied by means of magnetic susceptibility and heat capacity measurements. Analysis of the low temperature C(T) data yielded the Sommerfeld coefficient = 4.1 mJ $mol^{-1} K^{-2}$ and the Debye temperature Θ_D = 157 K. The specific heat jump observed at T_c was $\Delta C/ T_c$ = 1.41, indicating bulk superconductivity. The estimated electron–phonon coupling strength was λ_{el-ph} = 0.59, and the thermodynamic critical field H_c was found to about 120 Oe , suggesting that $CaBi_2$ is a moderate coupling type-I superconductor. Calculations of the electronic structure revealed a mixed quasi-2D and 3D character of the Fermi surfaces, which reflect the layered character of the crystal structure. Preliminary spectroscopic results suggest the presence of the topological nodal line states in freshly cleaved $CaBi_2$ single crystal. [2]

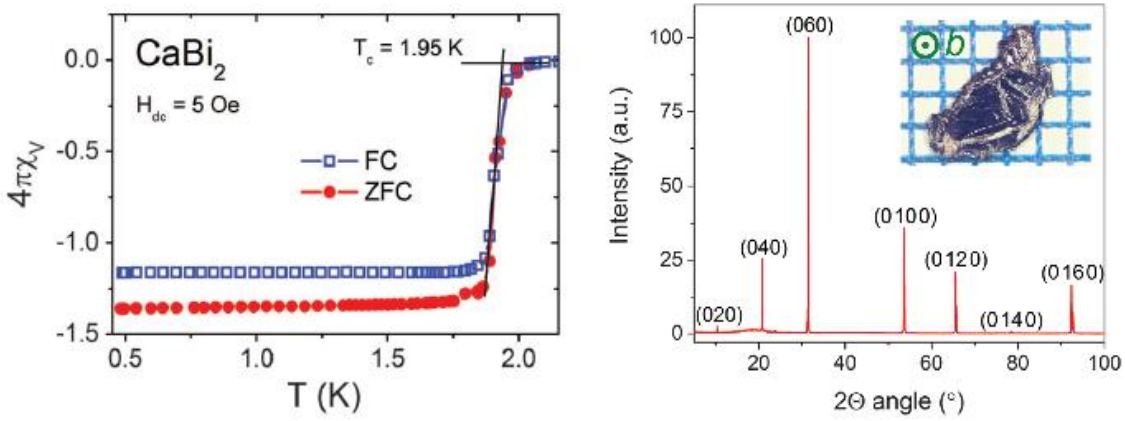

Fig. 1:*Left panel: zero-field cooling (ZFC) and field-cooling(FC) magnetic susceptibility vs. temperature. Right panel: X-ray diffraction on a single crystal shown in the inset. Miller indices of the Bragg planes are (0 k 0).*

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Inter-valley chiral topological superconductivity in a grapheneMoire superlattice

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Multiband effects in the filled skutterudites superconductors $PrOs_4Sb_{12}$ and $LaRu_4As_{12}$ probed by measurement of the lower critical field

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The temperatures dependencies of the lower critical field $H_{c1}(T)$ of the filled-skutterudite superconductors $LaRu_4As_{12}$ and $PrOs_4Sb_{12}$ were probed by local magnetic induction measurements down to $T = 0.16$ K. For $LaRu_4As_{12}$ with the relatively high superconducting critical temperature $T_c = 10.4$ K [1], we observe a sharp enhancement of $H_{c1}(T)$ deep in superconducting state below $T/T_c \approx 0.35$ that is independent on the crystallographic orientation. Remarkably, a sudden increase of $H_{c1}(T)$ at $T/T_c \approx 0.3$ is also seen in the heavy-fermion superconductor $PrOs_4Sb_{12}$ ($T_c = 1.85$ K) [2], in fair accord with the previous macroscopic studies. A lack of similar enhancements in the closely related superconductors $LaOs_4As_{12}$ ($T_c = 3.2$ K) and $PrRu_4As_{12}$ ($T_c = 2.3$ K) clearly indicates a minor significance of anisotropy effects. Therefore, we associate the unusual behavior of $H_{c1}(T)$ for $LaRu_4As_{12}$ and $PrOs_4Sb_{12}$ to a kink structure in their superfluid densities due to different contributions from two (or multiple) bands. Open question remains the symmetry of a minor gap in $PrOs_4Sb_{12}$, since no obvious trend to a saturation of $H_{c1}(T)$ was found in the limit $T = 0$.

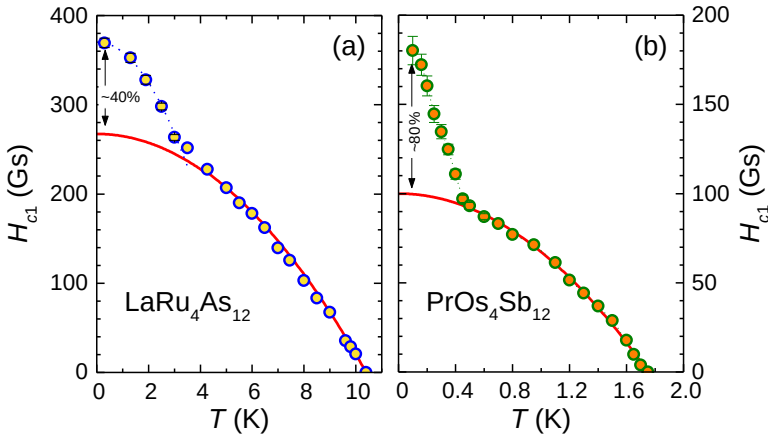

Fig. 1: Temperature dependences of the lower critical field $H_{c1}(T)$ for two filled skutterudite superconductors (a) $LaRu_4As_{12}$ and (b) $PrOs_4Sb_{12}$. Solid line is the $H_{c1}(T)$ dependences calculated in the BCS model with $\Delta = 1.764\ k_BT_c$. Both for s-wave $LaRu_4As_{12}$ and heavy fermion $PrOs_4Sb_{12}$ superconductors a pronounced enhancement of $H_{c1}(T)$ is found deep in the superconducting state, indicative of multiband effects.

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Transport and Calorimetry Study of 20% La-doped $CeIn_3$

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$CeIn_3$ is an antiferromagnt with T_N of 10 K, which becomes superconducting under pressure. At 2.6 GPa, the antiferromagnetic (AFM) phase is suppressed completely and the pressure-induced superconductivity shows its maximum critical temperature (T_C = 0.2 K), making this compound a good candidate to study relationship between superconductivity and AFM state. When Ce-site is doped with La, T_N is suppressed due to dilution effects of magnetic moments. We have studied 20% La-doped $CeIn_3$ under hydrostatic pressure up to 2.5 GPa.. In the doped compound, T_N is reduced to 8.1 K and coherence temperature deduced from resistivity measurements is also slightly lowered to 47 K from 52 K of $CeIn_3$ at atmospheric pressure. The critical pressure (P_c) where the magnetism is estimated to be suppressed completely is also slightly reduced to 2.47 GPa from 2.6 GPa of $CeIn_3$. Pressure dependences ofT_N and coherence temperature are similar in both pure and 20% La-doped $CeIn_3$. In this presentation, the detailed change of AFM state under pressure and the relationship between quantum critical point and superconductivity will be discussed via transport and calorimetry studies.

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Ce_2O_2Bi: A New Heavy Fermion Compound with Topological Bismuth-Square Net

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Recently the compounds with bismuth-square net have attracted tremendous interests due to its emergent topological characteristics. On the other hand, in the Ce-based rare earth compounds, Ce^{3+} ions usually play an important role in their properties. Here, we study the physical properties of layered Ce_2O_2Bi crystal, which is a combination of Bi^{2-} squared net and Ce^{3+} ion. In contrast to the non-magnetic counterparts like Y_2O_2Bi with a superconducting ground state, an antiferromagnetic (AFM) transition around 6.7 K is observed in the resistivity, susceptibility and specific heat data. The Sommerfeld coefficient γ_{Ce} extrapolated from the low temperature specific heat (below the AFM transition), is about 140 mJ/(mol.K^2)/Ce which is usually reduced because of the AFM ground state, indicating that Ce_2O_2Bi is a heavy fermion system. In addition, the resistivity increases with a minus logarithmic temperature dependence over the temperature range between 15 - 30 K，which is a signature of Kondo effect. The interplay between the Kondo effect and RKKY interactions, together with the conducting bismuth-square net layer make this system interesting. Further study of chemical doping or applying pressure is highly needed to investigate the possible quantum criticality in this new system.

Magnetization of Potassium Doped p-terphenyl and p-quaterphenyl by High Pressure Synthesis

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By using the high pressure synthesis method, we fabricated the potassium-doped para-terphenyl. The temperature dependence of magnetization measured in both zero-field-cooled and field-cooled processes shows step-like transitions at about 125 K. This confirms an earlier report about the possible superconductivity-like transition in the same system. However, the magnetization hysteresis loop exhibits a weak ferromagnetic background. The estimate on the diamagnetization of this step shows that the diamagnetic volume is only about 0.04% at low temperatures, if we assume that the penetration depth is much smaller than the size of possible superconducting grains. This magnetization transition does not shift with magnetic field, but is suppressed and becomes almost invisible above 1.0 T. The resistivity measurements fail because of an extremely large resistance. By using the same method, we also fabricated the potassium-doped para-quaterphenyl. A similar step-like transition at about 125 K was also observed by using a magnetization measurement (Fig. 1). Since there is an unknown positive background and the diamagnetic volume is too small, it is insufficient to conclude that this step is derived from superconductivity although it appears so.

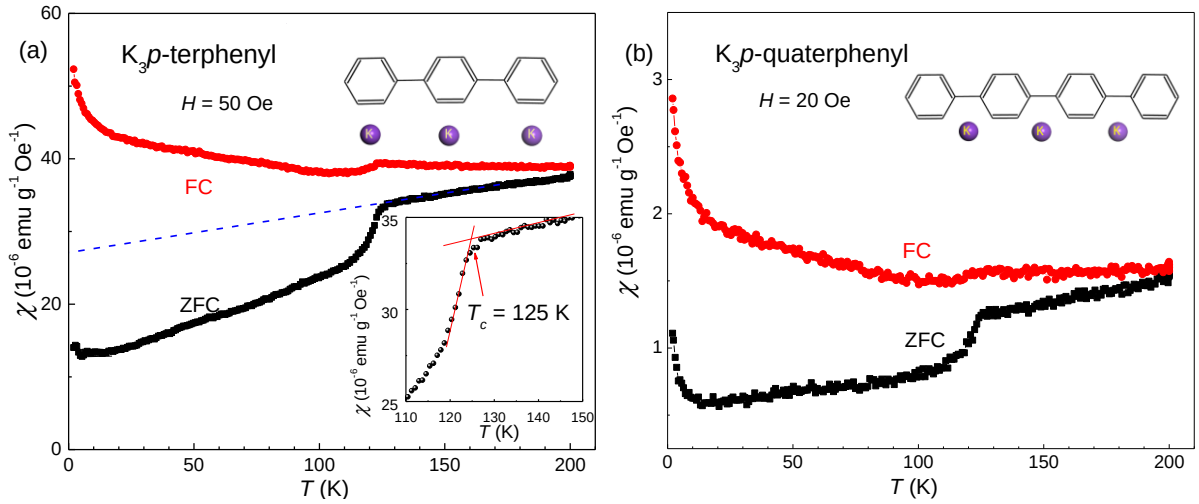

Fig. 1. *Temperature dependence of magnetic susceptibility measured in both ZFC and FC modes for high pressure synthesized (a) K_3p-terphenyl (measured at 50Oe) and (b) K_3p-quaterphenyl (measured at 20 Oe), respectively. Upper right insets in (a) and (b) present the schematic molecular structure of potassium-doped p-terphenyl and p-quaterphenyl. The bottom-right inset of (a) shows the enlarged view of magnetic susceptibility for the high pressure synthesized K3p-terphenyl near the transition temperature.*

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On the Characterization of the Main Phase in K_x*p*-terphenyl Systems

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The report of the Meissner effect in annealed samples of K_3Tp (Tp = *p*-terphenyl) has raised the interest in this deceptively simple material concerning superconductivity [1]. A limited crystallinity prevents the system to be properly analyzed by standard XRD, while purification techniques for minor potential superconducting phases are not available. Our experimental studies on the main phase show that both K_2Tp and K_3Tp mixing stoichiometries have identical Raman (solid state) and UV-vis (DME solution) spectra, being consistent with the molecular dianion by DFT and TDDFT simulations. Conductance vs. *T* plots shows an insulator (K_2Tp), and a metal (K_3Tp) with a Debye *T* similar to potassium, and no clear signs of Meissner effect in χ vs. *T* plots. The structural integrity of the *p*-terphenyl framework has been studied in mildly annealed samples of K_xTp at increasing processing time and *T*. Among the potential byproducts, K-doped poly-*p*-phenylene (K_xPPP) does not seem to explain the reported effects, so further efforts in the characterization of other minor phases are needed.

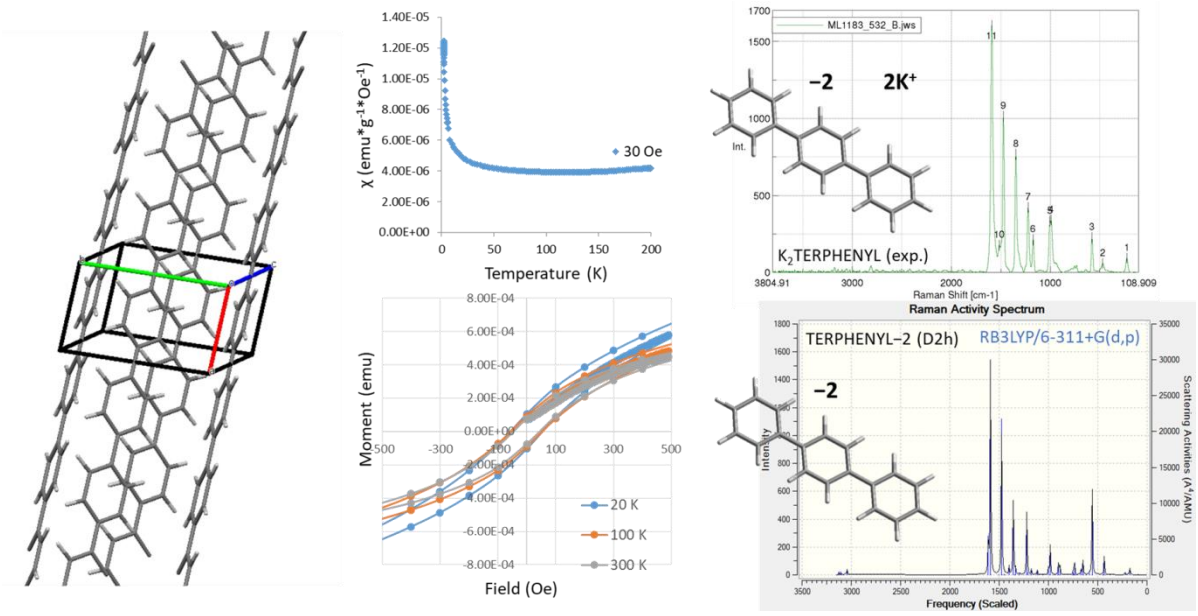

Fig. 1: *Idealized model of undoped PPP (left). Magnetic properties of K_3Tp (middle). Raman characterization of K_xTp (x=2, 3 or higher), consistent with Tp^{-2} (right).*

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Superconductivity in K doped p-terphenyl : First principles calculations of electron-phonon coupling

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Experiments have shown that P-terphenyl ($C_{18}H_{14}$) has superconducting state with transition temperature of 123K, when doped with potassium [1]. In order to explore the possible high T_c superconductivity in this material, we have performed the density functional theory calculations for the structural and electronic properties of the pristine and K_3 p-terphenyl. We have employed density functional perturbation theory to calculate the phonon dynamical matrices and hence electron-phonon interactions. Contributions of distinguished phonon modes to the electron-phonon coupling have been analyzed through the eigen-modes projection to the Eliashberg spectral function. It turns out that inter-molecular and potassium intercalant modes make most part for the large strength of the electron-phonon coupling (λ~1.66) in K_3 doped p-terphenyl. Superconducting T_c was estimated using McMillen formula.

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Stable Structural Phases of Potassium p-Terphenyl Compounds

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Extensive calculations using *ab initio* van der Waals-Density Functional Theory have been conducted to characterize thermodinamically stable phases of potassium intercalated para-terphenyl compounds [1]. The addition of K atoms into pristine p-terphenyl continuosly improves the compound stability up to a 3:1 stoichiometry. The crystal structure of the most stable phases dramatically depends on the exact composition of K_xTerphenyl. Actually, energies of formation of 0.82, 1.37, 1.78, 1.97, 2.27 and 1.06 eV are obtained for x=1, 1.5, 2, 2.5, 3 and 4, respectively. Only one of these most stable structures has been previously reported, that is, the one for 1:1 stoichiometry [2]. We show two of them in the Figure: K_2Terphenyl in the left panel which gives an insulating phase with a gap of 0.6 eV and K_3Terphenyl in the right panel which shows a Fermi level within a region of large density of states. Therefore, the last one is a metallic material and, consequently, a superconductor candidate. Unfortunately, no accordance with measured X-ray powder diffraction pattern has been presently achieved.

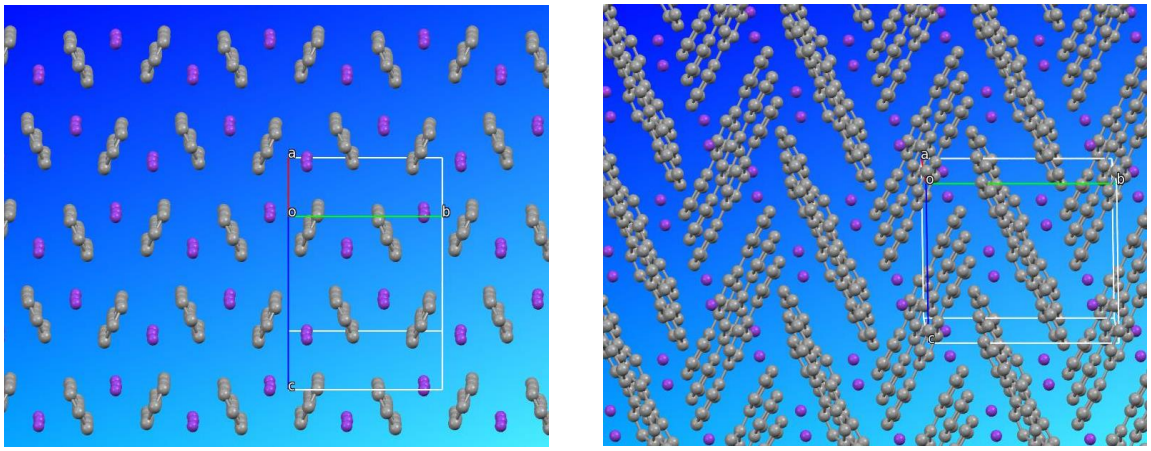

Fig. 1: *The two most stable yet inedited p-terphenyl arrangements induced by K intercalation. On the left panel a picture of the most stable K_2Terphenyl crystalline structure showing whole terphenyl planes that arrange in a herringbone pattern. On the right panel, the best K_3Terphenyl crystal formed doubling the layer periodicity to allow a herringbone structure of pairs of organic molecules.*

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Prediction of Quasi-One-Dimensional Topological Superconductor $Tl_{2-x}Mo_6Se_6$

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We propose that the quasi-one-dimensional molybdenum selenide compound $Tl_{2-x}Mo_6Se_6$ is a time-reversal-invariant topological superconductor induced by inter-sublattice pairing, even in the absence of spin-orbit coupling (SOC). At weak SOC, the superconductor prefers the triplet *d* vector lying perpendicular to the chain direction and two-dimensional E_{2u} symmetry, which is driven to a nematic order by spontaneous rotation symmetry breaking. The locking energy of the d vector is estimated to be weak and hence the proof of its direction would rely on tunneling or phase-sensitive measurements.

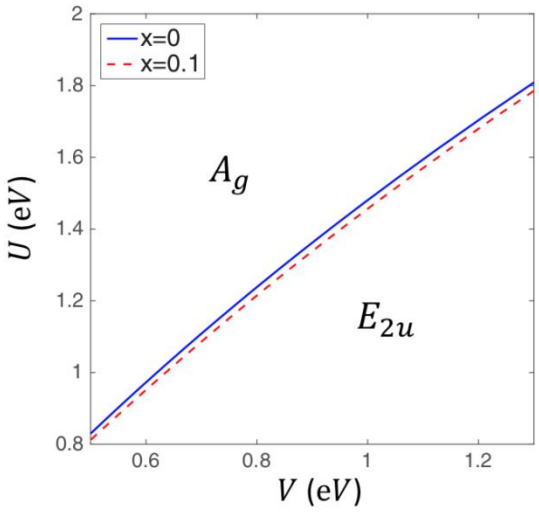

Fig. 1: *Superconducting phase diagram of $Tl_{2-x}Mo_6Se_6$ between A_g and E_{2u} states as functions of intra- and inter-sublattice interaction strengths, U and V.*

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Paramagnetic Resonances in Surface-Superconducting Topological Insulator Sb_2Te_3

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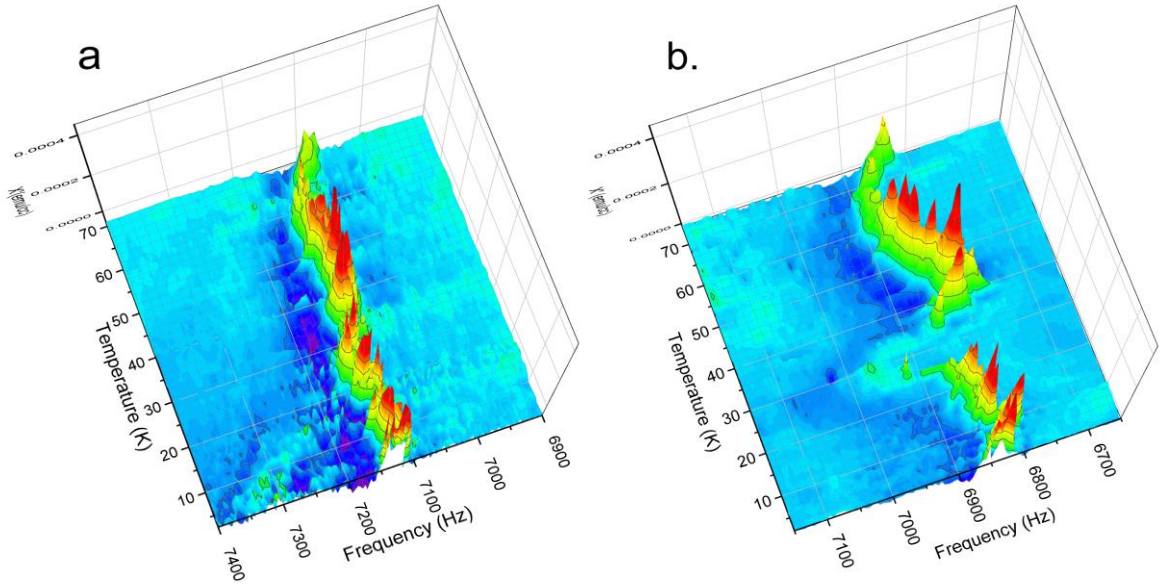
Recent discovery of surface superconductivity at remarkably high temperatures in a topological system Sb_2Te_3 [1] has brought to the fore the importance of disorder in inducing strong particle correlations on topological surfaces. The picture that has emerged from transport, magnetic susceptibility and STM experiments implies a system of Dirac puddles embedded in a 'normal' metal matrix comprising the 2DEG subsurface states, with global superconducting coherence mediated by interpuddle diffusion of quasiparticles through this mesoscopic Josephson Junction (JJ) network. Here we report on distinct resonances we observe in AC magnetic susceptibility $\chi(\omega, B,T)$ of both normal and superconducting Sb_2Te_3, where different period Shubnikov-de Haas quantum oscillations off- and on-resonance confirm the formation of patchy electronic surface states. The differences between χ resonances in the normal and in the superconducting Sb_2Te_3 are evident. The paramagnetic resonance frequency is only weakly temperature and field dependent in the normal Sb_2Te_3 while in the superconducting Sb_2Te_3 it onsets above the paramagnetic limiting field H_p and is distinctly dispersed in temperature, in correspondence with the Meissner and the global resistive transitions. The connection of paramagnetic χ resonances to the sub-gap modes of



JJs, and an interfacial `magic angle' misalignment is discussed.

Fig. 1: *Paramagnetic resonances in AC susceptibility of **a.** normal Sb_2Te_3, **b.** surface-superconducting Sb_2Te_3 measured in a 14 T field*.

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Superconducting proximity effect in Bi_2Se_3/FeSe heterojunction films grown by RF magnetron sputtering

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Three-dimensional topological insulators (Tis) are characterized by their nontrivial surface states, in which electrons have their spin locked at a right angle to their momentum under the protection of time-reversal symmetry. We study the proximity effect between superconducting FeSe films and Bi_2Se_3 topological insulator grown by RF magnetron sputtering. Due to the proximity effect, the superconducting state can penetrate into the topological surface state when the topological insulator surface and the superconductor surface are closely adjacent to each other.

Upper critical field study in ferromagnetic superconductor UCoGe

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The H_{c2} of the orthorhombic ferromagnetic superconductor UCoGe is a very strange case in terms of classical theories for superconductivity [1]. We show that the numbers of features in H_{c2} of UCoGe, including the huge anisotropy between the easy magnetization c-axis and the a,b plane, and the anomalous curvatures of the H_{c2} along different field directions, can be consistently understood with a simple quantitative model for the field dependence of the pairing strength [2]. We show that this change of pairing interactions for H//c (easy magnetization axis) is in agreement with the change of normal phase properties such as the specific heat, and quantitatively follows the prediction of a general microscopic theory for an orthorhombic *p*-wave superconductor [3]. It points out the major role of ferromagnetic fluctuations as a mechanism for superconductivity in this system [2,4].
For the transverse field direction H//b a combined study of spontaneous thermal and electrical transports suggests that vortex mobility in UCoGe is highly enhanced in this high field region, in which a freezing transition from a vortex liquid to a glass-like or solid lattice might occur. Meanwhile a sudden change in thermal conductivity is observed inside the superconducting phase. Altogether these results suggest a field-induced change in the superconducting phase [5].

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Electronic Band Structure and Superconducting Gap Symmetry in Organic Conductor λ-(BETS)$_2$GaCl$_4$

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The organic conductor λ-(BETS)$_2$GaCl$_4$ shows superconductivity (SC) below 5.5K [1]. This compound consists of four BETS and two $GaCl_4$ molecules in a unit cell, and BETS possesses 0.5 holes on average because of the anion $GaCl_4^{-1}$. By chemical substitution in the anions [2] or donor molecules [3], the SC phase is suggested to locate next to the Mott insulating phase.

As for the symmetry of the SC gap, experiments show a two-fold symmetry within the conductive plane [4, 5]. Recent measurements report a line-nodal *d*-wave gap [6], and a possible mixture of the extended *s*- and *d*-wave symmetries [7].

We present the band structure of this material obtained from first-principles calculations within density functional theory (DFT) and derive a four-band model from the maximally localized Wannier orbitals [Fig. 1(a)]. Then, considering the spin-fluctuation-mediated mechanism, we apply the random phase approximation to the four-band Hubbard model for λ-(BETS)$_2$GaCl$_4$. The results show a *d*-wave-like SC gap [Fig. 1(b)]. We will discuss the pairing components and compare to the case of well-studied κ-type compounds and to the experiments.

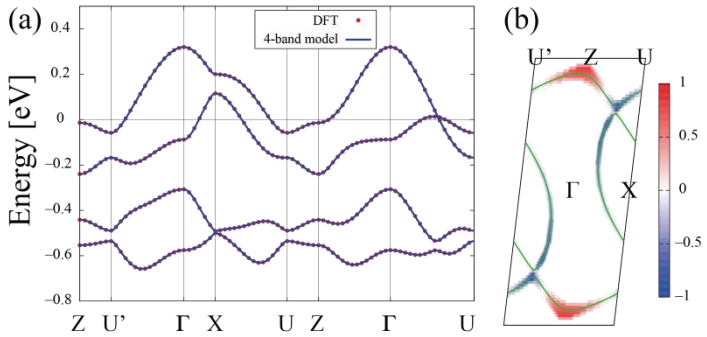

Fig. 1: *(a) Band structure obtained from DFT and four-band model. (b) Fermi surface (green thin curves) and SC gap function near the Fermi level, where the red (blue) contours represent the positive (negative) SC gap sign.*

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High Performance MgB_2 Wires by in situ powder-in-tube Process with $Mg(BH_4)_2$

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Conventional MgB_2 superconducting wires were fabricated with *in situ* powder-in-tube(PIT) technique with Mg and B powder. In this work, $Mg(BH_4)_2$ has been used as an dopant into the *in situ* PIT precursors. $Mg(BH_4)_2$ has been mostly studied as hydrogen storage material as it releases H_2 and subsequently forms MgB_2 in high temperature. The doped $Mg(BH_4)_2$ decomposition happened as the calcination process of the MgB_2 wires, which would increase the reactivity of the filling powder and improve grain coupling. Superconducting properties of the wires has been measured and microstructure of the MgB_2 formed in the wire has been investigated. High current density of 2.1×10^4 A/cm^2 at 6 T 4.2K and 6.7×10^4 A/cm^2 at 8 T 4.2K is achieve.

Griffiths Singularity of Superconductor-Insulator Transition in TiO Epitaxial Thin Films with Different Thicknesses

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Superconductor–insulator transition (SIT) [1] is one of the remarkable phenomena driven by quantum fluctuation. Recently, a totally different SIT with quantum Griffiths singularity drew a lot of attention due to its exotic properties such as a divergent dynamical critical exponent *z* [2]. Here, we report the behaviors of SIT in TiO epitaxial thin films with different thicknesses. At zero magnetic field, the thickness-tuned SIT was observed with its critical sheet resistance close to the quantum resistance $R_Q \equiv h/4e^2$=6.45 kΩ. Interestingly, through investigating the magnetic field dependent resistances at various temperatures, it was found that a series of crossing points form a continuous line of SIT "critical" points, as shown in Fig. 1a. The product of the critical exponents *zv* is obtained by the activated scaling law, as shown in Fig. 1b. When approaching the quantum critical point, the dynamic critical exponent is not a constant but a diverging value, which is consistent with the Griffiths singularity behavior. Similar Griffiths singularity of SIT could be obtained in TiO films with different thicknesses.

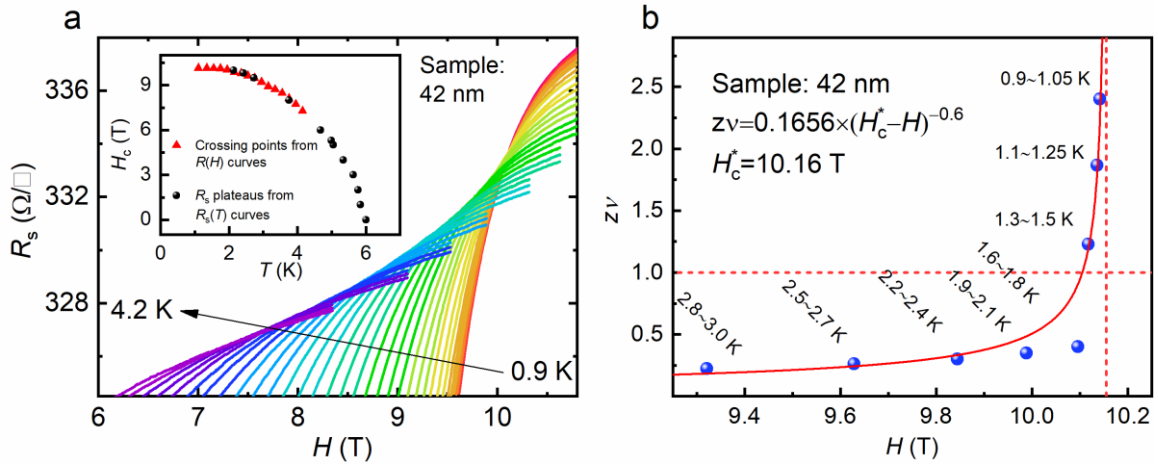

Fig. 1: (a) *Isotherm $R_s(H)$ curves measured at different T for the 42 nm sample. Inset: the critical magnetic fields $H_c(T)$ extracted from Crossing points of $R_s(H)$ curves at every two adjacent temperatures are denoted as red triangles on the transition boundary; the black dots come from the temperature plateaus on Rs(T) curves.* (b) *Exponent zv as a function of magnetic field H. The red solid line is the fitting by* $zv=C(H_c^*-H)^{-0.6}$. *Two red dash lines represent the constant values with* H_c^* *=10.16 T and zv=1, respectively.*

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High-temperature interface superconductivity in bilayer films grown by pulsed laser deposition

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In a seminal work Gozar *et al*.[1] reported the high-temperature interface superconductivity between metallic and insulating copper oxides grown in a unique atomic-layer-by-layer molecular beam epitaxy system. Surprisingly, almost 10 years after Gozar *et al.*'s discovery, similar achievement has scarcely been reported in samples prepared by pulsed laser deposition (PLD), a technique used widely in growing copper oxide films. Here we fabricated high-quality bilayer films of copper oxides by PLD, and observed interface superconductivity comparable with that reported by Gozar *et al.*[1]. In addition to the doping range ($x \leq 0.45$) that had been examined by Wu *et al.*[2], we explored a large number of bilayer films of $La_{2-x}Sr_xCuO_4/La_2CuO_4$ with larger x values (up to 2), and interface superconductivity was observed as well.

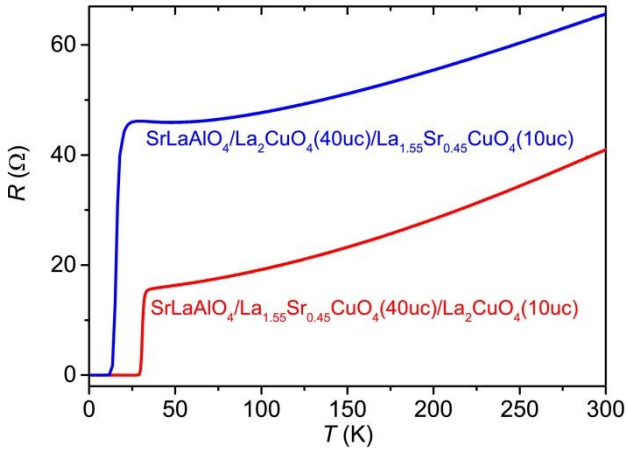

Fig. 1: *The dependence of resistance on temperature for bilayer films grown by PLD.*

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Development and Research of HTS Materials in SC “Bochvar Institute”

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Technologies of initial materials for coated conductors fabrication were developed in SC “VNIINM”: metal substrate tapes and targets for laser and magnetron sputtering.

There are 2 types of metal substrate tapes that were developed: textured Ni-W alloy substrate and non-textured stainless steel Cr25Ni18 (analogue to DIN T1.4845). The technology of the set of textured substrates with lengths of up to 200 meters were developed: homogeneous type substrates from Ni-5at.% W (Ni-5W), Ni-7W, Ni-9W alloys with 70 μm thickness and composite 3-layers substrate with total 100 μm thickness that consist of 2 outer thin layers (thickness of 20 μm each) of Ni-6W alloy and inner thick layer of paramagnetic stainless steel (thickness of 60 μm).

All types of substrates have desired quality of texture with more than 99% grain orientation along {100} direction. The measurements of tapes’ magnetic properties show that the increase of W content in alloy leads to the decrease of both Curie temperature and saturation magnetization M_{sat} values. The alloys with W content of more than 8 at.% are proved to be paramagnetic at 77 K while Ni-9W alloys are paramagnetic also at 4.2 K and such alloys are the best for coated conductors. However the increase of W tends also to poorer workability and complexity of good textured tapes fabrication. Compromise material can be Ni-7W. Another alternative way was to propose composite tapes with good workability like in Ni-5-6W homogeneous alloys but with 2 times lower M_{sat} because of decreased fraction of ferromagnetic alloy.

The technology production of metallic Zr-Y targets with Y content of 15±1 at.% for buffer YSZ layer by magnetron IBAD deposition was developed. The targets were fabricated in various forms to work with various deposition equipment: in plate form with dimensions of 400 x 100 x 5 mm and as tubes with 50 mm diameter and length up to 1200 m. Zr-Y alloy plates and tubes were soldered to the copper base to remove heat during deposition process.

The technology production of ceramic disk-shaped (diameters of up to 150 mm) and rectangular targets (that consist of multiple parts with nearly no size limitation) for Y_2O_3, CeO_2 buffer layers and superconducting Y-123 or Gd-123 layer deposition by PLD technique was developed. The deposited layers properties differ strongly with the density of the targets used. So the density of the fabricated superconducting targets has 90±3% of theoretical density and buffer targets – 90 - 95 %.

Fig. 1. – *Metallic Zr-Y and ceramic Gd-123 targets*

In addition to initial materials for coated conductors SC “VNIINM” conducted works with HTS 1G and magnesium diboride superconductors. The technology production of Bi-2223/Ag (Ag-Cu, Ag-Au) composite superconductors with the lengths of up to 150 meters and critical currents density of up to 1.1 $x10^4$ A/cm^2 was developed.

Improved Structure and Superconducting Properties of YBCO Films with Nanoparticles Derived from Chemical Solution Deposition

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Chemical solution deposition (CSD) has become an interesting way for $YBa_2Cu_3O_y$ (YBCO) coated conductors due to low cost and simple operation [1-4]. In this paper, YBCO films with nanoparticles (HfO_2, ZrO_2) were fabricated on single crystal substrates by CSD. The nanoparticles with different sizes were synthesized by solvothermal techniques [5]. The influences of nanoparticles morphology and size on the texture, microstructure and the flux pinning properties of YBCO nanocomposite films were discussed. The phase formation, morphology and superconducting properties of YBCO films were analyzed by X-ray diffraction scanning electron microscopy, atomic force microscopy and the four-probe method, respectively. The results indicated that the nanoparticles had weak epitaxy perturbation of YBCO film. The microstructure and texture of films were improved by the precursor solution with nanoparticles. Moreover, the nanoparticles could be as artificial pinning centers for the enhancement of critical current densities of YBCO films.

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Robust Dynamical Charge Density Waves in (Y,Nd)$Ba_2Cu_3O_{7-\delta}$

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There is increasing consensus that charge density waves (CDW) are a common occurrence in all families of high critical temperature superconductors [1,2]. This obviously raises the issue of their role in determining some of the unusual properties of these systems, both in the normal and in the superconducting state. Indeed, if charge order arises from a zero-temperature phase transition with a quantum critical point (QCP) near the optimal doping in a quasi-2D system [3], the quantum dynamical charge fluctuations are crucial in determining the charge order transition line. It is therefore crucial to establish the extension of dynamical CDW, both in temperature and doping. Up to now, quasi-static CDW have been revealed only in the underdoped region of the cuprate phase diagram, below a temperature T_{CDW} lower than the pseudogap temperature T^*. However, at higher doping and temperature, where the short-range fluctuating character of the CDW is expected to be more pronounced, Resonant Inelastic X-ray Scattering (RIXS) is an excellent tool of investigation.

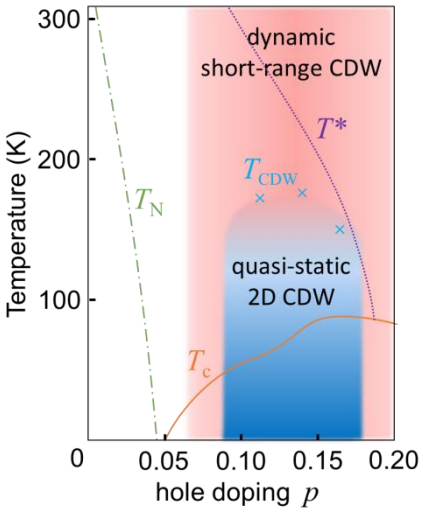

Fig. 2: *(Y,Nd)$Ba_2Cu_3O_{7-\delta}$ phase diagram.*

We have investigated by RIXS the extension in temperature of CDW in (Y,Nd)$Ba_2Cu_3O_{7-\delta}$ thin films with doping p = 0.11, 0.14, 0.17, 0.18 around the QCP. We have observed a clear evidence of CDW dynamical fluctuations, characterized by a finite energy of a few meV. They extend 1) up to the highest temperatures well above T^*, dominating the phase diagram (see Fig.1), and 2) over a broad range in momentum space, giving rise to a quite effective low-energy scattering mechanism for most of the quasiparticles on the Fermi surface [4]. This latter feature makes dynamic charge order an appealing candidate for producing the Marginal Fermi Liquid phenomenology, characterizing since the early times the peculiar properties of HTS cuprates.

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Unprecedented High Irreversibility Line in Nontoxic Cuprate Superconductor (Cu,C)$Ba_2Ca_3Cu_4O_{11+\delta}$

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One of the key factors limiting the high power applications for a type-II superconductor is the irreversibility line $H_{irr}(T)$ which reflects the very boundary of resistive dissipation in the phase diagram of magnetic field versus temperature. In cuprate family, the Y-, Bi-, Hg- and Tl-based systems have superconducting transition temperatures exceeding the liquid nitrogen boiling temperature (~77K). However, the toxic elements Hg and Tl in the latter two systems strongly constrain the possible applications. The Bi-based (2223) system is nontoxic, but the irreversibility magnetic field is strongly suppressed in the liquid nitrogen temperature region. For this purpose, the best perspective so far is relying on the $YBa_2Cu_3O_{7-\delta}$ ($T_c \approx 90$ K) system which is nontoxic and has a relatively high irreversibility magnetic field. Here we present the study of a nontoxic superconductor (Cu,C)$Ba_2Ca_3Cu_4O_{11+\delta}$ with $T_c = 116$ K. It shows an irreversibility field of 15 T at temperature of 82 K in Sample 1 and it even shoots up to 86K under 15 T in Sample 2 (Fig. 1), which is unprecedentedly high among all superconductors and it thus provides a great potential of applications in the liquid nitrogen temperature region. [1]

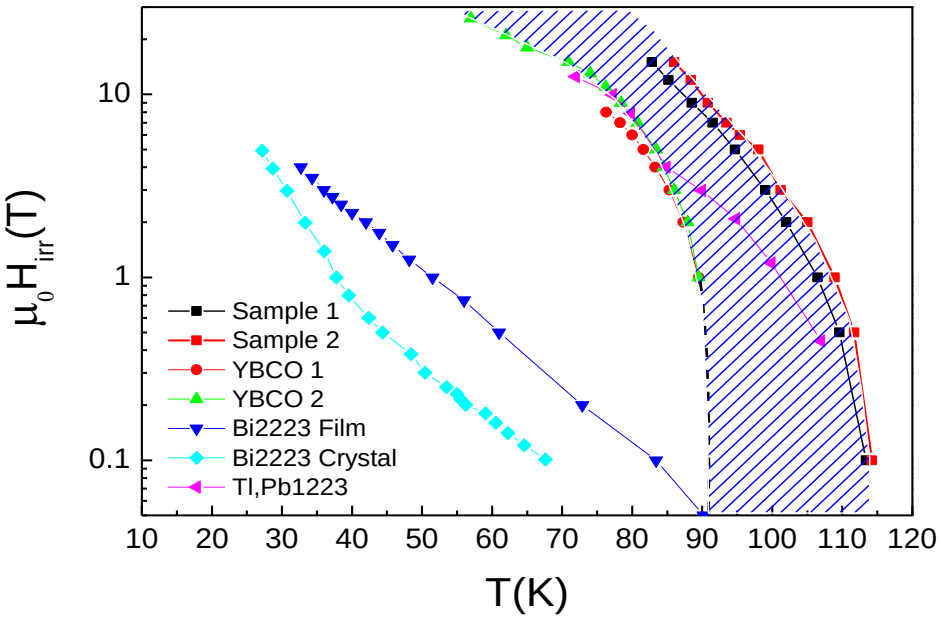

Fig. 1. *Irreversibility lines of different cuprate systems. Irreversibility lines for (Cu,C)-1234(this work, Sample 1 and Sample 2) , YBCO 1 and 2 (single crystals, H||c-axis), Bi-2223(thin film, blue down triangles), Bi-2223(single crystal, Cyan diamond) and (Tl,Pb)-1223 (pink triangles). The highlighted area indicates the region for zero dissipation above the boundary of YBCO. The dark dashed line shows the trend of irreversibility line of YBCO with T_c=91K.*

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Synchrotron X-ray diffraction study of structural disorder in YBCO and composite YBCO films

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REBCO (RE= Y or rare earths) thin films are characterized by a multitude of defects naturally occurring during the growth. Dislocations, stacking fault, local losses of stoichiometry or, in general, local depletion of charge carrier density are typical defects whose density and size can be only roughly influenced by adjusting the growth conditions or choosing the template for the film growth. Since cuprates can be listed among the strongly correlated electron systems, these defects all act as effective flux pinning centers, definitely improving the REBCO films transport properties. In the past 15 years, many efforts have been devoted to further enhance the flux pinning in High critical Temperature Superconductors (HTS) by means of the introduction of nanometric sized second phases acting as pinning centers (Artificial Pinning Centers, APC).

However, film intrinsic disorder arising from granularity or growth induced defects and APC growth are mutually affected: size and arrangement of second phase nano-particles are strongly affected by the film disorder related to the growth method and parameters while the additional micro-strain linked with the introduction of second phases stimulate the appearance of additional disorder acting as strain release mechanisms. A deep comprehension of the reciprocal influence mechanisms opens the possibility to functionalize the film disorder by the controlled introduction of second phases in order to create more complex pinning landscapes able to enhance the APC effect or extend the operative conditions where APC are active.

In this work, $YBa_2Cu_3O_{7-d}$ (YBCO) thin films and composite YBCO films with different types of APC, namely $BaZrO_3$ (BZO) and mixed BaY_2NbO_6+BaY_2TaO_6 (BYNTO) systems, have been grown by PLD (YBCO, YBCO-BZO e YBCO-BYNTO) and MOD (YBCO and YBCO-BZO) methods. Films transport properties have been evaluated by acquiring voltage-current characteristics as a function of applied magnetic field at different temperatures and magnetic field orientations. Results confirm the pinning enhancement due to APC with remarkable differences depending on the growth method and the second phase: strong *c*-axis correlated pinning enhancement in the high temperature - low to mid magnetic field range for PLD YBCO-BZO samples, strong *c*-axis correlated pinning enhancement in the low temperature - up to high magnetic field range for PLD YBCO-BYNTO samples and weak isotropic pinning enhancement for the MOD YBCO-BZO samples. A detailed structural characterization has been performed on selected samples by synchrotron X-ray diffraction measurements as a function of the temperature. Measurements have been performed at the XRD1 beamline, at ELETTRA (Ts, I) in grazing incidence geometry (GIXRD) with the aim of shading the light on the close relation existing between the APC induced disorder and the film intrinsic disorder. Our results suggest a complex scenario where the introduction of APC progressively drive the intrinsic film disorder to a correlated disorder state. Possible effects of the disorder-correlated disorder transition on the films pinning properties will be discussed.

Acknowledgments

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The two-gap feature in optimal electron-doped cuprates

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Dependence of the Hall conductivity on temperature and magnetic field in optimally doped $La_{2-x}Ce_xCuO_4$ (x=0.105) demonstrates that both the hole and the electron bands undergo Cooper paring. Magnetic field suppresses the dominant hole band paring more effectively, making the subdominant electron band paring visible. Positively charged Cooper pairs dominate the Hall signal in the mixed state at weak magnetic field near T_c, while at large field the negatively charged Cooper pairs take over. Sign reversals of the Hall conductivity induced by superconducting fluctuation occur in the transition and can be explained by a weakly coupled two band Ginzburg-Landau-Lawrence-Doniach model.

Observation of Topological Surface State in High Temperature Superconductor MgB_2

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While the hunt for the benchmark topological superconductor (TSc) has been an extremely active research subject in condensed matter research, low transition temperatures (T_c) and/or strong sensitivity to disorder and dopant levels in known TSc candidates have greatly hampered progress in this field. Here, we use Angle-resolved Photoemission Spectroscopy (ARPES) to show the presence of Dirac Nodal Lines (DNLs) and the corresponding topological surface states (TSS's) on the [010] faces of the T_c=39K s-wave BCS superconductor MgB_2[1], as exemplified in Fig. 1. This proposes MgB2 as a particularly promising platform for TSc research: not only is this nearly triple the current record of superconducting T_c among all candidate TSc's, but the nature of these DNL states should make them highly tolerant against disorder and inadvertent doping variations.

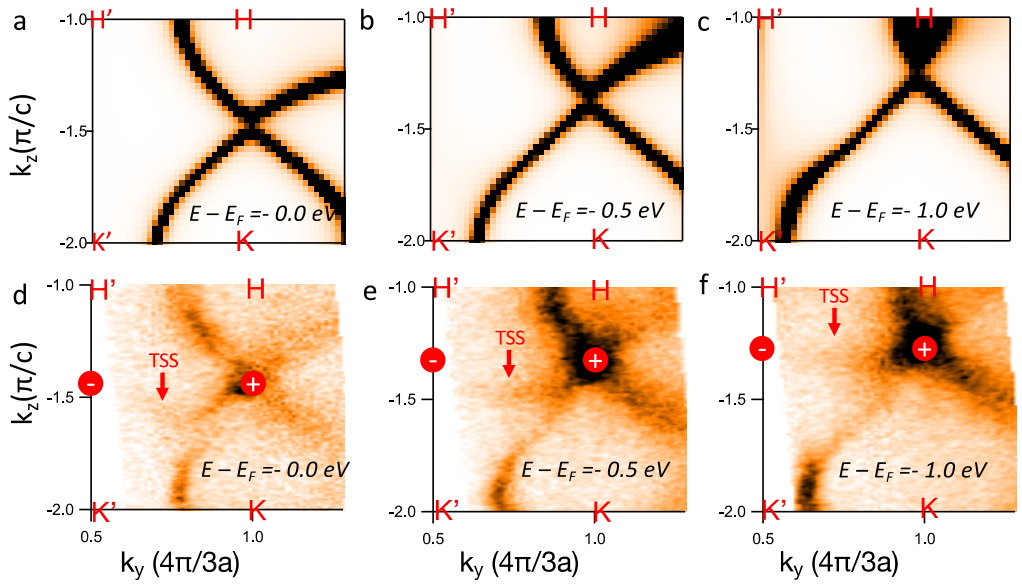

Fig. 1: *Comparison of DFT simulations of the bulk bands at a) E-E_F = 0; b) E-E_F = -0.5 eV; c) E-E_F = -1 eV with d) e) f) the corresponding ARPES spectra. The topological surface state (TSS) is seen connecting from the +π Berry phase monopole to the - π monopole.*

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4π periodic Andreev bound states in a Dirac semimetal

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Electrons in a Dirac semimetal possess linear dispersion in all three spatial dimensions, and form part of a developing platform of novel quantum materials. $Bi_{1-x}Sb_x$ supports a three-dimensional Dirac cone at the Sb-induced band inversion point. Nanoscale phase-sensitive junction technology is used to induce superconductivity in this Dirac semimetal. Radio frequency irradiation experiments reveal a significant contribution of 4-periodic Andreev bound states to the supercurrent in Nb-Bi0:97Sb0:03-Nb Josephson junctions. The conditions for a substantial 4π contribution to the supercurrent are favorable because of the Dirac cone's topological protection against backscattering, providing very broad transmission resonances and an enhanced lifetime of the 4π state. The large g-factor of the Zeeman effect from a magnetic field applied in the plane of the junction, allows tuning of the Josephson junctions from 0 to π regimes.

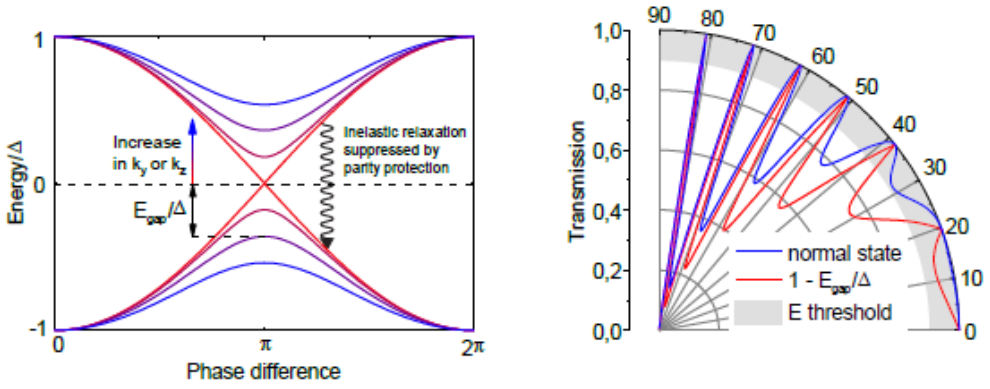

Fig. 1: *(Left) Andreev bound state energy spectrum as a function of the superconducting phase difference across a topological DSM-based Josephson junction for different values of the parallel momentum. For perpendicular modes (ky = kz = 0), the gap (E_{gap}) at φ = π is closed. These Andreev bound states give a 4π-periodic contribution to the current-phase relation. Inelastic relaxation from the upper to the lower branch is suppressed because of topological protection [2]. (Right) The normal state transmission (blue line) is shown as a function of the angle between the propagation direction and the normal to the interfaces. Broad transmission resonances occur at specific angles, enabling the Andreev bound states to cross zero energy, i.e. E_{gap} = 0 (red line).*

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Superconductivity in spin 3/2 topological insulators with carrier doping

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Topological materials of spin 3/2 electrons have attracted much attention. Spin-orbit coupled electrons may behave as higher spin states due to the mixture of spin and orbital angular momentum. In the presence of the two spin 3/2 bands with opposite orbital parity, the band inversion of them induces the high spin topological crystalline insulator. A promising candidate for this state is antiperovskites A_3BX with A=(Ca, Sr, La), B=(Pb, Sn) and X=(C, N, O) [1,2]. Moreover, it was experimentally observed very recently that the antiperovskite Sr_3SnO exhibits the superconducting transition with hole doping [3].

We theoretically investigate the superconductivity in the systems involving the two spin 3/2 electrons with opposite orbital parity [4]. In this system, under the interorbital pairing interaction, the odd-parity superconductivity is realized with the momentum-independent gap function. Evaluating transition temperature, we found that superconductivity with spin-0 Cooper pair is the most stable in the odd-parity superconductivity.

We demonstrate in this presentation that even the simplest spin-0 pairing hosts rich topological phases. In particular the high-doped phases are topological superconductivity with higher winding number originating from the high spin nature. We also discuss the bulk-edge correspondence in this topological superconductor on the basis of the numerical solution. As can be seen in Fig.1, the surface states exhibits characteristic twisted dispersion relation due to the existence of the multiple Majorana cones.

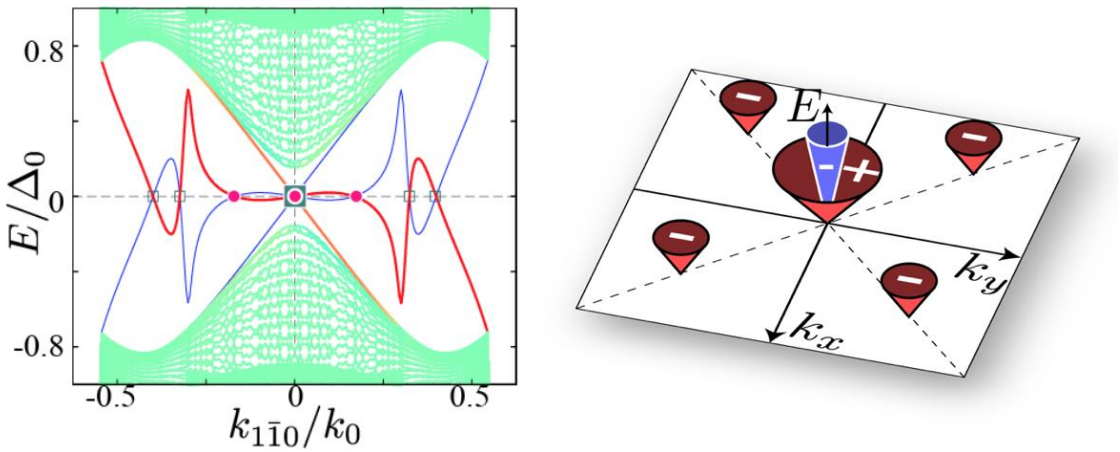

Fig. 1: *The surface state of topological superconductivity with higher winding number. Left panel shows energy dispersion along kx=-ky direction. Right panel is the schematics of surface Majorana cones with helicity ±1 in kx-ky plane, corresponding to filled symbols in the left panel.*

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D-vector Dependence of Local NMR Relaxation Rates T_1^{-1} and T_2^{-1}

in the Vortex State of Chiral and Helical P-wave Superconductors

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Local NMR relaxation rates in the vortex state of chiral *p*-wave superconductors with the *d*-vector ***d*//*z*** or ***d*//*x***, and helical *p*-wave superconductors are investigated by the quasiclassical Eilenberger theory [1]. We calculate the spatial and the resonance frequency dependences of the local NMR spin-lattice relaxation rate T_1^{-1} and spin-spin relaxation rate T_2^{-1} in the vortex lattice state. In superconductors without chirality in the order parameter, approaching the vortex core, the local NMR relaxation rates show enhancement due to the low energy bound states around the vortex center [2]. However, in the chiral *p*-wave superconductors with ***d*//*z***, the local NMR relaxation rate T_1^{-1} at the vortex core shows anomalous suppression instead of the enhancement when the chirality is antiparallel to the vorticity [3]. In this study [1], the local T_1^{-1} and T_2^{-1} in the vortex core region show different behaviors, depending on the relation between the NMR relaxation direction and the *d*-vector orientation. The results in the chiral *p*-wave superconductors with the *d*-vector ***d*//*z*** or ***d*//*x*** are summarized in Table 1, where we consider the $_{zz}$ component T_{2zz}^{-1} in $T_2^{-1}=(T_1^{-1}+T_{2zz}^{-1})/2$. When the NMR relaxation direction is parallel to the *d*-vector component, the local NMR relaxation rate is anomalously suppressed by the negative coherence effect due to the spin dependence of the odd-frequency *s*-wave spin-triplet Cooper pairs [1,3]. This behavior reflects Ising-type spin relaxation of Majorana state at the vortex core in chiral *p*-wave superconductors. The difference between the local T_1^{-1} and T_2^{-1} in the site-selective NMR measurement is expected to be a method to examine the *d*-vector symmetry of candidate materials for spin-triplet superconductors.

d-vector orientation	T_1^{-1} [$d\boldsymbol{M}$ // ***z***]	T_{2zz}^{-1} [$d\boldsymbol{M}$ // ***x***]
d // ***z***	Suppression	Enhancement
d // ***x***	Enhancement	Suppression

Table 1: *Behaviors of T_1^{-1} and T_{2zz}^{-1} at the vortex core, depending on the d-vector orientation* ***d*//*z*** or ***d*//*x****, in chiral p-wave superconductors.*

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Preparation of Bi-2212 high temperature superconductors with different precursor powders

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$Bi_2Sr_2CaCu_2O_x$ (Bi-2212) exhibited high performance under low-temperature and high magnetic field, which showed had great potential for the applications in high field magnets [1-3]. In this work, Bi-2212/Ag wire with different precursors powders were fabricated by powder in tube (PIT) method. Three precursor podwers were synthsized by modified coprecipitation process, freeze-dry process and spray pyrolysis methods, respectively. The decomposition behavior and phase formation of precursor powders were characterized by thermal analysis and X-ray diffraction. The microstructure and superconducting properties of Bi2212 wires were analyzed by scanning electron microscopy and the four-probe method. Bi2212 phase derived from spray pyrolysis could form more rapidly than those of other methods. The reduction of the volume of absorbed H_2O and CO_2 might be acquired by the powder prepared by spray pyrolysis. And the high critical current could be achieved in the Bi2212 wire by spray pyrolysis.

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STM/STS Study on Electronic Superstructures in High-T_c Cuprate $Bi_2Sr_2CaCu_2O_{8+x}$

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In this study, we performed STM/STS measurements at 8 K in underdoped (UD) crystals of $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) with a hole doping level of ~0.12, and examined three kinds of electronic superstructures: checkerboard modulation (CBM) [1–4], Cu–O–Cu bond-centered modulation (BCM) [5, 6] and quasiparticle interference modulation (QPIM) [5, 7].

In the UD samples, the STS spectrum was consistent with the existence of two energy gaps in the antinodal region; it exhibits broad peaks corresponding to the pseudogap (PG) at larger energies $|E| = \Delta_{PG}$ and subgap (SG) behavior at smaller energies $|E| = \Delta_{SG}$, which is comparable with the pairing gap size Δ_{pair}. We confirmed that CBM is observed in images of the local density of states (LDOS) for energies around Δ_{SG}, whereas BCM is observed in LDOS images for energies around Δ_{PG}. These two superstructures, which are characterized by energy-independent wavevectors or nondispersive, are formed in the same regions within Cu–O planes. This finding suggests that the spatial structure of electronic states in the antinodal region may change from CBM to BCM with the increase of energy.

We also confirmed that CBM coexists with another electronic superstructure, QPIM, arising from the interference of Bogoliubov quasiparticles on the nodal Fermi arc where the d-wave superconducting gap opens. As is well known, QPIM consists of seven independent components, and each of them is characterized by an energy-dependent wavevector. For one of the components, $\mathbf{q}_1$-QPIM, the wavevector is similar to that of the nondispersive CBM at energies around Δ_{SG}, wherein we found an interesting relation, depending on the polarity of STM bias voltage, between the phases of CBM and $\mathbf{q}_1$-QPIM. In this conference, we will report the detailed features on their coexistence.

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Incident-Energy Dependence of Lattice and Magnetic Excitations of $NdBa_2Cu_3O_6$ Measured by Resonant Inelastic X-Ray Scattering

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Electron-phonon coupling is the leading mechanism driving the formation of Cooper pairs in conventional superconductors. In unconventional superconducting cuprates, lattice vibrations are thought to play a crucial role in Cooper pairing in cooperation with magnetic excitations [1]. Resonant inelastic X-ray scattering (RIXS) is sensitive to both excitations. Indeed, during the intermediate state of the scattering process, the photoexcited core electron can either couple to lattice vibrations, hence the RIXS signal directly measures the electron-phonon coupling [2,3], or induce magnetic excitations, hence its sensitivity to bimagnons [4]. Single magnons are, on the contrary, direct "electronic" excitations, independent of the intermediate state lifetime. The intermediate state lifetime is inversely proportional to the width Γ of the absorption peak, according to Heisenberg uncertainty principle: $\hbar/\Gamma \sim 1$ fs [5]. However, when the incident energy is moved away ("detuned") from the absorption peak, the intermediate-state duration is reduced to $\hbar/\sqrt{\Gamma^2 + \Delta^2}$, where Δ is the detuning energy [5].

Figure 1 shows the RIXS spectrum of the antiferromagnetic parent compound $NdBa_2Cu_3O_6$ (NBCO) measured at the Cu L_3 edge absorption peak (black dots), and 0.5 eV below the resonance (white squares). As can be seen, lattice and magnetic excitations are clearly resolved in the spectra, and display a different behavior upon detuning.

I will present a systematic study of the low-energy excitations of NBCO upon detuning, and explain the different behavior of lattice and magnetic excitations with the help of simple theoretical models [2,3,6]. I will also show that RIXS is a complementary technique to inelastic neutron and x-ray scattering for the measurement of electron-phonon coupling.

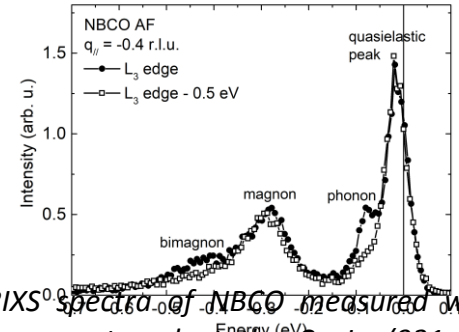

Fig. 1: *RIXS spectra of NBCO measured with incident energy tuned at the Cu L_3 (931 eV) absorption maximum (black dots), and 0.5 eV*

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Comparison of $BaZrO_3$ and $BaHfO_3$ dopants on the properties of YGBCO superconducting films grown by PLD

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There are numerous potential applications for superconducting tapes based on $REBa_2Cu_3O_{7-x}$ (REBCO, RE=rare earth elements) films coated on metal substrates. Flux pinning is the key to enhance the critical current density (J_c) of REBCO superconducting tapes for the high magnetic field applications because the critical current rapidly decreases at high magnetic field due to thermally fluctuated vortex motion. Introducing artificial pining centers (APCs) into the tapes is an effective way to enhance J_c. Especially, $BaMO_3$ (BMO, M = Sn, Hf, Zr, etc) materials form narrow nanorods and extremely enhance flux pinning in the pulsed laser deposition (PLD) processed REBCO tapes. The shape of the BMO nanorods depends on the growth conditions especially on temperature. For further improvement, it is necessary to discuss the vortex pinning mechanisms and the microstructure. In this study, $BaZrO_3$ (BZO) and $BaHfO_3$ (BHO) dopants are introduced and compared for improving the superconducting properties of $Y_{0.5}Gd_{0.5}Ba_2Cu_3O_{7-x}$(YGBCO) films. The YGBCO films with BZO and BHO dopants were fabricated on CeO_2 buffered IBAD-MgO substrates by PLD. It was found that addition of BZO to YGBCO films led to very little optimization of the growth conditions. At 77 K in zero applied magnetic field, the optimal BZO doped YGBCO superconducting film had high current density J_c of 3.25 MA/cm^2, while BHO doped YGBCO superconducting film with J_c of 2.5 MA/cm^2. However, compared with BZO doped YGBCO film, BHO doped YGBCO film exhibited higher critical current density values at 4.2 K for B//c, and it also showed the maximum pinning force density (Fp) value of above 800 GN/m^3 at near 8 T and 4.2 K, indicating that the BHO dopant was effective for flux pinning at low temperature.

Co-existence of Ferromagnetism and Superconductivity in Bi_2Se_3-doped FeSe

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The proximity effect of superconducting materials on topological insulators (TIs) is expected to host exotic physical phenomena, including the elusive Majorana fermion. Meanwhile, ferromagnetism in TIs has drawn a lot of interest, owing to the possible breaking of the time reversal symmetry of TIs. Close contact between a topological insulator, such as Bi_2Se_3, and a material with both superconducting and ferromagnetic properties, such as FeSe, is a direct approach for observing both effects.

In this work, Bi_2Se_3-doped FeSe (up to 9% weight ratio) samples were synthesized from self-flux method. The obtained samples have mixed hexagonal and tetragonal structures. The proportion of the tetragonal phase, along with the superconducting transition temperature, increases with increasing doping content when the dopant concentration is low, and decreases at higher dopant concentration. Superconducting phase coexisting with ferromagnetic phase were found in all samples. Doping of Bi_2Se_3 also changes the transport properties of FeSe samples, which are in agreement with the change of superconductivity. Our work revealed the relation between the amount of topological insulator Bi_2Se_3 and superconductivity of the compound.

Effects of Cross-Section Profiles on Synchronization of Distributed Intrinsic Josephson Junctions in Cuprate High-T_c Superconductors for Coherent Terahertz Radiation

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A stack of intrinsic Josephson junctions (IJJs) of cuprate high-critical-temperature (high-T_c) superconductors has been shown to generate intense and coherent terahertz (THz = 10^{12} Hz) electromagnetic radiation [1,2]. So far, the intense radiation from mesa structures of IJJs was demonstrated using single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$, where its superconducting energy gap of a few tens of meV corresponds to approximately 12 THz. The most intriguing physics of this peculiar phenomenon is the mutual synchronization among thousands of stacked IJJs with distributed widths due to the trapezoidal cross-section profile: The intense emission was observed at the characteristic frequencies that fulfill the geometrical cavity resonance conditions [1,3]. Meanwhile, an IJJ mesa has a trapezoidal cross-section profile due to the limited accuracy of microfabrication processes, which may produce a difference in junction characteristics.

It is important to control the cross-section profiles of IJJ mesas to reveal the fundamental mechanism that leads to the mutual synchronization among the stacked IJJs. In this study, we establish microfabrication processes to easily control the cross-section profiles of the IJJ mesas. We will show recent experimental results on the influence of the cross-section on the radiation characteristics and will discuss the synchronization mechanism.

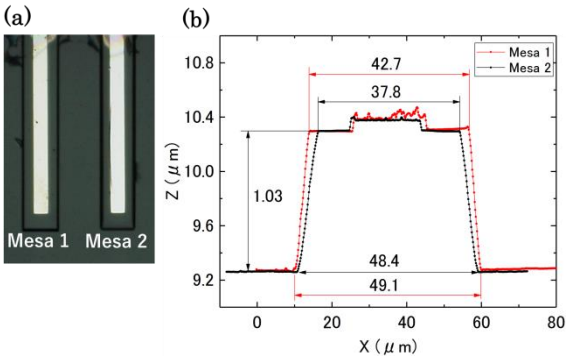

Fig. 1: *(a) Microscopy image and (b) cross-section profiles of two IJJ mesas. Mesas 1 and 2 have trapezoidal profiles with different distortions.*

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Comparison of I_c variations between coated conductor and Bi-2223 samples at different temperatures and magnetic fields

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Critical current (I_c) of YBCO coated conductor and Bi-2223 tape samples was measured at temperatures from 20K to 80K, applied magnetic field from 0 to 3.5T, magnetic field angle from 0 to 90°. I_c-temperature dependency, I_c-magnetic field dependency, and I_c- field angle dependency of those samples were investigated. The I_c variation characteristic at different conditions for each kind of sample was systematically studied. Comparisons in I_c performance at compatible conditions between these two categories of samples were made. This presentation will give the results of those studies. These results may be helpful for applications of HTS conductors.

^{63,65}CuNMR studies of superconducting T'-$La_{1.8}Eu_{0.2}Cu_{4+\delta}$ with Nd_2CuO_4 structure

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^{63,65}Cu NMR studies have been performed in T'-$La_{1.8}Eu_{0.2}CuO_{4+\delta}$ (T'-LECO) with the Nd_2CuO_4 structure. The paramagnetic ^{63,65}Cu NMR signals have been observed only in oxygen reduced T'-LECO which shows superconductivity below 22 K. The spectrum had a narrow center line and broadened satellites with a small electric field gradient in the paramagnetic state. From the peak of the spectrum, we measured ^{63}Cu Knight shift K and nuclear spin- lattice relaxation rate $1/T_1$.

The K is nearly temperature independent (about 0.3%) in the normal state, and decreases rapidly in the superconducting state below 20 K. The superconductivity is a spin singlet. The $1/T_1$ in normal state exhibits the temperature dependence affected by the large antiferromagnetic spin fluctuations. In superconducting state, $1/T_1$ decreases without superconducting coherence peak. The K and $1/T_1$ have revealed that the superconductivity has d- wave symmetry in T'-$La_{1.8}Eu_{0.2}CuO_{4+\delta}$ with the Nd_2CuO_4 structure [1].

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Tuning of the Superconductivity above 100 K in $TlSr_2CaCu_2O_7$ by Cation Substitutions

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In the Tl based compound $TlSr_2CaCu_2O_7$ (Tl-1212), single substitution (Pb or rare-earth element) in the Tl-1212 phase only reaches T_c of 80-90 K, and double substitutions (Pb and rare-earth element) is necessary to enhance the T_c of the Tl-1212 phase to above 100 K. To clarify further the role of Pb and rare-earth element substitutions, we prepared and characterized the superconducting properties of nominal $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.8}Pr_{0.2})Cu_2O_{7+z}$, $(Tl_{1-x}Bi_x)Sr_2(Ca_{0.8}Pr_{0.2})Cu_2O_{7+z}$, and $(Tl_{0.9-x-y}Pb_xBi_y)Sr_2CaCu_2O_{7+z}$ compounds. We find that superconductivity above 100 K can be achieved in both $(Tl_{1-x}Bi_x)Sr_2(Ca_{0.8}Pr_{0.2})Cu_2O_{7+z}$ and $(Tl_{0.9-x-y}Pb_xBi_y)Sr_2CaCu_2O_{7+z}$ systems in addition to the well-known $(Tl_{0.5}Pb_{0.5})Sr_2(Ca_{0.8}Pr_{0.2})Cu_2O_{7+z}$ compound. These results indicate that the substitution of the rare-earth element is not essential in enhancing the T_c above 100 K in the Tl-1212 phase and the improvemrnt of superconductivity in the Tl-1212 phase is mainly affected by the optimization of the hole carrier concentration.

Comprehensive Band Structure Study of Single-layer Cuprate Superconductors

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Since the discovery of high temperature superconductivity in the cuprates, this class of materials has been heavily investigated. However, even after 30 years of research, the mechanisms that lead to their unique behaviours are still not fully understood. Much focus has been given to their electronic structure. Since these materials exhibit strong electron correlations, density-functional-theory (DFT) has been considered too simplistic to correctly predict their band structure. Recently, we succeeded to resolve both the d_{x2-y2} and d_{z2} bands in La-based cuprates directly with angle-resolved photoemission spectroscopy (ARPES)[1]. On this poster, a comprehensive ARPES study across single layer hole-doped cuprates is given and it will be demonstrated how standard DFT calculations describe qualitatively the electronic structure of overdoped cuprates.

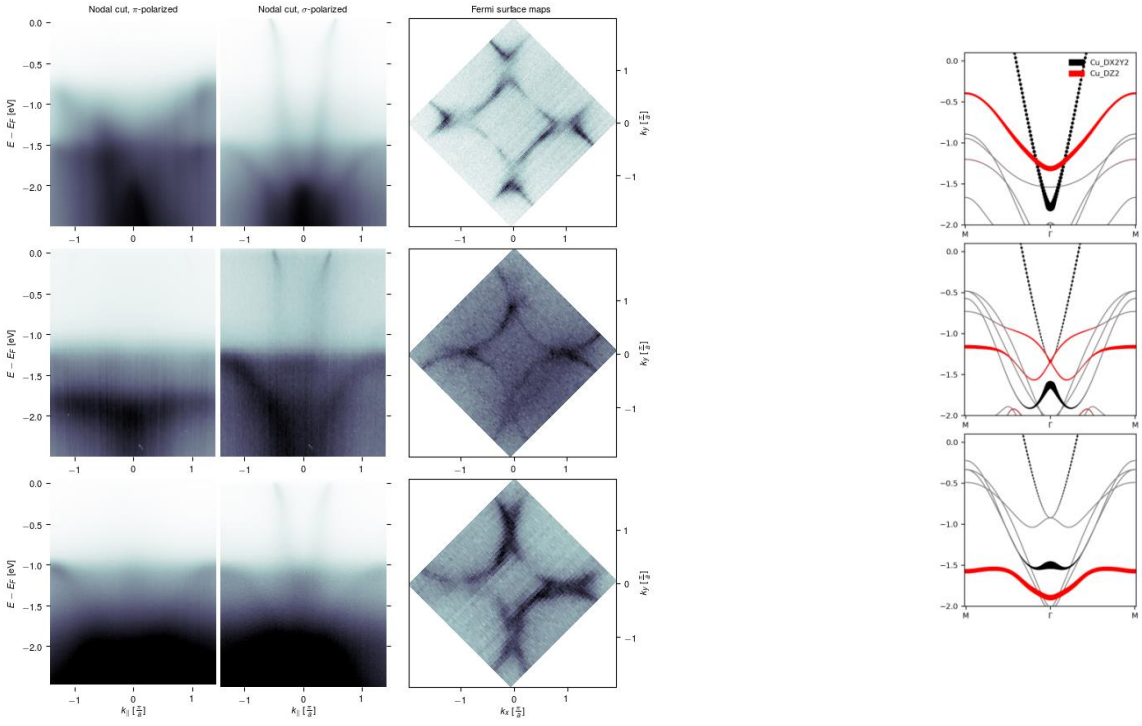

Fig. 1: ***Left:*** *ARPES band structures along high symmetry directions for horizontal (π) and vertical (σ) polarizations and Fermi surface maps for LSCO, Bi2201 and Tl2201 (from top to bottom).* ***Right:*** *Calculated band structures for the respective compounds. Indicated by color are the d_{x2-y2} and d_{z2} bands which can be "turned on and off" in ARPES using symmetry rules.*

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Phase Formation and Superconductivity in (Nb,Sn)$Sr_2RECu_2O_z$

(RE: rare-earth element, z≈8)

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So-called Nb-"1-2-1-2" compounds, $NbBa_2LaCu_2O_z$ and $NbBa_2PrCu_2O_z$ (z≈8) has been synthesized for the first time by Ichinose *et al*. [1] in 1989. In 2013, superconductivity has been confirmed for (Nb,Sn)$Sr_2SmCu_2O_z$ and (Nb,Sn)$Sr_2EuCu_2O_z$ with superconductivity transition temperature (T_c) of 30~40 K [2,3]. In this study, single-phase formation of $NbSr_2RECu_2O_z$ (RE: La, Nd, Sm, Eu, Gd, Dy, Ho, Er) and its superconductivity induced by Sn^{4+} substitution for Nb^{5+} are investigated. Samples are prepared by a solid-state reaction method, and formation of the Nb-"1-2-1-2" is not observed for RE's of Dy, Ho and Er, *i.e*., only RE's with relatively large ionic size form the "1-2-1-2". For the case of two RE's, RE=Eu and RE=Gd, nominal compositions of $NbSr_2EuCu_2O_z$ and $NbSr_2GdCu_2O_z$ give nearly single-phase samples. Superconductivity is observed for samples with nominal compositions of $(Nb_{0.8}Sn_{0.2})Sr_2RECu_2O_z$ (RE=Sm, Eu, Gd). For the case of RE=Gd, superconductivity has not been observed so far. Temperature dependence of resistivity of $(Nb_{0.8}Sn_{0.2})Sr_2GdCu_2O_z$ is shown in Fig. 1. Phase formation and superconductivity of Nb-"1-2-1-2" will be discussed.

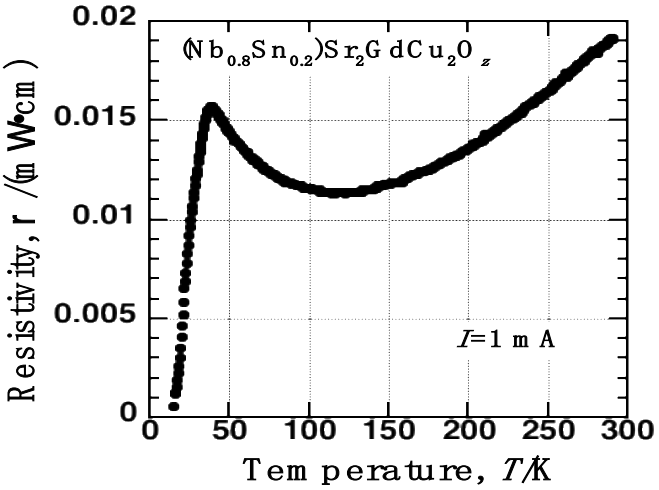

Fig. 1: *Temperature dependence of resistivity of (Nb,Sn)$Sr_2GdCu_2O_z$.*

References

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Preparation and Characterization of Bi-2223 Precursor Powder by Spray Pyrolysis Method

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The properties of precursor powder of are key parameters for superconducting of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tape. Based on commercial application, this study mainly reports the preparation and phase evolution of Bi-2223 precursor powder. The particle size of precursor powder mainly depends on concentration of metal nitrate solution, and average particle size increases with the increasing of concentration, and average particle size of 2μm can be obtained for 1M. DSC results show that reaction temperature of powder is about 800°C in air atmosphere, which is higher than 770°C in N_2-O_2(0.1%) atmosphere. Because of high activity, difference of atmosphere has no affect on reaction time. However, it has obviously effect on phase assemblages. Phase assemblages of Bi-2212, Ca2PbO4, $(Sr,Ca)_xCu_yO_\delta$ (AEC) and CuO can be obtained in air atmosphere, but Ca_2PbO_4 disappears and Pb can be doped into Bi-2212 to form (Bi,Pb)-2212 in N_2-O_2(0.1%) atmosphere, which can be indicated by the splitting of the XRD 200 and 020 peaks at 33.2°, and the disappearing of the peak at 18°. The results also show that the content of AEC phase increase with the increasing of particle size, and the dimension and content of CuO phase in precursor powder have an important effect on superconducting, which mainly affect on non-superconducting phases in final Bi-2223 tape. When the average particle size of precursor powder is about 2μm, the ideal dimension and content of CuO phase can be obtained.

Design and Characterization of Microstrip Patch Antennas for Efficient Terahertz Radiation from BSCCO Intrinsic Josephson Junctions

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The observation of coherent terahertz radiation from a stack of intrinsic Josephson junctions (IJJs) in the cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) highlighted the potential of using high-transition-temperature (high-T_c) superconductors as compact and convenient terahertz sources [1,2]. Previous studies found that the thermal management of terahertz-emitting sources to be a key requirement for improving their radiation characteristics, *i.e.*, an inevitable local temperature rise due to enormous Joule heating can suppress the radiation power significantly. Presently, the maximum power of 0.6 mW, which is the highest recorded radiation power among all available sources in the sub-THz regime, was obtained from an array of stacks under extremely inhomogeneous temperature conditions [3]. To generate high-power milliwatt-level radiation for practical applications, we need to mitigate impedance mismatch at the boundary between an emitting stack and a dielectric medium or free space.

In the present work, we demonstrate the design of a terahertz microstrip patch antenna for efficient radiation from a BSCCO IJJ stack. Figures 1(a) and 1(b) show the schematic and microscopy image of the IJJ stacks with the Delta Patch Antennas (DPAs). We established an effective process for fabricating the DPAs using laser lithography and a lift-off technique. In the poster presentation, we will discuss the influence of the DPAs on the radiation characteristics.

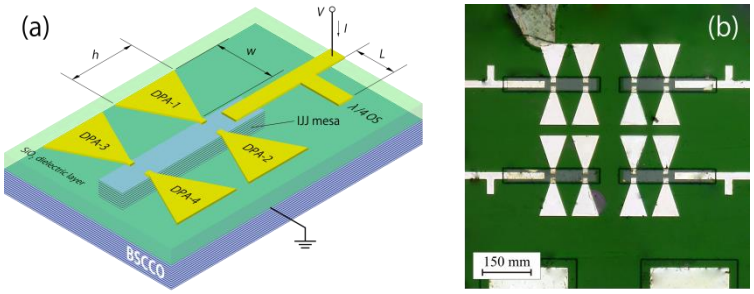

Fig. 1: *(a) Schematic of the BSCCO IJJ stack with four DPAs. (b) Microscopy image of the arrayed four IJJ stacks.*

Acknowledgments

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Chemical Solution Derived $YBa_2Cu_3O_7$ Nanocomposite Films with Preformed $BaMO_3$ (M=Zr, Hf) Nanoparticles for Enhanced Superconducting Performances

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Chemical solution deposited $YBa_2Cu_3O_{7-x}$ nanocomposite thin films from preformed oxide nanoparticles and TFA route offers great potential as scalable and low cost route to fabricate high magnetic field coated conductors [1, 2]. The use of preformed nanoparticles enables tight control of composition, size and concentration and therefore facilitates the tailoring of nanocomposite pinning properties for specific applications. For that, it is crucial to identify and understand where the vortex pinning is dominated by the different defects. Here we present our most recent study using two different preformed oxide nanoparticles, $BaZrO_3$ and $BaHfO_3$, which are both unreactive with $YBa_2Cu_3O_{7-x}$. We investigate the influence of nanoparticle concentration and characteristics (composition, size, shape) and the processing parameters on the epitaxial growth and defects landscape. We found that preformed $BaZrO_3$ allows a record load of 20 mol% in epitaxial $YBa_2Cu_3O_{7-x}$ leading to J_c@ 77K of 5 MA/cm^2 using $YBa_2Cu_3O_{7-x}$ seed layers. We demonstrate that flash-heated superconducting nanocomposites with 20 mol% preformed $BaHfO_3$ or $BaZrO_3$ perovskite secondary phases feature discrete and small (7 nm) nanoparticles and high density of short $YBa_2Cu_4O_8$ (Y248) intergrowths. We identify a synergy between Y248 intergrowth density and small nanoparticles to increase artificial vortex pinning centers. Also, we validate the multideposition process to successfully increase film thickness of epitaxial nanocomposites with competitive critical currents I_c at 77K.

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Stresses and superconducting properties of YBa2Cu3O7-x/(La,Sr)(Al,Ta)O_3, $YBa_2Cu_3O_{7-x}$/ $LaAlO_3$ and $YBa_2Cu_3O_{7-x}$/$SrTiO_3$ thin films

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Residual stress results from interface lattice mismatches between $YBa_2Cu_3O_{7-x}$ (YBCO) thin films and substrates, causing morphology defects in the film and variations on superconducting properties. In this study, we investigated small opposite-lattice misalignments in the microstructure of YBCO prepared on (La,Sr)(Al,Ta)O_3 (LSAT), $LaAlO_3$ (LAO) and $SrTiO_3$ (STO) substrates, and the resulting effects on their superconducting properties. Scanning electron microscopy (SEM) exhibited YBCO in c-axis oriented epitaxial growth on both substrates. Residual stress in the films was measured by x-ray diffraction (XRD) and calculated using a modified ψ method, assuming a biaxial stress state. The XRD results showed compressive stress in a YBCO/LSAT and YBCO/LAO system and tensile stress in a YBCO/STO system. The superconducting electrical transport results showed that higher J_c and T_c in YBCO thin films with compressive stress.

Thermodynamic evidence for a Fulde-Ferrell-Larkin-Ovchinnikov state in the iron-based superconductor KFe_2As_2

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We investigated the magnetic phase diagram near the upper critical field of the iron-based superconductor KFe_2As_2 by magnetic torque and specific heat experiments using a high-resolution piezorotary positioner to precisely control the parallel alignment of the magnetic field with respect to the FeAs layers. We observe the characteristic upturn of the upper critical field line together with a clear double transition when the field is strictly aligned in the plane. The critical field extends well beyond the Pauli limit at 4.8 T. This provides firm evidence that a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state exists in this iron-based KFe_2As_2 superconductor [1].

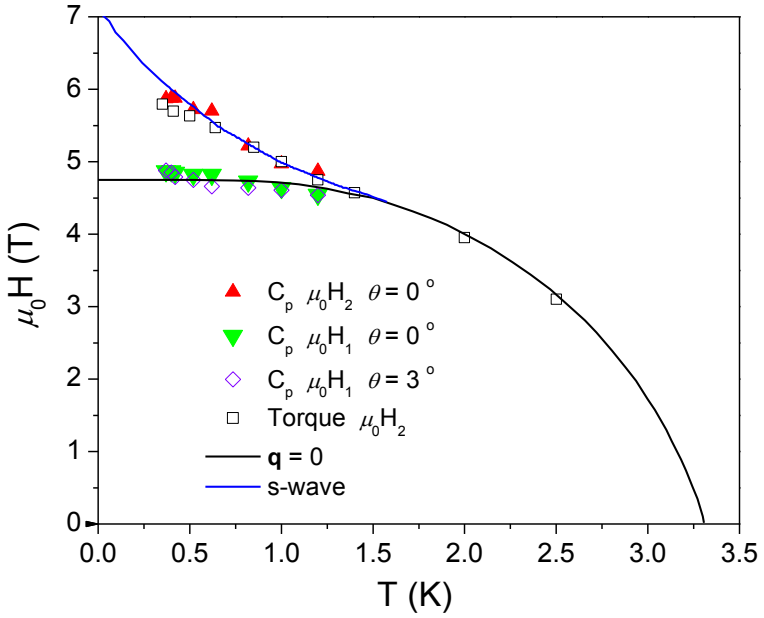

Fig. 1: *H–T phase diagram of KFe_2As_2 from magnetic torque and specific heat. H_1 represents the transition between the homogeneous superconducting state (q=0) and the FFLO state. The upper transition at H_2 separates the FFLO state from the normal state. The additional lines represent the H_{c2}(T) lines predicted for a purely Pauli-limited superconductor (q=0) [2] and for an isotropic s-wave superconductor with the FFLO state [3].*

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Transport Properties and Pinning Analysis for Co-doped $BaFe_2As_2$ Thin Films on Metal Tapes and Single Crystal Substrates

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We investigate the transport properties and pinning analysis of $BaFe_{1.84}Co_{0.16}As_2$ (Ba122:Co) thin films on metal tapes with a large in-plane misorientation and on CaF_2 single crystal substrates by pulsed laser deposition. High transport J_c occurs in both thin films, with 2.6 MA/cm^2 and 0.98 MA/cm^2 in 9 T at 4.2 K for thin films on CaF_2 and metal tapes [1, 2], respectively, promising for high field applications. Microstructure investigations reveal a high density of *ab*-planar defects (stacking faults) and localized vertical defects present in the sample. The Dew–Hughes mode analyses prove that pinning centers by surface defects and by point defects are responsible for *H*//*ab* and *H*//*c*, respectively. In particular, Pinning force analysis indicates a significant enhancement compared with similar Ba122:Co coated conductors. Therefore, the high Jc in high magnetic field for both *H*//*ab* and *H*//*c* are related to surface and point defects which act as the pinning centers in Ba122:Co films.

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Electron-electron interaction, mass enhancement, band shifts and VAN HOVE singularities in hole overdoped $Ba_{1-x}K_xFe_2As_2$ and $CsFe_2As_2$ superconductors

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The interplay and strength of high and low-energy mass renormalizations with band-shifts reflected by the positions of the Fe $3d_{xz}/d_{yz}$ derived saddle-point van Hove singularities (VHS) and band edges related ones in the normal state spectrum of the most strongly correlated hole-over doped AFe_2As_2 (A122) with A = K, Rb, Cs iron pnictides are discussed phenomenologically from ARPES data (Fig. 1a) and band-structure (GGA) calculations with full spin-orbit coupling. The large increase of the Sommerfeld coefficient γ of the el-specific heat C_p from K122 to Cs122 [1,2] is ascribed to an enhanced coupling to low-energy bosons in the vicinity of a quantum critical point to an yet unknown stripe phase [3] detrimental for superconductivity (I in Fig.1b) distinct from the commensurate tetragonal Mott one. We found no sizeable increase of correlations for Cs122 in contrast to Ref. [4]. The empirical (ARPES) VHS positions as compared with full relativistic GGA-predictions and SQGW calculations (U = 3.7 eV) including a k-dependent self-energy with spin-orbit coupling taken into account, point even to *weaker* correlations in Cs122 in qualitative accord with smaller scattering rates, low-T magnetic suscetibility χ(T) data [1] and a significantly smaller Wilson ratio $R_W(0)= \chi(0)/\gamma$ as compared with Rb122 and K122 [1,2]. In particular, the non-smooth increase of γ with hole doping in $Ba_{1-x}K_xFe_2As_2$ near x = 0.7÷0.8 points to topological electronic transitions of the Fermi surface followed by a moderate one near x = 1, points to a k-dependent self-energy. Estimates of our approach for the strength of correlations for other quasi-2D transition metal systems as Sr_2RuO_4 are briefly discussed.

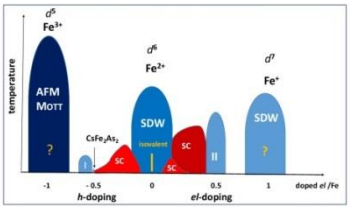

Fig. 1: *Phase diagram of differently doped superconducting (SC, red) and spin density wave SDW (blue) phases*

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Nematic and Magnetic Fluctuations in $Ba(Fe,Co)_2As_2$

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The magnetic order and structural transition are known to be suppressed near and beyond the optimal doping in Fe-based superconductors. Even in the paramagnetic state of a tetragonal structure, however, signatures of strong nematic fluctuations have been reported. The origin of the nematic fluctuation and its role for the superconductivity in terms of quantum criticality are being discussed intensively.

We investigate the ultrafast response of $Ba(Fe,Co)_2As_2$ superconductors. The polarization dependent ultrafast dynamics presents one of the clearest evidences for the nematic state. The overall relaxation dynamics shows two distinct anisotropic components. Although there is no static order in the normal state above T_c, one of the ultrafast components presents a clear evidence of the development of a fluctuating order. We will discuss the results in terms of spin and nematic fluctuations.

High-Resolution ARPES study of One-Monolayer FeSe Films on $SrTiO_3$: Dirac Semimetal and High-Temperature Superconducting Phases

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High-temperature superconductivity in one-monolayer (1-ML) FeSe film on $SrTiO_3$ is attracting considerable attention because of the high critical temperature above 65 K [1-3]. It has been established that high-temperature superconductivity in this system is triggered by electron doping [2-4], as in bulk iron-based superconductors. Intensive investigations revealed various intriguing properties of the electron-doped high-temperature superconducting phase. However, in contrast to the electron-doped phase, little is known about the undoped parent phase of 1-ML FeSe mainly due to the difficulty in controlling the carrier density. Here we report a novel approach to accurately tune carrier concentration to zero doping and demonstrate, by high-resolution angle-resolved photoemission spectroscopy, that the low-energy excitations in the undoped region are solely characterized by a Dirac-cone band arising from the nematic order [5]. The present result strongly suggests the emergence of two-dimensional Dirac semimetal phase in undoped one-monolayer FeSe.

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Enhanced Critical Current Density of Fe(Se, Te) Superconducting Bulks by Fluorine Doping

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[+] *These authors contributed equally to this work.*

$FeSe_{0.5}Te_{0.5}$ superconducting bulks with different content of fluorine doping were successfully fabricated by solid state sintering method. Both the critical current density J_c and H_{c2} were significantly enhanced, the values of which were increased about 7 times and 2 times in 0.05F-doped sample than undoped one, respectively. The flux pinning mechanism for different F doping content samples was systemically researched. It was noticed that the flux pinning type change from surface pinning in undoped to k pinning in 0.05F-doped sample, which enhanced the thermally activation energy U_0 greatly increasing 2 times than that in undoped sample leading the giant enhancement of J_c and H_{c2}. Furthermore, the charge-carrier mean free path fluctuation, δl pinning, is responsible for the pinning mechanism in $Fe_{1.0}Se_{0.5-x}F_xTe_{0.5}$. Further optimization of F doping content and preparation of Fe(Se, Te) wires and tapes with F doping are on the way.

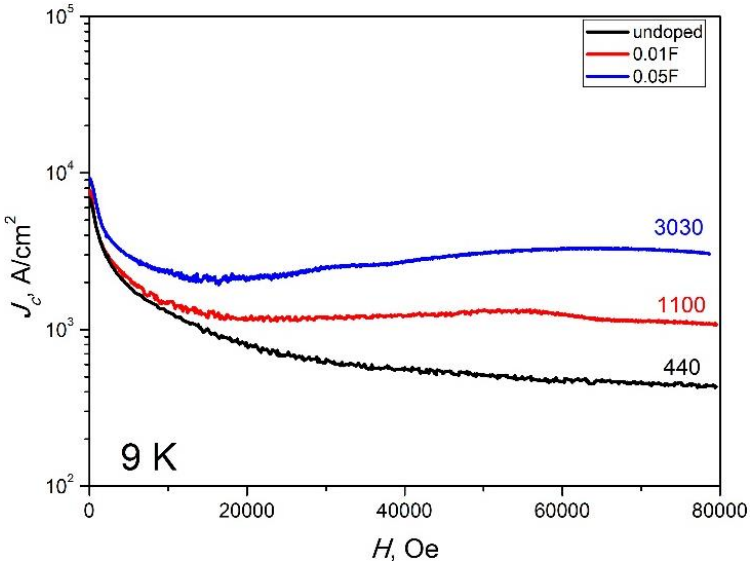

Fig. 1: *J_c vs. field at 9 K for the samples with different F doping content.*

Superconducting Quasiparticles in Electron-Doped FeSe Thin Films Studied by High-Resolution ARPES

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The recent discovery of high-temperature (T_c) superconductivity in one-monolayer FeSe thin films has attracted considerable attention [1-3] because the T_c value of ~ 65 K is the highest among iron-based superconductors despite the low T_c (< 10 K) character of bulk FeSe crystal. One of the key ingredients to trigger high-T_c superconductivity in one-monolayer FeSe is electron doping [2-4] which results in unique Fermi-surface topology distinct from that in bulk iron-based superconductors. To understand the origin of the T_c enhancement by electron doping, we have fabricated two types of high-quality electron-doped FeSe thin films, one-monolayer FeSe and Cs-doped FeSe, and investigated their electronic structure by high-resolution angle-resolved photoemission spectroscopy. In this presentation, we report the evolution of the quasiparticle band dispersions as a function of temperature and discuss the relationship with the emergence of high-T_c superconductivity.

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Superconducting properties of (La,Na)AFe_4As_4 (A = Rb, Cs) with 1144-type structure

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The Fe-based $AeAFe_4As_4$ (Ae = Ca, Sr, Eu, A = K, Rb, Cs) superconductors have a hybrid structure (1144-type structure) composed of two alternating 122-type structures, namely, $AeFe_2As_2$ (Ae = Ca, Sr, Eu) and AFe_2As_2 (A = K, Rb, Cs) [1-4]. The large contrast between the ionic radii of the Ae^{2+} and A^+ ions does not allow them to occupy the same atomic positions.

We recently discovered a new 122-type superconductor, (La,Na)Fe_2As_2[5], which does not include alkali earth metal elements (Ae) in its composition. The ionic radii of La^{3+} (r_{La} = 1.16 Å) and Na^+ (r_{Na} = 1.18 Å) are much smaller than those of Rb^+ (r_{Rb} = 1.61 Å) and Cs^+ (r_{Cs} = 1.74 Å), and the lattice constant, *a,* of (La,Na)Fe_2As_2 is close to that of AFe_2As_2 (A = Rb, Cs). These fact led us to expect that the combination of (La,Na)Fe_2As_2 and AFe_2As_2 (A = Rb, Cs) structural units could result in forming the 1144-type compound. We successfully synthesized the (La,Na)AFe_4As_4 (A = Rb, Cs) with 1144-type structure and observed superconductivity at approximately T_c = 25 K in (La,Na)AFe_4As_4. We determine the superconducting properties of (La,Na)AFe_4As_4 and discuss the superconducting state in (La,Na)AFe_4As_4.

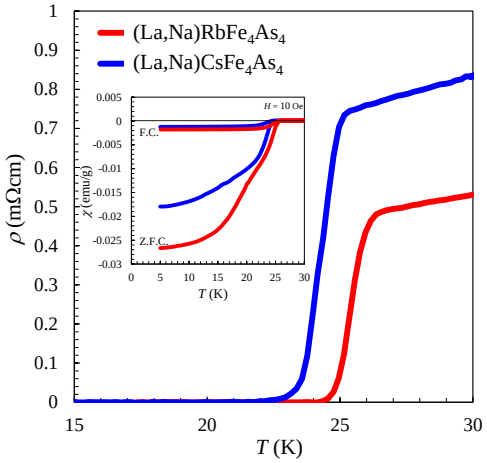

Fig. 1: *Temperature dependence of electrical resistivity of (La,Na)AFe_4As_4 (A = Rb, Cs). Inset shows the temperature dependence of magnetic susceptibility of (La,Na)AFe_4As_4 (A = Rb, Cs)*

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Characterization of the Single Crystalline Iron-based 112-type Parent Compound $EuFeAs_2$

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We have successfully grown single crystals of the iron-based 112-type parent compound $EuFeAs_2$ by a flux method. Single crystal X-ray diffraction revealed that the undoped $EuFeAs_2$ has an orthorhombic crystal structure with space group *Imm*2, and lattice parameters a = 21.285(9) Å, b = 3.9082(10) Å, and c = 3.9752(9) Å. La-substitution triggers a structural distortion in consideration of the monoclinic structure of $Eu_{0.9}La_{0.1}FeAs_2$ ($P2_1/m$)[1] we reported before. Two resistive anomalies were observed around 110 K and 45 K during the temperature dependent resistivity measurement. From the first derivative of resistivity with respect to temperature and from the heat capacity measurement, two adjacent phase transitions around 110 K can be distinguished, which we propose to be a structural phase transition (110 K) and a Fe^{2+}-related antiferromagnetic phase transition (98 K), respectively, referring to the similar results in Ca112 system[2]. The anomaly at 45 K is proved to be associated with a Eu^{2+}-related antiferromagnetic phase transition by the magnetic susceptibility measurements.

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Effect of electron correlations on spin excitation bandwidth in $Ba_{0.75}K_{0.25}Fe_2As_2$ as seen via time-of-flight inelastic neutron scattering

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Since the discovery of high-temperature superconductivity in iron-based superconductors (FeSC), many studies have been conducted to understand their electronic and magnetic properties. Earlier studies have suggested that FeSCs are weakly correlated materials, in sharp contrast to cuprate superconductors, in which Mott physics is more fundamentally tied to superconductivity. However, increasing evidence suggests that electron correlations in FeSCs are much stronger than previously thought[1,2]. The role of electron correlations is therefore the most interesting, yet not well understood, aspect of the physics of FeSCs.

Here we use inelastic neutron scattering (INS) to study the effect of electron correlations on spin dynamics in hole-doped FeSCs $Ba_{0.75}K_{0.25}Fe_2As_2$. By combining angle-resolved photoemission spectroscopy (ARPES) measurements and first-principles calculations, we show that the measured spin excitations are heavily renormalized due to the correlated Fe-3*d* bands with enhanced effective electron masses. These results highlight the strongly correlated nature of FeSCs that should be considered for a realistic treatment of the spin dynamics. In addition, the consistency between the results of the two momentum-resolved spectroscopy methods, INS and ARPES, demonstrates a quantitative link between the magnetic response and the underlying electronic structure of FeSCs. This opens up new possibilities for using INS as a momentum-resolved spectroscopy for determining the correlated electronic structure.

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Effect of wire diameter on the microstructure and J_c properties of $Ba_{0.6}K_{0.4}Fe_2As_2$ tapes

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For $Ba_{0.6}K_{0.4}Fe_2As_2$ superconducting tapes, which are made of round wires by flat rolling process [1], the final diameters of the wires are critical parameters for the transport critical current density (J_c). X-ray diffraction and scanning electron microscopy analysis revealed that the degree of texture is stronger in the samples rolled from wires with larger diameters. The hardness test showed that the highest density is obtained in the tapes rolled from wires of 1.8 mm in diameter in which the highest J_c of 3.31 × 10^4 A cm^{-2} at 4.2 K and 10 T was achieved. It is suggested that superior J_c performance can be obtained in the samples with both large texture degree and high core density. Enhancing the texture and density is one way if we want to make small sized tapes with high transport J_c.

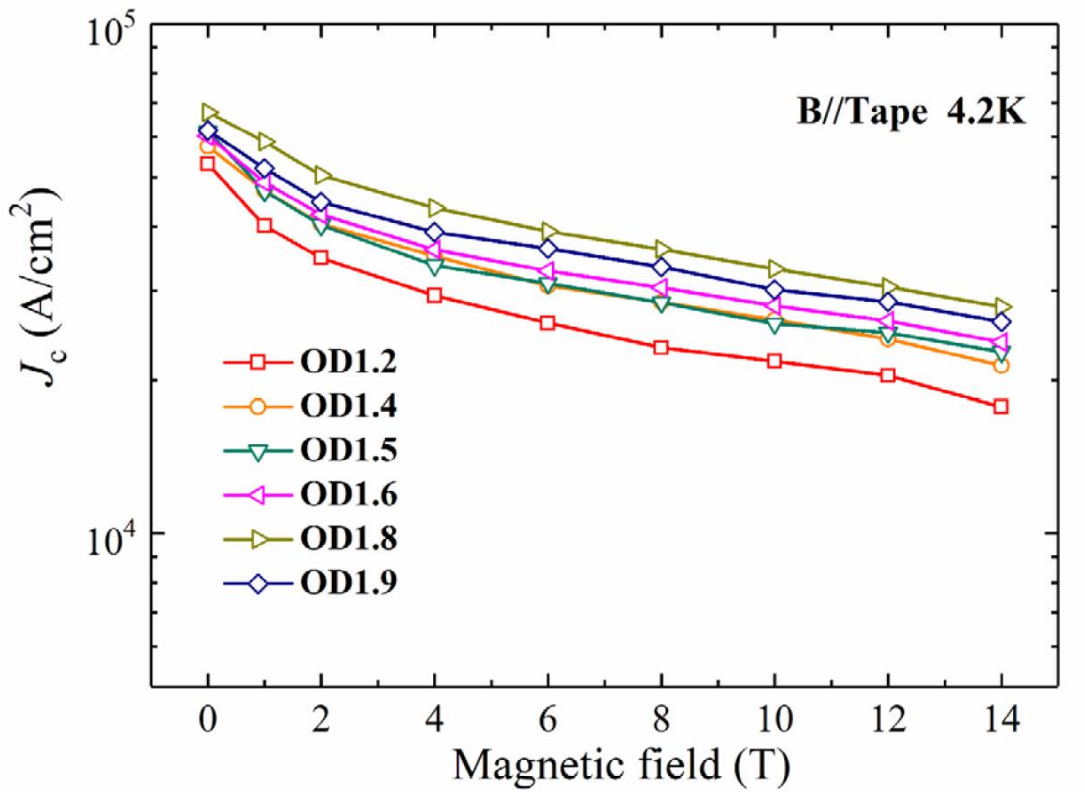

Fig. 1: *Magnetic field dependence of transport J_c at 4.2 K for $Ba_{0.6}K_{0.4}Fe_2As_2$ tapes rolled from wires with 1.2 mm, 1.4mm …and 1.9 mm in diameter, respectively.*

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Magnetic and Superconducting Properties of the Iron Arsenide Pnictides $Ba_{1-x}Na_xFe_2As_2$ as seen by Infrared Spectroscopy and Muon Spin Rotation

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The iron pnictides high-Tc superconductors exhibit a rich phase diagram with a close proximity of superconductivity and antiferromagnetic (AF) or commensurate spin-density-wave (SDW) orders [1]. In most compounds a so-called stripe-like antiferromagnetic state dominates the phase diagram that is accompanied by a structural transition from tetragonal to orthorhombic and involves an AF (FM) order of the in-plane oriented spins along the a-axis (b-axis) direction (o-AF state). This o-AF order coexists with bulk superconductivity even though both orders compete for the same electronic states. For the hole-doped $Ba_{1-x}Na_xFe_2As_2$ (BNFA) and $Ba_{1-x}K_xFe_2As_2$ (BKFA) [2] compounds there exists a second kind of AF that occupies a rather small part of the doping phase diagram (near optimal doping) for which the structure remains tetragonal and the spins are perpendicular to the FeAs layers and vanish on every second Fe site. The relationship of the t-AF order with superconductivity is so far not very well established.
Here we show from combined muSR and IR-spectroscopy data that this t-AF order competes much more severely with superconductivity than the o-AF order.

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(Li,Fe)OHFeSe Superconductor: Ion-exchange Synthesis of Large Single Crystal and Mn Substitution

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This presentation exhibits a hydrothermal ion-exchange technique, which is applicable for growing high-quality superconducting (Li,Fe)OHFeSe crystals of a size over 10 mm (T_c ~ 42 K) for the first time. Here also exhibits Mn-doped (Li,Fe)OHFeSe superconductor crystals via two hydrothermal routes, i.e. ion exchange (1-step) and ion release/introduction (2-step). The T_c and crystal lattice constant *c* of Mn-doped (Li,Fe)OHFeSe both display similar V-shaped evolutions with the increasing dopant concentration *z*, which indicates that a larger interlayer separation, or a weaker interlayer coupling, is essential for the high-T_c superconductivity in (Li,Fe)OHFeSe.

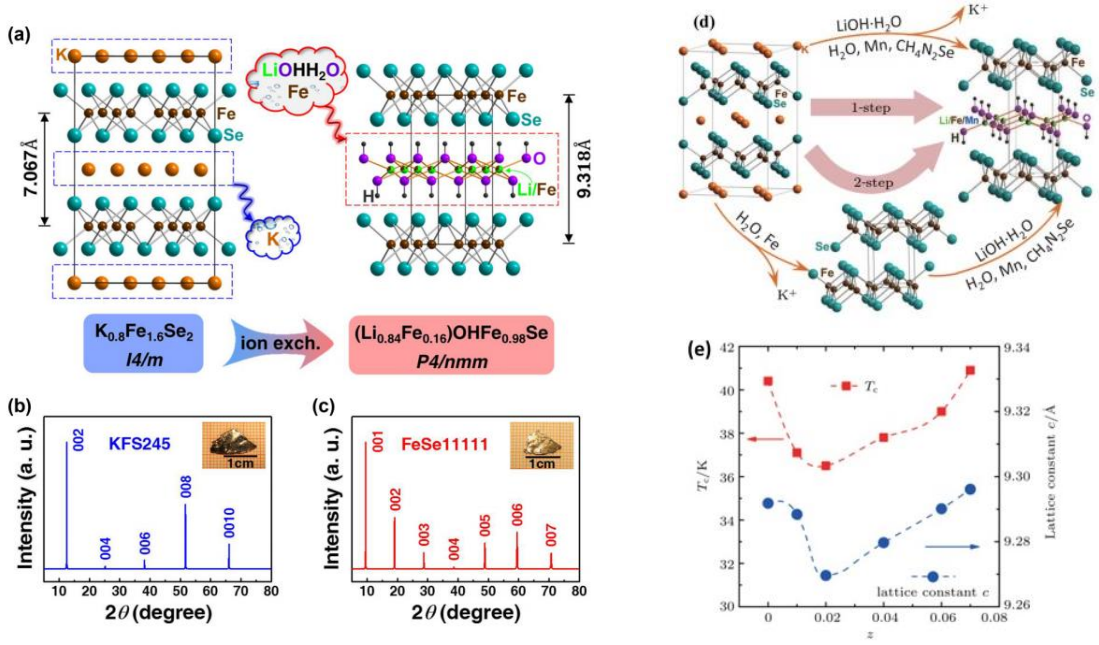

Fig. 1: (a) *A schematic illustration of the hydrothermal ionic exchange reaction.* (b) *and* (c) *The XRD patterns of KFS245 and (Li,Fe)OHFeSe crystal, respectively.* (d) *Sketch of two different hydrothermal routes, ion exchange (1-step) and ion release/introduction (2-step).(e)Lattice parameter c and superconducting transition temperature T_c as functions of Mn doping level z.*

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Magnetic Flux Structure in Phosphorus-Doped $EuFe_2As_2$ Single Crystals

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Magnetic flux structure on the surface of $EuFe_2(As_{1-x}P_x)_2$ single crystals with nearly optimal phosphorus doping levels x = 0.20, and x = 0.21 is studied by low-temperature magnetic force microscopy and decoration with ferromagnetic nanoparticles. The studies are performed in a broad temperature range. It is shown that the single crystal with x = 0.21 in the temperature range between the critical temperatures T_{SC} = 22 K and T_C = 17.7 K of the superconducting and ferromagnetic phase transitions, respectively has the vortex structure of a frozen magnetic flux, typical for type-II superconductors. The magnetic domain structure is observed in the superconducting state below T_C. The nature of this structure is discussed [1].

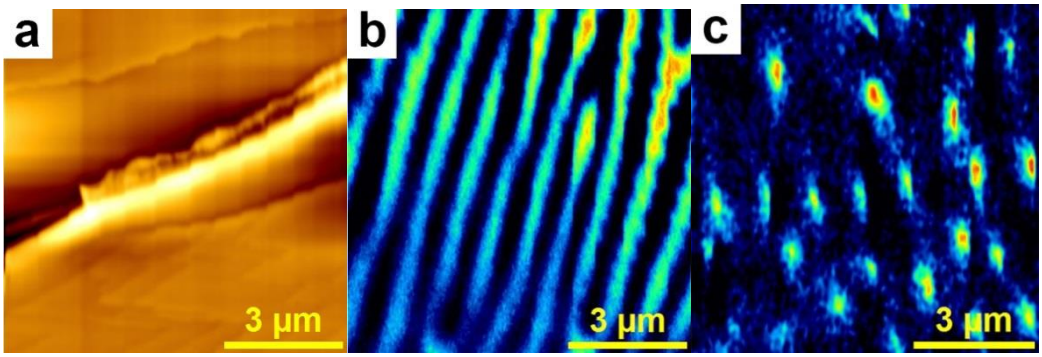

Fig. 1: *AFM topographic image and MFM images of magnetic flux structure on the (001) surface of $EuFe_2(As_{0.79}P_{0.21})_2$ single crystal. (a) AFM topography of the surface area in fully magnetized state of the Eu^{2+} ferromagnetic subsystem in magnetic field of $\mu_0 H$=-0.9 T parallel to the c-axis. (b) Magnetic domain structure after zero-field cooling (ZFC) to the minimum temperature T_{min}=4.16 K with subsequent heating up to T=17.27 K. (c) Vortex structure imaged after FC at T=18.15 K with the residual magnetic flux density Φ_0/a^2~0.6 mT.*

Spontaneous vortex-antivortex (V-AV) pairs are imaged in the vicinity of T_C upon heating in zero external magnetic field.

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Doping induced insulate transition in Superconductor $Ba_x(NH_3)_yFe_{2-z}S_2$

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The discovery of 26K superconductivity in f doped LaFeAsO[1] nark the beginning of a new family of superconductivity. Soon, the superconductivity of FeSe [2]and FeS. [3]are uncovered. These compounds share the similar structure of tetragonal iron arsenide/chalcogenide layers. These layers play a crucial role in the superconductivity. For FeAs and FeSe base materials, doping and intercalation are effective method to enhance the superconductivity. Unfortunately, in the system of FeS, the occurrence of iron vacancy is more frequently compared to the FeSe/As base materials. And the relationship between iron vacancy and superconductivity are worth to do some work.

Here we report a series materials of $Ba_x(NH_3)_yFe_{2-z}S_2$. The akali earth metal Ba and molecular NH_3 are co-intercalted into the FeS layers. The materials with different doping levels x share the same T_c=2.8K, but with the increase of doping level x, the iron vacancy y increase rapidly. And the transport property of the materials present a transition from superconductivity to insulation. In FeSe base materials-KFe_2Se_2[4], the similiar phenomenon is observed. But for KFe_2Se_2, the doping level is unchanged, we cannot observe the relationship between doping and iron vacancy. The Angle-resolved photoemission spectroscopy (ARPES) recognized a similar transition for K dosed FeSe film and FeSeS crystals[5]. The iron vacancy may play a important role in insulate transition in iron-base superconductivity phase diagram.

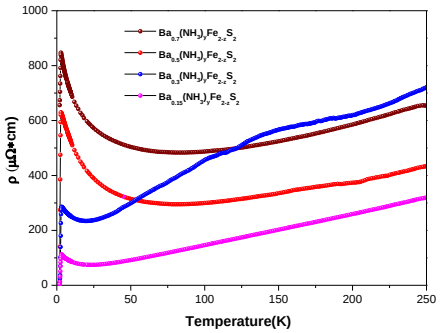

Fig. 1: *Temperature-dependent resistance between 2 and 250 K with different doping levels*

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Record Critical Current Density with Low Anisotropy in Highly-Textured 122 Iron-based Superconducting Tapes

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By using an optimized hot-press process to achieve a higher degree of grain texture in $Ba_{1-x}K_xFe_2As_2$ (Ba-122) tapes, we further increased the transport J_c to 1.5 × 10^5 A/cm^2 (I_c = 437 A) at 4.2 K and 10 T. The transport J_c measured at 4.2 K under high magnetic field of 27 T is still on the level of 5.5 × 10^4 A/cm^2. These J_c values are the highest ever reported for iron-based superconducting wires and tapes and are also superior to NbTi, Nb_3Sn and MgB_2 tapes or wires. In addition, at 20 K and 5 T, the transport J_c achieved was as high as 5.4 ×10^4 A/cm^2, offering a promising application potential in a 'moderate' temperature range which can be reached by liquid hydrogen or cryogenic cooling. We further measured the transport J_c under different magnetic field directions. The J_c anisotropy of the Ba-122 tape at 10 T and 4.2 K is 1.37, a value which is much smaller than that of the Bi-2223 and YBCO tapes. From the x-ray diffraction and the electron backscatter diffraction (EBSD), we find a high degree c-axis texture of the superconducting core. Most grains with a diameter lower than 2 μm are evenly oriented parallel to the tape surface and a large amount of low-degree misorientation angle can be detected by the EBSD. These are the reasons of such high transport J_c achieved in the Ba-122 tapes. These results further strengthen the position of iron based superconductors as a competitor to other superconductors in high field applications.

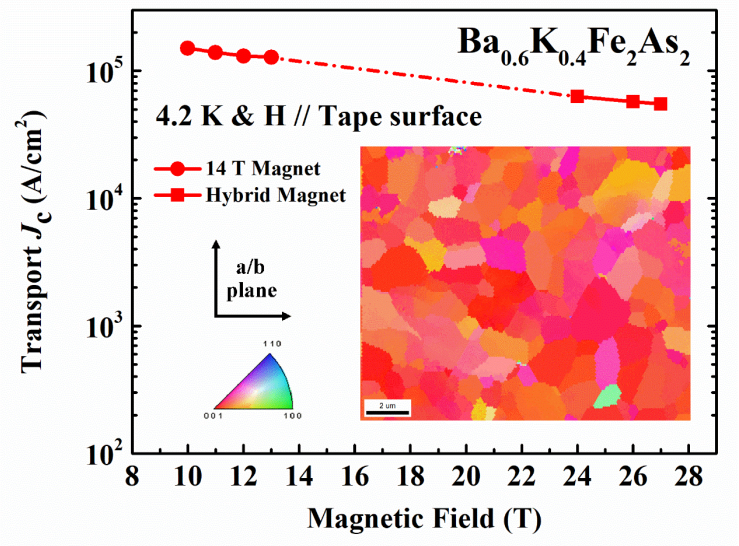

Fig. 1: *Magnetic field dependence of transport J_c for the hot-pressed Ba-122 tape at 4.2 K. The inset shows the inverse pole figure image in [001] direction of the tapes which measured by EBSD.*

Fabrication of superconducting joint between iron-based superconductor tapes

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Superconducting joints are essential for iron-based superconductor's applications in future. In this study, a process for fabricating superconducting joints between $Sr_{1-x}K_xFe_2As_2$ (Sr-122) tapes is developed for the first time. The Ag sheath was peeled off from one side of each sample. The exposed superconducting parts of the two tapes were joined and wrapped again with Ag foil. The diffusion bonding of the iron-based superconducting joint was achieved by hot-pressing process in Argon atmosphere. The superconducting properties, microstructures and the elements distribution of the joint regions had been investigated. The pressure and compressing time was optimized in order to enhance the transport current of the joints. At 4.2 K and 10 T, a transport critical current I_c of 57 A for the joint was obtained, which was approximately 63.3% of the current capacity of the tapes themselves. Furthermore, the joint resistance was below 10^{-9} Ω. These results demonstrate that the hot pressing was useful for fabricating the superconducting joint samples.

High Critical Current Density in Cu/Ag Composited Sheathed $Ba_{0.6}K_{0.4}Fe_2As_2$ Tapes via Hot Isostatic Pressing

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Iron-based superconductors (IBSs) with ultrahigh upper critical fields and low anisotropies have attracted significant attention in terms of the mechanism of superconductivity and high field applications since they were reported. A major concern for practical research is the fabrication of long wires with enhanced critical current density and low cost. In this paper, Cu/Ag composited sheathed $Ba_{0.6}K_{0.4}Fe_2As_2$ tapes were fabricated through hot isostatic pressing (HIP) method, a technique that is feasible for long wire manufacturing. Transport critical current density up to 5.6×10^4 A/cm^2 under 10 T was achieved in our tape by optimizing the heat treatment process parameters. Evidences have showed that these tapes have compact superconducting cores and moderate mechanical strength. Moreover, by partially replacing silver sheath with cooper, the cost of the tapes was markedly reduced, making it more promising for practical applications.

Structure and properties of new organic molecule intercalated FeSe superconductors

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Tetragonal β-FeSe and its superconducting intercalates have shown fascinating properties and aroused intense current interests of researchers. For example, the absence of antiferromagnetic order in β-FeSe and the absence of 'hole pocket' in electronic structure of $A_xFe_2Se_2$ (A=K, Rb, Cs) superconductors are different from the observations in iron pnictides, suggesting that FeSe-based superconductors are crucial systems to investigate the mechanism of high-Tc superconductivity in iron-based superconductors. Moreover, the Tc in the one-unit-cell FeSe thin film on a $SrTiO_3$ substrate is extremely high, reaching 65~109 K and raises the hope of further pursuing bulk iron selenide superconductors with even higher Tc. On the other hand, it was found that superconducting iron chalcogenides are generally metastable, where appropriate synthesis strategies are crucial to kinetically stabilize the superconducting phases and improve their superconducting properties.

Here, we report synthesize of high crystalline FeSe-based superconductors with organic molecules. Under soft chemical condition, the formation of acoustic cavitation induced transient but extreme local heating in otherwise cold liquids, which stimulate the reaction at low temperatures (~60 °C) without fragment the FeSe layers. We demonstrate that well-crystallized FeSe superconductors can be readily obtained in ***En***, 1,3-***DIA*** and diaminohexane (***N,N-DHA***) metal solutions within 12 hours, with Tc ~ 46K and superconducting volume fraction up to 91%. Three structural types are found in this series of intercalates, including body-centered tetragonal, body-centered orthorhombic and primary tetragonal. Structure determination is firstly realized based on neutron powder diffraction (NPD) data, which reveals that the $Na_{0.35(7)}(C_2N_2H_8)Fe_2Se_2$ compound adopts a tetragonal I4/m structure, in which $C_2N_2H_8$ molecules have strong disorder in orientation. The redox reactions indicate $Na_{0.35(7)}(C_2N_2H_8)Fe_2Se_2$ is stable in air while the alkali metals deintercalated easily. Moreover, a rare tetragonal to orthorhombic structure transition induced by glide of FeSe planes is also probed by high-temperature in-situ diffraction data, and the impact of orthorhombic structure distortion to superconductivity in electron doped FeSe is also carefully analyzed based on orbital resolved band structure calculations.

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Growth and Transport Properties of Fe(Se,S) thin films

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One of the current problems in the field of superconductivity is the role of electronic nematicity in superconductivity of iron based materials. An iron chalcogenide superconductor, FeSe shows nematicity at low temperatures without showing long-range magnetic order at ambient pressure, while a magnetic transition is observed in many other iron-based superconductors at temperature very close to the nematic transition temperature. Therefore, FeSe is considered to be one of the most suitable materials for investigating the relation between the nematicity and the superconductivity in iron based superconductors.

Intense studies have been done on the chemical substitution of Se by isovalent S in FeSe. With increasing S content, the nematic transition temperature decreases monotonically, and the superconducting transition temperature, T_c, slightly increases up to ~ 11 K and then starts to decrease. There is no significant change in T_c at the nematic end point (NEP). Interestingly, this behavior of T_c are in contrast to the case of Te-substituted FeSe thin films, where the sudden increase of T_c is observed at the NEP[1,2]. Because continuous substitution by Te is only possible in thin film samples, growth of Fe(Se,S) films is indispensable to elucidate whether the difference in the behaviors of T_c between Fe(Se,S) and Fe(Se,Te) is due to the difference between S- and Te-substitution or between film and film samples.

In this study, we have grown superconducting $FeSe_{1-x}S_x$ epitaxial films with $x \leq 0.43$ on $LaAlO_3$ substrates. Figure 1 shows the obtained phase diagram of the grown films. As x increases, the nematic transition temperature, T_s, decreases, and T_c shows a gradual decrease even at the NEP. In addition, samples with large x values shows a rapid increase of the resistivity with a kink at low temperatures, which is not observed for bulk samples at ambient pressure, indicative of emergence of a new phase transition (represented by T^* in Fig. 1). In spite of the presence of the new phase transition, the behaviors of T_c and T_s are similar to those of bulk samples. Considering the difference in the phase diagrams between $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ thin films, the most probable interpretation of our results is that the role of nematicity in superconductivity is not universal in iron chalcogenides[3].

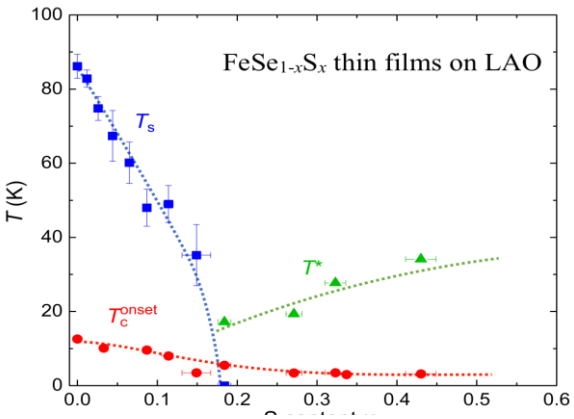

Fig. 1: *Obtained phase diagram of the grown $FeSe_{1-x}S_x$ thin films on LAO.*

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Nematicity and high temperature superconductivity in an orthorhombic iron-based superconductor $Na_{0.35}(C_3N_2H_{10})_{0.426}Fe_2Se_2$

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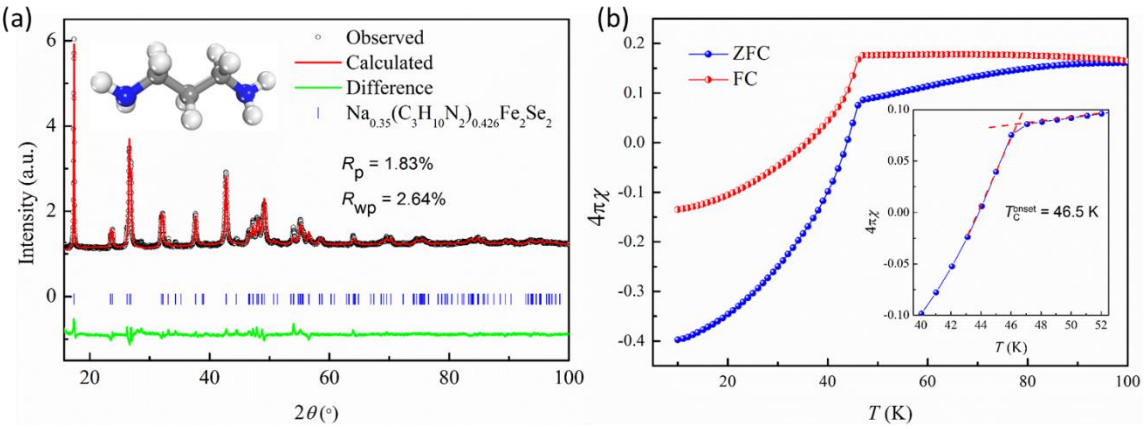
The electron-doped iron selenide $Na_x(C_3N_2H_{10})_yFe_2Se_2$ crystallize in a rare orthorhombic structure, which supplies an ideal platform to investigate the interplay between nematicity and superconductivity. In this study, we report the crystal structure of superconducting $Na_x(C_3N_2H_{10})_yFe_2Se_2$ and its lattice parameters from 300 K to 10 K. The room temperature orthorhombic structure is stabilized by ordered 1,3-*DIA* molecules along b axis in between the FeSe layers, and the *C*2 two-fold rotational symmetry of this superconductor is preserved down to 10 K, well below the superconducting transition temperature (T_c), 46.5 K. An abnormal change of the orthorhombic distortion with decreasing temperatures is found, opposite to most iron-based materials. First principles calculations reveal the orthorhombic distortion readily splits the iron $3d_{xz}$ and $3d_{yz}$ orbits at Γ point, while the degeneracy of the iron $3d_{xz}$ and $3d_{yz}$ orbits at M point is preserved. Our results support that the suppression of nematicity is not the prerequisite for superconductivity in iron chalcogenides.



(a) Refinement against powder X-ray diffraction data. (b) Temperature dependence of magnetic susceptibility $4\pi\chi(T)$ for $Na_{0.35(1)}(C_3N_2H_{10})_{0.426(1)}Fe_2Se_{1.95(1)}$ at low-temperature regions with H = 20 Oe. Inset of (b) presents the enlarged magnetic susceptibility around T_c. For clarity, only the ZFC curve is shown.

High throughput research to elucidate tunable superconductivity in FeSe

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FeSe, among all the Fe-based superconductors[1-3], can serve as the best playground to explore the superconducting mechanism for its structure simplicity[4-6]. It has been demonstrated that the superconductivity of FeSe can be tuned through the crystal lattice engineering as well as the electronic structure manipulation[7-12]. However, critical controversy has been aroused with respect to the roles of modified lattice and conduction carriers. The elucidation of such problem seems daunting owing to the demand for huge amounts of systematic work as well as the mutual restriction of both the samples and the probes. Here, we initiate a high throughput research[13] on FeSe to establish the lattice-T_c library. By which we are able to fabricate film sample with gradient superconducting transition temperature (T_c) from < 2 K to 12 K on centimeter substrate via single deposition, coming with ~ 1% expansion of the out-of-plane lattice and reduction of the in-plane lattice. In conjunction with transport and angular-resolved photoemission measurements on uniform FeSe films, it is found that following the same trend of T_c, the electron carrier density that first approaches and then surpasses the roughly constant number of hole carriers increases by ~ 6 times above T_c. These findings suggest that more conduction electrons benefit T_c, and the subsequent modification on d_{xy} orbital bands by the lattice modulation should have a significant effect on the conduction electrons. Apparently, a combination of high throughput and traditional experiments opens a promising avenue to elucidate the key ingredient to superconductivity and accelerate material researches[14,15].

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Multiple magnetic transitions in single crystal Ce12Fe57.5As41 and La12Fe57.5As41

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Measurements of magnetic and transport properties have been performed on needle-shaped single crystals of Ce12Fe57.5As41 and La12Fe57.5As41 synthesized by Sn-flux method. The availability of a complete set of data enables a side-by-side comparison between these two rare earth compound systems. Both compounds exhibit multiple magnetic transitions. A ferromagnetic transition with Curie temperatures of 100 K and 125 K for Ce12Fe57.5As41 and La12Fe57.5As41, respectively, and subsequent a spin rearrangement near the Curie temperature. The magnetic properties undergo complex evolution in the magnetic field for both compounds. An antiferromagnetic phase transition at about 60 K and 0.2 T is observed only for Ce12Fe57.5As41, and the transition temperature decreases with increasing field, indicating strong interaction between Ce 4f moments and Fe 3d moments. A temperature-field phase diagram are present for these two rare earth systems. In addition, a logarithmic temperature dependence of the electrical resistivity is observed in the two compounds within a large temperature range 150 K-300 K which is rarely found in the 3d-based compounds. It may be related to Kondo scattering described by independent localized Fe 3d moments interacting with conduction electrons.

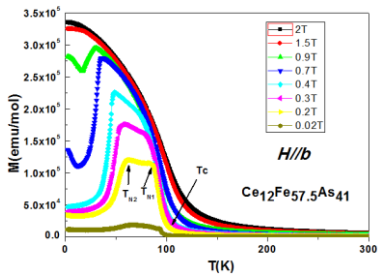

Fig. 1: Magnetic data for Ce12Fe57.5As41 show the dc magnetic moment in different field as a function of the temperature

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The Superconducting Phase Diagram in $Li_x(C_2H_8N_2)_yFe_2Se_2$

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Iron based superconductors have attracted a lot of attentions as the only unconventional high temperature superconducting families besides cuprates. Among iron based superconductors, electron doped FeSe exhibit unique properties, which is more helpful for comprehending the superconducting mechanism of iron based materials. Unlike iron pnictide superconductors, systematic control of electron concentration in bulk iron selenides is still lacking, mainly due to the appearance of Fe vacancies and phase separation occurred at high doping levels. Here we succeed in synthesizing $Li_x(C_2H_8N_2)_yFe_2Se_2$(x = 0.35, 0.4, 0.45, 0.5) pure phase samples by means of a solvothermal method. The relationship between superconducting transition temperature and the content of lithium is studied in details. This is the first time to modulate superconducting transition temperature by electron doping concentration in bulk selenide superconductors. The temperature dependent lattice parameters and crystal structure of $Li_{0.4}(C_2H_8N_2)_{0.5}Fe_2Se_2$ is also obtained based on neutron powder diffraction data.

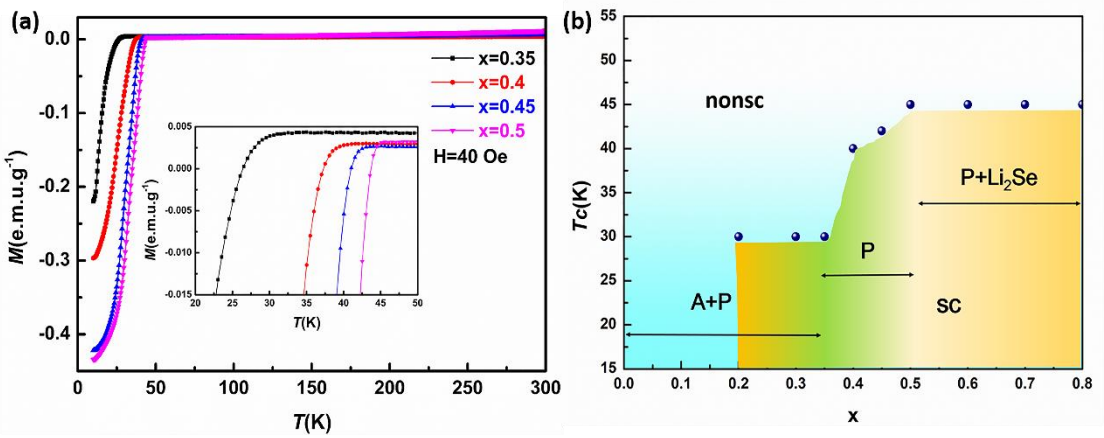

Figure 1. (a) M−T curves of samples with different nominal lithium contents under zero-field cooling. Inset: The enlarged lower temperature range under zero-field cooling. (b) The electronic and structure phase diagram for the $Li_x(C_2H_8N_2)_yFe_2Se_2$ series samples.

Search for Superconductivity in Ni^{2+} Doped $EuFe_2As_2$ at High Pressure

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The $EuFe_2As_2$ is one of the most interesting compounds among the iron pnictide superconductors. The coexistence of a Fe-related spin-density-wave, antiferromagnetic order of Eu^{2+} moments and superconductivity give the unique opportunity to study the interplay between those states [1]. Here we explore the consequences of the substitution of the iron by nickel.

The series of $EuFe_{2-x}Ni_xAs_2$ single crystals (x = 0.0; 0.04; 0.08; 0.12) has been grown using tin flux technique. Under ambient pressure spin-density-wave order is suppressed by nickel substitution. While the Eu^{2+} moments order change its character from antiferromagnetic to ferromagnetic. We have found no evidence of superconductivity down to 55 mK.

High pressure resistivity measurements were performed in a piston–cylinder-type pressure cell up to 2.5 GPa. The samples and a lead manometer were placed into a PTFE cell filled with a pressure-transmitting medium (Daphne 7373). The PTFE cell was inserted into the pressure cell and pressed by pistons made of nonmagnetic tungsten carbide.

The structural phase transition, as well as the spin-density-wave order of Fe sublattice, is suppressed gradually with increasing pressure. For samples with $x \geq 0.08$ at pressures higher than 0.7 GPa the SDW transition is fully suppressed. In contrast, the magnetic order of Eu sublattice persists over the whole investigated pressure range, displaying a non-monotonic variation. The exception is $EuFe_{0.88}Ni_{0.12}As_2$ for which the temperature of Eu^{2+} moments ordering increases continuously with pressure. We have not detect any sign of superconductivity under pressure.

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New Alkaline-Earth-Metal- and Ethylenediamine-Intercalated FeSe-Based and $MoSe_2$-Based Superconductors

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Transition metal chalcogenides with the two-dimensional layered structure have attracted interest owing to the appearance of superconductivity via the intercalation [1-9] or the application of pressure or electric field.

Recently, we have succeeded in synthesizing new intercalation superconductors $AE_x(C_2H_8N_2)_yFe_{2-z}Se_2$ (AE = Ca, Sr, Ba) with T_c ~ 43 K via the co-intercalation of alkaline-earth metal and ethylenediamine into FeSe using the solvothermal method. This value of T_c is nearly the same as that of both alkali metal- and ethylenediamine-intercalated $A_x(C_2H_8N_2)_yFe_{2-z}Se_2$ (A = Li, Na) [4,5]. This result suggests the existence of the upper limit of the charge transfer from intercalated alkali metal or alkaline-earth metal into the FeSe layers.

We have also succeeded in synthesizing new intercalation superconductors $AE_x(C_2H_8N_2)_yMoSe_2$ (AE = Ca, Sr, Ba) with T_c = 5.8, 6.2, 7.0 K, respectively, via the co-intercalation of alkaline-earth metal and ethylenediamine into semiconducting 2H-$MoSe_2$ using the solvothermal method. It has been found that the value of T_c increases with increasing ionic radius of AE and that values of T_c in the $MoSe_2$-based intercalation superconductors are related not to the interlayer spacing between $MoSe_2$ layers so much but to the Pauli paramagnetism, namely, to the electronic density of states at the Fermi level [2]. The T_c value tends to increase with increasing the ionic radius of AE, though the reason is not clear.

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Optical spectroscopy study of iron-based superconductor (Li,Fe)OHFeSe

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We performed an in-plane optical spectroscopy measurement on iron-based superconductor (Li,Fe)OHFeSe single crystals. At room temperature, the low frequency optical conductivity shows an incoherent characteristic; the Drude component is absent. With decreasing temperature, the Drude component develops and narrows rapidly. A well-defined plasma edge is observed in reflectance spectrum for temperature below 100 K, indicating a dramatically reduced scattering rate. The spectral weight contributed from free carriers is even smaller than that of FeSe single crystal. A number of phonon modes are visible in the measured spectra. We also observed clear spectral change below 160 cm^{-1} at 8 K associated with the formation of superconducting energy gap in the superconducting state. The energy scale of the superconducting gap is comparable to the value measured by ARPES technique. Similar to FeSe and other iron pnictides, a clear temperature-induced spectral weight transfer at high energy is observed for (Li,Fe)OHFeSe, being indicative of presence of strong correlation effect.

Highly Anisotropic Superconducting Gaps and BCS-like Critical Fluctuation in FeSe Single Crystal

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The exact structure of superconducting gaps in FeSe superconductor is an interesting issue which is still under debate. In order to solve this problem, we have measured the low-temperature specific heat of FeSe single crystal. Except for the superconducting transition at T_c (≈8.2K), an anomaly around 1 K is also observed. We have fitted the data with various kinds of gap structures. Our results suggest that the superconducting gaps are nodeless but highly anisotropic (Fig. 1). [1] In addition, we find that the specific heat jump near T_c is rather sharp without the trace of strong superconducting fluctuation (SCF), which is contrary to the picture that SCF may be strong in FeSe because of the vicinity to the Bose-Einstein condensate (BEC) and Bardeen-Cooper-Schrieffer (BCS) crossover region. Furthermore, we carried out magnetization measurement and Nernst effect measurement on FeSe single crystals, both of which confirm the narrow fluctuation region in FeSe. Associated with a very small Ginzburg number and further analyses, we conclude that the superconducting fluctuations are vanishingly weak above T_c in this material. [2]

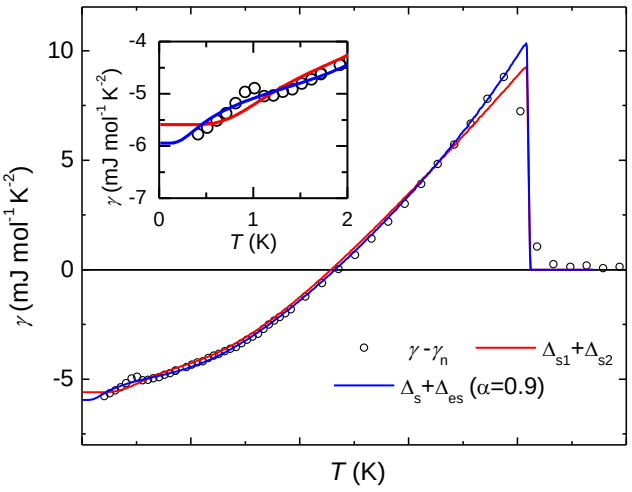

Fig. 1: *The electronic specific heat coefficient vs temperature (symbols), and the fitting curves with different combinations of gaps. The inset shows the enlarged view below 2 K.*

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Multiband Superconductivity and Large Anisotropy in FeS Crystals

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By using a hydrothermal method, we have successfully grown crystals of the newly discovered superconductor FeS, which has an isostructure of the iron-based superconductor FeSe. The superconductivity appears at about 4.5 K, as revealed by both resistive and magnetization measurements. It is found that the upper critical field is relatively low, with, however, a rather large anisotropy $\Gamma \approx 5.8$ (Fig. 1). A huge magnetoresistivity (290% at 9 T and 10 K, $H \parallel c$ axis) together with a nonlinear behavior of Hall resistivity vs external field are observed. A two-band model is applied to fit the magnetoresistance and nonlinear transverse resistivity, yielding the basic parameters of the electron and hole bands. [1]

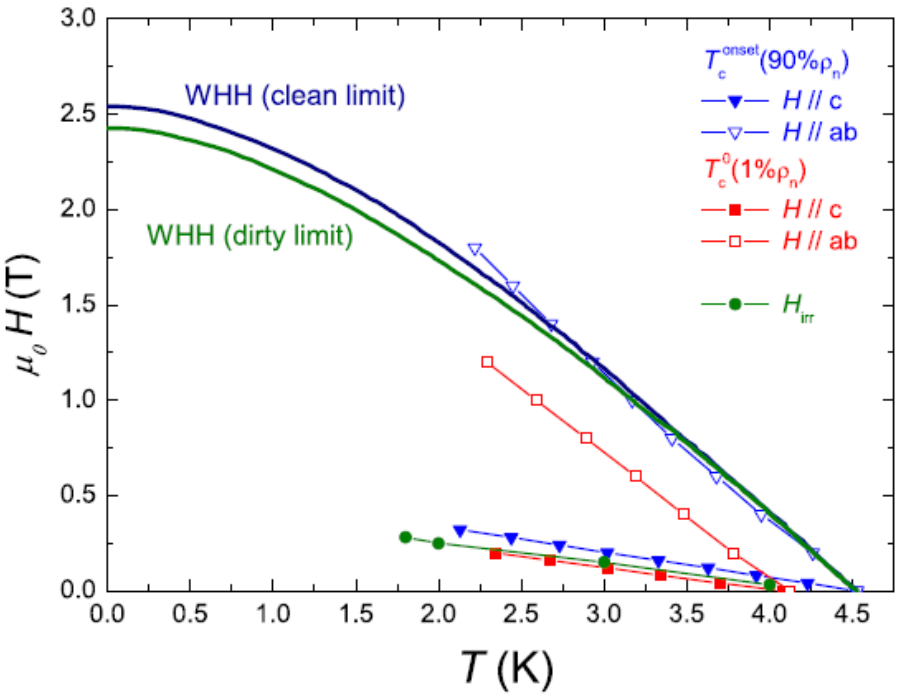

Fig. 1: *The phase diagram of the FeS crystal.*

Reference

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Superconductivity and Magnetism Study of Ruthenium-doped Iron Chalcogenides

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Since the discovery of superconductivity in F doped LaFeAsO in 2008 [1], a new research enthusiasm of superconductors has been ignited and numerous new iron based superconductors have been explored and well-studied. Nowadays as the tide of iron based superconductors receding, topological material becomes another valuable and popular research field in condensed mater physics. As one of the most extensively studied family of iron based superconductors, the iron chalcogenide plays a very special role between this two research fields. Some constructive research results suggest that an unusually relationship between the iron based superconductor and the topologic material was bridged up by $FeTe_{0.55}Se_{0.45}$ [2-4]. We believe that moderate Ru doping can both maintain the superconductivity of $FeTe_{0.55}Se_{0.45}$ and tune the spin orbital coupling (SOC) strength of the compound, which is usually important for the topological material study. Motivated by the above considerations, we carried out the superconductivity and magnetism study of ruthenium-doped iron chalcogenide recently. High quality single crystals of $Fe_{1-x}Ru_xTe$ (x = 0, 0.02, 0.04, 0.06, 0.08, 0.10) and $Fe_{1-x}Ru_xTe_{0.5}Se_{0.5}$ (x = 0, 0.02, 0.04, 0.06, 0.08, 0.10) were prepared by the Bridgeman method. The temperature dependent resistivity and magnetism measurements were performed by the physical property measurement system (PPMS) with electronic transport and vibrating sample magnetometer (VSM) accessories, respectively. The antiferromagnetic phase transition of FeTe at ~ 70 K can be slightly suppressed by Ru doping. The critical superconducting transition temperature of $FeTe_{0.5}Se_{0.5}$ is gradually suppressed to ~ 7.5 K from 15 K by 0.1 nominal Ru doping. We believe that our research results will make up the absence of related study and provide a basic guidance for further band structure measurement.

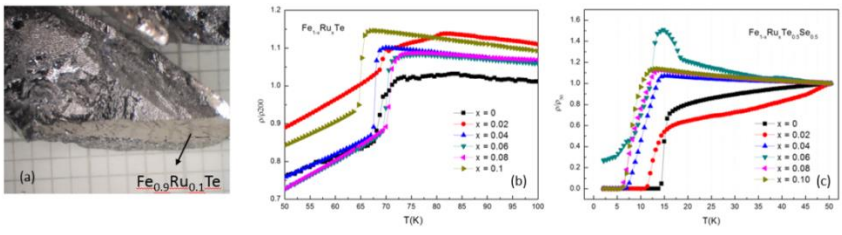

Fig. 1: (a) A picture of the prepared FeTe singlecrystal with 0.1 nominal Ru doping. (b) and (c) are the normarlized temperature dependent resistivity results of $Fe_{1-x}Ru_xTe$ and $Fe_{1-x}Ru_xTe_{0.5}Se_{0.5}$ (x = 0, 0.02, 0.04, 0.06, 0.08, 0.10)

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Superconducting (Li,Fe)OHFeSe Film of High Quality and High Critical Parameters

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This presentation exhibits a soft chemical film technique, which is applicable for growing a series of $(Li_{1-x}Fe_x)OHFe_{1-y}Se$ films with the superconducting critical temperature (T_c) from 4 K up to 42 K. The optimal bulk superconducting transition temperature T_c of 42.4 K is characterized by both zero electrical resistance and diamagnetization measurements. The upper critical field H_{c2} is estimated to be 79.5 T and 443 T for the magnetic field perpendicular and parallel to the ab plane, respectively. Moreover, a large critical current density J_c of a value over 0.5 MA/cm^2 is achieved at ~20 K. Such a (Li,Fe)OHFeSe film is therefore not only important to the fundamental research, but also promising in the field of high-T_c superconductivity application, especially in high-performance electronic devices and large scientific facilities such as superconducting accelerator.

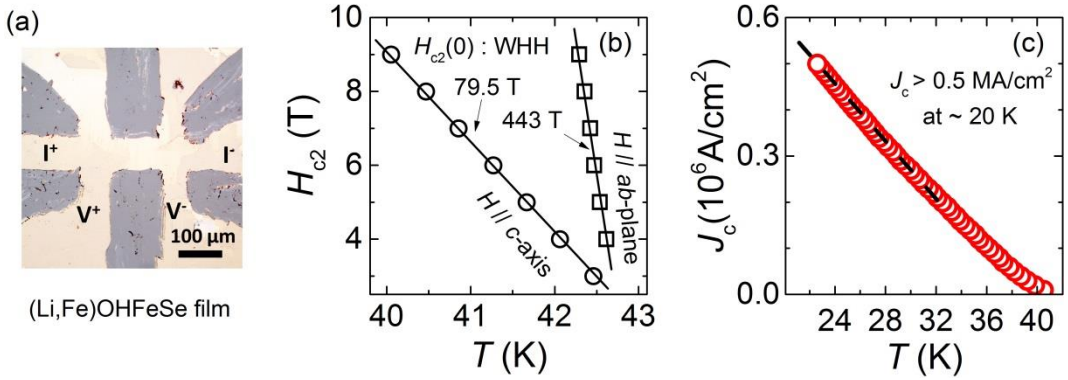

Fig. 1: *(a) The optical image of a patterned (Li,Fe)OHFeSe film on a $LaAlO_3$ substrate; (b) Temperature dependence of $H_{c2}(T)$ along the c-axis (circle) and within the ab plane (square); (c) The temperature dependence of J_c.*

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Transport Properties and Anisotropy of $CsCa_2Fe_4As_4F_2$ Single Crystals

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We succeeded in synthesizing the 12442-type iron-based superconductors *Ak*$Ca_2Fe_4As_4F_2$ (*Ak* = K, Rb, Cs) and *AkLn*$_2$$Fe_4As_4O_2$ (*Ak* = K, Rb, Cs; *Ln* = Nd - Ho). The series compounds show bulk superconductivity at T_c = 33–37 K. High quality single crystal $CsCa_2Fe_4As_4F_2$ was grown, and characterized by X-ray diffraction, magnetotransport and magnetization measurements. The anisotropic superconducting upper H_{c2} (T), lower critical field H_{c1} (T), the anisotropy parameter γ (T) and other related parameters are deduced.

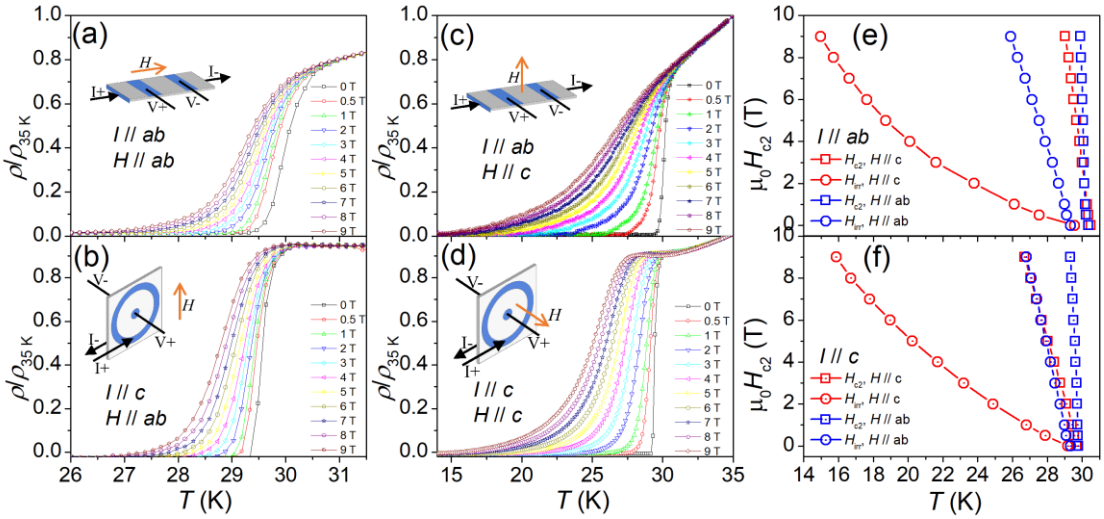

Fig. 1: *(a-d) Temperature and field dependence of the in-plane and out-of-plane resistivity for* $CsCa_2Fe_4As_4F_2$ *single crystal with external field applied along the c-axis and parallel to the ab-planes, respectively. (e-f) Upper critical field (H_{c2}) and irreversible field (H_{irr}) derived from the in-plane and out-of-plane resistivity measurements.*

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Organic ion intercalated FeSe-based superconductors

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Finding new derivative structure of FeSe-based superconductors with a high superconducting transition temperature (Tc) is of great significance. Here, in this work, an organic ion, Cetyltrimethyl Ammonium (CTA^+) intercalated FeSe-based superconductor $(CTA)_{0.3}FeSe$ with the Tc as high as 45 K is synthesized by electrochemical intercalation method. The as-prepared $(CTA)_{0.3}FeSe$ has a hybrid crystal structure consisting of double layers of CTA^+ and one layer of FeSe, which is consistent with a lateral-bilayer model. The superconductivity of $(CTA)_{0.3}FeSe$ is confirmed by magnetic susceptibility. Furthermore, a negative pressure effect on superconductivity dTc/dP = -5 K/GPa is observed. This is the first pure organic ion intercalated FeSe-based superconductor with a high Tc and high crystallinity. Our work offers a new method to modify the interface interaction between FeSe layer and the intercalator, and sheds new light on finding new FeSe-based superconductors with higher Tc.

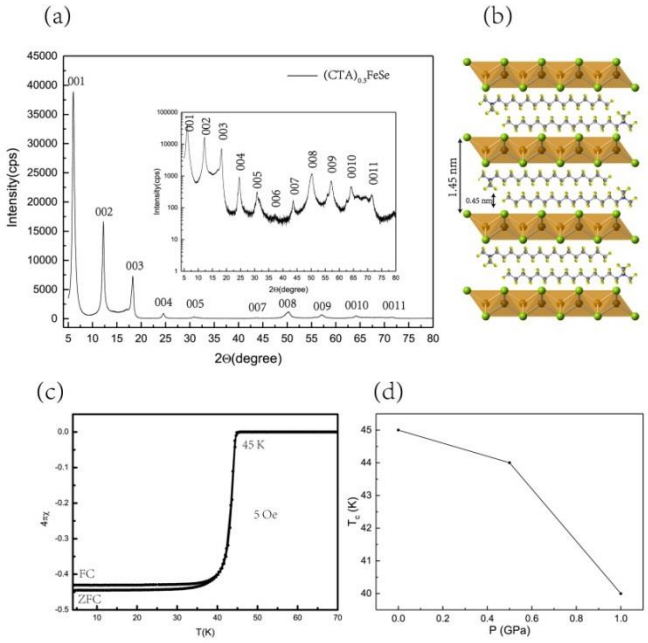

Fig. 1: *Characterization of (CTA)0.3FeSe. (a) XRD pattern of (CTA)0.3FeSe. (b) The crystal structure model for (CTA)0.3FeSe, which is consistent with a lateral-bilayer model. (c) magnetic susceptibility of (CTA)0.3FeSe under a magnetic field of 5 Oe. (d) Pressure-Tc diagram of (CTA)0.3FeSe under a pressure range of 0-1 GPa obtained by magnetic susceptibility.*

Collective Vortex Pinning and Merging of the Irreversibility Line and Second Peak Effect in Optimally Doped $Ba_{1-x}K_xBiO_3$ Single Crystals

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Measurements on magnetization and relaxation have been carried out on an optimally doped $Ba_{1-x}K_xBiO_{3+\delta}$ single crystal with T_c = 31.3 K. It is found that the data are well described by the collective pinning model leading to the glassy exponent of about μ ≈ 1.64–1.68 with the magnetic fields of 1 and 3 T. The analysis based on Maley's method combining with the conventional relaxation data yields a μ value of about 1.23–1.29 for the magnetic fields of 1 and 3 T. The second magnetization peaks appear in wide temperature region from 2 K to 24 K. We present a vortex phase diagram (Fig. 1) and demonstrate that the vortex dynamics in $Ba_{1-x}K_xBiO_3$ can be used as a model system for studying the collective vortex pining.

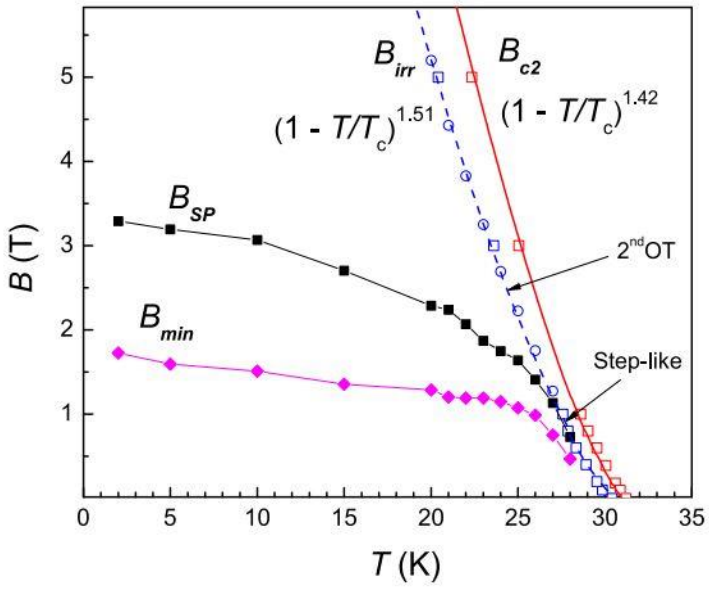

Fig. 1: *Vortex phase diagram of the optimally doped BKBO sample.*

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Structures and Physical Properties of $CsV_2Se_{2-x}O$ and V_2Se_2O

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By using solid-state reactions, we successfully synthesize new oxyselenides $CsV_2Se_{2-x}O$ (x =0, 0.5). These compounds containing V_2O planar layers with a square lattice crystallize in the $CeCr_2Si_2C$ structure with the space group of P4/mmm. Another new compound V_2Se_2O which crystallizes in space group I4/mmm (Fig. 1) is fabricated by topochemical de-intercalation of cesium from CsV_2Se_2O powder with iodine in tetrahydrofuran (THF). Resistivity measurements show a semiconducting behavior for CsV_2Se_2O, while a metallic behavior for $CsV_2Se_{1.5}O$, and an insulating feature for V_2Se_2O. A charge- or spin-density wave-like anomaly has been observed at 168 K for CsV_2Se_2O and 150 K for $CsV_2Se_{1.5}O$, respectively. And these anomalies are also confirmed by the magnetic susceptibility measurements. The resistivity in V_2Se_2O exhibits an anomalous log(1/T) temperature dependence, which is similar to the case in parent phase or very under-doped cuprates indicating the involvement of strong correlation. Magnetic susceptibility measurements show that the magnetic moment per V-site in V_2Se_2O is much larger than that of CsV_2Se_2O, which again suggests the correlation induced localization effect in the former. [1]

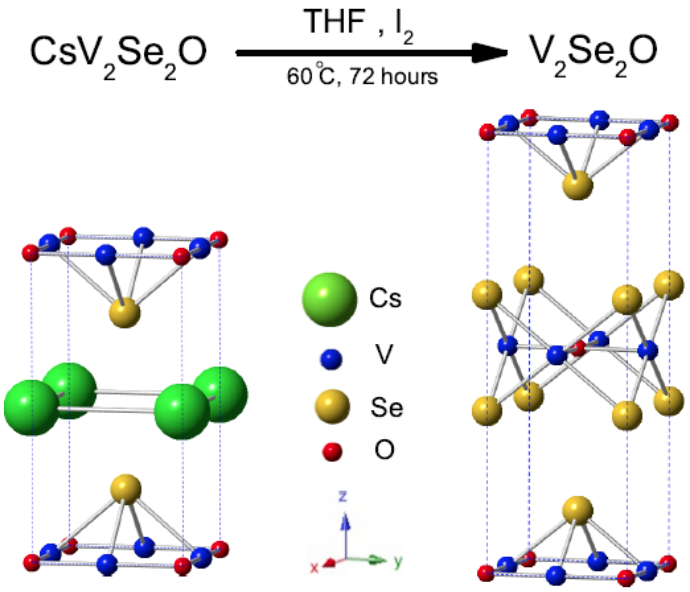

Fig. 1: *Synthesis and Schematic structures of CsV_2Se_2O and V_2Se_2O.*

Reference

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Changed structure and properties of MgB2 bulk superconductors with Mg(BH4)2 additions

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The effects of $Mg(BH_4)_2$ addition on the superconducting properties and microstructure of MgB2 bulk superconductors which are used the method of melting Mg powder into B powder were studied. $Mg(BH_4)_2$ sol was prepared by sol-gel method, then $Mg(BH_4)_2$ sol was heated and dried at 120°C for 4 hours to get $Mg(BH_4)_2$ powder. Mg powder and B powder of the mole ratio 1:2 were mixed with $Mg(BH_4)_2$ powder of 1-30wt%，the mixing process required Mg powder to be above B powder and $Mg(BH_4)_2$, then the mixture was made of a rectangular bulk in high pressure environment. The bulk was heat-treated at 680°C for 4 hours in flowing H_2. The powder X-ray diffraction analysis for the heat-treated sample showed that the major formed phase and the minor phases. The superconducting transformation temperature of MgB_2 with $Mg(BH_4)_2$ addition（1-30wt%）was between 36-38K. The result indicates that $Mg(BH_4)_2$ addition did not change the superconducting transformation temperature, but the critical current density of MgB_2 was changed as the additions of 1-30wt% $Mg(BH_4)_2$ powder. We also used atomic force microscopy and scanning electron microscopy to observe the morphological structure of its surface. By doping the $Mg(BH_4)_2$ into MgB_2, the surface structure and performance of the superconducting bulk are changed, it lays a foundation for the preparation of large superconducting shielding cavities.

Keywords： MgB_2, $Mg(BH_4)_2$ addition, superconductor, superconducting transformation temperature, critical current density

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Tailoring charge transfer and magnetism at interfaces of spin-orbit coupled oxide superlattices

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Identifying emergent novel quantum states at interfaces of correlated oxide heterostructure is well known as one of the most promising but challenging strategies to realize the high manipulation of materials at nanometer length scales. Particularly, controlling of both the electronic reconstruction due to charge transfer and the emergent ferromagnetism occurring at interfaces are of fundamental and technological importance. By delicately varying the separation between interfaces in $(SrIrO_3)_mSrTiO_3$ superlattices with atomic-layer precision, we demonstrate that the charge transfer occurring at the non-polar interface of $SrIrO_3$ and $SrTiO_3$ can be effectively tuned by changing the rotation of the oxygen octahedra at the boundary. Moreover, the ferromagnetism localized at the interfacial oxygen layer can be consequently switched on or off directly. This work demonstrates how charge transfer and interfacial ferromagnetism can be engineered at correlated oxide interfaces, which would shed light on the origin of such emergent phenomena and is promising for spintronic applications.

Coexistence and Competition between stripe and Neel antiferromagnetic order in highly Cr doped $BaFe_{1.9-x}Ni_{0.1}Cr_xAs_2$

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Neutron scattering measurements manifest two different long range antiferromagnetic orders, stripe spin-density-wave order and G-type Neel antiferromagnetic order, in the highly Cr doped $BaFe_{1.9-x}Ni_{0.}1Cr_xAs_2$, The Neel average moment and transition temperature increase with Cr doping level increasing, whereas the stripe average moment and transition temperature decrease slightly. The inelastic neutron scattering results above T_N show that the spin-spin correlation length and spin fluctuation energy at Q_{Neel} are large than those at Q_{stripe}, which suggest that those samples are more closer to cuprate and d-wave state is favored. Our results suggest that those samples could be the bridge between cuprate and iron-pnictide superconductors and help characterize the principles of high-T_c superconductivity.

Structural and Transport Properties of FeTe Films

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The 11-type iron-chalcogenides have attracted lots of attentions due to their simple structure, mild toxicity and accessibility of doping. Among them, FeSe and FeTe have a similar crystal structure. However, FeSe is a superconductor [1] while FeTe is a metal at low temperatures [2]. Density functional calculation revealed that FeTe can be a superconductor when doped with enough carriers [3]. For FeTe films, there are some reports that oxygen incorporation was needed to induce superconductivity [4, 5], while it was also found that FeTe film can be superconducting without intended oxygen incorporation [6]. We studied the structural and transport properties of a series of FeTe films grown at different substrate-temperatures in vacuum by pulsed-laser deposition. It is demonstrated that the FeTe films, deposited within a rather large substrate-temperature range, were all superconducting. The crystal structure, as well as the critical temperature for superconductivity (Tc), of the FeTe film strongly depends on the substrate-temperature, and a maximal Tc of nearly 10 K was realized with the optimum temperature. Transport measurements revealed that the superconducting region may not be homogeneous, which might come from the incorporation of the traces of oxygen during deposition or other factors, and this issue deserves further investigation. This work is helpful for understanding the mechanism of superconductivity in FeTe.

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High Quality Superconducting $FeSe_{0.5}Te_{0.5}$ Films Grown on $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ with Large Lattice Mismatch and Electric-field Modulation of Superconducting Transition

Chenguang Mei,[1,3,] Zhu Lin,[1,3,] Haoliang Huang,[4] Ruixin Zhang,[2,3] Chengchao Xu,[2,3] Qinghua Zhang,[2,3] Lin Gu,[2,3] Huaixin Yang,[2,3] Jianqi Li,[2,3] Guangming Zhang[1,3] & Yonggang Zhao[1,3]

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Heterostructures composed of superconductors and ferroelectrics are very important for applications and fundamental research [1-3]. $FeSe_xTe_{1-x}$ have generated tremendous interest in scientific community because of its simple structure, improved superconductivity (SC) with high pressure [4] and topological superconductivity [5]. While $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ (PMN-PT) is a very important ferroelectric material due to its excellent piezoelectric property. We used a novel two-step method to grow high quality $FeSe_{0.5}Te_{0.5}$ (FST) films on ferroelectric PMN-PT, which has a little bit rough surface and a large lattice mismatch with FST. FST films show epitaxial growth and much higher T_c (comparable to FST single crystal), which is in contrast to those deposited with the normal one-step method [6]. It was also found that the FST films undergo biaxial tensile strains and are relaxed over a threshold thickness for FST films with FST buffer of different thicknesses. Moreover, electric-field induced an increase of T_c. FST/PMN-PT provides a unique platform for studying the coupling between superconductivity and ferroelectricity, and is significant for understanding the interesting feature of $FeSe_xTe_{1-x}$.

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Optimized Conditions for ionic-liquid-gating assisted protonation to search for high-T_c phases in iron-based superconductors

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In cuprate and iron-based superconductors, charge doping in bulk materials are mostly achieved by solid reactions at high temperatures. There are also ongoing gating techniques to tune the carrier density, in order to achieve novel superconducting states. However, these gating techniques are only effestive for films or very thin crystals, and the gating setup also prevents spectroscopy studies.

Recently, we used a protonation technique, utilizing gating techniques with ionic liquid, to induce permanent electrons doping into large single crystal of iron-based superconductors. High- T_c phases are achieved; however, the volume fraction of the high-T_c phase is low. Here we present our improved protonation technique, which enhances the volume fraction of the high- T_c phase up to about 100%. Clear superconducting transitions are also observed in the resistivity data. This also allows for rich spectroscopic studies of the superconducting phases. we will also present our extended studies on more materials with this protonation technique.

Fabrication of FeSe Superconducting Wires Based on High-energy Ball Milling Aided Sintering Process

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After the first report of tetragonal FeSe phase with the superconducting critical temperature of ~8.0 K by Hsu *et. al.* [1], FeSe system has attracted more and more attentions for both fundamental researches and practical applications. It has been considered as one of the key materials to uncover the nature of superconducting mechanism by preparing single-layer FeSe ultra thin films [2-3]. On the other hand, FeSe can also be recognized as a potential candidate for practical applications in low temperature and high field in the form of long wires or tapes. Its advantages such as higher upper critical field of H_{c2} ~47 T [4], lower cost and lower toxicity of starting materials all suggest their potentials as practical superconductors. Thus in this study, high-energy ball milling (HEBM) process has been introduced to the preparation process of FeSe precursor powders. By achieving amorphous Fe_3Se_4 and small particles of Fe, the diffusion path between Fe and Se has been obviously decreased into atomic range. Therefore, with this HEBM aided sintering process, tetragonal FeSe phase can be obtained under very low temperature and non-superconducting hexagonal FeSe phase can be successfully avoided. The phase transition mechanism in this fabrication process involved with hexagonal FeSe phase, a superconducting tetragonal FeSe phase and a non-superconducting tetragonal FeSe phase has been deduced. The crucial parameters, including HEBM time, ball to powder ratio, sintering temperature, cooling rate have been optimized. Then precursor powders with high superconducting phase volume ratio and high critical temperature were adopted in a powder-in-tube process to fabricate FeSe superconducting wires. A transport critical current density of >300 Acm^{-2} has been achieved and further optimization process is on the way.

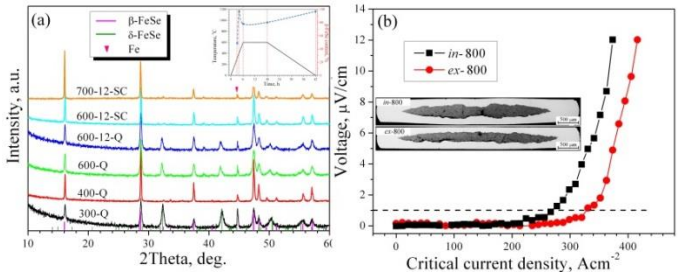

Fig. 1: (a) XRD patterns of Fe-Se system during HEBM aided sintering process with different sintering temperature; (b) *E-I* curves of FeSe tapes with different fabrication technique

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Anomalous transversal resistance in 122-type iron-based superconductors

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The study on the transverse resistance of superconductors is essential to understand the transition process of superconductivity. We investigated on the in-plane transverse resistance of $Ba_{0.5}K_{0.5}Fe_2As_2$ superconductors, based on the samples of ultra-thin micro-bridges fabricated from single crystals. An obvious anomalous transversal resistance was found at the temperatures around the superconducting transition region, although the magnetic order is absent in the optimal doping case. With the substitution of magnetic or nonmagnetic impurities into the superconducting layer, the anomalous transversal resistance phenomenon is dramatically enhanced. We find that the anomalous Hall effect, vortex motion, or spin-fluctuation can hardly be attributed to the origin of the anomalous transversal resistance, while the superconducting electronic nematic state related with the superconducting transition may contribute this phenomenon.

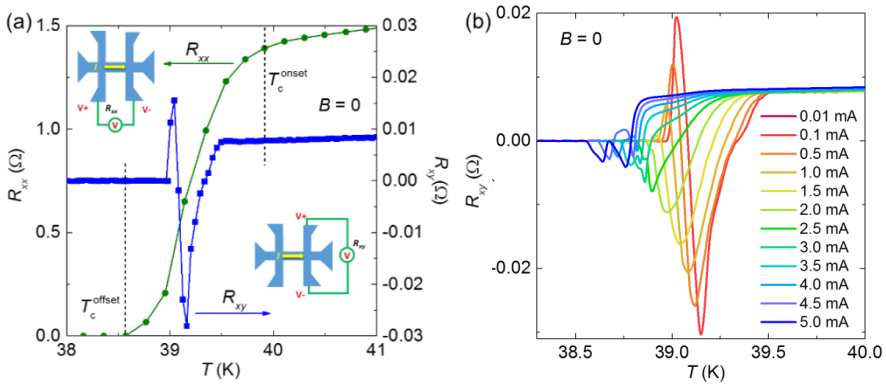

Fig. 1: *(a) Temperature dependence of R_{xx} and R_{xy} for BK micro-bridge. Inset schematic images reveal the measurements of R_{xx} and R_{xy}. (b) Temperature dependent R_{xy} for BK micro-bridges under different currents ranging from 0.01 mA to 5.0 mA.*

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Growth and Physical Properties of CaFeAsF Single Crystals

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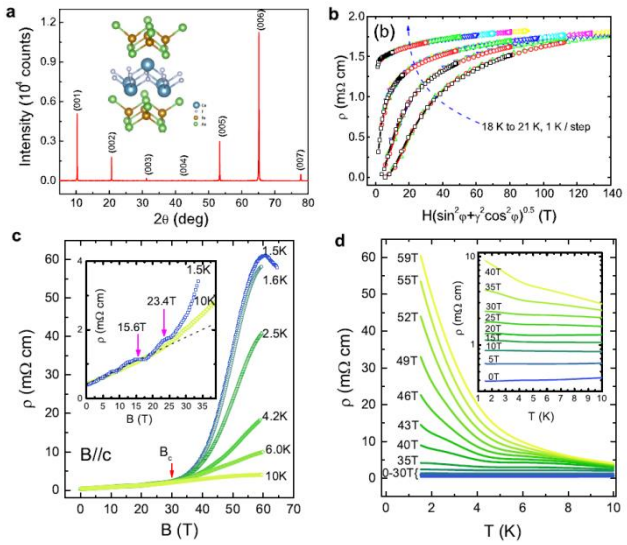
High-quality and sizable single crystals are crucial for studying the intrinsic properties of unconventional superconductors, which are lacking in the 1111 phase of the Fe-based superconductors. Here we report the growth physical properties of CaFeAsF single crystals using the self-flux method[1]. Owning to the availability of the high-quality single crystals, the structure and transport properties were investigated with a high reliability. The structure was refined by using the single-crystal x-ray diffraction data, confirming the reports earlier on the basis of powder data. The electronic structure was investigated by quantum oscillation measurements and band-structure calculations[2]. A magnetic-field-induced metal-insulator transition was observed under the high field near the quantum limit[3]. The superconducting crystals were also obtained by the similar method in the Co-doped



samples[4]. A strong anisotropy effect of the upper critical field was found in the superconducting samples with doping level of 0.12[5]. Our results supply a basis to propel the physical investigations on the 1111 phase of the Fe-based superconductors.

Fig. 1: X-ray diffraction pattern and transport properties of CaFeAsF (a, c, d) and Ca(Fe,Co)AsF (b) single crystals.

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Electron-plasmon interaction induced plasmonic-polaron band replication in epitaxial perovskite SrIrO3 films

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Electron-boson interactions are fundamental to a thorough understanding of exotic properties emerging in many-body physics. In photoemission spectroscopy, the emission of photo-electrons upon the absorption of photons would trigger collective excitations in solids, leading to the emission of phonons, magnons, electron-hole pairs, or plasmons, and it provides a reliable and pathway to study electron-boson interactions. While fingerprints of electron-phonon or electron-magnon interactions in this state-of-the-art technique have been well understood, much less information on electron-plasmon coupling is known, and - the direct observation of dispersive bands brought by electron-plasmon interactions is extremely challenging. Here, we report the discovery of electron-plasmon coupling induced plasmonic-polaron replica band in epitaxial perovskite $SrIrO_3$ films, in which the unique semimetallicity introduced by the delicate interplay of the electron-electron coupling, spin-orbit coupling and octahedron rotation render it an ideal platform to investigate the electron-plasmon interactions. Our findings demonstrate that the electron-plasmon many-body interaction should be considered on the equal footing with the acknowledged electron-electron repulsion and spin-orbit coupling to obtain a complete understanding of the quasiparticle dynamics in perovskite $SrIrO_3$ and other related 5d electron systems.

Improved superconductivity by increasing densityof MgB_2 perpared by hot-pressing

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The MgB_2 superconductor bulks were prepared by hot-pressing under the pressure of 35~95 MP, respectively and the effects of the applied pressure on the superconductivity were investigated. Increasing apllied pressure improved the density of the MgB samples and the critical current density (J_c) improved with the increase of the density. When the applied pressure exceeds 55MP, the density has been increased very little with increase of the applied pressure. However, the J_c has increased significantly. At the same, the superconducting critial temperature (T_c) decreased with the increase of the density. This indicated that applied high pressure introduces a new flux pinning mechanism.

Key words: MgB_2; Hot pressing; Superconducting property.

The Effect of Sintering Temperature on Superconductivity of MgB_2 Prepared by Hot-pressing

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The MgB_2 superconductor bulks were prepared by hot-pressing under the pressure of 55 MP at the different temperature 650℃, 700℃, 800℃, 900℃,1000℃, respectively, and the effects of sintering temperature on the superconducting properties of MgB_2 bulks were investigated. We found that the density of the bulk samples increased with the rise of sintering temperature and the density reached to the maximum value when the sintering temperature rose to 1000℃. However, the critical current density (J_c) did not increase with the increase of the density. This indicated that with the increase of the sintering temperature, the effect of density on J_c was not the dominant factor. The size and morphology of the grains and the purity of the MgB_2 samples played a leading role in the J_c. When the applied magnetic field was greater than 2 T, the J_c from sample prepared at 900℃ was the best.This indicated that the increase of sintering temperature altered the flux pinning mechanism in the MgB_2 sample.

Metallic hydrogen with a strong electron-phonon interaction at a pressure of 300-500 GPa

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Atomic metallic hydrogen with a lattice with FDDD symmetry is shown to have a stable phase under hydrostatic compression pressure in the range of 350-500 GPa. The resulting structure (Fig.1) has a stable spectrum regarding the collapse of the phonons.

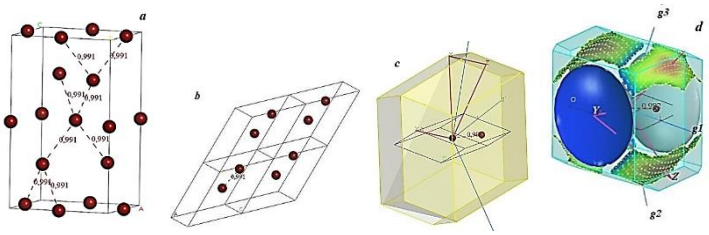

Fig.1. *a: Rectangular unit cell of the structure with the FDDD symmetry; b: four primitive orthorhombic cells of the structure shown in Fig.1a; c: inverse cell for the primitive cell, shown in Fig.1b; d: isosurfaces of the two bands crossing the Fermi level.*

Ab-unitio simulation method has been used to calculate the structural, electronic, phononic and other characteristics as well as the superconducting temperature of the metallic phase of the hydrogen [1-4] at a pressure of 350-500 GPA (Fig.2).

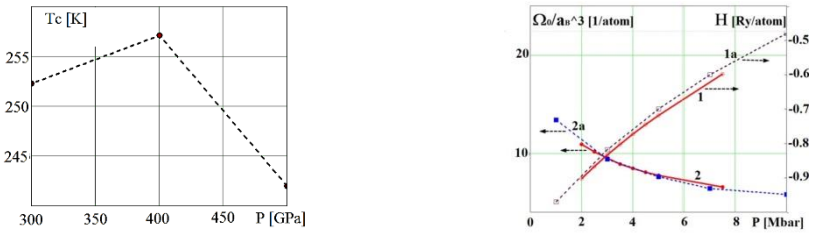

Fig. 2. *The dependence of the critical temperature of the structure with the FDDD symmetry on the pressure P.*

Fig.3.*The comparison of both the dependencies of enthalpy (1) (right vertical axis) and specific volume (2) (left vertical axis) per one atom vs the pressure P for the structure with FDDD symmetry with the similar dependencies (1A and 2A) for the metallic hydrogen phase from the work [4].*

The universal nature of the dependencies, established in [1], for all superconducting phases of the metallic hydrogen has been shown (Fig.3).

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Temperature Dependence of the 182-, 201-, 210 and 285-cm-1 Raman modes of the SmFeAsO1-xFx superconducting compounds

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By changing the sintering temperature, superconducting samples of SmFeAsO1-xFx with different qualities were obtained by solid state reaction. The optimal doped samples were obtained when the sintering temperature is fixed at 950^{o}C and for x=0.09. This samples show a superconducting transition at 56K. Raman spectroscopy measurements were performed at room temperature form 50 to 500 cm-1 and at different temperatures, above and below Tc, from 140 to 320 cm^{-1}. At room temperature the Sm-Eg, As-A1g, Fe-Eg and O-Eg active Raman modes were detected very well. At low temperatures we were able to detect only the Sm-A1g, As-A1g, Fe-B1g and the Fe-Eg modes. We perform a careful study of the changes in line shape, shifting position and linewidths of the 182-, 201-, 210- and 285-cm-1 as a function of the temperature to determine the relationship between superconducting transition and the electron-phonon interaction. The results of this study indicates that the emergence of the superconductivity in the SmFeAsO1-xFx compound is not related with the electron phonon interaction.

Electrical resistivity across a nematic quantum critical point

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The nematic electron fluid [1] has recently become a major theme in correlated electron research, especially after its observation in materials such as, among others, Fe-pnictides [2] and cuprates [3]. These material classes are found to exhibit striking deviations from conventional Fermi-liquid behaviour when tuning towards a putative quantum critical point (QCP). This quantum critical behaviour could be linked to the presence of nematicity though the existence of other forms of order, often intertwined with nematicity in the above mentioned materials, has made the link with nematicity difficult to identify.

$FeSe_{1-x}S_x$ is unique in this respect since nematic order appears to exist in isolation [4,5]. At low x values, $FeSe_{1-x}S_x$ exhibits a nematic phase below a temperature T_s which is gradually suppressed by S substitution, until T_s = 0 K at x_c ~ 0.16. However, the transition to the superconducting state has, until now, prevented access to the underlying normal state at low temperatures. In this work, we use static magnetic fields up to 35 T to destroy the superconducting state in $FeSe_{1-x}S_x$ ($0 \leq x \leq 0.25$) and follow the evolution of the electrical resistivity across the nematic QCP.

As summarized in Fig. 1, we observe classic signatures of quantum criticality, namely a divergence in the coefficient A of the T^2 resistivity (once the change in carrier density has been taken into account) on approaching the QCP from either side and, at the QCP itself, a strictly T-linear in-plane resistivity ($_{ab}$) that extends over more than a decade in temperature.

In addition to revealing the phenomenon of nematic quantum criticality, the observation of T-linear resistivity at a nematic QCP also raises the question whether strong nematic fluctuations could affect the transport properties of other strange metals as well.

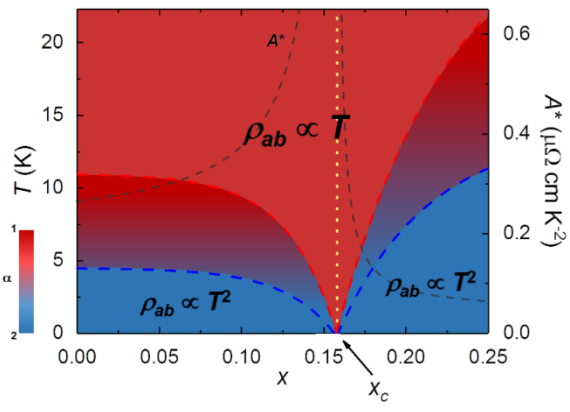

Fig. 1: *Evolution of $\rho_{ab}(T,x)$ in $FeSe_{1-x}S_x$ across the nematic quantum critical point*

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Superconducting $La_3Co_4Sn_{13}$ Compound Under Pressure

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The superconducting $La_3Co_4Sn_{13}$ material with transition temperature at T_c = 2.70 K, also presents a superlattice structural transition at T^* ~ 150 K, which doubles its lattice parameter in respect to the higher temperature phase. Questions whether these lattice distortions arise from a charge density wave (CDW) and the order parameter of the system, i.e., first or second-order, are still in debate. It has been suggested in isostructural non-magnetic intermetallic compounds that T^* can be suppressed to zero temperature, by combining chemical and external pressure, and a quantum critical point is argued to be observed near these critical doping/pressure. Our electrical resistivity and x-ray diffraction experiments under pressure, on $La_3Co_4Sn_{13}$ single and powdered crystals, reveal an enhancement of T_c and the decrease of T^* as a function of pressure. We show that superlattice structural transition remains a second-order phase transition under pressure and estimate its suppression at around 5.5 GPa, though no quantum critical behavior is observed up to 2.53 GPa. Thermal hysteresis loops are seen around T^* in electrical resistivity curves under pressure and we argue that this effect is due to the pinning of a partially gapped CDW phase, which sets in at T^*.

Time-reversal symmetry breaking superconductivity in (Pr,La)Pt_4Ge_{12}

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The superconducting state of the filled skutterudites $Pr_{1-x}La_xPt_4Ge_{12}$ was systematically investigated by zero-field muon spin relaxation (μSR), upper critical field and specific heat measurements. A continuous suppression of broken time-reversal-symmetry stiffness on approaching $x = 1$ is revealed, where $LaPt_4Ge_{12}$ is characteristic of conventional pairing. The magnetic phase (time-reversal violating) in $x \approx 0.7$ compound appears to occur at a distinct temperature T_m from the superconductivity transition temperature T_c, although this is still left in skepticism due to the experimental error. On the other hand, upper critical field study shows the onset of a second quadratic temperature region at $T_q \sim T_m$. Gap point nodes in $PrPt_4Ge_{12}$ is illustrated by the specific heat data. Absence of multiple specific heat jumps is observed. These results suggest that $PrPt_4Ge_{12}$ has a complicated superconductivity order parameter, including the possibility of chirality in the superconducting state.

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Enhanced Superconductivity in O Doped ThNiAsN

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We have synthesized and measured physical properties for a series of nickel-based arsenides $ThNiAsN_{1-x}O_x$ (x = 0.2 ~ 0.5). These compounds crystallize in a ZrCuSiAs-type structure (space group *P4/nmm*) and all of them present superconductivity at T_c = 2.9 ~ 6.0 K. Compared with the parent compound ThNiAsN [1], both *a* and *c* axes of these compounds shrink monotonously as O content increases, while the superconductivity critical temperature T_c shows a minimum of 2.9 K at x = 0.2. By employing the Ginzburg-Landau theory, we fit the zero-temperature upper critical field $H_{c2}(0)$ out of finite temperature data. The $H_{c2}(0)$ shows the same behavior versus x as T_c. We also carry out first principle calculations on electronic structures of these compounds. Results show that the density of states (DOS) behaves differently with T_c. Such a result, together with the fact that ThNiAsN shows no sign of magnetic order, suggests that phonon might play an important role in the T_c variation for O doped ThNiAsN.

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Effect of Oxygen Content on the Superconductivity of Titanium Monoxide Films

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Recently, titanium monoxide TiO_x epitaxial film has been found to possess an enhanced superconductivity (T_c ~7.4 K) [1] compared with its polycrystalline bulk form (T_c ~5.5 K) [2]. As we know, the oxygen content of TiO_x can be tuned in a significantly wide range $0.7<x<1.3$ without changing its cubic structure. Thus, it is intriguing to investigate the superconductivity of TiO_x single-crystalline films with different oxygen contents. Superconducting TiO_x films with different oxygen contents were successfully grown on Al_2O_3 substrates by using a pulsed laser deposition technique to ablate a pure titanium target in different oxygen pressure P_{O2}. X-ray diffraction results show that the TiO_x films are face-centered cubic structure with only (111) and (222) peaks. With increasing P_{O2}, the normal-state resistivity increases and the superconducting transition temperature gradually decreases. The temperature dependent upper critical fields (H_{c2}) for magnetic field perpendicular and parallel to the surfaces of films with different oxygen contents follows the WHH theory, and the spin-paramagnetic effect dominates the pair-breaking. The anisotropies of H_{c2} for different samples are close to 1, indicating that TiO_x films are a weak anisotropic superconductor. The effect of oxygen content on flux pinning of TiO_x films is also studied.

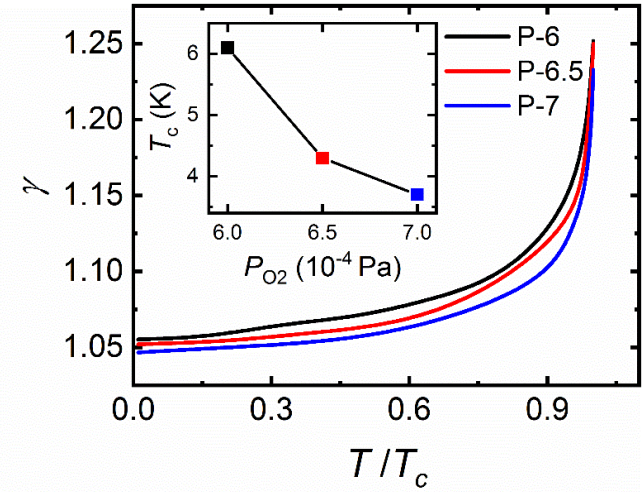

Fig. 1: *The anisotropy γ of H_{c2} by $H_{c2,(H\parallel(111))}/H_{c2,H\perp(111)}$ of TiO_x films (P-6, P-6.5, P-7). Inset: Oxygen pressure P_{O2} dependences of T_c.*

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S-shaped suppression of the superconducting transition temperature in Cu_xNbSe_2

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2H-$NbSe_2$ is the prototype and most frequently studied of the well-known transition metal dichalcogenide (TMDC) superconductors. Widely acknowledged to be a conventional superconductor, its transition temperature to the superconducting state (T_c) is 7.3 K – a T_c that is substantially higher than those seen for the majority of TMDCs, where Tcs between 2 and 4 K are the norm.[1-3] Here we report the intercalation of Cu into 2H-$NbSe_2$ to make Cu_xNbSe_2. As is typically found when chemically altering an optimal superconductor, T_c decreases with increasing x, but the way that T_c is suppressed in this case is unusual – an *S*-shaped character is observed, with an inflection point near x = 0.03 and, at higher x, a leveling off of the T_c near 3 K – down to the usual value for a layered TMDC. Electronic characterization reveals corresponding *S*-like behavior for many of the materials parameters that influence T_c.[4] To illustrate its character, the superconducting phase diagram for Cu_xNbSe_2 is contrasted to those of Fe_xNbSe_2 and $NbSe_{2-x}S_x$.

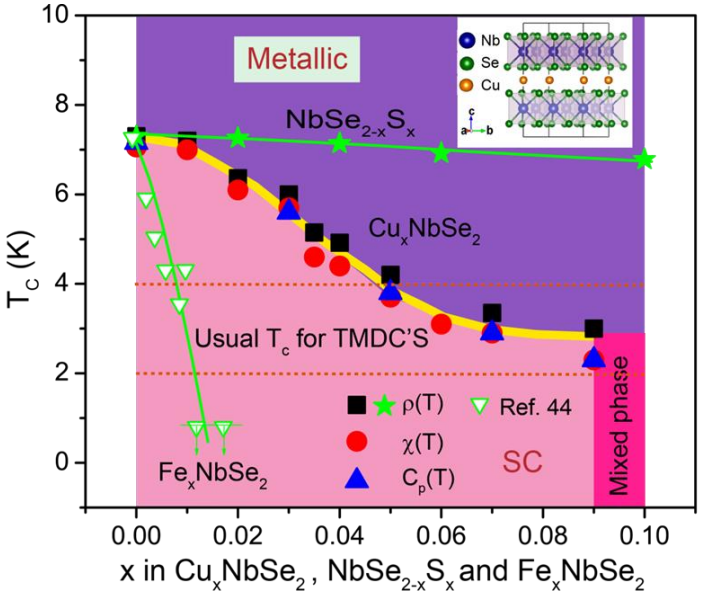

Fig. 1: *The superconducting phase diagram for 2H-Cu_xNbSe_2 compared to those of 2H-$NbSe_{2-x}S_x$ from the current study and 2H-Fe_xNbSe_2.*

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2D Superconductivity from Dimerization of Atomically Ordered $AuTe_2Se_{4/3}$ Cubes

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The emergent novel phenomena such as superconductivity, topological phase transition and non-trivial topological states can be observed in strict 2D crystalline matters. Artificial heterogeneous interfaces, one atomic thickness layers by either exfoliations or by pulsed atomic deposition are typical 2D materials of this kind. Although having 2D characters, most bulky layered compounds, however, do not possess these emergent properties. We report the 2D superconductivity in bulky material $AuTe_2Se_{4/3}$, where the reduction dimensionality is achieved through inducing the elongated covalent Te-Te bonds. This occurs through incorporating more electronegative Se atoms into non-layered $AuTe_2$, leading to the Au, Te and Se are atomically ordered with long Te-Te bonds of 3.18 Å and 3.28 Å. The superconductivity at 2.75 K was discovered, and moreover, the two-dimensional superconducting nature was established by the Berezinsky–Kosterlitz–Thouless topological transition.

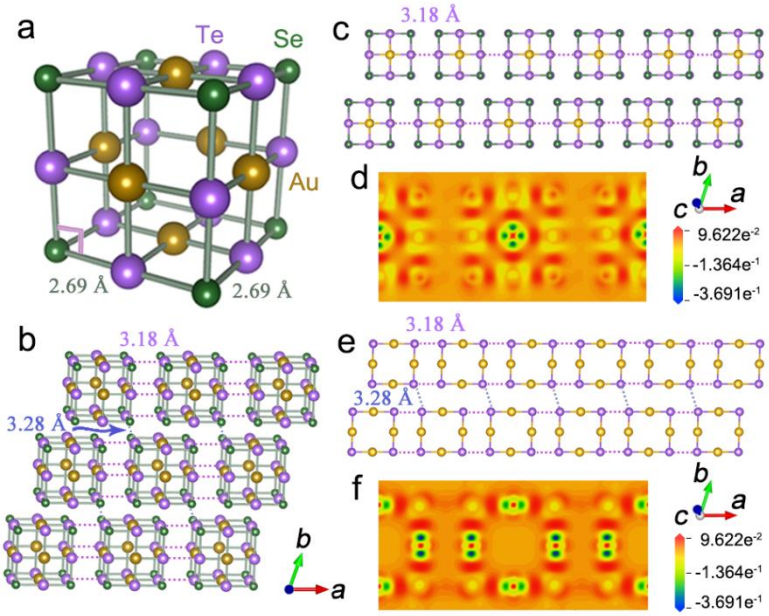

Figure 1. Crystal structure and electron density difference (EDD) of $AuTe_2Se_{4/3}$.

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Superconductivity Beyond 10 K in the Novel Quasi-one-dimensional Ternary Molybdenum Pnictides $A_2Mo_3As_3$ (A=K, Rb, Cs)

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Here we report the discovery of a series of ternary molybdenum pnictide based superconductors $A_2Mo_3As_3$ (A=K, Rb, Cs). Polycrystalline samples were synthesized by the conventional solid state reaction method. X-ray diffraction analysis reveals a quasi-one-dimensional (Q1D) hexagonal crystal structure with $(Mo3As3)^{2-}$ linear chains separated by K^+, Rb^+, or Cs^+ ions, similar to previously reported $K_2Cr_3As_3$, with the space group of P-6m2 (No. 187). The refined lattice parameters are a = 10.145(5) Å and c = 4.453(8) Å for $K_2Mo_3As_3$, a = 10.432 (1) Å, c = 4.4615 (6) Å for $Rb_2Mo_3As_3$ and a = 10.7405 (6) Å, c = 4.4654 (5) Å for $Cs_2Mo_3As_3$. Electrical resistivity, magnetic susceptibility, and heat capacity measurements exhibit bulk superconductivity with the onset T_c at 10.4 K in $K_2Mo_3As_3$ which is higher than the isostructural Cr-based superconductors. Electrical resistivity and magnetic susceptibility characterizations of $Rb_2Mo_3As_3$ and $Cs_2Mo_3As_3$ shows even higher onset T_c at 10.6 K and 11.5 K, respectively, which exhibit weak negative chemical pressure effect in these $A_2Mo_3As_3$ (A = K, Rb, Cs) superconductors contrary to the isostructural $A_2Cr_3As_3$ superconductors. Being members of the same group VIB transition elements and with similar structural motifs, these Cr and Mo based superconductors may share some common underlying origins for the occurrence of superconductivity and need more investigations to uncover the electron pairing within a quasi-one-dimensional chain structure. More interestingly, the $Cs_2Mo_3As_3$ superconductor exhibits much higher upper critical field around 60 T at zero temperature. The discovery of these MoAs/CrAs-based superconductors provide a unique platform for the study of exotic superconductivity correlated with both 3d and 4d electrons in these Q1D compounds.

Electronic properties of the noncentrosymmetric superconductor Th_7Fe_3

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Electronic properties of the noncentrosymmetric superconductor Th_7Fe_3 (Tc = 1.9 K) have been investigated using ^{57}Fe Mössbauer spectroscopy, specific heat measurements [1], and electronic band structure calculations. A sudden increase in the center shift $_{CS}(T)$, spectral area $A(T)$ and electric quadrupole splitting $_{Q}(T)$ is observed below $T^* \sim 60$ K. The temperature dependencies of $_{CS}(T)$, spectral area $A(T)$ follow the Debye model for $T > T^*$, whereas $_{Q}(T)$ can be described by an empirical $T^{3/2}$ equation in both two temperature ranges 2 K - T^* and T^* - 300 K. The behavior of $_{Q}(T)$ can more willingly be interpreted in terms of the Fe^{3+} charge distributions on the singlet d_{xy} ground state-doublet d_{xz}, d_{yz} of the T_{2g} and E_g excited states.

A good agreement between theoretical Schottky specific heat and experimental data is found. We argue that the anomaly detected in hyperfine parameters and specific heat substantially associates with change in the electronic state of the Fe atoms. We are convinced that a precursor crystal-electric field (CEF) effect has undergone before the onset of superconductivity sets in at lower temperature and the present data would spur new interest to researchers about the interplay between CEF and superconductivity.

The DFT calculations of densities of states and electronic band structures (EBS) show a mixture of Th 6d- and Fe 3d-electrons bands, being responsible for the superconductivity [2]. Furthermore, the EBS and Fermi surfaces disclose signifcantly anisotropic splitting associated with asymmetric spin-orbit coupling (ASOC). The ASOC sets up also multiband structure, which presumably favours a multigap superconductivity. Electron Localization Function reveals the existence of both metallic and covalent bonds, the latter may have different strengths depending on the regions close to the Fe or Th atoms. The DFT results of hyperfine parameters are compared with the Mössbauer experimental data.

Acknowledgements

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Improved Superconducting Properties in the $Mg^{11}B_2$ Low Activation Superconductor Prepared by Optimizing Microstructure

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In this study, amorphous ^{11}B powder was used as the raw material instead of natural B, with the purpose of solving the Tokamak plasma problem in controllable thermonuclear fusion. We investigated the sintering process and the phase formation for $Mg^{11}B_2$ samples through thermal analysis, phase identification and microstructure observation. Combined with the measurement of the superconducting properties, the effects of the isotope ^{11}B are concluded, and the critical current density of $Mg^{11}B_2$ sample prepared in this work is higher than that of natural MgB_2. In order to further improve the critical current density of $Mg^{11}B_2$ superconductor, the isotope effect of ^{11}B on carbon doping and J_c performance in MgB_2 with amorphous carbon and nano-SiC as a carbon-based source was systemically investigated. It is found that as the chemical activity of ^{10}B is higher than ^{11}B, the substitution of B by C can more easily occur on ^{10}B than on the ^{11}B site in the MgB_2 lattice.

Superconductivity and valence state in layered single-crystal $HfAs_{1.67}Te_{0.12}$

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We report a detailed study on single crystals of $HfAs_{1.67}Te_{0.12}$ within a PbFCl-type layered structure. The single crystals of the title compound were successfully grown using a chemical transport reaction. The temperature dependence of electrical resistivity ρ(T), AC magnetic susceptibility $\chi_{AC}(T)$ and specific heat C(T) show a bulk superconductivity with transition temperature T_c = 1.67 K. The jump of C/T at T_c is comparable to the traditional BCS weakcoupling model. A full H–T phase diagram is established using the results of $\rho(T, H)$ and C(T) under fields, suggesting a rather weak anisotropy [$H_{c2}^{//ab}(0)$ / $H_{c2}^{//c}(0)$] of 1.8 in orbital limit dominated three-dimension-like superconducting system. The mixed-valence states of Hf and As observed in the binding energy from x-ray photoelectron spectroscopy are consistent with the single-crystal x-ray diffraction analysis, indicating that the As–Te disorder prefers to occur in the [HfAs] layer and a large amount of vacancies are present in tetragonal As layer. As compared to $HfAs_{1.7}Se_{0.2}$ (T_c = 0.52 K), a positive-like vacancy effect on T_c has been confirmed in $HfAs_{1.67}Te_{0.12}$. The analysis of the Hall coefficient implies that the hole-type carriers dominate the transport properties, which is in good agreement with the hole pockets at Fermi surface obtained in a band structure calculation. The detailed study of single-crystal $HfAs_{1.67}Te_{0.12}$ provides a possible candidate to discuss the non-magnetic Kondo effect.

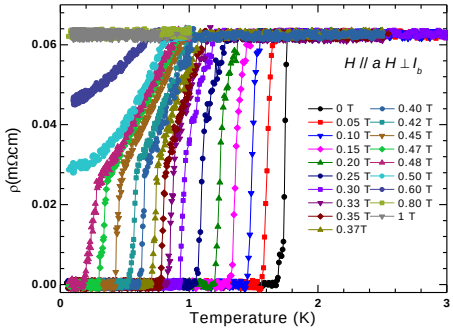

Fig. 1: *Temperature dependence of resistivity ρ(T) under fieldsWith and H // a (b).*

Superconductivity in alkaline earth metal–filled skutterudites BaxIr4X12 (X = As, P)

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We report superconductive iridium pnictides $Ba_xIr_4X_{12}$ (X = As and P) with a filled skutterudite structure, demonstrating that Ba filling dramatically alters their electronic properties and induces a nonmetal-to-metal transition with increasing the Ba content x. The highest superconducting transition temperatures are 4.8 and 5.6 K observed for $BaxIr_4As_{12}$ and $Ba_xIr_4P_{12}$, respectively. The superconductivity in $Ba_xIr_4X_{12}$ can classified into the Bardeen–Cooper–Schrieffer type with intermediate coupling.

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Superconducting and Mechanical Properties of 18-filament MgB_2 Long Wire Prepared by *in-situ* Method

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We fabricated a kilometer-length 18-filament MgB_2 wire by an *in-situ* powder in tube (PIT) method with Monel sheath and different heat-treatment conditions. It was found that the wire sintered at 630 °C for 1 hour resulted in the optimal transport properties and its critical current density (J_c) reached 1.05×10^5 A·cm^{-2} at 4.2 K and 4 T. Meanwhile, this wire has outstanding mechanical properties with a yield strength ($R_{p0.2}$) of 217 MPa and percentage elongation ($A_{50\,mm}$) of 26 %. To investigate the uniformity and practicability of this long wire, a MgB_2 coil with 88 mm in height, 80 mm in outer diameter and 60 mm in inner diameter has been made by using a wind-and-react process. The PIT-processed MgB_2 coil exhibited an operation current (I_{op}) of 90 A and generated a central self-field (B_o) of 0.6 T at 14 K without any external field.

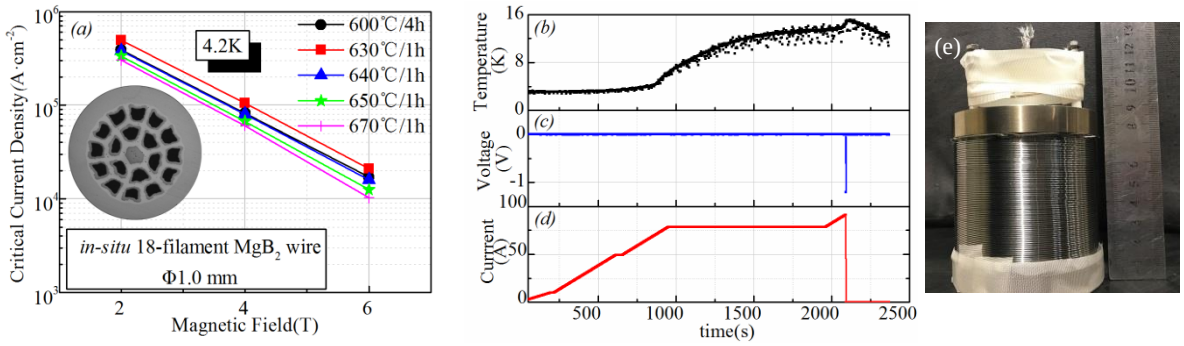

Fig. 1: *(a) J_c-B properties of 1.0 diameter 18-filament MgB_2 wires sintered with different heat treatments; the inset shows the optical micrograph of transverse cross-section of 18-filament MgB_2 wire; (b)-(d) Measurement results of the PIT-processed MgB_2 coil: (b) T-t characteristics, (c) U-t characteristics and (d) I-t characteristics; (e) Photograph of the PIT-processed MgB_2 coil.*

Electrochemical Li-intercalation to $KSr_2Nb_3O_{10}$ and $NaSr_2Nb_3O_{10}$

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Li-intercalation to the layered niobate $AB_2Nb_3O_{10}$ (A stands for alkali metal and B for alkali-earth metal), which has three NbO-layers, leads to the superconductivity. Kato et al. suggested the *T*c-dome with the *a*-axis length and the maximum *T*c of 6 K in $RbSr_2Nb_3O_{10}$ [1]. Recently, we succeeded in synthesizing $KSr_2Nb_3O_{10}$ and $NaSr_2Nb_3O_{10}$ using the ion exchange method [2]. As $KSr_2Nb_3O_{10}$ has the same *a*-axis length as that of $RbSr_2Nb_3O_{10}$, one expects high-*T*c superconductivity by the Li-intercalation. Using these two parent compounds, we have performed Li-intercalation using the electrochemical method. As a result, electrochemically Li-intercalated $KSr_2Nb_3O_{10}$ and $NaSr_2Nb_3O_{10}$ show the superconducting transitions at 6.0 and 2.4 K, respectively. The superconducting volume fraction (V_f) initially increased with increasing the duration of the electrochemical reaction, which should be responsible for the increase of the Li amount, i.e. the carrier concentration. However, the V_f decreased at long duration of the reaction, which resembled the results for $CsSr_2Nb_3O_{10}$ [1] and $KCa_2Nb_3O_{10}$. To resolve this problem, we measured x-ray photoelectron spectroscopy (XPS) for the Li-intercalated $KCa_2Nb_3O_{10}$ and $NaSr_2Nb_3O_{10}$. XPS spectra of these compounds showed that the A-cation peaks (K 2p and Na 1s peaks) disappeared in the compounds with the high Li-concentration, which may suggest the ion-exchange to Li metal. It should prevent the effective carrier doping to these systems. In this presentation, we will also discuss the relation between the *T*c and the local structure within the NbO layers in $AB_2Nb_3O_{10}$ system.

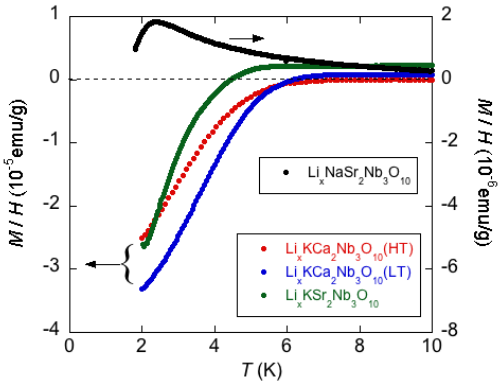

Fig. 1: Magnetic susceptibility of the Li-intercalated AB2Nb3O10.

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Study on High Jc and Low AC Losses NbTi/Cu0.5Mn Superconducting Wire for HIAF Magnets

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Abstract: Working with fast pluse current, low loss NbTi superconducting wires are required to reduce energy losses in High Intensity Heavy-Ion Accelerator Facility (HIAF) magnets. The new type of NbTi superconducting wires with high critical current and low losses are needed to develop. Firstly, NbTi/Cu0.5Mn superconducting wire with filaments of 12960 and 10080 and Cu/Sc ratio of 2.0 were designed and fabricated by double stacking method. Then this paper presents the microstructure and influence of aging heat treatment on the critical current density and break times of NbTi/Cu0.5Mn superconducting wire. Results show that when the aging time increases from 3 to 5, critical current density increases from 2520 to 2960 A/mm^2 at 5T&4.2K. However, break time of one billet increase from 0 to 3. The maximum length of wire is 3500m and the minimum length is 1000m. The Nb barrier fracture causes that the Ti-Cu compound formed between NbTi filaments and Copper during heat treatment. The Cu0.5Mn alloy is considered as the inter-filament matrix to reduce inter-filament coupling currents loss. The hysteresis losses of two types of NbTi superconducting wires were also investigated in this paper. When the diameter of NbTi filament reduces from 4.6 to 2.8μm, the hysteresis losses reduces from 42.8 to 17.3 J/cm^3 at ±3T. After the process optimization, NbTi/Cu0.5Mn superconducting wire with the critical current density (Jc) of 2920A/mm^2 at 5T&4.2K, with the hysteresis of 35.5 J/cm^3 at ±3T, with the average length of 2000m per piece, was achieved in mass production.

Superconducting properties of $Ta_{1/6}Nb_{2/6}Hf_{1/6}Zr_{1/6}Ti_{1/6}$ high entropy alloy

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We synthesized high entropy alloy (HEA) $Ta_{1/6}Nb_{2/6}Hf_{1/6}Zr_{1/6}Ti_{1/6}$ that contain multiple principal elements in similar distribution ratios. Randomly distributed five elements stabilize disordered with a body-centered cubic crystal structure of lattice parameter a=3.38 Å is characterized by x-ray diffraction. From the electrical resistivity, magnetization, and heat capacity measurements, we obtained superconducting properties such as the superconducting transition temperature Tc = 7.98 K, and upper-critical magnetic field $\mu_0 H_{c2} \approx$ 15 T. It is revealed that $Ta_{1/6}Nb_{2/6}Hf_{1/6}Zr_{1/6}Ti_{1/6}$ HEA is a type II and weak electron-phonon coupling *s*-wave superconductor in terms of Ginzburg-Landau and Bardeen-Cooper-Shrieffer (BCS) theory.

Superconducting Silicon Resonators

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Despite being one of the most studied materials, the BCS superconductivity at ambient pressure of silicon was long ignored due to the extreme doping concentration required to trigger superconductivity, more than three times the boron solubility limit in silicon [1]. This concentration, impossible to reach using conventional micro-electronic techniques, was obtained by the 'Epla' group at C2N using Gas Immersion Laser Doping (GILD), an out of equilibrium technique achieving epitaxial Si:B thin films with concentrations as high as 11 at.% ($6x10^{21}$ cm^{-3}).

The superconducting critical temperature Tc of the thin Si:B films only depends on the boron dose, increasing above a threshold value up to a maximum of 0.7 K [2]. The doping is 'box-like', homogeneous over the 10 to 300 nm thick layers, and spatially well-defined in the doped 2x2 mm^2 surface, with a sharp interface with the substrate, and without dopant aggregates [3].

The doping-tunable Tc and the mature silicon technology are coupled in superconducting silicon, allowing the conception of a large range of scalable quantum nanodevices, made of superconductors, metals and semiconductors coupled through extremely clean, transparent epitaxially grown interfaces.

We have thus realised the first silicon superconducting devices: SNS Josephson junctions where long-range proximity effect has been demonstrated [4], and superconducting quantum interference devices (dc-SQUID) [5].

In parallel to the study of the DC properties, we have started the investigation of the high frequency properties of Si:B, through the measurement of coplanar wavelength resonators coupled to a transmission line. We have explored the temperature dependence of the quality factor and resonant frequency, finding a good agreement with Mattis-Bardeen theory. The investigation of the power dependence has provided a measure of the non-linearity in the system. Finally, the multiple GHz resonant modes have shown an important kinetic inductance, expected from the Si:B high resistance and low Tc, which may lead to the development of silicon Kinetic Inductance Detectors.

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Acknowledgments : D. Bouville, G. Hallais, T. Klein, C. Marrache

Fermi surface reconstruction in 2*H*-$TaSe_2$ under high pressure mediated by interlayer interaction

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We report high pressure transport, Raman, X-ray diffraction measurements and first-principles calculations for a well known TMD material 2*H*-$TaSe_2$. The CDW is suppressed and the maximum superconductivity above 8 K is reached around 20 GPa. Meanwhile, the lattice parameter *c*, Raman modes (A_{1g} and $E_{2g}{}^2$), the Hall coefficient, and the upper critical field H_{C2} show significant anomalies around 20 GPa. Both the experimental and theoretical results strongly suggest that interlayer interactions are increased above 20 GPa, transforming the system from a two-dimensional one to predominantly a three-dimensional one due to pressure-induced closing of the gap between the neighboring Se-Ta-Se sandwiches. Such changes in the structural arrangement lead to three Van Hove singularities near the Fermi level, one of which gives rise to a hole pocket at the M point just above 20 GPa. Our results show that the interlayer interactions play a critical role in both suppressing the CDW order and enhancing superconductivity in the compressed state of 2*H*-$TaSe_2$. Both experimental data and theoretical results do not support a quantum critical point scenario to explain the superconducting dome-like behavior of the superconducting T_C.

A possibility of anisotropic s-wave pairing in BiS_2 layered superconductors

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BiS_2-based layered superconductors, $Bi_4O_4S_3$, $LaOBiPbS_3$ and $LnOBiS_2$ (*Ln* = rare earth), have attracted great attention due to the locally inversion symmetry breaking and sizable spin-orbit coupling [1]. The pairing mechanism and the gap structure remains controversial. Experimentally, the thermal conductivity measurement [2] indicates that they are fully gapped conventional superconductors. However, the measurement of angle-resolved photoemission spectroscopy (ARPES) suggests the presence of an anisotropic gap structure [3]. Generally, such anisotropy is considered to be an evidence of unconventional superconductivity. However, to considering multi-orbital effect, there is the possibility of an electron-phonon pairing mechanism.

Here, we consider a possibility of anisotropic s-wave states as multipole superconductivity [4] mediated by electron-phonon interaction. The effective 4-orbital model has been obtained by the first-principles downfolding [5]. Then, we construct an attractive extended Hubbard model with on-site interaction *g*, *g'* and inter-site interaction *V* between electrons at Bi and S atoms. From the superconducting gap equation, we find that the inter-site interaction between Bi and S enhances nodal s-wave states. Especially, cooperation between the on-site intra-orbital interaction *g* and the inter-site interaction *V* enhances anisotropic s-wave gap structure. Relatively small *g* leads to nodal structure (See Fig. 1), which may be comparable to the ARPES experiments [3]. We will discuss the details of gap structure and the pairing mechanism.

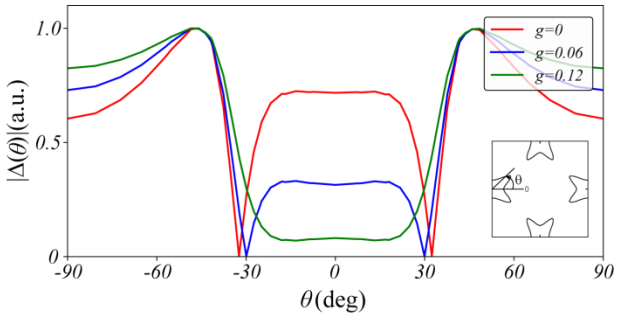

Fig. 1: the angular dependence of obtainded s-wave gap function on Fermi surface.

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Superconductivity in SnSb with natural superlattice structure

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We report the results of electrical resistivity, magnetic and thermodynamic measurements on polycrystalline SnSb, whose structure consists of stacks of Sb bilayers and Sn_4Sb_3 septuple layers along the *c*-axis [1]. The material is found to exhibit a zero resistivity transition at 2.48 K, while bulk superconductivity is established at a significantly lower temperature of 1.58 K. The origin of two superconducting transitions is discussed [2]. Our results demonstrate that superconductivity is possible in an undoped, natural superlattice phase originating from a topological semimetal, which suggests an alternative way to search for potential topological superconductors.

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Superconductivity in misfit layered compound $(SnSe)_{1.16}(NbSe_2)$

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$(SnSe)_{1:16}(NbSe_2)$ is one of the misfit layered compounds. Previous study on the powder sample of $(SnSe)_{1:16}(NbSe_2)$ did not observe superconductivity. Here we report the crystal growth and discovery of superconductivity in large size single crystals of $(SnSe)_{1:16}(NbSe_2)$, with a superconducting transition onset temperature T_c of 3.4 K. Powder X-ray diffraction (XRD) and high resolution transmission electron microscopy (HRTEM) clearly display the misfit feature between SnSe and $NbSe_2$ subsystems. The Sommerfeld coefficient inferred from specific-heat measurements is 16.73 mJ mol^{-1} K^{-2}. The normalized specific heat jump is estimated to be 0.98, and the electron-phonon coupling constant is estimated to be 0.80. The value of $H_{c2}(0)$ is about 7.82 T when the magnetic field is applied in the *ab*-plane, exceeding the Pauli paramagnetic limit slightly. Both specific-heat and H_{c2} data suggest that $(SnSe)_{1:16}(NbSe_2)$ should be a multi-band superconductor.

Possibly Better Superconductivity at Domain Boundaries in Two-Dimensional α-Mo_2C Crystals

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The α-Mo_2C is a newly emerging superconducting two-dimensional material that was recently grown by chemical vapor deposition, which could naturally form into different shapes (rectangles, hexagons, *et al.*) with single-domain or multi-domain structure. Here, the superconducting properties of rectangular (single-domain) and hexagonal (multi-domain) α-Mo_2C crystals were systematically investigated, which domain structures were revealed by the scanning transmission electron microscopy. We found that the transport properties in these two kinds of α-Mo_2C crystals behave differently. Compared with the rectangular single-domain samples, the zero-resistance superconducting transition temperature (T_{c0}) is obviously higher in the hexagonal multi-domain samples with much lower residual resistance ratio (*RRR*), as shown in Fig. 1. The highest T_{c0} in multi-domain samples is 5.2 K which is higher than the maximum T_{c0} = 3.5 K in the single domain samples. In addition, the higher *RRR* was observed in single domain samples with higher T_{c0}; while it is slightly smaller for multi-domain samples with higher T_{c0}. The enhanced superconductivity in multi-domain samples may be related to the better superconductivity at the domain boundaries. Further, hydrostatic pressure dependencies of the superconductivity in these two kind of α-Mo_2C crystals were studied up to 2 GPa.

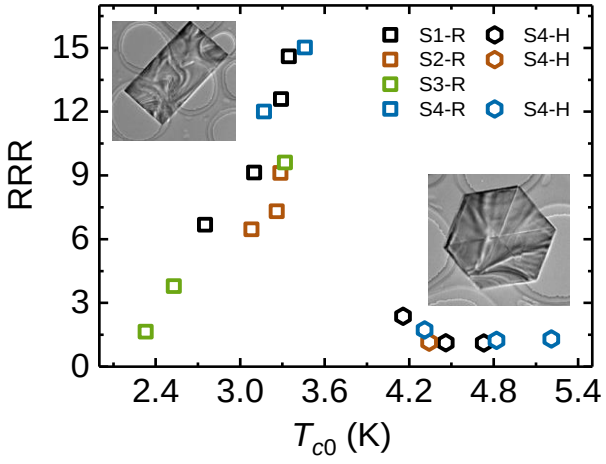

Fig. 1: *The residual resistance ratio ($RRR=R_{300K}/R_{6K}$) vs T_c. The different color (black, brown, green and blue) means the different batches of α-Mo_2C samples (S1, S2, S3 and S4). The square and hexagonal dots represent the samples with rectangular and hexagonal shapes, respectively.*

BiS_2-based layered superconductors with high-entropy-alloy-type blocking layers

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Since the discovery of BiS_2-based layered superconductors in 2012, this family of compounds has received much attention as a new class of layered superconductors. The crystal structure composed of alternate stacks of electrically conducting BiS_2 layers and blocking layers is similar to that of the cuprate or Fe-based high-transition-temperature (T_c) superconductors. [1] The chemical pressure effect in $REO_{0.5}F_{0.5}BiS_2$ is systematically controlled by the alloying effect at the RE site of the blocking layer and was found to be essential for inducing bulk superconductivity. The systematic shrinkage of the blocking layer was succeeded by using smaller RE elements. When the chemical pressure is optimally applied, the in-plane Bi-S1 bond distance decreases and bulk superconductivity is induced. [2] Furthermore, the in-plane chemical pressure effect suppresses in-plane local disorder at the S1 site, which is essentially linked to the emergence of bulk superconductivity in this system.

In this study, we used the concept of high-entropy-alloy (HEA) for the RE site of $REO_{0.5}F_{0.5}BiS_2$. Samples with RE = $La_{0.3}Ce_{0.3}Pr_{0.2}Nd_{0.1}Sm_{0.1}$, $La_{0.2}Ce_{0.2}Pr_{0.2}Nd_{0.2}Sm_{0.2}$, $La_{0.1}Ce_{0.1}Pr_{0.3}Nd_{0.3}Sm_{0.2}$, and $La_{0.1}Ce_{0.1}Pr_{0.2}Nd_{0.3}Sm_{0.3}$ (See the left panel of Fig. 1) were newly synthesized in this study. Superconducting properties were investigated from resistivity and magnetization measurements. Zero resistivity and clear diamagnetic susceptibility were observed for all the samples. The right panel of Fig. 1 shows that the plot of T_c as a function of lattice constant of *a* for the HEA-type samples located clearly higher temperature region than those of typical $REO_{0.5}F_{0.5}BiS_2$. This may indicate that the in-plane disorder is suppressed by the HEA effect, instead of lattice shrinkage (in-plane chemical pressure). [3]

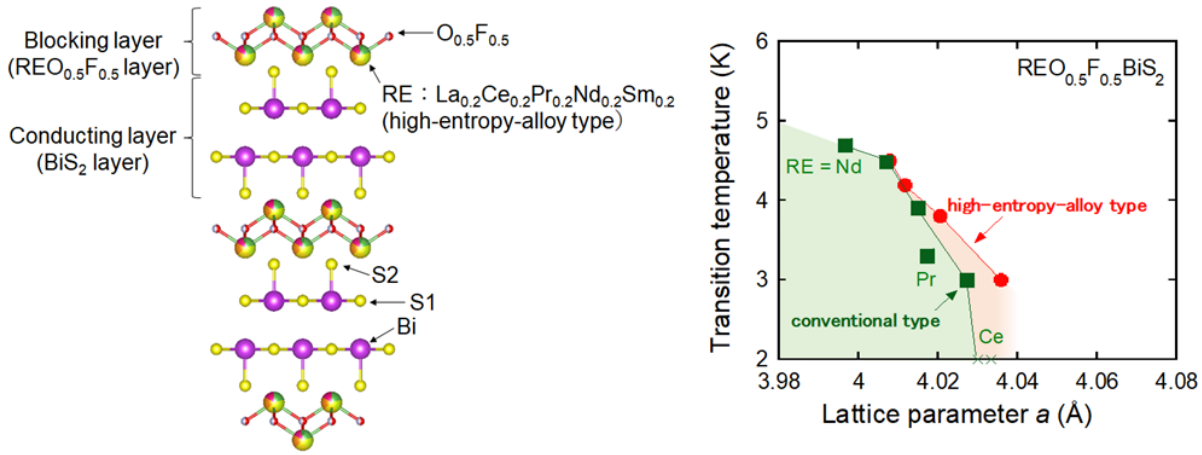

Fig. 1: *(left) Crystal structure of HEA-type $REO_{0.5}F_{0.5}BiS_2$. (right) Superconductivity phase diagram of typical and HEA-type $REO_{0.5}F_{0.5}BiS_2$.*

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Performance Improvements to Bronze Processed Nb_3Sn Strands

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High performance bronze processed Nb_3Sn superconducting strands are needed for a high field magnet system. Significant efforts can be found throughout the literature to optimize the current carrying capacity of Nb_3Sn superconducting wires. Bronze processed Nb_3Sn strands with different designs were manufactured in our study. An investigation to increase Sn concentration in the bronze to improve the critical current density (J_{cn}) was carried out. A high critical current density of 1169 A/mm^2 at 12 T, 4.2 K could be obtained by increasing the Sn concentration in the bronze to 16 wt%. The strand with combined Nb/Ta barrier has a low hysteresis loss value 254 mJ/cm^3 at ±3 T, 4.2 K. Different annealing temperature and holding time in the process were studied to investigate the influence on J_{cn}. Microstructure images show that the pre-reacted Nb3Sn particles are less when the annealing temperature is lower. But the J_{cn} of different samples are almost the same. It indicates that when the annealing temperature is as low as enough the J_{cn}. can not be effected.

Superconductivity in several Quasi-one-dimensional Ternary chromium Pnictide compounds

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The recently discovered Cr-based superconductors $A_2Cr_3As_3$ (*A* = K, Rb, Cs) with a quasi -one dimensional (Q1D) structure and the possible spin-triplet pairing superconductivity attracted much interest. Here we report a new series of Q1D Cr-based superconductors ACr_3As_3. KCr_3As_3 and $RbCr_3As_3$ single crystals were prepared by the deintercalation of alkali ions from $A_2Cr_3As_3$ single crystals. KCr_3As_3 single crystals exhibit superconductivity at 5 K after annealing, and the T_c of $RbCr_3As_3$ single crystals is up to 7.3K. It suggests a negative chemical pressure effect in ACr3As3 superconductors, contrary to that of 233-type superconductors. Note that 133-type superconductors are stable in air, and the superconductivity remains unaffected even after immersed in water for several days, which is in strong contrast to the sensitivity to air for 233 type superconductors. To enhance the T_c of Cr-based superconductors, we substituted K with Na in $K_2Cr_3As_3$ and tried to grow $Na_2Cr_3As_3$. Singlecrystlline $Na_2Cr_3As_3$ with Q1D lattice structure was prepared through ion-exchange method. It undergoes a superconducting transition at 8.6 K, the highest T_c in Cr-based superconductors. For the Na-doping $K_2Cr_3As_3$ samples, we discovered a novel individual phase $(K_{0.25}Na_{0.75})_2Cr_3As_3$, in which Na replaces the K atoms in 3k sites absolutely. It shows superconductivity with *T*c at 7.6 K. Our newly discovered Cr-based superconductors exhibit exotic characteriatics and can be served as platforms for further research on Q1D systems.

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Time-Dependent Reentrant Superconductivity in the Nonequilibrium State of KBi_2

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Novel electronic states often appear in nonequilibrium states, which are induced by external stimuli. In this presentation, we will report time-dependent superconductivity induced by a specific thermal process in a Laves-phase superconductor KBi_2. The compound KBi_2 has been reported to exhibit superconductivity with a transition temperature T_c = 3.6 K and crystallize in a cubic $MgCu_2$-type structure (space group *Fd*-3*m*, O_h^7, #227) [1,2].

We observed bulk superconductivity at T_c = 3.6 K in KBi_2 when the synthesis procedure in Ref. 1 was used. On the other hand, superconductivity disappeared (or T_c became below 1.8 K) when a specific heating process (rapid heating and cooling) was applied, as shown in Fig. 1(a). Interestingly, we observed that bulk superconductivity recovered when the sample was stored at room temperature for a long enough time (~500 hours) following another thermal cycle between room temperature and low temperature (1.8 K), as shown in Fig. 1(e). In the middle of the recovery process, reentrant superconductivity appeared as shown in Figs. 1(b) and 1 (c).

Reentrant superconductivity is known to occur because of the interplay between superconductivity and magnetic ordering. However, KBi_2 consists of no magnetic elements. Thus a novel mechanism should be invoked.

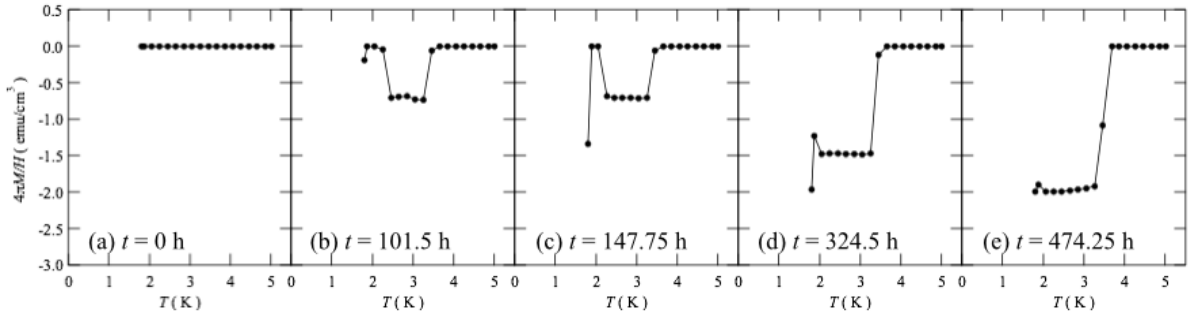

Fig. 1: *Magnetization divided by field M/H as a function of temperature in KBi_2 for various storing times t at room temperature. The measurements were performed in a zero-field-cooling condition with an applied magnetic field H = 10 Oe*

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Discovery of Superconductivity in BaPtSb with a Noncentrosymmetric Structure

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We will report on the discovery of superconductivity in BaPtSb with a PtSb ordered honeycomb network. We observed superconductivity at 1.64 K using specific heat and electrical resistivity measurements [1]. BaPtSb crystallizes in the *noncentrosymmetric* SrPtSb-type structure (space group *P*-6*m*2, D_{3h}^1, No. 187) [2]. The PtSb honeycomb network stacks along the *c*-axis so that spatial inversion symmetry is broken globally. This stacking is markedly different from that of SrPtAs, which crystallizes in the *centrosymmetric* KZnAs-type structure (space group $P6_3/mmc$, D_{6h}^4, No. 194) [3]. In *centrosymmetric SrPtAs, exotic superconductivity, such as chiral d-wave, has been theoretically predicted and experimentally examined. The discovery of superconductivity in noncentrosymmetric BaPtSb will provide us a unique opportunity to examine exotic superconductivity in a honeycomb network.*

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Superconductivity in Perovskite $Ba_{1-x}Ln_x(Bi_{0.20}Pb_{0.80})O_{3-\delta}$ (Ln= Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)

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$BaBiO_3$ is a double perovskite semiconductor with two crystallographic independent sites of Bi in the unit cell for Bi^{3+} and Bi^{5+} respectively (can be noted as $Ba_2Bi^{3+}Bi^{5+}O_6$).[1] After doping an element at A (Ba) or/and B (Bi) site, the band gap will be modified and superconductivity can be induced. For example, $BaPb_{1-x}Bi_xO_3$ ($0.05<x<0.30$), $Ba_{1-x}K_xBiO_3$ ($0.30<x<0.45$), and $(Na_{0.25}K_{0.45})Ba_3Bi_4O_{12}$ are superconductors. These superconductors are usually denoted as bismuth based superconductor. The atoms at B site are six coordinated to form a BO_6 octahedron and the octahedrons are linked to each other by corner-sharing oxygen atoms with the atoms at A site in the cavities formed by eight octahedrons. The symmetry of these compound may be cubic, tetragonal, orthorhombic, or triclinic because the distortion of BO_6 octahedron. The doping of K or Na at A site, or Pb at B site, decreases the electrons in the 6S orbit comparing to $BaBiO_3$, where there is one electron per 6S orbit. Therefore, these reported superconductors are belong to the hole-doped system. The inverse case is the electron-doped system. The hole-doped, electron-doped cuprate based or iron based superconductors are well known. However there is no electron-doped bismuth based superconductor to be reported until now. This is a challenge. In order to obtain the electron-doped bismuth based superconductor, +3 (or +4) ion should be doped into the A site. Here, the study on the series $Ba_{1-x}Ln_x(Bi_{0.20}Pb_{0.80})O_{3-\delta}$ (Ln= Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) is presented. The electron-doped superconductor is found in $Ba_{1-x}Ln_x(Bi_{0.20}Pb_{0.80})O_{3-\delta}$ with Ln=Ce, or Pr.

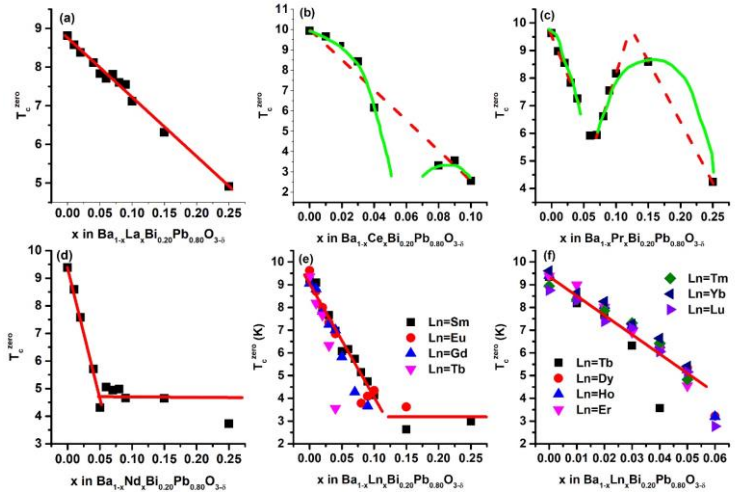

Fig. 1: *Composition dependent T^{zero}_c for $Ba_{1-x}Ln_x(Bi_{0.2}Pb_{0.8})O_{3-\delta}$.*

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A Ferroelectric Quantum Phase Transition Inside the Superconducting Dome of $Sr_{1-x}Ca_xTiO_{3-\delta}$

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$SrTiO_3$, a quantum paraelectric [1], becomes a metal with a superconducting instability after removal of a tiny amount of oxygen atoms [2]. It turns into a ferroelectric upon substitution of a little fraction of Sr atoms with Ca [3]. The two orders may be accidental neighbors or intimately connected, as in the picture of quantum critical ferroelectricity [4]. Here, we show that in $Sr_{1-x}Ca_xTiO_{3-\delta}$ ($0.2\% < x < 0.9\%$, $\delta < 0.1\%$) ,the ferroelectric order coexists with dilute metallicity and its superconducting instability in a finite window of doping. At a critical carrier density, which scales with the Ca content, a quantum phase transition destroys the ferroelectric order. We detect an upturn in the normal-state scattering and a significant modification of the superconducting dome in the vicinity of this quantum phase transition. The enhancement of the superconducting transition temperature with Ca substitution documents the role played by ferroelectric vicinity in the precocious emergence of superconductivity in this system, restricting possible theoretical scenarios for pairing.

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New Superconducting Phases in the Nb-Pd-(Se/S) System

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The recently discovered transition metal chalcogenide superconductor $Nb_2Pd_{0.81}S_5$ (T_c~6.6 K) exhibits a surprisingly high critical field (H_{c2}=37T), thus showing the highest $\mu_0 H_{c2}(0)/T_c(0)$ ratio ever (~5.6 T/K) [1]. Small variations in the Pd content strongly affect both the critical temperature and upper critical field. During crystal growth it is difficult to accurately control the exact amount of Pd, resulting in compounds with only very small variations in composition but with a broad range of T_c and H_{c2} values. Single crystals of the related $Nb_2Pd_{0.81}Se_5$ chalcogenide were successfully grown. Both magnetization and resistivity measurements confirm that the single crystals are superconducting with a $T_{c,onset}$ of ~4.6K and a H_{c2} ~20-30 T (Fig.1).

While growing crystals of the ternary compounds, we observed the formation of plate-like hexagonally shaped crystals that turned out to be Pd-intercalated 2D layered dichalcogenides, $NbSe_2$ and NbS_2. These compounds exhibit superconductivity with an intriguing proximity to a charge ordered state in $NbSe_2$ [2]. We have succeeded in controlling the growth of both Pd or Pt-intercalated $NbSe_2$ and NbS_2, never reported so far. Thus, providing new systems in which the relationship between the two ground states can be investigated with the aim of better understanding the unconventional superconductivity.

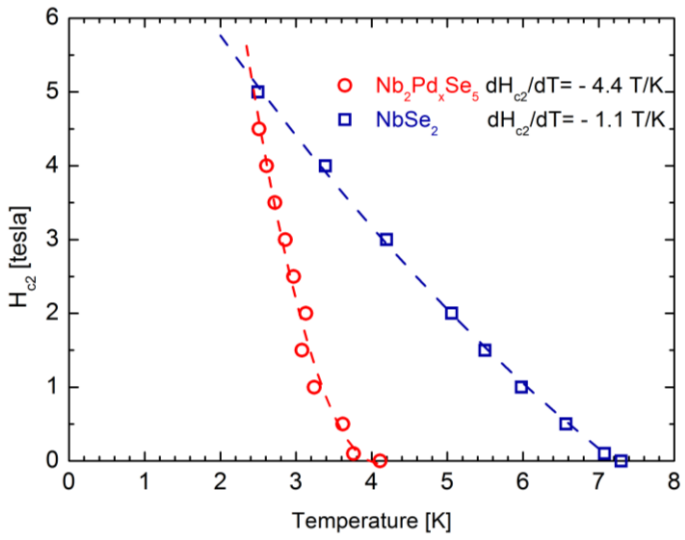

Fig. 1*: Variation of the upper critical field, H_{c2}, with temperature for $Nb_2Pd_{0.81}Se_5$ and the conventional superconductor $NbSe_2$.*

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The Superconducting NbTi Wire for Coils of the Superconducting Dipole Magnet for CBM Experiment at FAIR

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The superconducting dipole magnet for the Compressed Baryonic Matter (CBM) experiment at FAIR houses the Silicon Tracking System (STS), and provides a magnetic field integral of 1 Tm which is needed to obtain a momentum resolution of $\Delta p/p = 1\%$ for track reconstruction at FAIR beam energies. The magnet gap has a height of 140 cm and a width of 250 cm in order to accommodate the STS with a polar angle acceptance of ± 25° and a horizontal acceptance of ± 30°. The magnet is of the H-type with a warm iron yoke/pole and cylindrical superconducting coils in two separate cryostats.

About 1 tone of the NbTi conductor (wire) size 2.02 mm × 3.25 mm with filament diameter ~ 40 μm, single piece length 5 km and a Cu/SC ratio of about 7.4 is necessary for the making of superconducting coils.

NbTi conductors (wires) with a high Cu/nonCu ratio and a large cross-sectional area are usually made using the «wire-in-channel» technology. Current-carrying capacity in wires of this type is determined (limited) by the current-carrying capacity of the soldered SC insert. The "wire-in-channel" technology involves using of solders with harmful additives and uneven filament distribution in the copper matrix aggravating heat dissipation.

In this paper, we demonstrate the possibility of successfully producing the NbTi wire of size 2.02 mm × 3.25 mm with a single piece length of 5 km in the monolithic technology for CBM experiment at FAIR. Critical current exceeds 2270 A (E = 0.1 μV/cm; 5 T; 4,2 K) at the copper/non copper ratio 7.4:1.

Existence of Superconductivity in $FeGa_3$ with Mo Substitution

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$FeGa_3$ is a well-known intermetallic semiconductor compound with tetragonal structure and lattice parameters a = 0.626(3) nm and c = 0.655(5) nm [1,2]. In this work we report that the substitution of Fe atoms for Mo atoms in a specific stoichiometry can make superconductivity emerges from a semiconductor state. X-ray powder diffraction, magnetic susceptibility and electrical resistivity measurements was performed to determine respectively the sample's crystallographic quality, an estimate of the superconducting volume and the critical temperature which is close to 9.0 K. We also report that the upper critical field presents a divergent behavior compared to the usual monotonic quadratic dependence between the upper critical field and temperature. The electrical resistivity and the upper critical field divergent behavior can be observed in Fig.1 below.

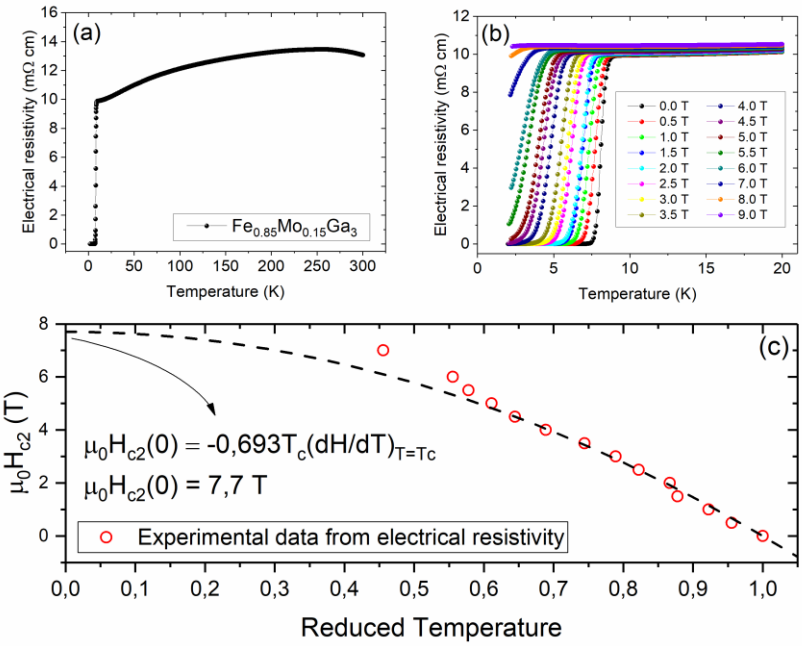

Fig. 1: *(a) Electrical resistivity dependence with temperature between 2.0 K and 300 K in absence of magnetic field, (b) Electrical resistivity measurements under magnetic field from 0.0 T to 9.0 T and (c) dependence of the upper critical field with reduced temperature.*

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The effect of graphene coated Si, Ti and Nb addition on the superconducting properties of MgB2 bulks

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The effect of graphene (G) coated Si, Ti and Nb additions on the superconducting properties of MgB_2 was studied systematically. The additives were prepared by a coating process and all introduced powders were scattered and combined with graphene. The coating process was useful for the uniform distribution of additives in MgB_2 samples. These additions could effectively lead to the refinement of MgB_2 grain size, which led to an enhancement of surface pinning mechanism. Meanwhile, the densities of all the doped samples were larger than that of pure samples, which ensured a better intergrain connection for supercurrent. Therefore, the critical current density of MgB_2 with 8 wt% graphene coated Nb addition got significant enhancement due to the improved grain connectivity and flux pinning properties.

Fabrication and properties of 19-filamentary MgB_2 Superconducting wires

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MgB_2 superconductors exhibit obvious advantages on superconducting magnetic resonance imaging system (MRI) within the temperature range of refrigerators working region (10-20 K) and medium strong magnetic field (0.6-3T). The appropriate conductor design is one of the most important issues for the fabrication of long multi-filamentary MgB_2 wires and tapes due to the plastic deformation on the composites containing powder and metal is heterogeneous during cold drawing and rolling process. Also, further enhancement in engineering critical current density (J_{ce}) and stability is possible by optimizing the conductor design of MgB_2 wires and tapes for cryogen-free magnet application. In this work, we reported the recent results on the fabrication of kilometre level, multi-filamentary MgB_2 wires with Monel alloys as the sheath material by in-situ PIT method and investigate their mechanical, microstructure and superconducting properties. The 500-meter level, Monel sheathed, 19 filamentary MgB_2 wires had been fabricated by in-situ PIT method. Microstructure analysis confirmed that the superconducting filament is uniformly distributed and the thickness of Nb diffusion barrier is also smooth without breaking points through the microstructure analysis of the wires at each fabrication stages. The mean diameter in MgB_2 superconducting cores was around 100 μm in final wires with the diameter of Φ1.0 mm. The tensile strength and yield strength of the wire heat-treated at 670℃/2h was around 396 MPa and 200 MPa respectively. The critical current density (J_c) was obtained 1.23×10^5 A·cm^{-2} at 4.2 K、4 T.

Superconductivity in layered CuAs-based oxyarsenides

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The parent compounds of cuprates and iron-based high tempera-ture superconductors are antiferromagnetic with typical layered structure. The critical structural unit in cuprates is a CuO_2 plane with Cu and O arranged in a square lattice.[1, 2, 3] We report two unprecedented CuAs-based layered superconductors that exhibit coexistence and competition of density wave instability and superconductivity. The superconducting critical temperature can be enhanced upon carriers doping, forming a superconducting dome. Simultaneously, comprehensive structural analyses reveal that the structure and anionic As-As bond lengths exhibit critical behaviors as the superconductivity is optimized at x=0.4. Our findings unravel a second class of Cu-based superconductors, whose paring mechanism might be different from that of the high temperature cuprates superconductors, but more close to that of iron based superconductors.

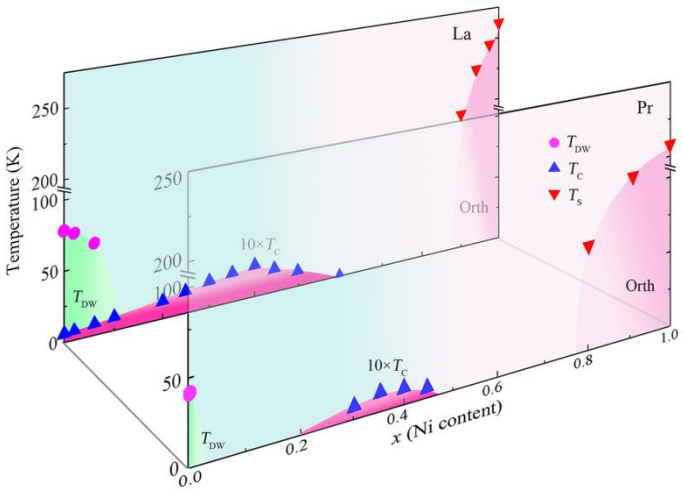

Figure 1. The electronic phase diagram of CuAs-based layered superconductors. It can be seen that the DW transition is suppressed and Tc is enhanced as x≤0.4.

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Superconductivity in a new ternary compound of the Ta-Zr-B system

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University of São Paulo

Recently was published the discovery of superconductivity in $Ta_{1-x}Hf_xB$ which presents maximum Tc close to 6.7 K on the Ta0.7Hf0.3B nominal composition. This material display strongly signature of a new multiband compound. Within this scenario in this work we shall show a systematic study in the $Ta_{1-x}Zr_xB$ series of the compounds. The results sustained by X-ray diffraction, resistivity, magnetization and heat capacity measurements suggest that all series crystallize in FeB prototype structure with maximum superconducting critical temperature close to 7.8 K for Ta0.8Zr0.2B nominal composition and this material display strongly signature of a new multiband compound.

Investigation of a new hexagonal superconducting Laves phase in the ternary system Hf-V-Ga

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The Hf-V-Ga ternary thermodynamic phase equilibrium shows the existence of five ternary intermetallic phases at 800^{o}C isotherm section. These phases are: $Hf_3V_2Ga_4$, HfV_2Ga_4, $Hf_3V_2Ga_6$, $Hf_5V_7Ga_8$, $Hf_6V_{12}Ga_7$. Recently the HfV_2Ga_4 was reported as a new superconductor with superconducting critical temperature at 4.1 K and with strong signature of multiband compound. This discovered stimulated the investigation for others superconducting compounds in this phase diagram. In this scenario, this work shows the existence of a new Hexagonal Laves phase of HfVGa composition with $MgZn_2$ prototype structure that reveals superconducting critical temperature close to 12.0 K. These results are supported by magnetization, resistivity and heat capacity measurements. So, these results show that a hexagonal Laves phase exist supported by X-ray diffraction and electronic microscopy. This phase was not reported in this ternary phase equilibrium diagram so far and, at same time, reveal that this phase represent a new superconductor material.

Superconductivity in $Zr_3V_2Ga_4$ with superconducting critical temperature close to 11 K

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The Zr-V-Ga thermodynamic phase diagram shows the existence of five ternary intermetallic phases in equilibrium in the isotherm section at 800°C. These phases are: Zr_3V_2Ga4, ZrV_2Ga_4, $Zr_3V_2Ga_6$, $Zr_5V_7Ga_8$ and $Zr_6V_{12}Ga_7$. The recent discovery of superconductivity in the HfV_2Ga_4 compound at 4.1 K and it´s strong signature of multiband compound [1], has stimulated the search for this behavior in this similar system, Zr-V-Ga. In this scenario, this work shows the existence of a new superconducting material with $Zr_3V_2Ga_4$ composition. This compound display a orthorhombic structure whose the prototype it is itself. In this stoichiometric bulk phase, superconductivity was found with a superconducting critical temperature close to 11.0 K. These results are supported by magnetization, resistivity, heat capacity measurements, X-ray powder diffraction and electronic microscopy.

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Crystal structure and physical properties of new layered oxychalcogenide $La_2O_2M_4S_6$ (M = Bi, Pb, Ag, Cd)

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Since the discovery of BiS_2-based superconductor in 2012 [1,2], many kinds of BiS_2-based superconductors have been discovered and the record of transition temperature (T_c) exceeded 10 K [3]. The typical structure of the BiS_2-based superconductor is represented as an alternate stacks of a conducting BiS_2 layer and an insulating (blocking) layers such as a LaO or SrF layer. Basically, the parent phase is an insulator with a band gap, and electron-doped phase shows superconductivity. Recently, we successfully analyzed the crystal structure of $La_2O_2Bi_2Pb_2S_6$ [4,5]: Bi and Pb are selectively occupy the BiS_2-like layer and the PbS-like layer, respectively. Namely, the structure can be regarded as an alternate stacks of the $LaOBiS_2$-type layer and the rock-salt-type PbS layer. In addition, on the basis of this stacking concept, we newly synthesized $La_2O_2Bi_3AgS_6$, in which the $Ag_{0.5}Bi_{0.5}S$ is inserted into the van-der-Waals gap of $LaOBiS_2$ [6]. In this presentation, we will show the synthesis, crystal structure, and physical properties of new $La_2O_2M_4S_6$ (M = Bi, Pb, Ag, Cd) and discuss the possibility of superconductivity in this new layered oxychalcogenide system.

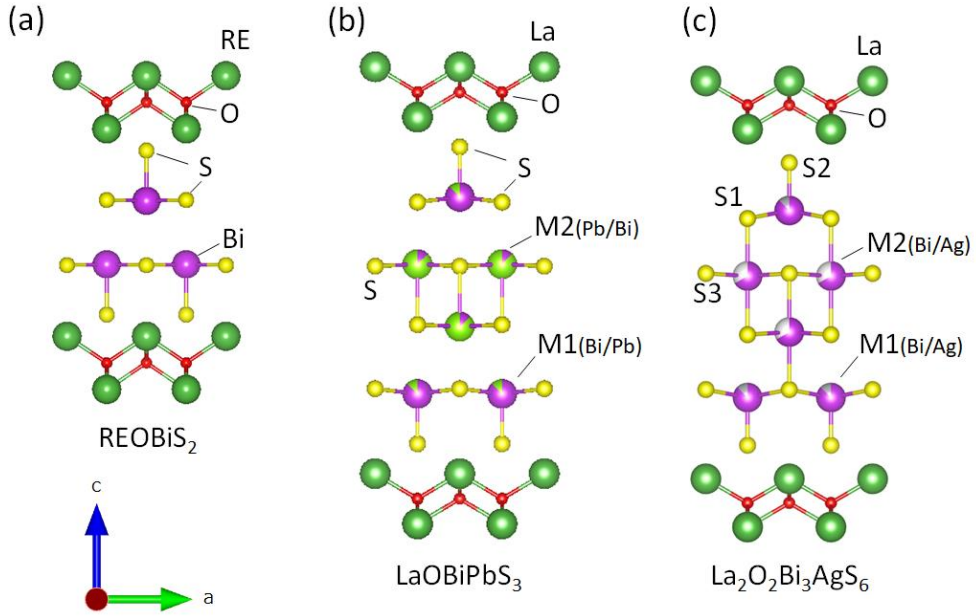

Fig. 1: *Schematic image of the crystal structure of (a)$REOBiS_2$ and (b,c)$La_2O_2M_4S_6$.*

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Superconductivity with First-Order Upper Critical Field in an Aluminum Cage Compound

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We present the discovery of superconductivity in an aluminum-based cage compound, and the physical characterization of nonsuperconducting members of the same family. The superconductor apparently exhibits Type-II superconductivity, but the transition develops a latent heat and hysteresis in very small fields. We discuss possible interpretations. Several related materials were not found to superconduct within the measured temperature range, but their resistivity obeys $\rho = T^4 + C$ over a wide temperature range, in some cases up to 50 K.

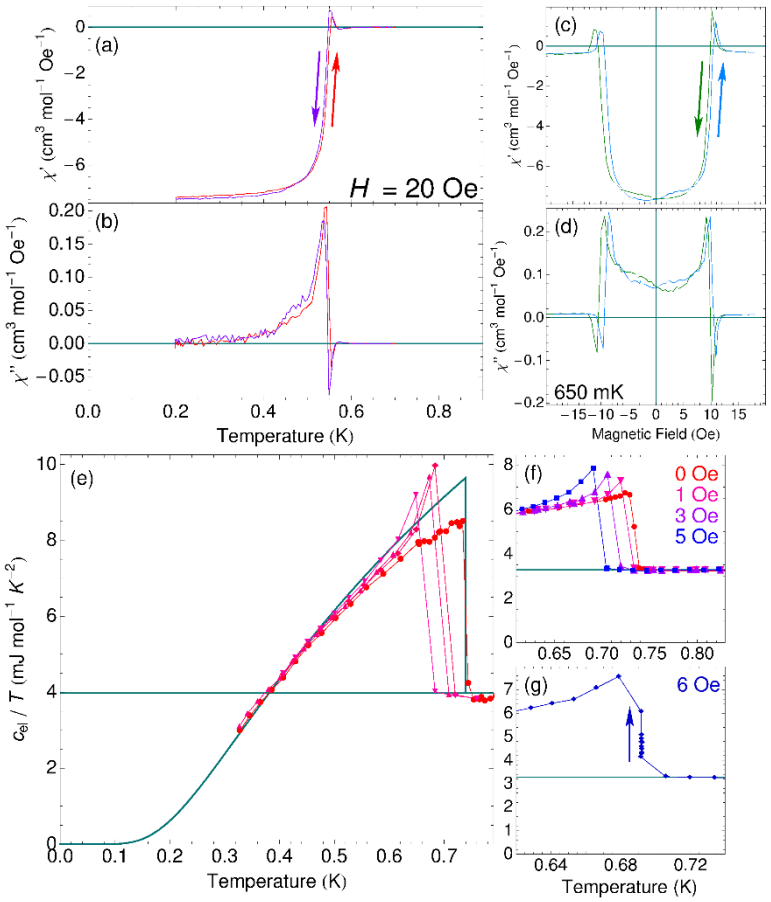

Fig. 1: *AC susceptibility and specific heat, demonstrating the appearance of a first-order component to the transition in low fields.*

$NaSn_2As_2$: a representative of a novel family of van der Waals-type superconductors

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Layered superconductors with van der Waals (vdW)-type structure has been attractive to investigate the physical properties of low-dimensional superconductors, as exemplified by transition metal dichalcogenides, graphite, metal nitride halides, and so forth. Herein, we report the SnAs-based layered superconductor $NaSn_2As_2$ [1]. Crystal structure of $NaSn_2As_2$ is a trigonal $R\bar{3}m$ space group, consisting of two layers of a buckled honeycomb network of SnAs, bound by the vdW forces and separated by Na ions, as shown in Fig. 1(a). Measurements of electrical resistivity and specific heat indicate the bulk nature of supercondcutivity with transition temperature of 1.3 K, as shown in Fig. 1(b). Because there are various structural analogues with tin-pnictide (SnPn) conducting layers, our results indicate that SnPn-based layered compounds can be categorized into a novel family of vdW-type superconductors, providing a new platform for studies on physics and chemistry of low-dimensional superconductors.

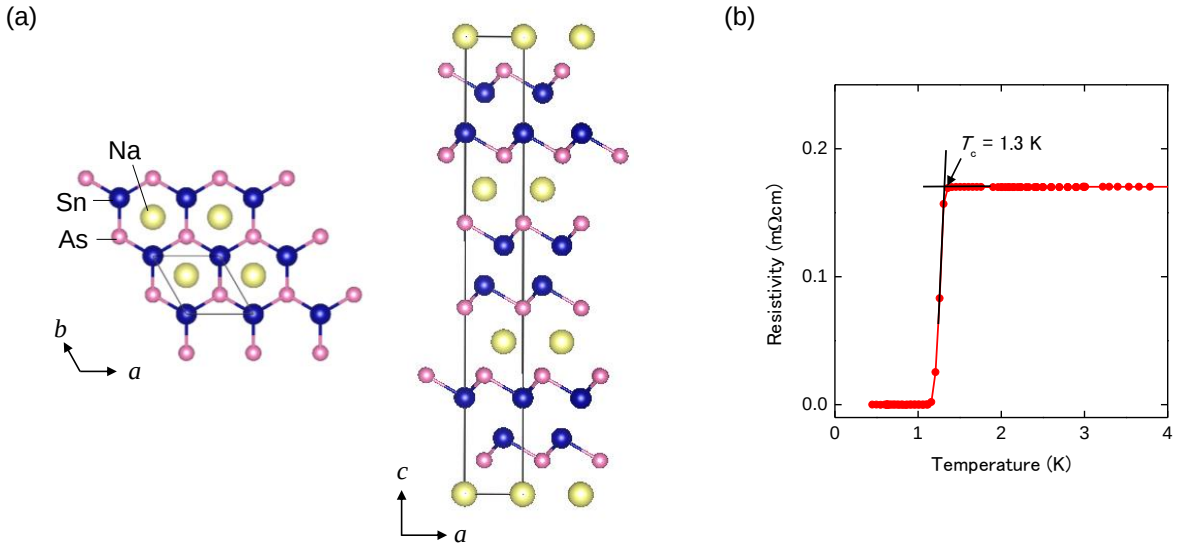

Fig. 1: *(a) Crystal structure of $NaSn_2As_2$. (b) Temperature dependence of electrical resistivity of $NaSn_2As_2$.*

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Superconductivity in the intermetallic Ce-based compound $CeIr_3$

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Combining rare earths with heavy transition metals such as iridium often produces compounds with scientifically interesting and technologically important physical properties. Ir-containing materials, where the presence of spin-orbit interactions may create complex electronic properties, have been investigated, for example, in the search for superconductivity [1,2,3].

In our work, $CeIr_3$ was synthesized by the arc-melting method followed by high temperature annealing. The normal and superconducting state properties were studied by using various techniques: magnetic susceptibility, heat capacity and electrical resistivity. Experimental results indicate a bulk superconducting transition at $T_c \sim 2.5$ K. The heat capacity data yield the Sommerfeld coefficient $\gamma = 25.1(3)$ mJ mol^{-1} K^{-2} and the Debye temperature $\Theta_D = 142(1)$ K. The electron phonon coupling coefficient, $_{el\text{-}ph} = 0.65$, and normalized heat capacity jump at T_c, $\Delta C/\gamma T_c = 1.24$, suggest that $CeIr_3$ is a weak coupling BCS superconductor. Theoretical calculations of the electronic structure are reported, and used in the analysis of the experimental results.

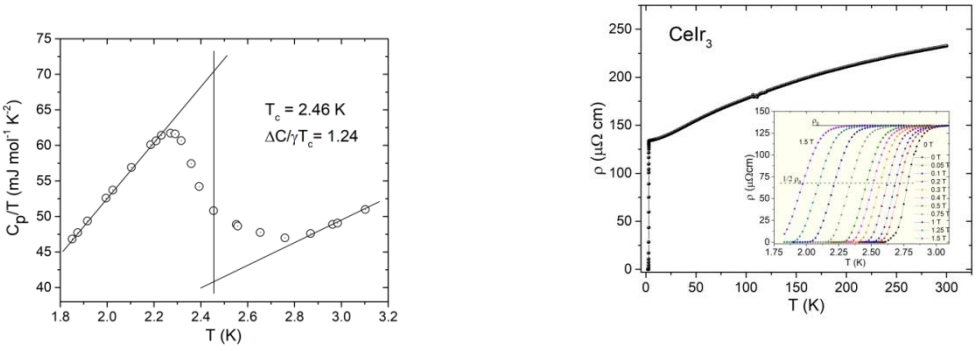

Fig. 3. *Left: Temperature dependence of the specific heat in zero field showing superconducting transition at T_c = 2.46 K. Right: Temperature dependence of the resistivity shown over the range 1.85 ≤ T ≤ 300 K. The inset shows the temperature variation of the resistivity in a set of magnetic fields.*

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Acknowledgement

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Superconducting origin from BaO_2-plane in $BaPb_{1-x}Bi_xO_{3-\delta}$

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It was well known that the CuO_2-plane is responsible for superconducting in cuprate superconductors. Substituting generates the changes in the superconducting properties. A mere 2% Zn in fully-oxygenated $YBa_2Cu_3O_{7-\delta}$ reduces both T_c and Δ_0 by as much as 30%. However, substitution of out of CuO_2-plane has a weak effect on T_c for $YBa_2Cu_3O_{7-\delta}$. In this paper, we have fabricated three serials samples, namely Pb for Bi in BaBiO3 and La/Ca for Ba in $BaPb_{0.77}Bi_{0.23}O_{3-\delta}$.The critical temperature was tested by transport measurement. The doping x dependence of critical temperature for $BaPb_{1-x}Bi_xO_{3-\delta}$ could be fitted well by a parabolic equation, $1-T_c/T_c^{max}=A(x-x_c)^2$ with A=120.68 and x_c=0.223. However, for $Ba_{1-y}Ca_yPb_{0.77}Bi_{0.23}O_{3-\delta}$, the critical temperature decreases rapidly with the Ca-doping level. For $Ba_{1-z}La_zPb_{0.77}Bi_{0.23}O_{3-\delta}$, the critical temperature decreases slow with the La-doping level. When z=0.5, the critical temperature decreases about half. Compared our results with that in cuprate superconductors, we think that the BaO_2-plane maybe act as superconducting layer, $BiO_2(PbO_2)$-plane act as the charge reservoir block.

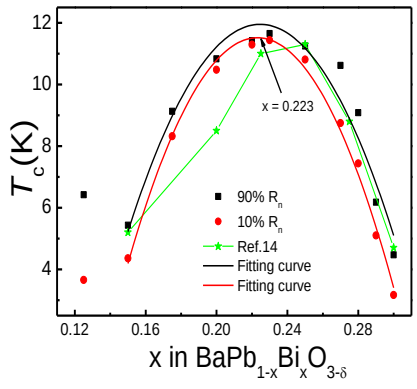

Fig.1 Doping x dependence of critical temperature for $BaPb_{1-x}Bi_xO_{3-\delta}$

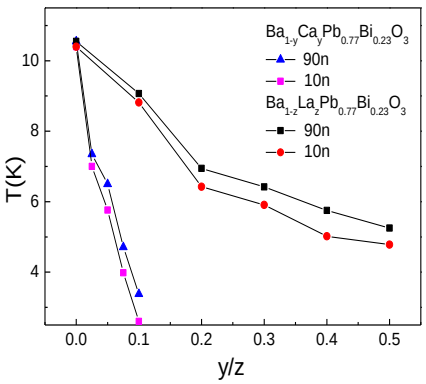

Fig.2 Doping y/z dependence of critical temperature for $Ba_{1-z}Ca_{(La)z}Pb_{0.77}Bi_{0.23}O_{3-\delta}$,

Evidence for a magnetic topological semimetal in CeBi from magnetotransport and magnetic measurements

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We here present results of magnetic and magnetotransport measurements on the topological semimetal CeBi. Our measurements show clear Shubnilov-de Hass oscillations which yielded the π Berry phase, demonstrating the nontrivial topological states. We also observed two antiferromagnetic orderings at 26 K and 13 K, thus classifying CeBi into the category of magnetic topological semimetals which are of highly potential use in electronic devices. The analysis on the measured resistivity also exposed a Kondo-like beheavior at low temperture. Moreover, our isothermal magnetization revealed multiple steps below 26 K, suggesting complex spin dynamics in CeBi.

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Pressure Induced Superconductivity in the New Compound $ScZrCo_{1-\delta}$

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It is widely perceived that the correlation effect may play an important role in several unconventional superconducting families, such as cuprate, iron-based and heavy-fermion superconductors. The application of high pressure can tune the ground state properties and balance the localization and itineracy of electrons in correlated systems, which may trigger unconventional superconductivity. Moreover, non-centrosymmetric structure may induce the spin triplet pairing which is very rare in nature. Here, we report a new compound $ScZrCo_{1-\delta}$ crystallizing in the Ti_2Ni structure with the space group of FD3-MS without a spatial inversion center. The resistivity of the material at ambient pressure shows a bad metal and weak semiconducting behavior. Furthermore, specific heat and magnetic susceptibility measurements yield a rather large value of Wilson ratio ~4.47. Both suggest a ground state with correlation effect. By applying pressure, the up-going behavior of resistivity in lowering temperature at ambient pressure is suppressed and gradually it becomes metallic. At a pressure of about 19.5 GPa superconductivity emerges. Up to 36.05 GPa, a superconducting transition at about 3.6 K with a quite high upper critical field is observed. Our discovery (Fig. 1) here provides a new platform for investigating the relationship between correlation effect and superconductivity. [1]

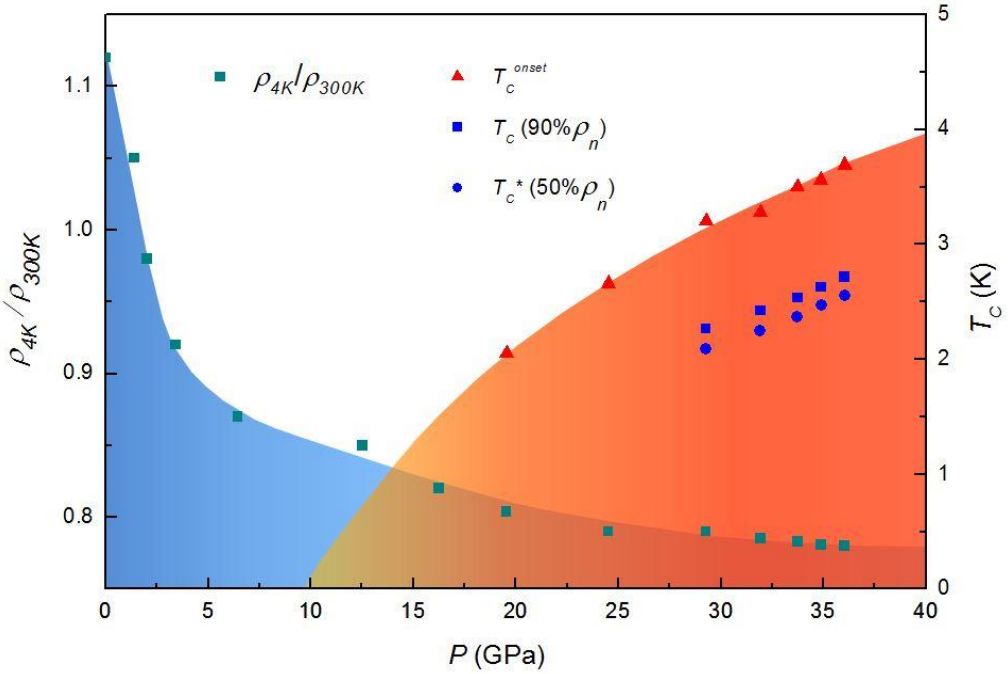

Fig. 1: *Phases diagram of* $ScZrCo_{1-\delta}$

Reference

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In-situ hydrostatic pressure induced significant suppression of magnetic relaxation and enhancement of flux pinning in $Fe_{1-x}Co_xSe_{0.5}Te_{0.5}$ Single Crystals

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We report the first study on the significant effect of in-situ hydrostatic pressure on the magnetic relaxation in $Fe_{1-x}Co_xSe_{0.5}Te_{0.5}$ single crystals. We find that vortex creep rates are significantly suppressed by pressure, and a crossover from elastic to plastic creep is observed. The pressure also induces vortex creep to move from the large bundle to the small bundle region. Our study indicates that in-situ hydrostatic pressure is very effective for not only significantly increasing the pinning energy and the critical current density, but also reducing the size of flux bundles to suppress the decrease in current density from vortex motion.

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Non-destructive evaluation of critical current on Bi-2212 cable

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High-temperature superconducting material of Bi-2212 is considered to be used in the next generation of fusion reactors such as CFETR due to extremely high critical current density as well as high critical field at low temperature. The critical current as well as its inhomogeneity is one of the important factors to evaluate the performance of the Bi-2212 wire, cable and conduct, and also it is important for the design of the superconducting magnet system. Non-destructive evaluation by using Hall sensor array is more effective and faster method for testing local critical current of high temperature superconductor compared with conventional contact-electrical method. In this work, we demonstrate non-destructive evaluation by using Hall sensor array for testing local critical current of Bi-2212 wire, cable and conduct.

Residual Stress Quantification in Nb_3Sn Thin Films for Superconducting Radio Frequency Applications

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Superconducting Radio Frequency (SRF) cavities generate high intensity alternating electric fields that are used to accelerate charged particles in accelerator complexes. Bulk Nb SRF cavities are well established and understood, however the substantial cost and limited thermal conductivity of these devices has necessitated the development of new manufacturing approaches based on the application of a superconducting thin film to a copper substrate [1].

Nb_3Sn has become widely used as a superconductor due to its high superheating critical field and critical temperature (T_c). This material is also well suited to thin film production, for example through Direct Current Magnetron Sputtering (DCMS) [2]. However, in order to produce the best possible films, deposition parameter optimisation is required.

The magnitude of residual stress within the Nb_3Sn thin film is particularly important for SRF applications. Before use, the coated cavity must be cleaned using high-pressure (100 bar) water rinsing for 2 hours. In order to achieve the required cavity frequency, a process known as tuning is also performed, during which the cavity is physically compressed or stretched. The likelihood of thin film peel off or cracking during these processes is highly dependent on the magnitude of residual stress induced during manufacture. Careful control of the residual stresses are also critical in ensuring the maximum possible T_c of the thin film [3].

X-ray Diffraction (XRD) is a well-established but relatively slow approach for average thin film residual stress quantification over mm to cm sized areas. In order to provide faster assessment, techniques based on cantilever deflections have also been developed [4]. However, in order to probe specific locations of interest and to quantify stress gradients at the precision required, microscale residual stress analysis using the ring-core Focused Ion Beam (FIB) and Digital Image Correlation (DIC) approach can be used [5].

In this study, we compare the residual stress estimates of DCMS Nb_3Sn thin films obtained using XRD, a macroscale cantilever bending approach and the ring-core FIB-DIC technique. A range of coating temperatures (600-750°C), pressures (1-50 µbar), heat treatments and the suitability of intermediate coating layers (Ta and Nb) have been investigated.

This study provides the insights necessary to optimise production parameters in order to meet the stringent requirements of the next generation of SRF cavities. Beyond this, the analysis demonstrates the capabilities and suitability of the ring-core FIB-DIC approach for residual stress quantification in superconducting thin films.

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Simulation of Quench and Recovery Characteristics of YBCO Coated Conductors in Three-Dimension of DC Resistive Superconducting Fault Current Limiters

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A DC resistive type Superconducting Fault Current Limiter (SFCL) can greatly reduce the fault current and protect the power equipment in DC systems. In the normal state, the YBCO coated conductors of resistive type SFCL will be in superconducting state. However, it may be quenched when a thermal disturbance energy impacts to it. Then the YBCO coated conductors will quench and sometimes even break when its temperature is too high. In the fault state, an attack of short-circuit fault current may damage the coated conductors of a DC SFCL. Thus it is necessary to investigate the quench and recovery properties of the YBCO coated conductors under thermal disturbance and short-circuit fault current attacks. The objective of this paper is to obtain the quench and recovery characteristics of DC resistive type SFCLs when the YBCO coated conductors are affected by thermal disturbance and short-circuit fault current attacks. Thermal conduction theory and finite element method were used to analyze the temperature propagation and recovery characteristics of YBCO coated conductors in three-dimensional. Simulated YBCO coated conductor was shown in Fig. 1. Simulation results show that the temperature and voltage of the YBCO coated conductors increased while the transport current through the tape and the magnitude of thermal disturbance increased. The quench propagation velocity was higher and the recovery time was shorter for copper stabilized layer than stainless steel stabilized layer. The temperature at the top layer and bottom layer was several Kelvin lower than the temperature at the middle layers due to the cooling of liquid nitrogen. The temperature in width direction is same.

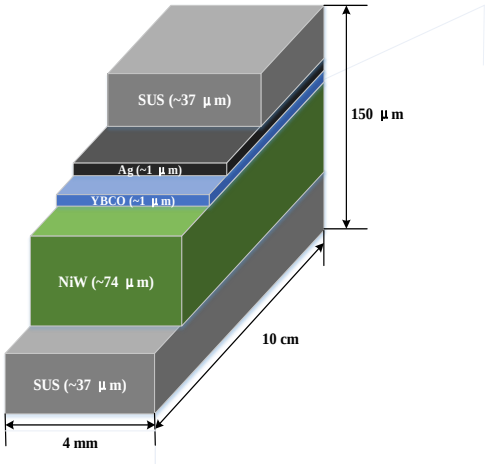

Fig. 1: *Schematic of simulated YBCO coated conductor*

Activities of Chinese National Technical Committee on Superconductivity

J. Li[1], Q.S. Yang[1], Y.P. Liu[1], G.M. Zhang[2], D.N. Zheng[1], L.X.You[3], X.J. Zhou

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SAC/TC265 was formally established in the year 2003, and the second committee started from 2017. On one hand, it works as the national technical committee on superconductivity of Standardization Administration of China (SAC), therefore is responsible for constructing the standardization systems in the field of superconducting technology in China. On the other hand, it also works as the Chinese sub-commission of IEC/TC90, therefore its tasks still include organizing domestic experts and institutions to participate in international superconductivity standardization activities. Up to now, the committee has contributed to the development of altogether 23 IEC International Standards on superconductivity, and meanwhile transformed 15 of them into Chinese national standards. Together with 2 independently developed one, the committee has established 17 Chinese national standards on superconductivity. 6 more projects have been approved and initiated, and progressing well, all are adopted from IEC standards. In the next few years the committee will speed up the adoption speed to match the launching speed of IEC/TC90. Besides, two more independent pre-standardization projects, “Measurement of the critical current and its uniformity along the length of the 2G HTS long tape” and “Measurement of twist pitch of NbTi and Nb_3Sn composite superconducting wires”, have finished experiments and the drafts have been submitted to SAC for approval.

Right now, the committee is making efforts to enhance the participation of enterprises in standardization activities, to develop Chinese national standards independently and most importantly to strengthen the tie with IEC/TC90. First, we would like to keep track of the latest progress of IEC/TC90; then, we can contribute; finally, we would like to propose new items and lead the project. Chinese experts are allocated to participate in each working groups, taking part in the meeting discussions and showing China’s position. They are required to respond to email discussions in a timely manner, giving opinions and advices. Domestic institutions are encouraged to participate in the world-wide pre-standardization round robin tests. A New Working Item Proposal (NWIP) for international standard, namely “Superconducting nanostrip single photon detector - dark count rate”, is ready for submission.

Numerical Simulation on Improving Stability of Magnetic Field of Persistent Current Mode 2G HTS Coils

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Persistent current mode coil based on single second-generation high-temperature superconducting (2G HTS) wire could avoid the joint resistance. After an excited field, current of the coil could sustain for a long time because the resistance of no-joint coil is low. This paper presents numerical simulation of magnet made of persistent current mode YBaCuO coils based on E-J power law. Bath with an external magnetic field, the self-field of model could increase to 1.5 T in the center of magnet. Inevitably, there still exists very little resistance in the coil, the current and center magnetic field would both decrease slowly in dozens of hours. To improve the stability of center magnetic field, we designed a pair of auxiliary coils. By magnetic field coupling, the auxiliary coils make the current of main coils more stable, and the intensity of center magnetic field sustain in a stable value for a longer period of time.

Enhancement of the electronic thermoelectric properties by charge density wave order

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The thermoelectric efficiency is given by the dimensionless figure of merit *ZT*. The *ZT* is characterized by the $ZT = \sigma S^2 T/\kappa$, where *S, σ, T,* and κ are the Seebeck coecient, electrical conductivity, absolute temperature, and thermal conductivity, respectively. Recently Our group suggested quasi 1-Dimensional Peierls system, In_4Se_{3-x}, as a new route to high efficient thermoelectric properties, with the Boltzmann transport calculations combined with density functional theory [1]. But the model calculation is not yet carried out which can offer more insights and it is still controversial that the long range order gap really can be benefit for thermoelectric properties because the entropy reduction by the ordered states is not good at the seebeck coefficent of which absolute values are corresponding to entropy. Here adopting minimal two band model, we calculated the thermoelectric properties by the kubo formula for the isotropic momentum charge density wave (CDW) order. Our results show that CDW gap dramatically enhance the electric thermoelectric properties and it will be presented why such a long range order gap can be benefit for the electronic thermoelectric properties in details.

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Experimental and Numerical Study of Wireless Power Transfer System Using High Temperature Superconducting Coils

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The wireless power transfer (WPT) system using a magnetic resonance has been studied extensively in the past ten years. In the present work, we construct a magnetic resonance wireless power transfer system with two coils using high temperature superconductors (HTS) and copper tapes respectively. Since the resistance and AC loss of HTS is much lower than that of copper coils, it is an effective way using high temperature superconductors with high *Q*-factor for WPT system to increase power transfer efficiency. Finite Element Method (FEM) was applied to compute the model of the two coils. The reflection coefficient and transmission coefficient of *S*-Parameter was analyzed under the mixed application of the superconducting coils and copper coils in the present study. Simulation and experimental results show that HTS coils are able to improve the transfer efficiency of a WPT system.

Design and analysis of new hybrid magnetic shielding system: application for magnetic nondestructive testing of circuit

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A new magnetic shielding system has been developed which combines three-axis active magnetic shielding and high-Tc superconducting ring. Shielding effects of system ware evaluated by both theoretical analysis and experiment measurements. It suggests that this system can effectively shield the interference of static and low frequency magnetic field to ensure the use of high precision magnetic sensors. The shielding factor (SF) can reach up to 80 dB. Then, magnetic nondestructive testing of circuit has been done in this shielding system. Imaging shows magnetic field distribution in different kinds of circuit clearly, which can be inverted to the information of the current density. The practicality of the shielding system has been proved by these results.

Critical current and superconducting phase homogeneity in FeAs-122 superconducting tapes

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Chemical doping, which induces superconductivity in iron-based superconductors, has great influence on the crystal structure, the superconducting transition temperature, the pinning landscapes and even the critical current density. Consequently, inhomogeneously distributed doping atoms will eventually affect the critical current of an applied superconductor. Herein, we study the superconducting phase homogeneity and its relation to critical current in iron-based superconducting tapes. We measure the specific heat of the rolled and hot-pressed $Sr_{1-x}K_xFe_2As_2$ tapes, and find that the Schottky anomaly that is obvious in the specific heat of the rolled tape disappears in the hot-pressed tape. Moreover, the hot-pressed tape has a higher fraction of superconductivity and a narrower distribution of superconducting transition temperature than the rolled tape. Combined with the magnetization data, we conclude that sintering under high pressure provides a better environment for complete chemical reaction and more homogenous dopant distribution, which is beneficial to the global current of a superconductor.

Multichannel Ultralow Field Magnetic Resonance Imaging Study Ultilizing Low-T_c SQUIDs

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Ultralow field (ULF) magnetic resonance imaging (MRI) obtains images in the static magnetic field typically on the orders of tens to hundreds of microteslas and has attracted considerable attention in recent years. In order to reduce the system cost and to carry out experiments in an open space, we constructed a four-channel low-Tc SQUID-based ULF MRI system in an urban laboratory without shielding. The extremely sensitive detectors, superconducting quantum interference devices (SQUID) have been introduced into ULF MRI system to overcome the obstacle of poor signal to noise ratio. We developed a variety of noise methods, e.g. active compensation technique [1], full-tensor gradient field shimming [2] and adaptive suppression of power line interference [3] to suppress external magnetic field and gradient noise interference. These techniques made MRI possible in an urban environment, leading us to construct a 4-channel unshielded system. We implemented 3D MRI with the 4-channel 2nd-order gradiometers as shown in Fig. 1. The sample was a piece of pepper with side lengths of 45 and 35 mm and a thickness of 20 mm. The in-plane spatial resolution reaches about 2 mm × 2 mm [4].

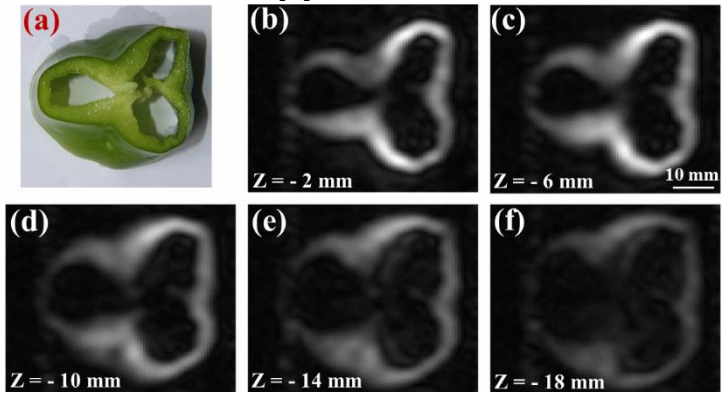

Fig. 1: *3D MRI images of a pepper sample obtained by the 4-channel SQUID system*

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Practical low-Tc SQUID Systems for Geophysics Applications

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The sensitivity of low-Tc superconducting quantum interference device (SQUID) is independent of frequency and external magnetic field environment at low frequency range (< 100 Hz), thus playing an indispensable role in outdoor geophysics prospecting. To overcome the challenge of strong transient magnetic field change and radio-frequency interference, we develop practical SQUID systems utilizing homemade magnetometers and planar gradiometers, as well as readout electronics. These SQUID systems have been successfully used in two typical applications, the transient electromagnetic method (TEM) and the airborne full-tensor magnetic gradient prospecting (FTMG). In TEM detection, SQUID magnetometers measure the secondary eddy-current response of the ground to the pulsed primary transmitting field. The metalliferous minerals can be located by calculating the resistivity. Due to SQUID' high sensitivity, we obtained the accurate location of abnormality in metal mineral areas and it was in good agreement with drilling information. Furthermore, a low-resistivity abnormality at about 1000 m deep was identified in Inner Mongolia. On the other hand, FTMG is recognized as the 3rd generation aeromag technique, and low-Tc SQUID is widely regarded as the optimal sensor for this application. We build up the world's 2nd practical airborne FTMG system with multi-chips of planar gradiometers and observe several abnormal gradient signals during flying tests. The system resolution reaches 0.02 nT/m (0.01 ~ 5 Hz). By further optimization, our practical SQUID system will be applied to both the scientific research and the engineering applications in the near future.

Surfaces smoothing for enhancing superconducting properties of NbN nanowires by ion beam figuring

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Ion beam figuring (IBF) technology has been applied in the field of manufacture optics for more than twenty years since it is able to achieve high precision figuring of surfaces. However, in this article, we applied IBF technology to smooth the SiOx layer surfaces to improve the interfacial properties between superconducting nanowires (NbN nanowires) and SiOx waveguides. IBF worked since the rms roughness of waveguide surfaces plunged to some tenths of nanometers (nm) from several nm, and increasing jc values of nanowires were obtained while better mechanical and superconducting properties of 5 nm Niobium nitride (NbN) ultra-thin films were found during the figuring process by using Atomic Force Microscopy (AFM) and helium temperature measurements (4.2 K). We demonstrate a promising way to fabricate multilayer-structure Superconducting nanowires single photon detector (SNSPD) by ion beam figuring.

Keywords: ion beam figuring, thin films, surfaces, superconducting, Niobium nitride

High Temperature Superconducting Magnets in PCS Mode

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Since the discovery of high temperature superconductors, people have made great efforts in developing conductors for practical application. Although progress was achieved in producing large current carrying conductors, such as PIT BSCCO wire and coated conductors, they cannot been used to build a magnet in persistent current state (PCS). This is because the coherence length of HTS is very short and a superconducting joint with high Tc is not available, thus large scale application of HTS is impossible, esspecially in the field of electric magnet. Here we present an alternative method to overcome the difficulty.

Stability of Superconducting Magnet and Wire Insulations

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In order to improve the stability of the superconducting magnets, e.g. MRI magnets, the NbTi superconducting wires were used to wind magnets without electrical insulation layers. The magnets were made with different induction values. As comparisons, the same kinds of wires with insulation layers were used to wind magnets of similar induction values. The magnets were tested at 4.2K in a LHe bath. The results were analyzed and theoretically investigated. The results reveal that non-insulation winding is beneficial to the magnet stability. However, the long charging and discharging period make it unacceptable for the technique to be put into practical applications.

Ferromagnetic Josephson Junctions Based on Epitaxial NbN/NiCu/NbN Trilayer

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We fabricated and characterized weakly coupled magnetic Josephson junction based on epitaxial NbN/$Ni_{60}Cu_{40}$/NbN trilayer structures on single crystal MgO (100) substrates. The NbN/$Ni_{60}Cu_{40}$/NbN junctions demonstrated typical Josephson effect with a nonlinear overdamped current–voltage characteristic and a characteristic voltage of 9.1 μV. The magnetic field dependence of the junction critical current showed a nearly ideal Fraunhofer-like pattern with a magnetic field shift of about 12 Oe due to the remanent magnetization of NiCu layer. The damped oscillation behaviors of the critical current were observed as a function of the ferromagnetic layer thickness at 4.2K and as a function of the temperature for specific ferromagnetic layer thickness, which evidence 0- π phase transitions. Numerical calculations based on the quasiclassical Usadel equations and the Green function fit very well with the experimental results. The current-phase relation of this NbN-SFS junction was also investigated, and the Shapiro step was clearly observed near the crossover between 0 and π ground states.

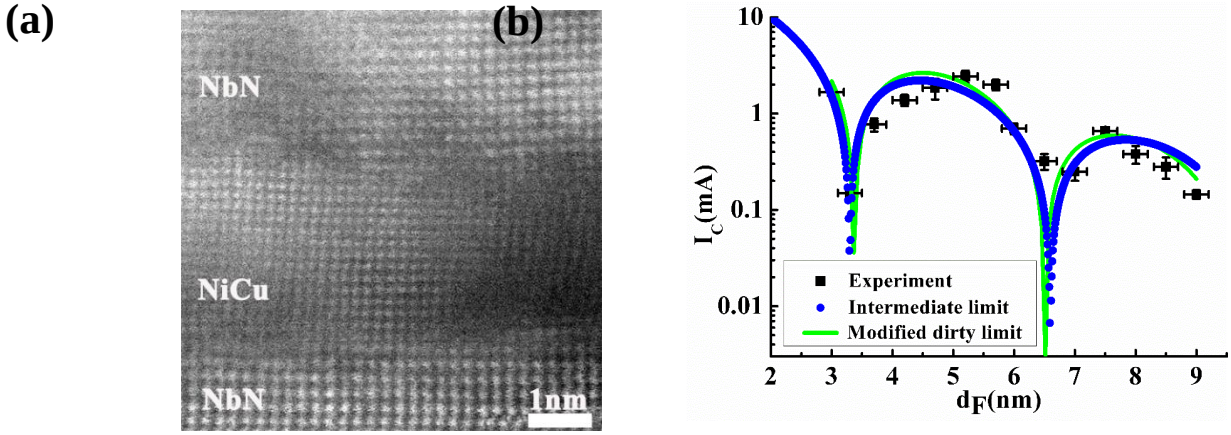

Fig. 1: *(a) Cross-sectional TEM image of the epitaxial NbN/NiCu/NbN trilayer; (b) Critical current vs NiCu thickness (0-π phase transition)*

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High Speed Superconducting Nanowire Single-Photon Detector with the Capability of Photon-Number-Resolving

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Abstract—Superconducting nanowire single-photon detectors (SNSPDs) offer low dark counts, high efficiency, high detection speed, wide spectral range, and the potential of photon-number resolving. Limited by the large kinetic inductance in superconducting nanowires, the detection speed of typical SNSPD can not exceed 100MHz. With the series connection of N nanowires each connected in parallel to a resistor, the series superconducting nanowire single-photon detector (SND)[1] is an effective method to realize photon-number resolving and fast photon detection, which also depends on high critical current and high detection efficiency.

In this paper, we demonstrate a 6-pixel SND with high efficiency and high detection speed fabricated from a 6nm NbN film on Si substrate. Response voltage pulses from n=1-6 photon detection events were observed and statisticed. To improve the critical current and lower dark count rate, We optimized the superconducting nanowires by rounded-corner structure with optimal curves. It shows a 10% raise in critical current, which contributes to realize high saturation system detection efficiency. The Device shows a system detection efficiency of more than 60% at λ=1550nm and a low maximum dark count rate of less than 200Hz. By optimizing the nanowire width and thickness, the device response cut-off wavelength is raised and the system efficiency shows saturation in a wide spectrum range from 1100nm to 2000nm. Here, the maximum repetition rate is the focus of attention. Even though the active area of this N=6 elements SND is 20μm×20μm, We observed a repetition rate range up to 300MHz at the same saturating counting rate measuring with a traditional 50Ω impedance readout. It indicates that series nanowire detector is an efficient method for ultrahigh detection speed with large active area. When interconnecting with a high input impedance cryogenic RF integrated circuit, we found the recover time constant τ of this 6-pixel SND reduced from 50ns to 7ns.

Index Terms —Series nanowire detector, Photon-number resolving, System quantum efficiency, Detection speed.

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Effect of Thickness on Superconducting Properties for Epitaxial NbN Films

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Niobium nitride (NbN) have attracted interest in superconducting electronics, and are widely used in many applications such as Josephson junctions, SQUIDs, superconducting single photon detectors (SNSPD), superconducting hot electron bolometers (HEB), because NbN has a large gap energy and a high critical transition temperature. For these applications, NbN films with different thickness are demanded depending on the purposes. The superconducting properties of NbN films depend on film thickness, we have measured the superconducting properties of a series of epitaxial NbN thin films with thickness ranging from 200 to 2.2 nm thinner than the coherence length (ξ~5 nm). The results show that the normal state resistivity ρ_n increases from 62 to 146 μΩ cm, the transition temperature T_C decreases from 16.6 to 8.9 K, the energy gap Δ reduces from 3.09 to 1.62 meV, the carrier density in NbN thin films decreases from 1.1×10^{29} to 5.56×10^{28} e/m^3, respectively, with reducing of NbN film thickness from 200 to 2.2 nm, while the upper critical field (H_{c2}~11 T) and superconducting coherence length remains approximately unchanged. By fitting our data with the McMillan theory, the T_C of epitaxial NbN films is found to be primarily determined by the carrier density that is thickness-dependent.

Temperature Dependence of Critical Current in YBCO Step-Edge Josephson Junctions

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We planned on measuring the temperature dependence of critical current in (100)-oriented YBCO step-edge Josephson junctions. We make the YBCO step-edge junctions on $LaAlO_3$ (100) substrates. We used a metal mask film which was deposited on LAO by DC sputtering and patterned by photolithography and chemical etching with Ar plasma treatment, to make the substrates had a step. After the mask film removed, YBCO thin film was deposited on LAO by pulsed laser deposition system (PLD). The angle between step and underside is around 45~60 degree and YBCO on step is (103)-oriented[1]. The one of the most important applications of Josephson junctions is SQUID, and it may be used under different environment temperature. There were many article reporting the temperature dependence of critical current in trilayer Josephson junctions but none reported the step-edge Josephson junctions[2,3]. We hope our research could be a reference for SQUIDs to give its suitable working temperature. In this article, we will give the big range temperature dependence of critical current, I-V curve of junctions at different temperature, and possibly, some discusses about the influence from the step.

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Memristor Behavior of 2D FeTe with High Temperature Phase Instability

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Iron-based superconductors are attracting lots of attention to study the basic mechanism and to improve T_c. While on the other hand, the various phases of Iron-based superconductor materials would give us more chances for electronics applications. Here, we studied two-terminal electronic transport properties of layered Iron Telluride (FeTe), which is considered as one of the parent materials of the simplest family of iron-based superconductors, around room temperature. Nonlinear I-V curve was observed and it turned to be memristor behavior, which would resulted from the transition between the various phases and phase instability at high temperature. This kind of high temperature phases related behavior would enrich the applications of Iron-based superconductor materials, as well as the understanding of the basic mechanism.

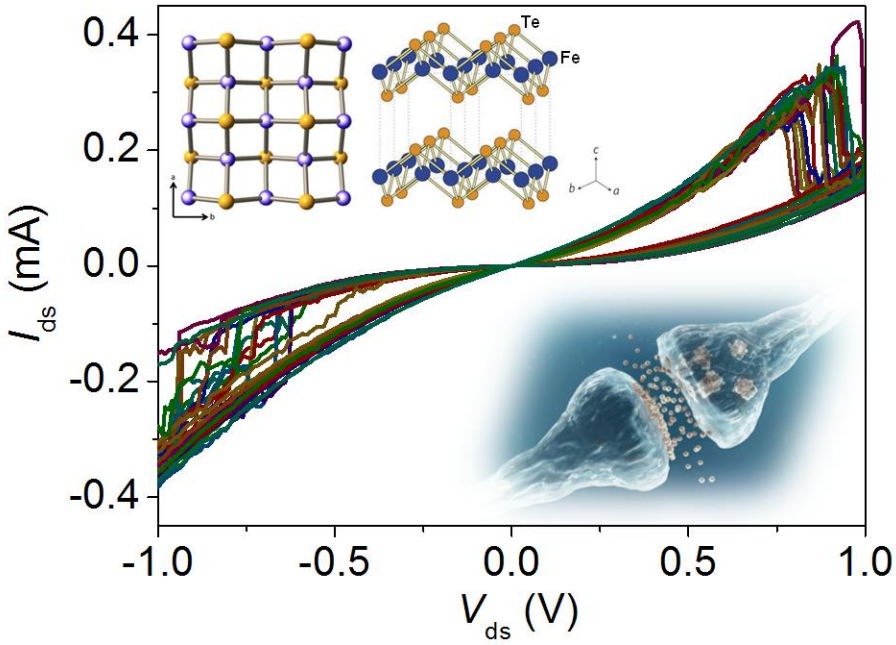

Fig. 1: *Memristor behavior of FeTe.*

The vortex physics and critical current density in Ca10(Pt n As8)(Fe2-x Pt x As2)5and Ca0.74(1)La0.26(1)(Fe1-xCox)As2

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The vortex physics were systematically studied in single crystals of Ca10(Pt n As8)(Fe2-xPt x As2)5 and Ca0.74La0.26(Fe1-xCox)As2. The critical current density, magnetic relaxation, and irreversible field were revealed by dynamic magnetization measurements. We analyzed the data within the framework of the critical state and a thermally activated flux-creep model. The results indicate the collective pinning mechanism dominated the vortex behavior. The anisotropy of vortex pinning and critical current density were also investigated. Unlike the cupertes, the multilayer pnictides superconductor exhibit a moderate anisotropy more suitable for industrial application.

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Statistics of Magnetic Field Threshold for Triggering Flux Avalanches in Nb Superconducting Films

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Superconducting materials expel the magnetic field from their bulk up to a certain field, where flux lines start to penetrate the material. Unfortunately, the motion of these fluxons leads to heating, which locally destroys superconductivity and thus limits the potential applications. Under certain conditions, flux penetration no longer occurs in small steps, but becomes abrupt and takes the form of flux avalanches propagating at ultrasonic velocities and resulting from thermomagnetic instabilities. The physics in this kind of system shows similarities with that of dielectric breakdown, fractures propagation, snow avalanches, or earthquakes [1]. In all these examples, the triggering of this phenomenon might have dramatic consequences, such as irreversible changes in the system. This makes the statistical study of the phenomenon very complex, since a large amount of samples replicas are required. However, avalanches in superconductors are an ideal playground to investigate the statistics of the phenomenon since they generally do not modify the material nor its properties.

Until now, theoretical predictions or experimental studies on the statistic distribution of the magnetic field necessary to trigger avalanches remain elusive. Moreover, the conditions and the parameters acting on the threshold field are unknown. In this work, we tackle these problems by performing magneto-optical imaging experiments [2] on a rectangular Nb thin film, where nanometric heating elements are used to clean the magnetic history of the sample in a few seconds. This allows to repeat the same experiment thousands of times and get access for the first time to the investigation of the statistic distribution of the avalanche phenomenon.

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Particle Size Effects on the Magnetic Properties of the SmFeAsO1-xFx Superconductors.

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SmFeAsO1-xFx superconducting sample was prepared by solid state reaction. The as sintered sample is divided in various pieces, which are softly ground by hand to obtain powder samples with different grain sizes and the same chemical stoichiometry. Samples with grain size (R) of 1680, 550, 470, 405, 345 and 220 nm were obtained. We measured the isothermal magnetization at different temperatures and different applied field ranges on all those samples. The lower critical field Hc1 was determined from the virgin magnetization region and the grain size dependence of Hc1 was determined, which shows a monotonically decreasing with grain size. The MH loops of the as sintered sample measured at different temperatures and applied field ranges, allow to see the transition from the coupled grains (intergrain) to the intragrain regime. When measuring the complete set of samples, MH loops also show a grain size dependence. Particularly drastic changes are observed when $R \rightarrow \lambda$. We explain the results by the extended Bean model, which considers a field dependence of Jc and the concept of the full penetration depth as a function of the grain size.

Direct Current Measurement of Hall Effect in the Mixed State for the Iron-chalcogenide Superconductors

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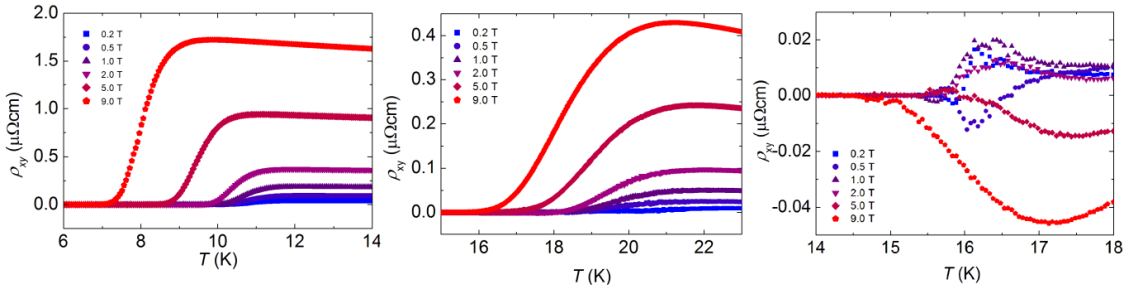
The sign of the Hall resistivity in the mixed state are different from that in the normal state, for some conventional superconductors and high Tc superconductors [1]. Recently, it was reported that the Hall resistivity of the iron-based superconductor, $Ba(Fe_{1-x}Co_x)_2As_2$, also shows the sign reversal below the transition temperature [2]. Moreover, a double sign reversal has been observed in some cuprates, such as $Tl_2Ba_2CaCu_2O_8$ [3]. Such anomalous behaviors of the Hall resistivity cannot be explained by basic models for vortex motion, such as the Bardeen-Stephen model [4], where the superconducting state and the normal state have the same Hall sign. So far, several theoretical approaches have been taken to explain the Hall sign change, and as the origin of sign reversal, many possibilities were proposed, such as the intensity of the vortex pinning in superconducting samples [5], the influence of the superconducting fluctuations [6], and the vortex core charge [7]. However, the origin of the Hall anomaly is still controversial, and consensus regarding this matter is not reached yet. In order to clarify this problem, we measure the Hall resistivity for the iron-chalcogenide superconductor $FeSe_{1-x}Te_x$ films near the transition temperature, and investigate how the composition and the pinning strength affect the Hall effect in the mixed state. As a result of experiments, we observe the sign anomaly for $FeSe_{0.5}Te_{0.5}$ films, but FeSe and $FeSe_{0.8}Te_{0.2}$ films do not show the sign reversal, as shown in Fig. 1. In addition, increasing applying current density, the sign change of the Hall resistivity in the $FeSe_{0.5}Te_{0.5}$ films vanished.



Together with those result, evaluation of the activation energy and the scaling exponent suggest the pinning strongly influence the Hall resistivity behavior.

Fig. 1: *The Hall resistivity for x=0 (left), 0.2 (middle) and x=0.5 (right).*

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Direct Visualization of the Nematic Superconductivity in $Cu_xBi_2Se_3$

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$Cu_xBi_2Se_3$ hosts both topological surface states and bulk superconductivity. It has been identified recently as a topological superconductor (TSC) with an extraordinary nematic, i. e. C_2-symmetric, superconducting state and odd-parity pairing. Here, using scanning tunneling microscopy (STM), we directly examine the response of the superconductivity of $Cu_xBi_2Se_3$ to magnetic field. Under out-of-plane fields ($B_\perp$), we discover elongated magnetic vortices hosting zero-bias conductance peaks consistent with the Majorana bound states expected in a TSC. Under in-plane fields ($B_{//}$), the average superconducting gap exhibits two-fold symmetry with field orientation; the long C_2 symmetry axes are pinned to the dihedral mirror planes under $B_{//}$=0.5 T but rotate slightly under $B_{//}$=1.0 T. Moreover, a nodeless Δ_{4x} gap structure is semi-quantitatively determined for the first time. Our data paint a microscopic picture of the nematic superconductivity in $Cu_xBi_2Se_3$ and pose strong constraints on theory.

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Evidences of Majorana Bound States in Fe(Te,Se) superconductor

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Majorana bound states (MBS) can arise as quasi-particle excitations in a vortex core of p-wave superconductors. Inspired by heterostructure proximity effect, Fu and Kane [1] proposed a realistic way to construct effective p-wave conditions with ordinary superconductor, which needs to induce full superconducting gap on non-degenerate Dirac surface states. Recently, we found a new platform ($FeTe_{0.55}Se_{0.45}$ single crystal) supporting pure Majorana-type excitations mimic Fu-Kane Model, which benefit from interband k-space proximity effect and strong correlation of materials.

By ultra-low temperature STM measurements [2], we found spatial non-split zero bias peak (ZBP) on the vortex core across a large range of magnetic fields and tunneling barrier conductance. The FWHM of ZBP are nearly system resolution limited. Further carefully study shows the intensity line profile of ZBP can be well explained by a theoretical model with only topological surface states [3] considered. Those observations provide strong evidences toward pure MBS on vortex core. At the meanwhile, temperature dependent experiments show the bulk vortex line play essential roles on protecting MBS on the material surface, which can be well explained by quasiparticle poisoning effects related to bulk mini-gap and thermal quasiparticle excitations.

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Study of the Superconductor–Insulator quantum phase transition using Nernst effect

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The superconductor-insulator transition (SIT) is a quantum phase transition that has proved to be an interesting subject of study owing to the two very dissimilar microscopic mechanisms by which it can be brought about. The fermionic mechanism is dominated by amplitude fluctuations of the superconducting order parameter ψ_0, whereas in the bosonic case, it is the phase ϕ that fluctuates. These mechanisms are not always easy to address in experiment. Whereas resistivity-vs-temperature curves show some qualitative differences, the other extensively used probe for the SIT, namely tunnelling experiment, is not sensitive to it. A special case of interest is the SIT of amorphous Indium Oxide, which has never shown full conformity with either mechanism.

To probe this SIT, we used Nernst effect, which is generated by either fluctuating Cooper pairs (fermionic) or mobile vortices (bosonic) in the vicinity of the SIT. We find Nernst effect on the insulating side of the SIT, the first of its kind, which proves the presence of vortex-like fluctuations even when the sample is not a superconductor. The dependence of the Nernst coefficient on disorder is in good qualitative agreement with a theoretical model developed for Josephson-coupled superconducting chains [1]. The underlying thermodynamic variable, the off diagonal Peltier coefficient α_{xy}, shows excellent scaling properties across the SIT, with critical exponent $\nu \approx 0.7$ and $z \approx 1$, corresponding to the (2+1)D-XY model in the clean limit. This indicates a weakly disordered 2D quantum system dominated by quantum fluctuations.

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Ultra-long-lived quasiparticles in FeSe revealed by broadband microwave spectroscopy

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FeSe, a compound which becomes superconducting below 9 K, is an ideal system for studying Fe-based superconductivity: it has a simple crystal structure, is superconducting at stoichiometric composition, and is available as high-quality single crystals. Here we report measurements of its surface resistance Rs(ω,T) from 0.1 to 20 GHz and from 1.2 to 10 K, performed using a home-built broadband microwave spectrometer. Using a phenomenological model, we have extracted the complex optical conductivity $\sigma(\omega,T)$ of FeSe. At finite temperature and frequency, the real part of the optical conductivity, $\sigma1(\omega,T)$, is determined entirely by the response of quasiparticles which have been thermally excited out of the superconducting ground state. Thus, $\sigma1(\omega,T)$ contains information on both the quasiparticle excitation spectrum and the quasiparticle charge dynamics. We find that $\sigma1$ is strongly peaked below Tc, indicating a rapid collapse in quasiparticle scattering which outpaces the condensation of quasiparticles into the superconducting ground state. Only in Ortho-I $YBa_2Cu_3O_{6.993}$ has such a dramatic reduction in quasiparticle scattering been observed. The low-temperature scattering rate in FeSe is in fact several times smaller than that in $YBa_2Cu_3O_{6.993}$ and is indicative of ultra-long-lived quasiparticles [1].

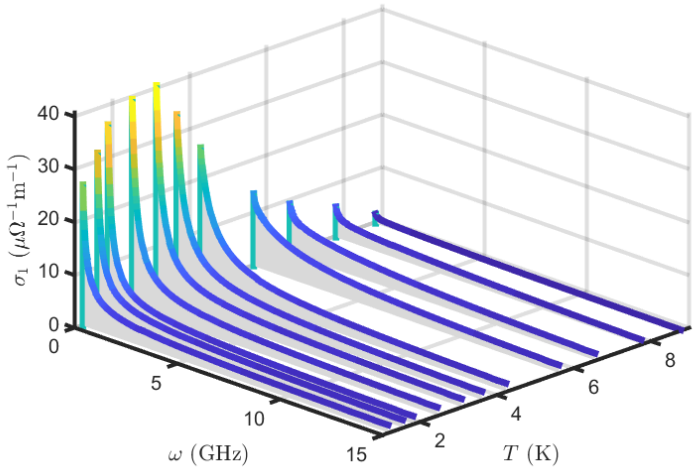

Fig. 1:*Temperature- and frequency-dependent quasiparticle conductivity of FeSe.*

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Coexistence and Competition between Pseudogap and Superconducting Quasiparticles in Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ by Ultrafast Time-resolved Optical Reflectivity

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We report ultrafast time-resolved optical reflectivity investigation of the dynamic densities and relaxations of pseudogap (PG) and superconducting (SC) quasiparticles (QPs) in the underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (T_c = 82 K). We find evidence of two distinct PG components in the positive reflectivity changes in the PG state, characterized by relaxation timescales of τ_{fast} ≈ 0.2 ps and τ_{slow} ≈ 2 ps with abrupt changes in both amplitudes A_{fast} and A_{slow} at T^*. The former presents no obvious change at T_c and coexists with the SC QP. The latter's amplitude starts decreasing at the SC phase fluctuation T_p and vanishes at T_c followed by a negative amplitude signifying the emergence of the SC QP, therefore suggesting a competition with superconductivity. From the temperature dependencies, we obtained the SC gap $\Delta_{SC}(0)$ = 17 ± 1 meV and two PG gaps Δ_{PGfast} = 48 ± 2 and $\Delta_{PGslow}(0)$ = 116 ± 17 meV, consistent with the SC gap nearby the node, the antinodal PG and the high-energy hump feature at the antinode.

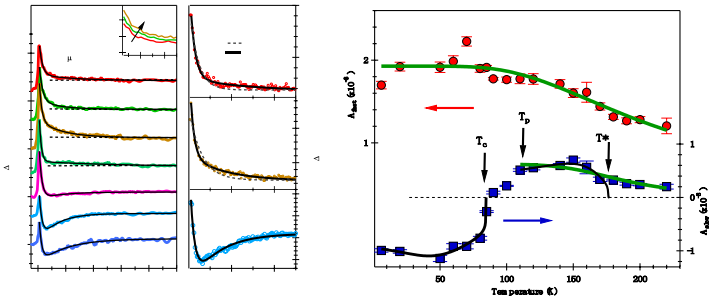

Fig. 1: *Left: (a) Time-resolved reflectivity changes ΔR/R of UD-Bi2212 (T_c = 82 K) measured at 30 μJ/cm² over a range of temperatures. The inset depicts the evolution of the fast decay around T*. (b)-(d) Representative curves of the reflectivity changes (open circles) at temperatures 200, 150 and 50 K, with single-component (dashed lines) and two-component exponential fits (solid lines). Right: Temperature evolution of the amplitudes, with fitting by Rothwarf-Taylor model.*

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Electron-phonon Coupling in Iron-based Superconductors and Its Correlation with T_c

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We report a systematic infrared study of the detailed behavior of the in-plane infrared-active phonon modes (the Fe-As mode at about 253 cm^{-1}) in CaFeAsF, $BaFe_2As_2$, Co-, P- and K-doped $BaFe_2As_2$. In the parent compounds CaFeAsF and $BaFe_2As_2$, we find that this phonon mode develops a strongly asymmetric line shape in the spin-density-wave state and note that this behavior can be explained in terms of a strong coupling with the Dirac fermions. The effect of K-, Co- and P-doping on this phonon mode is further studied. Our studies show that the Co- and P-doping lead to a blue shift of this phonon mode in frequency, which can be simply interpreted by the change of lattice parameters induced by doping. In sharp contrast, an unusual red shift was observed in the K-doped compound, at odds with the above explanation. This anomalous behavior in K-doped $BaFe_2As_2$ is more likely associated with the coupling between lattice vibrations and other channels, such as charge or spin. This coupling scenario is also supported by the asymmetric line shape and intensity growth of the phonon in the K-doped compound.

Electronic and structural instabilities in high-T_c cuprates Hg1201 and Hg1212

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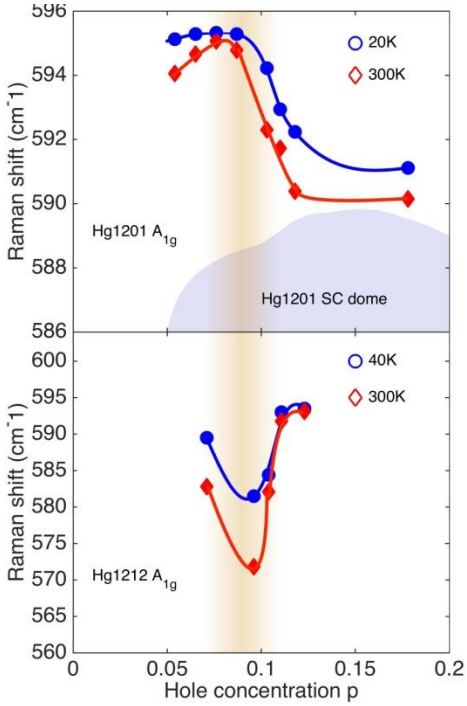
Using resonant X-ray diffraction (RXD) and Raman scattering, we have studied charge-ordering phenomena and lattice dynamics in single-layer $HgBa_2CuO_{4+\delta}$ (Hg1201) and double-layer $HgBa_2CaCu_2O_{6+\delta}$ (Hg1212). Charge correlations have been observed with both techniques in underdoped samples, and an onset-temperature maximum is observed around the same doping (p ~ 0.09) in both materials. Raman scattering further reveals that the frequency of a prominent A_{1g} phonon, which involves apical oxygen movement along the c axis, exhibits an anomaly at the same doping in both systems even up to room temperature (Fig. 1), indicative of a structural instability in the underdoped regime that precedes the charge-ordering phenomena. Our observation points towards a fundamental change, in both the lattice and the electronic structure, in the Hg-family cuprates near p ~ 0.09, which may



be responsible for the dome-shaped charge-ordering phenomena in the phase diagram.

Fig. 1: *The behavior of the energy of A_{1g} phonon near 590 cm^{-1} as a function of doping.*

Reduction annealing effects oncrystal structure of Pr_2CuO_4 studied by multiple structural analysis

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$InNd_2CuO_4$-typeelectron-doped cuprate $RE_{2-x}Ce_xCuO_{4-\delta}$(RE = Pr, Nd, Eu, Sm), both carrier doping by Ce substitution and post-annealing procedure are necessary forthe emergence of superconductivity. By the oxygen reduction annealing,antiferromagnetic order is suppressed and superconducting state appears. Therefore, the role of oxygen reduction is important to be clarified to understand the relation among electronic structure, antiferromagnetic spin correlations and superconductivity.Models of structural variation induced by the annealing wereproposed.Excess oxygen atoms at the apical sites [1] and Cu defects on the CuO_2 plane in the as-grown samplesare removed by the annealing[2], resulting into the reduction of random potential on CuO_2 plane by the chemical disorders. However, the real number of occupancy at each oxygen sites in as-grown and annealed samples isstill controversial, since the parameter for occupancyis highly sensitive to models as well as the quality of experimental data.

To investigate the reduction annealing effects on the crystal structure, we performed neutron powder diffraction and x-ray absorption fine structure measurements (XAFS) on as-sintered and annealed $Pr_2CuO_{4-\delta}$.An average crystal structurewas determined by Rietveld analysisofneutron diffraction pattern, anda local structure was also evaluated by pair distribution function (PDF)analysis on neutron diffractiondata and extended x-ray absorption fine structure (EXAFS) analysis.Results of Rietveld analysis showed that both a- and c-axis lattice constantsare larger in the annealed sample, indicating structural modifications by the annealing. However, there were nosignificant differencein the structural parameters regarding oxygen between the as-sintered and the annealed $Pr_2CuO_{4-\delta}$.(The R-factor is less than 2%, meaning that the structural parameters are accurately determined.) Similarly, we found no/negligible effects of annealing on the local structure. Since the evaluation of clear differencein the structural parameters was difficult within the experimental accuracy, we simulated the atomic-selective diffraction patterns with varying the occupancy of apical oxygen and in-plane oxygen.The results of simulation demonstrated thatthe intensity of particular Bragg peaks showed observable difference between the as-sintered and the annealed samples, and thenegligible change of the diffraction pattern by the annealing could not be reproduced by a simple model. These results of structural analysissuggestthat the variation of average and local structure of $Pr_2CuO_{4-\delta}$caused by the annealing is more complicated than the previous proposed models.

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Spin excitation of quasi-1D superconductor $BaFe_2S_3$

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Understanding the physical origin of the magnetism in iron-based superconductors is the very first step to reveal the mechanism of high temperature superconductivity, which is induced by chemical doping into the parent compounds with long-ranged antiferromagnetic (AF) order [1]. Since the static moment in iron pnictides forms a collinear or bi-collinear square spin lattice (stripe-type) on iron sites, it is proposed that the magnetism is possibly from pure local moment similar to cuprates. However, the elementary magnetic excitations give strong evidences of itinerant magnetism from Fermi surfaces nesting, while both low-energy spin excitations from itinerant electrons and high-energy fluctuations are essentially coupled with each other to drive the superconductivity [2].

Recently, a new series of iron-based compounds $BaFe_2S_3$ is identified to be a one-dimensional (1D) structure with spin ladders on iron site (space group Cmcm) [4]. the magnetic order with T_N =119 K of $BaFe_2S_3$ can be treated as 1D analogue to the stripe type magnetism in iron pnictides (Fig 1)[1]. Moreover, $BaFe_2S_3$ is surprisingly found to be a superconductor with Tc=14 K under high pressure around 11 GPa [5], forming a similar phase diagram to iron pnictide superconductors and cuprate spin ladder system (Fig 1)[2,3,6].

We have perform a spin excitation measurement on $BaFe_2S_3$. The clear dispersion along c-axis has been mapped out. The temperature dependence shows a critical-like behaviour. All the evidence shows a three dimensional behaviour.

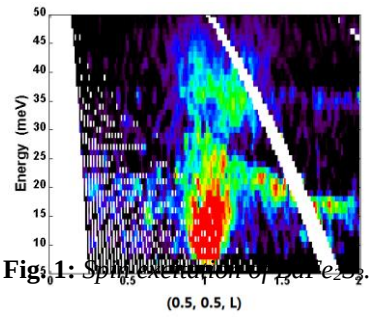

Fig. 1: *Spin excitation of $BaFe_2S_3$.*

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Unconventional Antiferromagnetic Quantum Critical Point in an Iron Pnictide

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Superconductivity in iron-based superconductors is closely adjacent to the antiferromagnetic and nematic orders and their disappearances may result in quantum critical points. However, these quantum transitions are always overshadowed by superconductivity, which makes them hard to study in detail. Here we show that just 3% of Cr substitution of Fe can fully suppress superconductivity in BaFe2(As1-xPx)2 and reveal a quantum phase transition at x ~ 0.42, where non-Fermi-liquid behaviors, such as linear temperature dependence of resistivity, enhancement of effective mass of electrons and the unconventional ω/T scaling of spin excitations, are observed. While both the antiferromagnetic and nematic orders disappear at this doping, only magnetic quantum critical point is observed. Our results reveal a magnetic quantum critical point in BaFe2(As1-xPx)2 system and suggest that non-Fermi-liquid behaviors in iron-based superconductors can be solely resulted from the antiferromagnetic quantum critical fluctuations.

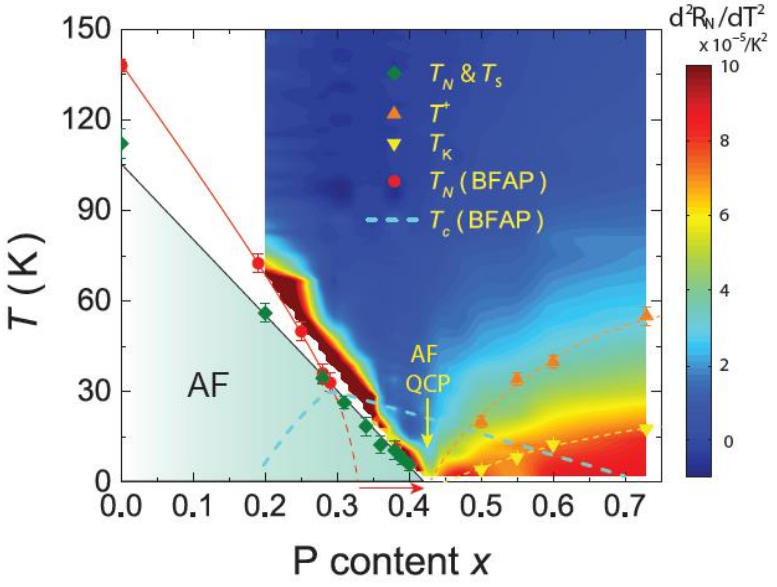

Fig. 1: *Phase diagram of $Ba(Fe_{0.97}Cr_{0.03})_2(As_{1-x}P_x)_2$ [1].*

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Neutron Spin Resonance in the 112-Type Iron-Based Superconductor

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We use inelastic neutron scattering to study the low-energy spin excitations of the 112-type iron pnictide $Ca_{0.82}La_{0.18}Fe_{0.96}Ni_{0.04}As_2$ with bulk superconductivity below T_c = 22 K. A two-dimensional spin resonance mode is found around E_R = 11 meV, where the resonance energy is almost temperature independent and linearly scales with T_c along with other iron-based superconductors. Polarized neutron analysis reveals the resonance is nearly isotropic in spin space without any L modulations. Because of the unique monoclinic structure with additional zigzag arsenic chains, the As 4p orbitals contribute to a threedimensional hole pocket around the Γ point and an extra electron pocket at the X point. Our results suggest that the energy and momentum distribution of the spin resonance does not directly respond to the k_z dependence of the fermiology, and the spin resonance intrinsically is a spin-1 mode from singlet-triplet excitations of the Cooper pairs in the case of weak spin-orbital coupling.

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Structure of spin excitations in heavily electron-doped $Li_{0.8}Fe_{0.2}ODFeSe$

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Heavily electron-doped iron-selenide high-transition-temperature (high-Tc) superconductors, which have no hole Fermi pockets, but have a notably high Tc, have challenged the prevailing s± pairing scenario originally proposed for iron pnictides containing both electron and hole pockets. The microscopic mechanism underlying the enhanced superconductivity in heavily electron-doped iron-selenide remains unclear. Here, we report neutron scattering measurements of the spin excitations in single-crystalline Li0.8Fe0.2ODFeSe. The momentum structure of the spin excitations is energy-dependent and shows a twisted dispersion. We will discuss the structure of spin excitation and its relationship with superconductivity in these materials.

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Direct evidence of hidden local spin polarization in novel superconductor $LaO_{0.55}F_{0.45}BiS_2$

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Conventional Rashba spin polarization is caused by the combination of strong spin-orbit interaction (SOI) and spatial inversion asymmetry. However,Rashba- and Dresselhaus-type spin split states are predicted in $LaOBiS_2$ system by recent theory even though the total crystal structure is centrosymmetric, stemming from local inversion asymmetry of each active BiS_2sublayer [1] of the system. By performing high-resolution Spin-ARPES measurement at ESPRESSO endstation of Hiroshima Synchrotron Radiation Center (HiSOR), our studies present direct spectroscopic evidence for the local spin polarization in the vicinity of X point of both valence band and conduction band. Especially the transition from Rashba-like to Dresselhaus-like spin texture has been observed in the conduction band for the first time.

As shown in Fig. 1(a), the conduction bandsplitsinto innerand outer branches along $k_x$direction. Fig. 1(b) shows unambiguously spin polarized states at "1" to "4" momenta and spin polarizations at positions "1" and "2" are opposite to those of positions "3" and "4" in the spin-resolved EDCs spectra such that the spin reversal can be observed on opposite sides of "X" pointas a time-reversal invariant momenta-(TRIM).Similarly,we also performed spin-ARPES measurement along k_y direction and observed spin reversal at two sides of "X" momenta again(not shown here). In addition, the spin-ARPES results of highest valence band (HVB) also shows local spin polarization (not shown here)so that Dresselhaus-like spin texture of LCB and Rashba-like counter-helicalspin texture ofHVB are established.Our studies present direct evidence for the existence of local Rashba and Dresselhaus spin polarizationsaroundTRIM X point innovel BiS_2 based superconductor. The demonstration not only expands the range of spintronic materials but also serves as a new platform for research of superconductivitycaused by spin-split conduction band[2].

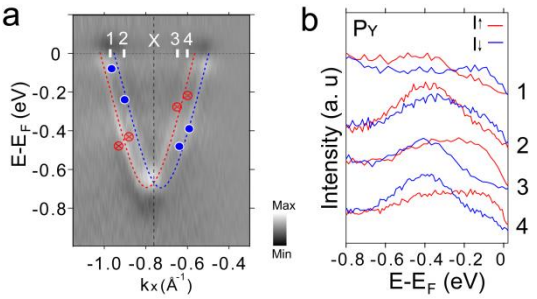

Fig. 1 (a) Conduction band dispersion around X point (second derivative). "1" to "4" represent the momenta where we performed spin-ARPES measurement. (b) Spin-resolved EDCsat "1" to "4"momenta.

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Magnetic Quantum Critical Points Free From Phase Interference in Fe1-xCoxAs and Fe1-xCoxP

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Tracing crystal-field splittings in the heavy-fermion superconductor $CeIrIn_5$

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Crystal electric field states in rare earth intermetallics show an intricate entanglement with the
many-body physics that occurs in these systems and that is known to lead to a plethora of electronic phases. Here, we attempt to trace different contributions to the crystal electric field (CEF) splittings in $CeIrIn_5$, a heavy-fermion superconductor and member of the $CeMIn_5$ (M= Co, Rh, Ir) family. To this end, we utilize high-resolution resonant angle-resolved photoemission spectroscopy (ARPES) and present a spectroscopic study of the electronic structure of this unconventional superconductor over a wide temperature range. As a result, we show how ARPES can be used in combination with thermodynamic measurements or neutron scattering to disentangle different contributions to the CEF splitting in rare earth intermetallics. We also find that the hybridization is stronger in $CeIrIn_5$ than $CeCoIn_5$ and the effects of the hybridization on the Fermi volume increase is much smaller than predicted. By providing the first experimental evidence for $4f^1_{7/2}$ splittings which, in $CeIrIn_5$, split the octet into four doublets, we clearly demonstrate the many-body origin of the so-called $4f^1_{7/2}$ state.

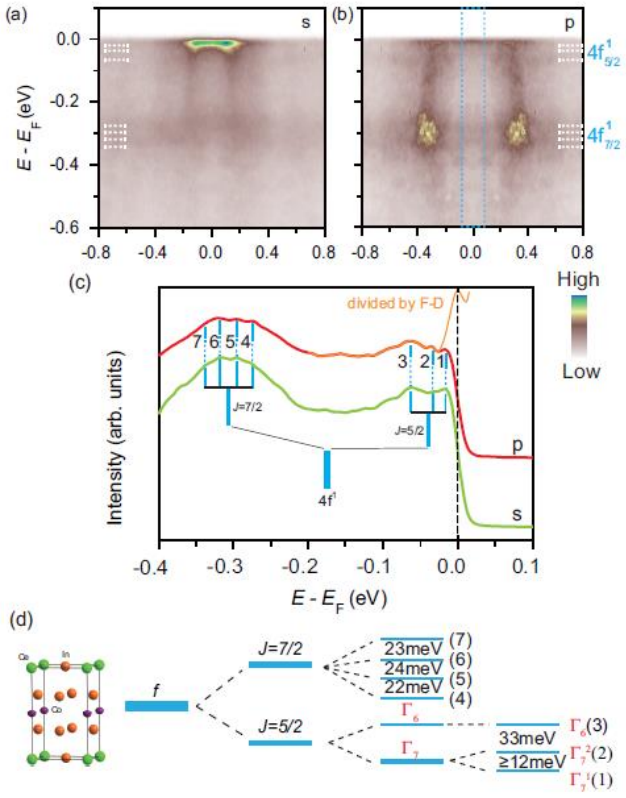

Fig. 1: *Crystal field splittings in $CeIrIn_5$.*

Topological Insulator and Dirac Semimetal States in Iron-based Superconductors

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Topological insulators/semimetals and unconventional iron-based superconductors have attracted major recent attentions in condensed matter physics. However, there is little overlap between these two fields, although the combination of topological bands and superconducting states will produce more exotic topologically superconducting states and Majorana bound states (MBSs), a promising candidate for topological quantum computations. With the progress in laser-based spin-resolved and angle-resolved photoemission spectroscopy (ARPES) with very high energy- and momentum-resolution, we resolved the topological insulator (TI) bands and topological Dirac semimetal (TDS) bands near Fermi level (E_F) in the iron-based superconductors Li(Fe,Co)As and Fe(Te,Se). The TI and TDS bands can be separately tuned to E_F by carrier doping, allowing a detailed study of different superconducting topological states in the same material. Our results show the generic coexistence of superconductivity and multiple topological states in iron-based superconductors, and provide a potential platform for the study of multiple topological superconductivity.

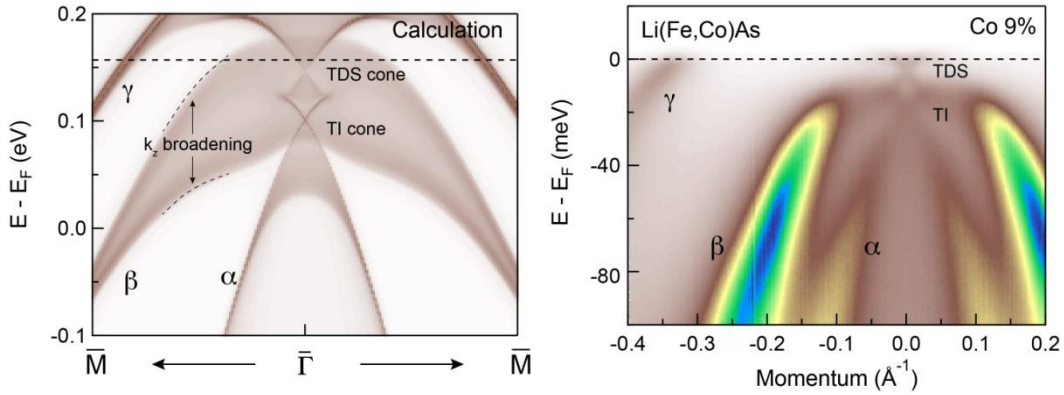

Fig. 1: *Left: calculated surface spectrum of LiFeAs. Right: ARPES intensity plot of Li(Fe,Co)As.*

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Scaling of the Superconducting Gap with Orbital Character in FeSe

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We used synchrotron-based high-resolution angle-resolved photoemission spectroscopy (ARPES) to map the three-dimensional momentum dependence of the superconducting gap in FeSe. We found that on both the hole and electron Fermi surfaces, the magnitude of the gap follows the distribution of d_{yz} orbital weight. Furthermore, we theoretically determined the momentum dependence of the superconducting gap by solving the linearized gap equation using a tight binding model that quantitatively describes both the experimental band dispersions and orbital characters. By considering a Fermi surface only including one electron pocket, as observed spectroscopically [1, 2], we obtained excellent agreement with the experimentally determined gap structure. Our finding of a scaling between the superconducting gap and the d_{yz} orbital weight supports the interpretation of superconductivity mediated by spin-fluctuations in FeSe [3].

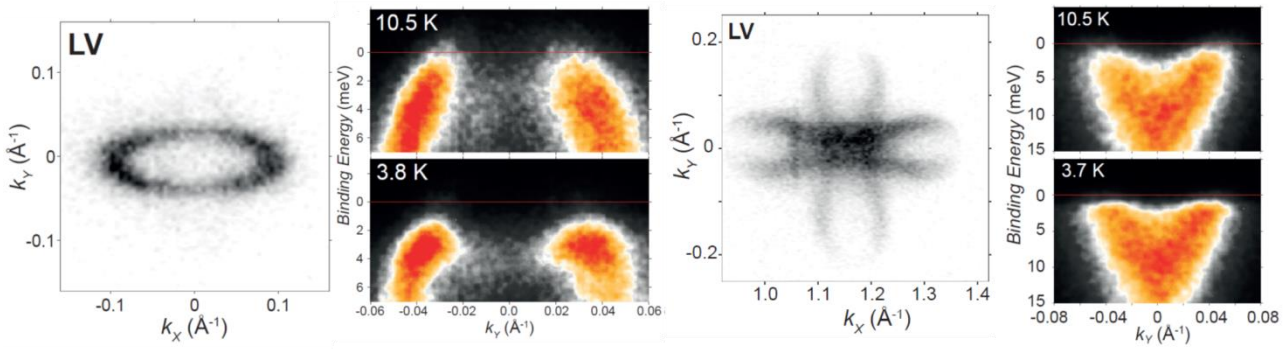

Fig. 1: *Fermi surface maps and high-symmetry dispersions above and below T_c of twinned FeSe samples for the hole pocket (left) and electron pocket (right). ARPES spectra measured in linear vertical polarization with photon energies of 37eV for -point and 28eV for A-point correspondently.*

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Infrared Probe of the Gap Evolution across the Phase Diagram of $Ba_{1-x}K_xFe_2As_2$

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We present an optical study of $Ba_{1-x}K_xFe_2As_2$ single crystals with *x* ranging from 0.2 (underdoped) to 0.4 (optimally doped) [1]. In the superconducting state, the opening of the superconducting gaps can be clearly observed in all compounds, as evidenced by a sharp upturn in the reflectivity [Fig.1(a)-1(d)] and a strong suppression of the optical conductivity [Fig.1(e)-1(h)] in the low-frequency range. For K40 (optimally doped), the flat unity response of the reflectivity [Fig.1(d)] and the vanishingly small optical conductivity [Fig.1(h)] below the gap energy (~160 cm^{-1}) suggest s-wave gaps, i.e. the absence of unpaired quasiparticles in the superconducting gap. However, with decreasing K concentration, the flat unity response in the reflectivity disappears and unpaired quasipartiles emerge in the optical conductivity spectra, indicating the presence of in-gap states. These observations point to a change of the paring symmetry with decreasing K content, which is likely to originate from strong interplay between magnetism and superconductivity in underdoped $Ba_{1-x}K_xFe_2As_2$.

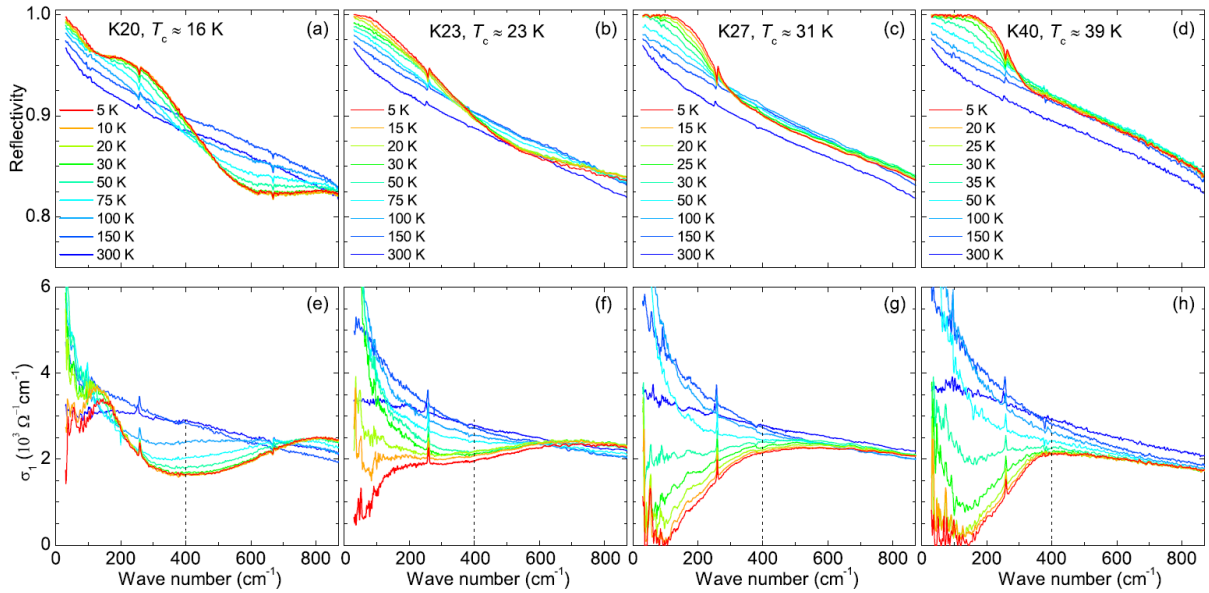

Fig. 1: *Far-infrared reflectivity (a)-(d) and optical conductivity (e)-(h) of $Ba_{1-x}K_xFe_2As_2$ with x = 0.2 (K20), 0.23 (K23), 0.27 (K27) and 0.4 (K40).*

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Photoexcitation-induced New Metastable State with Modulated Josephson

Coupling Strengths in Electron-doped Cuprate $Pr_{0.88}LaCe_{0.12}CuO_4$

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The photoexcitation-induced change of c-axis dynamics in terahertz (THz) range has been a hot topic in the field of high-T_c superconducting cuprates. To the best of our knowledge, all the reported research was entirely devoted to the hole-doped systems up to now. Here, we report near-infrared pump c-axis THz probe measurement on an electron-doped cuprate superconductor $Pr_{0.88}LaCe_{0.12}CuO_4$ with T_c =22 K. The major effect of the intense pump is to induce a splitting of Josephson plasma edge in reflectivity along c-axis below T_c, which seems long-lived and does not exhibit observable decay up to the longest measured time delay 210 ps. As increasing the pump fluence, the splitting effect gets more significant. The measurement reveals that intense near-infrared pump turns to drive the system from an equilibrium superconducting state with uniform Josephson coupling strength to a new metastable superconducting phase with modulated Josephson coupling strengths, rather than destroying superconductivity or exciting quasiparticles to unoccupied states far above the Fermi level.

Using Vortices to Probes the Unconventional Superconductivity in UPt_3

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With three different superconducting mixed (vortex) phases the heavy-fermion material UPt_3 can be considered a paradigm for unconventional superconductivity. Despite more than three decades of study, a definitive understanding of the superconducting state in this material has remained elusive. The order parameter structure that is consistent with a number of experiments is an odd-parity, *f*-wave orbital state of E_{2u} symmetry. Here the order parameter is chiral and breaks time reversal symmetry in the low-temperature superconducting B-phase.

We have performed small-angle neutron scattering (SANS) studies of the vortex lattice (VL) in UPt_3 in the B- and C-phases with $\boldsymbol{H} \parallel \boldsymbol{c}$. This led to the discovery of a previously unknown non-monotonic VL rotation in the B-phase with increasing field. The VL rotation most likely arises from a competition between multi-band Fermi surface effects and core effects that become increasingly important as the vortex density increases. Furthermore, the magnitude of the VL rotation show a subtle magnetic field history dependence; VLs prepared with the field parallel or anti-parallel with respect to initial direction with which one enters the B-phase are rotated by different amounts. This directly demonstrate an internal degree of freedom, associated with the relative orientations of the internal orbital angular momentum of the Cooper pairs and the global phase winding set by the applied magnetic field. We interpret this as a manifestation of the chiral B phase, leading to different vortex core structures for the two field histories. Furthermore, a spontaneous disordering of the VL with a characteristic time scale of tens of minutes is observed in the B phase. This may be due to the presence of chiral currents.

This work was supported by the US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Awards DE-SC0005051 (University of Notre Dame; neutron scattering) and DE-FG02-05ER46248 (Northwestern University; crystal growth and characterization). A portion of this research used resources at the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. Part of this work is based on experiments performed at the Institut Laue-Langevin, and at the Swiss spallation neutron source SINQ. We are grateful to L. DeBeer-Schmitt, C.D. Dewhurst, J. Gavilano, G. Nagy and U. Gasser for assistance with the SANS experiments.

Existence of the superconductivity cooperative hidden phase with orbital polarization in $Sr_{0.64}Na_{0.36}Fe_2As_2$ superconductor

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In a particular range of the underdoped $Sr_{1-x}Na_xFe_2As_2$ (SNFA), a fully restored C_4 lattice rotational symmetry from the higher temperature o-AFM phase is found to be persisted into the superconducting phase [1]. Despite the magnetic structure undergoes a spin-flop transition forming a double-**Q** nested SDW phase which significant depletes the low energy density of states at the Fermi surface [2], this seemingly strong competition does not entirely destruct the superconducting order and the T_c maintains roughly around 12 K throughout the C_4 region. The superconducting pairing mechanism in iron-based superconductors (FeSC) has been strongly argued that the electronic nematic instability plays an essential role [3], although spin or orbital fluctuation is more responsible for such instability still to be justified. Very recently, temporal dependent experimental techniques showing the C_4 symmetry is found broken dynamically in varies of FeSCs [4-6] hence strongly support for the existence of nematicity fluctuations. It is thus initiated the question that whether the C_4 phase of SNFA could be unified in this picture.

Initially, we are inspired by the evidence of the strong nematic susceptibility in the C_4 phase which is provided by the resistivity anisotropy. Under a moderate uniaxial strain, a clear diverging of the resistance along two orthogonal directions appears slightly above the T_c in the C_4 phase. To further explore this anisotropic phenomena, we applied the ultrafast pump-probe polarimetry on an unstrained single crystal with the probing energy at 1.55 eV. As an optical probe, this technique uniquely allows us to reveal the information about orbital anisotropy with a transient melted magnetic order background within 1 ps [7]. Furthermore, by driving the system into an excitation state permits to access the electronic landscape which is different from the thermal equilibrium state [8]. Hence possible to reveal the adjacent phases close to the ground state. Within 1 ps scale, our data is clearly showing a remnant optical anisotropy signal in the C_4 phase. We also proved this remnant signal is not a residual strain induced effect from the o-AFM phase. Importantly, we found the cooperating behavior of the anisotropy signal with the onset of the superconducting transition. In the longer time scale, the optical anisotropy persists but with a smaller magnitude, which is appearing like a pump triggered restoration of a C_2 phase with a different origin than the o-AFM one. This is suggesting the C_4 phase ground state is in a close proximity to a novel C_2 phase, which is hidden at the low temperatures.

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Revealing pseudogap in $Sr3(Ru_{0.985}Fe_{0.015})_2O_7$ by optical spectroscopy study

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High energy spin fluctuation on iron-based superconductor $LaFePO_{0.9}$

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Spin fluctuation is regarded to be key factor for the mechanism of unconventional superconductors such as high temperature superconductors. It has been observed in many iron-based superconductors so far. We had performed systematic study on powder samples of LaFeAs(O,F). According to the results, spin fluctuation was observed at Q~1.2 $Å^{-1}$ corresponding to -*M* point Fermi Surface (FS) nesting vector on superconducting sample of LaFeAsO1-*x*F*x* (*x*=5.7, 8.2%) with same extent of parent $LaFeASO_{1.0}$ [1]. On the other hand, spin fluctuation was not clearly observed on electron-overdped sample (*x* = 15.8%, T_c ~ 7 K) whose T_c is highly suppressed [2]. These results indicate correlation of superconducivity and spin fluctuation originating from -*M* point Fermi Surface (FS) nesting.

LaFePO1-y is the 1st iron-based superconductor, whose characteristics are low T_c (~ 5 K) and the existence of line nodes in the superconducting gap function. The line-node symmetry is originated from sign reversal of the order parameter, which reminds us of magnetism-madiated superconductivity, but the spin fluctuation was not observed clearly on $LaFePO_{1-y}$ [3].

Here we report the observation of spin fluctuation at higher energy ($E \geqq 30$ meV) on $LaFePO_{0.9}$. Inelastic neutron scattering measurements were performed on powder samples of $LaFePO_{0.9}$ ($T_c \sim$ 5 K), and $LaFeAsO_{0.918}F_{0.082}$ (T_c=29 K) as reference material by using Fermi chopper spectrometer at 4SEASONS (BL01) in J-PARC MLF.

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Neutron Diffraction Study on Magnetic Structures and Transitions in $Sr_2Cr_3As_2O_2$

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$Sr_2Cr_3As_2O_2$ is composed of alternating square-lattice CrO_2 and Cr_2As_2 stacking layers, where CrO_2 is isostructural to the CuO_2 building-block of cuprate high-T_C superconductors and Cr_2As_2 to Fe_2As_2 of Fe-based superconductors [1]. Current interest in this type of materials [2] and chromium pnictides [3,4] is raised by theoretic prediction of possible superconductivity. In this neutron powder diffraction study, we discovered that magnetic moments of Cr(II) ions in the Cr_2As_2 sublattice develop a C-type antiferromagnetic structure below 590 K, and the moments of Cr(I) in the CrO_2 sublattice form the La_2CuO_4-like antiferromagnetic order below 291 K. The staggered magnetic moment 2.19(4) μB/Cr(II) in the more itinerant Cr_2As_2 layer is smaller than 3.10(6) μB/Cr(I) in the more localized CrO_2 layer. Different from previous expectation, a spin-flop transition of the Cr(II) magnetic order observed at 291 K indicates a strong coupling between the CrO_2 and Cr_2As_2 magnetic subsystems.

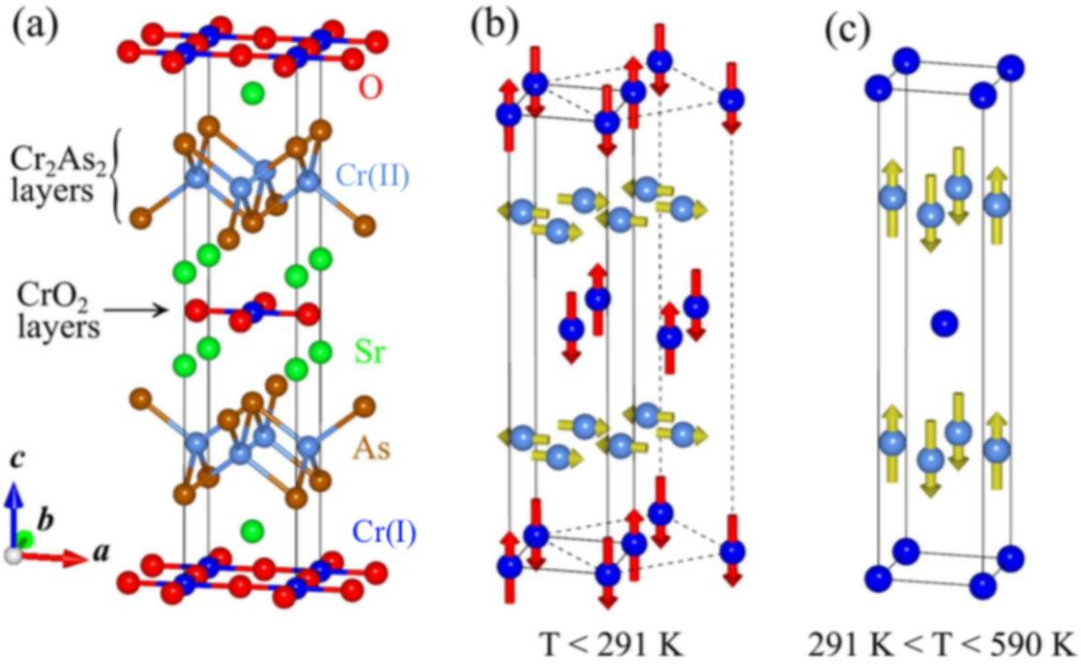

Fig. 1: (a) Crystal structure of $Sr_2Cr_3As_2O_2$. (b) The magnetic structure below 291 K when both CrO_2 layer and Cr_2As_2 layer order. (c) The magnetic structure above 291 K when only the Cr_2As_2 layer orders. The solid lines in (b) and (c) are the structural unit cell identical to the cell in (a), and the dash lines in (b) are the magnetic unit cell.

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Phase Diagram of the Newly Discovered Superconductors $TlNi_{2-x}Co_xSe_2$ Investigated by Neutron Diffraction

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There have been intense studies in Ni-based chalcogenides since the discovery of superconductivity in $TlNi_2Se_2$ [1]. The phase diagram of newly discovered superconductors $TlNi_{2-x}Co_xSe_2$ was investigated by single-crystal neutron diffraction here. Superconducting phase, commensurate magnetic phase and incommensurate magnetic phase were confirmed in the entire composition range of $0 \le x \le 2$. The evolution of these three phases was revealed by neutron diffraction results on magnetic moment $\langle M \rangle$ and Néel temperature T_N, as shown in Fig. 1. Superconductivity is gradually suppressed with Co substitution of Ni. By increasing Co content, the AFM coupling in $TlNi_{2-x}Co_xSe_2$ is enhanced initially, and comes to a maximum value for the sample around x = 1.4. The AFM coupling is weaken with further substitution of Ni by Co atoms, and $TlNi_{2-x}Co_xSe_2$ finally form an incommensurate helix for x approaching 2 which is rather rare in Co-based compounds. In the incommensurate phase, the propagation vector was found to change with temperature.

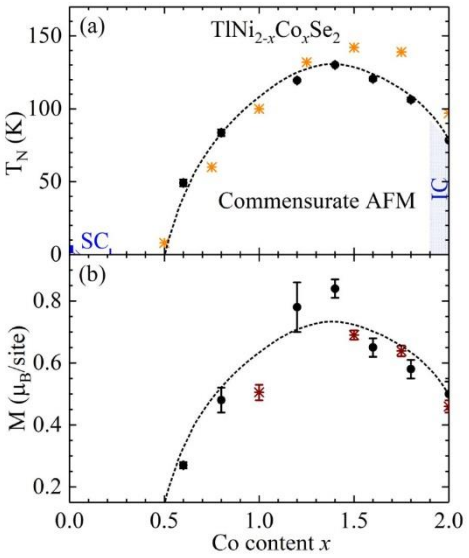

Fig. 1: (a) *The phase diagram of $TlNi_{2-x}Co_xSe_2$. (b) The refined magnetic moment of each sample in the unit of Borh magneton per transition metal ion site as a function of Co content x with $0.6 \le x \le 2.0$.*

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Avoided Quantum criticality and Spin glass in V-doped $BaFe_2As_2$

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We report an investigation of the structural, magnetic and electronic properties of $Ba(Fe_{1-x}V_x)_2As_2$ using x-ray, transport, magnetic susceptibility and neutron scattering measurements. The Vanadium substitutions in Fe sites are possible up to 40%. Hall effect measurements indicate strong hole-doping effect through V doping, while no superconductivity is observed in all samples down to 2K. The antiferromagnetic (AFM) and structural transition temperature of $BaFe_2As_2$ is gradually suppressed to finite temperature then vanishes at x=0.245 with the emergence of spin glass behavior, suggesting the avoidance of quantum critical point (QCP). Our results demonstrate that the avoided QCP and spin glass state which were previously reported in the superconducting phase of Co/Ni doped $BaFe_2As_2$ can also be realized in magnetic impurity doped non-superconducting $Ba(Fe_{1-x}V_x)_2As_2$

On the other hand, we would also like to report our recent results on the recovering of long range AFM order with large ordered moment in V-doped $Ba(Fe_{0.92}Co_{0.08})_2As_2$.

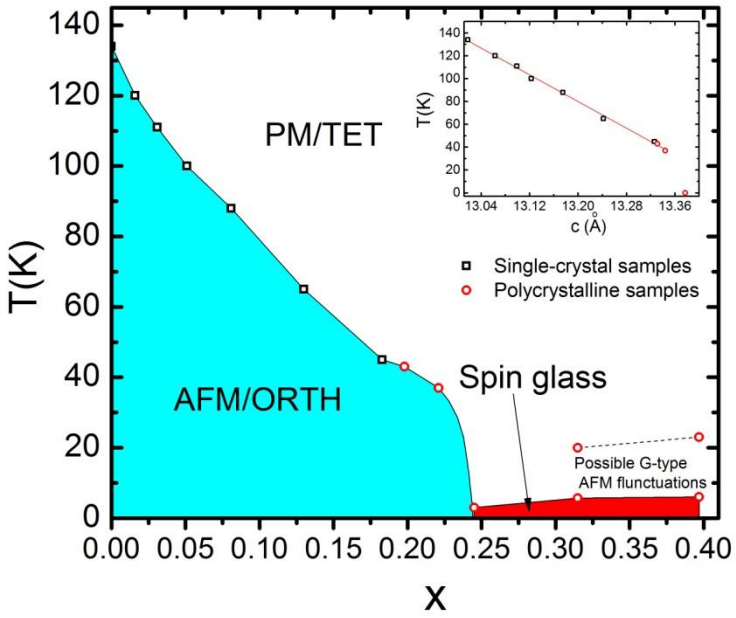

Fig. 1: *Phase diagram of $Ba(Fe_{1-x}V_x)_2As_2$*

AnApproach from SR to Pseudogap Statesin Underdoped $La_{2-x}Sr_xCuO_4$

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The origin of the so-called pseudo-gap state suggested to appear in Cu-based high-T_C superconductorsis still an open question. Muon spin relaxation (μSR) technique was employed to examine the pseudo-gap state. μSR is a sensitive tool to detect small changes in theinternal magnetic fields whichallows thestudy on the pseudo-gapstate from the view point of magnetic properties. In our previous μSR study on the underdoped $La_{2-x}Sr_xCuO_4$ (LSCO), tiny changes in the zero-field (ZF) μSR time spectrum from the Gaussian shape were confirmed even in the higher temperature region from around 100 K [1].The origin of the changes in ZF-μSR time spectra could be due to the appearance of small internal magnetic fields which are different from those that originate from the surrounding nuclearspinsand could be discussed in relation to the pseudo-gap state [2-4]. We are developing analysis functions in order to deduce detailed information from those small changes in ZF-μSR time spectra and to discuss their magnetic properties. Those analysis functionsrepresent intermediate distributions between Gaussian andLorentzian [5,6].Both distribusions relate to magnetic properties. We will examine μSR databy using those analysis functions and discuss the possible magnetic origins.

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Distinct Parent Phase and Doping Evolution to Superconductivity in Single-Layer FeSe/$SrTiO_3$ Films

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The single-layer FeSe/$SrTiO_3$ films have attracted much attention because of its simple crystal structure, distinct electronic structure and record high superconducting transition temperature (T_C). The origin of the dramatic T_C enhancement in single-layer FeSe/$SrTiO_3$ films and the dichotomy of superconductivity between single-layer and multiple-layer FeSe/$SrTiO_3$ film are still unclear. Here we report a comprehensive high resolution angle-resolved photoemission spectroscopy measurements on the electronic structure evolution with doping in single-layer and multiple-layer FeSe/$SrTiO_3$ films. We find that the single-layer FeSe/$SrTiO_3$ films have a unique parent phase and a route of doping evolution to superconductivity that are distinct from multiple-layer FeSe/$SrTiO_3$ films. In multiple-layer FeSe/$SrTiO_3$ films, superconductivity occurs by suppressing the nematic order in the parent compound with electron doping. In the single-layer FeSe/$SrTiO_3$ films, the parent phase is a Mott-like insulator without a nematic order; its doping evolution is similar to doping a Mott insulator. These observations indicate that there is a strong electron correlation in the single-layer FeSe/$SrTiO_3$ films and the doping evolution is distinct from that of all the other iron-based superconductors. Our results provide key insight in understanding the high temperature superconductivity in single-layer FeSe/$SrTiO_3$ films.

Formation of Coherent Superconducting State from Incoherent Normal State in Optimally-Doped $Ba_{0.6}K_{0.4}Fe_2As_2$ Superconductor

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In conventional superconductors, the normal state is a Fermi liquid with well-defined Fermi surface and well-defined quasiparticles. Superconductivity is realized by Fermi surface instability and pairing of quasiparticles [1]. In high temperature cuprate superconductors, superconductivity can be realized in underdoped region where there is no well-defined Fermi surface and quasiparticles [2,3]. It is important to investigate whether and how superconductivity can be realized in a system with well-defined Fermi surface but without well-defined quasiparticles. Here we report that $Ba_{0.6}K_{0.4}Fe_2As_2$ superconductor is such a system with sharp Fermi surfaces but without quasiparticles in the normal state. Our high resolution angle-resolved photoemission measurements provide direct evidence on the absence of normal state quasiparticles along the Fermi surface and other non-Fermi liquid behaviors, although sharp coherent peak is observed in superconducting state. The superconducting gap exhibits an unusual temperature dependence: it is nearly a constant in the entire superconducting state. These observations provide a new platform and key insights to study superconductivity in a non-Fermi liquid system.

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ARPES investigation of electronic structure of Ce-based heavy fermion $CePt_2In_7$

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Electronic structure of low dimensional Ce-based heavy fermion compound $CePt_2In_7$ has been investigated by high resolution angle-resolved photoemission spectroscopy (ARPES), utilizing tunable photon energies with sufficient energy and momentum resolution. In this talk, we will show the Ce 4f electrons of $CePt_2In_7$. The crucials 3D *k*-space nature of electronic structure and strong scattering also will be discussed. Our experimental and calculated electronic structure show a good agreement. Support for this work was provided by National Natural Science Foundation of China (51502351, 11574402), and the Project of Innovation driven Plan in Central South University (2016CXS032).

Spin-Orbit Coupling in Iron-Based Superconductors via Spin-ARPES

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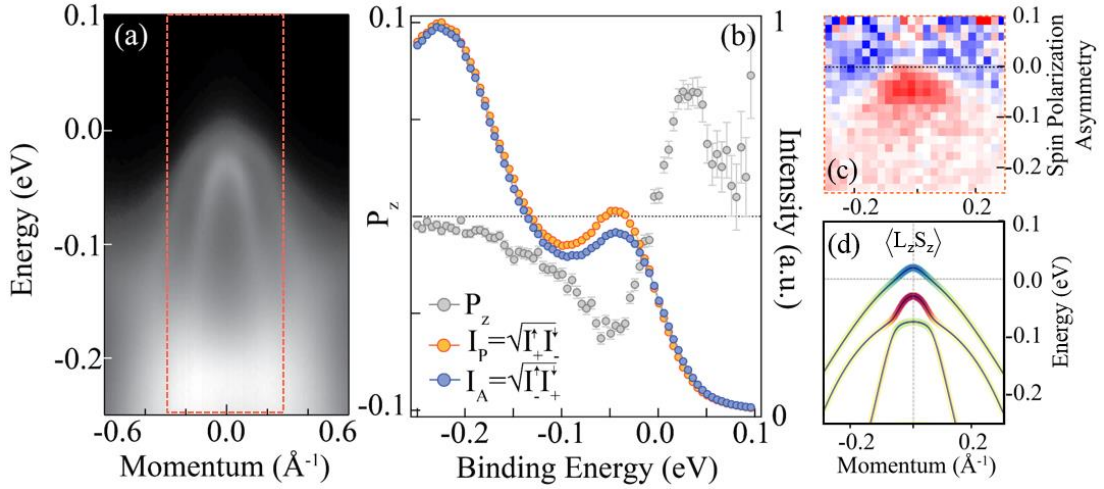
Experimental and theoretical evidence has mounted for the important role spin-orbit coupling (SOC) may play in modifying the low energy electronic structure of various unconventional superconductors and the implications this interaction bears for Cooper pairing[1,2,3]. The iron-based superconductors (FeSCs) are among these materials: a high density of Fe 3d states converging in energy and momentum near the Fermi level renders the FeSCs highly susceptible to perturbations such as nematicity and SOC.

To explore the influence of SOC on the electronic structure, we have employed Circularly Polarized Spin and Angle-Resolved Photoemission Spectroscopy (CPS-ARPES) to study LiFeAs and FeSe—canonical members of both the iron pnictide and chalcogenide families[5]. By combining the orbital selectivity of circularly polarized light with a spin-filtering VLEED detector, CPS-ARPES resolves orbital and spin vectors with the full momentum and energy resolution of conventional ARPES. As illustrated in the Figure, we establish a momentum-dependent entanglement of the spin and orbital degrees of freedom on the hole pockets at the Brillouin zone centre, raising questions about the influence of SOC on the putatively spin-fluctuation based pairing mechanism in the FeSCs[2,4].



CPS-ARPES on FeSe: (a) ARPES near Γ point. (b) Spin polarization asymmetry (P_z) with experimental CPS-EDCs near Γ. (c) P_z over dashed region from (a). (d) Tight-binding model with colourscale indicating $\langle L_zS_z \rangle$ which connects directly to experimental results in (c).

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Quantum metallic state in 2D superconductor with intrinsic electronic phase inhomogeneity

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The superconductor to insulator(SI) transition has been intensively studied in thin film superconductors by tuning the thickness, disorder or external magnetic field for decades1, 2. The observation of an intermediate metallic state in two dimensional (2D) films3-5 invokes interest in the nature of this exotic ground state. Most of the dissipation mechanisms were attributed to weak disorder, or quantum fluctuation in a single ordered phase. However, SI transition in a 2D superconductor with mixed quantum ordered phases was rarely investigated. Here, we report the observation of anomalous metallic state in the magnetic field driven SI transition in ion-gel gated 1T-TiSe26, in which superconductivity and charge density wave (CDW) order coexist. We establish a 3D phase diagram in terms of three tuning parameters: magnetic field, temperature and carrier density. Unambiguously, we show that the field-dependent evolution of such quantum metallic state should be described by Bose metal and vortex quantum creeping model rather than the previously reported single model. We conjecture that the complex field dependence of resistivity is due to the evolution of 2D topology of the superconductivity-CDW superlattice. One key feature is the significant lower HC2 value compared to that of other crystalline quantum metallic systems. Our finding demonstrates that 2D quantum fluctuation and the inherent electronic phase inhomogeneity in our system facilitate the emergence of exotic quantum states, such as spatial inhomogeneous SC, narrow anomalous metallic state. Our research may be illuminating to the investigation of systems like High-Tc cuprates, which also have mixed electronic phases.

Orbital Order and Spin Nematicity in FeSe

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In FeSe superconductor, lattice rotational symmetry is spontaneously broken in a 'nematic' phase below T_{nem} ~ 90 K. Due to the absence of magnetic ordering, the origin of the nematic phase is under strong debate. Here, combining measurement on the splitting of ^{57}Fe and ^{77}Se NMR spectra in ^{57}Fe enriched FeSe single crystal below T_{nem}, we confirm a spin nematic phase with remarkable in-plane anisotropy in local spin susceptibility, which becomes substantial below T_{sn} ~ 75 K rather than immediately below T_{nem}. This novel spin state also inherently breaking the in-plane rotational symmetry of electronic low energy spin dynamics. In addition, a prominent involvement of $3d_{xy}$ orbital to orbital order is also suggested by the present result, which is beyond previously proposed two-orbital model. The present result brings crucial understanding on the nature of the electronic nematicity in FeSe.

(π, π) spin fluctuation and pseudogap behavior in $(CTA)_{0.3}FeSe$ superconductor

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We conducted ^{77}Se NMR measurements on a newly discovered organic ion intercalated FeSe-based superconductor $(CTA)_{0.3}FeSe$ with T_c~44K. With temperature decreasing, $1/T_1T$ firstly decreases and then shows an upturn behavior when temperature approaches to T^*~ 65K while the declining Knight shift (K_s) becomes saturated, suggesting an antiferromagnetic spin fluctuations. Below T^*, a clear suppression of $1/T_1T$ and K_s is observed above T_c, which is ascribed to a pseudogap behavior similar with that in cuprates. In addition, the anisotropy of $1/T_1$ (R_{ac}) is about 0.5-1 around T^*, indicating that the low-energy spin fluctuation centered at (π, π) is dominated for the upturn behavior in $1/T_1T$ above T*. Moreover, the Korringa relation is roughly satisfied above T^*,implying a renormalized Fermi-liquid behavior in the high temperature region. The present results would stimulate further study on pseudogap physics in iron-selenide derived Fe-based superconductors.

Impurity Effects on Ferromagnetic Fluctuations in Heavily Overdoped Bi-2201 Cuprates

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It has been proposed that ferromagnetic (FM) fluctuations due to itinerant electrons exist and are related to the suppression of superconductivity in the heavily overdoped (HOD) regime of the hole-doped high-T_c cuprates [1,2]. Recently, from measurements of the electrical resistivity, magnetization, muon spin relaxation (μSR) using single crystals of Bi-2201 cuprates, we have found that two-dimensional FM fluctuations exist and are enhanced with hole doping in the HOD regime [3,4]. In order to clarify details of FM fluctuations, we have investigated impurity effects on the FM fluctuations using non-magnetic-Zn- and magnetic-Fe-substituted $Bi_{1.74}Pb_{0.38}Sr_{1.88}Cu_{1-y}(Zn,Fe)_yO_{6+\delta}$ single crystals.

Figure shows the temperature dependence of the muon-spin relaxation rate λ of HOD $Bi_{1.74}Pb_{0.38}Sr_{1.88}Cu_{1-y}(Zn,Fe)_yO_{6+\delta}$. For impurity-free $y = 0$, it is found that λ increases gradually with decreasing temperature, indicating the development of spin fluctuations [4]. For 3% Zn-substituted y(Zn) = 0.03, it is found that the enhancement of λ with decreasing temperature weakens, while λ of 5% Fe-substituted y(Fe) = 0.05 is enhanced. These results suggest that FM fluctuations are probably enhanced (suppressed) by the magnetic (non-magnetic) impurity. Assuming that HOD Bi-2201 resides in the crossover regime between itinerant and localized spin systems, the degradation of FM fluctuations by non-magnetic Zn is probably due to both bad nesting on the Fermi surface caused by impurities and spin dilution effects. On the other hand, the enhancement of FM fluctuations by magnetic Fe may be related to the stabilization of FM fluctuations induced by Fe^{3+} moments rather than bad nesting by impurities. The steep increase in λ of the y(Fe) = 0.05 sample below 10 K might be due to a possible static order of Fe spins and/or the enhancement of FM fluctuations promoted by Fe spins.

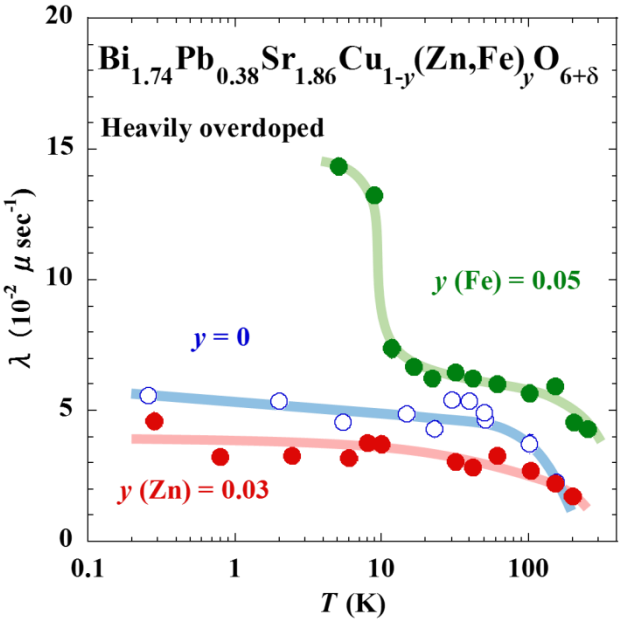

Figure. Temperature dependence of the muon-spin relaxation rate λ of HOD $Bi_{1.74}Pb_{0.38}Sr_{1.88}Cu_{1-y}(Zn,Fe)_yO_{6+\delta}$.

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Ultrafast Dynamics Evidence of High Temperature Superconductivity in Single Unit Cell FeSe on $SrTiO_3$

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We report the time-resolved excited state ultrafast dynamics of single unit cell (1 UC) thick FeSe films on $SrTiO_3$ (STO), with FeTe capping layers. By measuring the photoexcited quasiparticles' density and lifetime, we unambiguously identify a superconducting (SC) phase transition, with a transition temperature T_c of 68 (− 5/+2) K and a SC gap of $\Delta(0) = 20.2 \pm 1.5$ meV. The obtained electron-phonon coupling strength λ is as large as 0.48, demonstrating the likely crucial role of electron-phonon coupling in the high temperature superconductivity of the 1 UC FeSe on STO systems. We further find a 0.05 THz coherent acoustic phonon branch in the capping layer, which provides an additional decay channel to the gluing bosons.

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The energy gap and amplitude mode in charge-density-wave superconductor $Bi_2Rh_3Se_2$

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$Bi_2Rh_3Se_2$ is a compound showing coexistence of superconductivity and charge density wave (CDW) states. We grew single crystal samples and performed optical spectroscopy and ultrafast pump-probe measurements to investigate the single particle and collective excitations of the compound. With temperature cooling below T_{CDW}~250 K, the reflectivity spectrum shows a clear suppression around 1000 cm^{-1}, which could be assigned to the formation of CDW gap energy. It leads to a ratio of $2\Delta/T_{CDW}$~5.7. Our pump-probe measurement revealed a coherent oscillation that softened by approaching 190 K, which is lower than T_{CDW}. The frequency of the oscillation is about 1.3 THz, which comes from the amplitude mode of CDW collective excitations. We also find that the relaxation of photoinduced reflectivity of $Bi_2Rh_3Se_2$ single crystals lasts for a long time, up to a nanosecond order.

Mott transition and collective charge pinning in electron doped Sr*2*IrO*4*

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We studied the in-plane dynamic and static charge conductivity of electron doped Sr2IrO4 using optical spectroscopy and DC transport measurements. The optical conductivity indicates that the pristine material is an indirect semiconductor with a direct Mott-gap of 0.55 eV. Upon substitution of 2% La per formula unit the Mott-gap is suppressed except in a small fraction of the material (15%) where the gap survives, and overall the material remains insulating. Instead of a zero energy mode (or Drude peak) we observe a soft collective mode (SCM) with a broad maximum at 40 meV. Doping to 10% increases the strength of the SCM, and a zero-energy mode occurs together with metallic DC conductivity. Further increase of the La substitution doesn't change the spectral weight integral up to 3 eV. It does however result in a transfer of the SCM spectral weight to the zero-energy mode, with a corresponding reduction of the DC resistivity for all temperatures from 4 to 300 K. The presence of a zero-energy mode signals that at least part of the Fermi surface remains ungapped at low temperatures, whereas the SCM appears to be caused by pinning a collective frozen state
involving part of the doped electrons.

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Raman Scattering Study of Phase Transitions in Correlated-Electron Materials

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In correlated-electron materials, the interactions among the electrons' charge, spin, and orbital, as well as the lattice degrees of freedom may lead to a rich variety of self-organization phenomena of the electrons, which can often be described by the notion of spontaneously broken symmetries (or so-called continuous phase transitions). Raman scattering is sensitive to symmetry breaking via the appearance of new Raman-active phonon peaks and/or the splitting of originally degenerate peaks. The polarization selection rules of such phonons further help us infer the symmetries of the new structure. With these advantages, we use Raman scattering to investigate phase transitions in the iron-based and titanium-based superconductors.

Raman scattering can measure the local property of materials with small laser spot (about micrometer), and it can be used to detect spontaneous point-group symmetry breaking without resorting to single-domain samples. Here, we use this technique to determine the temperature of nematic phase transition in $BaFe_2As_2$, the parent compound of the "122" Fe-based superconductors. We show that an applied compression along the Fe-Fe direction, which is commonly used to produce untwinned orthorhombic samples, changes the structural phase transition at temperature T_s into a crossover that spans a considerable temperature range above T_s. Even in crystals that are not subject to any applied force, a distribution of substantial residual stress remains, which may explain phenomena that are seemingly indicative of symmetry breaking above T_s. Our results are consistent with an onset of spontaneous nematicity only below T_s and support the fact that there is no electronic nematic above T_s.

We use Raman scattering to investigate the parent compound of titanium based superconductor $BaTi_2As_2O$, which exhibits the tetragonal to orthorhombic structural phase transition at T_s = 200 K. By observing two lattice soft modes with very similar energies in the orthorhombic phase, we conclude that the lattice degrees of freedom play an important role in driving the phase transition. Previous density-functional theoretical analysis suggests that the lattice symmetry of $BaTi_2As_2O$ can change from P4/mmm to Pbam upon cooling through T_s[1]. Facilitated by this result, we infer a two-dimensional order parameter to be associated with the structural phase transition. This order parameter reduces to two one-dimensional representations in the low-symmetry phase, consistent with the existence of two soft modes with very similar energies as have been detected in our experiments. Our electronic Raman spectra exhibit a distinct electronic signal with a large energy scale below T_s, which is interpreted as due to a strong electronic response to lattice deformations.

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Insulator-to-superconductor transition in highly two-dimensional iron-based superconductor $(CaFe_{1-x}Pt_xAs)_{10}Pt_3As_8$

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In the phase diagram of $Ca_{10}(Pt_3As_8)(Fe_{1-x}Pt_xAs)_{10}$, above the superconducting (SC) and antiferromagnetic (AFM) dome, there exists a semiconducting like behavior, which mimics the pseudogap cuprates. Investigating the origin for the semiconducting like behavior would provide us important clue for the pairing mechanism. In this work, we have synthesized the parent compound and the optimal doped $Ca_{10}(Pt_3As_8)(Fe_{1-x}Pt_xAs)_{10}$, and measured their optical properties, respectively. From their optical conductivity, we found that the diminishing of the low-energy spectral weight in the normal state, corresponding to the semiconducting-like behavior, is related to the AFM fluctuation. On the other hand, we've realized the magnetic-enhanced electron-phonon coupling and that the far-infrared absorption peak in the optimal doped sample could be well described by the large polaron model, indicating the formation of large polaron in the semiconducting dome. Intriguingly, we notice that the polaron peak collapsed into the superfluid below Tc~12K. Thus, we propose that the magnetism induced polaron also participate in the unconventional pairing. Our study would provide a clue for pairing mechanism in unconventional high-Tc superconductors.

A New Prospect of Bilayer Splitting Bands by ARPES based on Time-of-Flight

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The Superconducting(SC) Gap, which is directedly related to superconducting transition, has been researched for several decades. Cuprate, as a significant group in high-temperature superconductors was claimed to be d-wave symmetrized [1]. While recently, different opinion referred that it was a fault made by measuring wrong layers. Here we propose a new prospect of the double-layer cuprate, $Bi_2Sr_2CaCu_2O_{8+\delta}$(Bi2212), measured by Angle-Resolved Photoemission based on Time-of-Flight(ARToF) with 11eV laser. Similar measurements have been applied nearly twenty years ago with hemispherical electron analyzer. While ARToF working with 11eV laser provides the information of 2D momentum space within one detection more completely and precisely. By analyzing the energy distribution curves(EDCs), the SC gap of both bonding band and antibonding band can be extracted clearly from nodal cut to antinodal direction. The distinctly different trends offer a new viewing about the relations between the crystal structure and SC gap, which reveal something new about SC transition. Since evidences showed strong relations between crystal structure, such as c axis or the number of CuO layers, with transition temperature(Tc), by analyzing this phenomenon systemically about temperature and doping dependences, we may open a new viewing to SC transition mechanism.

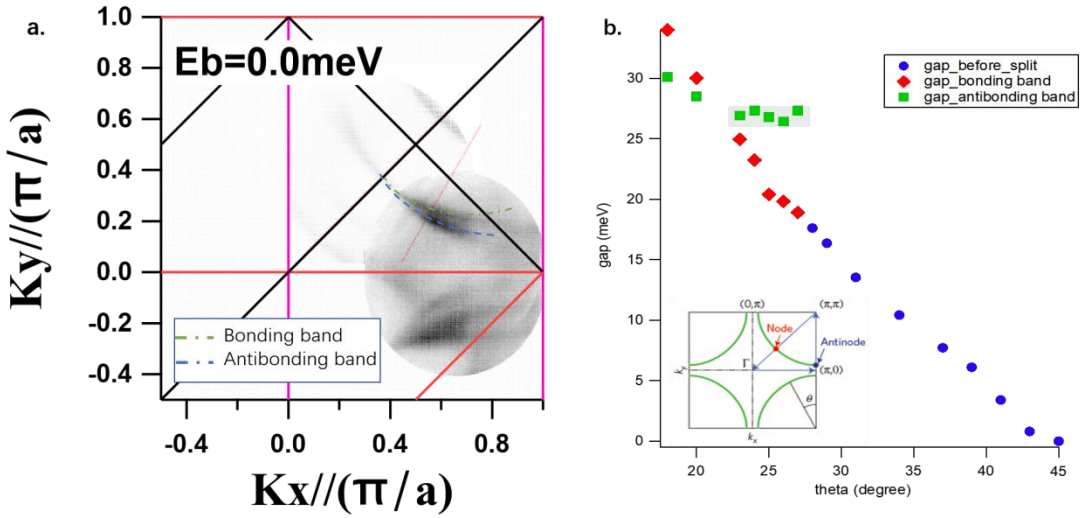

Fig. 1: *a. The fermi surface detected by ARToF with 11eV laser. b. The SC gap with momentum from nodal direction to antinodal direction. (Theta is the angle between the cut and the axis)*

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Laser ARPES study on CDW and superconducting order competition in the Se-doped $ZrTe_3$

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How the superconducting phase competes or coexists with various magnetic or charge ordering phase is a long standing fundamental issue in modern condensed matter physics. Especially in the low-dimensional systems like high Tc cuprates, heavy fermion superconductors, iron-based superconductor, and classical charge density wave (CDW) systems, superconducting order can emerge in the vicinity of multiple-order environment. More and more experimental evidences that have been collected recently point to a close relationship between superconductivity and the phase competition or coexistence. These systems can serve as a playground for investigating the nature of CDW order, and most importantly, its relationship with superconductivity. In this talk, we will present our newly developed ToF based Laser ARPES system with sub-meV energy resolution and, for the first time, its successful application in studying the complete electronic structure of classical quasi-1D CDW superconducting system $ZrTe_{3-x}Se_x$ (x=0, 0.01, 0.04). Our high resolution result reveal rather different observation on the ARPES spectral signature associating with the CDW and superconducting order with respect to the earlier reports. Both 3D band and zone center and qusi-1D bands along BZ boundary reveal quite unusualand clear electron self-energy anomaly below CDW transition temperature T_{CDW}. And a new quasi-particle develops on the quasi-1D band along the BZ boundary along the line (B-D). All these spectral feature are strongly affected by the Se-ion substitution which suggest competition of the CDW and superconducting in microscopic level.

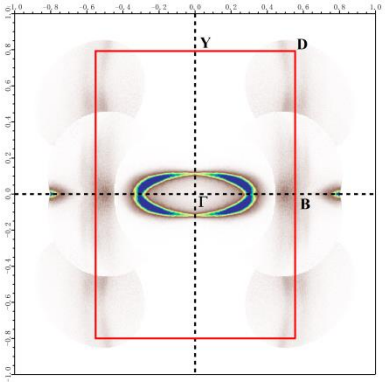

Figure 1. Fermi-surface of the ZrTe3 around 1st BZ deduced by the ToF-based Laser ARPES system

Evidence for Multiple Underlying Fermi Surface and Isotropic Energy Gap in the Cuprate Parent Compound $Ca_2CuO_2Cl_2$

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The parent compounds of the high-temperature cuprate superconductors are Mott insulators. It has been generally agreed that understanding the physics of the doped Mott insulators is essential to understanding the mechanism of high temperature superconductivity [1]. A natural starting point is to elucidate the basic electronic structure of the parent compound. Here we report comprehensive high resolution angle-resolved photoemission measurements on $Ca_2CuO_2Cl_2$, a Mott insulator and a prototypical parent compound of the cuprates. Multiple underlying Fermi surface sheets are revealed for the first time. The high energy waterfall-like band dispersions [2] exhibit different behavior near the nodal and antinodal regions. Two distinct energy scales are identified: a *d*-wave-like low energy peak dispersion [3] and a nearly isotropic lower Hubbard band gap. These observations provide new information on the electronic structure of the cuprate parent compound, which is important for understanding the anomalous physical properties and superconductivity mechanism of the high temperature cuprate superconductors.

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Evidence for short-range magnetic order in the nematic phase of FeSe from anisotropic in-plane magnetostriction and susceptibility measurements

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The nature of the nematic state in FeSe remains one of the major unsolved mysteries in Fe-based superconductors. Both spin and orbital physics have been invoked to explain the origin of this phase. Here we present experimental evidence for frustrated, short-range magnetic order, as suggested by several recent theoretical works, in the nematic state of FeSe[1]. We use a combination of magnetostriction, susceptibility and resistivity measurements to probe the in-plane anisotropies of the nematic state and its associated fluctuations. Despite the absence of long-range magnetic order in FeSe, we observe a sizable in-plane magnetic susceptibility anisotropy, which is responsible for the field-induced in-plane distortion inferred from magnetostriction measurements. Further we demonstrate that all three anisotropies in FeSe are very similar to those of $BaFe_2As_2$[2], which strongly suggests that the nematic phase in FeSe is also of magnetic origin.

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Nodeless Superconductivity in the Caged Compound $Lu_5Rh_6Sn_{18}$ with Broken Time Reversal Symmetry

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The $R_5Rh_6Sn_{18}$ (R = Lu, Y) superconductors, which have a caged crystal structure, have attracted interest due to the observation of broken time reversal symmetry in the superconducting state from muon-spin relaxation measurements.[1,2] Here we have measured the London penetration depth shift $\Delta\lambda(T)$ of single crystals of$Lu_5Rh_6Sn_{18}$ along various crystallographic directions down to 350 mK using a self-induced tunnel diode-oscillator (TDO) based technique. The $\Delta\lambda(T)$ of $Lu_5Rh_6Sn_{18}$ exhibits an exponential temperature dependence below around $0.3T_c$ along all directions, giving clear evidence for fully gapped superconductivity.Furthermore, upon converting the penetration depth to the normalized superfluid density $\rho_s(T)$,we find that the data is well accounted for using a single gap s-wave model. Further theoretical and experimental studies are required in order to reconcile the apparent single-gap s-wave superconductivity with the broken time reversal symmetry.

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Enhancement of Critical Current Density in Helium Ion irradiated $Ba(Fe,Co)_2As_2$ Thin Films

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The effect of 600 keV He^+ ion irradiation on the temperature and magnetic field dependence of the critical current density J_C of high quality $BaFe_{1.84}Co_{0.16}As_2$ thin films is investigated. The films are prepared by pulsed-laser-deposition on CaF_2 substrates. The irradiation dosage is varied between $1x10^{13}$ to $1x10^{16}$ ions/cm^2 at room temperature. Upon irradiation, the critical temperature T_C drops slightly from 23 K for the unirradiated sample to about 18.5 K for the sample with the highest irradiation level. The J_C values of the samples are calculated from the magnetic hysteresis data using the Bean critical state model. The results showed that J_C is increased significantly for samples with irradiation levels below $5x10^{13}$ while J_C is reduced for heavily irradiated samples. The analysis of the dependence of pinning force on magnetic field shows that the pinning behavior is not changed in the irradiated samples, suggesting more pinning centers of similar nature to those presented in the unirradiated samples are introduced by the irradiation process. The results indicate that the irradiation of light element ions (He^+) with relatively low energy could increase the critical current density in iron based superconductors.

Evidence of Coulomb interaction induced Lifshitz transition and possible robust hybrid Weyl fermion in superconductor T_d $MoTe_2$

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Among the crystallographic phases of transition-metal dichalcogenides (TMDs), the orthorhombic T_d lattice type attracted great interest due to its exotic transport and topological properties. Particularly, the emergence of superconductivity in the low temperature T_d phase of $MoTe_2$ may be the key for realizing future topological quantum devices. Along this route, unveiling the so far unexplored bulk band structure is one of the key steps. Here we report the bulk electronic structure of $MoTe_2$ measured by soft x-ray angle-resolved photoemission spectroscopy. Our results show that on-site Coulomb interaction causes a Lifshitz transition of the Fermi surface and is essential for a precise theoretical description of the electronic structure of $MoTe_2$. Furthermore, a hybrid Weyl semimetal state in Td $MoTe_2$ with a pair of energy bands touching at both type-I and type-II Weyl nodes near the chemical potential is suggested by our results. Unveiling the importance of Coulomb interaction opens up a new route to comprehend the unique properties of $MoTe_2$, with implications for potential applications based on the interplay between correlation, strong spin-orbit coupling and superconductivity in this van der Waals material.

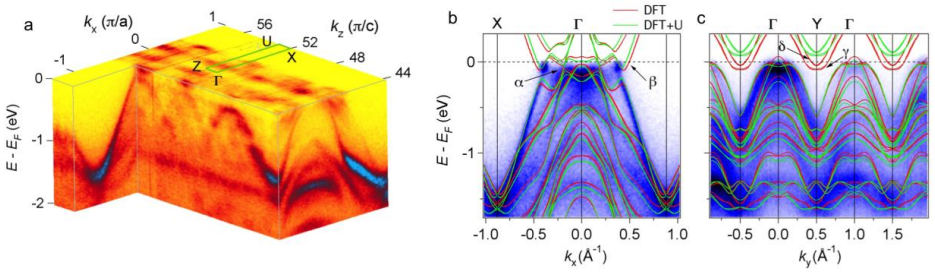

Fig. 1: *a, Bulk electronic structure of $MoTe_2$. b-c, ARPES spectrum near E_F along theΓ-X andΓ-Y directions, respectively. The overlaid solid lines are the energy bands calculated by using the DFT+U (green) and DFT (red) methods, respectively.*

On the Tc enhancement mechanism at the FeSe/$SrTiO_3$ interface

Tianlun Yu

Fudan University

At the interface between monolayer FeSe films and SrTiO3 substrate thesuperconducting transition temperature (Tc) is unexpectedly high, triggering a surge ofexcitement. The mechanism for the Tc enhancement has been the central question, as it maypresent a new strategy for searching for higher Tc materials. To reveal this enigmaticmechanism, by combining advances in high quality interface growth, 16O ⟷ 18O isotopesubstitution, and extensive data from angle resolved photoemission spectroscopy, we providestriking evidence that the high Tc in FeSe/SrTiO3 is the cooperative effect of the intrinsicpairing mechanism in the FeSe and interactions between the FeSe electron and SrTiO3phonon. Furthermore, our results point to the fascinating prospect that similar cooperationbetween different Cooper pairing channels may be a general framework to understand anddesign high-temperature superconductors.

Orbital Origin of Extremely Anisotropic Superconducting Gap in Nematic Phase of FeSe Superconductor

Cong Li
IOP

The iron-based superconductors are characterized by multiple-orbital physicswhere all the five Fe 3***d*** orbitals get involved. The multiple-orbital nature givesrise to various novel phenomena like orbital-selective Mott transition, nematicityand orbital fluctuation that provide a new route for realizing superconductivity. The complexity of multiple-orbital also asks to disentangle the relationshipbetween orbital, spin and nematicity, and to identify dominant orbital ingredients that dictate superconductivity. The bulk FeSesuperconductor providesan ideal platform to address these issues because of its simple crystal structure and unique coexistence of superconductivity and nematicity. However, theorbital nature of the low energy electronic excitations and its relation to thesuperconducting gap remain controversial. Here we report direct observationof highly anisotropic Fermi surface and extremely anisotropic superconductinggap in the nematic state of FeSe superconductor by high resolution laser-basedangle-resolved photoemission measurements. We find that the low energy excitations of the entire hole pocket at the Brillouin zone center are dominated bythe single ***d***xzorbital. The superconducting gap exhibits an anti-correlation relation with the ***d***xzspectral weight near the Fermi level, i.e., the gap size minimum(maximum) corresponds to the maximum (minimum) of the ***d***xzspectral weightalong the Fermi surface. These observations provide new insights in understanding the orbital origin of the extremely anisotropic superconducting gap in FeSesuperconductor and the relation between nematicity and superconductivity inthe iron-based superconductors.

Laser-ARPES Study onElectron Scattering in ExtremelyOverdoped Bi2201Superconductor

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Comparison between Effects of 1.19 GeV Pb and 320 MeV Au Irradiations on Critical Current Density in $Ba_{0.6}K_{0.4}Fe_2As_2$

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Introduction of columnar defects to superconductors through heavy-ion irradiation enhances their critical current density (J_c) [1,2]. It has been demonstrated that the maximum value of J_c and the corresponding dose depend on ion species and its energy [3]. Here, we compare effects of high-energy (1.19 GeV Pb) and low-energy (320 MeV Au) heavy-ion irradiations on the critical temperature (T_c) and J_c of 122-type iron-based superconductor $Ba_{0.6}K_{0.4}Fe_2As_2$. Magnetic field dependences of J_c of $Ba_{0.6}K_{0.4}Fe_2As_2$ irradiated by 1.19 GeV Pb (B_Φ=8 T) and 320 MeV Au (B_Φ=4 T) are shown in Figs.1 (a) and (b), respectively. The J_c values at 2 K under self-field in both cases are similar, and correspond to the maximum in each case. The difference in the optimum B_Φ in the two cases may originate from the different diameters and lengths of created defects. We also demonstrate that introduction of splayed columnar defects or coexistence of columnar defects and point defects enhance J_c more than the case of only parallel columnar defects.

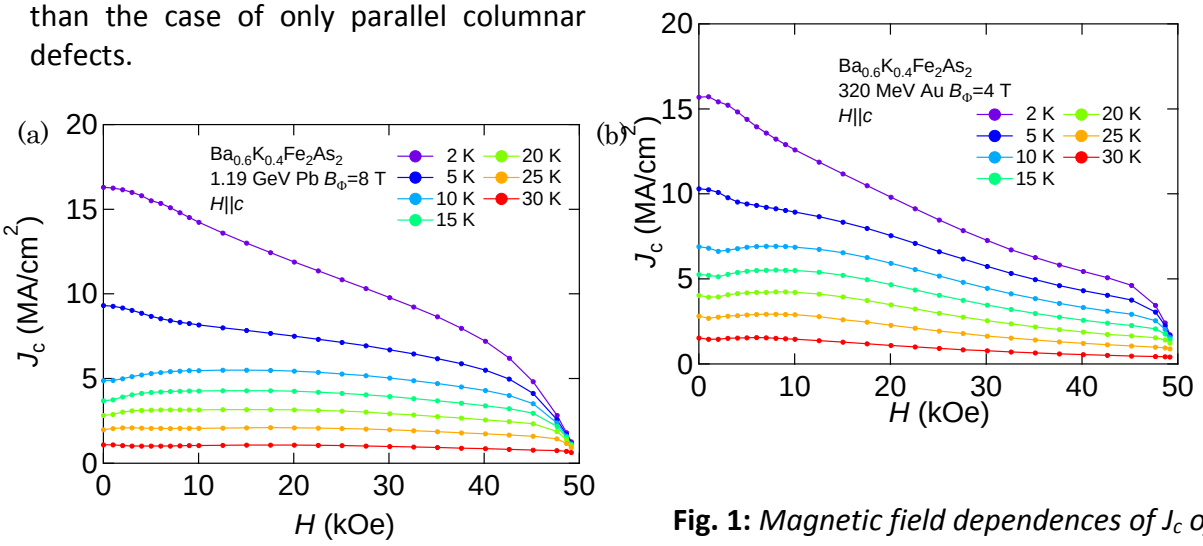

Fig. 1: *Magnetic field dependences of J_c of (a)1.19 GeV Pb irradiated $Ba_{0.6}K_{0.4}Fe_2As_2$ (B_Φ=8 T) and (b)320 MeV Au irradiated $Ba_{0.6}K_{0.4}Fe_2As_2$ (B_Φ=4 T).*

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Demonstration of the Photon-number Resolving and Spatial Resolution Detector withHigh Input Impedance Cryogenic RF Amplifier

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Compared with other single photon detectors, superconducting nanowire single photon detectors (SNSPDs) have showed many superior performances, such as several units of 10-4 s-1 dark counts, as low as 16 ps timing jitter, and wide spectral response from the visible to infrared. However, SNSPD usually operates in a strong nonlinear mode. Even if multiple photons are absorbed at the same time, only one pulse signal is generated, but in many occasions such as spectral analysis, communication, cosmic observation and quantum information processing, etc. Not only does it need to respond to incident photons, but it also needs to distinguish the number of incident photons and even the temporal information and spatial location of photon incidence. Recently, [1]some research groups have proposed a device structure which is based on the series connection of N nanowires, each connected in parallel to a resistor R_P, The spatial resolution and photon number resolution can be achieved by setting the size and number of resistors(R_P) when all the detecting sections are biased with the same bias current (I_B) close to the critical current (Ic). Series array of superconducting nanowires can be read in the conventional way, but when the number of pixels in series is large,a special cryogenic RF amplifier with high input impedance will be needed to distinguish the amplitude of pulses caused by different number of incident photons.To meet this demand of series array of superconducting nanowires, we also designed and fabricated the monolithic integrated cryogenic RF amplifiers with high input impedance based on Tower Jazz's 1.8μm SiGe BiCMOS process. Moreover, by connecting devices with our amplifiers, our device can achieves photon number resolution and spatial resolution functions with a quantum efficiency of approximately 60% at 1550nm.

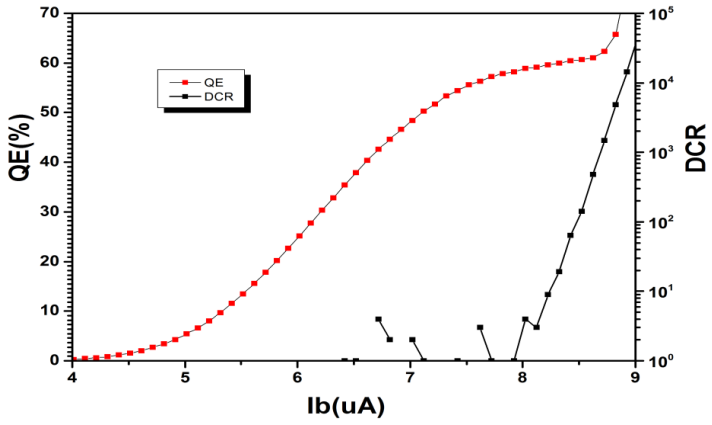

Fig. 1*Single-photon system quantum efficiency at 1550nm and dark count rate, as a function of the bias current.*

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The Electronic Structure of Bi2212 Measured By Laser-based ToF-ARPES

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Here, we present our new results of Bi2212 measured by Laser-based ToF-ARPES. We have measured different doping from under doped to over doped at temperature from far below Tc to T*. The unique detecting mechanism of ToF-ARPES greatly enhance the stability and accuracy of the experimental data and provides most reliable high quality ARPES spectra suitable for quantitative analysis. We will show the detailed gap evolution with momentum, temperature and doping. We also extract the normal self energy and pairing self energy to study the electrons' interaction.

Growth, characterization and electronic structure measured by new generation laser-based ARToF-ARPES of high temperature superconductor $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$

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We present our new generation laser-based ARToF-ARPESmeasurements on $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$.High quality single crystals with wide Pb doping range(x=0.2,0.4,0.6,0.8)havebeen successfully grown by the traveling solvent floating zone technique and they are characterized byvarious measurements.Especially with the ultra-high energy and momentum resolution,a systematic change ofwell-known incommensurate modulation vector(q) withincreasing Pb doping is revealed by ARPES for the first time.The unique detecting mechanism of ARToF-ARPES greatly enhance the stability and accuracy of the experimental data and provides most reliable high quality ARPES spectra suitable for quantitative analysis, for example, analyzing the superconducting fluctuation spectra through measured ARPES results, in a more comprehensive and advanced way.

Spectroscopic Evidence of Low Energy Gaps Persisting Towards 120 Kelvin in Surface-Doped p-Terphenyl Crystals

Haoxiang Li

University of Colorado Boulder

The onset of a weak Meissner-like signal has been observed at 120K in recent K-doped *para*-terphenyl samples, suggesting the possibility of superconductivity. Using high-resolution photoemission spectroscopy on potassium surface-doped *para*-terphenyl crystals, we uncover low energy (12 meV) gaps that persist to approximately 120 K – the same temperature as the onset of the Meissner-like signal. Among a few potential origins, we argue that the onset of electron pairing within molecules is the most likely origin for these gaps. This implies that enhancing inter-molecular coupling in this or related compounds could lead to the development of phase coherence between molecules and the development of true superconductivity.

Double quantum criticality in superconducting tin-arrays/graphene hybrid

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Two magnetic-field-induced quantum critical behaviors were recently discovered in two dimensional electron gas (2DEG) at $LaTiO_3/SrTiO_3$ interface andinterpretedbydisordered superconducting puddles coupled through 2DEG. In this scenario, the 2DEG is proposed to undergoa spontaneous phase separation and breaks up into locally superconducting puddles in a metallic matrix.However, as the inhomogeneous superconducting 2DEG is only illative,this proposal still lacks the direct experimentaldemonstration. Here, we artificially constructed superconducting puddles-2DEG hybrid system by depositingtin nanoislands array on single crystalline monolayer graphene, where the two quantum critical behaviors are reproduced.Through the finite size scaling analysis on magnetoresistivity, we show that the two quantum critical behaviors result from the intra- and inter-island phase coherence, respectively, which are further illustrated by the phase diagram.This work provides a platform to study superconducting quantum phase transitions in a 2D system and helps to integrate superconducting devices into semiconductor technology.

Doping study of quasi-one-dimensional S=1/2 Heisenberg antiferromagnetic spin system$Sr_{2-x}(PbCl_2)_xCu(BO_3)_2$

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Abstract

We report the magnetic properties on the compound $Sr_2Cu(BO_3)_2$which has quasi-one-dimensional spin structure with spin gap;The crystal structure of $Sr_2Cu(BO_3)_2$has the nearest neighbor CuO_4 pair which forms a spin dimer linked by triangular BO_3along the*ac*-plane.[1]In this study, we investigated a doping effect of $PbCl_2$ on the polycrystalline β-$Sr_2Cu(BO_3)_2$ to increase carrier concentration expecting the spin gap to be suppressedwith $PbCl_2$ doping concentrations andsuperconductivityto be appeared.When we dope the $PbCl_2$ on the*β*-$Sr_2Cu(BO_3)_2$ by $Sr_{2-x}(PbCl_2)_xCu(BO_3)_2$(x=0, 0.0005, 0.01, and 0.1), the lattice parameters are systematically changed, indicating the effective substitution of the elements. In magnetic susceptibilities, the ratio of Weiss temperature of the In-Gap signalsto Neel temperature,Θ_D/T_Nindicates the significant increasedspin frustrationsas doping concentration increases but it still didn't show any suppressions of spin gap size. Here we will discuss these unconventional magnetic responseswith doping in details.

Keywords:Quasi-one-dimensional, Spin frustration, Magnetic order

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Effects of particle irradiation on critical current density in $CaKFe_4As_4$ single crystals

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Iron-based superconductors (IBS) have been investigated as promising materials for practical applications because of their large critical current densities (J_c) at high magnetic fields and temperatures. It is known that J_c in superconductors can be further enhanced by introducing defects using particle irradiations. In our previous studies, remarkable effects have been demonstrated in IBS by irradiating heavy-ions and protons into Co or K doped Ba-122 single crystals [1,2]. Recently, another promising IBS $CaKFe_4As_4$ was found [3] and has started to attract interest due to its high J_c in the pristine sample [4]. In this reports, we will investigate the effects of several ion irradiations such as Xe, Au, and proton into $CaKFe_4As_4$ single crystals. One of the results using 800 MeV Xe is summarized in the Fig. 1. By Xe irradiation, J_c under self-field is strongly enhanced with increasing dose-equivalent matching field (B) up to 13 MA/cm^2. Effects of other ion irradiations on J_c will be also discussed.

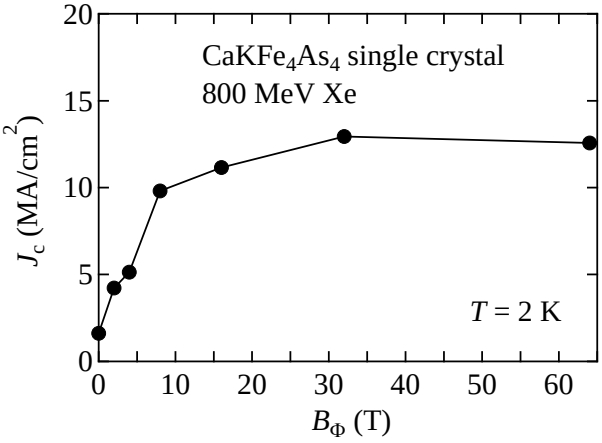

Fig. 1: *The B dependence of J_c of irradiated $CaKFe_4As_4$ at 2 K under self-field.*

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Defect-assisted Tunneling and Compressibility Measurements in Graphene-hexagonal Boron Nitride Stacked Devices.

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The electronic transport through quantum dots is extremely sensitive to the electrostatic environment. Such dots, used as single electron transistors (SET), are a useful probe for electronic charging. In this work we report electronic transport measurements on a graphite-hBN-graphene tunneling device utilizing a few-layer hBN as a tunnel barrier. Graphene is gated via a second hBN flake. We find the graphite-graphene electronic transport to be dominated by tunneling through a dot-like defect in the hBN spacer. The bias-gate stability trace exhibits strong dependence on graphene density at zero magnetic field, demonstrating the utility of the dot as a probe for graphene ground-state density of states. At finite magnetic fields, these traces map the zeroth Landau level of the graphene layer. Finally, at elevated bias the dot also serves as a discrete energy current injector into the graphene layer, thereby providing an additional probe to the excited state spectrum. We suggest this defect-assisted tunneling as a new paradigm for sensitive device-based spectroscopy.

Tuning Pair-Breaking at the Surface of Topological Superfluid Helium-3

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Since the discovery of superconductivity in heavy-fermion metals and oxide materials the majority of emerging superconducting materials exhibit unconventional pairing. In contrast to s-wave superconductors, they are extremely sensitive to quasiparticle scattering off non-magnetic defects and surfaces. Topological superfluid ^{3}He, with unconventional p-wave pairing, provides a model system to understand the influence of surface scattering in the absence of other pair-breaking processes. Here we confine superfluid ^{3}He within a cavity of height D=196 nm, comparable to the Cooper pair diameterξ_0. We precisely determine the effect of surface scattering on both the superfluid transition temperature T_c, Fig. 1, and the energy gap; and compare these measurements toquasiclassical calculations. We demonstrate that the pair-breaking can be tuned in situ by adjustment of the isotopic composition of the helium surface boundary layer. We show that suppression of superfluidity is eliminated by coating the cavity surfaces with a thin superfluid ^{4}He film, opening the way to studies of superfluid ^{3}He in the quasi-2D limit. On the other hand, with a magnetic surface boundary layer of solid ^{3}He, an unexpectedly large and unexplained suppression of T_c is observed.

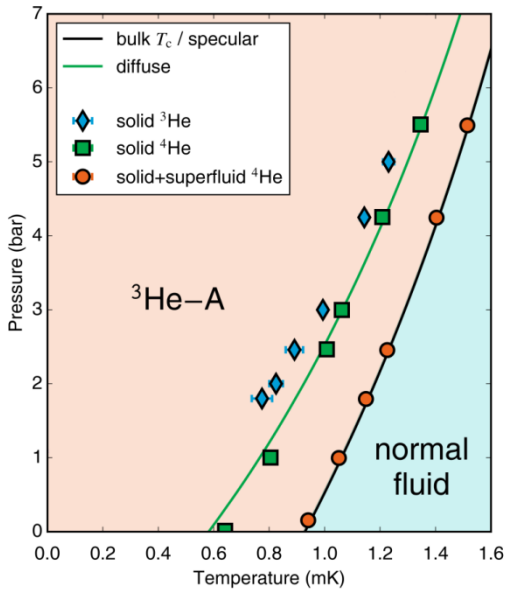

Fig. 1:*Crticial temperature of superfluidity in ^{3}He confined to a D=196 nm slab. Hydrostatic pressure acts a tuning parameter that controls the effective confinement D/ $\xi_0$between 2.5 and 5.2. Three boundary layers were prepared by varying the amount of ^{4}He added to the ^{3}He sample.Anomalous suppression of the superfluidity is observed in the presence of magnetic solid ^{3}He. When this solid is displaced with ^{4}He, the measurements show good agreement with the predictions for diffuse quasiparticle scattering at atomically rough surfaces. The suppression is virtually eliminated by adding a superfluid ^{4}He coating, as predicted for specular surface scattering.*

Spatially-Modulated States in Superfluid Helium-3 under Confinement

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The phase diagram of p-wave spin-triplet superfluid ^{3}He is strongly modified by confinement on a length scale comparable to the Cooper pair diameter ξ_0. In the topological *B* (Balian-Werthamer) phase in slab geometry of thickness $D \sim 10\xi_0$,domain walls between regions of degenerate order parameter orientations are predicted to have negative surface energy, leading to a spontaneously modulated *stripephase*[1-3]. In this proposed state several components of the 3×3 p-wave order parameter matrix periodically change sign, forming a pair density wave, similar to the Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state.

We report an experimental investigation of this prediction, in which we ruled out the stripe phase, and found evidence for a different modulated state [4]. In our experiment the confinement was provided by a microfluidic cavity of well-characterised regularslab geometry of thickness D=1144±7 nm. NMR was used to determine spatial averages of various combinations of the order parameter components. These were found to deviate from the predictions for both the translationally-invariant B phase and the stripe phase, Fig. 1a,b. We interpret thesedata in terms of a spatially-modulated phase with unequal amount of domains of the two different orientations, Fig. 1c-e. The inferred strong imbalance points towards a regular *polka dot phase*, Fig. 1c,d, rather than disordered structures, Fig. 1e. Similar phases have been discussed as variants of FFLO states [5]. The domain morphology may be governed by energetic considerations, or manifest lower nucleation barrier fordots relative to stripes.

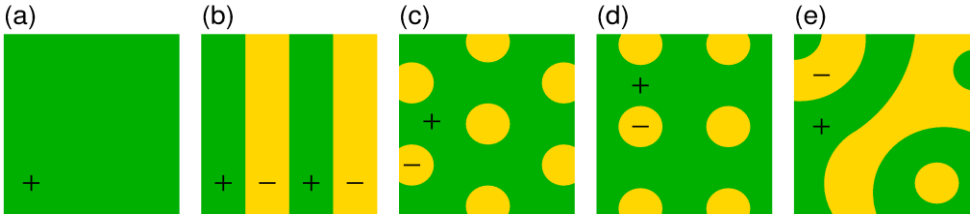

Fig. 1:*Proposed domain configurations in a slab of ^{3}He-B. View perpendicular to the plane of the slab. +/- represents the sign of the amplitude of the L_z=S_z=0 Cooper pairs (assuming the slab in xy plane).* ***(a)*** *translationally-invariant B phase found when surface energy of the domain walls is positive;* ***(b)*** *the predicted stripe phase;* ***(c,d)*** *proposed polka dot phase with hexagonal or square symmetry;* ***(e)*** *a disordered domain structure.*

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The application of HTS rf SQUID in Ultra low field NMR system

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The HTS(high temperature superconductor) SQUID-based ultra low field(ULF) NMR system is an emerging technology allows NMR study in microtesla-range fields. We utilize a HTS rf SQUID which is fabricated by our group to replace the HTS dc SQUID in ultra low field NMR system[1], and to study the performance of the HTS rf SQUID sensor. A pre-polarized solenoid coil is setup to generate a Bp field of 16 mT/A to produce a strong nuclear spins in water sample along the x direction. The measurement field B_0 is along the z direction in our research and with a controlled filed range from 0 -100 μT. A LC circuit is used to transmit NMR signals from to the rf SQUID sensor. The rf SQUID sensor's field sensitivity in the white noise range is about 100 fT/Hz$^{1/2}$ measured in a well shielded space, however, the sensitivity is degraded to about 200 fT/Hz$^{1/2}$, which is attributed to the trapped flux lines caused by large Bp pulses in the pick-up loop of the SQUID sensor. The NMR signals are measured from 2500 Hz to 3100 Hz with our rf SQUID sensor.

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The coexistence of superconductivity and magnetism in $NdO_{0.5}F_{0.5}BiS_2$: A muon spin rotation study

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The superconductivity in BiS_2 based layered compounds $Bi_4O_4S_3$ and $REO_{0.5}F_{0.5}BiS_2$ (*RE*=La, Nd, Pr, Ce, and Yb) has attracted much interest, since these compounds are layered in structure and similar to that of high T_c cuprates and Fe-pnictides. It is interesting that *T*c of $LaO_{0.5}F_{0.5}BiS_2$ increases from 2.7 K to above 5 K when La is replaced by Nd. Similarly, *T*c of LaFeAsO goes from 27 K to above 50 K. We have performed muon spin rotation measurements on ambient-pressure-grown polycrystalline $NdO_{0.5}F_{0.5}BiS_2$ down to 0.025k to investigate the relationship between superconductivity and magnetism in this compound.

Inducing strong superconductivity in WTe_2 by proximity effect

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The search for proximity-induced superconductivity in topological materials has generated widespread interest in the condensed matter physics community. The superconducting states inheriting nontrivial topology at interfaces are expected to exhibit exotic phenomena such as topological superconductivity and Majorana zero modes, which hold promise for applications in quantum computation. However, a practical realization of such hybrid structures based on topological semimetals and superconductors has hitherto been limited. Here, we report the strong proximity-induced superconductivity in type-II Weyl semimetal WTe_2, in a van der Waals hybrid structure obtained by mechanically transferring $NbSe_2$ onto various thicknesses of WTe_2. When the WTe_2 thickness ($\boldsymbol{t_{WTe_2}}$) reaches 21 nm, the superconducting transition occurs around the critical temperature ($\boldsymbol{T_c}$) of $NbSe_2$ with a gap amplitude ($\boldsymbol{\Delta_p}$) of 0.38 meV and an unexpected ultra-long proximity length ($\boldsymbol{l_p}$) up to $\mathbf{7\ \mu m}$. With the thicker 42nm WTe_2 layer, however, the proximity effect yields $\boldsymbol{T_c \sim 1.2\ K}$, $\boldsymbol{\Delta_p = 0.07\ meV}$ and a short $\boldsymbol{l_p}$ of less than $\mathbf{1\ \mu m}$. Our theoretical calculations, based on the Bogoliubov-de Gennes equations in the clean limit, predict that the induced superconducting gap is a sizable fraction of the $NbSe_2$ superconducting one when $\boldsymbol{t_{WTe_2}}$ is less than 30 nm, and then decreases quickly as $\boldsymbol{t_{WTe_2}}$ increases. This agrees qualitatively well with the experiments. Such observations forms a basis in the search for superconducting phases in topological semimetals.

Unveiling the superconducting mechanism of $Ba_{0.51}K_{0.49}BiO_3$

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The mechanism of high superconducting transition temperatures (Tc) in bismuthates remains under debate despite more than 30 years of extensive research. Our angle-resolved photoemission spectroscopy studies on $Ba_{0.51}K_{0.49}BiO_3$ reveal an unexpectedly 34% larger bandwidth than in conventional density functional theory calculations. This can be reproduced by calculations that fully account for long-range Coulomb interactions — the first direct demonstration of bandwidth expansion due to the Fock exchange term, a long-accepted and yet uncorroborated fundamental effect in many body physics. Furthermore, we observe an isotropic superconducting gap with $2\Delta_0=k_BT_c = 3.51 \pm 0.05$, and strong electron-phonon interactions with a coupling constant $\lambda \sim 1.3 \pm 0.2$. These findings solve a long-standing mystery—$Ba_{0.51}K_{0.49}BiO_3$ is an extraordinary Bardeen-Cooper-Schrieffer (BCS) superconductor, where long-range Coulomb interactions expand the bandwidth, enhance electron-phonon coupling, and generate the high Tc. Such effects will also be critical for finding new superconductors.

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Giant Phonon Softening and Enhancement of Superconductivity Induced by Copper/Phosphorus Doping of $BaNi_2As_2$

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The effects of chemical substitution on the structural and superconducting phase transitions of $BaNi_2As_2$ were studied. We found an abrupt increase in the superconducting transition temperature T_c from 0.6 K in the triclinic phase with less doping to 2.5-3.3 K in the tetragonal phase with more doping at x = 0.067 for $BaNi_2(As_{1-x}P_x)_2$ and at x = 0.16 for $Ba(Ni_{1-x}Cu_x)_2As_2$. Specific-heat data suggested that doping-induced phonon softening was responsible for the enhanced superconductivity in the tetragonal phase, as shown in Fig.1 [1, 2].

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Optimization, Preparation and Characterization of Nanowires for High Efficiency Superconducting Nanowire Single Photon Detector

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This article has mainly done the following three aspects of the work:
1.Experiments verify the effect of current concentration on the critical current of superconducting nanowires.
2.Optimize the design of round nanowires, prepare right-angle nanowires, semicircular nanowires and optimized round nanowire devices with the same width, and measure their detection efficiency and dark count respectively. The experiment shows that under the same process conditions The detection efficiency of the optimized round nanowire device is about 20% higher than that of the right angle nanowires and semicircular devices, and it is easier to reach saturation, and the dark count rate is also lower.
3.Devices with different widths of rounded nanowires were fabricated. After RIE etching, their I-V curves and the critical current of the nanowires were measured, and the critical current density of the nanowires was calculated. Through the contrast experiments of four different nanowire shapes, the linear relationship between the critical current of the nanowire and its effective line width can be explained.

Keywords: Optimized fillet nanowires, critical current density, effective line width, dark count

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Evidence of line-nodes in superconducting gap function in $K_2Cr_3As_3$from specific heat measurements

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We present low-temperature specific heat measurements of the quasi-one-dimensional superconductors $K_2Cr_3As_3$. Our result shows a sharp specific-heat jump around T_C ~ 6.1K with $\Delta C/\gamma_n T_C \sim 2.5$, which is much larger than the BCS prediction for a weak-coupling superconductor. It indicates that this superconductor is in the strong-coupling regime. After subtracting the lattice contribution and the Schottky anomaly from the total specific heat data, the low temperature electronic specific heat is proportional to T^2at different fields and also proportional to $\sqrt{H}$ at different temperatures below 2.5K. These results indicate that line nodes are present in the superconducting gap function of $K_2Cr_3As_3$.

NMR studies on the magnetic fluctuations in the artificial heavy-fermion superlattices of $CeCoIn_5/YbCoIn_5$ and $CeCoIn_5/YbCoIn_5$

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The progress in the epitaxial-growth technique enabled us to synthesize an artificial heavy-fermion (HF) superlattices (SLs) of alternately stacked block layers (BLs) with a few atomic layer thickness. These SLs provide a new platform to study the two-dimensional electronic properties, interaction between different BLs, and magnetic properties at the interfaces [1]. Actually, it was shown from the angle dependence of the superconducting (SC) upper critical field H_{c2} that two dimensional superconductivity is realized in the $CeCoIn_5$ (HF superconductor)/ $YbCoIn_5$ (conventional metal) SL [2]. In addition, the ratio of H_{c2} / T_c of this SL becomes larger with decreasing the $CeCoIn_5$-BL thickness due to the suppression of the Pauli pair-breaking effect by the Rashba interaction [3]. Another interesting SL is the $CeCoIn_5$ (HF superconductor)/ $CeRhIn_5$ (spin-density-wave metal) SL. The H_{c2} of this SL is enhanced by applying pressure. Since the H_{c2} is determined by the Pauli pair-breaking mechanism, and is proportional to $\Delta/g\mu_B$ in this case, the enhancement of H_{c2} suggests the increase of the SC gap Δ by critical antiferromagnetic (AFM) fluctuations [4].

We performed ^{59}Co-NMR measurements on the $CeCoIn_5/YbCoIn_5$ and $CeCoIn_5/CeRhIn_5$ SL focusing on the $CeCoIn_5$ BL to investigate whether spin fluctuations at the $CeCoIn_5$ BL are different between two SLs or not. We consider that ^{59}Co-NMR is one of the best experimental techniques in the SL samples, since the NMR can derive the magnetic information only from the target BLs.

We found that $1/T_1T$ of $CeCoIn_5$ BL in the $CeCoIn_5/YbCoIn_5$ SL is smaller than that of the $CeCoIn_5$ films. The suppression of $1/T_1T$ is consistent with the previous ^{115}In-NMR study [5]. On the other hand, $1/T_1T$ of the $CeCoIn_5$ BL in the $CeCoIn_5/CeRhIn_5$ SL does not show such a suppression, but larger component shows up at low temperatures although the same $1/T_1T$ component remains. We show that the AFM fluctuations at the $CeCoIn_5$ BL are clearly different between two SL samples, and suggest that the interface interactions, which depends on the adjacent BLs, are the most important interaction to determine the magnetic properties of the $CeCoIn_5$ BL.

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Breakdown of single spin-fluid model in the heavily hole-doped superconductor $CsFe_2As_2$

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Although Fe-based superconductors are correlated electronic systems with multiorbital, previous nuclear magnetic resonance (NMR) measurement suggests that a single spin-fluid model is sufficient to describe its spin behavior. Here, we first observed the breakdown of single spin-fluid model in a heavily hole-doped Fe-based superconductor $CsFe_2As_2$ by site-selective NMR measurement. At high-temperature regime, both Knight shift and nuclear spin-lattice relaxation at ^{133}Cs and ^{75}As nuclei exhibit distinct temperature-dependent behavior, suggesting the breakdown of the single spin-fluid model in $CsFe_2As_2$. This is ascribed to the coexistence of both localized and itinerant spin degree of freedom at 3d orbitals, which is consistent with the orbital-selective Mott phase. With decreasing temperature, the single spin-fluid behavior is recovered below $T^* \sim 75$ K due to a coherent state among 3d orbitals. The Kondo liquid scenario is proposed to understand the low-temperature coherent state.

μSR investigation of quasi-one-dimensional superconductor $K_2Cr_3As_3$

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Recently Bao *et al.* reporteda quasi-one-dimensional superconductor $K_2Cr_3As_3$ with T_c ~ 6.1 K[1]. The superconducting pairing symmetry in $K_2Cr_3As_3$ remains enigmatic. The absence of Hebel-Slichter coherence peak of $1/T_1$ below T_c, as shown by ^{75}As NMR measurements, indicates the unconventional nature of superconductivity[2]. The temperature dependence of the change in the penetration depth ($\Delta\lambda(T)$) measured by the tunnel diode oscillator between 0.4 K to 8 K suggests that line nodes exist in superconducting gap[3]. Moreover, measurements of penetration depth ($\lambda(T)$) using μSR above ~ 1 K indicated that the temperature dependent penetration depth can be fitted by either BCS s-wave model or d-wave model, but d-wave model obtained better goodness-of-fitting (χ^2)[4]. In this poster, we show the results from μSR measurements down to 30mK. Both BCS s-wave model and d-wave model are applied to fit the whole temperature range and the Knight shift below T_c is also presented[5].

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Nodal superconductivity coexists with low-moment static magnetism in single-crystalline tetragonal FeS: A muon spin relaxation and rotation study

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We report muon spin relaxation and rotation (μSR) measurements on hydrothermally grown single crystals of superconducting tetragonal FeS, which help to clarify the controversial magnetic state and superconducting gap symmetry of this compound. μSR time spectra were obtained from 280 K down to 0.025 K in zero field (ZF) and applied fields up to 75 mT. In ZF, the observed loss of initial asymmetry (signal amplitude) and increase of depolarization rate Λ_{ZF} below 13 K indicate the onset of static magnetism, which coexists with superconductivity below Tc. TF μSR results indicate a linear temperature dependence of the superfluid density at low temperature, consistent with nodal superconductivity. The *s+d*-wave model gives the best fit to the observed temperature and field dependencies, and yields an in-plane penetration depth value $\lambda_{ab}(T=0) = 241(3)$ nm.

Large nematic susceptibility in the double-Q C4 magnetic phase of $Ba_{1-x}Na_xFe_2As_2$

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We have studied the nematic susceptibility across the Na-doped Ba122 phase diagram via the Young's modulus, obtained using a three-point bending technique in a capacitance dilatometer [1]. Outside the double-Q phase region, the behavior is found to be very similar to that of K-doped $BaFe_2As_2$ [2]. Deep inside the C4 re-entrant magnetic phase we still observe a sizeable nematic susceptibility, in spite of the well-developed magnetic order. This demonstrates that nematic degrees of freedom have not been frozen out in this phase, and our result is consistent with recent theoretical calculations [3], which predict an enhanced nematic susceptibility. Our finding is expected to be relevant in particular with respect to the relation between superconductivity and nematic fluctuations (e.g. nematic quantum critical point) [4,5]. Finally, we observe a softening of the shear mode below T_C within the C4 re-entrant phase, which is attributed to the strong competition between superconductivity and this magnetic phase[6].

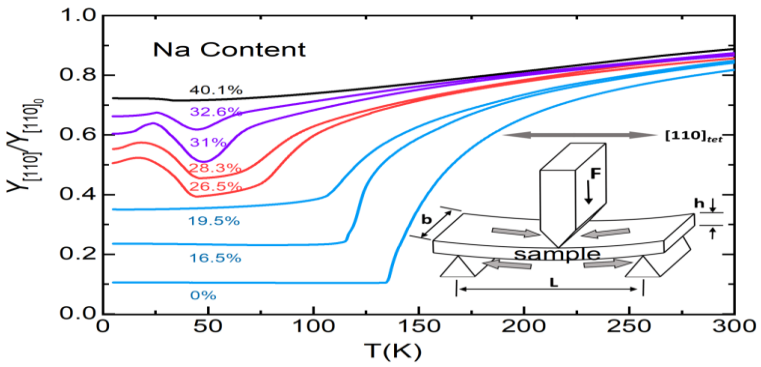

Fig. 1:*Normalized Young's modulus, $Y_{[110]}/Y_{[110]0}$ versus temperature obtained via a static three-point bending measurement inside a capacitance dilatometer. Insert: illustration of setup.*

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Single Level and Multi-Level Kondo Effect in Granular Aluminum Films

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We investigated two types of granular aluminum(Al-Al_2O_3) thin films, having an enhanced critical temperature up to three times more than bulk Al. The mentioned types of samples are obtained by sample preparation on liquid nitrogen cooled substrates or on roomtemperature substrates, where lower deposition temperatureresults in higher maximum Tc and smaller average grain size. In both types, upon decreasing the coupling between the grains Tc is first rising, up to a maximum value where the coupling between the grains is "optimal".Reducingthe coupling between the grains further, Tc decreases until it vanishes at very low coupling. The degree of coupling is controlled by evaporation of clean Al incontrolled partial O_2 pressure[1].

In both types, samples with maximum Tc show almost no change in the normal stateresistivitycurves as a function of temperature.As well, the normal state resistivity showsnon-monotonous temperature dependence. Upon coolingthe resistivity first decreases, reaches a broad minimum, then increases and finally decreases again at low temperatures toward the superconducting state[1].

We will discuss these results within the theory of Florens et al[2,3], predicting that in a regime where the discrete level width exceeds the level separation, a multi-level Kondo effect is expected for quantum dots (QD), showinga non-monotonous temperature dependence of the conductance. We will mainly focus on how does increasing the grain size is being reflected in the temperature dependence of the resistivity curves and how it is in line with the Multi-level Kondo effect. This interpretation of the experimental data is in line with the previously reported presence ofmagnetic moments in these films[4].

In relation to the observed Tc enhancement, Choi et al[5] have studied the Josephson effect through a QD connected to two superconducting leads. They showed that if $T_K>\Delta$ the pair correlation function Δ_d on the dot is larger than in the leads, $\Delta_d>\Delta$. Enhancement ratio Δ_d/Δ in the range of 3 to 5 for $0.1<\Delta/T_K<0.2$ is of the same order as the T_c enhancement in our granular films. The gap Δ was obtained directly by THz measurements using a Mach-Zehnder interferometer at temperatures down to $T<0.5T_c$.

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Metal Induced Superconductivity between Metallic Ti and MoS_2

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Interface between two differnt materials exhibits interesting properties such as interface superconductivity which has been observed in single-atom Pb layer on a semiconducting substrate and the metallic interface between a $LaAlO_2$ layer and a $SrTiO_3$ substrate [1, 2]. Here, we report metal induced superconductivity between metallic Ti and molybdenum disulphide (MoS_2). We fabricated an ionic-liquid field effect transistor (FET) based on MoS_2 (Fig. 1a). Ti/Al (10/100 nm) electrodes were patterned onto thin MoS_2 flake, and Au/Ti gate electrode (10/100 nm) was patterned onto the substrate. A droplet of ionic liquid covered both channel and the gate electrode.

By employing the three probes shown in Fig. 1a, we observed three transitions at 3.7K, 2.8K and 1.0K (Fig. 1b). From the *I-V* curves and the temperature dependence of differential resistance, we concluded that these transitions correspond to the superconducting transition of MoS_2 under the Ti layer (metal induced superconductivity), ion-gated MoS_2 channel and Al, respectively. Additionally, we characterize the metal induced superconductivity by measuring the superconducting gap, and we will discuss the results.

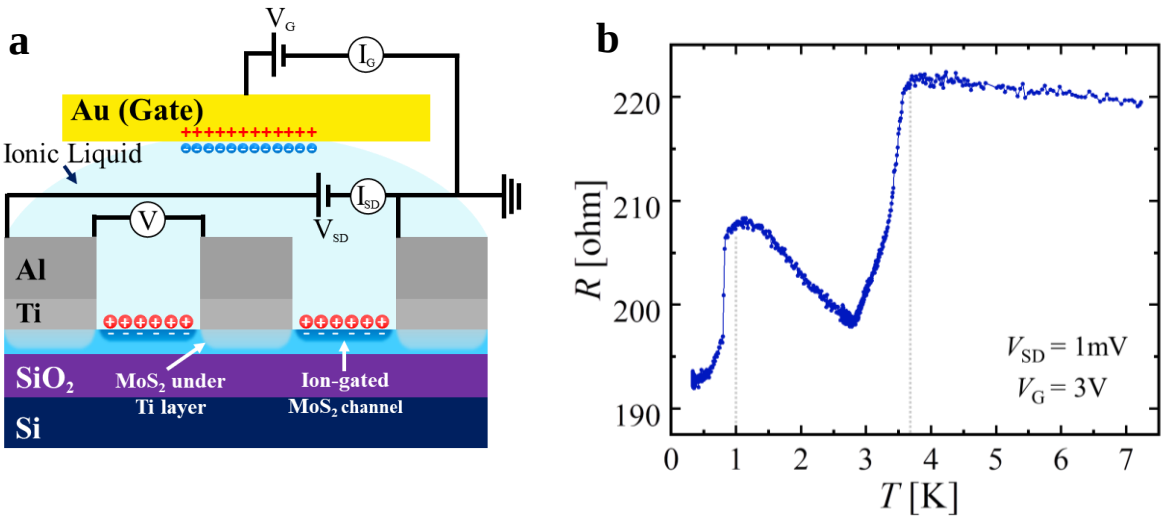

Fig. 1: a, *Schematic illustration of ionic liquid FET.* **b,** *Temperature dependence of Resistance*

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Magnetic Interference Effects on Differential Conductance Curve of SNS Junction Made of a Metallic Channel in Zinc Oxide based Electrical Double Layer Transistor (N) Sandwiched between two Superconducting Niobium Electrodes (S)

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Recently, electric double layer transistors (EDLTs) which are able to accumulate a high two dimensional charge-carrier at the surface of solid substance have attracted considerable attention to drastically control electric properties of the solid in the field of condensed matter physics[1-3]. An EDLT is a type of electric field-effect transistor (FET) that uses ionic liquids as a gate. Since the sheet carrier density of the EDLT is ten times larger than the upper limit of the sheet carrier density of the conventional FETs, there are many reports on the superconducting state induced on the surface of various EDLT channel semiconductors. On the other hand, details of electric transport characteristics between the superconducting electrodes and the two-dimensional electron system induced by EDLT (EDL-2DES) are not clear.Here, we report electrical transport measurements of a SNS junction structure with EDL-2DES induced at the surface of Znic Oxide (ZnO) sandwiched between niobium (Nb) superconducting electrodes. No obvious superconducting current was observed in the current-voltage characteristics of this junction. However, it was observed that the magnetic field interference effects appeared in the differential conductance curve. We discuss the origin of this magnetic field interference effect and mention a possibility that the metal-induced gap-state (MIGS) under the superconducting electrode and two kinds of barrier play an important role in the electric transport properties in the junction.

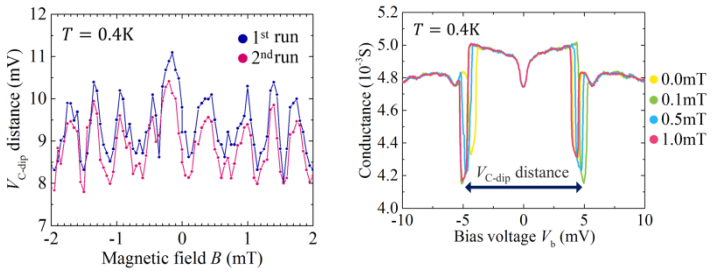

Figure: *the magnetic field interference effects appeared in the differential conductance curve*

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Critical Temperature Enhancement From Quantum Confinement in $Nb_xSrTi_{1-x}O_3$ Thin Films

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The quantum confinement in a quasi-2D geometry, e.g. in the form of a thin film, create quantized subbands in the confined direction, thus modifying both the density of states and the pairing interaction. Such modifications can dramatically influence the critical properties like the superconducting critical temperature: the exact solution of the BCS gap equation at *Tc* for any density and thickness reveals oscillations of *Tc* as a function of film thickness, which are called shape resonances. For a sufficient confinement strength, the peak *Tc* along oscillations in quasi-2D can be considerably higher than the bulk critical temperature. Exploring such confinement-induced variations of *Tc* could open new frontiers in tuning the superconducting properties of nanostructured materials through different confinement geometries. Here we show that $Nb_xSrTi_{1-x}O_3$ thin films embedded in STO show an enhancement of *Tc* consistent with predictions based on quantum confinement. A good qualitative agreement between theory and experiment is obtained if density inhomogeneities are taken into account.

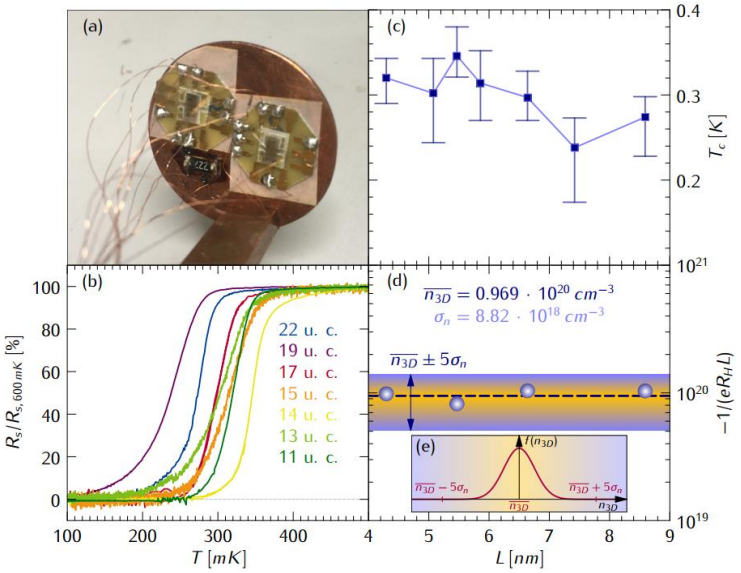

Fig. 1: *Superconducting transition and superconducting Tc oscillation of the $Nb_xSrTi_{1-x}O_3$ samples.*

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Probing Quantum Confinement and Electronic Structure at Polar Oxide Interfaces*

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Polar discontinuities occurring at interfaces between two different materials constitute both a challenge and an opportunity in the study and application of a variety of devices. In order to cure the large electric field occurring in such structures, a reconfiguration of the charge landscape sets in at the interface via chemical modifications, adsorbates or charge transfer. In the latter case, one may expect a local electronic doping of one material: one sparkling example is the two-dimensional electron liquid (2DEL) appearing in $SrTiO_3$ once covered by a polar $LaAlO_3$ layer. Here we show that tuning the formal polarization of a $(La,Al)_{1-x}(Sr,Ti)_xO_3$ (LASTO:*x*) overlayer through chemical composition modifies the quantum confinement of the 2DEL in $SrTiO_3$ and its electronic band structure. The analysis of the behavior in magnetic field of superconducting field-effect devices reveals, in agreement with *ab initio* calculations and self-consistent Poisson-Schrödinger modelling, that quantum confinement and energy splitting between electronic bands of different symmetries strongly depend on the interface total charge densities. These results not only strongly support the polar discontinuity mechanisms with a full charge transfer to explain the origin of the 2DEL at the celebrated $LaAlO_3/SrTiO_3$ interface, but also demonstrate an effective tool for tailoring the electronic structure at oxide interfaces.

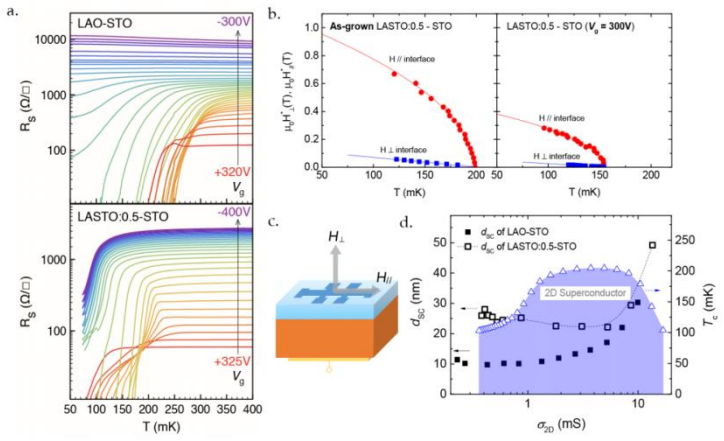

Fig. 1: *Superconducting properties and phase diagram of the LASTO:0.5/STO interface.*

* Paper accepted in Advanced Science.

Transport measurements of underdoped $YBa_2Cu_3O_{7-x}$ under high pressure and magnetic field

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The CDW observed in the cuprates superconductors is associated with a Fermi surface reconstruction that takes place in the underdoped side of the phase diagram and leads to the sign change of the Hall coefficient (R_H). This sign change of R_H provides a useful bulk probe to track the evolution of the CDW as the material is tuned across the phase diagram. Here we have used hydrostatic pressure to change T_c in YBCO and magnetic fields up to 38T to suppress superconductivity, so that the normal state behaviour of R_H can be studied [1]. Results will be presented showing how the CDW evolves with pressure and doping in YBCO samples.

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Anomalous Surface Magnetisation in Nonsymmorphic Single Crystal Superconductor In_2Bi

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Nonsymmorphic superconductors are of particular interest as the combination of nonsymmorphic crystalline symmetries (e.g. glide symmetry) and particle-hole symmetry in the superconducting state is predicted to support topologically protected surface states [1, 2]. Here we studied single crystals of nonsymmorphic superconductor In_2Bi that crystallises in $P6_3/mmc$ space group. The single crystalline phase of the samples was confirmed by the X-ray diffraction. The superconducting properties were characterised by SQUID magnetometry. We show that In_2Bi is a low $\kappa \approx 1.2$ type-II superconductor, similar to Nb [3], with $T_c = 5.85$K (κ is Ginzburg-Landau parameter). The sharp superconducting transition ($\mathbf{\Delta}T < 0.1$K) and an almost reversible magnetisation, corresponding to low bulk pinning, are consistent with the high quality of the samples. We find that In_2Bi shows an unusual magnetic response in the vicinity of the superconducting transition: (i) a notable hysteresis in both field-dependent magnetisation, $M(H)$ near H_{c2} in increasing/decreasing magnetic field; (ii) an additional diamagnetic response (not related to the usual surface superconductivity) that appears below the critical field for surface superconductivity (H_{c3}) and above H_{c2}. Our DFT calculations of In_2Bi band structure revealed the presence of surface states for several different surface terminations. Accordingly we propose that the above features of magnetisation are likely to be signatures of symmetry- or topology- protected surface states, as predicted by theory [4]. We demonstrate that this anomalous surface magnetisation is weakly sensitive to bulk pining but disappears after the surface of a sample is mechanically degraded.

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Superconducting Proximity and Electric Field Effect on Monolayer Graphene/Single-unit-cell $Bi_2Sr_2CaCu_2O_{8+x}$ Van der Waals Heterostructure

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The proximity induced superconductivity in monolayer graphene by cuprate superconductors offers a chance to study unusual high temperature superconductivity in single-atom-thick. The interface quality is the key to the pronounced proximity effect, while the cuprate grown by pulsed laser ablation deposition method usually has nanoscale surface roughness. Here we fabricate the monolayer graphene/single-unit-cell cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+x}$(Bi2212) Van der Waals heterostructure by mechanically exfoliating Bi2212 down to the single-unit-cell that has a flat surface at the atomic level. Using point contact measurement on this heterostructure, we found a proximity-induced superconducting gap at graphene whose characteristics are observable up to 50 K. Moreover, the heterostructure exhibits the tunneling field effect transistor feature under the large bias current. The graphene/cuprates heterostructure provides an important platform to study the novel temperature superconductivity and develop potential device applications.

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The Electronic Structure of $LaIn_3$ and $CeIn_3$ films

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Fudan University

In recent years, Heavy-fermion systems have attracted more and more attention for the coexistence of various interesting physical properties such as superconductivity and anti-ferromagnetism. Compared with the Heavy-fermion material CeIn3, LaIn3 has the same crystal structure but different superconductivity properties and the magnetic ground state, which may be caused by the influence of *f* electrons. To study the intrinsic mechanism how *f* electrons changes the superconductivity and magnetism, we grew CeIn3 and LaIn3 films by molecular beam epitaxy and measured them by angular resolved photoemission spectroscopy. For the first time, we get the electronic structure of CeIn3 and LaIn3 films and observe the difference brought by *f* electrons in the electronic structure, providing an opportunity for further studying the relationship between superconductivity and anti-ferromagnetism. In the meantime, a slight change possibly resulting from the difference of lattice parameters in the electronic structure is also observed.

AC losses in superconducting wires and tapes - a comparative study of the behavior in $Sr_{0.6}K_{0.4}Fe_2As_2$ and MgB_2

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Iron pnictide based superconducting wires and tapes carry promising potential for use in high-power applications due to their relatively low sensitivity to high magnetic fields at the 10 to 30K temperature range, which is easily attainable using conduction cooling. For such applications, the superconductor is often exposed to AC current ripple at the kHz regime, typical of switching control algorithms. Therefore, it is crucial to study the energy losses under such conditions and understand the mechanisms governing these losses.

We describe herethe first study of AC losses in self-field of iron-based seven-core silver-sheathed$Sr_{0.6}K_{0.4}Fe_2As_2$ (Sr122) superconducting tape, and compare its behavior with commercially available MgB_2 wires and tapes studied earlier [1, 2]. The tape was measured at various temperatures below T_c in AC transport current of frequencies up to 18kHz. Normalized loss per cycle per meter recorded at various temperatures exhibit non-monotonic behavior; increasing with increasing frequency and peak at around 5kHz. Further frequency increase reduces the losses. Analysis of the amplitude dependent losses suggest that at low frequencies hysteresis losses within the superconductor dominate, whereas at high frequencies eddy currents in the tape become the dominant loss mechanism.

A comparison of these results with previous data obtained for a Monel sheathed MgB_2 wire [1] shows that the losses in the pnictide tape are orders of magnitude lower. Apparently, the high-permeability of the magnetic Monelamplifies the time-dependent flux change in the metal and hence the eddy current losses, which then dominate the entire energy losses. A comparison to a Ti-sheathed MgB_2 tape [2] demonstrates that its losses are comparable with these of the pnictide tape; at low frequencies the Ti-MgB_2 tape exhibits lower losses but at high-frequencies the pnictide wins.

The results presented here suggest that a further development of multi-filament, small twist-pitch pnictide superconducting wires and tapes may be beneficial for high-current applications.

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Tunneling Spectroscopy of Gate-induced Superconductivity in MoS_2

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The ability to gate-induce superconductivity by electrostatic charge accumulationis a recent breakthrough in physics and nano-electronics [1, 2]. With the exception of $LaAlO_3/SrTiO_3$ interfaces, experiments on gate-induced superconductors have been largely confined to resistance measurements, which provide very limited information about the superconducting state. Here, we report the study of gate-induced superconductivity in MoS_2 by performing tunneling spectroscopy to determine the energy-dependent density of states (DOS) for different levels of electron density *n* [3]. In the superconducting state, the DOS is strongly suppressed at energy smaller than the gap, , which is maximum (~ 2 meV) for *n* of ~ 10^{14} cm^{-2} and decreases monotonously for larger *n*. A perpendicular magnetic field *B* generates states at *E* < that fill the gap, but a 20% DOS suppression of superconducting origin unexpectedly persists much above the transport critical field. Conversely, an in-plane field up to 10 T leaves the DOS entirely unchanged. Our measurements exclude that the superconducting state in MoS_2 is fully gapped and reveal the presence of a DOS that vanishes linearly with energy, the explanation of which requires going beyond a conventional, purely phonon-driven Bardeen-Cooper-Schrieffer mechanism.

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Electronic Structure in the Antiferromagnetic State of Ni-doped $TlCo_2Se_2$

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The 122* series of alkalie doped iron-selenides superconductors($A_xFe_{2-y}Se_2$, A=K, Rb, Cs, Tl) haveattracted a lot of attention because they possess unique electronic structure with only electron Fermi pockets. However, many intriging physical properties are still in debatedue to the intrinsic phase separation[1-4]. In Ni doped $TlCo_{2-x}Ni_xSe_2$ (TCNS)with antiferromagnetic (AFM) ordering ground state, it is verifiedby X-ray diffraction, neutron diffraction[5,6] and electro probe micro-analyzer that the $TlCo_{2-x}Ni_xSe_2$crystals are homogeneousand free of phase separation as well as superconducting in heavily doped ones, which makes them quite suitable plateform for deep investigations on the correlation between magnetizatism and superconductivity (SC). In this work, we present ARPESstudy for TCNS (x=0, 0.6, 1.2, 1.6, 1.9, 2.0) samples. The parent TCS (x=0)sample has an incommensurate spiral spin structre. With the increase of Ni doping content, the Néel temperature (T_N) increase firstly and then decrease above x_c. Meanwhile, the lattice parameters vary. The AFM ordering disappears at x≅1.7 eventually after which superconductivity occurs with maximum T_c~4 K for x=2.The superconducting temperature becomes higher with the doping concentration increases. ARPES results show a Dirac cone band along Γ-M direction. It shifts down obviously with dopingwhich might be owing to the chemical potential. We also shown that the AFM-SC evolution in TCNS can be understood in the form of the change of their effective band width, which is closely related to the iternerant and elecoron correlation. The study of Fermi surfaces evolution can clarify if there exists carrier-doping-induced phase transition in this system. By studing the evolution of carrier concentation and band width, our results faciliate to figure out the electronic structure for deep understanding on the complex phase diagram in the system.

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Impurity Effects on the Superconductivity in $LaO_{0.5}F_{0.5}BiS_2$

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The discovery of superconductivity in $LaO_xF_{1-x}BiS_2$ compounds captured the attention of physicists worldwide. The compounds have layered crystal structure composed of superconducting BiS_2 layers and insulate layers of La (O, F). The layered crystal structure is analogous to those of high-temperature (high-T_c) cuprate and Fe-based superconductors. Regarding the symmetry of the superconducting gap, the magnetic penetration depth measurements and specific heat measurements for the La-based and Nd-based BiS_2 superconductors have indicated the full gap with *s*-wave [1-3]. However, angle-resolved photoemission spectroscopy (ARPES) measurement suggested the large superconducting-gap anisotropy and attracted much attention [4]. Recently, the point contact spectroscopy measurement suggested the gap symmetry is unconventional pairing symmetry [5]. In order to clarify superconducting gap symmetry and bulk nature of superconductivity, Sb is added as an impurity to the Bi site in the typical BiS_2 superconductor—$LaO_{0.5}F_{1-0.5}BiS_2$. And then, we investigated the effects of impurity on superconductivity by specific heat measurements.

Single crystals of $LaO_{0.5}F_{0.5}Bi_{1-y}Sb_yS_2$ (y=0.00, 0.06) were grown by using a CsCl/KCl-flux method under ambient pressure. The specific heat was measured in the temperature range of 0.3K~10K by PPMS. Figure 1 shows temperature dependences of the electronic specific heat for y=0.00 and 0.06. The electronic specific heat was obtained by subtracting the lattice contribution βT^3 from the total specific heat $C(T)$. There are clear jumps that correspond to the superconducting transitions of both the two samples. The presence of the jumps clearly indicates the bulk nature of superconductivity in these compounds. For the pure sample of y=0, it fits well with BCS theory and the energy gap is full gap with *s*-wave in weak-coupling limit. For the impurity-doped sample (y=0.06), the T_c is suppressed by ~0.4 K; T_c/T_c ~ 20% for 6% Sb-doping. Interestingly, below the T_c, the C/T curves are going to be coincident with each other in spite of the suppression of T_c. This result suggests that the superconducting gap is a full gap with no sign change.

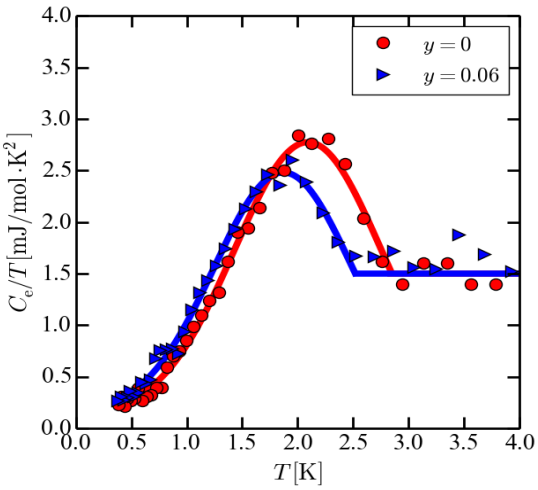

Fig. 1: *T dependences of electronic specific*

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Manifestation of charge carriers and vortex systems incoherence in electron-doped cuprates

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Investigations of highly correlated systems that are near the point of a quantum phase transition between fundamentally different ground states (from metallic to dielectric, from antiferromagnetic to superconducting, etc.) are of the great interest. Strong fluctuations that develop in the vicinity of a continuous quantum phase transition lead to significant electron correlations, which makes it difficult to describe these systems within the framework of the standard Fermi liquid theory. Moreover, the problem of the relationship between superconductivity and magnetism is always topical in condensed matter physics.

The in-plane and out-of-plane temperature and magnetic field dependencies of the magnetoresistivity and Hall resistivity in the single-crystal films of $Nd_{2-x}Ce_xCuO_4/SrTiO_3$ were investigated.

Analysis of the resistivity anisotropy coefficient indicates that the transfer in the *c* direction is sharply incoherent in the coexistence region of the antiferromagnetic and superconducting ordering (x = 0.135, 0.145) and approaches the coherent phase in the superconducting phase (x = 0.15).

The anisotropic character of the Hall coefficient in $Nd_{2-x}Ce_xCuO_{4+\delta}/SrTiO_3$ films with different orientations of the *c* axes (001) and (1$\bar{1}$0) indicates the presence of incoherent transport of charge carriers between conducting planes and the features of the vortex motion in a two-dimensional system [1,2].

We assume that the coexistence (and competition) of the two types of ordering in the quantum wells of CuO_2 facilitates the incoherent nature of carrier transport along the *c* axis in the electron-doped single-crystal films. The influence of nonstoichiometric disorder on the anisotropy of magnetoresistance and Hall resistance is also discussed.

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Nematic superconducting state in the 122-type superconductors

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Nematic order often breaks the tetragonal symmetry of iron-based superconductors. It arises from regular structural transition or electronic instability in the normal phase. In this work, we studied on the nematic superconducting state on both electron-type $BaFe_{2-x}Ni_xAs_2$ and hole-type $Ba_{1-x}K_xFe_2As_2$ superconductors, by measuring the angular dependent in-plane magnetoresistivity and the second upper critical in the vicinity of the superconducting transition. An obvious evidence of the nematic superconducting state is observed for both superconductors, while the symmetry behavior depends on the doping level and temperature. We will introduce the possible origin for the nematic superconducting state.

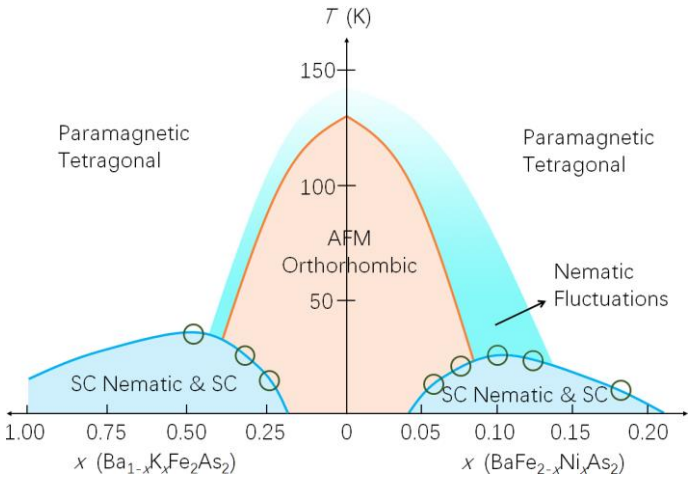

Fig. 1: *Phase diagram of electron-type $BaFe_{2-x}Ni_xAs_2$ and hole-type $Ba_{1-x}K_xFe_2As_2$ superconductors.*

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Interface Induced Zeeman-protected Superconductivity in Ultrathin Crystalline Lead Films

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Two dimensional (2D) superconducting systems are of great importance to exploring exotic quantum physics. Recent development of fabrication techniques stimulates the studies of high quality single crystalline 2D superconductors, where intrinsic properties give rise to unprecedented physical phenomena. Here we report the observation of Zeeman-type spin-orbit interaction protected superconductivity (Zeeman-protected superconductivity) in 4 monolayer (ML) to 6 ML crystalline Pb films grown on striped incommensurate (SIC) Pb layers on Si(111) substrates by molecular beam epitaxy (MBE). Anomalous large in-plane critical field far beyond the Pauli limit is detected, which can be attributed to the Zeeman-protected superconductivity due to the in-plane inversion symmetry breaking at the interface. Our work demonstrates that in superconducting heterostructures the interface can induce Zeeman-type spin-orbit interaction (SOI) and modulate the superconductivity.

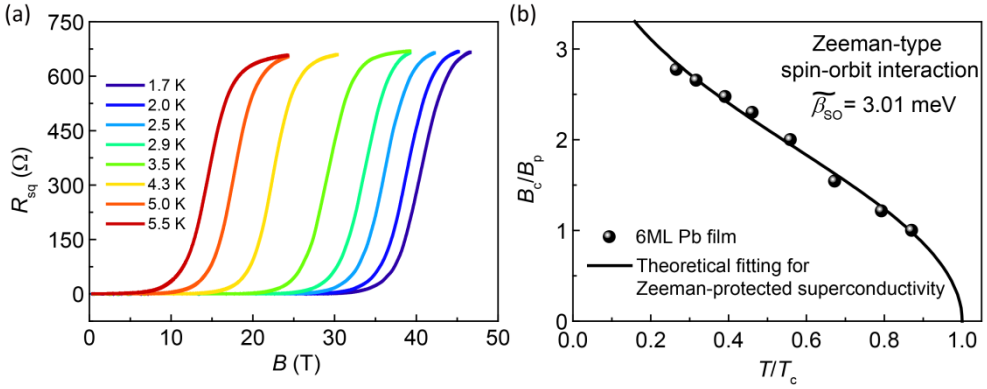

Fig. 1: *Evidence of Zeeman-protected superconductivity in 6ML crystalline Pb film.*

TF-μSR Study on Noncentrosymmetric Superconductor $PbTaSe_2$

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In a noncentrosymmetricsuperconductor, the lack of inversion symmetry introducesan antisymmetric spin-orbit coupling. This may split theelectron bands by lifting the spin degeneracy, allowingadmixture of spin-singlet and spin-triplet pairing states. Recently, the layered, noncentrosymmetric compound $PbTaSe_2$ is found to be superconducting belowT_c= 3.7 K. The gap symmetry of $PbTaSe_2$ still remains controversial. We have performed transverse field muon spin rotation experiments on single crystal of $PbTaSe_2$down to 0.2 K. The temperature dependence of in-plane penetration depth can be fit with a fully gapped two-band model, consistent with previous published data. However, the *c*-axis penetration depth shows novel temperature dependence.

Universal Pressure Dependent Superconductivity Phase Diagrams for Tetradymite Topological Insulators

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The recent discovery of three dimensional topological insulators (3D-TIs) that bear highly insulating state in bulk and non-trivial topological surface state (TTS) provides a unique platform to find new phenomena and to know connection between topological nature and superconductivity. In this poster we will demonstrate pressure-induced two superconductivity phase transitions in the quintessential tetradymite topological insulators Bi_2Te_2Se (BTS) and $Bi_{1.1}Sb_{0.9}Te_2S$ (BSTS). Then we compare the superconducting phase diagram of BTS and BSTS with prior works on Bi_2Se_3 and Bi_2Te_3 and as a consequent to uncover the universality of the pressure dependent superconductivity phase diagrams in the tetradymite topological insulators. It is expected that our finding can lead to a new insight into understanding the phase diagrams and the connection between the topological state and the superconducting states of these fascinating tetradymites.

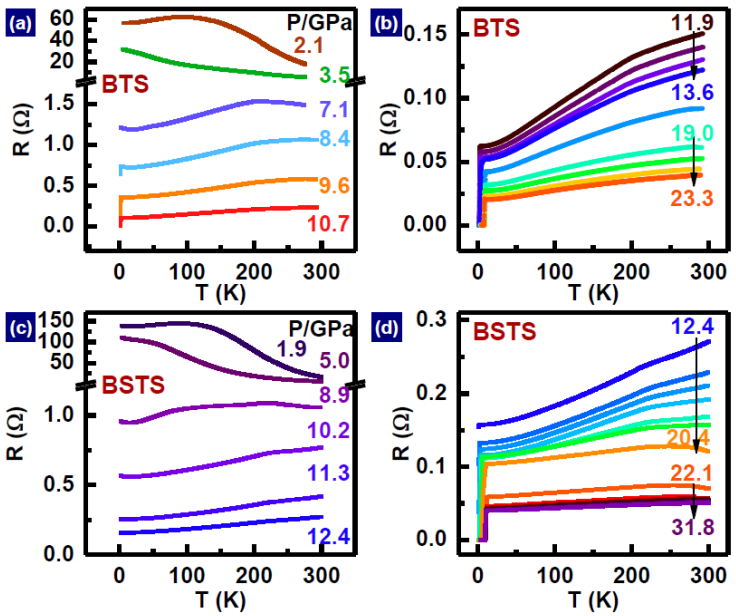

Fig. 1: *Temperature dependence of resistance in BTS and BSTS*

Spin Excitations in the New 1144-Type Iron-Based Superconductor $CaKFe_4As_4$

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We use neutron scattering to study the spin excitations in the new superconducting iron pnictide CaKFe4As4, one of the newly discovered 1144-type iron-based superconductors. For the low-energy magnetic excitations, triple spin resonance modes with odd and even L-symmetries are found. The appearance of odd and even L–symmetries of spin resonance modes in CaKFe4As4 is attributed to the non-degenerate spin excitations from Fe-As bilayer similar to the cuprate superconductors with Cu-O bilayer. While, the high energy spin excitations show a nearly temperature independent behavior with a band top around 220 meV, which is very similar to the hole-doped 122 system.

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Reference:
Tao. Xie, *et al.* Phys. Rev. Lett. 120, 267003 (2018).
Tao. Xie, *et al.* unpublished manuscript.

Universality of Pseudogap and Emergent Order in Lightly Doped Mott Insulators

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High temperature superconductivity as it manifests in the cuprates was for long time suspected to be strongly related to the copper oxide layers, and therefore specific to only this family of materials. Using spectroscopic-imaging scanning tunneling microscopy, we visualize the electronic states of the iridate $(Sr_{1-x}La_x)_2IrO_4$, which is chemically radically different from the cuprates but also an effective Mott insulator. We find that above a certain doping threshold, a phase separated state emerges, with the nucleation of pseudogap puddles around clusters of dopant atoms [1]. Within these puddles, we observe the same iconic electronic order that is seen in underdoped cuprates. At lower doping, we measure fully gapped Mott spectra, with a gap value that is in disagreement with photoemission and optical experiments. We find that this is evidence for poor electronic screening in the lightly doped iridates, and we develop an algorithm able to extract the intrinsic value of the gap, reconciling our measurement with literature and illustrating the importance of considering field penetration when performing STM experiments on poorly screened quantum materials [2].

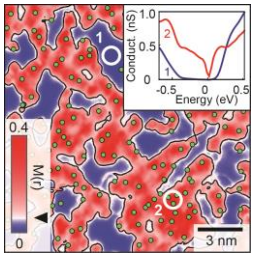

Fig. 1: *Nanoscale phase separation between Mott insulating phase (in blue, with typical spectrum #1 in the inset) and pseudogap phase (in red, with typical spectrum #2 in the inset). The pseudogap phase nucleates around clusters of dopant atoms, the positions of which are indicated with green dots.*

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STM/STS measurements on heavy fermion $CeRhIn_5$ thin films

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It is a long-standing important issue in heavy fermion physics whether *f*-electrons are itinerant or localized when the magnetic order occurs. There are two controversial scenarios about itinerancy of *f*-electrons in magnetic ordered phase in the vicinity of the quantum critical point (QCP). One is the spin-density wave (SDW) scenario, in which large Fermi surfaces due to the *c-f* hybridization remain even in magnetic ordered phase. The other is the Kondo breakdown scenario, in which the *c-f* hybridization state disappears in the magnetic state and only small Fermi surfaces due to conduction electrons appear.

$CeRhIn_5$ is a typical heavy fermion compound with antiferromagnetic (AFM) ground state. A drastic change of the Fermi surface at the QCP under pressure has been reported by de Haas-van Alphen (dHvA) measurements [1]. This has been discussed in terms of the abrupt change of the Fermi surface from small to large ones at the QCP, which supports the Kondo breakdown scenario [2]. On the other hand, specific heat measurements report that the large electronic specific coefficient γ persists even below T_N [3, 4]. This suggests the presence of heavy quasiparticles in the magnetically ordered state, implying a large Fermi surface, which is consistent with the SDW scenario. To clarify which of these two scenarios holds for $CeRhIn_5$, it is important to probe the existence of the heavy quasi-particles in a wide temperature range.

Here, we report the measurements of the *c-f* hybridization gap in the density of states as a probe for the itinerancy of *f*-electrons over a wide temperature range in $CeRhIn_5$ using scanning tunneling microscopy (STM) which has high energy resolution in atomic scale. By the state-of-the-art molecular beam epitaxy technique [5], we have successfully prepared an atomically flat surface of $CeRhIn_5$, which is difficult to be obtained by cleavage of single crystals. The conductance spectra above T_N clearly resolve the energy gap due to the *c-f* hybridization as well as the crystal electric field excitations. These structures persist even below T_N. Moreover, an additional dip in the conductance spectra develops due to the AFM order. These results provide direct evidence for the presence of itinerant heavy *f*-electrons participating in the Fermi surface even in the magnetically ordered state of $CeRhIn_5$, which supports the SDW scenario [6].

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Tunneling spectroscopy study of several essential issues in unconventional superconductors and development of combi-LMBE-STM system

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Tunneling spectroscopy study in unconventional superconductors disclosed extremely complicated electronic states during the past three decades, which is of great help to understand the high-T_c superconducting mechanism. Here, we study the tunneling spectra in parent cuprate $Pr_2CuO_{4\pm\delta}$ and spinel oxide superconductor $LiTi_2O_4$ thin films by point-contact technique. We suggest that the normal-state gap in $Pr_2CuO_{4\pm\delta}$ stems from disorder-induced electron-electron interaction[1]. In addition, we observe prominent electron-phonon coupling in $LiTi_2O_4$ for the first time, which may attribute to oxygen vacancies enhanced Jahn-Teller distortions[2]. In order to improve the efficiency and accuracy in building the phase diagram of unconventional superconductors, we design and set up a combi-LMBE-STM system, which can deposite films with continuous doping and measure their electronic states in-situ. The preliminary experiments are expected on this system in the coming few months.

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Crystal and Electronic structure of HTSC cuprates and related Antiferromagnetic Phases as Function of Temperature

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The height of CuO_5-pyramides (d_{apical}) demonstrates a minimum between ~150 K and ~250 K (Figure 1*a*, [1]) as it is established using X-ray and neutron powder diffraction for HTSC-cuprates. Electronic structure was calculated ab initio based on crystal structure data for HTSC cuprates $Y_{1-x}Ca_xBa_2Cu_3O_y$ [2] and $Tl_{0.8}Hg_{0.2}Ba_2Ca_2Cu_3O_y$ [3]. It is shown that apical bond compression is accompanied by the appearance of the peak at 0.3-0.4 eV under Fermi level in electronic structure [4]. This peak is associated with localization of electronic states of barium and apical oxygen situated at the top of CuO_5-pyramid. These localized states dissolve when temperature decreases below ~150 K. We establish that antiferromagnetic cuprates Y_2BaCuO_5 and $BaCuO_2$ demonstrates similar behavior (Figure 1*b*). Possible origin and common features of crystal and electronic structure of HTSC and AFM cuprates are under discussion.

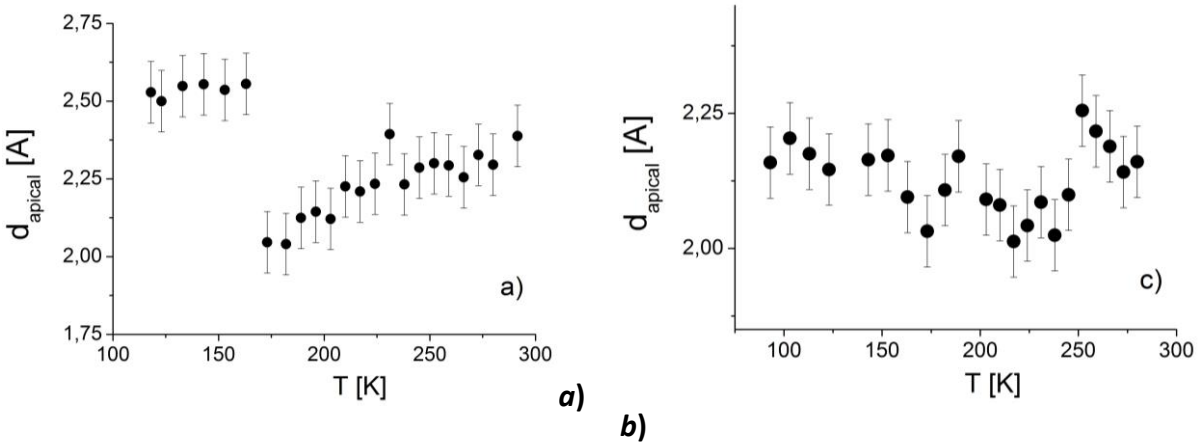

Fig. 1: *Apical bond length (d_{apical}- the height of CuO_5-pyramides) for HTSC-$Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{6.7}$ (a) and AFM- Y_2BaCuO_5 (b).*

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A full superconducting gap in noncentrosymmetric Re_6Hf by point-contact Andreev reflection spectroscopy

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We report a fully gapped s-wave symmetry in the noncentrosymmetric superconductor Re_6Hf with a superconducting transition temperature Tc ~ 6.0 K by point-contact Andreev reflection spectroscopy. The point-contact conductance spectra can be well fitted by the s-wave Blonder-Tinkham-Klapwijk (BTK) model, where the superconducting gap follows a standard BCS behavior as a function of temperature or magnetic field. The gap at 0 K is estimated to be $\Delta_0 = 0.92$ meV, yielding $2\Delta_0 / k_B T_c \approx 3.56$. Hence, our results are consistent with a fully gapped pairing symmetry with a negligible contribution of spin-triplet superconducting component in Re_6Hf.

Development of sensitive 3D vector VSM and applications to characterization of HTSC

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In most cases of magnetic measurement, magnetic moment could be taken as a scalar quantity, when only one component of vector magnetic moment is sufficient since the direction of the measured has been predetermined. Whereas, some magnetic researches require full components of vector magnetic moment or direction of magnetic moment is unknown, when the macro magnetic moment is not directly stimulated by pure magnetic field, but rather influenced by other kind of fields such as stress, heat or radiation[1]. Unfortunately, no commercial instrument has function of simultaneously full vector measurement. Therefore, 3d vector vibration sample magnetometer (VSM) has been designed and developed for advanced magnetic investigations. To get the three components of magnetic moment simultaneously, we have designed a sophisticated coil set, where well-pairing coil array can measure three components independently, with high sensitivity and low cross talking among each component. Furthermore, a multichannel precision lock-in amplifier (LIA) has also been developed for detection of three-component signals of magnetic moment with high efficiency[2-4]. Preliminary result shows that developed vector VSM has sensitivity below 1e-7 emu and angle resolution below 1 degree. To enhance the convenience of various physical research, our vector VSM measurement system has been connected and integrated to a cryo-free low temperature and high field platform. The picture of the vector VSM and typical measurement for HTSC has been shown in Figure 1. We expect wider cooperation with magnetic researchers around the world.

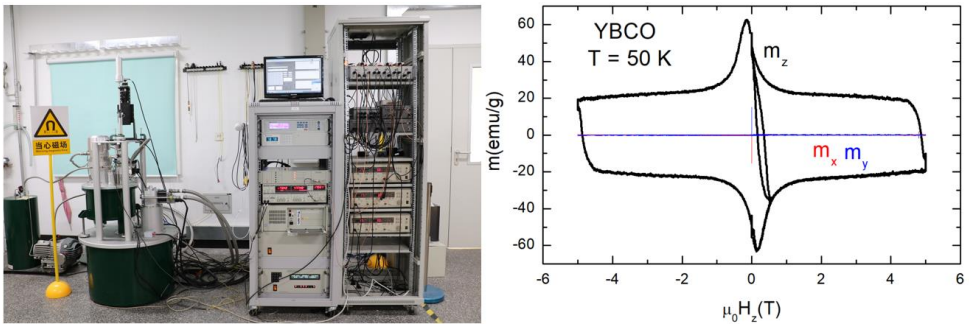

Fig. 1: *Picture of the vector VSM and a typical measurement result for HTSC.*

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Orbital order and quantum nematic fluctuations in $NaFe_{1-x}Co_xAs$

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In cuprate and iron-based high-temperature superconductors, the magnetic order has been extensively studied and its critical quantum fluctuations is thought to be important for electrons to form into Cooper pairs. In iron pnictides, in additional to the magnetic order, there also exists an electronic nematic order that breaks rotation symmetry. Whether the nematic fluctuations plays an equal role is still under debate. $NaFe_{1-x}Co_xAs$ is a system where magnetic and nematic transitions are well separated. Here we report nuclear magnetic resonance (NMR) measurements on $NaFe_{1-x}Co_xAs$ ($0 \le x \le 0.056$) that revealed orbital and spin nematicity occurring at a temperature T^* far above T_s in the tetragonal phase [1]. We show that the NMR spectra splitting and its evolution can be explained by an incommensurate orbital order that sets in below T^* and becomes commensurate below T_s, which brings about the observed spin nematicity [1]. In the poster, we will present experimental evidence for quantum nematic fluctuation [2], and discuss its role on various properties and superconductivity itself.

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Structural phase transition, precursory electronic anomaly, and strong-coupling superconductivity in quasi-skutterudite $(Sr_{1-x}Ca_x)_3Ir_4Sn_{13}$ and $Ca_3Rh_4Sn_{13}$

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The interplay between superconductivity and structural phase transition has attracted enormous interests in recent years. For example, in Fe-pnictide high temperature superconductors, quantum fluctuations in association with structural phase transition have been proposed to lead to many novel physical properties and even the superconductivity itself. Here we report a finding that the quasi-skutterudite superconductors $(Sr_{1-x}Ca_x)_3Ir_4Sn_{13}$ (x = 0, 0.5, 1) and $Ca_3Rh_4Sn_{13}$ show some unusual properties similar to the Fe-pnictides, through ^{119}Sn nuclear magnetic resonance (NMR) measurements [1]. In $(Sr_{1-x}Ca_x)_3Ir_4Sn_{13}$, the NMR linewidth increases below a temperature T^* that is higher than the structural phase transition temperature T_s. The spin-lattice relaxation rate ($1/T_1$) divided by temperature (T), $1/T_1T$ and and the Knight shift K increase with decreasing T down to T^*, but start to decrease below T^*, and followed by more distinct changes at T_s. In contrast, none of the anomalies is observed in $Ca_3Rh_4Sn_{13}$ that does not undergo a structural phase transition. The precursory phenomenon above the structural phase transition resembles that occurs in Fe-pnictides. In the superconducting state of $Ca_3Ir_4Sn_{13}$, $1/T_1$ decays as $\exp(-\Delta/k_BT)$ with a large gap $\Delta = 2.21\ k_BT$, yet without a Hebel–Slichter coherence peak, which indicates strong-coupling superconductivity where phonon damping suppressed the coherence peak. Our results provide new insight into the relationship between superconductivity and the electronic-structure change associated with structural phase transition.

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NMR study on $Sr_xBi_2Se_3$

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As a topological insulator, Bi_2Se_3 has attracted a lot of research attention. Recently, it was reported that Cu doping in Bi_2Se_3 produces bulk superconductivity with a maximum Tc ~ 4 K, and possible topological superconductivity was also suggested. Sr doping in Bi_2Se_3 is also reportedly to induce superconductivity with a large superconducting volume fractions and with an unexpected two-fold electronic symmetry, which also attracts experimental interests in the search for possible topological superconductivity in this compound. In this poster, we report our recent NMR results on $Sr_xBi_2Se_3$.

Reduction in Néel Temperature of Nanocrystalline La_2CuO_4 Probed by μSR and NMR

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Finite size effects in nano-scale order introduce novel phenomena in magnetic materials. For instance, Punnoose *et al*. have reported the reduction in the Néel temperature, T_N, of CuO from 290 K down to 40 K when the size of the CuO particle is about 5 nm [1-3]. We examined such kind of nano-sized effects in the typical Mott insulator La_2CuO_4 (LCO). We aim to clarify how magnetic properties of LCO changes with changing in the particle size by using muon spin relaxation (μSR) and NMR methods. In the case of the particle size of 96 nm, as shown in Fig. 1, clear muon spin precession due to the appearance of long-range magnetic ordering was observed below about 60 K which is much lower than that observed in bulk LCO (~300 K). The saturated internal field at the muon sites was about 420 G which is the same as that observed in bulk LCO. This result means that T_N in nano-sized LCO is significantly suppressed compared with bulk one. The ^{139}La-NMR results also showed that internal fields started to appear around the same temperature estimated from μSR measurement. We report μSR and NMR results on other LCO samples which have different sizes and discuss possible reasons of the reduction in T_N in nano-sized LCO.

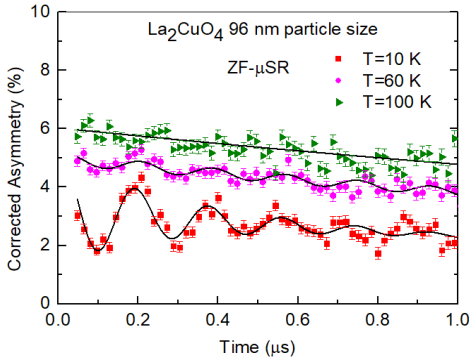

Fig. 1: *μSR time spectra at various temperatures in nano-sized La_2CuO_4 with a particle size of 96 nm. Solid lines are the best-fit results assuming the single cosine function to reproduce the muon-spin precession behavior.*

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Universal T-linear Resistivity and Planckian Limit in Overdoped Cuprates

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The linear temperature dependence of the electrical resistivity is a peculiar phenomenon that has been observed in a few cuprates near their pseudogap critical point p^* as $T \rightarrow 0$ [1, 2]. It could be the signature of quantum criticality, as seen in the organics and heavy fermions, for example [3]. We report new resistivity data in high magnetic fields (to suppress superconductivity at low T) on a highly overdoped sample of $Bi_2Sr_2CaCu_2O_8$ (T_c = 50 K) [4], close to p^* [5]. This sample reveals a T-linear resistivity at low T, with the same slope per CuO_2 plane as Nd-LSCO near its own critical point [2]. We show that the value of this slope, for both hole-doped and electron-doped cuprates, is linked to the effective mass m^* of the charge carriers via a universal scattering rate $1/\tau = k_B T/\hbar$, namely the Planckian limit [6]. Therefore, the slope of T-linear resistivity follows the variation of m^* and this explains two intriguing experimental observations: 1) the decrease of the slope with doping in LSCO [1]; 2) the much larger values in hole-doped than electron-doped cuprates.

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AC Resistance of Driven Vortices in a Superconductor Measured by Microwave Technique

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Understandings of the physics of driven vortices in a superconductor is a challenging issue owing to the nonlinearity, the randomness of pinning sites, and the multi-degree of freedom. The moving vortices dissipate energy via the viscous drag force and the dynamic pinning force. The microscopic nature of dissipation processes related to the pinning is still under debates despite its importance for practical applications of superconducting magnets. It is also essential for the elucidating the solid friction since the equation of motion for the vortex is analogues to that of the atom or asperity at the solid-solid interface [1]. In order to investigate the microscopic origin of the dissipation, we measured the ac resistivity of driven vortices by using a superconducting transmission line resonator.

We fabricated the superconducting resonators with leads for introduction of dc driving current. The resonators were made of rf sputtered Nb films. The center frequencies of the resonators were 3.7 GHz and 7.9 GHz. The current dependence of the center frequency, f_0, and the inverse of the quality factor, Q^{-1}, was measured with increasing dc current. Distinct changes were observed in both f_0 and Q^{-1}. As we increase the dc current, f_0 changed parabolically as indicated in Fig. 1, which was understood as the suppression of the order parameter of the superconductor by dc current. This also indicates that the motion of vortices had little influence on f_0. On the other hand, Q^{-1} increased above 71 mA, where macroscopic translational motion of vortices occurs. We plotted both the change of the resistance, ΔR, calculated from the Q^{-1}, and the translational velocity in Fig. 2. It revealed that ΔR depends on the frequencies, and it was difficult to interpret within the framework of the simple mean-field model [2]. We are now trying to understand these behaviors both experimentally and theoretically.

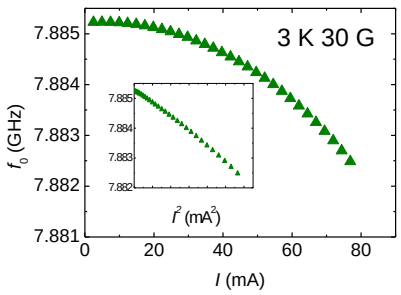

Fig. 1: The dc driving current, I vs the change of the center frequency, f_0. The inset shows the I^2 vs f_0.

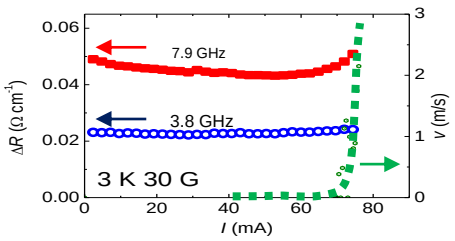

Fig. 2: The dc driving current, I vs the change of the resistance per unit length, ΔR, and the translational velocity, v.

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Nodeless superconductivity in the SnAs-based van der Waals type superconductor $NaSn_2As_2$

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We grew the single crystals of the SnAs-based van der Waals (vdW)-type superconductor $NaSn_2As_2$ and systematically measured its resistivity, specific heat, and ultralow-temperature thermal conductivity. The superconducting transition temperature T_c = 1.60 K of our single crystal is 0.3 K higher than that previously reported. A weak but intrinsic anomaly situated at 193 K is observed in both resistivity and specific heat, which likely arises from a charge-density-wave (CDW) instability. Ultralow-temperature thermal conductivity measurements reveal a fully-gapped superconducting state with a negligible residual linear term in zero magnetic field, and the field dependence of κ_0 / T further suggests $NaSn_2As_2$ is an *s*-wave superconductor.

Coexistence of Static Magnetism and Superconductivity in $Pr(O_{0.5}F_{0.5})BiS_2$ as Revealed by Muon Spin Rotation/Relaxation

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BiS_2-based superconductors *Ln*$(O_{0.5}F_{0.5})BiS_2$ (*Ln* =La, Ce, Pr, Nd and Yb) have attracted much interest, since these compounds are layered in structure and similar to that of high T_c cuprates and Fe-pnictides. $La(O_{0.5}F_{0.5})BiS_2$ is a pure superconductor whose T_c is 2.7 K. Interestingly, a higher T_c of 4.2K was obtained after replacing non-magnetic ion La with magnetic Pr ion. We have performed muon spin relaxation/rotation measurements on ambient-pressure-grown polycrystalline $PrO_{0.5}F_{0.5}BiS_2$ down to 0.025 K. Our data suggest the coexistence of static magnetism and superconductivity in $Pr(O_{0.5}F_{0.5})BiS_2$.

Structural phase transition, two superconducting domes, and microscopic coexistence of antiferromagnetism and superconductivity in $LaFeAsO_{1-x}F_x$ ($0 < x \leq 0.75$)

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Antiferromagnetism and electronic nematicity are two noteworthy characteristics of iron-based superconductors, which also hold clues to the underlying of the unconventional superconductivity in this new class of high-Tc materials. In this presentation, we report ^{75}As nuclear magnetic resonance (NMR) and transmission electron microscopy (TEM) studies on $LaFeAsO_{1-x}F_x$. We have constructed a complete phase diagram and explored the connection between different orders [1]. There are two superconducting domes in this material [2]. By NMR and TEM, we demonstrate that a C4-to-C2 structural phase transition (SPT) takes place above both domes, with the transition temperature Ts varying strongly with x. In the low-doping regime of $x \leq 0.2$, the SPT is followed by an antiferromagnetic (AF) transition. For $x = 0.03$, we find that AF order and superconductivity coexist microscopically via ^{75}As nuclear spin-lattice relaxation rate ($1/T_1$) measurements. In the coexisting region, $1/T_1$ decreases at T_c but becomes proportional to T below $0.6T_c$, indicating gapless excitations. Therefore, in contrast to the early reports, the obtained phase diagram for $x \leq 0.2$ is quite similar to the doped $BaFe_2As_2$ system. The electrical resistivity in the second dome can be fitted by $\rho = \rho_0 + AT^n$ with $n = 1$ and a maximal coefficient A at around $x_{opt} = 0.5 \sim 0.55$ where T_s extrapolates to zero and T_c is the maximal, which suggests the importance of quantum critical fluctuations associated with the SPT. Our results provide insight into the relationship between SPT, antiferromagnetism and superconductivity.

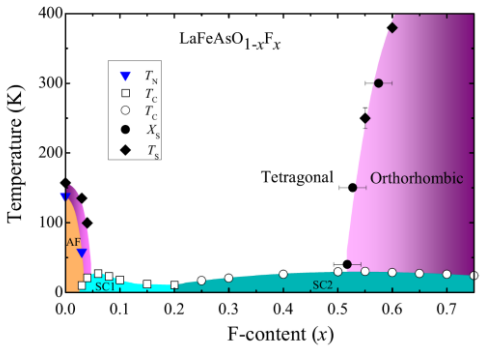

Fig. 1: *The complete phase diagram for $LaFeAsO_{1-x}F_x$.*

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Gapped Spin-1/2 Excitations in a Kagome Quantum Spin Liquid Compound $Cu_3Zn(OH)_6FBr$

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Quantum spin liquid (QSL) is a novel state where spins with strong correlations do not order down to zero temperature. It is characterized by the pattern of long range entanglement that has no classic counterpart. It was proposed as a mechanism for high-temperature superconductivity and as a material system for topological quantum computation. Zn doped barlowite $Cu_3Zn(OH)_6FBr$ with a Kagome lattice does not experience any phase transition down to 50 mK[1]. The spin susceptibility measured by ^{19}F NMR goes away completely at the zero-temperature limit, which indicates a gapped QSL state. Moreover, the magnetic field dependence of the spin susceptibility reveals a spin-1/2 excitation, i.e. spinons, resembling charge fractionalization in the fractional quantum Hall state[2].

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Continuous Change of Landau Renormalizations of Superfluid Density in Heavy Fermion Superconductors $Ce_{1-x}Yb_xCoIn_5$

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We have measured the superconducting penetration depth Λ (T) in the heavy-fermion/ intermediate-valent superconducting alloy series $Ce_{1-x}Yb_xCoIn_5$ using transverse-field muon spin relaxation to study the effect of intermediate-valent Yb doping on Fermi-liquid renormalization. From Λ (T), we determine the superfluid density ρ, and find that ρ decreases continuously with increasing nominal Yb concentration *x*, i.e., with increasing mixed valence. The temperature dependent renormalization in normal fluid density ρ_N from the velocities is proportional to temperature dependent renormalization due to thermal excitations, $m^*(T)/m^*(0)$ for both heavy-fermion and mixed valence limits, indicating temperature dependent Fermi-liquid Landau parameters of superconducting quasi-particles entering these two different physical quantities are the same. These results represent an important advance in understanding of both mixed valence and heavy-fermion superconductivity phenomena.

The quantum Hall effect and scaling law in bulk-insulating Sn doped $BiSbTe_2S$ devices

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We investigate the quantum Hall effect (QHE) and related scaling law in bulk-insulating Sn doped $BiSbTe_2S$ devices. With high sample quality, the magnetic tuned quantum Hall (QH) plateau accuracy is more than 99%. We show that the transport behaviour in QH regime change from thermal activation to variable range hopping(VRH) at 20K. Meanwhile, we find that the derivative of the Hall resistance and the width of the longitudinal resistance R_{xx} peaks at the plateau transition regime display power-law type temperature dependence , $(dR_{yx}/dB)^{max} \propto T^{-\kappa}$ and $\Delta B \propto T^{-\kappa}$ with κ = 0.18, respectively. These results open a new perspective on classification of topological insulator (TI) surface.

Multigap Nodeless Superconductivity in $CsCa_2Fe_4As_4F_2$ Probed by Heat Transport

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Recently, a new family of iron-based superconductors called 12442 was found and μSR measurements on $CsCa_2Fe_4As_4F_2$ and $KCa_2Fe_4As_4F_2$ polycrystals, two members of the family, indicated that both of them have a nodal superconducting gap structure with *s* + *d* pairing symmetry. Here, we report the synthesis of $CsCa_2Fe_4As_4F_2$ single crystals (T_c = 29.3 K) and the ultra-low-temperature thermal conductivity measurements on these crystals. Unlike the μSR measurements, a negligible residual linear term κ_0/T in zero field and the field dependence of κ_0/T obtained in our work suggest multiple nodeless superconducting gaps in $CsCa_2Fe_4As_4F_2$, rather similar to $CaKFe_4As_4$ or moderately doped $Ba_{1-x}K_xFe_2As_2$. The results can be well explained by the charge homogenization.

Transport Property of Ferromagnetic Superconductor Y_9Co_7 under Pressure

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Y_9Co_7 is a ferromagnetic superconductor, where superconducting (SC) state arises below 3 K in the itinerant ferromagnetic (FM) state with Curie temperature of 6 K [1]. Much efforts have been extended to understand the relationship between SC and FM, but its SC mechanism is still under debate. In this study, we investigate the effect of pressure on SC and FM phases of polycrystalline Y_9Co_7 by measuring electrical resistivity and ac susceptibility. Upper critical field, $H_{c2}(0)$, is about 0.6 Tesla at ambient pressure and increases to 1.8 Tesla at 2.4 GPa. Interestingly, the temperature dependences of the upper critical field, $H_{c2}(T)$, near the zero-field SC transition temperature T_c, change from an upward convex at ambient pressure to a downward concave at pressures above 1.0 GPa, the critical pressure where FM phase is suppressed below T_c and SC volume fraction becomes large. These results suggest the competition between SC and FM states in Y_9Co_7 and may shed light on understanding the interplay between the two broken symmetries.

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Atomic visualization of copper oxide structure in infinite-layer cuprate $SrCuO_2$

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We report the atomic-scale structure of epitaxial films of parent infinite-layer compound $SrCuO_2$ prepared on $SrTiO_3$ by molecular beam epitaxy. *In-situ* scanning tunneling microscopy study reveals a stoichiometric copper oxide (CuO_2)-terminated surface featured by 2×2 reconstruction, caused primarily by structural distortions of four adjacent CuO_2 plaquettes. Furthermore, the subsurface Sr atoms have been rarely discernible, showing intra-unit-cell rotational symmetry breaking. These observations can be reasonably modelled by a periodic up-down buckling of oxygen ions on the CuO_2 plane. Further post-annealing leads to the removal of surface oxygens and an incommensurate stripe phase. Our study provides indispensable structural information to help understand the exotic properties of cuprate superconductors.

Magneto-Optical Imaging of Vortex Lattice Melting at Low Fields in the Presence of Disorder in a $Ba_{0.6}K_{0.4}Fe_2As_2$ Single Crystal

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We study vortex lattice melting phenomenon in a single crystal of iron based $Ba_{0.6}K_{0.4}Fe_2As_2$ superconductor (T_c = 38 K) at low magnetic fields. High sensitivity differential magneto-optical imaging (DMOI) technique is used to search for a vortex disordering transition by imaging changes in local magnetic field in these single crystals. Using DMOI, we image a dilute vortex lattice melting phenomena in these pnictide crystals [1]. We find evidence for a jump in local magnetic field ~ 3 G which corresponds to a jump in local density of vortices as the vortex state transforms from a solid to a liquid phase. This jump in magnetization is sharp enough to suggest a first order transition at low field melting transition. From the jump in magnetization we estimate an entropy change associated with the vortex solid to liquid transition to be about ~ 0.5k_B per FeAs layer. Conventionally it is expected that a first order transition would be destroyed in the presence of disorder/pinning, which is expected to be large in pnictides and yet we find signatures of a strong first order melting phenomena. We show the first order melting features appear in our crystals which have large critical currents of the order of 10^4 A/cm^2, which indicates the presence of significant pinning in the sample. The melting phenomena is seen to occur at a unique location (B_m, T_m) in the field - temperature vortex matter phase diagram. In a B_m - T_m phase diagram we identify a boundary between dilute vortex liquid state and vortex solid phase and this phase boundary is shown to fit to the theoretically predicted expression for low-field melting phenomenon [2]. Furthermore, using scaling analysis of the *MT* data we explore the dimensionality of the vortex matter in the system. Scaling analysis suggest reduced dimensionality of the vortex lines in the sample. From anisotropy magnetization measurements we show the presence of extended defects in the sample is responsible for reducing the dimensionality of the vortex lines. The reduced dimensionality of the vortex line we argue is responsible for precipitating a low field first order vortex lattice melting phenomenon in these Pnictide crystals in the presence of anisotropic extended defects.

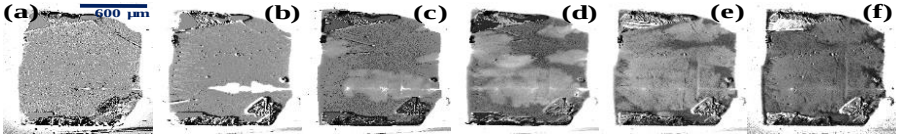

Fig. 1: *Figure (a)-(f) are the differential MOI images captured at 30.2 K with B at 12, 20, 36, 50, 70 and 100 G respectively. These figures show the propagation of melting of vortex solid into vortex liquid state across the whole sample.*

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Diagonal Nematicity in the Pseudogap Phase of $HgBa_2CuO_{4+}$

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One of the most critical issues in high-T_c cuprates concerns nature of the enigmatic pseudogap state, where the Fermi surface is partially gapped below the pseudogap temperature T^*. In particulr, it has been a longstanding controversial issue whether the pseudogap is associated with a crossover or a phase transition. Recently, by using ultrasensitive in-plane torque magnetometry in $YBa_2Cu_3O_{7-\delta}$, we have reported the thermodynamic evidence of a nematic transition, a spontaneous breaking of in-plane rotational symmetry at T^* [1]. However, $YBa_2Cu_3O_{7-\delta}$ has orthrhombic lattice structure, which already breaks the four-fold in-plane rotational symmetry. Therefore, more direct expreriments in a tetragonal system are highly required.

Here, we report the results of the torque magnetometory in $HgBa_2CuO_{4+\delta}$ with tetragonal structure [2]. Our key finding is that a distinct two-fold in-plane anisotropy develops below T^*, which provides conclusive evidence for a nematic phase transition. Remakably, the nematicity in $HgBa_2CuO_{4+\delta}$ develops along the [110] diagonal direction, in sharp contrast to the bond-nematicity in $YBa_2Cu_3O_{7-\delta}$ along the [100] direction. Moreover, the growth of diagonal nematicity in $HgBa_2CuO_{4+\delta}$ is suppressed when short-range charge-density-wave (CDW) order occurs [3], indicating a competing relationship between the diagonal nematic and CDW orders in $HgBa_2CuO_{4+\delta}$.

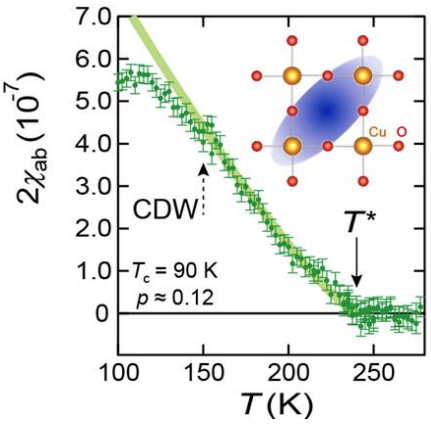

Fig. 1: *Temperature dependence of in-plane magnetic anisotropy in* $HgBa_2CuO_{4+\delta}$.

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Se Isotope Effect in The Layered $BiCh_2$-Based(Ch = S,Se) Superconductor $LaO_{0.6}F_{0.4}Bi(S,Se)_2$

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The layered bismuth chalcogenide ($BiCh_2$-based) superconductor [1], discovered in 2012, is a new class of layered superconductor with a maximum T_c of 11 K, but the pairing mechanisms of the superconductivity in the $BiCh_2$-based systems have not been understood. Resently, theoretical calculations [2] and angle-resolved photoemission spectroscopy (ARPES)[3] proposed unconventional pairing mechanisms for the superconductivity of $BiCh_2$-based systems.

Here, we report the Se isotope effect in the $BiCh_2$-based superconductor $LaO_{0.6}F_{0.4}Bi(S,Se)_2$ with ^{76}Se and ^{80}Se isotopes. Because superconductivity emerges in the BiCh-plane, and the conduction band is composed of Bi-6p orbitals hybridized with Ch-p orbitals, the Se isotope effect should be useful for discussing whether the superconductivity is mediated by phonon or not.

The temperature dependence of the magnetization and resistivity showed that T_c did not change between ^{76}Se and ^{80}Se samples. This indicates the exponent $_{Se}$ is close to zero, which may indicate that the pairing mechanisms in $LaO_{0.6}F_{0.4}Bi(S,Se)_2$ is not mediated by phonons and the unconventional superconductivity emerges in the $BiCh_2$-based supercondctors [4].

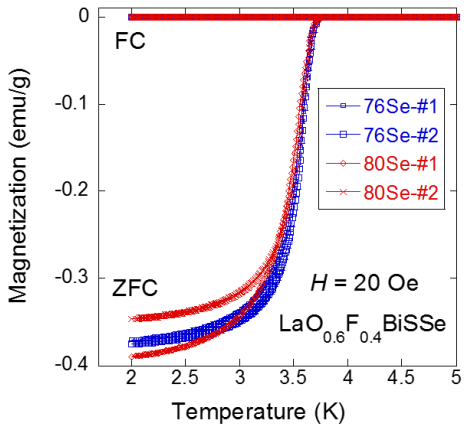

Fig. 1: *Temperature dependences of the magnetization for the $LaO_{0.6}F_{0.4}Bi(S,Se)_2$ with the ^{76}Se and ^{80}Se samples.*

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The SQCRAMscope: Scanning Quantum Cryogenic Atom Microscope

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Microscopic imaging of local magnetic fields provides a window into the organizing principles of complex and technologically relevant condensed matter materials. However, a wide variety of intriguing strongly correlated and topologically nontrivial materials exhibit poorly understood phenomena outside the detection capability of state-of-the-art high-sensitivity, high-resolution scanning probe magnetometers. We have recently introduced the Scanning Quantum Cryogenic Atom Microscope (SQCRAMscope), a quantum-noise-limited scanning probe magnetometer that can operate from room-to-cryogenic temperatures. By employing a magnetically levitated atomic Bose-Einstein condensate (BEC) that can be scanned near the surface of a cryogenically cooled material, the microscope achieves unprecedented DC-field sensitivity at micron-scale resolution. We present recent work advancing the capabilities of this new magnetometry technique and will mention its application to imaging transport in pnictide superconductors through the electron nematic transition.

Irradiation of Gd-doped YBCO Coated Conductors by Ar Ions

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Abstract—Defects produced by ion irradiation can be effective pinning centers, thus enhancing the in-filed critical current of high temperature superconductors. Gd-doped YBCO coated conductors were irradiated by 261.60 MeV Ar ions with different fluence. Superconducting parameters after irradiation were analyzed. With the increasing of fluence, onset transition temperature increased first and then decreased. Critical current density has the same trend with the variation of $T_{c,onset}$. Both critical current density and transition temperature show a tendency of enhancement with the fluence of $1.3*10^{12}$ ions/cm^2. Superconducting state will be destroyed when fluence over the threshold value.

A 5K high voltage electrical breakdown measuring system incorporating a Gifford-McMahon cryocooler

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Impregnating resins as electrical insulation materials in ITER magnets and feeder system are required to be radiation stable, good mechanical performance and high voltage electrical breakdown strength. In present ITER project, the breakdown strength need over 30 kV/mm, for future reactor, it would greater than this. For developing good property insulation materials to satisfy the requirements of future fusion reactor, high voltage breakdown strength measurement system at low temperature has been developed under the vacuum environment. In this paper, we will introduce our work on the design and construction of this system. This measuring system consists of two parts: the electrical supply system, which will provide the high voltage up to 60 kV from a high voltage power supply between the two electrodes; the temperature controlling system, which include a G-M cryocooler and the heating sample holder. A temperature controlled was added to adjust the temperature of the sample preciously. To provide the sufficient time for the high voltage breakdown test, the cooling system is designed to keep the sample at any temperature from 5K to 300K for more than 300 seconds according to the IEC standard.

Flexible Vortex Ice and Vortex Ice-like Systems in Tailor-made Nanostructured Superconductors

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Abstract Theoretical proposals for spin ice analogs based on nanostructured superconductors have suggested larger flexibility for probing the effects of fluctuations and disorder than in the magnetic systems[1-3]. By using scanning Hall probe microscopy, we directly unveil the particularities of vortex ice or vortex ice-like systems by direct observation of the vortex distribution in tailor-made nanostructured superconducting film, such as the kagome lattice of paired antidots and kagome lattice of elongated antidots[4-5]. Besides confirming some of the theoretical predictions at $H_1/2$ (half matching field), we unveil the role played by interstitial vortices, an unanticipated additional degree of freedom leading to even more robust vortex-ice states at $2H_1/3$. The vortex ice states with interstitial vortices are similar to stuffed spin ice[6]. By reducing the kagome lattice spacing, we demonstrate that the ordered vortex ice states cannot be further stabilized when the inter-vortex interaction increases[4]. In the kagome lattice of elongated antidots, we demonstrated that the long-range interaction is unable to lift the degeneracy between different vortex states and the pattern formation is mainly ruled by the nearest-neighbor interaction[5]. As such, we observed simple rules characterizing the flexible vortex configurations, which is very similar to the ice rules (we name it ice-like system). The vortex ice and vortex ice-like systems can provide new opportunities to explore the physics of general ice systems, frustration and order-disorder transitions in complex energy landscapes[4-5, 7].

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Type-I Superconductivity with an Unusual Surface State in the Dirac Semimetal $PdTe_2$

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Recently, the transition metal dichalcogenide $PdTe_2$ was reported to be a Type-II Dirac semimetal [1,2]. It is also a superconductor below T_c = 1.6 K [3]. The detection of topological features in the band structure raises the question whether superconductivity has a topological nature [2].We here report an in-depth characterization of the superconducting properties of $PdTe_2$ by means of magnetic and transport measurements on single crystals [4]. Surprisingly, dc-magnetization data show that $PdTe_2$ is a Type-I superconductor (see Figure). Our crystals also show the intermediate state as evidenced by the differential paramagnetic effect. The superconducting state is characterized by a London penetration depth λ = 39 nm, a coherence length ξ = 439 nm and a Ginzburg-Landau parameter κ = λ/ξ = 0.08. Remarkably, for applied fields $H_a > H_c$ superconductivity with a full screening signal persists till 34.9 mT for $T \rightarrow 0$. This we attribute to superconductivity of the surface sheath with a critical field H_c^S. Interestingly, H_c^S(T) cannot be explained by the standard Saint-James behavior for surface superconductivity, *i.e.* a critical field $H_{c3} = 2.39 \times \kappa H_c$ [5]. The unusual phase diagram with bulk and surface sheath superconductivity is discussed in view of the topological electronic structure of $PdTe_2$.

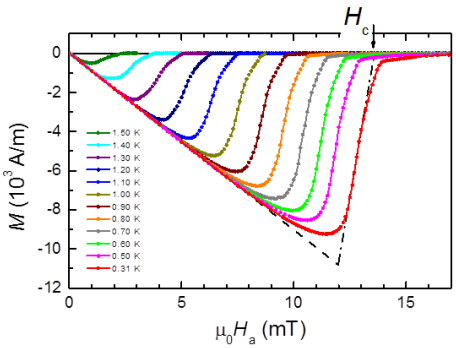

Fig. 1: *DC magnetization per unit volume (SI units) as a function of applied field for $PdTe_2$ at temperatures from 0.31K (right) to 1.50K (left), as indicated*

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Absence of Local Fluctuating Dimers in Superconducting $Ir_{1-x}(Pt, Rh)_xTe_2$

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The compound $IrTe_2$ is known to exhibit a transition to a modulated state featuring Ir-Ir dimers, with large associated atomic displacements [1-2]. Partial substitution of Pt or Rh for Ir destabilizes the modulated structure and induces superconductivity [3-6]. It has been proposed that quantum critical dimer fluctuations might be associated with the superconductivity [3]. Here we test for such local dimer correlations and demonstrate their absence. X-ray pair distribution function approach reveals that the local structure of $Ir_{0.95}Pt_{0.05}Te_2$ and $Ir_{0.8}Rh_{0.2}Te_2$ dichalcogenide superconductors with compositions just past the dimer/superconductor boundary is explained well by a dimer-free model down to 10 K, ruling out the possibility of there being nano-scale dimer fluctuations in this regime. This is inconsistent with the proposed quantum-critical-point-like interplay of the dimer state and superconductivity, and precludes scenarios for dimer fluctuations mediated superconducting pairing.

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Nanoscale assembly of superconducting vortices with STM tip

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Abstract

Vortices play a crucial role in determining the properties of superconductors as well as their applications. Therefore, characterization and manipulation of vortices, especially at the single vortex level, is of great importance. Among many techniques to study single vortices, scanning tunneling microscopy (STM) stands out as a powerful tool, due to its ability to detect the local electronic states and high spatial resolution. However, local control of superconductivity as well as the manipulation of individual vortices with the STM tip is still lacking. Here we report a new function of the STM, namely to control the local pinning in a superconductor through the heating effect. Such effect allows us to quench the superconducting state at nanoscale, and leads to the growth of vortex-clusters whose size can be controlled by the bias voltage. We also demonstrate the use of an STM tip to assemble single quantum vortices into desired nanoscale configurations.

Keywords: *vortices*, *STM*, *superconductor*

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Point-contact Andreev Reflection Spectroscopy Study on the Noncentrosymmetric Superconductor $PbTaSe_2$

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Point-contact Andreev reflection spectroscopy (PCARS) has been applied to investigate the superconducting gap structure in the noncentrosymmetric superconductor $PbTaSe_2$ with superconducting transition temperature T_c~ 3.8 K. Soft-PCARS on $PbTaSe_2$ displays two characteristic conductance peaks around 0.6 meV for the conductance curves $G(V)$ at 0.3 K. However, a single gap s-wave BTK model fails to fit the conductance curves of soft PCARS at low temperatures, which are better fitted by a two-gap BTK with both gaps following the typical BCS temperature behavior. The large and small gaps vanish at a distinct magnetic fields H = 0.1 and 0.3 T, possibly suggesting their bulk and surface origin, respectively. In contrast, the needle-anvil type mechanical PCARS has detected a lower superconducting T_c ~ 3.0 K, which is likely to be caused by a local pressure from the tip, since $PbTaSe_2$ is known sensitive to pressure. In addition, the conductance curves $G(V)$ can be well fitted by a single gap. Our results strongly support the mutigap nature of the superconductivity in $PbTaSe_2$, where one gap is readily suppressed under pressure.

Superconductivity in a Chiral WS_2 Nanotube

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Superconductivity in low dimensional Transition Metal Dichalcogenides (TMD) materials has been attracting significant attention in recent years. Among them, the TMD nanotube is a fascinating platform for researching superconductivity because of its unique cylindrical geometry with chirality. Here we report the first observation of superconductivity in an individual multi-walled tungsten disulfide (WS_2) nanotube, which is realized by electrochemical doping via liquid gating technique [1]. When the magnetic field is applied parallel to the axis of nanotube, the characteristic periodic magnetoresistance oscillation is observed, known as Little-Parks effect originated from the interference of supercurrent along the circumference of nanotube. Remarkably, the chirality effect on superconductivity has also been observed as a second harmonic resistance for the first time, which indicates that forward and backward supercurrent flows are not equivalent because of the inversion symmetry breaking. The chiral signal is significantly enhanced in the superconducting state, and displays an unprecedented quantum oscillation in conjunction with the Little-Parks effect. In addition, we have further investigated the diameter dependence of superconductivity, which might be important to reveal the microscopic mechanism of superconductivity in a bended lattice. The present result indicates that the second harmonic resistance should be a new approach for research of the nanoscaled superconductor with inversion symmetry breaking.

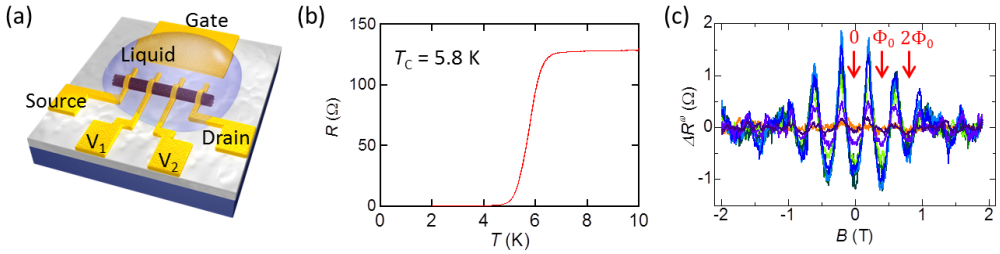

Fig. 1: *(a) Schematic figure of WS_2 nanotube device with liquid gate. (b) The temperature dependence of the resistance and superconducting transition with T_C of 5.8 K. (c) The Little-Parks oscillation at different temperature, subtracted from parabolic background.*

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Quantum Phase Escape from Finite Voltage State of Bi2Sr2Ca1-xYxCu2Oy Intrinsic Josephson Junctions

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Intrinsic Josephson junctions (IJJs), naturally formed in layered superconductors such as Bi-based cuprates, have attracted much interest for quantum-engineering applications such as THz wave emitters [1] and quantum devices utilizing macroscopic quantum tunneling (MQT) [2]. IJJs are also ideal systems to study the cooperative phenomena in several superconducting junctions strongly coupled with each other, in contrast to artificial arrays of conventional Josephson junctions. We recently observed the unusual enhancement of phase retrapping effects in the phase switching rate from finite voltage states of IJJs [3], strongly suggesting that AC Josephson current occurred in a phase-switched junction gives significant influence to the phase switches in other junctions near the switched junction. This feature uniquely observed in IJJs is quite important for the coherent emission of THz waves from IJJs as well as the unresolved issue in higher-order phase switches, where MQT survives up to a much higher temperature than the value predicted in the conventional theory [4,5].

In this presentation, we report a comparative study of quantum phase escape from finite voltage states of IJJs fabricated from Bi2Sr2Ca1-xYxCu2Oy (x=0, 0.15, 0.3) crystals [6]. We found that the enhancement of crossover temperatures to the quantum phase escape from the finite voltage state is commonly observed, in spite of a large difference in a critical current density, as shown in Fig. 1. Together with the microwave irradiation experiments, we argue that the influence of the phase-running state after the switch from the zero-voltage state is crucial to resolve this unusual behavior.

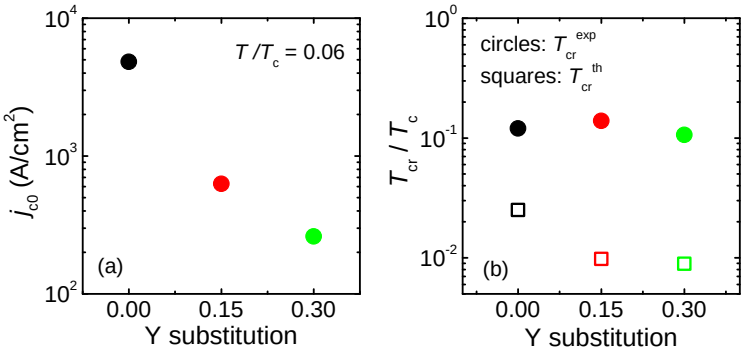

Fig. 1: (a) *Dependence of the fluctuation-free critical current density in higher-order phase switches on the content of Y substitution.* (b) *Comparison between experimental and theoretical values of the crossover temperature to MQT state in higher-order phase switches as a function of the content of Y substitution.*

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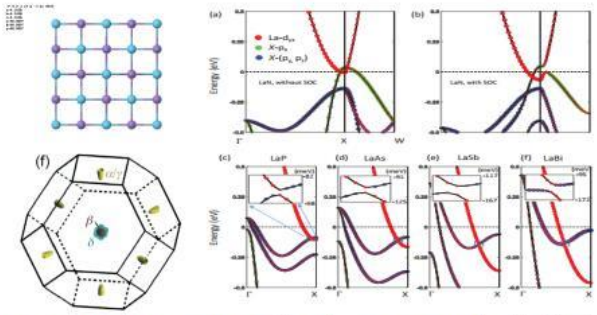
Transport behavior of possible SC material LaX series.

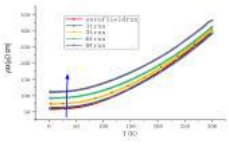
Desheng Wu, Wei Wu,Yuting Shao, Yanjie Li, Shihang Na, **Jianlin Luo**

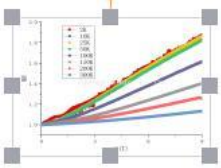
Proposal:by chemical pressure or doping method ,we could turn topological material to superconductor.



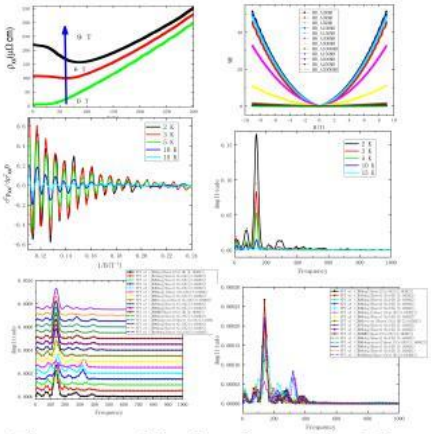
single crystal grow method： we grow LaP single crystal by CVT method;LaSb/As by Sn/Sb flux method

Transport behavior of LaP single crtystal

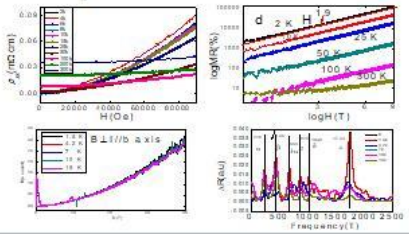




Transport behavior of LaAs



Transport behavior of LaSb



Visualizing the Electronic Structure of Thin Layers of Cuprates

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For cuprates, the complexity of electronic phase diagram and crystal structure bring big challenges to uncover the high transition temperature (High-T_C) superconductivity. It is important to simply the crystal structure for capturing the essential components hosting High-T_C superconductivity. It is equally essential to figure out the indispensable electronic structure and electronic orders as we consider the formation of High-T_C superconductivity. To achieve these goals, novel view angles are highly desirable to simplify these issues experimentally. For the layered materials with strong electronic anisotropy, it is natural to search the interlayer coupling effect by controlling the dimensionality. Therefore, spatial confinement towards 2D limit has been long pursed as a tuning parameter for layer-stacked cuprates. However, little information on electronic structure has yet been achieved for thin layers of cuprates. Here we fabricate thin layers of cuprates and use scanning tunneling microscopy to uncover the electronic states.

Experimental Exploration of Interface Superconductivity in Epitaxial SnSe2 Films

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We report on direct observation of interface superconductivity with Tc = 4.84 K in single-unit-cell $SnSe_2$ films grown on graphitized SiC(0001) substrate. Tunneling spectrum in the superconducting state reveals rather conventional character with a fully gapped order parameter. The occurrence of superconductivity is further confirmed by the presence of vortices under external magnetic field. Through interface engineering, we unravel the mechanism of superconductivity that originates from a two-dimensional electron gas formed at the interface of $SnSe_2$ and graphene. Besides, we have searched interface superconductivity in different $SnSe_2$-based heterostructures. Our finding opens up novel strategies to hunt for and understand interface superconductivity based on heterostructures.

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Quasiparticle interference and charge order in a heavily overdoped non-superconducting cuprate

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One of the key issues in unraveling the mystery of high T_C superconductivity in the cuprates is to understand the normal state outside the superconducting dome. Here we perform scanning tunneling microscopy and spectroscopy measurements on a heavily overdoped, non-superconducting $(Bi,Pb)_2Sr_2CuO_{6+\delta}$ cuprate. Spectroscopic imaging reveals dispersive quasiparticle interferences and the Fourier transforms uncover the evolution of momentum space topology. More interestingly, we observe nanoscale patches of static charge order with $\sqrt{2} \times \sqrt{2}$ periodicity. Both the dispersive quasiparticle interference and static charge order can be qualitatively explained by theoretical calculations, which reveal the unique electronic structure of strongly overdoped cuprate.

Large Negative Thermal Hall Response Inside the Pseudogap Phase of Cuprates

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The nature of the pseudogap phase of cuprate superconductors, one of the most mysterious object of quantum matter, still remains today highly debated in the community [1 - 4]. After 30 years of research in this field, an unexplored avenue to study this phase is the thermal Hall effect κ_{xy}. This new type of experiment has recently become among the most reliable and effective way of detecting long expected topological magnetic phase like quantum spin liquid [5] or quantum spin ice [6].

By performing measurements on a wide range of doping in cuprates for different families of materials, and as lowering the temperature below the Pseudogap temperature T^*, results show a surprisingly large and negative thermal Hall response that deviates from the positive electrical Hall conductivity. This suggests a first discrepancy of nature between heat and charge carriers, which in a metal are supposedly the same. This signal persists down to very low doping where quasiparticles are localized by strong interactions and cannot carry heat anymore; it even remains large in the Mott insulator parent compound. This experiment points towards either a universal transverse thermal conduction from magnetic excitations as a smoking gun for an underlying magnetic order or a related spin liquid phase inside the pseudogap phase [7], or it might as well reveal the topological nature of the pseudogap [2].

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Observation of Supermodulation in $LaO_{1-x}F_xBiSe_2$ by Scanning Tunneling Microscopy/Spectroscopy

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$BiCh_2$ (Ch=S,Se) based superconductors *Ln*$OBiS_2$ (*Ln* = La, Pr, Ce, Nd, Yb, Bi) show suprconductivity by the partially substitution of F ion for O ion. At the F concentraion of x=0.5, Ferm surface along a (π, π) direction connects. Some theoretical calculations predicted, when this change of Fermi surface is occured, the charge density wave (CDW) state attributed to the nesting picture appears. Although the appearence of the CDW was suggested by transport experiments in $EuFBiS_2$ [1], this has not been confirmed by direct observations.

Here, we report the observation of the electronic supermodulation in $LaO_{1-x}F_xBiSe_2$ single crystals (x=0.1, 0.5) by scanning tunneling microscopy and spectroscopy [2,3]. On the surface of both crystals prepared by cleavage, square lattice formed by Bi atoms were seen at the positive bias voltage. Furthermore, the electronic supermodulation with the period of about 5 times of the lattice constant was observed at the negative bias voltage along the diagonal directions of Bi square. These directions correspond to the theoretically predicted directions of the CDW. However, the observed period of the supermoduration is inconsistent with the predicted CDW. Furthermore, the observation of the supermodulation in x=0.1 sample is also inconsistent with the theoretical prediction. These results indicate this supermodulation seems not to be described by the predicted nesting picture. We will show the detail of the supermodulation observed in $LaO_{1-x}F_xBiSe_2$ (x=0.1, 0.5) in the presentation.

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STM Observation of Charge Density Wave States in 2H-$TaS_{2-x}Se_x$

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Layered transition metal dichalcogenides 2*H*-TaS_2 and 2*H*-$TaSe_2$ undergo phase transition to CDW states at low temperature. These materials also show superconductivity at 0.8 K and 0.14 K, respectively. It was reported by electrical resistivity measurements that the CDW transition is suppressed and the superconducting transition temperature increases up to 4.3 K when S is partially substituted by Se, i.e. 2*H*-$TaS_{2-x}Se_x$ ($0 < x < 2$). This indicates that the CDW competes with the superconductivity [1]. However, how the CDW transition is suppressed by the substitution and what kinds of states are realized when the CDW state is suppressed have not been investigated.

In this study, we performed scanning tunneling microscopy and spectroscopy (STM/STS) measurements on 2*H*-$TaS_{2-x}Se_x$ ($0 < x < 2$) at 4.2 K. We observed CDW in the samples which do not show the clear CDW transition in electrical resistivity measurements. The observed CDW was found to have a lot of phase defects. We will discuss the CDW state in 2*H*-$TaS_{2-x}Se_x$ ($0 < x < 2$) from the STM images and the tunneling spectra.

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Superconductivity with Twofold Symmetry in $Bi_2Te_3/FeTe_{0.55}Se_{0.45}$ Heterostructures

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Topological superconductors are supposed to have order parameters with odd parity, which has become a hot topic in nowadays condensed matter physics. It was predicted that superconductivity with order parameters of twofold symmetry may exist due to the presence of odd parity. In some compounds with chemical doping, such as $MxBi_2Se_3$ (M = Cu, Nb and Sr), some traces of this long sought topological superconductivity have been reported with the observation of twofold feature in NMR and angle-resolved specific heat measurements. Proximity effect is another way to induce possible topological superconductivity. Here we report the proximity effect induced superconductivity in Bi_2Te_3 thin film on top of an iron-based superconductor $FeTe_{0.55}Se_{0.45}$. By using the quasiparticle interference technique, we demonstrate clear evidence of twofold symmetry of the superconducting gap. The gap minimum is along one of the main crystalline axis following the so-called Δ_{4y} notation (Fig. 1 C-K). This is also accompanied by the elongated vortex shape (Fig. 1 A-B) mapped out by the density of states within the superconducting gap. [1]

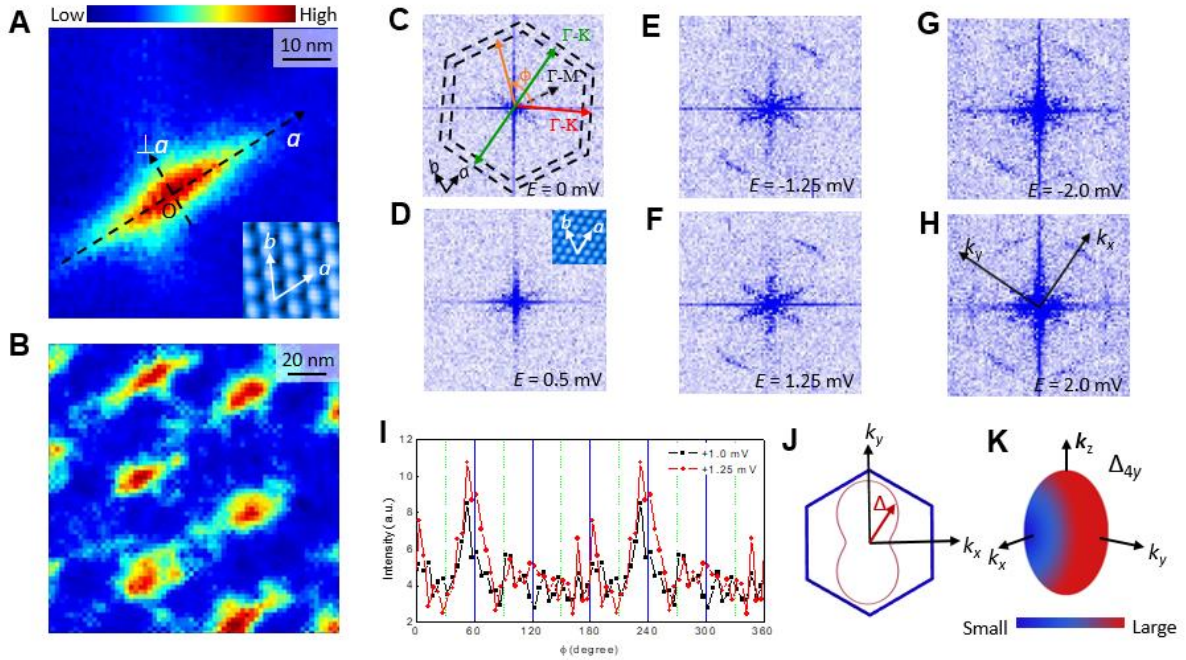

Fig. 1: *Elongated vortices and twofold superconducting gap resolved by QPI measurements.*

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Reduction Annealing and Electronic States in Single Crystals of T'-Cuprate $Pr_2CuO_{4+\delta}$

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It has been reported that thin films and powder samples of RE2CuO4 (RE : rare earth) with the so-called T' structure, which is parent compounds of the electron-doped high-Tc cuprates, exhibit superconductivity by the appropriate reduction annealing [1,2]. In order to investigate the electronic states of the parent compound of the T'-cuprate, we have grown the single crystal of $Pr_2CuO_{4+\delta}$ in the low-oxygen pressure and performed electrical-resistivity and magnetization measurements using reduced single crystals under various reduction annealing. Using the protect [3] and low-temperature [4] annealing, it has been found that, as shown in Fig. 1, the ab-plane resistivity $_{ab}$ decreases and a metallic behavior is observed above ~220 K for the protect-annealed crystal. Moreover, the metallic temperature region expands above ~150 K for the protect and following low-temperature annealed crystal. These suggest that the excess oxygen residing in the as-grown crystal is well removed from the as-grown crystal by the reduction annealing. Therefore, further reduction probably leads to the fully metallic and superconducting states in Pr_2CuO_{4+} .

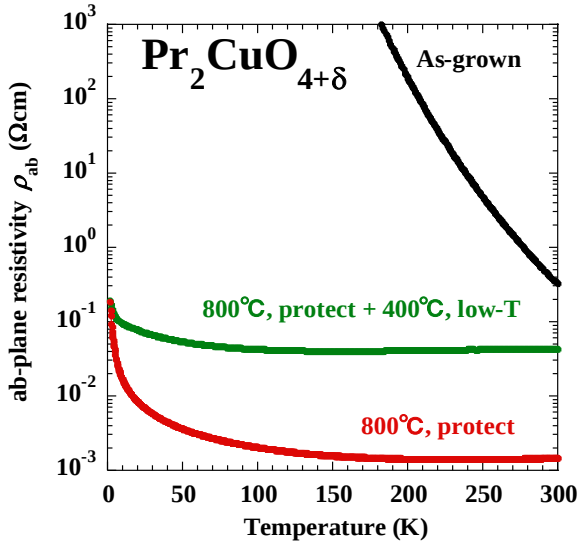

Fig. 1: *Temperature dependence of the ab-plane electrical resistivity in single crystals of* $Pr_2CuO_{4+\delta}$.

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Tunable Josephson junction based on black phosphorus

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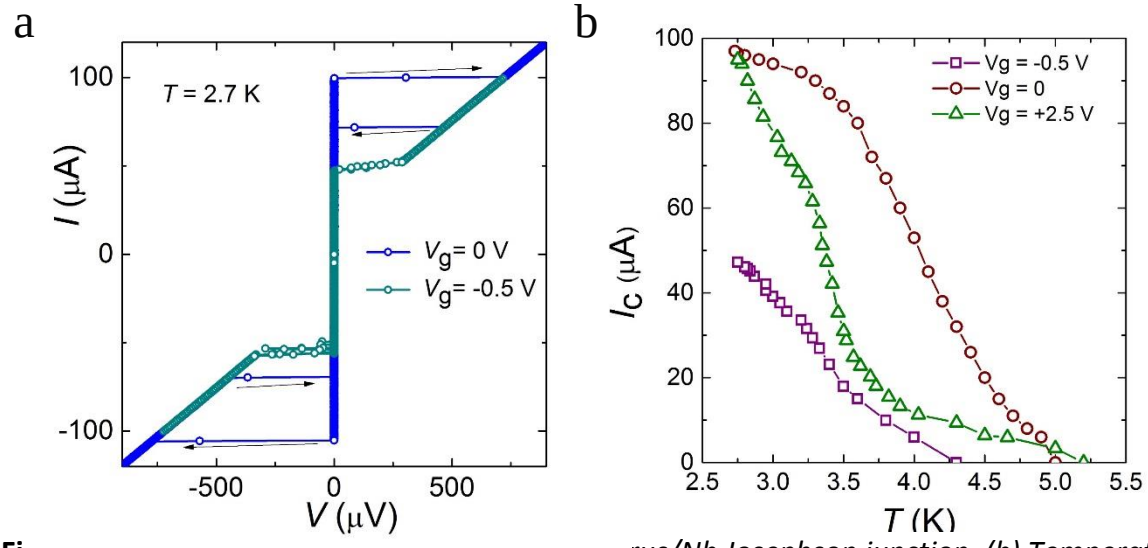
Much efforts have been made for the realization of hybrid Josephson junctions incorporating various materials (such as graphene) for the fundamental studies of exotic physical phenomena. Black phosphorus is a layered structure of two-dimensional material, showing semiconductor properties in low-dimensional state, which is suitable as a barrier layer to regulate the characteristics of Josephson junction for that the charge density can be modified by applying gate. Here, we sandwiched a cleaved black phosphorus with a few layers as conducting spacer between superconducting electrodes, and utilized ionic liquids as gate dielectrics. The critical current density of the Josephson junction is observed a systematically modification with respect of gate voltage, and the corresponding Shapiro-step in IV curves and Fraunhofer patterns in magnetic field dependent critical current are adjusted as well. The present result reveals that the ionic liquid gating is a practice way to control the characteristic of Josephson junction with a barrier layer of band-tunable black phosphorus.



Fi *rus/Nb Josephson junction. (b) Temperature dependence of the junction critical current versus* V_g.

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Superconductivity and charge-density wave in iodine-doped nodal-line semimetal In_xTaSe_2

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Topological materials have become a hot spot in condensed matter systems in recent years, and many efforts are carried out to search new topological phases such as Dirac/Weyl semimeatals, topological superconductors and triple point topological metals, etc. Here we report a new kind of topological semimetal In_xTaSe_2 with Weyl-type nodal rings according to the first-principle calculations, the same as $InNbS_2$[1]. Moveover, once a little iodine is doped in In_xTaSe_2, charge-density wave (CDW) is observed at 117 K by resistivity and scanning tunneling microscopy (STM). In addition, superconducting transition emerges at 1.18 K as expected. As a first topological material with CDW, it provides a new platform for studying the interplay between CDW and topological phase, which maybe offer a new origin of CDW[2].

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Superconducting Proximity Effect of Bi (110) Films on $NbSe_2$ Substrate Studied by STM

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Interfacial effect is one of the interesting phenomena in condensed matter physics. Here we report the Bi (110) thin films grown on a superconducting $NbSe_2$ substrate using molecular beam epitaxy (MBE) method. With low temperature STM, we observe U-shaped superconducting gap on different layers at 0.4K. The gap is gradually suppressed when applying a magnetic field up to 2 T. Vortex is detected on the flat surface of the Bi thin films. This heterojunction provides a platform for further studying topological superconductivity and searching for the Majorana fermion. [1-4]

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22 T superconducting magnet for scanning tunneling microscopy at dilution refrigeration temperatures

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We report progress in the set-up and operation of a superconducting high magnetic field solenoid of 22T with a dilution refrigeration insert for Scanning Tunneling Microscopy. We discuss the design of the STM and the damping system, consisting of a concrete floor suspended on a 1 Hz spring system. The suspension was engineered to avoid interference with the stray magnetic field of the solenoid. We report on first experimental tests of the superconducting coil, consisting of quantum oscillation measurements on the topological semimetal PtBi2 and discuss stability to quench up to 22 T and ramping speed. We also discuss the design of the STM itself, optimized to provide mechanical isolation from the dilution refrigeration and using essentially non-magnetic construction elements. Finally, we report recent STM experiments made at low magnetic fields on the new CaKFe4As4 family of compounds.

STM Investigation of the Field-induced Magnetic Phase Transitions in CeSb

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CeSb is a strongly-correlated system with low carrier density and very complex magnetic phase diagrams. Recent transport measurements and theoretical calculations even imply CeSb may belong to a new class of Kondo lattice materials with Weyl fermions in the ferromagnetic state. Although various experimental methods and theoretical calculations have been performed to study CeSb, there still exist many debatable issues and STM studies of CeSb have rarely been reported before. We used scanning tunneling microscopy to study the electronic and magnetic properties of CeSb single crystals at low temperatures. The dI/dV spectra under various external magnetic fields have been taken on both clean surface and typical surface defects at T = 4.2 K. A gap with a size of 20 meV has been observed on pristine surface at low temperatures. This gap can be well fitted by a Fano-line shape, giving a T_K~100 K. The fitting result and the disappearance of the gap at higher temperatures both imply a *p-f* hybridization effect at low temperatures. First-principles calculations also suggest this gap should be attributed to the enhanced *p-f* mixing at low temperatures. A small dip gradually appears at E =7 meV when an external magnetic field $\geq$ 2.0 T was applied perpendicular to the (001) plane. This phenomenon can be observed on clean regions as well as surface defects. Both experimental and theoretical results indicate the emergence of the small dip is caused by the magnetic phase transitions from the antiferromagnetic (AFM) state to the field-induced ferromagnetic (FM) state.

Pressure-Induced Isostructural Phase Transition and Charge Transfer in FeSe

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Layered Fe-based materials emerged as a new class of high temperature superconductor since 2008. The mechanism of superconductivity in these materials, however, is a contentious issue. Nematic ordering is thought to be an important ingredient, but the apparent absence of magnetic ordering in FeSe, which is the Fe-based superconductor with the simplest structure, has caused confusion over what drives the nematicity. Recent investigations on FeSe show that probable connection between magnetic ordering and superconductivity which can be tuned by chemical doping or application of physical pressures [1-3]. Here, a combination of high-pressure X-ray diffraction (XRD) with fine pressure step, X-ray absorption experiments with high quality sample as well as first principle calculation allows us to uncover the comprehensive structural and electronic properties in superconducting FeSe.

Extensive investigations of the crystallographic phase diagram and electronic properties of the Fe-based superconductor FeSe has been performed under extreme conditions (high pressure (HP) and low temperature (LT)) by synchrotron X-ray diffraction (XRD) and X-ray absorption spectroscopy (XAS). An isostructural phase transition (Tetragonal (T) → collapsed Tetragonal (cT)) is discovered in FeSe at ~2.8 GPa based on the axial ratio *c*/*a* with finer pressure step as observed in Fe-As-based superconductor such as $EuFe_2As_2$. We also find a pressure-induced cT → MnP-type phase transition at 7.6 GPa in FeSe, which is consistent with the documented pressure-induced high-spin → low-spin transition (~ 6-7 GPa). These results reveal the pressure-induced structural phase transition sequence in FeSe at room temperature to be T → cT → cT+MnP-type at pressures of 0 to 10.6 GPa, enriching the crystallographic phase diagram. The HPLT XRD data also indicate that a sluggish structural phase transition (*Cmma* → *Pnma*) begins at 7.5 GPa, and these two phases coexist up to 26.5 GPa. The HP X-ray absorption near-edge spectroscopy (XANES) measurement shows that Eo of Se experiences a pressure-induced shift to high energy, evidencing strongly charge transfer between Fe and Se under high pressure. Our results shed lights on the correlation between crystallographic/electronic structure and superconductivity in this material.

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Hopping Conductance and Dissipation Effect in Three Dimensional $Pb_x(SiO_2)_{1-x}$ Granular Films

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The transport properties near the superconductor-insulator transition (SIT) in disordered systems continue to attract intense theoretical and experimental attention [1]. The mechanisms of hopping transport in insulating side and the quantum metallic phase with disorder degree being small are ambiguous and need to study further [2-5]. Granular film can provide a platform to investigating new physical mechanisms [6]. Therefore, in order to find the exact nature near SIT, we have investigated the low-temperature transport properties of three dimensional $Pb_x(SiO_2)_{1-x}$ granular films with Pb volume fraction *x* ranging from ~0.47 to ~0.74. The results are summarized as follows.

For $x \le 0.50$, below the superconducting transition temperature of Pb bulk (T_c), the resistivity increases abruptly and then tends to saturation with further decreasing temperature. It is found that in the abrupt increase region the resistivity obeys an activation law, which can be explained by the recent theory in granular superconductors proposed by Lopatin et al [2]. Moreover, it is found that the magneto-resistivity is negative and the single grain charging energy is greater than the superconducting energy gap, which indicates that the electron instead of the Cooper pair dominates the hopping processes. The "quasireentrant" phenomenon, which often appears in 2D granular film, is observed in films with $0.51 \le x \le 0.53$. For films with *x* slightly larger than percolation value x_c, the resistivities sharply drop by an order of magnitude when the temperature is decreased below the superconducting transition temperature T_c, and then slowly decrease with further decreasing temperature. Considering there is at least one conductive-path which is formed by the connected Pb nanogranules in our granular film, we attribute the nonzero resistivity effect at low temperature region to the combination effect of thermal activation and macroscopic quantum tunneling.

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Ising Superconductivity and Quantum Phase Transition in Macro- Size Monolayer $NbSe_2$

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Two-dimensional (2D) transition metal dichalcogenides (TMDs) have a range of unique physics properties and could be used in the development of electronics, photonics, spintronics, and quantum computing devices. The mechanicalexfoliation technique of microsize TMD flakes has attracted particular interest due to its simplicity and cost effectiveness. However, for most applications, large-area and high-quality films are preferred. Furthermore, when the thickness of crystalline films

is down to the 2D limit (monolayer), exotic properties can be expected due to the quantum confinement and symmetry breaking. In this paper, we have successfully prepared macro-size atomically flat monolayer NbSe2 films on bilayer graphene terminated surface of 6H-SiC(0001) substrates by a molecular beam epitaxy (MBE) method. The films exhibit an onset superconducting critical transition temperature (Tc onset) above 6 K and the zero resistance superconducting critical transition

temperature (Tczero) up to 2.40 K. Simultaneously, the transport measurements at high magnetic fields and low temperatures reveal that the parallel characteristic field Bc//(T = 0) is above 5 times of the paramagnetic limiting field, consistent with Zeemanprotected Ising superconductivity mechanism. Besides, by ultralow temperature electrical transport measurements, the monolayer NbSe2 film shows the signature of quantum Griffiths singularity (QGS) when approaching the zero-temperature quantum critical point.

Evolution of pseudogap phase under pressure and endpoint of CDW in Nd-LSCO probed by transport measurements

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The pseudogap phase is the chief mystery of cuprate high-temperature superconductors. In $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO), a clear signature of this phase is an upturn at low temperature in both electrical [1] and thermoelectric [2,3] transport properties, which agree with direct Angle Resolved Photoemission Spectroscopy data [4]. It was observed recently that this upturn could be suppressed by the application of hydrostatic pressure near the pseudogap critical point at $p^* \sim 0.23$, showing that pressure moves p^* to lower dopings [5]. We have measured the Seebeck and Nernst effects in the high-field normal state of Nd-LSCO at $p = 0.22$ under pressure. We show that the suppression of the upturn with pressure is also detectable via these thermoelectric probes which are more sensitive to the pseudogap. Under 2.0 GPa, we observe a 3-fold decrease in the magnitude of the Seebeck coefficient at $p = 0.22$. The upturn flattens out and the curve declines towards the flat line as seen in $p = 0.24$ where no pseudogap is present. Moreover, we observe that the effect of pressure on $p = 0.24$ right above p^* is to decrease the Seebeck coefficient, which we discuss in relation to the van Hove singularity.

We have also determined the endpoint of Charge Density Wave (CDW) phase in Nd-LSCO with Seebeck coefficient measured for different dopings in high magnetic fields and low temperatures and proved that it is well-separated from pseudogap's critical point (p*) [6].

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Detection of bosonic mode as a signature of magnetic excitation in one-unit-cell FeSe on $SrTiO_3$

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We report an in situ scanning tunneling spectroscopy study of one-unit-cell (1-UC) FeSe film on $SrTiO^3$(001) (STO) substrate. In quasiparticle density of states, bosonic excitation mode characterized by the "dip-hump" structure is detected outside the larger superconducting gap with energy comparable with phonon and spin resonance mode in heavily electron-doped iron selenides. Statistically, the excitation mode, which is intimately correlated with superconductivity, shows an anticorrelation with pairing strength and yields an energy scale restricted by twice the superconducting gap coinciding with the characteristics of magnetic resonance in cuprates and iron-based superconductors. The local response of tunneling spectra to magnetically different Se defects all demonstrates the induced in-gap quasiparticle bound states, indicating an unconventional sign-reversing pairing. These results tend to support the magnetic nature of the excitation mode and possibly reveal a signature of electron–magnetic-excitation coupling in high-temperature superconductivity of 1-UC FeSe/STO.

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Scanning tunneling microscopy study of the Hidden Order in heavy fermion material URu_2Si_2

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URu_2Si_2 is a famous sample due to its Hidden Order(HO). This material undergoes a phase transition at 17.5K, while since its discovery in 1985, the order parameter of the new phase under 17.5 K is still not found. Quasi-localized U 5f electrons interplay with the conducting electron, so-called heavy fermion behavior also exist in this system. Interestingly, in the HO phase under 1.5k, superconductivity(SC) arises. Experiments suggested gap nodes of the SC order parameter, even breaking time reversal symmetry in the SC state. Here we present ultra-low temperature STM measurement on single-crystal URu_2Si_2 sample. Clean surface with atomic resolution is observed. Quasi-particle interference shows complicated fermi-surface and scattering pattern. We find that the intrinsic defects on the surface have different affect on the HO gap, while the Fano line-shape preserves at any circumstances. Our research gives the information on the defect affect on the HO state in atomic scale.

A high T_c Superconductor Reveals Caroli-de Gennes-Matricon Vortex States

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For more than two decades, the electronic structure of the vortices in high-temperature superconductors (HTS) has been challenging theory. As a matter of fact, most of the observations made by scanning tunnelling spectroscopy in the vortex cores of HTS have revealed unusual features. Among these, the detection of a robust pair of electron-hole symmetric states at finite subgap energy in $YBa_2Cu_3O_{7-\delta}$ (Y123) [1] was in total contradiction with the expected signature of a d-wave superconductor vortex core, characterized by a strong zero-bias conductance peak.

In a recent series of scanning tunnelling spectroscopy experiments on Y123, we found that these subgap conductance peaks are not a specific signature of the vortices, but are part of an electronic background uniformly measured across the entire surface, whether a magnetic field is applied or not [2]. This finding led us to consider a simple model assuming that the total tunnelling current is the combination of two additive channels: one associated with the quasiparticle excitations expected for a clean *d*-wave superconductor with YBCO band structure; the other corresponding to an unknown non-superconducting background where the subgap peaks belong. According to this two-channel analysis, the superconducting condensate contributes only 15% to 20% of the total tunnelling signal, explaining the difficulty of detecting the BCS fingerprints in this material. Because the dominant background is spatially uniform and simply adds to the total tunnelling current, we can eliminate this unknown contribution by subtracting a spectrum measured away from the vortex cores from all the tunnelling spectra measured in the vortex phase. The remaining signal can be modelled in the Bogoliubov-de Gennes framework, by computing the spatial dependence of the LDOS in the presence of vortices and performing the same subtraction. We find a remarkable correspondence between the model and the data, demonstrating that the vortex cores in HTS cuprates are not exotic but present the expected quasiparticle LDOS [3]. The model provides further insight into the vortex-core structure, which is different for each vortex due to an irregular lattice and depends on the Fermi surface topology more than on the gap symmetry. The origin of this dominant background conductance remains an open question, together with the question of whether the same model applies to other HTS cuprates.

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Pressure tuning the pseudogap critical point: evidence from Seebeck and Nernst effect

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The pseudogap phase is the chief mystery of cuprate high-temperature superconductors. In $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO), a clear signature of this phase is an upturn at low temperature in both electrical [1] and thermoelectric [2,3] transport properties, which agree with direct Angle Resolved Photoemission Spectroscopy data [4]. It was observed recently that this upturn could be suppressed by the application of hydrostatic pressure near the pseudogap critical point at $p^* \sim 0.23$, showing that pressure moves p^* to lower dopings [5]. We have measured the Seebeck and Nernst effects in the high-field normal state of Nd-LSCO at $p = 0.22$ under pressure. We show that the suppression of the upturn with pressure is also detectable via these thermoelectric probes which are more sensitive to the pseudogap. Under 2.0 GPa, we observe a 3-fold decrease in the magnitude of the Seebeck coefficient at $p = 0.22$. The upturn flattens out and the curve declines towards the flat line as seen in $p = 0.24$ where no pseudogap is present. Moreover, we observe that the effect of pressure on $p = 0.24$ right above p^* is to decrease the Seebeck coefficient, which we discuss in relation to the van Hove singularity.

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Superconductivity in Pristine 2H_a-MoS_2 at Ultrahigh Pressure

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We extend pressure beyond the megabar range to seek after superconductivity in the 2H_a-MoS_2 via electrical transport measurements. We found that superconductivity emerges with an onset critical temperature T_c of ca. 3 K at ca. 90 GPa. Upon further increasing the pressure, T_c is rapidly enhanced beyond 10 K and stabilized at ca. 12 K over a wide pressure range up to 220 GPa. Synchrotron x-ray diffraction measurements evidenced no further structural phase transition, decomposition, and amorphization up to 155 GPa, implying an intrinsic superconductivity in the 2H_a-MoS_2. DFT calculations suggest that the emergence of pressure-induced superconductivity is intimately linked to the emergence of a new flat Fermi pocket in the electronic structure. Our finding represents an alternative strategy for achieving superconductivity in 2H-MoS_2 in addition to chemical intercalation and electrostatic gating.

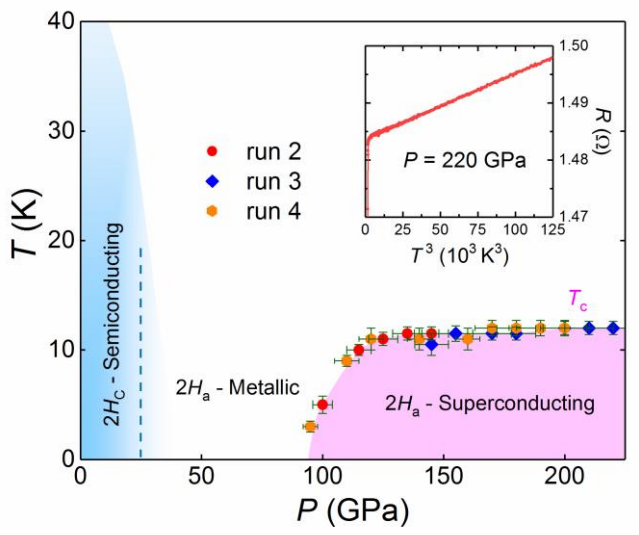

Fig. 1: *Pressure-temperature (P-T) phase diagram of 2H-MoS_2. The vertical dashed line demarcates the boundary between the semiconducting and metallic states.*

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Heavy fermion quantum criticality at dilute carrier limit in $CeNi_{2-\delta}(As_{1-x}P_x)_2$

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Quantum criticality describes a continuously second-order phase transition at zero temperature, which has been discussing in a number of strongly correlated electron systems intensively [1,2]. $CeNi_{2-\delta}As_2$ is a Kondo compound with an antiferromagnetic (AFM) transition temperature T_N = 4.8 K and a Kondo temperature T_K ~ 4 K [4]. $CeNi_2P_2$ is an isostructural, nonmagnetic, intermediate valence Kondo lattice metal [5]. $CeNi_{2-\delta}As_2$ and $CeNi_2P_2$ are thus located at the opposite sides of the quantum critical point (QCP) in the Doniach phase diagram. In particular, due to the possible Ni vacancies in $CeNi_{2-\delta}As_2$, the charge carrier density is expected to be small.

Here we report the experimental evidence of a QCP around x_c = 0.55 for the $CeNi_{2-\delta}(As_{1-x}P_x)_2$ ($\delta \approx 0.07$-0.22) system with a low carrier density. Evidence for low carrier density is found for $0.1 \le x \le 0.7$. In the vicinity of the QCP, a divergent effective carrier mass is evidenced from ρ_0 and γ_0, and the NFL behavior is manifested by $\rho_{xx} \sim T$ and $C/T \sim -\log T$. We find the interesting result that the NFL behavior of the electrical resistivity and specific heat persists over a nonzero range of doping concentration for $x_c < x < 0.9$; the Fermi liquid behavior is not recovered until $x \ge 0.9$. Our present work thus offers a new candidate material for studying the universality classes of quantum criticality, and highlights the effect of the low density of conduction electrons in the nickel-based pnictides.

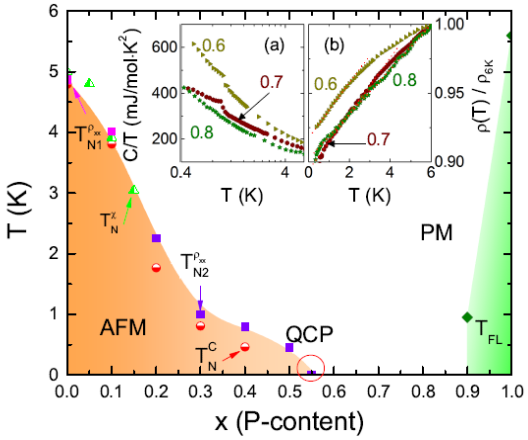

Fig. 1: *Phase diagram of $CeNi_{2-\delta}(As_{1-x}P_x)_2$.*

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Pressure-induced Superconductivity and Topological Quantum Phase Transitions in a Quasi-one-dimensional Topological Insulator: Bi4I4

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Superconductivity and topological quantum states are two frontier fields of research in modern condensed matter physics. The realization of superconductivity in topological materials is highly desired, however, superconductivity in such materials is typically limited to two- or three-dimensional materials and is far from being thoroughly investigated. In this work, we boost the electronic properties of the quasi-one-dimensional topological insulator bismuth iodide β-Bi4I4 by applying high pressure. Superconductivity is observed in β-Bi4I4 for pressures where the temperature dependence of the resistivity changes from a semiconducting-like behavior to that of a normal metal. The superconducting transition temperature Tc increases with applied pressure and reaches a maximum value of 6 K at 23 GPa, followed by a slow decrease. Our theoretical calculations suggest the presence of multiple pressure-induced topological quantum phase transitions as well as a structural-electronic instability.

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High Magnetic Field Magnetotransport and ARPES Measurements on a Magnetic Semimetal $EuCd_2Sb_2$

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By combining high magnetic field magnetotransport and ARPES measurements, we show that $EuCd_2Sb_2$, an analogue to $EuCd_2As_2$ which previously predicted to host magnetic Dirac points protected jointly by the inversion and the nonsymmophic time-reversal symmetry, hosts an antiferromagnetic (AFM) order at about 7.5 K and a striking Shubnikov-de Hass oscillation behavior at high magnetic field exceeding 10 T. Transport data analysis further revealed a nontrivial Berry phase π associated with the Dirac dispersion supported also by the ARPES measurements. Our work clearly demonstrates that $EuCd_2Sb_2$ and $EuCd_2As_2$ belong to the same material class in which the Dirac dispersion below the magnetic ordering temperature is gapped owing to the lack of C_3 symmetry by the A-type AFM structure. This material class could serve as an excellent platform for the study of the interplay between magnetism and topological states.

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Thermoelectric anisotropy in $Ba(Fe_{1-x}Co_x)_2As_2$ iron-based superconductor

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We report the in-plane anisotropy of the Seebeck and Nernst coefficients as well as of the electrical resistivity determined for the series of the strain-detwinned single crystals of $Ba(Fe_{1-x}Co_x)_2As_2$. Two underdoped samples (x = 0.024, 0.045) exhibiting the transition from the tetragonal paramagnetic phase to the orthorhombic spin density wave (SDW) phase (at T_{tr} = 100 and 60 K, respectively) show an onset of the Nernst anisotropy at temperatures above 200 K, which is significantly higher than T_{tr}. In the optimally doped sample (x = 0.06) the transport properties also appear to be in-plane anisotropic below $T \approx 120$ K, despite the fact that this particular composition does not show any evidence of long-range magnetic order. However, the anisotropy observed in the optimally doped crystal is rather small and for the Seebeck and Nernst coefficients the difference between values measured along and across the uniaxial strain has opposite sign to those observed for underdoped crystals with x = 0.024 and 0.045. For these two samples, insensitivity of the Nernst anisotropy to the SDW transition suggests that the nematicity might be of other than magnetic origin.

STM Studies of Density Modulations in the Pseudogap State of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Pseudogap (PG) of cuprate superconductor is believed to provide an important clue to the mechanism of high Tc superconductivity. Charge Density Wave (CDW), which recently reported in PG states, has been shown by a number of experimental tools, but its origin is not clear. We discovered the Density of States Wave (DOSW) in PG phase of Bi2Sr2CaCu2O8+δ using variable temperature STM and it is similar to the reported CDW's wave vectors. However, this DOSW is different from the previously discovered CDW - dispersion, particle – hole antisymmetry and the correlation length is not a conventional one. On this talk, we try to resolve the relationship between Fermi Arc of ARPES data and the DOSW modulation we observed.

Superconductivity across Lifshitz Transition and Anomalous Insulating State in Surface K–dosed ($Li_{0.8}Fe_{0.2}OH$)FeSe

Mingqiang Ren[1], Yajun Yan[1], Xiaohai Niu[1], Ran Tao[1], Die Hu[1], Rui Peng[1], Binping Xie[1,2], Jun Zhao[1], Tong Zhang[1,2*], Dong-Lai Feng[1,2*]

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In iron-based superconductors, understanding the relation between superconductivity and electronic structure upon doping is crucial for exploring the pairing mechanism. Recently, it was found that, in iron selenide (FeSe), enhanced superconductivity (T_c of more than 40 K) can be achieved via electron doping, with the Fermi surface only comprising M-centered electron pockets. By using surface K dosing, scanning tunneling microscopy/spectroscopy, and angle-resolved photoemission spectroscopy, we studied the electronic structure and superconductivity of ($Li_{0.8}Fe_{0.2}OH$)FeSe in the deep electron-doped regime. We find that a Γ-centered electron band, which originally lies above the Fermi level (E_F), can be continuously tuned to cross E_F and contribute a new electron pocket at Γ. When this Lifshitz transition occurs, the superconductivity in the M-centered electron pocket is slightly suppressed, and a possible superconducting gap with a small size (up to ~5 meV) and a dome-like doping dependence is observed on the new Γ electron pocket. Upon further K dosing, the system eventually evolves into an insulating state. Our findings provide new clues to understand superconductivity versus Fermi surface topology and the correlation effect in FeSe-based superconductors.

Drive the Dirac Electrons into Cooper Pairs in Possible Topological Superconductor $Sr_xBi_2Se_3$

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Topological superconductors are a very interesting and frontier topic in condensed matter physics. Despite the tremendous efforts in exploring topological superconductivity, its presence is however still under heavy debate. The Dirac electrons have been proven to exist on the surface of a topological insulator. It remains unclear whether and how the Dirac electrons fall into Cooper pairing in an intrinsic superconductor with the topological surface states. Here we show the systematic study of scanning tunneling microscope/spectroscopy on the possible topological superconductor $Sr_xBi_2Se_3$. We first demonstrate that only the intercalated Sr atoms can induce superconductivity. Then we show the full superconducting gaps without any in-gap density of states as expected theoretically for a bulk topological superconductor. Finally, we find that the surface Dirac electrons will simultaneously condense into the superconducting state within the superconducting gap (Fig. 1). This vividly demonstrates how the surface Dirac electrons are driven into Cooper pairs. [1]

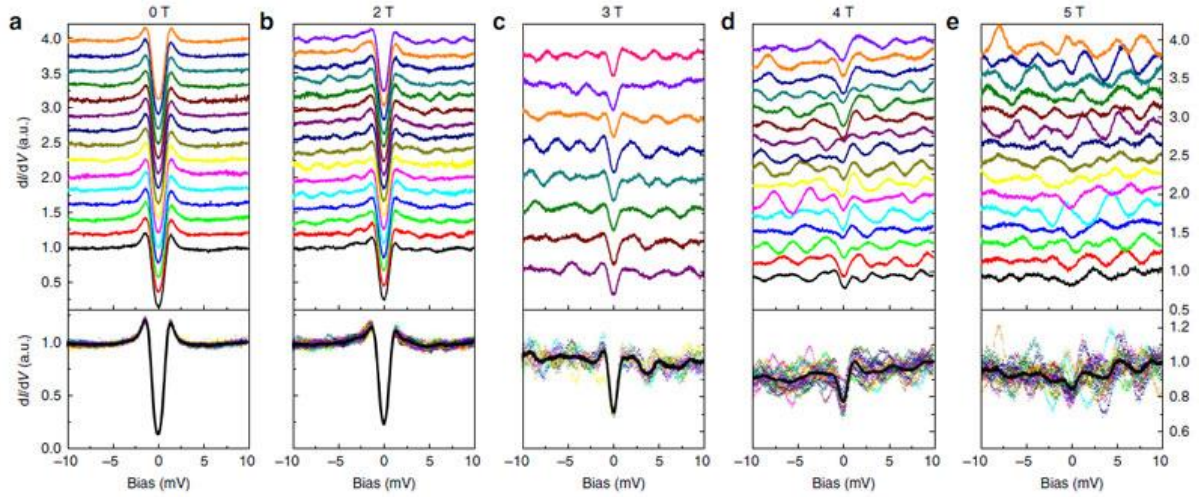

Fig. 1: *The spatially resolved spectra obtained over the same area at different magnetic fields. The oscillations on the spectra are the Landau levels oscillations with magnetic fields. One can see that the oscillations are strongly suppressed within the gap especially when compared with the averaged spectra shown as black curves in the bottom panels.*

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Sign Reversal Superconducting Gap Revealed by Phase Referenced Quasi-particle Interference in $(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$

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By measuring the spatial distribution of differential conductance near impurities on Fe sites, we have obtained the quasi-particle interference (QPI) patterns in the $(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$ superconductor with only electron Fermi surfaces. By taking the Fourier transform on these patterns, we investigate the scattering features between the two circles of electron pockets formed by folding or hybridization. We treat the data by using the recent theoretical approach [1] which is specially designed for the impurity induced bound states. It is found that the superconducting gap sign is reversed on the two electron pockets (Fig. 1), which can be directly visualized by the phase-referenced QPI technique, indicating that the Cooper pairing is induced by the repulsive interaction. [2] We show that this method is also applicable for data measured in $Bi_2Sr_2CaCu_2O_{8+\delta}$, and the direct evidence of the sign change is observed. [3] This method provides an easy and feasible way for detecting the gap function of unconventional superconductors.

$(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$ $Bi_2Sr_2CaCu_2O_{8+\delta}$

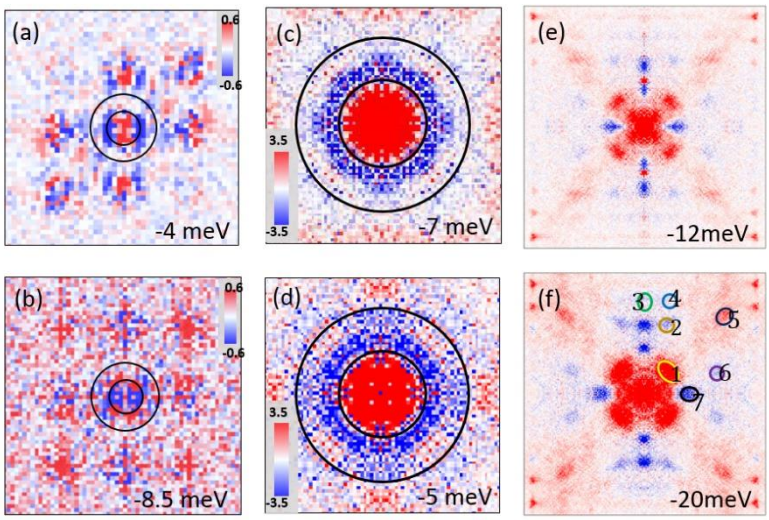

Fig. 1: *Phase-referenced QPI patterns g(q,E) at different energies in $(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$. (a-d) The phase-referenced signal between two circles are most negative at negative energy in $(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$, which is an evidence for sign revisal. (e,f) Different signs of scattering patterns at negative energy for different kinds of scattering channels in $Bi_2Sr_2CaCu_2O_{8+\delta}$.*

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Discrete Energy Levels of Caroli-de Gennes-Matricon States in Quantum Limit Due to Small Fermi Energy in $FeTe_{0.55}Se_{0.45}$

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Caroli-de Gennes-Matricon (CdGM states were predicted in 1964 as low energy excitations within vortex cores of type-II superconductors. In the quantum limit, the energy levels of these states were predicted to be discrete with the basic levels at $\pm \mu\Delta^2/E_F$ (μ = 1/2, 3/2, 5/2, …) with Δ the superconducting energy gap and E_F the Fermi energy. However, due to the small ratio of Δ/E_F in most type-II superconductors, it is very difficult to observe the discrete CdGM states, but rather a symmetric peak which appears at zero-bias at the vortex center. In this study, we report a clear observation of these discrete energy levels of CdGM states in $FeTe_{0.55}Se_{0.45}$ (Fig. 1). The rather stable energies of these bound state peaks versus space clearly validate our conclusion. Analysis based on the energies of these CdGM states indicates that the Fermi energy in the present system is very small. [1]

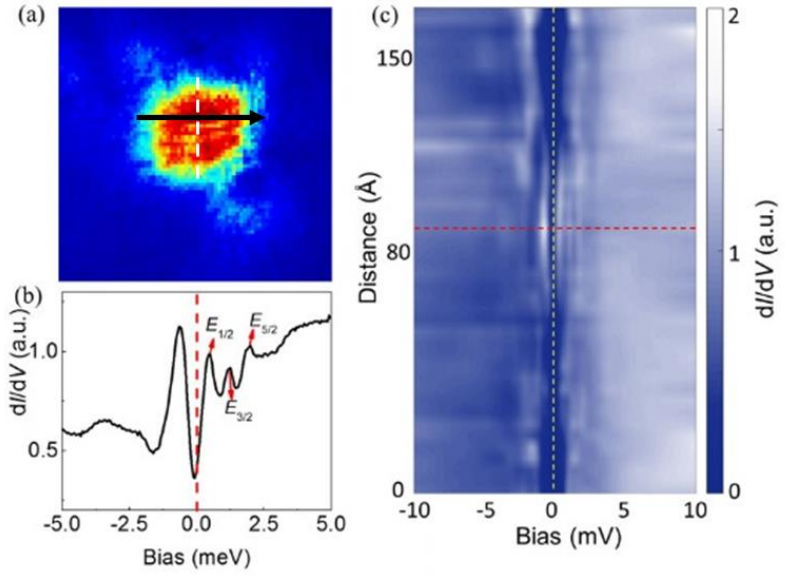

Fig. 1: *Vortex image and CdGM states measured on $FeTe_{0.55}Se_{0.45}$. **a** Image of a single vortex. **b** Tunneling spectrum measured at the center of the vortex core. It is clear to see three peaks with the energy marked by $E_{1/2}$, $E_{3/2}$, $E_{5/2}$. **c** 2D Color plot of spatial profile of the spectra crossing the vortex.*

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Determination of the Sign Reversal Superconducting Gaps on $(Li_{1-x}Fe_x)OHFe_{1-y}Zn_ySe$

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Iron pnictides are the only known family of unconventional high-temperature superconductors besides cuprates. It was widely accepted that superconductivity is spin-fluctuation driven and intimately related to their fermiology, specifically, hole and electron pockets separated by the same wave vector that characterizes the dominant spin fluctuations, and supporting order parameters (OP) of opposite signs. This picture was questioned after the discovery of intercalated or monolayer form of FeSe-based systems without hole pockets, which seemingly undermines the basis for spin-fluctuation theory and the idea of a sign-changing OP**.** Using the recently proposed phase-sensitive quasiparticle interference technique[1], we show that in LiOH intercalated FeSe compound the OP does change sign, albeit within the electronic pockets (Fig. 1). This result unifies the pairing mechanism of iron based superconductors with or without the hole Fermi pockets and supports the conclusion that spin fluctuations play the key role in electron pairing. [2]

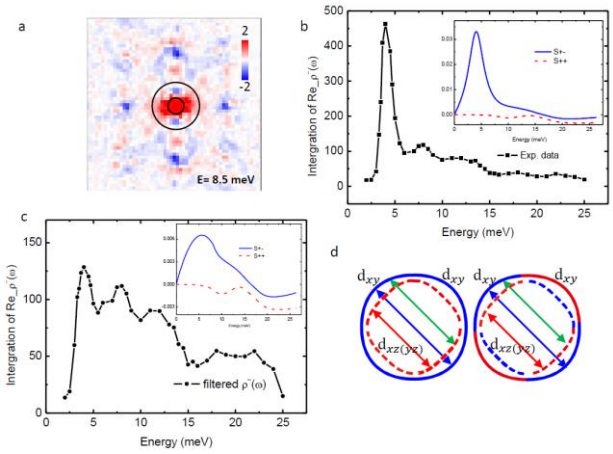

Fig. 1: *Determination of sign reversal of the superconducting order parameter. The energy dependent experimaltal real-part difference of FT-QPI $\delta\rho^-$ are consistent with therotical calculation based on S± pairting. Two possible sign-reversal scenarios are proposed, and the blue and red colors represent the opposite signs of the order parameter.*

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Electron-Hole Balance and the Anomalous Pressure-Dependent

Superconductivity in Black Phosphorus

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Here we report the *in situ* high-pressure (up to ~50 GPa) Hall-effect measurements on single-crystal black phosphorus. We find a strong correlation between the sign of the Hall coefficient, an indicator of the dominant carrier type, and the superconducting transition temperature (T_C). Importantly, we find a change from electron dominant to hole-dominant carriers in the simple cubic phase of phosphorus at a pressure of ~17.2GPa, providing an explanation for the puzzling valley it displays in its superconducting T_C vs pressure phase diagram. Our results reveal that hole carriers play an important role in developing superconductivity in elemental phosphorus and the valley in T_C at 18.8 GPa is associated with a Lifshitz transition.

Influence of persistent photoconductivity on superconductivity in the STO/LAO interface

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We study the superconductivity in STO/LAO interfaces. It is common practice to keep a freshly prepared sample in the dark for several hours prior to cool down. During this period the conductance relaxes to a stable state eliminating contributions from trapped photoelectrons. It has been reported that high intensity light can put doped STO in a persistent photoconducting state which only relaxes at elevated temperatures. We find persistent photoconductance at moderate illumination and study its influence on low temperature transport.

Tuning the Pairing Interaction in a *d*-Wave Superconductor by Paramagnons Injected through Interfaces

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Interplay between unconventional superconductivity and quantum critical fluctuations associated with exotic ordering is a key issue hotly debated in many classes of superconductors. Here, to study how the superconductivity is modified when these fluctuations are directly injected through the interface, we fabricate superlattices consisting of alternating atomic layers of *d*-wave superconductor $CeCoIn_5$ and antiferromagnetic (AFM) metal $CeRhIn_5$. In theses superlattices the ground state can be tuned in a wide range by applying pressure. The antiferromagnetic transition temperature T_N in these superlattices is strongly suppressed with pressure, similar to the bulk, whereas the superconducting temperature T_c is little affected. Above a critical pressure where T_N vanishes, we find a striking enhancement of the upper critical field relative to T_c. This implies that the AFM critical fluctuations in $CeRhIn_5$ layers grow to dominate the entire material, giving rise to extremely strong-coupling superconductivity by maximizing the force holding together the *d*-wave superconducting electron pairs.

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Impurity Effect in Heavy Fermion Superconductors Studied by STM

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Local electronic effects in the vicinity of an impurity provide pivotal insight into the origin of unconventional superconductivity, especially when the materials are located on the edge of magnetic instability. Since *d*-wave superconductor $CeCoIn_5$ is located in the vicinity of quantum critical point at ambient pressure, it is an ideal system to explore the effect of impurities in unconventional superconductivity. It has been reported that long range magnetic order is induced by substituting In atoms by nonmagnetic impurities, such as Cd, Hg and Zn [1, 2]. In addition, nuclear quadrupole measurements have suggested that the magnetic order is triggered by the formation of antiferromagnetic droplet around an impurity [3]. Altenatively, I has been reported that *Q*-phase, where superconducutivity coexits with spin dendity wave order, appears in Nd-doped $CeCoIn_5$ [4]. However, the role of the impurities is still unclear because local measurements are still missing.

Here, in order to investigate the local electronic structure around the impurities, we performed measurements of scanning tunneling microscopy (STM) which has high energy resolution in atomic scale. We have successfully prepared an atomically flat surface of $CeCoIn_5$ which contains impurities by molecular beam epitaxy, which is difficult to be obtained by cleavage of bulk crystals (Fig. 1) [5]. In my presentation, we will discuss about results of *in situ* STM measurements of the films.

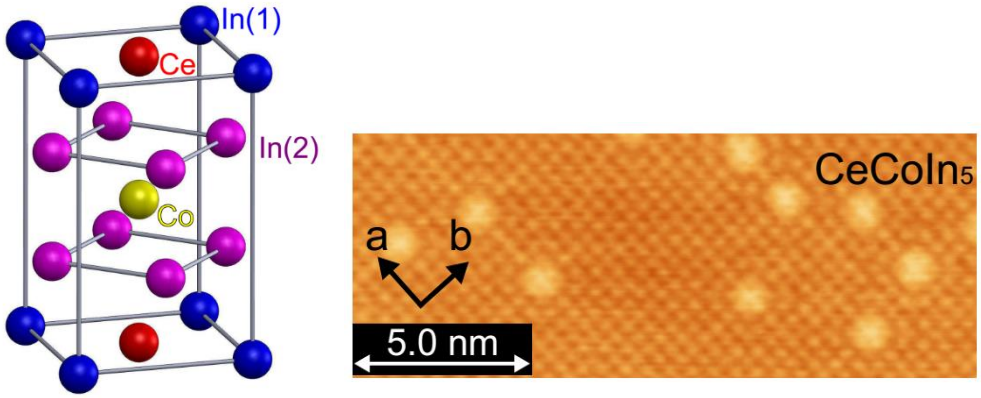

Fig. 1: *Crystal structure of $CeCoIn_5$ and its STM image.*

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Gap structure evolution in $Ba_{1-x}K_xFe_2As_2$ single crystals studied by point-contact Andreev reflection spectroscopy

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Point-contact Andreev reflection measurements have been carried out on optimal and overdoped $Ba_{1-x}K_xFe_2As_2$ single crystals along *c*-axis. The conductance peaks from Andreev reflection have been obviously observed near zero-bias. The measured spectra can be well fitted by the modified Blonder–Tinkham–Klapwijk (BTK) model, and the multi-superconducting-gap structures have been obtained for different samples. We can find obvious gap structure evolution for the samples of different doping levels. Temperature or field dependent of superconducting gaps have also been obtained in different samples. We also find some possible bosonic mode features with the energy values consistent with other kind of measurements.

Superconductivity in half-Heusler Compound TbPdBi

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We have studied the half-Heusler compound TbPdBi through resistivity, magnetization, Hall effect and heat capacity measurements. A semimetal behavior is observed in its normal state transport properties, which is characterized by a large negative magnetoresistance below 100 K. Notably, we find the coexistence of superconductivity and antiferromagnetism in this compound. The superconducting transition appears at 1.7 K, while the antiferromagnetic phase transition takes place at 5.5 K. The upper critical field H_{c2} shows an unusual linear temperature dependence, implying unconventional superconductivity. Moreover, when the superconductivity is suppressed by magnetic field, its resistivity shows plateau behavior, a signature often seen in topological insulators/semimetals. These findings establish TbPdBi as a new platform for study of the interplay between superconductivity, magnetism and non-trivial band topology.

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High-T_c superconductivity in a ruthenate

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The search for high-T_c superconductors is a fascinating topic in condensed matter physics. It is widely believed that high-T_c superconductivity in the cuprates emerges from doped Mott insulators. Recently, 4*d* and 5*d* transition metal oxides with a layer perovskite structure have attracted much attention because the possibility of the emergence of high-T_c superconductivity has been recognized in several studies. Indeed, monolayer films in iron pnictides indicate the enhancement of T_c to above 100 K. By tuning film thickness from monolayer to nanometer range, transition metal dichalcogenides have an exotic ground state different from bulk crystals due to negative pressure effect. Thus, the layered nanoscale films play a key part for exploring the emergence of superconductivity from high-temperature in layered perovskite 4*d* and 5*d* transition metal oxides, which may detect intrinsic superconductivity at mesoscopic scales.

In this presentation, we report the observation of high-T_c superconductivity in Ca_2RuO_4 nanofilm single crystals. A thin film of Ca_2RuO_4 exhibits supercurrent for current-voltage characteristics and typical Berezinskii-Kosterlitz-Thouless transition. Surprisingly, the highest onset transition temperature was ~ 100 K. We also found the current-induced and film-tuned superconductor-insulator transitions. Based on the results, we show the universality class and intrinsic inhomogeneity in the quantum phase transition. Finally, we discuss that why the thin films in Ca_2RuO_4 become the superconductivity from high-temperature. The fabrication of nanofilms made of layered material enables us to discuss rich superconducting phenomena in *4d* and *5d* Mott insulators.

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Correlation between non-Fermi-liquid behavior and superconductivity in (Ca, La)(Fe,Co)As_2 iron arsenides: A high-pressure study

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Non-Fermi-liquid (NFL) phenomena associated with correlation effects have been widely observed in the phase diagrams of unconventional superconducting families. Exploration of the correlation between the normal state NFL, regardless of its microscopic origins, and the superconductivity has been argued as a key to unveiling the mystery of the high-T_c pairing mechanism. Here we systematically investigate the pressure-dependent in-plane resistivity (ρ) and Hall coefficient (R_H) of a high-quality 112-type Fe-based superconductor $Ca_{1-x}La_xFe_{1-y}Co_yAs_2$ (x =0.2, y =0.02). With increasing pressure, the normal-state resistivity of the studied sample exhibits a pronounced crossover from non-Fermi-liquid to Fermi-liquid behaviors. Accompanied with this crossover, T_c is gradually suppressed. In parallel, the extremum in the Hall coefficient $R_H(T)$ curve, possibly due to anisotropic scattering induced by spin fluctuations, is also gradually suppressed. The symbiosis of NFL and superconductivity implies that these two phenomena are intimately related. Further study on the pressure-dependent upper critical field reveals that the two-band effects are also gradually weakened with increasing pressure and reduced to the one-band Werthamer-Helfand-Hohenberg limit in the low-T_c regime. Overall, our paper supports the picture that NFL, multigap, and extreme $R_H(T)$ are all of the same magnetic origin, i.e., the spin fluctuations in the 112 iron arsenide superconductors.

Nonreciprocal Transport by Vortex Ratchet Motion in 2D Superconducting MoS_2

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Transition metal dichalcogenide (TMD) crystals are becoming a potential platform for investigating intrinsic physical properties of 2D superconductors owing to its high-crystallinity [1]. One of the most important characteristics of two-dimensional (2D) TMDs is the threefold symmetry in its single layer form. In this presentation, we report the nonreciprocal superconducting transport in 2D noncentrosymmetric MoS_2.

In a previous work, it is reported that the longitudinal resistance depends on the current direction parallel to the armchair edge around superconducting transition temperature, which can be attributed to the nonreciprocal paraconductivity [2]. We studied nonlinear transport at low temperature, where vortex ratchet motion is dominant. The nonreciprocal signals satisfy the characteristic directional dependence, reflecting the intrinsic crystal structure. We also measured current dependence of the nonreciprocal signals, which shows the similar behavior as vortex ratchet effect in systems with artificial asymmetric potentials [3]. In the presentation, we will discuss the possible relation between nonreciprocal signals and vortex dynamics. The present results suggest that nonreciprocal signals have a great potential for investigating vortex dynamics in 2D noncentrosymmetric superconductors.

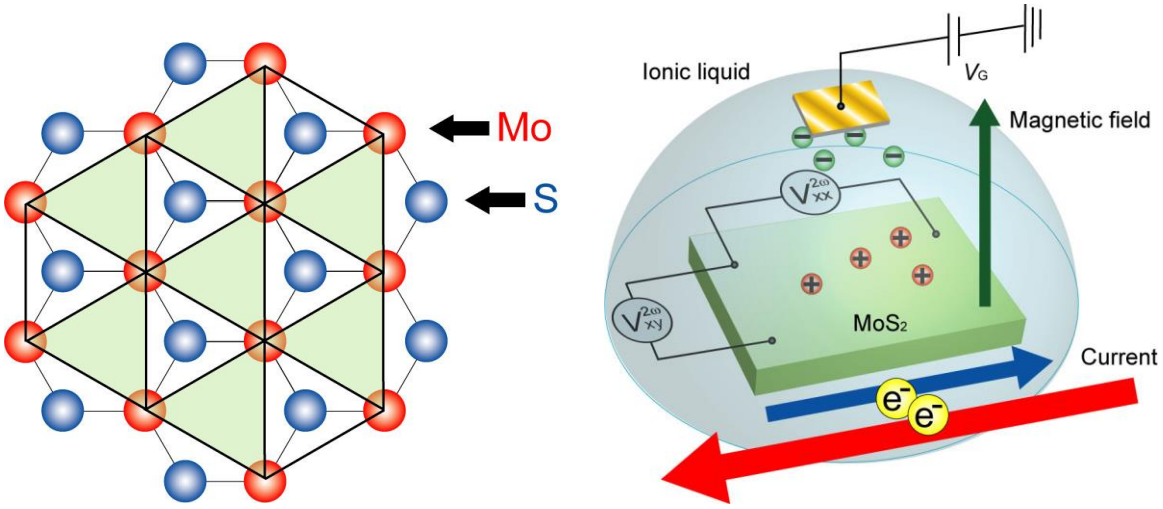

Fig. 1: *Trigonal crystal structure of MoS_2 and measurement setup.*

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Unusual Evolution of Electronic Nematicity in the Heavily Hole-Doped $Ba_{1-x}Rb_xFe_2As_2$

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It is well established that tetragonal-to-orthorhombic structural transition in $BaFe_2As_2$ is driven by electronic nematic instability, and several experiments have provided evidence for the B_{1g} nematic fluctuations (using 1 Fe/cell notation) in the tetragonal phase [1,2]. The nematicity with B_{1g} symmetry is suppressed by hole doping, and considered to vanish in the overdoped region.

On the other hand, in the heavily hole-doped $BaFe_2As_2$, the strong increase of effective mass with doping has been found [3]. Theoretically, it has been proposed that these strongly enhanced electron correlations are connected to approaching the assumed half-filled Mott insulting phase at $3d^5$ configuration [4]. In this context, AFe_2As_2 (A = K, Rb, Cs) with $3d^{5.5}$ configuration can be seen as a proximity to Mott insulator, indicating the similarity to underdoped high-T_c cuprates, which exhibit various forms of the exotic orders. In particular, the electronic nematicity could emerge in AFe_2As_2 due to the quantum melting of the localized Mott insulating state, as demonstrated in cuprates [5].

Here we report the systematic elastoresistance measurements in $Ba_{1-x}Rb_xFe_2As_2$, which allow us to evaluate the nematic fluctuations. In the overdoped regime, we find that B_{2g} nematic fluctuations, whose director is rotated 45 degree from that of the usual nematicity, become more significant and have stronger temperature dependence compared with B_{1g} nematic fluctuations. This result presents evidence for the nematicity with B_{2g} symmetry in iron-based superconductors close to the $3d^{5.5}$ configuration, whose origin is different from that in underdoped regime near the $3d^6$ antiferromagnetic state.

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Disorder induced switching from antiferromagnetic to paramagnetic ground state in under doped iron-based superconductors

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Competition between spin-density wave (SDW) and superconducting (SC) orders in under doped iron based superconductors leads to the common composition-temperature phase diagram with the magnetic SDW transition line intersecting the maximum of SC dome. Below intersection point, SC phase emerges from anti-ferromagnetic ground state, with possible coexistence of SDW and SC states inside of SC dome on microscopic scale, and extension of SDW transition line in SC phase [1].

We investigate the effects of point disorder introduced by low-temperature electron irradiation on the superconducting and magnetic transition lines in single crystals of $BaFe_2(As_{1-x}P_x)_2$. Depression by point-like disorder of critical temperature, T_c, of SC state [2], is followed by faster decrease of the SDW transition, T_{SDW}. Evolution of whole composition - temperature phase diagram tuned by point disorder indicates shift of putative Quantum Critical Point (QCP) [3]. For composition close to intersection point, complete suppression of SDW phase by disorder opens the possibility to tune the ground state from antiferromagnetic to paramagnetic for the same chemical composition. We investigated properties of the vortex matter in this region for different degrees of disorder. Novel transition line beneath superconducting dome was identified by abrupt change in temperature dependence of the critical current. Correlation between irradiation induced shift of T_{SDW}, and evolution of this line with disorder points to the same origin, namely extension of SDW transition in the superconducting state.

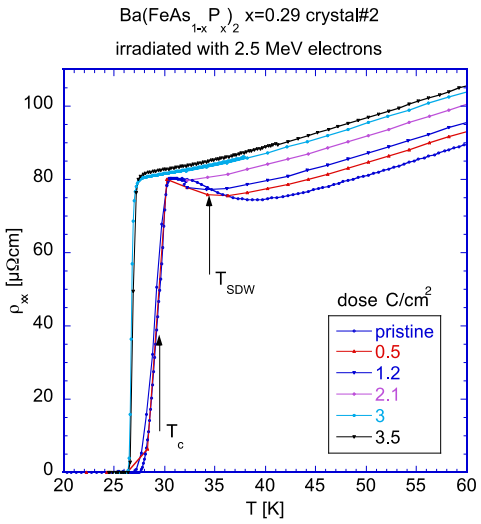

Fig. 1 *Resistivity vs. temperature curves of $BaFe_2(As_{1-x}P_x)_2$ after step by step electron irradiation. SDW transition, marked by an upturn in pristine material is shifts down and*

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Half-integer Thermal Hall Effect in α-$RuCl_3$: a signature of Majorana fermions

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Recently, quantum spin liquids (QSLs), which show no magnetic order even at zero temperature due to strong quantum fluctuations, have aroused great interest. In 2006, a QSL model of two-dimension honeycomb lattice with exactly solved ground state was proposed [1]. In this Kitaev model, as a result of fractionalization of quantum spins, itinerant Majorana fermions and localized Z_2 fluxes appear. The Mott insulator α-$RuCl_3$ is considered to be a promising candidate for the Kitaev spin liquid [2]. Although α-$RuCl_3$ shows a zigzag type antiferromagnetic order at T_N = 7 K at zero magnetic field, its magnetic order is suppressed by magnetic field applied parallel to the ab-plane, leading to the emergence of a possible QSL state [3, 4].

Here, we report the thermal Hall effect in α-$RuCl_3$, which provides a key feature of Majorana fermion excitations. In the low-temperature regime of the QSL state in the presence of parallel field, we found that the 2D thermal Hall conductance κ_{xy}^{2D}/T reaches a plateau as function of applied magnetic field. Remarkably, κ_{xy}^{2D}/T attains a quantization value of $(\pi/12)(k_B^2/\hbar)$, which is exactly half of κ_{xy}^{2D}/T expected in the integer quantum Hall effect. This half-integer thermal Hall conductance, which has been predicted in chiral topological superconductors [5-7], provides a direct signature of topologically protected chiral edge currents of charge neural Majorana fermions, particles possessing half degrees of freedom of conventional fermions [8]. From these signatures, we conclude the fractionalization of spins into itinerant Majorana fermions and Z_2 fluxes predicted in Kitaev QSL [1]. Moreover, above a critical magnetic field, the quantization disappears and κ_{xy}^{2D}/T goes to zero rapidly, indicating the presence of a topological quantum phase transition between the states with and without chiral Majorana edge modes.

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Observation of phase-sensitive symmetry gap for Fe-based superconductors from Nb/Al/$Ba_{1-x}K_xFe_2As_2$ hybrid Josephson junction

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We studied on the pairing symmetry of 122-type iron-pnictides superconductors via to the *c*-axis hybrid Josephson junctions between $Ba_{1-x}K_xFe_2As_2$ and Nb. The temperature dependent resistance is observed three distinct superconducting transitions, among which the transition at relatively low temperature of 6 K demonstrates to the junction, while the others to the superconductors. The *I-V* curve reveals the typical behavior of resistively shunted junctions (RSJ) model, and Shapiro-steps under microwave irradiation of 40 GHz. The critical current density shows a typical Fraunhofer-like modulation under in-plane magnetic field. The temperature dependence of the I_cR_N product is linear, satisfying with de Gennes' dirty limit theory. The strong *c*-axis Josephson effect can exclude a pure *d*-wave symmetry. Simultaneously, the small value of the I_cR_N product corresponding to the energy gap may rule out the conventional *s*-wave and the s_{++} symmetry, while consistent with the anisotropic *s*-wave like *s+d* state.

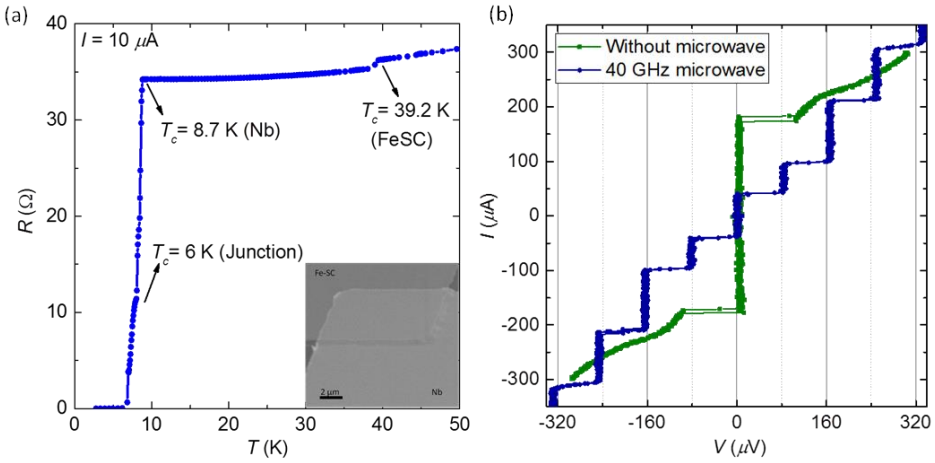

Fig. 1: *(a) R-T characteristic with the inset of a SEM image of the junction. (b) I-V characteristic of the hybrid Josephson junction and Shapiro steps under microwave.*

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Gate-Induced Superconductivity in SnX_2

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Exploration of two-dimensional (2D) superconductivity in new material systems has attracted intensive research interest in condensed matter physics.[1-2] Here, we report the discovery of gate-induced 2D superconductivity in layered SnX_2. By using the latest developed solid ionic gating technique, we continuously tuning carrier concentration through intercalating Li/Na/K ions into mechanically exfoliated SnX_2 flakes. As increasing Li content, a gate-induced superconductivity with T_c ~7 K is obtained for the optimal-doped sample (Fig. 1). This T_c value was higher than the maximum previously reported for 1T SnX_2 (~3.9 K) via electrostatic ionic gating.[3] Such results provide a new perspective to expand the material matrix available for gate-induced 2D superconductivity and the fundamental understanding of superconductivity.

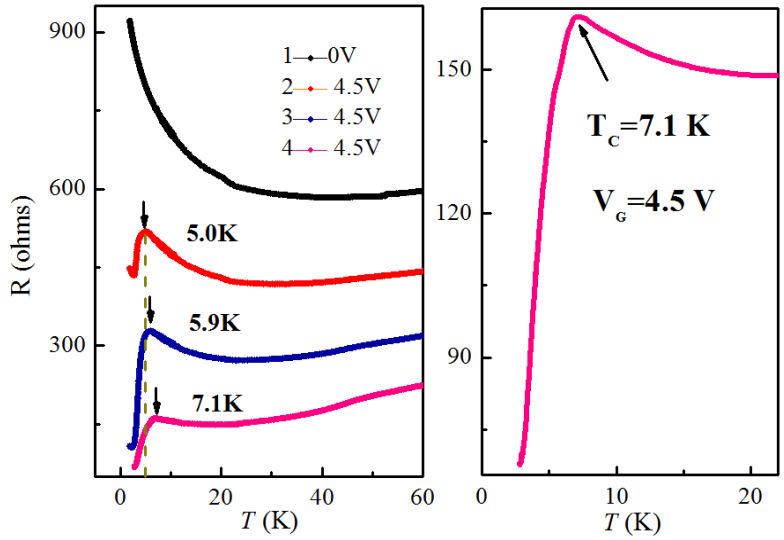

Fig. 1: *Temperature-dependent resistance between 2 and 50 K with V_G =4.5V. A semiconductor-to-superconductor transition occurs at T_c = 7.1 K.*

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Magnetic Field Induced Ordering in Electron-doped Cuprate $La_{2-x}Ce_xCuO_{4\pm\delta}$

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Emergence of superconductivity at the instabilities of antiferromagnetism (AFM), spin/charge density waves have been widely recognized in unconventional superconductors [1]. In cuprates, spin fluctuations play a predominant role in superconductivity with electron dopants [2]. The existence of an AFM critical end point is still in controversy for different probes. Here, by tuning the oxygen content, a systematic study of the Hall signal and magnetoresistivity up to 58 Tesla on optimally doped $La_{2-x}Ce_xCuO_{4\pm\delta}$(x = 0.10) thin films identifies two characteristic temperatures at 62.5 ± 7.5 K and 25.0 ± 5 K, linking respectively to two- and three- dimensional AFM, evident from the multidimensional phase diagram as a function of oxygen and Ce dopants [3, 4]. In addition, we capture traces of an unknown ordering in the process of electronic transport, which contributes positive magnetoresistance. The characteristic temperature T_b of this order, at which the long-range order disappears and the fluctuation enhanced, is positively correlated with superconductivity temperature *T*c, and essentially distinct with two- and three- dimensional AFM characteristic temperatures. The new finding maybe reveals existence of undiscovered order in $La_{2-x}Ce_xCuO_{4\pm\delta}$ similar to hidden-order in heavy fermion superconductor.

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Interplay between nematic fluctuations and superconductivity in $BaFe_{2-x}Ni_xAs_2$

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We have systematically studied uniaxial pressure dependence of the superconducting transition temperature T_c along both the Fe-Fe and Fe-As-Fe directions in $BaFe_{2-x}Ni_xAs_2$. Our analysis identifies two mechanisms by which uniaxial pressure p affects T_c: one arising from an isotropic (i.e. non-nematic) lattice mode, manifested as a linear dependence of T_c on p, and one arising from a shear lattice mode that couples to nematic fluctuations, manifested as a non-linear dependence of T_c on p. While the latter effect leads to a nearly doping-independent suppression of T_c, signaling the competition between nematicity and superconductivity, the former effect leads to a continuous change of dT_c/dp with doping, resulting in an enhancement of T_c in the overdoped side, but a suppression in the underdoped side. Surprisingly, the sign change of dT_c/dp in the isotropic channel coincides with the putative nematic quantum critical point, whose soft mode is in the anisotropic channel. Our results provide important insight into the interplay between nematic fluctuations and superconductivity in iron-based superconductors.

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Nematic Fluctuations in NaFe1-xNixAs

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We report elastroresistivity measurements on single crystals of NaFe1−xNixAs. The nematic susceptibility is defined as proportional to the change of resistivity under uniaxial pressure, whose temperature dependence can be well fitted by a Curie-Weiss-like function. Surprisingly, the sign of nematic susceptibility changes from positive to negative with just slight Ni doping, which is contrary to the expectation that electron doping should always lead to positive nematic susceptibility. Compared to our previous results on BaFe2-xNixAs2 system, although the mean-field nematic transition temperature from the Curie-Weiss fitting of the nematic susceptibility becomes zero around optimal doping, our results do not support the presence of a nematic quantum critical point in this system. We will also provide discussions on the possible influence of nematic fluctuations on the zero-pressure resistivity.

The Study of Quantum Critical Point in $BaFe_{2-x-y}Ni_xCr_yAs$ Based Superconductors

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Previous studies have shown that iron based superconductors may have antiferromagnetic and nematic quantum critical points, but it can not be observed directly due to the presence of superconductivity. Our previous works have shown superconductivity in the $BaFe_{2-x}Ni_xAs$ system can be suppressed by dopping an amount of chromium. At the same time, the antiferromagnetic order changes from incommensure to commensure, from short-range to long-range. Therefore, the antiferromagnetic and nematic quantum critical points may be studied by completely suppressing superconductivity. Here, I will show our recent research of the antiferromagnetic and nematic phases on the chromium dopped $BaFe_{2-x}Ni_xAs$ by the electron resistance measurement.

Stabilization of three-dimensional charge order in YBa2Cu3O6+x via epitaxial growth

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University of California， San Diego

Incommensurate charge order (CO) has been identified as the leading competitor of high-temperature superconductivity in all major families of layered copper oxides, but the perplexing variety of CO states in different cuprates has confounded investigations of its impact on the transport and thermodynamic properties. The three-dimensional (3D) CO observed in YBa2Cu3O6+x in high magnetic fields is of particular interest, because quantum transport measurements have revealed detailed information about the corresponding Fermi surface. Here we use resonant X-ray scattering to demonstrate 3D-CO in underdoped YBa2Cu3O6+x films grown epitaxially on SrTiO3 in the absence of magnetic fields. The resonance profiles indicate that Cu sites in the charge-reservoir layers participate in the CO state, and thus efficiently transmit CO correlations between adjacent CuO2 bilayer units. The results offer fresh perspectives for experiments elucidating the influence of 3D-CO on the electronic properties of cuprates without the need to apply high magnetic fields.

Studies of the Superconducting Order Parameter in the Heavy-Fermion Superconductor $CeCoIn_5$ *via* Planner Tunneling Spectroscopy at High Magnetic Field

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The heavy-fermion superconductor $CeCoIn_5$ is a $\mathbf{d_{x^2-y^2}}$ symmetry superconductor as shown by thermal transport, thermodynamic, and Andreev reflection, measurements.[1,2] Interestingly, the wave vector-modulated spin density wave-like ***Q***-phase, appears to be intertwined with the superconducting phase in the low-temperature and high-field regime of the phase diagram. [3] Despite several recent scanning tunneling spectroscopic measurements [4], precise phase-sensitive measurements are still needed to unveil the detailed spectroscopic nature of the ***Q***-phase. We present planer tunneling spectroscopy (PTS) results in the c-axis direction as a function of temperature down to 20 mK and magnetic field up to 18 T; with the field applied both parallel and perpendicular to the junction. The data at 20 mK exhibit sharp coherence peaks and the estimated gap size is 0.65 meV. Under applied field we reproducibly find excess conductance and a gap-like feature that persists well above T_c and Hc_2. We plan to present PTS in the ab-plane, both nodal and anti-nodal directions and discuss our results in the context of the ***Q***-phase.

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Theory of electronic states in Ta2NiSe5 under pressure as a candidate material of excitonic phase

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Transition metal chalcogenide Ta2NiSe5 known as a candidate material for excitonic insulator shows a structural phase transition from orthorhombic (semiconductor) to monoclinic (semiconductor) at *Ts* = 328*K* under ambient pressure. Flattening of the top of the valence band below *Ts* was observed by angle-resolved photoemission spectroscopy (ARPES) and the possibility of excitonic order was proposed as the origin of the structural transition[1, 2]. Theoretically, the experimental results were well accounted for by the BCS type mean-field analysis of the excitonic order based on the three-chain Hubbard model for Ta2Ni chain which reproduces the _rst principles calculation for Ta2NiSe5 at ambient pressure[3]. When the pressure is applied for Ta2NiSe5[4, 5], the structural phase transition temperature *Ts* is suppressed and the system changes from semiconducting to semimetallic both above and below *Ts*, and then, *Ts* finally becomes zero at a critical pressure 8GPa, around which the superconductivity is observed.
We investigate the three-chain Hubbard model in the semimetallic case under pressure and _nd that the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) excitonic state characterized by the condensation of excitons with _nite center-of-mass momentum corresponding to the nesting vector between the electron-hole Fermi surfaces is stabilized by the imbalance between electrons and holes due to the difference in degeneracy between the two-fold degenerate conduction bands and the non-degenerate valence band[6, 7]. We also performed a similar calculation in the quasi-one-dimensional three-chain Hubbard model with a interchain hopping, and revealed that three types of FFLO excitonic orders are realized from three types of nesting vectors between the imbalanced two *c* and one *f* Fermi surfaces[8].
In this presentation, we report the result of examining whether the structural phase transition from orthorhombic to monoclinic due to the electron-lattice coupling and the FFLO excitonic order are realized consistently.

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Superconducting Critical Temperature for a Dirty Nano-structured Superconductor

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Superconducting critical temperature T_c is important for applications of superconductor. T_c depends not only on material properties but also on size and shape for nano-structured superconductors. Parmenter theoretically showed that smaller pure superconductor shows higher T_c, using the BCS theory [1]. Nishizaki experimentally showed that the high pressure torsion (HPT) on bulk of Nb makes many fine grain in the bulk [2], and these grains enhance T_c. Nishizaki also showed that the HPT decreases T_c of bulk of V. Nishizaki discussed that impurities in the bulk, for example oxygen atoms, decrease T_c. However, Anderson showed that non-magnetic impurities do not affect on T_c. So to reconcile the Anderson's theorem and Nishizaki's experiment, we study the T_c for a dirty nano-structured superconductor.

We theoretically study the size, shape and impurity effects on T_c for nano-sized superconductor, using finite element method [3] to solve the Bogoliubov–de-Gennes (BdG) equations. In previous study, we found that T_c oscillatory increases with decreasing size of pure superconductor. In addition, narrower pure superconductor shows higher T_c. We take impurity effects into account as random potential, and then the BdG equations for FEM becomes

$$\begin{aligned}
&\sum_j P_{ij}^e u_j^e + \sum_j Q_{ij}^e(\mathrm{D}) v_j^e = E \sum_j I_{ij}^e u_j^e \\
&-\sum_j P_{ij}^e v_j^e + \sum_j Q_{ij}^{e*}(\mathrm{D}) u_j^e = E \sum_j I_{ij}^e v_j^e
\end{aligned}
\qquad
\left(
\begin{aligned}
P_{ij} &= \frac{1}{2k_F x} \sum_a K_{ij}^{eaa} + \sum_{i_1} I_{ii_1 j}^e V_{imp\, i_1}^e - m I_{ij}^e \\
Q_{ij} &= \sum_{i_1} \mathrm{D}_{i_1}^e I_{iji_1}^e
\end{aligned}
\right),$$

where V_{imp} is the random potential. Solving these equations, we find that random potential enhances T_c increase because of localization of superconducting order parameter (Fig. 1).

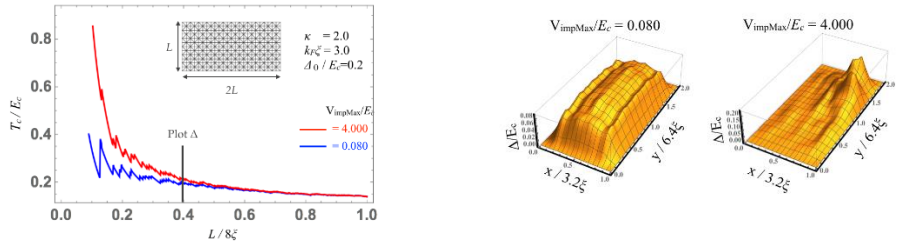

Fig. 1: Size dependence of T_c for dirty superconductor (V_{impMax} / E_c = 0.008 and 4.000) and each distribution of order parameter at L = 3.2 ξ, where V_{impMax} is the Max of random impurity potential, E_c is the cut-off energy of BCS and ξ is the coherence length at T = 0.

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Topological transition in a family of non-centrosymmetric superconductors

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Recently, the relationship between superconductivity and topological properties has attracted much attention in condensed matter physics. Furthermore, in noncentrosymmetric superconductors a finite antisymmetric spin-orbit coupling can lead to Cooper pairs with a mixture of singlet and triplet states, and therefore it is important to explore the properties of new superconductors lacking inversion symmetry. We recently found evidence that the isostructural materials Lanthanide compound are all noncentrosymmetric superconductors. Here we report electronic structure calculations for all three systems, which is particularly important for understanding the influence of the spin-orbit coupling on the band structure near the Fermi energy. The calculation results show that the band structures of all these materials are topologically non-trivial with Weyl nodes. Moreover, there are differences in the Z2 topological index between the different materials, suggesting that the topological properties of this family of superconductors can be tuned.

Possible High-T_c Superconductivity Originating from Wide- and Narrow-Bands; Study on 1D and 2D Lattices

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One of the simplest models of the high T_c cuprates is the single-band Hubbard model on a square lattice. Considering the superconductivity originating from spin fluctuation on this model, the strong spin fluctuation gives rise to the strong d-wave pairing interaction and strong quasiparticle renormalization. The former enhances superconductivity, but the latter suppresses it. In order to circumvent the latter problem, the systems with coexisting wide- and narrow-bands have been proposed [1, 2]. According to the previous study on the two-leg ladder lattice[1], when the Fermi level within the wide-band lies close to, but not within the narrow-band, high T_c superconductivity can occur due to the large number of interband pair-scattering and the small renormalization of the quasiparticles. To show the generality of the above picture, we study, within the fluctuation exchange approximation, quasi-one dimensional Hubbard models on two- and three-leg ladder lattices with diagonal hoppings, as well as the diamond chain and crisscross-ladder lattices[3], all of which have coexisting wide- and narrow-bands. In addition, we also study two-dimensional Hubbard models on lattices with coexisting wide- and narrow-bands within the same formalism. We investigate the commonalities and differences among these models, and discuss the relation between superconductivity and coexisting wide/narrow bands.

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Possibility of High-T_c Superconductivity in Ruddlesden-Popper Type Materials: Incipient Narrow Bands Originating from "Hidden Ladder" Electronic Structure

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While an ideal situation for enhancing T_c in unconventional superconductors would be to simultaneously have a strong pairing interaction and a small renormalized electron mass, but usually we have a dilemma that the two conditions are incompatible. One of the present authors proposed a way to circumvent this by considering systems with coexisting wide and narrow bands, such as the two-leg Hubbard ladder with the second-neighbor hopping [1]. If the Fermi level is set close to, but not right within, the narrow band, the electrons in the wide band, where the renormalization is not strong, can form Cooper pairs with a strongly pairing interaction mediated by the large number of interband pair-scattering channels.

As a way to realize this situation in actual materials, we introduce here the concept of a "hidden ladder" electronic structure in the bilayer Ruddlesden-Popper compounds. When the bands with t_{2g} orbital character form the Fermi surface, the anisotropy of the orbital makes an electron in the $d_{xz/yz}$ orbital mainly hop in the x/y direction, along with the z direction normal to the bilayer. This means that the $d_{xz/yz}$ orbital form a ladder with x/y and z directions being the leg and rung directions, respectively (Fig.1). This leads us to propose that $Sr_3Mo_2O_7$ and $Sr_3Cr_2O_7$ are candidates for the hidden ladder materials with the right posotion of the Fermi level. Based on the analysis of the linearlized Eliashberg equation within the fluctuation exchange approximation, we discuss possible occurrence of high-T_c superconductivity in these materials originating from the large number of interband pair-scattering channels between the wide and the "incipient" narrow bands [2]

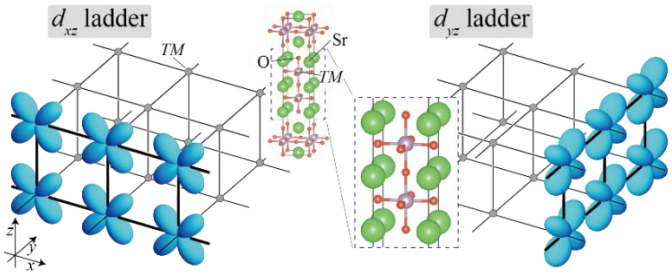

Fig. 1: *Schematics of hidden ladders composed of d_{xz} (left panel) and d_{yz} (right) orbitals in the bilayer Ruddlesden-Popper compound $Sr_3TM_2O_7$ (TM: transition metal). The crystal structure is also displayed (center).*

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Non-equilibrium electron dynamics after a quench of the interaction in the doped 2D Hubbard model

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We theoretically investigate the effect of chemical doping on the real-time non-equilibrium dynamics of interacting electrons. For this purpose, we have developed a Keldysh generalization of the fluctuation-exchange approximation~(FLEX) to explore the time-evolution of the repulsive Hubbard model on the square lattice after interaction quenches.

We shall first present the real-time FLEX algorithm, and highlight its merits over the previously introduced Keldysh FLEX [1] suitable for studying steady-state dynamics. We then discuss the relaxation dynamics of the system in both electron-doped and hole-doped regimes. In both regimes, the system evolves towards a thermal state which locally satisfies the fluctuation-dissipation theorem with momentum-dependent observables becoming steady upon thermalization of local quantities, such as the spectral function. We also show that the effective nonlocal interaction, within the FLEX, is changed transiently.
Finally, we shall describe how the details of the quench protocol, i.e., duration of the quench and the final Hubbard interaction, affect the relaxation dynamics of the system towards thermalization.

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Muon's Perturbation on the Local Spatial Distribution of Cu-Spin in La_2CuO_4 Simulated by Density Functional Theory Calculations

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The muon spin relaxation (μSR) method is a powerful tool to investigate electronic states of the Cu-based high-T_C superconducting oxides. To reveal muon positions inside La_2CuO_4 (LCO) gives us useful information to achieve deeper understandings of the electronic states in its magnetically ordered state. However, any unified method to investigate muon positions have not yet been firmly established. For this reason, the SR results achieved on LCO even in the early stage of the high-T_C history, have not yet been fully explained [1-3]. We are approaching this matter by using the density functional theory (DFT) calculation method, with a supercell framework, and including only one muon as a dilute charged impurity. The on-site Coulomb repulsion energy, U = 8 eV, was taken into account to include the correlation energy between neighboring *3d* orbitals of the Cu atoms. Three minimum potential positions were estimated from DFT calculations and set to be the initial muon-stopping positions. Those positions are indicated in Fig. 1 as M1, M2, and M3. The muon positions were then optimized in supercells which contain 2×2×1 and 4×4×2 unit cells, including the effect of local lattice deformations caused by the muon itself. Expected dipole fields at the muon position were estimated by taking into account the zero-point vibration motion of the muon and the distribution of electronic spins of Cu. The results of our investigations

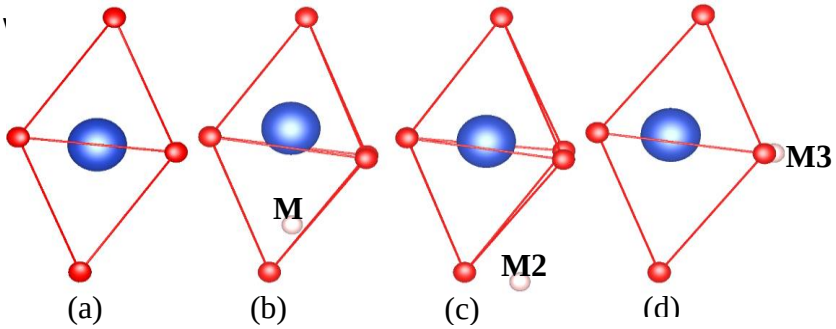

Fig. 1: *Comparison of CuO_6 octahedra after the relaxation of lattice structure and the muon position in the case of (a) without the muon and putting the muon at initial minimum potential positions of (b) M1, (c) M2 and (d) M3.*

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First Principles Investigations on a New 1111-type Fe-based Superconductor: ThFeAsN

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Recent discovery of superconductivity at 30K in stoichiometric ThFeAsN compound [1], in absence of spin density wave order [2] stipulate a possibility of non-magnetic origin of high temperature superconductivity. In contrary to the experimental results, first principles calculation within GGA predicts a stripe antiferromagnetic ground state in this system [3]. In order to explore the emergence of superconductivity in ThFeAsN, we perform electronic structure calculations within density functional theory (DFT). Our first principles electronic structure calculations reveal the semi metallic behavior of ThFeAsN, which resembles with that of the LaFeAsO and most of the other Fe-based superconductors. Fig. 1 depicts our calculated orbital projected band structure of ThFeAsN in non-magnetic state. The dominance of Fe d_{yz}, d_{xz} and d_{xy} orbitals at the Fermi level is in well agreement with that of the previous experimental as well as theoretical results [1,4].

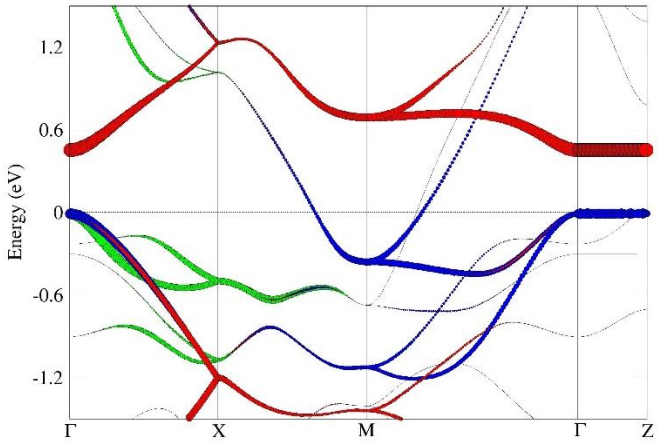

Fig. 1: *Calculated orbital projected [Fe- d_{yz} (green), d_{xz} (blue), d_{xy} (red)] band structure of ThFeAsN with GGA optimized structure in non-magnetic state.*

Moreover, we observe (see Fig. 1) that the system is very close to Lifshitz transition (near Γ points), which is likely to play an important role in superconductivity [5]. Further theoretical investigations are required to understand the mechanism of superconductivity in this system.

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Emergence of d_{xy}-Wave Superconductivity in a Doped Spin-1 Chain

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We propose a doped spin-$1/2$ two-leg diagonal ladder model (or a composite spin model) to simulate a doped spin-1 chain. Many features of Haldane phase are obtained. By using density matrix renormalization group method for an open chain, we find that the system hosts finite spin gap and edge state. Numerical results show that the pairing channel with power-law decaying correlations belongs to spin singlet d_{xy} symmetry. Meanwhile we apply the renormalized mean field approach to solve this doped spin-$1/2$ two-leg ladder. Both the pairing field and resonating valence bond field appear in the diagonal and horizontal bonds, the pairing symmetry still obeys d_{xy} symmetry. In addition, superconducting order exhibits a dome-like shape as a function of doping level and vanishes at doping level around 0.4. Our work provides a physical understanding on the origin of d_{xy} pairing symmetry in doped spin-1 chain which seems to be related to the superconductivity in Fe-based compounds.

Electron-Phonon Coupling and Superconductivity in NbN Polytypes

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Materials that show both topological properties and superconductivity have received considerable interest in recent years because of possible realization of Majorana fermions, i.e., particles with their own anti-particles in such condensed matter systems [1]. Therefore, it is highly desirable to investigate for the materials that have topological properties and superconductivity. Niobium nitride (NbN), a well-known transition metal nitride, is a good superconducting material in its cubic structure (δ-NbN) with transition temperature Tc of 17.3 K [2]. Recent experiments on hexagonal NbN (ε-NbN) also revealed the existence of superconductivity with a Tc of 11.6 K [3]. On the other hand tungsten carbide (WC) type NbN possesses topological properties with band crossing that has a three-fold degeneracy along a particular k-vector path in the Brillouin zone [4]. Therefore, NbN is a good candidate that shows both topological properties as well as superconductivity.

In this contribution we study the electronic structure, lattice dynamics and electron-phonon interactions in δ-NbN, ε-NbN and WC-NbN by means of density functional theory with generalized gradient approximation [5, 6]. The electronic band structure and density of states for the three structures of NbN have been studied. From the density of states it is clear that *d*-states of Nb are dominant in the vicinity of Fermi level. The phonon density of states and Eliashberg functions show that electron-phonon coupling in δ-NbN is stronger than ε-NbN and WC-NbN. In particular, we find that electron-phonon coupling constant λ is equal to 0.98 for δ-NbN, 0.16 for ε-NbN and 0.11 for WC-NbN. By using Allen-Dynes formula the superconducting transition temperature T*c* is estimated to be 18.2 K for δ-NbN, and 0 K for ϵ-NbN and WC-NbN with a smearing parameter (σ) value of 0.02 Ry. Both ϵ-NbN and WC-NbN show superconductivity with a Tc of 1.08 K and 0.89 K respectively for σ value of 0.18 Ry.

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Competing orders and fluctuations in the nematic phase of iron-based Superconductors

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By studying a two-orbital spin-fermion model, we investigate the characteristics and interplay of various nematic orders in the Fe-based superconductors. We find several nematic orders are in strong competition in the nematic phase, as a consequence of the spin-driven nematicity. We also find that order parameters with A_{1g} and/or B_{2g} symmetries, though not ordered, can acquire large fluctuations when the system is driven crossing the nematic transition. Our results provide important clues in understanding several recent experiments on the nematic phase of iron-based superconductors.

Orbital-driven two-dome superconducting phases in iron-based superconductors

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Recent several experiments revealed that novel bipartite magnetic/superconducting phases widely exist in iron pnictides and chalcogenides. Nevertheless, the origin of the two-dome superconducting phases in iron-based compounds still remains unclear. Here we theoretically investigated the electronic structures, magnetic and superconducting properties of three representative iron-based systems, i.e. $LaFeAsO_{1-x}H_x$, $LaFeAs_{1-x}P_xO$ and KFe_2As_2. We found that in addition to the degenerate in-plane anisotropic xz/yz orbitals, the quasi-degenerate in-plane isotropic orbitals drive these systems entering into the second parent phase. Moreover, the second superconducting phase is contributed by the isotropic orbitals rather than the anisotropic ones in the first superconducting phase, indicating an orbital-selective pairing state. Based on these findings, we propose a general rule of the orbital symmetry, Fermi surface and pairing symmetry for realizing high-Tc superconductivity. These results imply an orbital-driven mechanism and shed light on the understanding of the two-dome magnetic/superconducting phases in iron-based and other multiorbital superconducting compounds.

Supercurrent as a Probe for Topological Superconductivity in Magnetic Adatom Chains

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A magnetic adatom chain, proximity coupled to a conventional superconductor with spin-orbit coupling, exhibits locally an odd-parity, spin-triplet pairing amplitude. We show that the singlet- triplet junction, thus formed, leads to a net spin accumulation in the near vicinity of the chain. The accumulated spins are polarized along the direction of the local d-vector for triplet pairing and generate an enhanced persistent current flowing around the chain. The spin polarization and the "supercurrent" reverse their directions beyond a critical exchange coupling strength at which the singlet superconducting order changes its sign on the chain. The current is strongly enhanced in the topological superconducting regime where Majorana bound states appear at the chain ends as shown in Fig. 1. The current and the spin profile offer alternative routes to characterize the topological superconducting state in adatom chains and islands.

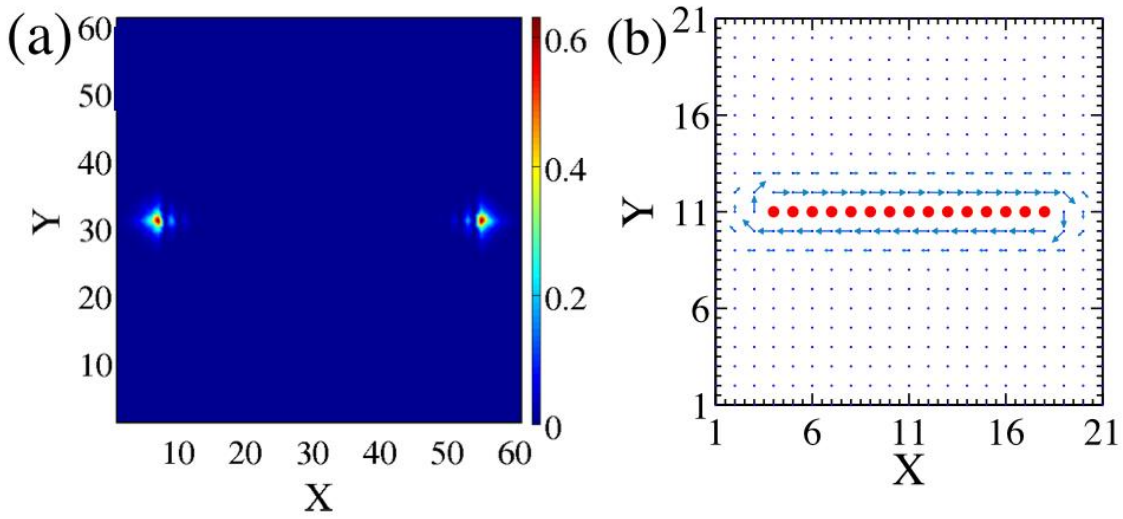

Fig. 1: (a) Probability density of zero energy states showing the pair of Majorana states at the two ends of the magnetic adatom chain. (b) The supercurrent flow around the adatom chain.

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Prediction of High-Pressure Phase Stability and Superconductivity of $GaScH_6$

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Superconductivity has always attracted the attention of many researchers. Since Ashcroft predicted high-temperature superconductivity in H-rich hydrides in 2004 [1], extensive theoretical studies have explored potential superconductivity in compressed binary hydrides, and some of them were predicted to be promising superconductors. Such as GaH_3 [2], H_3S [3] and so on. Most encouragingly, H_3S was observed to be a very good superconductor with a remarkably high T_c of ~200 K under pressure [4], which further stimulates researchers to search for the high-temperature superconductor in hydrogen-rich hydrides. However, a large number of studies were focused on binary hydrides, ternary hydrides have not been well explored to date.

Here, we take an extensive exploration on a ternary hydrides of $GaScH_6$, to search for the stable phases and high-temperature superconductors under pressure. It is found that $GaScH_6$ was predicted to be stable with *Pm*-3 structure under pressure. Moreover, the electron–phonon coupling calculation estimated that $GaScH_6$ has a high T_c of 89 K at 100 GPa. The stable pressures of the *Pm*-3 Phase are accessible in the experiment. Our calculation will stimulate the further experimental synthesise for ternary hydrides under high pressure.

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Possible s-wave superconducting state in twisted bilayer graphene

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Bilayer graphene with small twisted angle has been studied for a long time. The low-energy electrons behave like massless Dirac fermions with a renormalized Fermi velocity which is much smaller than that of monolayer graphene, corresponding to the flat bands in the low-energy regime. Moreover, the low-energy electronic states are highly localized and correlated, and the Van Hove singularity is brought to be very near the charge neutral point. Thus, the chemical potential can be easily tuned to cover the localized bands by a gate voltage. Recently, the discovery of superconductivity in such system has aroused tremendous excitement. After this discovery, many possible ground states and pairing glues are proposed by theoretical works, most of which give d+id or p+ip gap symmetry. Since many characters including the critical temperature, band width and phase diagram of bilayer graphene system are similar to heavy fermion superconductors, the recent debate on the gap symmetry of heavy fermion compound $CeCu_2Si_2$ reminds us that the s-wave may also be a reasonable gap symmetry of the bilayer graphene system if the interband scattering is strong enough. In this work, we study the gap symmetry of this system based on a four-orbital model and the Eliashberg formalism which was used in our previous work to study the gap symmetry of $CeCu_2Si_2$. As a result, the s-wave indeed dominates when the interband scattering is strong enough. Otherwise, the d+id wave dominates. The study of the evolution of eigenvalues of Eliashberg equation with chemical potential shows that the dominant eigenvalue reaches the maximum near the Van Hove singularity at hole-doping region.

Variational Monte-Carlo Study of the Bilayer Hubbard Model

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In a single band Hubbard model on a square lattice, the pairing interaction becomes the largest at half-filling, but superconductivity does not take place due to the occurence of a Mott transition. However, a dynamic cluster approximation (DCA) calculation [1] suggested that in the bilayer case, one can move away from the Mott region by increasing the inter-layer hopping and at the same time still achieve a large paring interaction strength, thereby resulting in a possibility of extremely high T_c superconductivity near half-filling.

The bilayer Hubbard model at half-filling has been studied using various methods recently. The persistence of an extended paramagnetic metallic phase at small on-site interactions U has been put forward based on cluster DMFT [2] as well as finite-temperature determinantal quantum Monte-Carlo calculations [3]. However, a functional renormalization group study [4] exhibited that the metallic region is restricted to the U =0 line, reflecting the persistent perfect nesting in the bilayer lattice.

In the present study, we revisit the problem of superconductivity in the doped bilayer Hubbard system using the multi-variables variational Monte-Carlo method [5,6], which can deal with the electron correlation effect accurately. We calculate the pairing correlation function for various parameter values, and identify the regime where superconductivity is strongly enhanced. We compare the result with those of DCA [1], and investigate the effect of the inter-layer hopping on the Mottness.

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Dynamical effects of BCS-BEC crossover in the Holstein model

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We present a study of the half-filled Holstein model employing the dynamical mean-field theory in combination with Wilson's numerical renormalization group technique. Here, we investigate how the dynamical effects such as soft phonon modes appear and correlate with superconductivity as the BCS and Bose-Einstein condensation (BEC) regimes are crossed as the onsite electron-phonon coupling g is varied. The pairing gap Δ as a function of g shows qualitatively different behavior for adiabatic ($t/\omega_{ph}>>1$) and antiadiabatic ($t/\omega_{ph}<1$) phonons due to the retardation effect, where t is the hopping amplitude and ω_{ph} is the phonon frequency. The soft phonon mode emerges at the critical coupling g_{c1} separating metal and local pair insulating states in the normal state. With introducing the pairing gap, the maximum superconducting T_c coincides with g_{c1} and the soft phonon mode is restored back because of the gap opening, yet the Goldstone mode of local pair phase fluctuations emerges beyond $g>g_{c1}$ in the superconducting state.

Electronic structure of Co-doped BaZn2As2

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The research of DMS has attracted a lot of attentions due to its potential application in the spintronics [1]. To date, the carriers in most DMSs are p-type [2].

Recently, our group have successfully synthesized a bulk form DMS, Ba(Zn1-xCoxAs)2, with n-type carriers [3].

In this poster, we present the electronic structure of n-type Diluted Magnetic Semiconductor (DMS) Ba(Zn1-xCoxAs)2. We have employed the PBE functional, the MBJ functional and the HSE06 functional to study the electronic structure and magnetic properties of the system. With the PBE functional, the parent compound exhibits metallic band structure and density of state, while with the MBJ and HSE06 functional, the system is semiconducting with an indirect gap of ~0.45 eV and ~0.31 eV, respectively. With Co doping, the system remains metallic from the PBE functional calculation, and each Co contributes 2.8 μB moment under isolated dopant approximation; the system remains semiconducting in the HSE06 functional calculation, and each Co contributes 3.0 μB moment. The minority spin state close to the Fermi level is more affected by the Co doping, and the effect of dopant on majority spin state is about 6 eV below the Fermi level.

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Manipulating charge-density-wave in monolayer 1*T*-$TiSe_2$ by strain and charge doping

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The charge density wave (CDW) and superconductivity in layered transition metal dichalcogenides (TMDs) are two fundamental collective quantum phenomena, and both arise from electronic instabilities in condensed matter physics. Recently, experiments demonstrated that the CDW transition temperature of 1*T*-$TiSe_2$ increases from 200 K in the bulk to 230 K in the monolayer.[1,2] Hence, the monolayer 1*T*-$TiSe_2$ provides an ideal platform for obtaining the CDW phase with higher transition temperature even above room temperature. This motivates us to search for methods to tune the CDW order of the monolayer 1*T*-$TiSe_2$. Here we investigate the effects of the in-plane biaxial strain and charge doping on CDW order of monolayer 1*T*-$TiSe_2$ by using the first-principles calculations.[3] Our results show that the tensile strain can significantly enhance the CDW order, while both compressive strain and charge doping (electrons and holes) suppress the CDW instability. The tensile strain may provide an effective method for obtaining higher CDW transition temperature on the basis of monolayer 1*T*-$TiSe_2$. We also investigate the potential superconductivity in charge-doped monolayer 1*T*-$TiSe_2$. Controllable electronic phase transition from the CDW state to the metallic state or even the superconducting state can be realized in monolayer 1*T*-$TiSe_2$, which makes 1*T*-$TiSe_2$ possess a promising application in controllable switching electronic devices based on CDW.

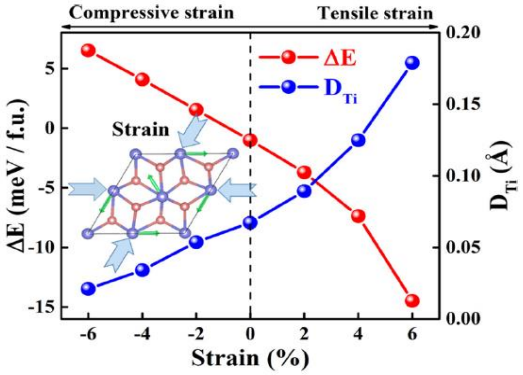

Fig. 1: CDW formation energy (left) and average displacements of Ti atoms from the high symmetry positions (right) as a function of biaxial strain.

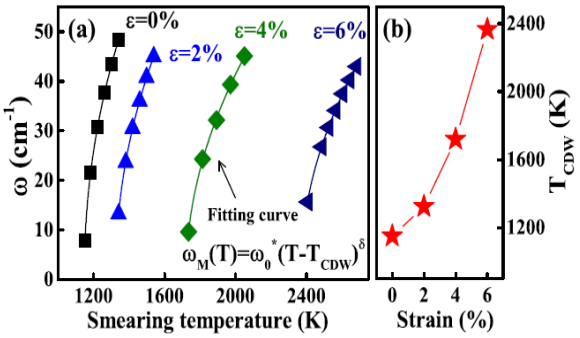

Fig. 2: (a) Phonon frequencies of softened acoustic mode at the *M* point as a function of the electronic temperature. (b) Fitted CDW transition temperatures under tensile strain.

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Phonon-mediated high-temperature superconductivity: in search of RTSC

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Recent measurements have set a new record for the superconducting transition temperature at which a material losses electrical resistivity and exhibits ideal diamagnetism. Theory-oriented experiments show that compressed hydride of Group VI (hydrogen sulfide) exhibits superconducting state at 203 K [1,2]. Moreover, a Group V hydride (phosphorus hydride) has also been studied and its T_c reached a maximum of 103 K. The experimental realisation of the superconductivity in H_3S and PH_3 inspired us to search for other hydride superconductors and way to increase critical temperature in already known hydrides [3,4].
In the first step, we investigate the possibility of achieving the room-temperature superconductivity in hydrogen sulfide through increasing external pressure, a path previously widely used to reach metallization and superconducting state in novel hydrogen-rich materials. The electronic properties and superconductivity of H_3S in the pressure range of 250-500 GPa are determined by the first-principles calculations. Our calculations indicate that H_3S in the range of the extremely high pressures is a conventional strong-coupling superconductor with a high superconducting critical temperature, however, the maximum critical temperature does not exceed the value of 203 K.

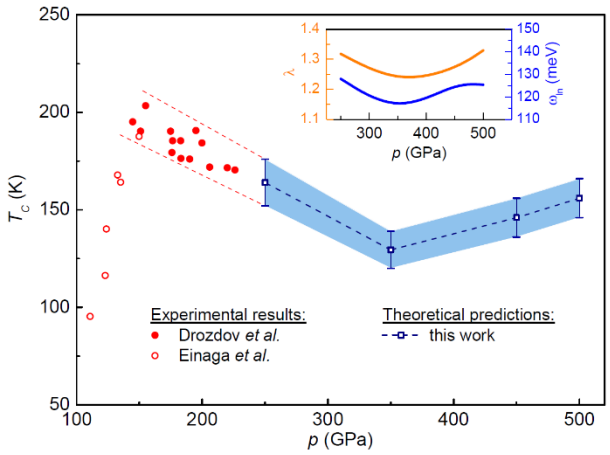

Fig. 1: *The critical temperature as a function of the pressure [4].*

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Nanoscale Phase Separation and Coexistence of Insulating, Metallic and Superconducting Phases in Underdoped Cuprates

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We study the carrier localization and delocalization, which manifest themselves via metal-insulator and superconductor-insulator transitions, the charge segregation and nanoscale (local) phase separation, and the formation of the coexisting insulating, metallic and superconducting phases in underdoped cuprates. We argue that the underdoped cuprates are more disordered and inhomogeneous systems (where dopants and polaronic carriers are distributed inhomogeneously) than optimally doped cuprates. We show that in such underdoped high-T_c materials, the strong electron correlations, carrier-defect-phonon and carrier-phonon interactions together with the strong disorders and inhomogeneities are responsible for carrier localization, formation of impurity and polaronic bands, disorder- and correlation- driven metal-insulator transitions (MITs) in deeply underdoped cuprates, new MITs in moderately underdoped cuprates, nanoscale phase separation into insulating (carrier-poor) and metallic or superconducting (carrier-rich) regions and coexistence of nanoscale insulating, metallic and superconducting phase in the doping range $p \approx 0.02$-0.13. We demonstrate that these phenomena are manifested in the temperature dependence of the magnetic susceptibility $\chi(T)$ which exhibits the insulating and metallic behaviors in the normal state of underdoped $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7-\delta}$.

The Behaviors of the Electronic Specific Heat of High-T_c Cuprates Near the Superconducting and Pseudogap Transition Temperatures.

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We study the doping- and temperature-dependent behaviors of the electronic specific heat C_e of high-T_c cuprates and identify the λ-like anomaly in C_e near the superconducting transition temperature T_c and BCS-like anomaly in C_e near the pseudogap formation temperature $T^*>T_c$. We consider the doped cuprate superconductor as a multi-carrier model system which is composite of different types of charge carriers. The normal-state electronic specific heat C_{en} of underdoped to overdoped cuprates below a BCS-like pseudogap temperature T^* is calculated taking into account three contributions coming from (i) the excited components of polaronic Cooper pairs, (ii) the ideal Bose gas of incoherent Cooper pairs, and (iii) the unpaired carriers bound to impurities. Above T^*, two contributions to C_{en} coming from the unpaired carriers residing both in the polaronic band and in the impurity band calculated within a two-component degenerate Fermi-gas model. The total electronic specific heat $C_e=C_{en}+C_{es}$ below T_c is calculated by considering the contribution C_{en} and the contribution C_{es} coming from the superconducting bosonic Cooper pairs. We found that our theoretical predictions of the behaviors of C_e (i.e., a λ-like anomaly near T_c and a BCS-type anomaly above T_c near T^*) are in fair quantitative agreement with the well-established experimental data for C_e in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7-\delta}$.

Rectification effect in a nanostructured superconducting film with a square array of antidot triplets

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We study the stability of vortices pinning and dynamics in a superconducting thin strip containing a square array of antidot triplets on the nonlinear Ginzburg-Landau (GL) theory. Compared with the regular square array of circular holes, the vortices may not be pinned inside the circular holes any more but stabilized at the center of the antidot triplets depending on the geometry parameters. Moreover, the influences of the geometry parameters and the polarity of the applied current on the current-voltage (***I***-***V***) characteristics are also studied. The critical current for the sample into normal state becomes smaller as hole diameter ***D*** is smaller and the spacing ***B*** between the holes is larger. Due to the asymmetric pinning sites, our numerical simulations demonstrate that the positive and negative rectified voltage appeared alternately in the resistive state of the sample under an ac current.

Phase Separation in 2D Spin-Pseudospin Model

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One of the topical problems in the physics of high-T_c cuprates is the coexistence and competition of spin, superconducting, and charge ordering. Recently [1] we argued that an unique property of high-T_c cuprates is related to the charge-transfer instability in the CuO_2 planes. This implies accounting of the three manyelectron valence states $CuO_4^{5-,6-,7-}$ on an equal footing as a well-defined charge triplet and allows us to use of the S=1 pseudospin formalism [1]. To consider the competition of spin and charge ordering in cuprates, a simplified static 2D spin-pseudospin model was proposed [2-4], which takes into account both the conventional spin exchange interaction and the on-site and inter-site charge correlations. In the static limit, this model is equivalent to the 2D dilute antiferromagnetic Ising model with charged impurities. In this model, five different phases are realized in the ground state, depending on the concentration of charged impurities (n) and the ratio between the exchange (J) and the inter-site charge interaction (V) constants and the on-site correlation parameter ( ). It is shown that the antiferromagnetic (AFM) phase is unstable for a strong exchange with respect to the phase separation (PS) into the charge and spin subsystems, which behave like immiscible quantum liquids, whereas in the charge-ordered (CO) phase the doped charges are randomly distributed. An analytical expression is obtained for the PS critical temperature, and it agrees well with the results of Monte Carlo (MC) simulation.

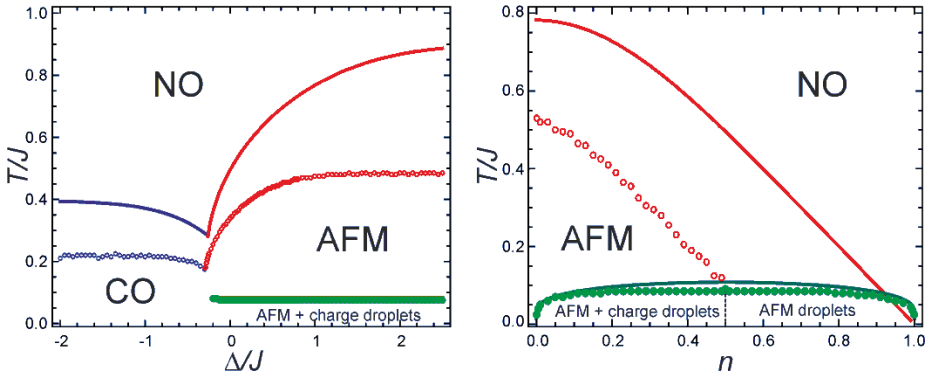

Fig. 1: *Left panel: (T,)-diagram at n=0.1, right panel: (T,n)-diagram at =1 for the strong exchange case (V/J=0.1). The solid lines show the mean field value of critical temperature. Hollow and filled circles denote the MC results for the ordering the PS temperature respectively. NO denotes the non-ordered phase.*

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A Factor Governing the Ceiling of Optimal Tc of diverse high Tc superconductors

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Explaining the high critical temperature (*T*c) in cuprates and iron-based superconductors is one of the major job in the study of high-*T*c superconducting mechanism. Owing to the difficulty of theoretical developments, experimental laws revealing the key factors affecting *T*c are of growing significance. A good experimental law may trigger the breakthrough of mechanism study by giving the key clue to the pairing interaction. Here we report a unique feature of electronic band structure in all high-*T*c superconductors, and its relevance to *T*c. We categorized the high-*T*c superconductors into groups according to the neighboring cations sandwiched by the Cu-O planes or Fe-As layers. In each group, only one superior superconductor (showing the highest optimal *T*c) was selected. It is found that the energy level of the outmost core-shell electrons is relevant to the optimal *T*c. As shown in Fig.1, *the deeper the energy level of the outmost core-shell electrons, the higher the optimal Tc could reach*. We demonstrate that the interaction between the valence electrons and the outmost core-shell electrons shouldn't be overlooked, and the orbital coupling between core electrons may have great impacts on superconductivity. It implies that the fluctuation of the outmost core-shell electrons is a new candidate of pairing glue. This work is supported by the Ministry of science and technology key special project of China, "Engineering Special Database and Material Big Data Technology for Material Genome": 2016YFB0700503-7.

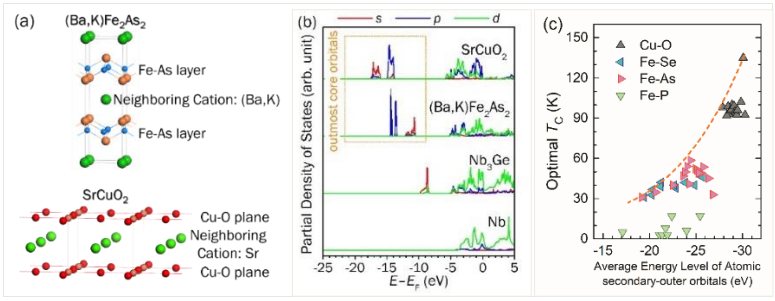

Fig. 1: *a) the neighboring cations in typical high-Tc superconductors. b) A unique electronic characteristic of high-Tc superconductors: orbital coupling between outmost core electrons. c) Dependence of optimal Tc on the energy level of coupling core orbitals. The dot curve is not a fitting line, but an upper boundary. Each data point represents one superior compound we select. The data of optimal Tc and atomic orbital energy level come from Ref. [1] and appendix of Ref. [2], respectively.*

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Why Tc is So Low in High-Tc Cuprates:

the Importance of the Dynamical Vertex Structure

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We have applied the dynamical vertex approximation (DΓA) [1], one of the diagrammatic extensions of the dynamical mean field theory (DMFT) [2], for studying d-wave superconductivity in the repulsive Hubbard model on a square lattice. The result well reproduces the cuprate superconducting phase diagram, with a reasonable Tc and a superconducting dome (Fig. a). We have also decomposed the vertex correction contributions to Tc and traced back the dominant scattering processes, and found that local *particle-particle* diagrams (Fig. b) strongly screen the bare interaction near the Fermi level, which act to suppress the pairing interaction and Tc. We identify in detail how the dynamical vertex structure is inherited from the local vertex to the magnetic vertex (spin-fluctuations) and, eventually, to the pairing interaction [3].

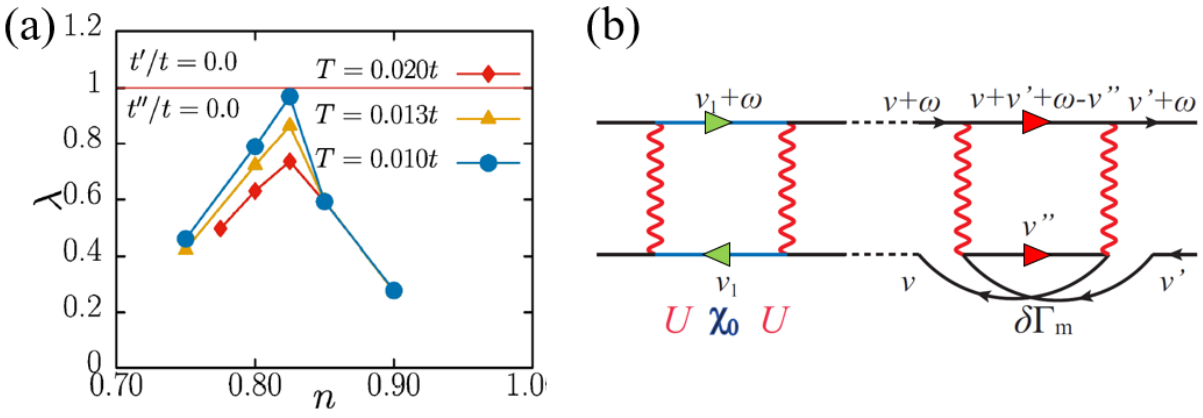

Figure: *(a) Filling dependence of the superconductivity (eigenvalue of Eliashberg eq.) at several T's. (b) Typical diagrams that contribute to the magnetic vertex.*

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Relevance of atomic multiplet structure to models of cuprate layers

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We calculate the spectra of two holes doped in a CuO$_{2}$ layer with Cu-d^{10} and O-2p^{6} including the full multiplet structure for both atoms. Distinct from previous studies that treated Cu as an impurity within a featureless O-2p band, we dealt with the lattice of Cu and employed the tight binding band structure to describe the O-2p band. We claim that the combination of the full Cu-3d multiplets and realistic O-2p band structure is important to understand the correlated properties of cuprates.
We also explored the connection between this model and the conventional three-orbital Emery model in terms of the renormalization of Cu-O hybridization.

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d-wave superconductivity in the presence of nearest neighbor Coulomb repulsion

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Dynamic cluster quantum Monte Carlo calculations for a doped two-dimensional extended Hubbard model are used to study the stability and dynamics of d-wave pairing when a near neighbor Coulomb repulsion V is present in addition to the on-site Coulomb repulsion U. We find that d-wave pairing and the superconducting transition temperature T_c are only weakly suppressed as long as V does not exceed $U/2$. This stability is traced to the strongly retarded nature of pairing that allows the d-wave pairs to minimize the repulsive effect of V. When V approaches $U/2$, large momentum charge fluctuations are found to become important and to give rise to a more rapid suppression of d-wave pairing and T_c than for smaller V.

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Vortices and Skyrmion-Like States in 2D System of Charged Hard-Core Bosons

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Competition of charge ordering and superconductivity in high-T_c cuprates has raised interest to the model systems with non-zero diagonal and off-diagonal order parameters. The charge degree of freedom in cuprates can be described in terms of a pseudospin S=1 model [1]. In the large negative-U limit, the system becomes equivalent to a charged hard-core bosons (CHCB) on a square lattice which in their turn is equivalent to the highly anisotropic 2D quantum S=1/2 magnetic system with a constant total magnetic moment.

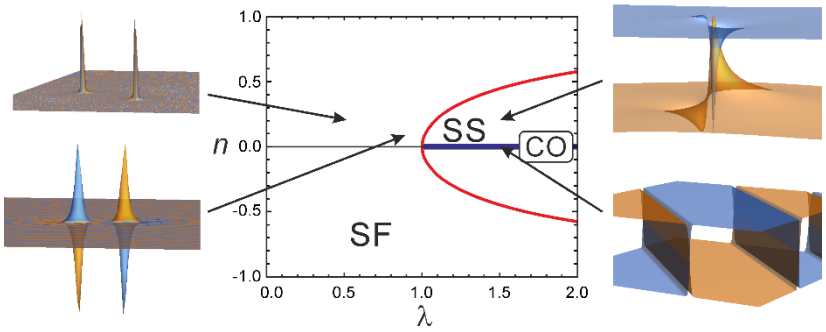

Fig. 1: *The well-known ground states phase diagram of CHCB consists of superfluid (SF), supersolid (SS) and charge-ordered (CO) phases. Inhomogeneous excitations in terms of local charge density are shown for various inter-site repulsion parameter and average charge density n. Our numerical calculations show the almost plane vortices with strong charge inhomogeneity in the vortex core in the SF phase, the extended skyrmion-like excitations in the SS phase, linear domains in the CO phase.*

The continuous quasi-classical approximation was developed for the 2D system of CHCB [2] to explore metastable inhomogeneous states analogous to inhomogeneous localized excitations in magnetic systems, such as vortices, skyrmions and so on. In the system of CHCB, these states correspond to an inhomogeneous distribution of the charge and the superfluid densities [2,3]. Asymptotic analysis shows that in the SF phase the excitations are vortices with a charge inhomogeneity of “ferro” and “antiferro” ordering type in the vortex core. Near the border with the SS phase, the “antiferro” type vortices begin to dominate; their inflation is preceded by a change in the homogeneous ground state from the SF to SS phase. In the SS phase, we find that asymptotic behavior of localized excitations is consistent with skyrmion-like solutions. They include coherent excitations both of the superfluid component and the boson density and result in appearance of domains of CO and SF phases. In the CO phase, typical inhomogeneities are linear domains. The domain walls have non-zero values of the SF order parameter that leads to a filamentary superfluidity.

The work supported by Act 211 Government of the Russian Federation, agreement № 02.A03.21.0006 and by the Ministry of Education and Science, projects 2277 and 5719.

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Second harmonic generation in the Weyl semimetal TaAs from a quantum kinetic equation

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Abstract

We classify the sources of second harmonic generation (SHG) of the Weyl semimetal TaAs by collisionless quantum kinetic equation into three kinds: i.e., injection current from the canonical band dispersion, shift current from a gauge invariant shift vector, and anomalous current from Berry curvature associated with the Fermi surface. Importantly, by using the realistic band model for TaAs, we predict that the SHG in TaAs is predominately contributed by the shift current, while the anomalous current has a minute contribution when the Weyl point is exactly located on the Fermi surface. Moreover, we highlight that the SHG contributed by the anomalous current decays fast with the increasing frequency of incident photons, and could be enhanced by proper electron or hole doping of TaAs.

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“Flat/Steep” Band Model for Superconductivity

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Since its discovery, superconductivity has remained an intriguing problem in condensed matter physics. So far the superconductivities discovered in high Tc cuprate, organic and Fe-based systems have remained not fully understood. On the other hand, with regard to the material aspect, the theories for superconductivity are at an even more embarrassing status, because no practical guides have been provided for searching new superconductors. In the last few years, we have tried to find a fingerprint for superconductors from a chemical point of view for the pairwise constrains of itinerant electrons [1-5], which leads to a “flat/steep” band model for superconductivity. The model has been successfully applied to explain the superconductivities of many superconducting systems [6-7]. In this work, we will briefly discuss our recent axiomatic effort for our model [8] by applying the concept of “generalized coherent state” for fermions. The main focus will be on our recent work [9] for Y_2O_2Bi, which shows clearly how the “flat/steep” band condition is created due to the doping of oxygen in the Bi-layer and thus leading to the superconductivity. The result sheds a new light to reflect upon the role of the oxygen doping in high Tc cuprates.

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Theoretical Insights into Potassium Hydride Formation in Potassium Aromatic Systems

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To clarify the stability of the alkali-metal intercalated aromatic system, we investigate the formations of potassium hydride in potassium-phenanthrene and potassium-para-terphenyl systems by using the density functional theory. The stoichiometric ratios between potassium and aromatic molecules are 1:1, 2:1 and 3:1 to simulate the experimental elementary partitions [1-3]. The calculated reaction enthalpies for two and three stoichiometric partitions of potassium provide a reasonable explanation for the experimental observation of potassium hydride, demonstrating that the stoichiometric ratio between alkali metal and aromatic molecule should be 1:1 and 2:1 at certain condition in the stable alkali-metal-doped materials. For boht systems, the potassium-intercalated compounds are very stable with the energies far below the reactants and the direct hydrogen abstraction of potassium from pure phenanthrene (see **Fig.**1) and para-terphenyl are quite difficult, indicating that extra potassium is necessary to form potassium hydride. It is also worth noting that more potassium will facilitate the hydrogen abstraction reaction, which is shown by the exothermic reaction enthalpy at 3:1 stoichiometric ratio. Our theoretical results are useful for elucidating stoichiometric ratio and the mechanism to form potassium hydride in alkali-metal-doped phenanthrene and alkali-metal-doped para-terphenyl.

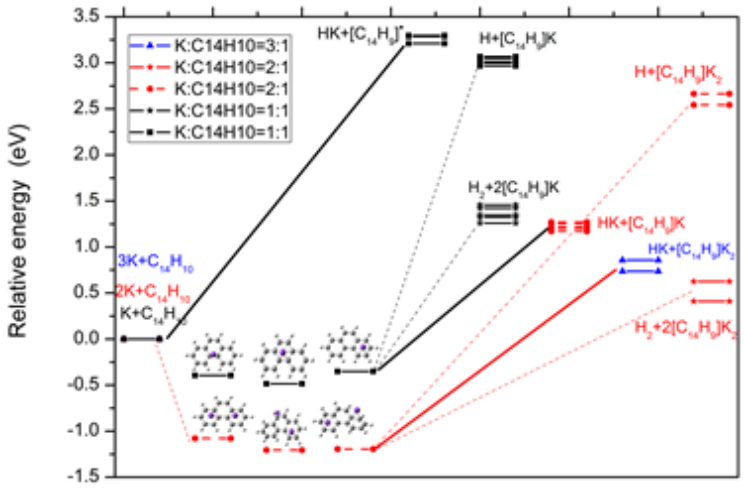

Fig. 1: *Reaction mechanisms at different stoichiometric ratios.*

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Superconductivity of ABi_2 Compounds (A=Rb, Cs, Ca): the Role of Bi and the Influence of the Spin-Orbit Coupling.

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Elemental bismuth has unusual electronic properties including Dirac-like bands. This makes the Bi-based compounds interesting in many fields of physics, for example as topological insulators.

In this work superconductivity, discovered two-years ago in $CaBi_2$ [1] (T_c = 2 K) and of other two members of the ABi_2 (A=Rb, Cs) family is analyzed. $RbBi_2$ and $CsBi_2$ superconductors, with T_c=4.25 K and 4.75 K respectively, have a 3-dimensional *fcc* structure [2], while $CaBi_2$ is orthorhombic [1] with a quasi-2D structure.

The electronic structure of these compounds, calculated within the density functional theory, is presented. Dynamic properties and the electron-phonon interaction functions (Eliashberg functions) are computed for the first time. Superconducting critical temperatures are determined using the Allen-Dynes equation.

Calculations indicate that the spin-orbit coupling has a very strong effect on the electron-phonon interaction and superconductivity in these compounds. It is related to the fact, that the Bi atoms play a key role in superconductivity, while the remaining atoms act as a charge reservoir.

As Rb and Cs are isoelectronic, and Ca has one electron more, the effect of an additional electron and the change of the crystal structure is discussed. Moreover, Ca atom is more than three times lighter than Cs and it causes changes in phononic structure as will be shown.

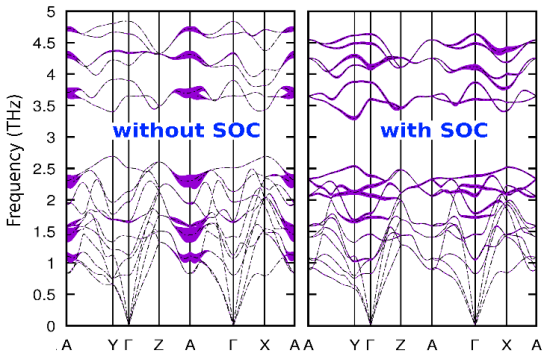

Fig. 1: *Example of influence of the SOC: the phonon linewidth (marked with violet line) of $CaBi_2$ in the case without and with SOC.*

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Prediction of a Metallic Phase for Tricesium Pentacene Compound

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New possible structures for the compounds formed by intercalation of an alkali metal into a molecular crystal formed by polycyclic aromatic hydrocarbon (PAH) molecules have been theoretically searched for. Among them a crystalline framework in which PAH molecules show a slipped parallel geometry provides an interesting alternative to the usual herringbone arrangement customarily shown by pristine crystal structures of PAHs. While these different crystalline structures are energetically unfavorable for potassium alloying, they are energetically preferred at the highest cesium load (3:1 stoichiometry). The most remarkable feature of the proposed structure is the avoidance of the magnetic instability that leads to insulating phases of herringbone crystals when a 3:1 proportion of metal-picene is reached. After the evaluation of the corresponding energies of formation, a robust metallic scenario is found for Cs_3Pentacene, making it possible the observation of superconductivity. Data in Table 1 summarize our research. Details can be found in a forthcoming publication.

Compound	Structure (Space group)	Volume (Å^3)	Spin Polarization (e)	Total Energy (eV)	Formation Energy (eV)
Potassium	isolated atom		1	1.804	
	bcc crystal (Im$\bar{3}$m)	69.42	0	1.044	-0.760
Cesium	isolated atom		1	1.838	
	bcc crystal (Im$\bar{3}$m)	107.24	0	1.154	-0.684
Pentacene	isolated molecule		0	-216.071	
	herringbone crystal (P$\bar{1}$)	688.67	0	-435.542	-3.400
	slipped parallel crystal (P$\bar{1}$)	346.01	0	-217.629	-3.116
Picene	isolated molecule		0	-216.703	
	herringbone crystal ($P2_1$)	696.37	0	-436.627	-3.221
CsPentacene	herringbone crystal (P$\bar{1}$)	887.85	2	-435.194	-1.960
	slipped parallel crystal (C2/m)	445.12	0.945	-217.409	-1.584
Cs_2Pentacene	herringbone crystal (P$\bar{1}$)	910.16	0	-436.146	-5.220
	slipped parallel crystal (P$\bar{1}$)	456.05	0	-217.865	-4.804
Cs_3Pentacene	herringbone crystal (P$\bar{1}$)	980.69	0	-434.462	-5.844
	slipped parallel crystal (C2/m)	498.45	0	-217.239	-5.860
	slipped parallel crystal (P$\bar{1}$)	498.41	0	-217.244	-5.870
K_3Picene	herringbone crystal ($P2_1$)	825.43	2	-432.768	-2.405
	slipped parallel crystal ($P2_1/m$)	890.36	0	-431.677	-1.314
Cs_3Picene	herringbone crystal ($P2_1$)	973.29	2	-432.564	-2.861
	slipped parallel crystal (P1)	491.79	0	-216.086	-2.468
	slipped parallel crystal (P$\bar{1}$)	981.59	0	-432.390	-2.687

Table 1: *Main properties of the studied compounds formed by the intercalation of an alkali metal (Cs or K) into the structure of a polycyclic aromatic hydrocarbon (pentacene or picene). Volume, spin polarization and total energy are given per cell. Formation energies are always given for pairs of organic molecules in order to make comparisons easier.*

Angular Superconducting Gap in $YBa_2Cu_3O_{7-\delta}$

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A versatile Hamiltonian that includes the effects of harmonic electron- and phonon-fields, electron-phonon interactions, anharmonic phonon fields and defects is used to develop many body quantum dynamics of phonons followed by Dyson's equation formalism which enables to develop the phonon Green's function. The general theory invokes the pairon formation which is a necessary notion for high temperature superconductivity (HTSC). However for the study of angular superconducting gap the modified form of Born-Mayer-Huggins potential (MBMHP) in phonon Green's function has been adopted to obtain the interaction energy of spectrum of renormalized phonons and electrons in the form of renormalized quasiparticle dispersion in the representative high temperature superconductor (HTS) $YBa_2Cu_3O_{7-\delta}$. The obtained renormalized quasiparticle dispersion has been given in Fig. 1 which show highly anisotropic nature. Using renormalized quaisparticle dispersion plot the superconducting gap Δk measured in momentum space with respect to Fermi surface angle θ° and using relation $\Delta_{SG} = \hbar v_p \Delta k$ where v_p is phonon velocity the angular superconducting gap (Δ_{SG}) plotted as function of d-wave order parameter $\left|\cos(k_x a) - \cos(k_y b)\right| / 2$ (or $\cos(2\theta^\circ)$) along with experimental results in Fig. 2. The theoretical results are found in good agreement with experimental results. The d-wave order parameter is a measure of anisotropy the therefore the present results reflect the strong anisotropy superconducting gap in $YBa_2Cu_3O_{7-\delta}$. The renormalized frequency highly influenced by electron-phonon interaction, anharmonicities and defects which may pioneer to understand the pairing mechanism in cuprate HTS.

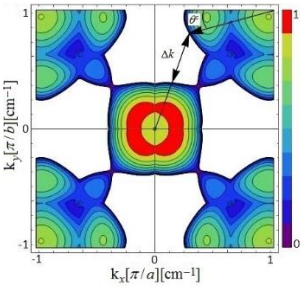

Fig. 1: *Renormalized frequency plot.*

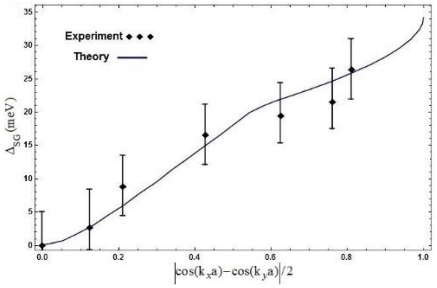

Fig. 2: *Angular superconducting gap.*

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Density Functional Theory Simulation of Spin Distribution Perturbed by Muon in $YBa_2Cu_3O_6$

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The antiferromagnetic (AF) interactions in Cu-based high-T_C superconductors is a key to understand the high-T_C superconductivity. $YBa_2Cu_3O_6$ ($YBCO_6$) is the mother system of the Y-system high-T_C superconductor. This system is well known as a Mott insulator with the long-range AF ordering with T_N = 350 K.[1] The AF ordering disappears with increasing doped holes introduced by additional oxygen and the superconductivity appears.[2] We utilized the muon-spin relaxation (μSR) technique to study the microscopic electronic and magnetic properties of $YBCO_6$. The μSR is extremely sensitive to probe the local magnetism due to the large gyromagnetic ratio of the muon spin.[3] But it has difficulties in investigating quantitative information of hyperfine interactions due to the unknown positions of the injected muons in the materials and the complicated local perturbation caused by the muons to its surroundings.[4]

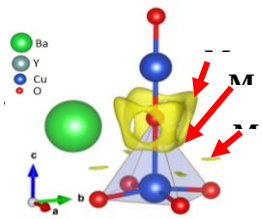

Fig. 1: Possible initial muon stopping

We are developing a research method to address those issues by using density functional theory (DFT) calculations. As the muon has a positive charge, it prefers to stop at a local minimum potential position in materials. We found three possible initial muon sites in $YBCO_6$ marked as M1, M2 and M3 as shown in Fig. 1. In order to investigate local perturbations caused by the muon as a dilute charged impurity, we modeled a supercell which contains 4×4×2 unit cells and only one muon. We then calculated relaxations of the atomic positions throughout the whole the supercell. We also included changes in the local electronic states and the spin density distribution of surrounding electrons. Taking into account the zero-point vibration energy of the muon, and comparing with μSR experimental data, we reveal information about muon positions and its surrounding electronic state.

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Quasi-particle Density of States in $Bi_2Sr_2CaCu_2O_{8+\delta}$ Extracted with the Maximum Entropy Method

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With the developed maximum entropy method, the quasi-particle density of states (DOS) at temperatures from 4.2K to high above the critical temperature T_c is obtained by inversion directly from the experimentally measured superconductor-insulator-superconductor (SIS) tunneling data performed on three different $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples. The evolution of the extracted DOS with temperature and doping is interpreted with the reference to the Eliashberg theory. Bosonic modes accompanying superconductivity or related to pseudogap, as well as their temperature-dependent energies, are extracted from the DOS modulations. In the derivative curve of the DOS with respect to the energy, a kink is found in the superconducting state, indicating the coexistence of the pseudogap and superconductivity.

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Simulation of the NMR Response of Cuprates Above and Below the Superconducting Temperature

Xi Chen

Nuclear magnetic resonance (NMR) experiments play an essential role in the study of high T_C cuprates, showing fundamentally different features in the Knight shift and the spin-lattice relaxation rate comparing to conventional superconductors. However, to date, the theoretical and numerical analysis of the NMR response below critical temperature ($T_{C)}$ is limited to RPA-based calculations or phenomenological models. Here we study the temperature and doping evolution of these quantities on the two-dimensional Hubbard model using dynamical cluster approximation with Nambu formalism. We recover the suppression of the Knight shift at the pseudogap on-set temperature and its quick decrease below Tc. We also analysis the spin-lattice relaxation rate 1/(T1T) and the role of vertex correction in the dynamical spin susceptibility. Both the Knight shift and the spin-lattice relaxation rate are consistent with NMR experimental results of high Tc cuprates.

Physics of high-Tc overdoped copper oxides

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We show that the main physical mechanism, responsible for the unusual properties of the overdoped $La_{2-x}Sr_xCuO_4$, is the topological quantum phase transition with the emergence of the fermion condensation (FC). This observation can open avenue for chemical preparation of high-Tc materials with Tc up to room temperatures. We have shown that the underlying physical mechanism responsible for the unusual properties of the overdoped compound $La_{2-x}Sr_xCuO_4$ (LSCO) observed recently [1,2] may very well involve a topological quantum phase transition that induces fermion condensation. Since the topological FC state violates time-reversal symmetry, the Leggett theorem no longer applies. Instead, we have demonstrated explicitly that the superfluid number density n_s turns out to be small compared to the total number density of electrons. We have also shown that the critical temperature Tc is a linear function of n_s, while $n_s(T)$ is proportional Tc -T. Pairing with such unusual properties is as a shadow of fermion condensation -- a situation foretold by an exactly solvable model [3] long before the experimental observations were obtained by Bozovic et al. [1,2] and demonstrating that both the gap and the order parameter exist only in the region occupied by fermion condensate. Thus, the experimental observations [1,2] can be viewed as a direct experimental manifestation of FC. Additionally, we have demonstrated that at T>Tc the resistivity varies linearly with temperature, while for $x>x_c$ it exhibits metallic behavior, the resistivity is proportional T^2. Thus, the superconductivity formalism adapted to the presence of a fermion condensate captures all the essential physics of overdoped LSCO and successfully explains its most puzzling experimental features, thereby allowing us to close the colossal gap existing between the experiments and Bardeen-Cooper-Schrieffer-like theories [3,4].

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Strain-induced spin/charge supercurrent flow in Dirac/Weyl superconductor

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Low energy excitations in Dirac/Weyl superconductors are Dirac/Weyl quasiparticles, which have the degrees of freedom of chirality, or a monopole charge in momentum space. The monopole charge is a source or drain of the Berry curvature in momentum space which induces novel transport phenomena related to chiral anomaly in Dirac/Weyl superconductors. On the other hand, a strain-induced pseudo-magnetic field in Dirac/Weyl systems [1,2]. The coupling charge of the strain-induced field is momentum, namely chirality of Dirac/Weyl points. This implies that an emergent chiral magnetic field is realized by applying mechanical strain to Dirac/Weyl systems, and induces chiral anomaly phenomena as a similar way to the electromagnetic field in Dirac/Weyl semimetals [3,4].

However, physical consequences of the chiral magnetic field acting on Cooper pairs in Dirac/Weyl superconductors have not yet been well understood. In this presentation, we discuss novel phenomena induced by the chiral magnetic field in Dirac/Weyl superconductors. We derive the quasiclassical Eilenberger equation which includes effects of the chiral magnetic field, and demonstrate that Cooper pairs do not directly couple to the chiral vector potential. This means that neither Meissner effect nor vortex state due to the chiral magnetic field occurs. In spite of lack of the coupling to the chiral vector potential, a pseudo-Lorentz force due to the chiral magnetic field indeed acts on Cooper pairs, making a sharp contrast to a Lorentz force due to a usual magnetic field which do not directly couple to Cooper pairs composed of momentum k and –k. It is found that the pseudo-Lorentz force remarkably generates charge/spin supercurrent flow parallel to the chiral magnetic field for Weyl/Dirac superconductors. This phenomenon is akin to the chiral magnetic effect in Weyl semimetal, which gives rise to an equilibrium current parallel to an applied magnetic field in Weyl semimetals. Our finding also implies that the Fulde-Ferrell state where Cooper pairs have center of mass momentum along the chiral magnetic field is realized in the case that supercurrent flow is prohibited by a boundary condition.

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Mechanism of Fully Gapped Superconductivity Mediated by Multipole Fluctuations: Important Roles of Strong Spin-Orbit Interaction

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$CeCu_2Si_2$ is one of the typical heavy fermion superconductor near magnetic instability. In this compound, it has been widely believed that d-wave state is realized induced by magnetic fluctuations. However, recent experiments have revealed that fully gapped s-wave superconductivity without any sigh-reversal emerges near antiferromagnetic (AFM) phase. [1] These facts lead to a fundamental question: Why the s-wave phase appears against the strong on-site Coulomb repulsion in heavy fermion compoud near AFM?

To understand this question, we study microscopic paring mechanism on the basis of multi-orbital periodic Anderson model with strong spin-orbit interaction (SOI). We solve the linearized gap equation including the vertex corrections (*U*-VCs) given by Aslamazov-Larkin (AL) processes as shown in Fig.1(a). *U*-VC plays important roles near AFM since it leads to strong orbital-spin interference. In addition, *U*-VC enhances attractive paring interaction induced by electric multipole fluctuations near AFM. As a results, s-wave superconductivity emerges near AFM against the strong magnetic fluctuations as shown in Fig. 1(b). In summary, s-wave phase appears due to the significant roles of *U*-VC that describes cooperation of electric and magnetic fluctuations. Because of the strong SOI in 4f systems, fluctuations of various higher multipoles, which are absent in 3d electron system, contribute to superconducting mechanism [2].

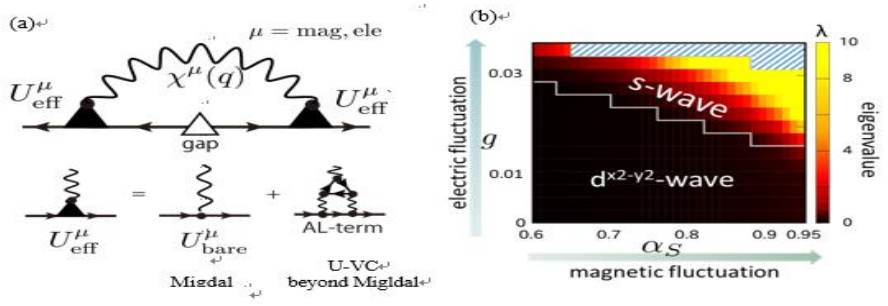

Fig. 1 *(a) Linearized gap equation with U-VC (top) and AL process (bottom) in U-VC. (b) Obtained phase diagram.α_S is magnetic stoner factor and g is quadrupole interaction driven by electron-phonon interaction. S-wave phase emerges in wide region against the strong Coulomb repulsion.*

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A holographic superconductor in higher derivative gravity theory

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In this work [1], we investigate the holographic superconductor [2-4] for AdS black holes. In particular, the p-wave holographic superconductor with planar event horizon topology for a specific Lovelock gravity [5] is studied. The dual gravity theory is characterized by a self-interacting scalar field nonminimally coupled to the gravity theory which is labeled by an integer *k*. As the Lovelock theory of gravity corresponds the most general metric based on the fundamental assumptions of general relativity, it is a desirable theory to describe the higher dimensional spacetime geometry. The present study implements the p-wave holographic superconductor by including a Maxwell field which nonminimally couples to a complex vector field [6] in a higher dimensional background metric. In the probe limit, we find that the condensation curve possesses the main features of the Ginzburg-Landau theory. It is also found that the critical temperature decreases with the increase of the index *k* of the background black hole metric, which shows that a larger *k* makes it harder for the condensation to take place. For the most part, the observed properties of the conductivity as a function of frequency is in accordance with the experimental observation. We also note that the index *k* affects the conductivity and the gap frequency of the holographic superconductors.

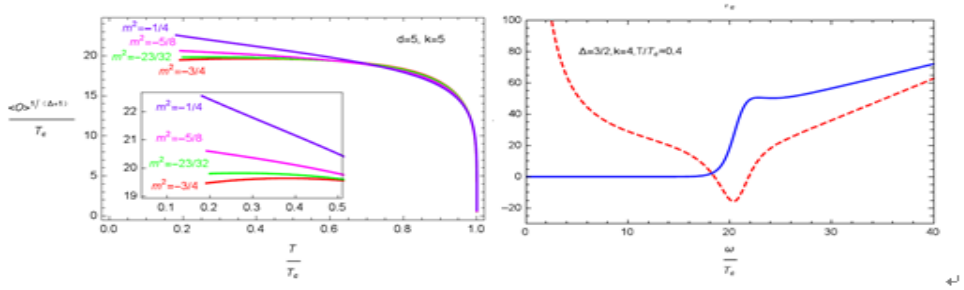

Fig.1 Left: condensation curve as function of temperature for various parameters; Right: the calculated gap in terms of real (blue solid curve) and imaginary (red dotted curve) as a function of frequency.

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Superconductivity from valence fluctuations

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Electron-phonon coupling is, so far, the only realizable source of attractive potential for conventional (s-wave) superconductivity in condensed matter systems. In two prototypical heavy-fermion superconductors, CeCoIn5, and CeCu2Si2, recent experiments have suggested the presence of conventional superconductivity in a small parameter space, where decades of studies suggested unconventional pairings. Interestingly, the materials have insufficient electron-phonon coupling strength to cause such conventional pairing. Here we present a theory of superconductivity
from valence fluctuations between conduction and localized bands which are present in heavy-fermion materials. We find that when we account of multiple valence fluctuations, there is a solution for robust conventional superconductivity with typical s-wave pairing symmetry. The results are consistent with recent experimental results.

Bosonization of Cooper Pairs and Novel Bose-liquid Superconductivity in High-T_c Cuprates

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We demonstrate that the bosonization of Cooper pairs of polarons and the novel Bose-liquid superconductivity occur in underdoped, optimally doped and moderately overdoped cuprates, while the BCS-type Fermi-liquid superconductivity is realized only in heavily overdoped cuprates where the polaronic effects disappear and Cooper pairs of quasi-free carriers (electrons or holes) behave like fermions. Bosonic Cooper pairs and related diamagnetism persist in the normal state of underdoped to overdoped cuprates below a pseudogap temperature T^* and only part of such Cooper pairs condenses into a Bose superfluid at the superconducting temperature T_c. In these high-T_c cuprates, the superconducting transition at T_c is more λ-like than the BCS transition or than the usual Bose-Einstein condensation (BEC) and a new first-order phase transition occurs somewhat below T_c or even far below T_c, which is also not expected in the BCS-like (*s*- and *d*-wave) pairing and BEC models. By solving the two-dimentional (2D) and three-dimentional (3D) mean field equations for attracting bosons, the novel superconducting states (i.e., a vortex-like state existing below the temperature $T_v = T_c^{2D}$ lower than T^* but higher than $T_c = T_c^{3D}$ as well as two distinct superconducting phases below T_c) and properties of underdoped to overdoped cuprates are self-consistently determined and compared with the key experimental findings. The full and correct phase diagram of high-T_c cuprates is clearly established.

Ferroelectric-like Order in Spin-Orbit-Coupled Superconductors

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In principle, metals cannot exhibit ferroelectricity because the electric polarization is screened by conduction electrons. However, in 1965, Anderson and Blount predicted the existence of ferroelectric (FE) metals in which a FE-like structural transition occurs in the metallic state [1]. A lot of experiments have been devoted to searches of FE metal for half a century, and recently, a FE-like structural phase transition was observed in metallic $LiOsO_3$[2]. Following the discovery of a FE metal, the relationship between ferroelectricity and superconductivity has also received a lot of attention. And then, in 2017, experimental evidence which indicates the coexistence of the superconductivity and the FE-like order, *i.e.* electric-dipole order, was obtained in $Sr_{1-x}Ca_xTiO_{3-\delta}$[3]. This experimental result suggests the close correlation between ferroelectricity and superconductivity.

In the presentation, we will show results of our theoretical study about FE superconductivity, in which a FE-like structural phase transition occurs in the superconducting state. We investigated the thermodynamic stability of FE superconductivity based on the analysis of a model of electron-lattice coupled two-dimensional Rashba superconductor. In our model, the Rashba spin-orbit coupling is treated as a molecular field of the electric-dipole order (Fig. 1). It is shown that the electric-dipole order is induced by the magnetic field when the system is superconducting (Fig. 2). Furthermore, we clarify the FE superconductivity in a very low carrier density regime, which corresponds to the case of $Sr_{1-x}Ca_xTiO_{3-\delta}$. It is demonstrated that the coexistent phase of the superconductivity and electric-dipole order can be stabilized without applying the magnetic field in the low carrier density regime. Our results would open a way to control the electric polarization by superconductivity, that is, superconducting multiferroics.

Fig. 1: *Schematics of the electric-dipole order.*

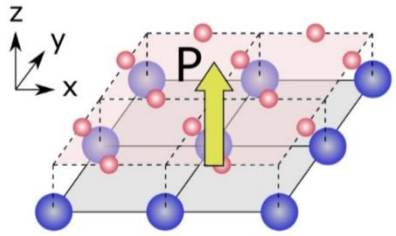
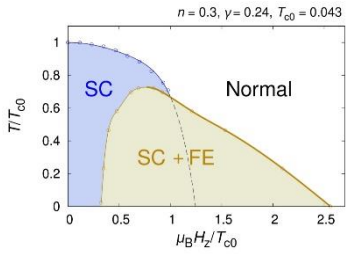


Fig. 2: *Superconducting phase diagram.*



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Quantization of Electronic Excitations in Vortex Cores: Semi-Classical Approach

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The energy $\varepsilon_n(p_z)$ of the electronic excitations localized in single Abrikosov vortices in type-II superconductors is treated. The semi-classical approximation is used to study the solutions of the Bogoliubov-de Gennes equations for these excitations. The study is focused on the dependence of $\varepsilon_n(p_z)$ on the radial quantum number n and the momentum along the vortex axes, p_z.

The quantization rule in a superconductor takes the form $\int p_r dr = 2\pi\hbar(n+1)$ where $p_r(r)$ is the radial momentum and the integration is over a periodic trajectory of a classical motion in the phase space (r, p_r). These trajectories (see Fig. 1) have four turning points. Two regular (1 and 3) are caused by the vortex field and defined by the magnetic quantum number μ. Two others (2 and 4) are caused by Andreev reflection and defined by the superconducting gap at infinity Δ_0.

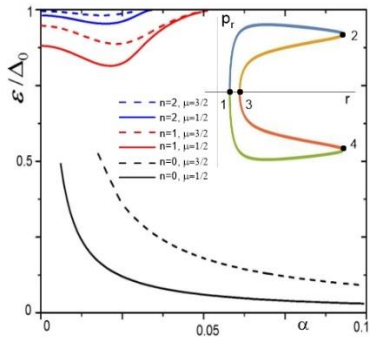

Fig. 1: *Energy levels in a vortex core ($p_z = p_F \cos\alpha$).*

Numerical solution of the quantization rule demonstrates the existence of a series of quantized energy levels with the energy $\varepsilon_n(\mu, p_z) < \Delta_0$ (see Fig. 1).

Covariant Gaussian Approximation in Ginzburg–Landau Model

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Condensed matter systems undergoing second order transition away from the critical fluctuation region are usually described sufficiently well by the mean field approximation. The critical fluctuation region, determined by the Ginzburg criterion, $|T/Tc - 1| \ll Gi$, is narrow even in high Tc superconductors and has universal features well captured by the renormalization group method. However recent experiments on magnetization, conductivity and Nernst effect suggest that fluctuations effects are large in a wider region both above and below Tc . In particular some ‘‘pseudogap’’ phenomena and strong renormalization of the mean field critical temperature T_{mf} can be interpreted as strong fluctuations effects that are non-perturbative (cannot be accounted for by ‘‘gaussian fluctuations’’). The physics in a broader region therefore requires more accurate approach. Self consistent methods are generally ‘‘non-conserving’’ in the sense that the Ward identities are not obeyed. This is especially detrimental in the symmetry broken phase where, for example, Goldstone bosons become massive. Covariant gaussian approximation remedies these problems. The Green’s functions obey all the Ward identities and describe the fluctuations much better. The results for the order parameter correlator and magnetic penetration depth of the Ginzburg–Landau model of superconductivity are compared with both Monte Carlo simulations and experiments in high Tc cuprates.

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Unconventional superconducting gap structure protected by space group symmetry

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Classification of a superconducting gap is one of the central subjects in the research field of unconventional superconductivity. Momentum dependence of the superconducting gap is closely related to symmetry of the superconductivity and the pairing mechanism. Since the superconducting gap structure can be identified by various experiments, combined studies of superconducting gap by theory and experiment may clarify the characteristics of superconductivity. Most of the theoretical studies have been based on the classification of order parameter by the crystal point group, which is summarized by Sigrist and Ueda (called Sigrist-Ueda method) [1]. However, their classification may not provide an exact classification of the superconducting gap.

For example, several studies have shown that the space group symmetry ensures the unconventional gap structures beyond the results of the Sigrist-Ueda method [2-5]. These theories classify not the order parameter, but the superconducting gap itself. Therefore, rigorous results are obtained for gap structures. Regarding point nodes, furthermore, many studies have discussed Weyl nodes in superconductors, namely point nodes protected by a nontrivial topological number [6-8]. However, there are only a few and less-known results about point nodes connected with crystal symmetry [2, 3].

In this study, we classify unconventional line nodes and point nodes beyond the results of the Sigrist-Ueda method using the group-theoretical analysis of the superconducting gap. First, we review the results of symmetry-protected line nodes, clarifying the condition for the existence of line nodes protected by nonsymmorphic symmetry. Next we show our original and useful results; nonsymmorphic-symmetry-protected line nodes appear only on the Brillouin zone face of a primitive or orthorhombic base-centered Bravais lattice. We classify all space groups under the additional constraint. Second, we consider the gap structures on high-symmetry n-fold (n = 2, 3, 4, and 6) axes in the Brillouin zone, as examples of the symmetry-protected point nodes. Surprisingly, the analysis shows the existence of point nodes depending on the Bloch-state angular momentum j_z on a 3- or 6-fold axis. Furthermore, we suggest that such "j_z-dependent point nodes" are realized in a heavy fermion superconductor UPt_3. We also discuss superconducting gap structures in UBe_{13}, SrPtAs, etc.

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A New Theory of Superconducting Materials and Superconducting Mechanisms

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In this paper, the twelve-tone equal temperament, the periodic table of twelve temperament chemical elements and the theory of magneto-electric coupling are introduced. According to the twelve-tone equal temperament, the music rule of the elements stoichiometry of superconducting materials at critical temperature is given, according to the periodic table of the chemical elements of twelve rhythms, the music regularity of the chemical compositions of high temperature superconducting materials is given, and the theory of superconducting mechanism is given according to the theory of magneto-electric coupling. Among them, the mechanism of fermions pairing is given, the expression of superconducting current density is given, and the equivalence relation between zero resistance and perfect diamagnetism is shown, etc. These theories are applicable to all kinds of superconducting materials, which are suitable for conventional and unconventional superconductors, as well as for superconductors under high pressure, film, interface and radiation conditions. It provides a theoretical basis for the explanation of superconductivity and the search for superconductors with higher critical temperatures.

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Two recent results on the theories of the superconducting Sr2RuO4

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We will present two recent progress on the theories of the superconductivity in Sr2RuO4. In one [1], we performed systematic random phase approximation calculations of a three-orbital model with spin-orbit coupling. We show that this material is more unstable towards even-parity s- or d-wave pairings at intermediate interaction strength. The p-wave pairing emerges as the leading instability *only* in the extreme weak-coupling limit. In the other [2], we explored the consequence of the three-dimensional spin-orbital entanglement in the electronic structure. We propose that the odd-parity *Eu* pairing in Sr2RuO4 should be inherently three-dimensional in nature. Under appropriate conditions this *Eu* pairing may stabilize into a time-reversal invariant nematic phase. Although these results may not hold the final answer to the enigmatic superconductivity in Sr2RuO4, the proposed pairings respectively exhibit salient properties consistent with a number of key experimental observations which are otherwise incompatible with the chiral p-wave order. Hence our results shed new light on Sr2RuO4.

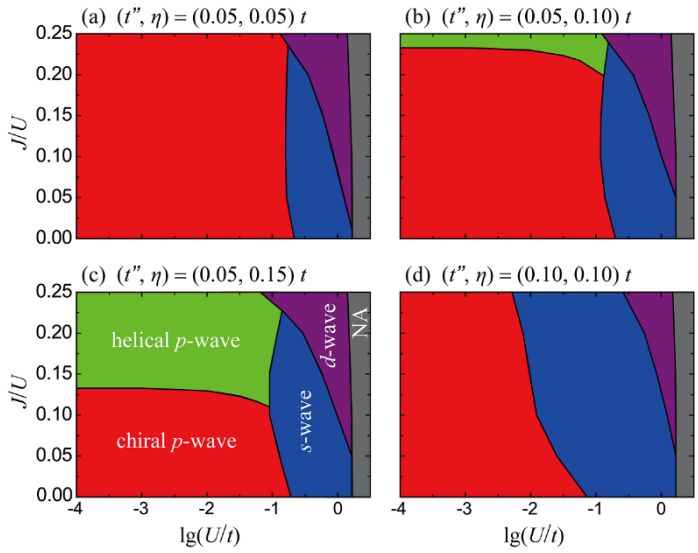

Fig. 1: *RPA phase diagrams as a function of the Coulomb interactions, U and J, the latter being the Hund's coupling. t'' and η are orbital hybridization and spin-orbit coupling, respectively. See Ref. [1].*

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The superconducting transition temperature in the two-band electron-phonon system with interband pairing

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Eliashberg theory, generalized accounting the special properties of two-band electron-phonon (EF) systems [1] is used for the study of Tc in the pnictides. The pairing within the full width of the electron band, and not only in a narrow band near the Fermi surface is considered [2]. It is found that the effect of the pairing of electrons belonging to different bands (Fig.1) is crucial to the appearance of the effect of high Tc in these materials.

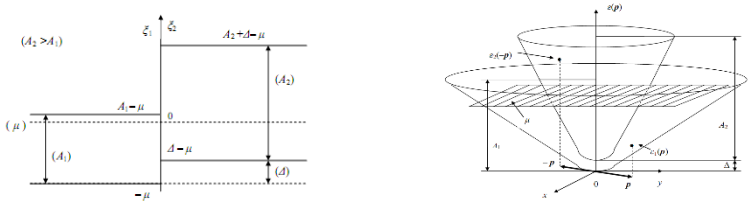

Fig.1. a. *Diagram of two energy bands of electrons . $\xi_{1(2)}$ is the electron energy of 1st (2nd) -bands, measured from the chemical potential μ; $A_{1(2)}$ is the width of 1st (2nd) zone; Δ is the distance (in energy) between the bottom of 2nd and 1st band respectively,* ***b.*** *Energy surface of the electrons from the 1st and 2nd bands in the momentum space.*

The equations for the complex order parameter are obtained with the use of the generalization of the Eliashberg theory to the case of pairing of the carriers from two different bands in the framework of the phonon (boson) mechanism. It is shown that with the selection of the parameters of two zones, the carriers of which are involved in the pairing, one can achieve a sharp increase in the superconducting transition temperature (Fig.2) with interband coupling constant of order unity.

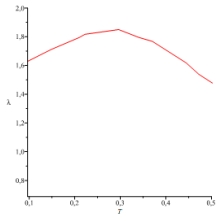

Fig. 2. *The plot of interdependence of T_c and interband coupling constant λ for the electrons (holes) of the two adjacent bands in terms of the band parameters.*

The conclusion about the possibility to easily comply with the terms of the existence of materials with high superconducting transition temperature T_c not inferior T_c in cuprates from this work is emerging.

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Simultaneous Phase Transitions of Superconductivity and Electric Hexadecapole in Iron Pnictide $Ba(Fe_{1-x}Co_x)_2As_2$

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Emergence of superconductivity attributed to orbital degeneracy has recently been paid great attention. Iron pnictide superconductor $Ba(Fe_{1-x}Co_x)_2As_2$ has three hole-like Fermi surfaces around point and two electron-like Fermi surfaces near X-point. Two sheets around point especially have almost two-dimensional shape and are close to each other. They consist of two-fold degenerate Fe-3*d* orbitals $d_{y'z}$ and $d_{zx'}$ with E_g under tetragonal point group symmetry D_{2d}, where the *x*' and *y*' (*x* and *y*) axes are directed along the nearest (second nearest) Fe-Fe bonds. Ultrasonic measurement is a powerful tool for the investigation of electron systems with orbital degeneracy because the elastic strain and rotation induced by transverse ultrasonic waves couple to electric multipoles.

We observed divergent behavior of the elastic constant C_{66} and the ultrasonic attenuation $_{66}$ toward the structural phase transition temperature T_s=65 K in parent compound $BaFe_2As_2$ [1]. The *d*-electrons occupied in $d_{y'z}$ and $d_{zx'}$ orbitals have the angular momentum L_z with A_2 and the electric quadrupoles $O_{x'y'}$ with B_1 and $O_{x'2-y'2}$ with B_2. Since $O_{x'2-y'2}$ couples to the elastic strain $_{xy}$ through the quadrupole strain interaction as $-gO_{x'2-y'2}$ $_{xy}$, the electron system undergoes ferro-quadrupole order (also known as ferro-orbital or nematic order) accompanied by lattice distortion from tetragonal to orthorhombic class. In contrast, the ultrasonic attenuation coefficient $_{66}$ in $Ba(Fe_{0.929}Co_{0.071})_2As_2$ shows divergence toward the superconducting transition temperature T_{SC}=23 K and C_{66} shows finite decrease of about 23% without structural transition [1, 2]. We found that the coupling between rotation $_{xy}$ and electric hexadecapole H_z that consists of two-electron state with A_2 as $-g'H_z$ $_{xy}$, which leads to the critical slowing down phenomena toward T_{SC}. It is of critical importance that anisotropic quadrupole interaction consisting of $O_{x'2-y'2}$ and $O_{x'y'}$ brings about ferro-hexadecapole ordering and the simultaneous superconducting state in $Ba(Fe_{0.929}Co_{0.071})_2As_2$. This system would be an unconventional superconductor with the symmetry breaking of the U(1) gauge and A_2 under the point group D_{2d}.

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The Electron-Phonon Interaction with Forward Scattering Peak in *FeSe* on $SrTiO_3$

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The theory of the electron-phonon interaction *(EPI*) with strong forward scattering peak *(FSP)* in an extreme delta-peak limit [1] is recently applied in [2] for the explanation of high $T_c \sim 100\ K$ in a monolayer *FeSe* grown on $SrTiO_3$ > and TiO_2 substrates. The *EPI* is due to a long-range dipolar electric field created by high-energy oxygen vibrations ($\Omega \sim 90\ meV$) at the interface [2]. In leading order with respect to T_{c0}/Ω the mean-field critical temperature $T_{c0}=\langle V_{epi}(\boldsymbol{q})\rangle_q/4 \sim (aq_c)^2 V_{epi}(0)$ and the gap $\Delta_o=2T_{c0}$ are due to an interplay between the maximal *EPI* pairing potential $V_{epi}(0)$ and the *FSP*-width q_c. For $T_{c0} \sim 100\ K$ one has $\Delta_o \sim 16\ meV$ in a satisfactory agreement with ARPES experiments. In leading order T_{c0} is mass-independent and a very small oxygen isotope effect is expected in next to leading order. In clean systems T_{c0} for *s*-wave and *d*-wave pairing is degenerate but both are affected by non-magnetic impurities, which are pair-weakening in the *s*-channel and pair-breaking in the *d*-channel.

The self-energy and replica bands at $T=0$ and at the Fermi surface are calculated and compared with experimental results at $T \neq 0$ [2]. The *EPI* coupling constant $\lambda_m=\langle V_{epi}(\boldsymbol{q})\rangle_q/2\Omega$ is mass-dependent ($M^{1/2}$) and at $\omega \ll \Omega$ makes the slope of the self-energy $\Sigma(\boldsymbol{k},\omega) \approx -\lambda_m \omega$ and the replica intensities $A_i \sim \lambda_m$ mass-dependent. This result, overlooked in the literature, is contrary to the prediction of the standard Migdal-Eliashberg theory for *EPI*. The small oxygen isotope effect in T_{c0} and pronounced isotope effect in $\Sigma(\boldsymbol{k},\omega)$ and *ARPES* spectra A_i of the replica bands in *FeSe* films on $SrTiO_3$ and TiO_2 is a smoking-gun experiment for validity of the *EPI-FSP* theory to these systems. The *EPI-FSP* theory predicts a large number of low-laying pairing states, thus causing internal pair fluctuations. The latter reduce T_{c0} additionally, by creating a pseudogap state for $T_c<T<T_{c0}$ Possibilities to increase T_{c0}, by designing novel structures are discussed in the framework of the *EPI-FSP* theory[3].

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Local Quantum Order Induced Hole Transport in High-temperature Cuprate Superconductors

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The anomalous transport in pseudogap, strange metal and vortex liquid phases of cuprate superconductor (SC), are investigated in a unified framework of hole transport induced by intertwined local quantum orders such as charge density wave (CDW), loop current order and vortex. Based on a checkerboard model which assumes a lattice of 'quantum dots' (i.e. order), we derive a sheet conductance $\boldsymbol{G_{\square} = \gamma N e^2/h}$, where $\boldsymbol{\gamma = 3.15}$ is effective terminal number, and $\boldsymbol{N = \pi R_h^2 n_h}$ is channel number which equals to hole number in a dot, while $\boldsymbol{R_h}$ and $\boldsymbol{n_h}$ are channel radius and hole density, respectively.

In a vortex liquid, $\boldsymbol{R_h}$ is suppressed at both macroscopic (SC sample) and mesoscopic scale, and dominated by the inter-core distance scale, at which the damping is enhanced by quasiparticle tunneling between adjacent cores. The predicted resistivity is quantitatively verified by magnetoresistance data in Bi-2212 and LSCO [1]. Furthermore, by an energy balance argument, we derive a Nernst effect model which yields accurate description of data in Bi-2201 and Bi-2212 over a wide range of temperature and field [2], which then allows a determination of the local superfluid density from data, with its linear *T* dependence. Finally, a constant ratio connecting resistivity, Nernst signal and diamagnetism in intermediated field regime near $\boldsymbol{T_c}$ is predicted, i.e., $\boldsymbol{-M\rho/(e_N T) = 1}$, also validated by data.

For normal state at high fields or high temperature, a multi-state dilation invariance argument yields $\boldsymbol{R_h = \xi_{CDW}[1 + (\lambda_h^*/\xi_{CDW})^4]^{1/4}}$ where $\boldsymbol{\xi_{CDW} \approx 4a_0}$ is correlation length of CDW and $\boldsymbol{\lambda_h^*(T) = \hbar/\sqrt{3 m_h k_B T}}$ is the reduced thermal de Broglie wave length of hole. The model thus defines a transition at $\boldsymbol{\lambda_h^*(T_h) = \xi_{CDW}}$, corresponding to transition from static to fluctuating orders, beyond which arises the celebrated linear $\boldsymbol{T}$ dependence of resistivity. Predicted resistivity (with a single fitting parameter $\boldsymbol{m_h}$) for Bi-2201 agrees very well with data (see Fig.1a). Derived values of $\boldsymbol{m_h/m_e}$ are between 1.36 and 2.93, agreeing with 2.2~$\boldsymbol{3}$ measured with optical conductivity. Furthermore, predicted transition temperature $\boldsymbol{T_h}$ also agrees well with recently measured onset temperature of static field-induced CDW [3], i.e., $\boldsymbol{T_{CDW}}$ (see Fig.1b) .

Therefore, a unified phenomenology of quantum transport in cuprate SC is proposed, providing a new tool to study transitions in high temperature SC.

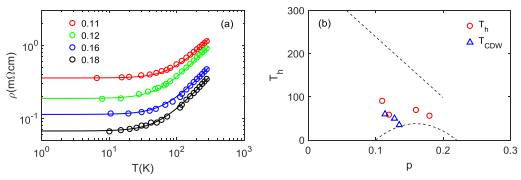

Fig. 1: (a) Resistivity in Bi-2201. Points are normal state data, and solid lines are predictions. (b) Comparison between $\boldsymbol{T_h}$ and $\boldsymbol{T_{CDW}}$.

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Time-reversal and/or translational symmetry breaking in d-wave nano-superconductors

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Sato et al. have shown the bulk-edge correspondence between the zero-energy Andreev bound states on [110] surfaces of a high-Tc cuprate superconductor and a topological invariant protected by time-reversal symmetry (TRS) [1]. We show that spontaneous disappearance of topological protection occurs with an alternative superconducting order parameter appearing on a surface [2]. We self-consistently solve the Bogoliubov-de Gennes equations and the d-wave gap equation in d-wave nanoislands and nanoribbons. Time-reversal symmetry is spontaneously broken at a lower temperature than the superconducting transition temperature. We find that this phase transition is of second order. This order parameter has extended s-wave symmetry and it characterizes the energy gap of the split Andreev bound states on the surfaces. In narrow nanoribbons, translational symmetry can also be broken. We illustrate the width and temperature dependence of these phases.

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A Strange Metal from Gutzwiller correlations: Transverse Transport, Optical Response and Rise of Two Relaxation Rates

Transverse Transport, Optical Response and Two Relaxation Rates of $t-J$ Model in ∞ Dimensions*

2:03 PM–2:15 PM

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(Physics, Univ of California-Santa Cruz)

Using two approaches to strongly correlated systems, the extremely correlated Fermi liquid theory and the dynamical mean field
theory, we compute transverse transport coefficients, the Hall constants, Hall angles, and longitudinal and transverse optical response of the $U=\infty$ Hubbard model in the limit of infinite dimensions. We focus on two successive low-temperature regimes, the Gutzwiller correlated Fermi liquid (GCFL) and the Gutzwiller correlated strange metal (GCSM). We find that the Hall angle $\cot\theta_H$ exhibits a kink that has been seen experimentally but has escaped being commented upon earlier. It is found that $\cot\theta_H \propto T^2$ in GCFL regime, and then shows a downward bend into GCSM regime. Drude peaks are found for both the optical conductivity and the optical Hall angles below certain characteristic energy scales. By comparing the relaxation rates extracted from fitting to the Drude formula, we find that in the GCFL regime there is a single relaxation rate controlling both longitudinal and transverse transport, while in the GCSM regime two different relaxation rates emerge. We trace the origin of this behavior to the dynamical particle-hole asymmetry of the Dyson self-energy, arguably a generic feature of doped Mott insulators.

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Pseudogap-generated a coexistence of Fermi arcs and Fermi pockets in cuprate superconductors

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Based on the t − J model in the fermion-spin representation, the coexistence of the Fermi arcs and Fermi pockets in cuprate superconductors is studied by taking into account the pseudogap effect [1]. It is shown that the pseudogap induces an energy band splitting, and then the poles of the electron Green's function at zero energy form two contours in momentum space, however, the electron spectral weight on these two contours around the antinodal region is gapped out by the pseudogap, leaving behind the low-energy electron spectral weight only located at the disconnected segments around the nodal region. In particular, the tips of these disconnected segments converge on the hot spots to form the closed Fermi pockets, generating a coexistence of the Fermi arcs and Fermi pockets. Moreover, we find the magnitude of the charge order wave vector Q_{CD} increases with the increase of the second-neighbor hoping t', which explains that and the experimentally observed differences of the magnitudes of the charge-order wave vector among the different families of cuprate superconductors at the same doping concentration are attributed to the different values of t'.

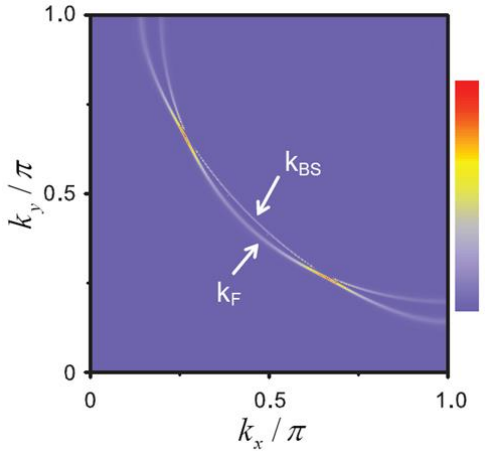

Fig. 1: *The map of the electron spectral indensity A(k,0) at δ=0.15 with T=0.002J for t/J=2.5 and t'/t=0.3*

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Momentum and Doping Dependence of the Band Renormalization and Scattering Rates in Iron-based Superconductors Determined by ARPES

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Unconventional/high temperature superconductivity (SC) is believed to occur in correlated systems. A prerequisite for the understanding of the mechanism of superconductivity is the understanding of the electronic structure in the normal state. While in the single-band cuprates the starting point for the description of correlation effects in the normal state is the Mott-Hubbard model, in the multi-band iron-based superconductors, besides the onsite Coulomb interaction, also Hund's exchange interaction has to be taken into account. Using angle-resolved photoemission spectroscopy we have studied the momentum dependence of the band renormalization and the energy dependent scattering rates of charge carriers in various transition metal pnictides and iron chalcogenides as a function of the doping concentration. In this way we obtain information on the location of the hot spots on the Fermi surface determining antiferromagnetism and superconductivity as well as on the location of the cold spots determining the normal state transport properties. The aim is to obtain a microscopic understanding of the electronic structure of these systems in the normal and in the superconducting state. The experimental results are compared with current models such as quantum critical scenarios, spin-Fermion models, and DFT+DMFT calculations of Hund's metal behavior.

Theoretical Formalism of Andreev Reflection Spectroscopy for Three-dimensional Triplet Pairing Superconductors

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We propose a general theoretical formalism of Andreev reflection spectroscopy for three-dimensional (3D) spin triplet pairing superconductors, which can supply a theoretical support for distinguishing the singlet and triplet pairing state by point contact Andreev reflection (PCAR) measurements. Motivated by recent PCAR experiment on unconventional superconductivity in Bi/Ni bilayers, our theoretical conductance spectroscopy of the triplet Anderson-Brinkman-Morel (ABM) state superconductivity can nicely describe all the main features of their experimental measurements. Moreover, we discuss the PCAR experimental consequences of 3D Balian-Werthamer (BW) state and 2D chiral p-wave state.

Magnetic-interaction-induced Superconductivity in Metals

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Abstract: In this paper, a microscopic theory of magnetic-interaction-induced pairing in superconductivity of metals was developed on the basis of four idealized assumptions: (1) only a small number of electrons are involved in superconductivity; (2) magnetic interactions between electron spins lead to superconductivity; (3) there are different electronic states, i.e., doubly-occupied, singly-occupied (spin up or down) and empty states; (4) the average kinetic energy of electrons complies with the equipartition theorem of energy. A formula to estimate T_C was thus derived. It was found that, T_C is not only related to the electron density and the critical magnetic field, but also to the degrees of freedom of electrons. The T_C values calculated from this formula are in good agreement with the experimental results for most metals. According to this theory, T_C generally increases with decreasing dimension of metals. For example, T_C in the 3-dimensional (3D) Al metal is 1.19K, but increases to 1.46K in 2D and 2.06K in 1D.

PACS numbers: 74.20. Mn, 75.47. Np, 74.20. –z, 74.20. De

High-T_C Superconductivity Induced by Magnetic Interactions

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Abstract: In this paper, a microscopic theory of magnetic-interaction-induced pairing in superconductivity of high temperature superconductors (HTSC) was developed on the basis of four idealized assumptions: (1) only a small number of electrons(or holes) are involved in superconductivity, and its density is $n\delta^2$; (2) magnetic interactions between electron spins lead to superconductivity; (3) there are different electronic states, i.e., the on-site doubly-occupied electrons forming anti-ferromagnetic insulator states, the off-site doubly-occupied electrons forming superconducting states, the singly-occupied (spin up or down) electrons forming normal states and the empty states; (4) the average kinetic energy of electrons (or holes) complies with the equipartition theorem of energy. Based on these assumptions, an approximate effective Hamiltonian was suggested. A parabolic relation between T_C and the doping concentration δ was found and thus the phase diagram for HTSC has been explained. It was also found that, T_C is related to the anti-ferromagnetic interaction energy J (or critical magnetic field B_C) and the degrees of freedom of electrons i. The T_C values are thus calculated from this theory to be 92.8K for $YBa_2Cu_3O_{6.15}$, 40.3K for La_2CuO_4, and 58K for $SmOF_eAs$, which are in good agreement with the experimental results of 92K, 40K, and 54K, respectively. It was estimated that, T_C in the slab HTSC is higher than that in the bulk, and T_C for $SmOF_eAs$ can be up to 116K.

PACS numbers: 74.20. Mn, 74.72. -h, 75.50. Ee, 74.25.Dw

Towards a Standard Model for Condensed Matter Physics: From Peierls and Mott to High T_c Superconductivity

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One of the most significant outstanding challenges in the field of Condensed Matter Physics is a unified description of the origins of behaviors embodied in models such as the BCS theory of Superconductivity, the Heisenberg Ferro/Antiferromagnet, the Hubbard Model of strong electron correlations and others. Phenomena such as high temperature superconductivity [1] and metal-insulator transitions [2] in materials such as the vanadium oxides have to-date defied rigorous mathematical descriptions that can be used by engineers to produce new generations of ultra-high performance/low power devices. In this work the physics of metal oxide crystals is reformulated via the scattering amplitudes of a Yang-Mills [3] theory based on an SU(2) gauge group.

Scattering vertices which describe the interactions of Dirac Spinors and Vector bosons have a wealth of degrees of freedom from which unusual phenomena can arise. Polar crystals, such as those of metal oxides have vibrational mode eigenvectors which can create unusual charge and magnetic fluctuations, as seen in the paramagnetic metal to antiferromagnetic insulating transitions of pure and doped vanadium dioxides [2]. If these charge and spin modes are combined into a lattice gauge field in the usual way, the SU(2) vertex which results [3]:

$$\bar{\psi}\gamma^{\mu}\vec{W}_{\mu}\cdot\vec{\tau}\psi$$

where $\vec{W}_{\mu}$ is a 3-vector of acoustic phonon modes, and $\vec{\tau}$ = (σ^1, σ^2, σ^3) is a 3-vector of the Pauli matrices, when combined with the electromagnetic gauge field (A_{μ}) contains as limiting cases: BCS theory (standard electron-longitudinal phonon coupling), ferro- and antiferromagnetic ordering, Cooper pairing of electrons *via* magnetic fluctuations, and Mott and Peierls metal-insulator transitions.

In this work it is shown that a Yang-Mills approach to Condensed Matter may provide the underlying theoretical basis for transitions which open energy gaps, and provide significant insights on how to control them.

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Surprises in the t-J model: Implications for Cuprates

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The t-J model is a paradigmatic model for the study of strongly correlated electron systems. In particular, it has been argued that it is an appropriate model to describe the cuprate high-T_c superconductors. It turns out that a comprehensive understanding of the gamut of Physics encoded by the t-J model is still an open problem. In recent years some remarkable experiments on the cuprates, for example, discovery of nodeless superconductivity in underdoped samples [PNAS 109, 18332 (2012)], discovery of s-wave like gap in the pseudogap phase[Phys. Rev. Lett. 111, 107001 (2013)], and observation of polar Kerr effect (PKE) [Phys. Rev. Lett. 112, 047003 (2014)], have thrown up new challenges for this model. Here, we present results demonstrating that, within the slave-particle formulation of the t-J model, the d-wave superconductor is unstable at low doping to its own anti-symmetric phase mode fluctuations when the effect of fluctuations is treated self-consistently. We then show that this instability gives way to a time reversal symmetry broken d + is-SC in the underdoped region which has superfluid stiffness consistent with Uemura relation, even with a large pair amplitude. We argue that our results are consistent with existing experiments on cuprates and suggest that Josephson (SQUID interfermetry) experiments can clearly distinguish the d + is-SC from a host of other possibilites alluded to be contributing to the physics of underdoped cuprates.

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Spin-orbit coupling and time-reversal symmetry breaking in a multiband superconductor

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The study of non-centrosymmetric and multiband superconductors is currently a topic of great interest. Half-Heusler superconductors, such as YPtBi, fall into both those categories and have recently attracted a lot of attention due to their possible spin-3/2 pairing [1,2]. In this work we explore the fitness of the pairing states in the weak coupling limit and find a rich phase diagram with several different phases (Fig. 1). In the limit of strong spin-orbit coupling the predicted time-reversal symmetry breaking state with inflated nodes is realized [3,4]. This state displays reentrant behavior for weak spin-orbit coupling and a first-order phase transition into the time-reversal symmetric state. The time-reversal symmetric state exhibits a nodal and nodeless phase, shows an enhancement over the critical temperature predicted by Ginzburg-Landau theory, and a first-order phase transition into the normal state.

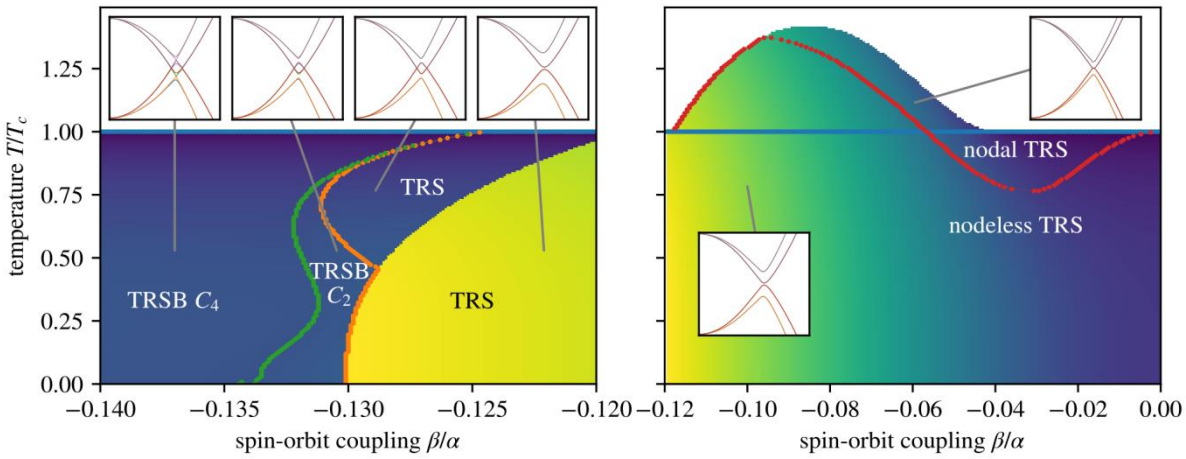

Fig. 1: *Phase diagram of the YPtBi model Hamiltonian in the spherically symmetric limit.*

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Non-hermitian topological quantum wires with balanced gain and loss

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We study a one-dimensional topological superconductor, the Kitaev chain, under the influence of a non-Hermitian but PT-symmetric potential. This potential introduces gain and loss in the system in equal parts. We show that the stability of the topological phase is influenced by the gain/loss strength and explicitly derive the bulk topological invariant in a bipartite lattice and compute the corresponding phase diagram using analytical and numerical methods. Furthermore we find that the edge state is exponentially localized near the ends of the wire despite the presence of gain and loss of probability amplitude in that region.

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Electronic Structure of Bilayer Cuprate Superconductors

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One of the important issues [1,2] is whether the behavior of the low-energy electron quasiparticle excitations in cuprtae superconductors determined by the electronic structure is universal or not? Here the electronic structure of the bilayer cuprate superconductors in the normal-state is studied based on the bilayer t-J model [3]. It is shown that although the electron quasiparticle excitation spectrum of the bilayer cuprate superconductors is split into the bonding and antibonding components by the bilayer splitting, the electron interaction directly from the interlayer coherent hopping in the kinetic-energy by the exchange of spin excitations does not provide the contribution to the pseudogap state, while only the electron interaction directly from the intralayer hopping in the kinetic-energy by the exchange of spin excitations induces the pseudogap [4], and then the main behavior of the low-energy electron quasiparticle excitations is a universal feature for the single-layer [5] and bilayer cuprate superconductors [3]. In particular, the weight of the electron quasiparticle excitation spectrum on the electron Fermi surface around the antinodal region is suppressed by the pseudogap, which leads to the original electron Fermi surface is broken up into the Fermi pockets located around the nodal region [3,6]. Moreover, the striking peak-dip-hump structure generates by the the peak structure in the electron quasiparticle scattering rate [7] is enhanced by the bilayer splitting.

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Pairing Symmetry of Interacting Fermions on Twisted Bilayer Graphene Superlattice

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Unconventional superconductivity in magic angle graphene bilayers is discovered recently [1, 2]. Here, we [3] study the pairing symmetry of an effective Hamiltonian for interacting fermions on a twisted bilayer graphene superlattice with the determinant quantum Monte Carlo method. The model has the symmetry of a triangle lattice and a nearly-flat low energy band features which underlie the magic-angle twisted bilayer graphene superlattice. We also show that the low temperature phase is insulating at half-filling, even for relatively weak interactions. The natures of the spin and pairing correlations upon doping are determined, and exhibit an electron-hole asymmetry consistent with experiments. Among the pairing symmetries allowed, we demonstrate that the dominating channels are d-wave (Fig. 1), opening the possibility of condensation into an unconventional $d_{x^2-y^2} + id_{xy}$ phase, which is characterized by an integer topological invariant and gapless edge states.

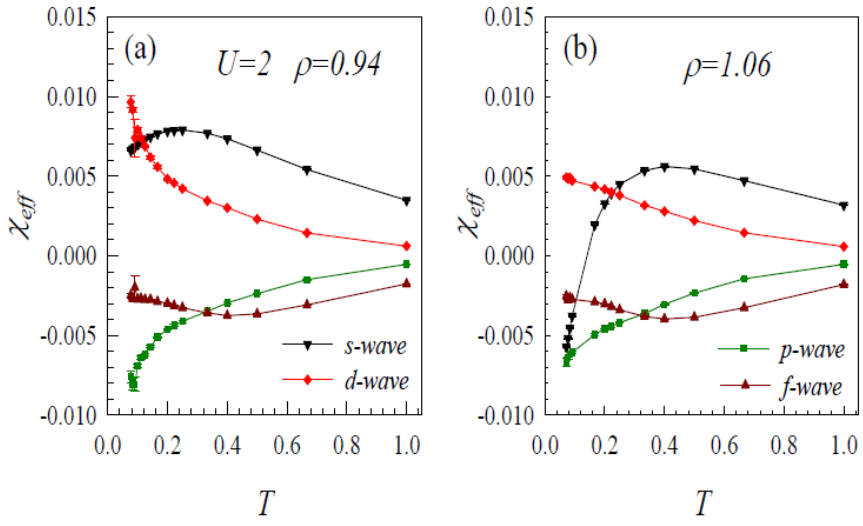

Fig. 1: *The effective pairing susceptibility at ρ= 0.94 (a) and ρ= 1.06(b) as a function of temperature for different pairing channels. The χ_{eff} of d-wave increases rapidly at low temperatures.*

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Autocorrelation of Quasiparticle Excitation Spectral Intensities and Its Connection with Joint Density of States in Cuprate Superconductors

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The pseudogap phenomenon in cuprate superconductors is the most mysterious puzzle in the research of superconductivity [1,2]. Within the kinetic-energy driven superconducting mechanism [3,4], the autocorrelation of the quasiparticle excitation spectral intensities and its connection with the high joint density of states in the superconducting-state of cuprate superconductors is studied by taking into account the interplay between the pseudogap and superconducting gap [5]. It is shown that the quasiparticle excitation spectral weight on the constant energy contours around the antinodal region is gapped out by the pseudogap, leaving behind the quasiparticle excitation spectral weight only located at the disconnected segments around the nodal region. However, the highest intensity regimes on the disconnected segments does not appear at the nodes, but locates exactly around the tips of these disconnected segments [5]. Concomitantly, the spots (then the sharp peaks) in the autocorrelation of the quasiparticle excitation spectral intensities with the wave vectors qi connecting the tips of these disconnected segments are directly correlated to the regions of the highest joint density of states [5]. In particular, these sharp peaks are weakly dispersive in momentum space, and such dispersive behavior in momentum space can be attributed to charge ordering [6,7]. Moreover, these wave vectors qi are also qualitatively consistent with those observed from the Fourier transform scanning tunneling spectroscopy experiments [8].

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Effect of the Hund's rule and orbital anisotropy in the two-band Hubbard model: a finite-temperature slave-spin treatment

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The interest in the role of orbital degeneracy, Hund's rule, and multiple bands in strongly correlated electron materials has increased in the last years due to the study of transition metal oxides, colossal magnetoresistance, and the new iron-based superconductors. Recently it was shown that Hund's rule has a complex effect on correlations: it modifies the critical value of the correlation above which a Mott insulator is formed in a way that depends on the number of electrons per site and the orbital character [1]. Here, we use the Slave-Spins Mean-Field Theory (SSMFT) [2] to study the temperature dependence of paramagnetic phases of the two-band Hubbard-Kanamori model and compare the one-band results with the slave-bosons mean-field method [3]. We pay particular attention to how the Hund's rule and bandwidth anisotropy affects the coherence temperature T_{coh} that signal the crossover from a Fermi liquid to a regime without quasiparticles, i.e., a bad metallic state. By calculating the quasiparticle spectral weight Z of each band, we can identify the T_{coh} as the temperature where they collapse. Near the Mott metal-insulator transition, we find this T_{coh} to be much lower than the Fermi temperature of the uncorrelated Fermi gas and to follow the effect of the Hund's rule on the ground state. We also explore the consequence of band anisotropy and discuss the appearance of a different T_{coh} for each band, or otherwise the emergence of a common energy scale for two different bands.

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Pairing symmetry determined by local density of states around impurities in heavy-fermion superconductors

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Motivated by recent experimental progress in high-resolution scanning tunneling microscopy techniques, we investigate the local density of states around impurities as a probe of pairing symmetry in heavy-fermion superconductors. For $CeCoIn_5$, we based on T-matrix approach obtain a sharp nearly zero-energy resonance states considering an unitary impurity scatterings, and find qualitative differences in the spatial pattern of the tunneling conductance modulated by the nodal structure of the superconducting gap, which together with the STM measurement help to confirm the d_{x2-y2} pairing symmetry in $CeCoIn_5$ [1,2]. By first-principle calculations, we reproduce the realistic multiband Fermi-surface topology of $CeCu_2Si_2$, and study the problem within an effective two hybridization band model. Our calculations reveal that different pairing candidates could yield qualitatively distinct features characterized by impurity induced resonance states, and provide an unambiguous justification for the ongoing debate about the superconducting gap symmetry of $CeCu_2Si_2$ at ambient pressure [3].

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Theory of Higgs Spectroscopy for Superconductors in Nonequilibrium

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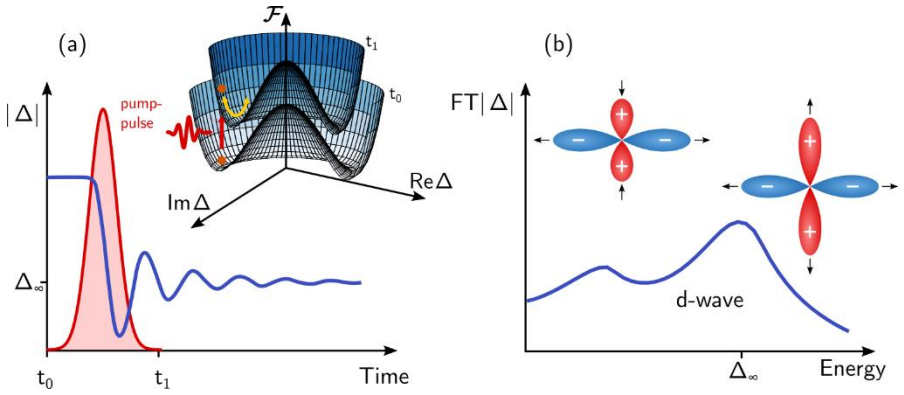
In superconductors, a fundamental collective excitation of Cooper pairs exists which arises due to the spontaneous U(1) symmetry breaking. This mode is called Higgs mode in analogy to high-energy physics. In recent years, Higgs oscillations in s-wave superconductors in nonequilibrium excited by short THz laser pulses were intensively studied. It is known that this oscillation has a characteristic frequency of two times the energy gap. For d-wave superconductors one can find additional modes resulting from asymmetric oscillations of the energy gap [1]. This allows a clear distinction between s- and d-wave symmetry. We analyze such quantum quenches induced by short THz lasers in a general formalism for multiple different gap symmetries found in unconventional superconductors [2]. Depending on the gap and quench symmetry, which can be controlled experimentally by the pulse direction and polarization, different Higgs modes may occur which can be classified by the underlying lattice point group similar to phonon spectroscopy. These modes show up in experimental quantities like the amplitude oscillation of the optical conductivity or the ARPES spectrum in time-resolved experiments. We propose that Higgs oscillations in nonequilibrium have a great potential to become a versatile spectroscopic method for investigations of ground state properties and gap symmetries of superconductors. Together with phase information extracted from experiments of such kind the gap symmetry of new superconducting materials can be revealed.

Fig. 1: (a) *Higgs oscillations of the energy gap Δ induced by a short THz laser pulse. The short pulse acts as a quantum quench. The system ends up in an out of equilibrium position and starts to oscillate around the new minimum. (b) Depending on the gap symmetry and quench symmetry (here d-wave with an A_{1g} quench) multiple Higgs modes can arise. Used as a spectroscopic tool, the analysis of Higgs modes for new materials can reveal the gap symmetry.*



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Theoretical study on the phonon softening in iron-based superconductors

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Recently the softening of a transverse acoustic phonon across the structural transition has been observed in several iron-based superconductors by neutron scattering measurements [1]. To understand this theoretically, we construct a Gintzburg-Landau model to describe the interplay between the phonon mode and the nematic order by taking into account the spin-phonon coupling. By calculating the phonon self-energy, we find the nematic fluctuations across the structural transition give rise to the observed phonon softening, which modify the phonon dispersion from linear to quadratic at the critical point. Our results also show that the ferroorbital order alone cannot account for the phonon softening, therefore providing new evidence on the magnetic origin of the nematicity in iron-based superconductors.

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Nodeless gap induced by proximity effect in monolayer CuO_2 on BSCCO substrate

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We present a detailed analysis on the hopping between monolayer CuO_2 and bulk CuO_2 plane in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ substrate. With a two-band model, we demonstrate that the nodeless gap can only exist when the hole concentration in monolayer CuO_2 plane is very large. We argue that the possible phase separation may play important role in the recent experimental observation of nodeless gap.

Doping and Momentum Dependence of Pairing Interactions in Cuprate Superconductors

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Superconductivity is caused by the interaction between electrons by the exchange of collective bosonic excitations, however, this bosonic glue forming electron pairs is manifested itself by the electron spectral function of the effective interaction $\alpha^2F(k, \omega)$ [1,2]. Within the framework of kinetic-energy-driven superconducting mechanism [3,4], the low-energy electronic structure of cuprate superconductors both in the normal- and superconducting- states is studied [5]. Both the normal self-energy in the particle-hole channel and pairing self-energy in the particle-particle channel induced by the same interaction between electrons by the exchange of spin excitation are evaluated and employed to caculate the doping and momentum dependence of the electron spectral functions of the effective interactions [5] $\alpha^2F_{ph}(k, \omega)$ in the particle-hole channel and $\alpha^2F_{pp}(k, \omega)$ in the particle-particle channel, respectively. Below the superconducting transition temperature T_c, both effective interactions $\alpha^2F_{ph}(k, \omega)$ and $\alpha^2F_{pp}(k, \omega)$ are nearly independent of energy over the energy range up to 300 meV, except for the low-energy peak structures, where both $\alpha^2F_{ph}(k, \omega)$ and $\alpha^2F_{pp}(k, \omega)$ show a peak around 50~70 meV and a sharp peak around 5~10 meV in the antinodal region, however, this peak structure is absent for $\alpha^2F_{pp}(k, \omega)$ in the nodal region due to d-wave symmetry. Well above T_c, the effective interaction $\alpha^2F_{pp}(k, \omega)$ disappears, while the weight of the low-energy peaks in the effective interaction $\alpha^2F_{ph}(k, \omega)$ is suppressed. In particular, it's also shown that this peaks structure in the effective interactions around the antinodal region is directly responsible for the striking peak-dip-hump structure observed in the electron quasiparticle excitation spectrum of cuprate superconductors [6].

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Exciton condensation temperature and odd frequency pairing in a transition metal dichalcogenide 1*T*-$TeSe_2$

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We studied the exciton condensation in the transition metal dichalcogenide 1T-$TiSe_2$ to understand the mechanism of charge density wave (CDW) phase by using Eliashberg-type CDW gap equation. The linearized CDW gap equation with statically screened Coulomb interaction was solved to find transition temperature T_c for realistic $TiSe_2$ model which has one hole band centered at Γ point and three electron bands located at M points in 2D hexagonal lattice. We found that the calculated transition temperature T_c agree with measured T_c, and that T_c as a functon of band gap and chemical potential are consistent with the experiments for pressure and doping (Cu-intercalated materials). For more understanding, we calculated CDW pairing self-energy as a function of frequency by solving Eliashberg-type CDW gap eqaution with both screened Coulomb and phonon interactions. The results show the possibility of odd frequency pairing in the excitonic insulator phase of 1T-$TiSe_2$.

Introspection of Mechanism Theories of Superconductivity

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How much do we really understand the mechanism of superconductivity after more than one century? If we do, why do we remain in disputing with each other for the mechanism without a consensus? Should we introspect the original theory, radically discard something and refrush our ideas, concepts and logics?

The authors have been working on this issue for more than 20 years and are pesenting a new concept of and approach to the mechanism of superconductivity: (1) Coulomb interaction between two electron-like quasiparticles in momentum space is attractive, leading to Cooper pairs [1]; (2) The final stable structure in the ground state is a quartet-two Cooper pairs configuration of four electron-like quasiparticles [2]; (3) Instead of introducing a very simplified BCS like Hamiltonian, a diagrammatical iteration approach of Feynman diagrams on the basis of the field theory is used to obtain an analytical solution that leads to the transition temperature of superconductivity, involving the dielectric constant, interlayer distance, etc. in the formula of T_c [3]; (4) Both of low and high-temperature superconductivity (HTS) can be undeerstood in a unified theory and all the anormalies for HTS observed in the normal state can be consistently explained by and deduced from the theory [4].

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The driving mechanism and the form of the orbital order in the iron-based superconductors

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We study the driving mechanism and the form of the orbital order in the electronic nematic phase of the iron-based superconductors within the random phase approximation of a five-band model. We find that the orbital order can be driven by magnetic correlation energy, which is shown to be significantly lowered when a d-wave orbital order is spontaneously formed. The magnetic correlation energy increases as one introduces an orbital order of either on-site or extended s-wave form. More specifically, we figure that the on-site orbital order is disfavored by the Hund's rule coupling and the extended s-wave orbital order is disfavored by the stripy magnetic correlation pattern in the iron-based superconductors. This provides an explanation for the ubiquitous d-wave form of the observed orbital order in iron-based superconductors.

Absence of the Asymmetry in Phace Diagram

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The optical conductivity of cuprate superconductors, which consists of a low-energy non-Drude peak and a higher energy band, is diffrent from that of the normal metal[1]. Within the framework of the fermion-spin theory[2,3] and in the full charge-spin recombination scheme[4], the charge dynamics of the cuprate superconductors in both the hole- and electron-doped side is studied. It is shown that the anomalous behavior of the optical conductivity can be attributed to the emergence of the normal-state pseudogap, which transfer a part of the low-energy spectral weight to the higher energy region to form the unusual midinfrared band. It is also found that both the hole- and electron-doped cuprate superconductors have similar properties in optical conductivity, which reflects the absence of the asymmetry in phace diagram[5].

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Fluctuation Effects on the Phase Diagram of Cuprate High-T_c Superconductors Based on the *t-J* Model

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The *t-J* model, treated based on the slave-boson approach, is one of the promising model to describe the essence of high-T_c superconductivity in cuprates. Using this model, various magnetic and electric properties have been discussed and they achieved some level of success. Although, these theories, so far, succeeded in catching the qualitative features of the cuprates, the effects of fluctuations (quantum or classical) beyond the mean-field level have not been studied sufficiently.

In this paper, we study the fluctuation effects on the phase diagram of the *t-J* model by self-consistently incorporating the Gaussian fluctuations into the mean field treatment. In the phase diagram of the *t-J* model, there appear several phases including superconductivity (S) and antiferromagnetism (AF). We especially pay attention to these two phases and treat them on an equal footing. We do not use the so-called Ginzburg-Landau type expansion, since the nonlinearity of the free energy of *t-J* model is subtle and complicated [1].

The basic idea of our treatment is to approximate the nonlinear potential $U(\vec{m})$ ($\vec{m}$ is the order parameter including both S and AF) that appears in the free energy functional of the *t-J* model as $U(\vec{m}) \to {}^t\vec{m} \cdot B \cdot \vec{m}$. The matrix B, describing the "mass" of the fluctuations is determined self-consistently so that the Gaussian-fluctuation effects are incorporated.

We studied the δ-T (doping-temperature) phase diagram of the *t-J* model using this method and obtained the following "fluctuation renormalized" phase diagram.

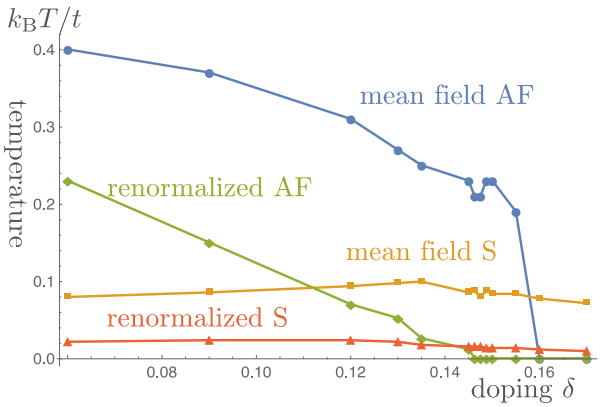

Fig. 1: *The phase diagram of the t-J model. Results of the mean-field theory and the renormalized one using the present method are shown.*

We stress that any similar results have not been obtained until now. Although our method is not very useful near the critical points, we believe it gives overall picture of the fluctuation effects in *t-J* model with a desirable accuracy. We studied only the thermal (classical) fluctuations here, however the present method can also treat quantum ones.

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Magnetic Field dependent Raman Response in Over-electron-doped Cuprates

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The theory of Raman scattering in electron-doped cuprate superconductors under the magnetic field is investigated based on the t-J model. The evolution of magnetic field dependent Raman response in the over-doped region in the B1g and B2g channel is studied. The results show the peak and intensity in the B1g and B2g symmetry decrease as the magnetic field increased. It is also shown the overall density of Cooper pairs gives the same depletion with the increase of the magnetic fields.

Theory of proximity effect in d_{xy}-wave superconductor with Rashba spin-orbit interaction

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We study the anomalous proximity effect in diffusive normal metal (DN)/unconventional superconductor junctions, where the local density of states (LDOS) in the DN has a zero-energy peak due to the penetration of the odd-frequency spin-triplet *s*-wave pairing. In this study, we consider a two-dimensional unconventional superconductor on the substrate in the presence of a Rashba spin-orbit coupling (RSOC) λ, where the Rashba vector is parallel with the *z*-direction. The anomalous proximity effect, originally predicted in spin-triplet *p*-wave superconductor junctions, is sensitive to the RSOC when the direction of the **d**-vector is parallel with the *z*-direction. It disappears with the increase of λ. When the direction of the **d**-vector is on the *xy*-plane, the zero-energy surface Andreev bound states (ZESABS) can remain with the increase of λ and an anomalous proximity effect exists even for large λ values. On the other hand, the anomalous proximity effect can be switched on by the large λ values in the spin-singlet *dxy*-wave superconductor junctions. The resulting zero-energy LDOS and the magnitude of the odd-frequency spin-triplet *s*-wave pair amplitude with the increase of λ.

Non-Fermi Liquid Scattering Against Emergent Bose Liquid: Manifestations in the Kink and Other Exotic Quasiparticle Behaviors in the Normal-State Cuprate Superconductors

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The normal state of cuprate superconductors exhibits many exotic behaviors qualitatively different from the Fermi liquid, the foundation of condensed matter physics. Here we demonstrate that non-Fermi liquid behaviors emerge naturally from scattering against an emergent Bose liquid. Particularly, we find a *finite* zero-energy scattering rate at low-temperature limit that grows linearly with respect to temperature, against clean fermions' generic non-dissipative characteristics. Surprisingly, three other seemingly unrelated experimental observations are also produced, including the well-studied ``kink'' in the quasi-particle dispersion, as well as the puzzling correspondences between the normal and superconducting state. Our findings provide a general route for fermionic systems to generate non-Fermi liquid behavior, and suggest strongly that by room temperature the doped holes in the cuprates have already formed an emergent Bose liquid of tightly bound pairs, whose low-temperature condensation gives unconventional superconductivity.

Inequivalence of the zero-momentum Limits of Transverse and Longitudinal Dielectric Response in the Cuprates

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We address the question of the mismatch between the zero momentum limits of the transverse and longitudinal dielectric functions for a fixed direction of the driving field observed in the cuprates. This question translates to whether or not the order in which the longitudinal and transverse momentum transfers are taken to zero commute. While the two limits commute for both isotropic and anisotropic Drude metals, we argue that a scaleless vertex interaction that depends solely on the angle between scattered electron momenta is sufficient to achieve non-commutativity of the two limits even for a system that is inherently isotropic. We demonstrate this claim for a simple case of the Drude conductivity modified by electron-boson interactions through appropriate vertex corrections, and outline possible consequences of our result to optical and electron energy loss spectroscopy (EELS) measurements close to zero momentum transfer

Substrate-supported triplet superconductivity in Dirac semimetals

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Stimulated by the success of graphene and its emerging Dirac physics, the quest for versatile and tunable electronic properties in atomically thin systems has led to the discovery of various chemical classes of 2D compounds. In particular, honeycomb lattices of group-V elements, such as silicene and germanene, have been found experimentally. Whether it is a necessity of synthesis or a desired feature towards application, most 2D materials demand a supporting substrate. In this work, we highlight the constructive impact of substrates to enable the realization of exotic electronic quantum states of matter, where the buckling emerges as the decisive material parameter adjustable by the substrate. At the example of germanene deposited on MoS2, we find that the coupling
between the monolayer and the substrate, together with the buckled hexagonal geometry, conspire to provide a highly suited scenario for unconventional triplet superconductivity upon adatom-assisted doping.