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HTSC 2022

ABSTRACT BOOK

13th International Conference on Materials and Mechanisms of Superconductivity & High Temperature Superconductors

July 17 - 22, 2022
Vancouver, BC
CANADA

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Mr. Steef Smit

Momentum-dependent scaling exponents in strange metals: ARPES meets semi-holography

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ARPES is unique in providing k-space sensitive access to the frequency- and temperature-dependence of the self-energy for interacting electron systems, a quantity linked to the lifetime of the electronic states. This underpins the central role for this experiment in research into quantum materials displaying emergent phenomena such as high T_c superconductivity and topological states of matter. To date all ARPES data and their analysis take the self energy to be dependent only on ω and T, and *not* on k.
Recently published laser-ARPES data from the bilayer cuprate BSCCO-2212 show that the ω- and T-dependence of the normal state self-energy exhibits power-laws [1], which tie in with ideas of quantum critical behavior across a wide range of doping levels – one of the fingerprints of a *strange metal* phase. Theoretical understanding of this phase is limited, despite decades of research. Recently, the Anti-de Sitter / Conformal Field Theory (AdS/CFT) approach [2] has been proposed to hold the answer, something we set out to test.
Here, we present new ARPES data from the normal state of the single-layer BSCO-2201 strange metal system, recorded over a wide range of temperature and frequency, obtaining some of the highest quality data ever recorded on these materials. The experimental data demand that the self-energy is frequency-, T- *and* k-dependent, which is a first. This provides compelling arguments for the relevance of AdS-CFT models as they prescribe that the power laws describing the lifetime must depend on ω-, T- and k. These new data therefore set the

scene for a quantitative comparison of ARPES experiments with an AdS-CFT-based theories.

We show how a semi-holographic approach, known as the Gubser-Rocha model [3] captures all the essentials of the nodal ARPES data. Consequently, this combination of experiment and theory provides compelling arguments that not only do strange metals represent a novel quantum critical *phase*, but also that their real-life properties can be described using holographic emergence principles.

[1] T. J. Reber, et al., Nature Communications10, 5737 (2019), 1509.01611.
[2] J. Zaanen, et al., Holographic Duality in Condensed Matter Physics(2015)
[3] S. S. Gubser and F. D. Rocha, Gravitation and Cosmology81, 1 (2010).

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Mr. Maximilian Holst

Effects of Symmetry and Topology on the Order Parameters and Edge Currents of 2D Tetragonal Superconductors

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We analyze the implication of consecutive symmetry reductions on the order parameters and edge currents of two-dimensional tetragonal superconductors. More specifically, we consider situations where the so-called key symmetries of Cooper pairing, inversion and time-reversal symmetry, are broken. For our discussion we employ both a symmetry-based Ginzburg-Landau analysis as well as microscopic self-consistency calculations within the Bogolyubov-de Gennes framework.
In this way we obtain important insights into the interplay between symmetry and topology. For example, in a system with Rashba spin-orbit coupling (inversion-symmetry breaking) and perpendicular Zeeman spin polarization (time-reversal-symmetry breaking), we find that spin/charge edge currents change smoothly across phase boundaries between trivial and helical/chiral superconducting phases, emphasizing the importance of symmetry over topology for the realization of edge currents in this system.

References

[1]. M. F. Holst, M. Sigrist, M. H. Fischer, arXiv:2108.12337 (2021).

Charge-based quantum fluctuations in cuprates

R. Arpaia[1,2], L. Martinelli[2], M. Moretti Sala[2], S. Caprara[3], A. Nag[4], N.B Brookes[5], P. Camisa[2], Q. Li[6], M. Garcia-Fernandez[4], K.-J. Zhou[4], E. Schierle[7], Y.Y. Peng[6], T. Bauch[1], C. Di Castro[3], M. Grilli[3], F. Lombardi[1], L. Braicovich[2,5], G. Ghiringhelli[2]

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The phase diagram of high temperature cuprate superconductors (HTS) is dominated by the strange metal region, whose origin has been associated since decades to a quantum phase transition occurring at a temperature T^* where the pseudogap opens. However, the evidence for the quantum critical point (QCP) at the doping p^*, and for its associated quantum critical fluctuations, still remains elusive. Moreover, several recent experiments are pointing out to the subordinal role pseudogap has in shaping up the strange metal region [1]. To shed light among the different possible scenarios, charge density fluctuations (CDF) can be used as a benchmark. These short-ranged, dynamical, modulations of charge, recently discovered in all the families of cuprate HTS [2,3], are indeed ubiquitous in the strange metal region and have been supposed to be responsible for the unconventional properties therein observed [4].

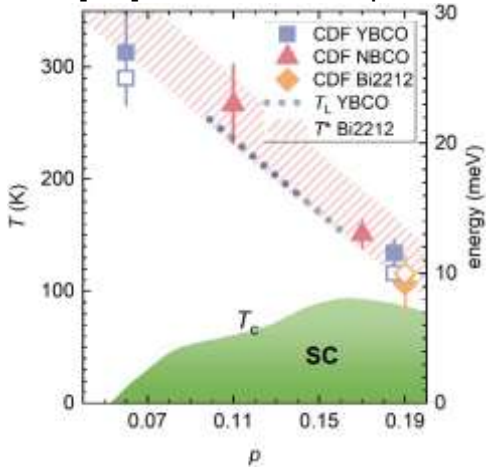

Fig. 1: *The CDF energies ω_0 determined from the RIXS spectra, and their corresponding T values, are presented vs p for different cuprate families. These values are compared with T* of Bi2212 and with T_L, where the strange metal ends, of YBCO [1].*

Using resonant x-ray scattering, we have explored CDF in two families of HTS, looking at the doping and temperature dependence of their intensity and energy in a broad range going from the strongly underdoped regime up to the putative QCP at $p^* \approx 0.19$ [5]. The CDF intensity is strongest at p^*, where the energy is rather small although finite, while it weakens at low doping, where the energy becomes as high as ~25 meV. The *T-p* line we can build from the energy values is in good quantitative agreement with the wedge separating in the phase diagram the strange metal from the underdoped region (see Fig.1). These observations suggest an intimate connection between CDF and the quantum fluctuations, associated to a QCP at p^*. Our results illustrate the leading role of charge order in driving the anomalous metallic state of cuprates.

References

[1]. E. Wahlberg, R. Arpaia *et al.*, Science **373**, 1506 (2021). [2].
R. Arpaia *et al*., Science **365**, 906 (2019).
[3]. R. Arpaia, G. Ghiringhelli, J. Phys. Soc. Jpn. **90**, 111005 (2021). [4].
G. Seibold, R. Arpaia *et al*., Commun. Phys. **4**, 7 (2021).
[5]. R. Arpaia *et al*., manuscript in preparation (2021).

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Andrew Yuan

Strain-induced Time Reversal Breaking and Half Quantum Vortices near a Putative Superconducting Tetra-critical Point in Sr_2RuO_4

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It has been shown that many seemingly contradictory experimental findings concerning the superconducting state in Sr_2RuO_4 can be accounted for as resulting from the existence of an assumed tetra-critical point at near ambient pressure at which $d_{x^2-y^2}$ and $g_{xy(x^2-y^2)}$ superconducting states are degenerate [1]. We perform both a Landau-Ginzburg and a microscopic mean-field analysis of the effect of spatially varying strain on such a state. In the presence of finite xy shear strain, the superconducting state consists of two possible symmetry-related time-reversal symmetry (TRS) preserving states: $d \pm g$. However, at domain walls between two such regions, TRS can be broken, resulting in a $d + ig$ state. More generally, we find that various natural patterns of spatially varying strain induce a rich variety of superconducting textures, including half-quantum fluxoids. These results may resolve some of the apparent inconsistencies between the theoretical proposal and various experimental observations, including the suggestive evidence of half-quantum vortices.

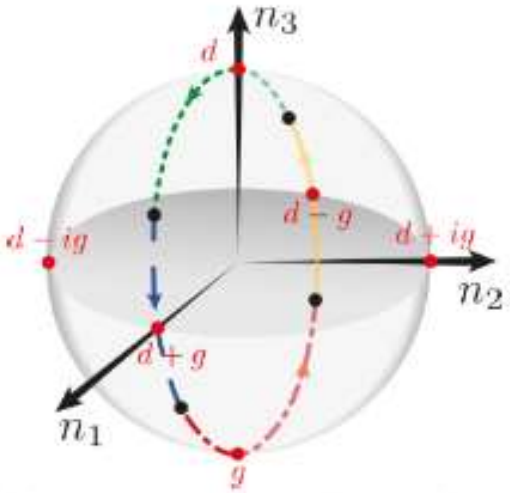

Fig. 1: A strain induced half quantum fluxoid. Trajectory of the superconducting order parameter along the Bloch sphere. TRS is preserved along the path.

References

[1]. S.A. Kivelson, A.C. Yuan, B.J. Ramshaw, and R. Thomale, "A proposal for reconciling diverse experiments on the superconducting state in Sr_2RuO_4," npj Quantum Materials **5** (2020)

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Maria Navarro Gastiasoro

Theory of Superconductivity Mediated by Rashba Coupling in Incipient Ferroelectrics

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Experimental evidence suggests that superconductivity in $SrTiO_3$ is mediated by a soft transverse ferroelectric mode which, according to conventional theories, has negligible coupling with electrons. A phenomenological Rashba type coupling has been proposed on symmetry arguments, but a microscopic derivation is lacking. Here we fill this gap and obtain a linear coupling directly from a minimal microscopic model of the electronic structure. We find that the effective electron-electron pairing interaction has a strong momentum dependence. This yields an unusual situation in which the leading s-wave channel is followed by a sub-leading p-wave state which shows a stronger pairing instability than the d-wave state. The bare Rashba coupling constant is estimated for the lowest band of doped $SrTiO_3$ with the aid of first-principles computations and found to be much larger than previously thought. We argue that although for a uniform system the BCS coupling λ is small, it can produce the right order of magnitude for T_c in the presence of structural inhomogeneities.

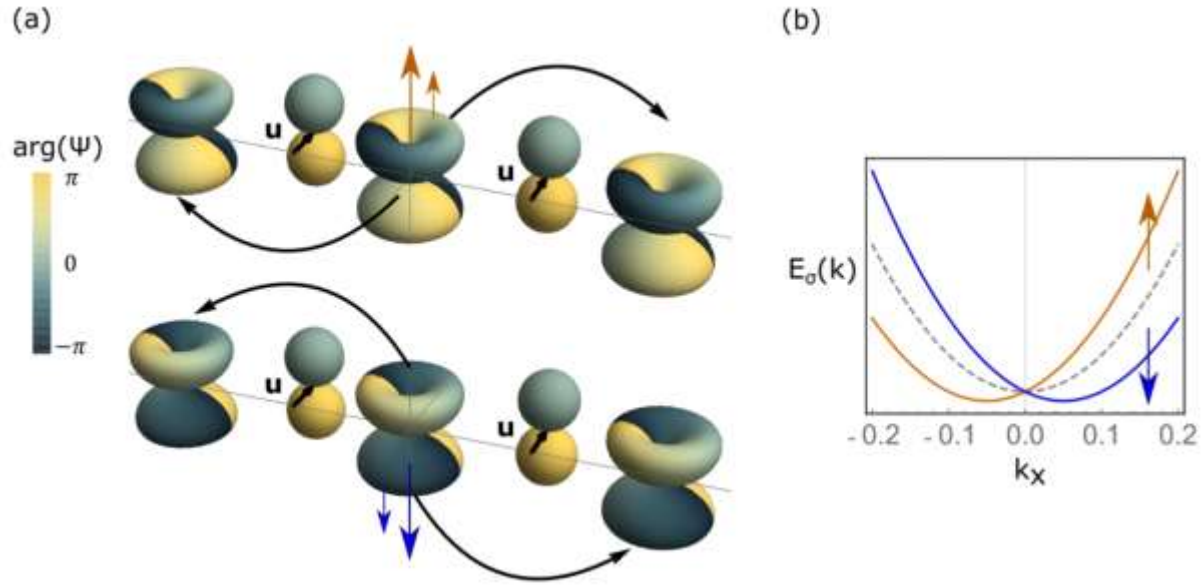

Fig. 1: *Rashba coupling of the spin-orbit coupling (SOC) bands |3/2,±3/2> induced by a finite polar displacement **u**, representing a frozen-phonon out of equilibrium. (a) The induced hopping (black curved arrows) changes sign along the bond and is pseudo-spin dependent. The orange and blue arrows show the polarization of the spin parallel to the angular momentum. Right movers and left movers have different energies as shown in (b), where the characteristic Rashba SOC band splitting is shown. The gray dashed line represents the doubly degenerate SOC bands when **u**=0.*

References

[1]. Maria N Gastiasoro, M. E. Temperini, P. Barone, J. Lorenzana, arXiv:2109.13207 (2021).

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Prof. Stephen Hayden

Charge Density Waves and Fermi-Surface Reconstruction in the Clean Overdoped Cuprate Superconductor $Tl_2Ba_2CuO_{6+\delta}$

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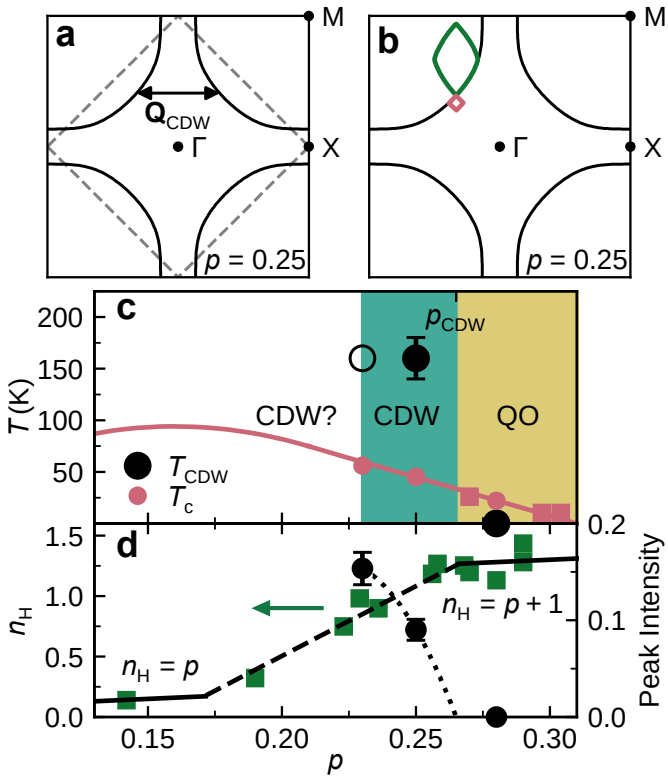
Hall effect and quantum oscillation measurements on high temperature cuprate superconductors show that underdoped compositions have a small Fermi surface pocket whereas when heavily overdoped, the pocket increases dramatically in size. The origin of this change in electronic structure has been unclear, but may be related to the high temperature superconductivity. We show [1] that the clean overdoped single-layer cuprate $Tl_2Ba_2CuO_{6+\delta}$ (Tl2201) displays CDW order with a remarkably long correlation length $\xi \approx 200$ Å which disappears above a hole concentration $p_{CDW} \approx 0.265$. We show that the evolution of the electronic properties of Tl2201 as the doping is lowered may be explained by a Fermi surface reconstruction which accompanies the emergence of the CDW below p_{CDW}. Our results demonstrate importance of CDW correlations in understanding the electronic properties of overdoped cuprates.**Fig. 1:** Charge density wave and Fermi surface reconstruction in Tl2201 (p=0.25). (a) Fermi surface of Tl2201. The dashed line is the antiferromagnetic Brillouin zone of the cuprates. (b) CDW order may cause a reconstruction yielding electron (red) and hole (green) pockets. (c) Phase diagram of overdoped Tl2201. CDW order is observed for doping $p<p_{CDW}\approx0.265$ (dark green region). High-frequency quantum oscillations are observed for p>0.27 (sand coloured region and red squares). CDW existence is undetermined in light green region. CDW onset temperatures T_{CDW} are shown by black circles, for p=0.23 the open circle represents an upper bound. Red line is superconducting T_c. (d) The high-field Hall number (green squares). Lines of $n_H = p$ and $n_H = p+1$ are marked, with connecting dashed line. CDW peak intensity for $T=T_c$ (black circles).



References

[1]. C. C. Tam et al., arXiv:2109.04279 (under review, Nature Comms.)

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Dr. José Lorenzana

What Could be the Superconducting Critical Temperature of Silver Fluoride Analogues of Cuprates?

J. Lorenzana[1], A. Grzelak[2], K. Koteras[2],T. Jaroń[2], J. Gawraczyński[2], N. Bachar[3], Ke-Jin Zhou[4], M. Derzsi[2,5], H. Su[6], D. Kurzydłowski[2,7], R. Piombo[1], P. Barone[8], M. N. Gastiasoro[1], Z. Mazej[9], G. Ghiringhelli[10], D. van der Marel[3], W. Grochala[2]

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We use density functional theory and exact diagonalization in small clusters to analyze different spectroscopies[1,2] in silver fluorides (neutrons, XPS, RIXS, optics). We find that AgF_2 is a charge-transfer insulator with strong analogies with parent cuprates but also some important differences. In particular, a strong buckling of AgF_2 planes substantially reduces the superexchange constant *J* to nearly 70% of a typical cuprate value and disfavors metallization. This "buckling problem" can be greatly diminished or solved by epitaxial engineering[3] of flat silver fluoride analogues in appropriate substrates. To estimate the maximum superconducting T_c attainable by doping, we first study systematically a strong correlation previously found in monolayer cuprates between T_c and *J* confirming its validity. Extrapolating to fluorides we reach the conclusion that T_c in monolayers can reach nearly 200 K.

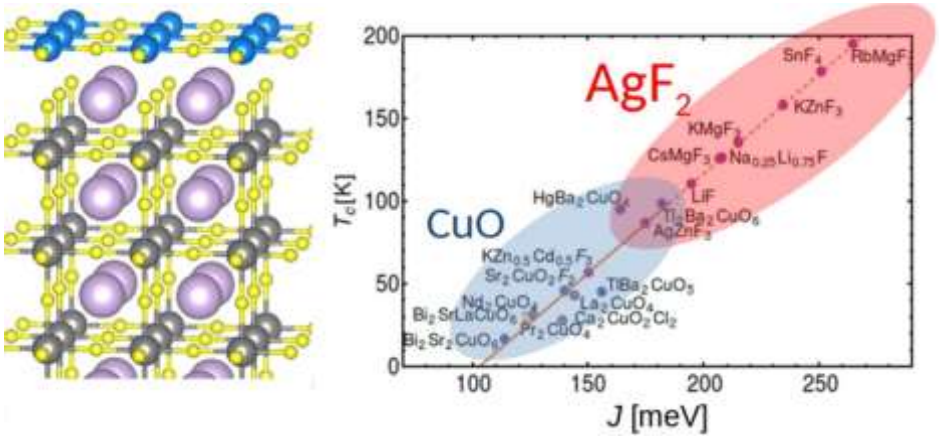

Fig. 1*: Left: AgF_2 monolayer in a $RbMgF_3$ substrate. Right: Correlation between maximum T_c of monolayer cuprates and J (blue region). The red region shows the extrapolated T_c of monolayer AgF_2 labeled by the substrate.*

References

[1] J. Gawraczyński, et al. PNAS **116**, 1495 (2019).

[2]N. Bachar, K. Koteras, J. Gawraczńyski, W. Trzcinski, J. Paszula, R. Piombo, P. Barone, Z. Mazej, G. Ghiringhelli, A. Nag, K.-J. Zhou, J. Lorenzana, D. van der Marel, and W. Grochala, Charge Transfer and dd Excitations in AgF_2, arXive:2105.08862 (2021).
[3] A. Grzelak, et al. Phys. Rev. Mater. **4**, 084405 (2020).

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Prof. Ziqiang Wang

Time-Reversal Symmetry Breaking Charge Order and Topological Pair Density Wave in Kagome Superconductors AV_3Sb_5 (A=K, Cs, Rb)

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The new family of vanadium-based kagome lattice compounds AV_3Sb_5 (A=K, Cs, Rb) are non-magnetic metals with a Z_2 nontrivial band structure [1, 2]. They undergo charge density wave (CDW) transitions at and superconducting transitions below. Recent STM studies reveal a highly unusual CDW state hinting at a triple-Q order of circulating orbital current and plaquette flux [3], which is supported by the large intrinsic anomalous Hall conductivity and the evidence for time-reversal symmetry breaking observed in muon spin rotation and optical Kerr rotation experiments. Between and, a rotational symmetry breaking order develops at a temperature coinciding with that of a unidirectional charge order [4]. At low temperatures, a primary pair density wave (PDW) was detected and found to be responsible for the observed pseudogap behavior above and the spatial modulations of the superconducting gap and coherence peak in the ground state [5], in striking analogy to the high-T_c cuprates. We discuss the implications of these and other remarkable findings in this family of materials. We argue that the essential part of the phenomenology can be captured by doped orbital Chern insulators with circulating orbital currents on the kagome lattice. We show that the emergent Chern Fermi pockets can give rise to the “mother” PDW state at the observed wave vectors [6]. We further demonstrate that the unique hexagonal symmetry allows an orbital-driven mechanism for intrinsic chiral topological PDW superconductors.

References

[1] B. R. Ortiz, et al., Phys. Rev. Mater. **3**, 094407 (2019).
[2] B. R. Ortiz, et al., Phys. Rev. Lett. **125**, 247002 (2020).
[3] Y.-X. Jiang, et al., Nat. Mater. **20**, 1353 (2021).
[4] H. Zhao, et al., Nature **599**, 216 (2021).
[5] H. Chen, et al., Nature **599**, 222 (2021).
[6] S. Zhou and Z. Wang, arXiv:2110.06266, (2021).

Kateryna Foyevtsova, Dr. George Sawatzky, Dr. Ilya Elfimov

Elusive Fermi surface of infinite-layer nickelates

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Understanding the electronic structure of infinite-layer nickelates (ILNs) is an important step in the studies of their superconductivity. One of the most extensively discussed features of the ILN electronic structure is the strongly dispersive electron pocket band at the A point in the Brillouin zone. Its presence distinguishes the ILNs from the formally iso-electronic cuprates and is believed to be responsible for the observed metallic behavior of the ILN parent compounds. Yet, despite its indisputable importance, the origin and consequences of the electron pocket band are still lacking a focused analysis. Also disturbing is the fact that little attention has been paid so far to the fate of the “self-doped” holes that are required to be present in the system by the principle of charge neutrality. Here, we use electronic structure calculations and the local density approximation + U method to elucidate the strikingly dissimilar and rather elusive nature of the self-doped electrons and holes in the ILN parent compounds and discuss their realistic Fermi surface. We argue that the electronic structure of the ILNs combines in a unique way features that are commonly found in Kondo systems, on one hand, and in electrides, on the other.

Carina Aiello Belvin

Exciton-Mediated Antiferromagnetic Conducting State in a van der Waals Correlated Insulator

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[2] Center for Correlated Electron Systems, Institute for Basic Science, Seoul, Korea
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Excitons in strongly correlated materials have recently attracted interest due to their unique coupling to spin and orbital degrees of freedom. The non-equilibrium driving of such dressed excitons provides a promising platform for realizing unconventional many-body phenomena and phases of matter not present in equilibrium. In this talk, I will present our work on the van der Waals correlated insulator $NiPS_3$ in which we photoexcite its newly discovered spin–orbit-entangled excitons arising from Zhang-Rice states. By monitoring the temporal and spectral evolution of the terahertz conductivity, we simultaneously observe the creation of mobile charge carriers via exciton dissociation and the generation of a long-wavelength antiferromagnetic coherent magnon. Together, these findings indicate the emergence of a transient conducting phase that preserves long-range antiferromagnetism, a state that cannot be reached in this material by simply tuning the temperature. More broadly, our results offer a path towards the optical manipulation and control of magnetism through excitons [1].

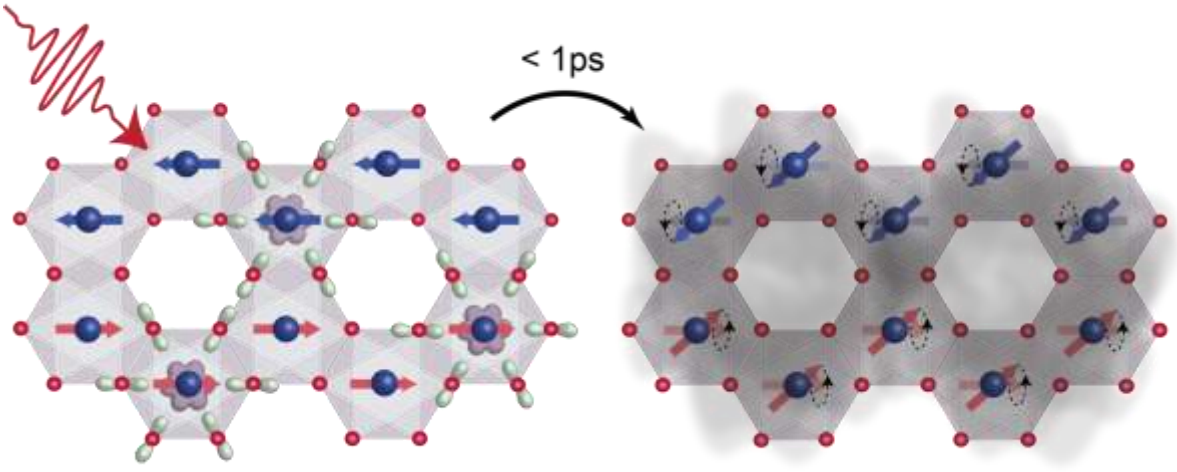

Fig. 1: *Cartoon of the photoinduced dynamics. A near-infrared pump pulse excites the spin–orbit-entangled excitons, whose wavefunctions are shown in purple and green (left panel). Through their coupling to the underlying antiferromagnetic order, the excitons launch a coherent spin precession (denoted by the circular motion of the red and blue arrows, right panel). Within 1 ps, the excitons also*

dissociate into itinerant carriers yielding a conducting state (gray shading) on top of the persisting long-range antiferromagnetic order.

References

[1]. C. A. Belvin *et al*., *Nat. Commun.* **12**, 4837 (2021).

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Prof. Jörg Fink

Scattering Rates of Quasi-Particles: from Fermi Liquids via Marginal Fermi Liquids to "Super-Planckian" Systems.

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The scattering rate of quasi-particles determines transport, thermal, and magnetic properties of metals. There are also indications, that e-e interactions, such as scattering by excitations of spin fluctuations, mediate superconductivity in unconventional superconductors.
We have studied the energy dependence of scattering rates in various metals: the nearly-free electron system Sodium, in cuprate superconductors, and in Fe-based superconductors. Sodium shows a perfect quadratic increase of the scattering rate as a function of energy: $\Gamma=\alpha E^n$, n=2. The α value does not support the often discussed importance of spin fluctuations in alkali metals.
The scattering rates of doped cuprates was studied by numerous groups. It can be described in terms of a marginal Fermi liquid: $\Gamma=\alpha E^n$, n=1. We think that the constant susceptibility, which is needed to describe this behavior, can be explained by intra-band excitations which also explain our EELS results on the collective excitations (plasmons).
In the electron-doped ferropnictides, a scattering rate close to a marginal Fermi liquid was derived. In the hole-doped ferropnictides, an exponent bigger than one (n~3) was observed for optimally doping [1-3]. This behavior was recently termed "super-Planckian". In a first approximation, the size of the exponent is linked to the superconducting transition temperature [2]. Recent ARPES studies of iron chalcogenides also showed a scattering rate, the energy dependence of which is beyond the Planckian bond.

The work was done in collaboration with P. Gegenwart, C. Meingast, F. Hardy, S. Wurmehl, Y. Nayak, E.D.L. Rienks, J. Bannies, R. Kurleto, B. Büchner ….

References

[1] J. Fink et al. Phys. Rev. B **99**, 245156 (2019).
[2] J. Fink et al. Phys. Rev. B **103**, 155119 (2021).
[3] M. Hemmida et al. Phys. Rev. B **103**, 195112 (2021).

Steve Dodge

Optical response of photoexcited insulating copper oxides

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We study the optical response to photoexcitation in three insulating cuprates, $YBa_2Cu_3O_6$, $Sr_2CuO_2Cl_2$, and La_2CuO_4, and develop a model for their response as a function of frequency and time. In earlier work, we showed that photoexcitation creates mobile carriers that soften the charge-transfer gap and decay on picosecond timescales [1,2]. Measurements as a function of time, fluence, and both pump and probe photon energies revealed that the photocarriers exhibit many-body recombination on femtosecond timescales, which we were able to describe with a simple kinetic model [2]. In the present work, we show that it is necessary to include electron-boson coupling to describe the spectral evolution with time. We find that the spectral response can be decomposed approximately into two components, which we assign to photocarriers and to the bosons given off as the carriers relax. The response depends primarily on the photocarrier density at early times, but as time evolves the bosonic contribution becomes stronger, with a relative amplitude that depends on the probe frequency. Our results offer new and more general insights into the evidence for photoinduced superconductivity.

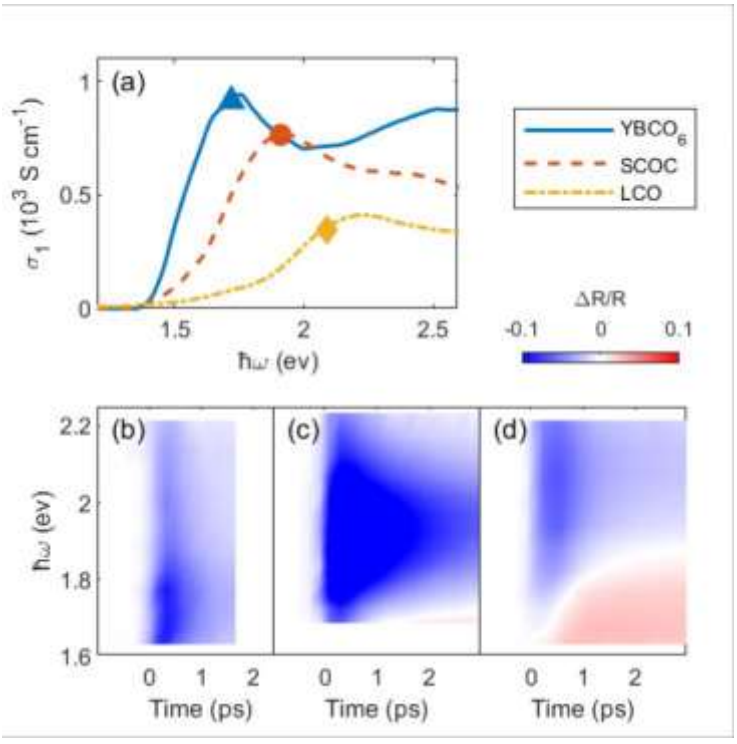

Fig. 1: *(a) Equilibrium optical conductivity of $YBa_2Cu_3O_6$ (YBCO6), $Sr_2CuO_2Cl_2$ (SCOC), and La_2CuO_4 (LCO), with the energy of the maximum $|\Delta R/R|$ from photoexcitation indicated by filled markers. Differential reflectivity of (b) $YBa_2Cu_3O_6$ (c) $Sr_2CuO_2Cl_2$ (d) La_2CuO_4 at a pump energy of 2.8 eV.*

References

[1]. J. C. Petersen et al., Phys. Rev. B **96**, 115133 (2017).
[2]. D. S. Sahota et al., Phys. Rev. Research **1**, 033214 (2019).

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Prof. Sumitendra Mazumdar

Valence Transition Theory for the Pressure-Induced Dimensionality Crossover in Superconducting $Sr_{14-x}Ca_xCu_{24}O_{41}$

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Pressure-induced superconductivity (SC) in the ladder compound $Sr_{14-x}Ca_xCu_{24}O_{41}$ is preceded by a 1D-to-2D dimensional crossover [1] that has never been theoretically understood. The resistivity along the interladder direction, which is incoherent at all temperatures at ambient pressure, is metallic at all temperatures under pressure of 4 GPa. Furthermore, the ratio of the resistivities along the ladder leg direction and along the interladder direction drops by a factor of 4 at 50 K under pressure [1]. This experiment already indicated that SC in $Sr_{14-x}Ca_xCu_{24}O_{41}$is a 2D effect unrelated to ladder-based theories of SC. This has been further confirmed in recent theoretical work by us in which we have shown that superconducting pair-pair correlations decay extremely rapidly in the multiband ladder containing both copper (Cu) and oxygen (O), precluding quasi-long range order [2].

We present here the theoretical explanation of the pressure-induced dimensionality crossover in $Sr_{14-x}Ca_xCu_{24}O_{41}$. We have performed highly accurate DMRG calculations of coupled multiband ladders, dimensionality effects in which are measured through computations of intra and interladder O-O bond orders (charge-transfers). The ratio of intraladder versus interladder bond orders is very large for realistic parameters and carrier densities, in agreement with the experimentally observed 1D behavior under ambient pressure [1]. We show that assumption of pressure-induced increase of carrier density fails to explain the dimensionality crossover. We then show that the recently proposed valence transition model [3], within which there occurs a current-driven discrete jump in Cu^{2+}-to-Cu^{1+} ionicity in cuprates, leading to negative charge-transfer gap and a very large increase in the number of charge carriers on the O-sites readily explains the dimensionality crossover. We argue that similar valence transition is behind the experimentally observed and unexplained very large doping-induced carrier densities in hole- [4] and electron-doped [5] layered cuprates. SC (but not magnetic behavior) emerges from the correlated 1/4-filled band of holes on O-sites within our theory.[3]

References

[1] T. Nagata et al., Phys. Rev. Lett. 81, 1090 (1998)
[2] J.-P. Song, S. Mazumdar and R. T. Clay, Phys. Rev. B 104, 104504 (2021)
[3] S. Mazumdar, Phys. Rev. B 98, 205153 (2018)
[4] S. Badoux et al., Nature volume 531, pages 210-214 (2016)
[5] R. L. Greene et al., Adv. Rev. Condens. Matter Phys 11 213 (2020)

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Prof. Floriana Lombardi

Restoring the strange metal phase in underdoped cuprated via suppression of Charge Density Wave

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The "strange metal" phase of High Critical Temperature Superconductors (HTS) is one of the most striking manifestations of the strong electron-electron correlation correlations in these materials. At optimal doping it manifests as a linear temperature dependence of the resistivity that persists to the lowest *T* when superconductivity is suppressed. This behavior is fundamentally different from that observed in more conventional metals, where a *T*-linear dependence of the resistivity is found, only at high temperatures, where phonon scattering dominates the transport. For underdoped cuprates this behavior is lost below the pseudogap temperature *T**, where Charge Density Waves (CDW) together with other intertwined local orders characterize the ground state. The association between the departure from the *T*-linear resistivity and the occurrence of the pseudogap phenomenon has long been speculated. However, there is no consensus on the physics at play and, more importantly, on the causality hierarchy among pseudogap, local orders, and strange metal phenomenology. To address this challenge we have tuned the ground state of underdoped the HTS by using the geometric modification of its unit cell under under the strong strain induced by the substrate. We show that the *T*-linear resistivity of highly strained, ultrathin and underdoped $YBa_2Cu_3O_{7-\delta}$ films is restored when the CDW amplitude, detected by Resonant Inelastic X-ray scattering, is suppressed [1]. This observation points towards an intimate connection between the onset of CDW and the departure from the strange metal behaviour in underdoped cuprates. Our results also illustrate the potential of using strain control to manipulate the ground state of quantum materials.

References

[1] E. Wahlberg,R. Arpaia, G. Seibold, E. Trabaldo, S. Caprara , U. Gran, L. Braichovich, G. Ghiringhelli , T. Bauch and F. Lombardi Science **373,** 1506 (2021)

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Dr. Christoph Meingast

Phonon softening, nematicity and charge density waves in $BaNi_2(As_{1-x}P_x)_2$

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$BaNi_2As_2$ undergoes a series of charge-ordering phase transition upon cooling, first from a tetragonal to an incommensurately charge-ordered orthorhombic phase and then to a commensurate triclinic phase [1,2]. The suppression of these phase transitions by either P-substitution of As, or by Sr-substitution of Ba leads to an increase of T_c up to about 3.5 K, which has been attributed to either soft phonon behavior [3] or B1g nematic fluctuations [4]. Here we study P-substituted $BaNi_2As_2$ using high-resolution thermal expansion, Young's modulus, heat capacity and transport measurements, from which a detailed phase diagram is obtained. Both the phonon softening (via a Grueneisen analysis) and the question of nematicity (via Young's modulus data) will be addressed. In addition, we examine the closely related Fe-substituted system, $Ba(Ni_{1-x}Fex)_2As_2$, which, although not superconducting down to 0.4 K, exhibits a novel second-order structural quantum critical point with a diverging low-temperature Grueneisen parameter.

References

[1] M. Merz, et al., Phys. Rev. B **104**, 184509 (2021). [2] S. Lee, et al., Phys. Rev. Lett. **122**, 147601 (2019). [3] K. Kudo, et al., Phys. Rev. Lett. **109**, 097002 (2012). [4] C. Eckberg et al., Nat. Phys. **16**, 346 (2020).

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Dr. Motoharu Kitatani

Calculation of the Phase Diagram of Nickelate Superconductors

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We have calculated the superconducting phase diagram of the recently discovered nickelate superconductors. First, we analyzed the multi-orbital system with a combination of density functional theory and dynamical mean field theory (DFT+DMFT). The results show that the system can be described by a one-band Hubbard model with an additional electron reservoir at least around the superconducting doping region. We then calculated the critical temperature of this simplest model by using the dynamical vertex approximation and obtained a Tc-dome structure centered around 20% Sr-doping [1], which is in good agreement with subsequent experiments. Within the present framework, the recent experimental results on the effect of strain and pressure can be reasonably understood as the change of tight-binding model parameters (i.e., hopping and the interaction strength). We further discuss palladates as a possible alternative to nickelates for optimizing these parameters and obtaining a higher-Tc in practice [2].

References

[1]. M. Kitatani, L. Si, O. Janson, R. Arita, Z. Zhong, and K. Held, npj Quantum Mater. **5**, 59 (2020)
[2]. M. Kitatani et al., in preparation.

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Dr. Marie-aude Méasson

Low-energy Collective Mode and Quantum Fluctuations in High-T_c Cuprates

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We unveil low-energy mode and quantum fluctuations, both of the same pure symmetry, in prototypical High-Tc cuprates determined by polarized Raman spectroscopy. We present their intriguing behavior over a large range of doping, from strongly under-doped up to optimal doping, as a function of temperature and in very high magnetic field up to 30 T.

The collective mode is strongly coupled to dissipative particle - hole excitations as evidenced by its very strong Fano-like shape enhancement as a function of increasing temperature or magnetic field. In addition, although measured above the superconducting transition, it presents a dome-like shape in the T-x phase diagram, with a complete collapse at optimal doping, and with a trend consistent with the preformed Cooper pairs scenario. The quantum fluctuations, as evidenced by a quasi- elastic (QE) mode, also follow the dome-shape tendency and surprisingly become less long-lived with decreasing temperature.

From the high magnetic field dependence of both the collective and QE modes – the enhanced Fano-shape without disappearance of the collective mode, the large decrease of the FWHM of the QE mode while the charge-density-wave simultaneously changes into a long-range 3D one, we show that both modes are promising fingerprints of the relationship between charge-density-wave and superconductivity and we discuss their nature.

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Mr. Leonardo Martinelli

Spin and orbital excitations beyond the nearest neighbor interactions: spinon pairs and dispersing *dd*s in infinite-layer $CaCuO_2$

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The building block of cuprate high Tc superconductors are CuO_2 planes where, in the absence of charge doping, the spin ½ sites interact via a huge antiferromagnetic exchange. The resulting ground state has $(x^2 - y^2)$ ferro-orbital symmetry and Néel antiferromagnetic order. The corresponding elementary excitations are commonly well described as local (non-dispersive) *dd* excitations and $\Delta S = 1$ magnons (plus multi-magnons), respectively. However longer range interactions cannot always be neglected. We have performed Resonant Inelastic X-ray Scattering (RIXS) measurements on the infinite-layer compound $CaCuO_2$, where the absence of apical oxygens leads to larger than usual hopping integrals *t* and *t'*, superexchange *J*, and ring-exchange J_c [1]. In the orbital spectrum we find clear sign of dispersive orbital excitations (Fig. 1, top panel), and the lifting of the xz/yz degeneracy, which indicates a partially delocalized nature, reminiscent of what happens in 1-dimensional spin chains [2]. Even more interestingly, the magnetic spectral region shows clear anomalies close to (1/2,0), where the spectral weight of the magnon peak decreases and another higher-energy excitation takes the majority of the spectral weight (bottom panel). Through an innovative combination of polarization-resolved, ultra-high resolution (BW=26meV) and detuning RIXS measurements, we establish that the anomalous feature indeed has $\Delta S = 1$ character, and that its properties are more consistent with a spinon-pairs continuum than with multi-magnons. We therefore find clear signatures of exotic physics beyond the canonical ferro-orbital, AF Néel ground state, driven by extremely large hopping *t* [3].

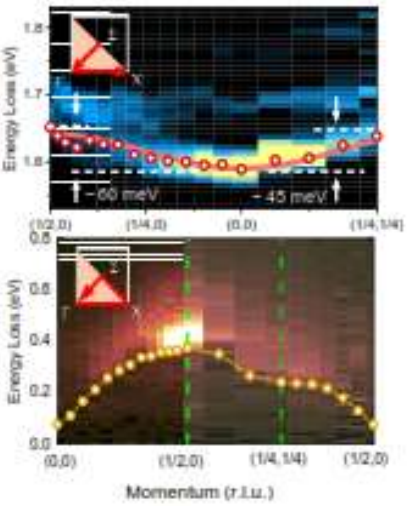

Fig. 1: *Intensity of the xy excitation (top) and of the continuum of spinon pairs (bottom) as a function of momentum transfer along high symmetry directions reported in the insets. Dots represent the energy of the xy orbital (top) and magnon (bottom).*

References

[1]. Peng, Y. Y., et al. *Nat. Phys.* **13** (2017): 1201-1206.
[2]. Schlappa, J., et al., *Nature* **485** (2012): 82-85.
[3] L. Martinelli, et al., arXiv:2110.06666 (2021).

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Prof. Anton Andreev

Giant magnetoconductivity in non-centrosymmetric superconductors

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We discuss a novel physical mechanism which gives rise to a giant magnetoconductivity in non-centrosymmetric superconducting films. This mechanism is caused by a combination of spin-orbit interaction and inversion symmetry breaking in the system, and arises in the presence of an in-plane magnetic field $\mathbf{H}_{\parallel}$. It produces a contribution to the conductivity, which displays a strong dependence on the angle between the electric field **E** and $\mathbf{H}_{\parallel}$, and is proportional to the inelastic relaxation time of quasiparticles. Since in typical situations the latter is much larger than the elastic one this contribution can be much larger than the conventional conductivity thus leading to giant microwave absorption.

References

[1]. M. Smith, A. V. Andreev, B. Z. Spivak, Phys. Rev. B **104**, L220504 (2021).
[2] M. Smith, A. V. Andreev, and B. Z. Spivak, Ann. Phys. **417**, 168105 (2020).
[3] M. Smith, A. V. Andreev, and B. Z. Spivak, Phys. Rev. B **101**, 134508 (2020).
[4] M. Smith, A. V. Andreev, M. V. Feigel'man, and B. Z. Spivak, Phys. Rev. B **102**, 180507(R) (2020).

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Prof. Götz Seibold

Low energy electrodynamics of strongly disordered superconductors

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In the last decades the failure of the BCS paradigm of superconductivity in several correlated materials led to a profound modification of the description of the superconducting phenomenon itself. A case in point is the occurrence of Cooper pairing and phase coherence at distinct temperatures, associated respectively with the appearance of a single-particle gap and a non-zero superfluid stiffness. This particular behavior is observed in several materials, which range from high-temperature cuprate superconductors to strongly disordered films of conventional superconductors. For the latter system scanning tunneling microscopy measurements have revealed that the superconducting state becomes inhomogeneous, segregating into domains of large and suppressed superconducting order parameter. In this contribution we will discuss the static and dynamical response of such systems based on studies of the attractive Hubbard model with strong on-site disorder and by including fluctuations beyond the Bogoljubov-de Gennes approach. It turns out that paramagnetic processes mediate the response of all collective modes, with a substantial contribution of charge/phase fluctuations [1,2,3]. In particular, we show that for strongly disordered superconductors phase modes acquire a dipole moment and appear as a subgap spectral feature in the optical conductivity which even survives long-range Coulomb interactions. The same processes turn out to dominate also the third-order current at strong disorder [4]. In this regard we show that disorder strongly influences the polarization dependence of the non-linear response, with a marked difference between the homogenous and the disordered case. Our results are particularly relevant for recent experiments in cuprates, whose band structure is in a first approximation reproduced by our lattice model.

References

[1]. G. Seibold *et al.*, Phys. Rev. B **92**, 064512 (2015).
[2]. T. Cea *et al.*, Phys. Rev. B **89**, 174506 (2014).
[3]. G. Seibold *et al.*, Phys. Rev. Lett. **108**, 207004 (2012).
[4]. G. Seibold et al., Phys. Rev. B **103**, 014512 (2021).

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Dr. Jonathan Buhot

Superconductivity in H3S Bulk and in YHx Films at Very High Pressures

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The quest for room temperature superconductivity has always been one of the most intense topics in condensed matter physics. Boosted in the eighties with the discovery of cuprates superconductors above liquid nitrogen temperature (77K), it has moved a step forward in 2015 with the synthesis of sulfur hydride H3S and its superconducting critical temperature of about 200 K at a high pressure of 155 GPa [1]. This cornerstone discovery has led to the high-pressure synthesis of other superhydrides such as LaH10 [2], YH6 [3] and YH9 [4] exhibiting superconductivity close to room temperature and to the synthesis of a carbonaceous sulphur hydride compound showing signs of superconductivity at room-temperature [5]. Spectroscopic evidences for the superconducting state in these new superhydride compounds are limited due to the megabars pressures required, but remain highly desirable to understand the nature of their superconductivity and help the search for new materials with critical temperature at lower pressures.
We report successful synthesis of high-temperature superconducting H3S at 155 GPa from elemental sulphur and ammonia borane (NH3BH3) as a hydrogen donor. We clearly identify the known H3S superconducting phase (Im-3m) by X-ray diffraction and the resistivity measurement shows a sharp drop at Tc = 197K. Furthermore, by using
Raman spectroscopy, which is a well-known technique for probing lattice dynamics
and also electronic excitations such as superconducting gaps [6], we observe a broad excitation at about 750 cm-1 (~ 90 meV) only within the superconducting phase of H3S, i. e. for $T < 197K$. We discuss the possible relation of this excitation with the quasiparticle peak usually observed at twice the energy of the superconducting gap [7] and the implications on the mechanism of superconductivity in H3S.
Moreover, finding new routes that facilitate the synthesis of new hydrides superconductors is crucial. Here, we report the use of deposition techniques to prepare hydrides superconductors films of YHx [8]. We will briefly present XRD, R(T, B), Hc2(T) and discuss remaining challenges in sample synthesis.

References
[1]. A. P. Drozdov, et al., Nature 525, 73 (2015). [2]. A. P. Drozdov, et al., Nature 569, 528 (2019). [3]. I. A. Troyan et al., Advanced Materials 33, 2006832 (2021). [4]. P. P. Kong et al., Nature Communications 12, 5075 (2021). [5]. E. Snider et al., Nature 586, 373 (2020).
[6]. T. P. Deveraux and R. Hackl, Reviews Modern Physics 79, 175 (2007). [7]. G. Blumberg et al., Physica C 456, 75 (2007).
[8]. J. Buhot et al., Physical Review B 102, 104508 (2020).

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Dr. Alexander Boris

Optical spectral weight across the strange-metal regime in highly overdoped $La_{2-x}Ca_xCuO_4$ thin films

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We have used atomic layer-by-layer oxide molecular beam epitaxy to grow epitaxial thin films of $La_{2-x}Ca_xCuO_4$ with x up to 0.5, greatly exceeding the solubility limit of Ca in bulk systems, and characterized their doping levels through measurements of the optical conductivity [1]. The films up to the highest doping levels are superconducting with T_c of 15 to 20 K. Our approach opens up a previously inaccessible regime of the phase diagram to experimental investigation. In particular, we explored the doping - dependent optical spectral weight (SW) of $La_{2-x}Ca_xCuO_4$ over an exceptionally wide range across the critical doping $x_c \approx 0.2$. In the underdoped regime, the SW transfer is dictated by dominant planar Cu-3$d_{x^2-y^2}$ and O-2$p_{x,y}$ orbital effects. In the overdoped regime, the plasma frequency remains unchanged, and the hybridized Cu-3$d_{3z^2-r^2}$ and apical O-2p_z nonplanar orbitals start to contribute to the SW transfer. Our results may explain the observed two charge sectors in the cuprate strange-metal region [2].

References

[1]. G. Kim, *et al.*, PNAS **118**, e2106170118 (2021).
[2]. J. Ayres *et al.*, Nature **595**, 661 (2021).

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Satoshi Ejima

Photoinduced η-pairing in pumped Mott insulators

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Optical pumping is not only an excellent tool to investigate complex many-body systems but also allows the creation of new phases of quantum matter with tunable properties. Inducing superconductivity by light pulses in low-dimensional materials with strong electronic correlations is certainly one of the most fascinating options in this regard. Here, we numerically prove photoinduced superconducting-like η-pairing states in a half-filled fermionic Hubbard chain at both zero and finite temperature. The result, obtained by combining the matrix-product-state based infinite time-evolving block decimation technique and the purification method, applies to the thermodynamic limit. Exciting the Mott insulator by a laser electric field docked on via the Peierls phase, we track the time evolution of the system and determine the optimal parameter set for which the nonlocal part of the η-pair-correlation function becomes dominant [1]. For such a pump, we explore the possibility of quasi-long-range order. In the high-laser-frequency strong-Coulomb-coupling regime, we find a remnant enhancement of the Brillouin-zone boundary pair-correlation function. By contrast, the spin dynamic structure factor loses spectral weight in the whole momentum space, reflecting the suppression of antiferromagnetic correlations due to the buildup of η-pairing. Clear signatures of the photoinduced Mott-insulator to metal phase transition are also recorded for the time-dependent photoemission spectra and dynamic charge structure factors [2].

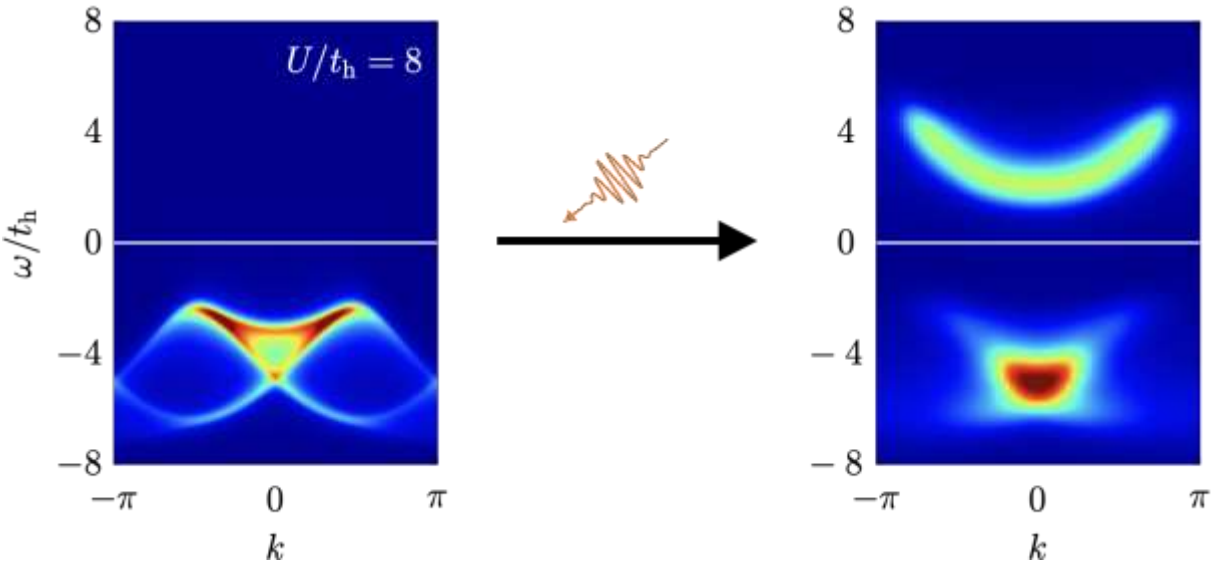

Fig. 1: *Photoemission spectra of the Mott insulator before (left) and after (right) pump irradiation [2].*

References

[1]. S. Ejima, T. Kaneko, F. Lange, S. Yunoki and H. Fehske, Phys. Rev. Res. **2**, 032008(R) (2020).
[2]. S. Ejima, F. Lange and H. Fehske, arXiv:2110.08574

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Prof. Richard Greene

Strange metal transport and violation of the conjectured Planckian scattering rate limit in electron-doped cuprates

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I will discuss recent transport studies on thin films of the electron-doped cuprate system La2-xCexCuO4 that exhibit strange metal transport in the normal state down to 35 mK. These results strongly suggest that the high-Tc superconductivity emerges from this strange metal normal state. The strange metal behavior is manifested as a linear-in-T resistivity from 35 mK to 20K and a ~T^2 resistivity from 50K to 400K over a range of doping above and below a Fermi surface reconstruction at x = 0.14 [1-2]. Other indications of strange metal behavior include an anomalous low temperature linear-in-H magnetoresistance and an anomalous low temperature lnT thermopower [3-5] over the same range of doping. These behaviors are expected at a quantum critical point, but here they are found over a rather extended doping range. At the present time these results have not been explained and they represent a challenge to the theory of the cuprates. Recently we studied our electron-doped cuprate films via a combination of dc conductivity and optical conductivity [6]. From this study we conclude that the electron scattering rate far exceeds the conjectured Planckian bound on inelastic scattering at temperatures above 20K. This suggests that recent highly publicized claims of a Planckian bound on transport in solids are not universal and that the temperature dependence of the normal state resistivity of the cuprates remains an unexplained mystery.

References

[1]. T. Sarkar et al., Phys. Rev. B 103, 224501 (2021)
[2]. T. Sarkar et al., Phys. Rev. B 98, 224503 (2018)
[3]. R. L. Greene et al., Ann Rev Cond. Matt. Phys. 11, 213 (2020)
[4]. T. Sarkar et al., Sci. Adv. 5, eeav6753 (2019)
[5]. P. R. Mandal et. al., PNAS 116, 5991 (2019)
[6]. N. P. Poniatowski et al., arXiv:2109.00513 (2021), to be published in PRB

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Mr. Toshiya Ikenobe

Possible Surface Superconductivity in the Nodal-Line Semimetal NaAlSi

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NaAlSi crystallizes in an anti-PbFCl-type layered structure[1)] and exhibits superconductivity below T_c = 6.8 K.[2,7)] The superconductivity seemed to be of the conventional *s*-wave type based on phonon-mediated Cooper pairing.[3-6)] However, very recent bulk measurements using single crystals of NaAlSi showed the possibility of a complex superconducting gap.[7)] Interestingly, electronic state calculations showed that NaAlSi is a nodal-line semimetal.[5,8,9)] Nontrivial topological surface states were predicted in the calculations; a drumhead band at around the point in the (0 0 1) surface and a flat band along the line in the (1 0 0) surface.[9)]

We studied the resistive transitions under magnetic fields using plate-like single crystals of NaAlSi such as shown in Fig. 1. A significant reduction in resistivity was observed at a pre-transitional region (B_{c2}^{on}–B^*) above the bulk superconducting transition at B_{c2}^{off}– B_{c2}^{on} only in the case that the magnetic field was perpendicular to the plane, not parallel to the plane (Fig. 1). No anomaly was observed at T^*(B^*) in the specific heat measurement, suggesting the existence of a fractional superconductivity different from the bulk superconductivity. In addition, the thickness dependence of the behavior in the pre-transition region suggests that a fractional superconductivity occurs at the side surfaces of crystal, although the details have not yet been clarified. Meanwhile, the field dependence of the resistivity on the magnetic field parallel to the plate shows a sharp superconducting transition (Fig. 1), indicating that there is a field-angle dependence in resistive transition. In order to understand the origin of the fractional superconductivity, we measured the field dependence of the superconducting transition in electrical resistivity as a function of the magnetic field angle. We show that the fractional superconductivity likely occurs at the side surface of crystal, even when the bulk superconductivity is suppressed by magnetic field.

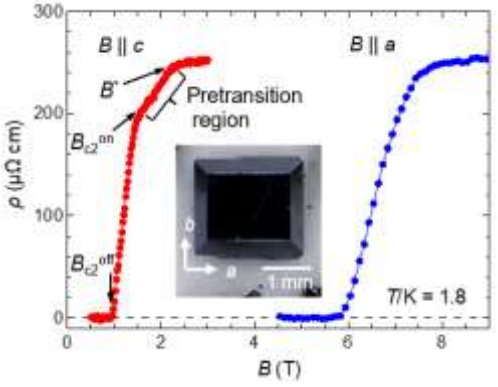

Fig. 1: *Magnetic field dependence of the resistivity of a single crystal NaAlSi at 1.8 K [7]. The red and blue curves are for B || c and a, respectively.*

References

[1]. W. Westerhaus et al., Z. Naturforsch. B 34, 352 (1979).
[2]. S. Kuroiwa et al., Physica C 466, 11 (2007).
[3]. L. Schoop et al., Phys. Rev. B 86, 174522 (2012).
[4]. H. M. Tütüncü et al., Philos. Mag. 96, 1006 (2016).

[5]. L. Muechler et al., APL Materials 7, 121103 (2019).
[6]. H. Y. Wu et al., Phil. Mag. Lett. 99, 29 (2019).
[7]. T. Yamada et al., J. Phys. Soc. Jpn. 90, 034710 (2021).
[8]. L. Jin et al., J. Mater. Chem. C 7, 10694 (2019).
[9]. X. Yi et al., J. Mater. Chem. C 7, 15375 (2019).

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Dr. Toni Helm

Angle-dependent magnetotransport and Hall-effect studies around the field-induced reentrant superconducting phase of UTe_2

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The potential spin-triplet superconductor UTe_2 has attracted a lot of attention due to its recently discovered superconducting ground state that emerges below 1.6 K [1,2]. The material is a highly anisotropic paramagnet that exhibits a metamagnetic transition above 35 T [3]. In addition, field- and pressure-induced superconductivity has been demonstrated adding to its complexity [4,5]. These are only a few of the most recent exciting findings for this material leaving many open questions, e.g., about the role of magnetism in the establishment of its superconducting ground state.

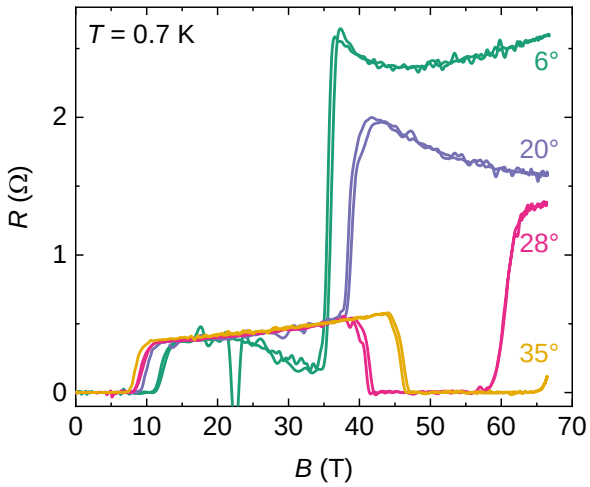

Fig. 1: *Magnetoresistance of UTe_2 recorded in a 70 T pulse magnet system at 0.7 K for various angles in the bc pane, where 0° denotes B || b [6].*

We investigated its magnetoresistivity and Hall-effect response in pulsed magnetic field up to 68 T for FIB-microfabricated devices. Our findings confirm the existence of the high-field reentrant superconducting phase for a tilt angle around θ = 30° off the *b* axis at fields above 40 T pinned to the metamagnetic transition. We determined the upper critical field to H_{c2} at T = 0.7 K. Our analysis of H_{c2}(T) indicates unconventional superconductivity. Furthermore, we show that the high-field Hall coefficient, and hence the charge carrier distribution near the Fermi level, experiences drastic field-induced changes.

References

[1]. S. Ran et al., Science 365, 684 (2019).
[2]. D. Aoki et al., J. Phys. Soc. Jpn. **88**, 043702 (2019).
[3]. Q. Niu et al., Phys. Rev. Res **2**, 033179 (2020).
[4]. D. Aoki et al., J. Phys. Soc. Jpn. 90, 074705 (2021).
[5] S. Ran et al., Nat. Phys.**15**, 1250-1254 (2019)
[6]. T. Helm et al., *unpublished* (2021)

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Mr. Shahar Simon

Thickness-Dependent Tunneling Spectra of 2H-TaS_2

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Transition metal dichalcogenide (TMD) superconductors have attracted much attention, in part due to the relative ease with which thin flakes can be mechanically exfoliated, and due to their strong Ising spin-orbit coupling (ISOC) and expected unconventional electron pairing and topological states, making them a focus of interest in recent years.
2H-TaS_2 is a superconducting TMD with critical temperature T_c=800mK in bulk flakes, and greatly enhanced T_c in thinner samples. This is in stark contrast to the extensively studied TMD superconductor 2H-$NbSe_2$ which displays the opposite trend.
We measure the tunneling spectra of 2H-TaS_2 flakes of various thicknesses ranging from bulk to monolayer by fabricating van der Waals (vdW) tunnel junction heterostructures using mechanical exfoliation and dry transfer. The observed tunneling spectra cannot be fitted with a simple BCS model, and the superconducting gap increases from in bulk samples to in our thinnest samples.
We measure the spectra in different temperatures and magnetic fields in in-plane and out-of-plane orientations, revealing hints of two-band superconductivity, anisotropy of the order parameter and Ising protection of superconductivity up to a field of 8.5T in-plane in thin samples.
These measurements are the first detailed mapping of the thickness dependence of the spectrum of 2H-TaS_2 and may serve as the first step in its integration into the arsenal of vdW materials used in the fabrication of further, potentially more complicated nano-devices.

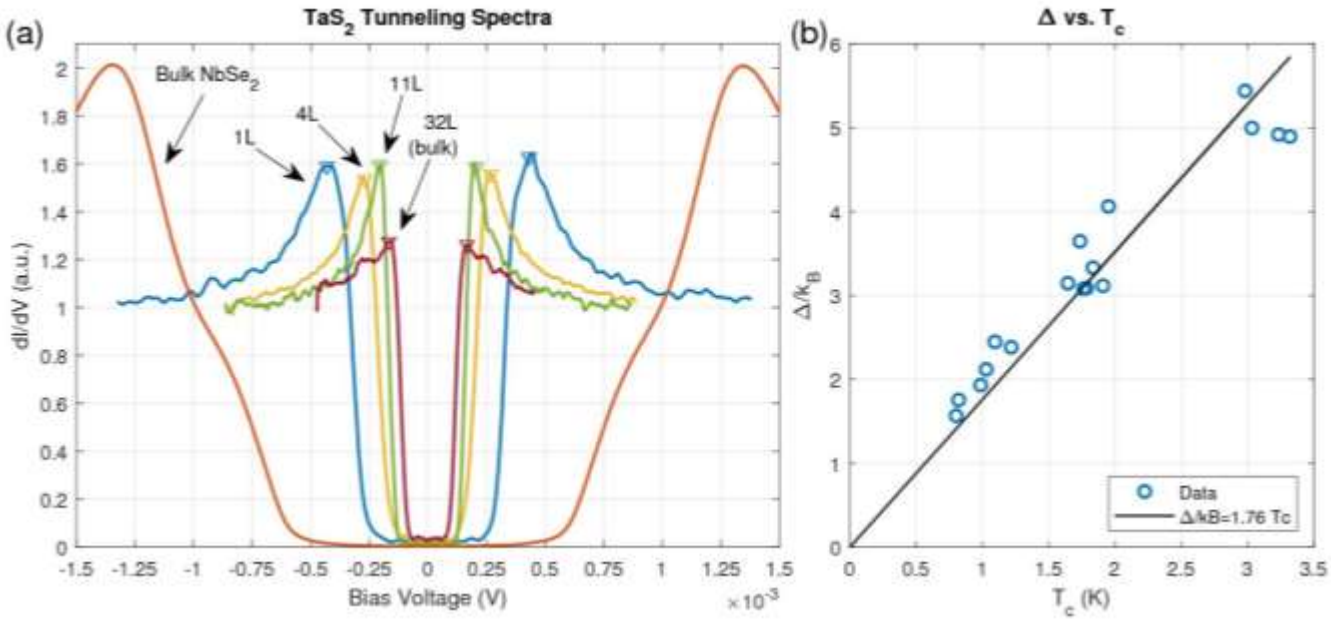

Fig. 1: *(a) Tunneling spectra of TaS_2 flakes of varying thicknesses (indicated in number of layers). Bulk 2H-$NbSe_2$ spectrum (indicated, red) plotted for comparison. (b) Observed superconducting gap vs. measured critical temperature of all devices measured. BCS linear relation plotted alongside.*

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Prof. Yoram Dagan, Itai Silber, Omer Green, Haim Beidenkopf, Amit Kanigel

Two-fold Symmetric Superconductivity in 4Hb-TaS_2 Induced by 1D Charge Order

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TaS_2 in its 4Hb polytype comprises of alternatingly stacked layers of 1H and 1T. Its superconducting state appears at an order of magnitude higher temperature comparing to the 1H TaS_2. Signatures of time reversal symmetry breaking appearing right at the superconducting transition temperature have been recently reported [1].
Here we report extensive transport measurements suggesting that a two-fold order is formed below the commensurate charge density wave transition temperature, 315K. These findings are consistent with scanning tunneling spectroscopy observing modulations of the density of states with a stripe-like features aligned with a crystal axis. Surprisingly, the superconducting state has the same symmetry with the weakest superconducting state formed along a particular crystal axis.
While specific heat measurements suggest that the amplitude of the order parameter is roughly constant around the Fermi contour, the phase of the order parameter can vary with momentum direction. We discuss various scenarios for the anomalous two-fold symmetry relating the charge density wave and the superconducting order parameter.

References

[1]. A. Ribak, R. M. Skif, M. Mograbi, P. K. Rout, M. H. Fischer, J. Ruhman, K. Chashka, Y. Dagan, and A. Kanigel, Sci. Adv. 6, 9480 (2020).

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Dr. Michal Šindler

Vortex Mass in YBaCuO Observed by Far-infrared Magnetic Circular Dichroism

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The resonance of far-infrared (THz) light with cyclotron motion of vortices enables us to estimate their effective mass. We present an experimental method of observing the magnetic circular dichroism in transmission of thin superconducting films threaded by Abrikosov vortices. We measure the magneto-transmitance of nearly optimally doped $YBa_2Cu_3O_{7-\delta}$ thin film using right (+) and left (-) handed circularly polarised submillimeter waves. Our results confirm the dominant role of quasiparticle states in the vortex core [1] and yield the diagonal fluxon mass of 2.2 x 10^8 electron masses per centimeter at 45 K and zero-frequency limit, and even larger off-diagonal mass of 4.9 x 10^8 m_e/cm [2].

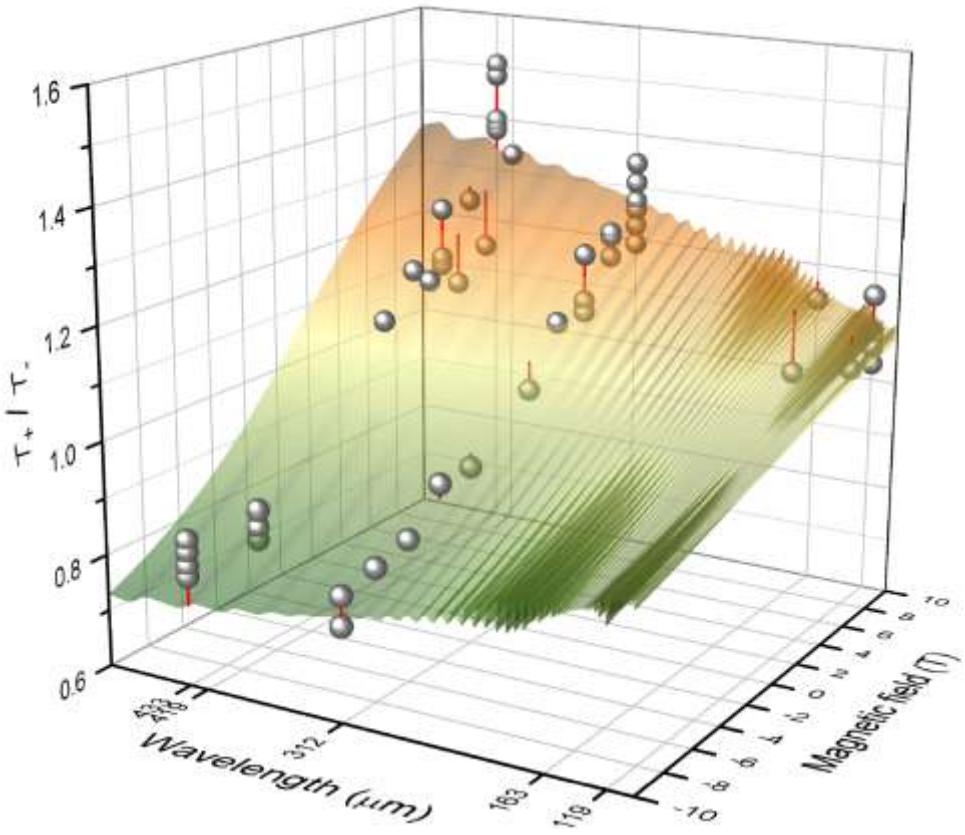

Fig. 1: *Magneto-transmittance ratio T+/T− for the laser lines 119, 163, 312, 419, and 433 μm [2]. The theoretical prediction following Kopnin-Vinokur theory [1] (colored surface) with no free fitting parameter is compared with experimental values (spheres) observed at a temperature of 45 K*

References

[1]. N. Kopnin, and V. M. Vinokur, Phys. Rev. Lett. 81, 3952 (1988).
[2]. R. Tesař, M. Šindler, C. Kadlec, P. Lipavský, L. Skrbek, and J. Koláček, Sci. Rep. **11,** 21708 (2021).

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Mr. Takemi Kato

Three-Dimensional Nature of Charge-Density Wave in Kagome Superconductor KV_3Sb_5 Studied by ARPES

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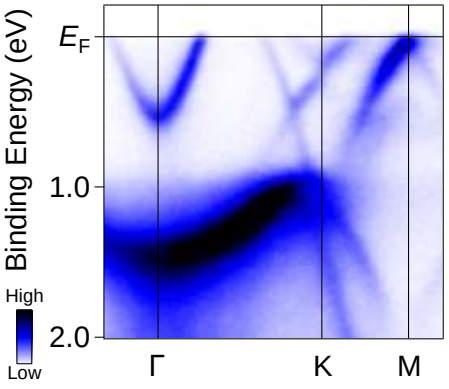
Kagome lattice which consists of a two-dimensional network of corner-sharing triangles provides an excellent platform for exploring new quantum phenomena arising from electronic correlations and non-trivial band topology. Recently, a family of AV_3Sb_5 (AVS: A = K, Rb, Cs) has been discovered to be a novel kagome superconductor with superconducting transition temperature T_c of 0.92-2.5 K [1-3]. In addition, AVS shows charge-density wave (CDW) below T_{CDW} = 78-103 K, and attracts much attention because of the possible unconventional nature of CDW and its interplay with superconductivity and non-trivial topology. On the other hand, the electronic states relevant to the CDW formation are still under intensive debate and the mechanism of CDW and superconductivity is still far from being established.

In this study, we have investigated the three-dimensional electronic structure of KV_3Sb_5 by photon-energy-tunable angle-resolved photoemission spectroscopy (ARPES) [4] and established the multi-orbital nature of the valence band structure in KV_3Sb_5 [Fig. 1]. Our high-resolution measurements also revealed a drastic electronic reconstruction and an energy gap opening triggered by the CDW transition. We will also report the CDW-gap anisotropy in the three-dimensional momentum space and discuss the mechanism of CDW.



References

[1] B. R. Ortiz *et al*., Phys. Rev. Mater. **3**, 094407 (2019). [2] B. R. Ortiz *et al*., Phys. Rev. Mater. **5**, 034801 (2021). [3] B. R. Ortiz *et al*., Phys. Rev. Lett. **125**, 247002 (2020). [4] T. Kato *et al*., *submitted*.

Fig. 1: *ARPES intensity plot along the ΓKM cut for KV_3Sb_5 measured with hv = 114 eV at T = 120 K.*

Vanishing nematic order beyond the pseudogap phase in overdoped cuprate superconductors

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Understanding the character of the enigmatic pseudogap phase is a fundamental problem in the physics of the cuprate superconductors. Key to this problem is identifying what types of order, if any, are associated with pseudogap. Advances in experimental techniques repeatedly hint at a complex interplay between different electronic phases: charge density wave (CDW) order, superconductivity, magnetism, nematicity having very similar energy and temperature scales. However, their relationship to the pseudogap remains unclear.

In this talk, using resonant x-ray scattering [1] we will establish that electronic nematicity—a rotational symmetry breaking of the electronic structure—is linked to the onset of the pseudogap phase in a canonical La-based cuprate. We will show the vanishing of electronic nematic order, either by raising the temperature through the onset of the pseudogap phase or by increasing hole doping through the pseudogap critical point (see Fig. 1). Our findings, reported in Ref. [2], anticipate that electronic nematicity may play a larger role in understanding the cuprate phase diagram than previously recognized, possibly having a crucial role in the phenomenology of the pseudogap phase.

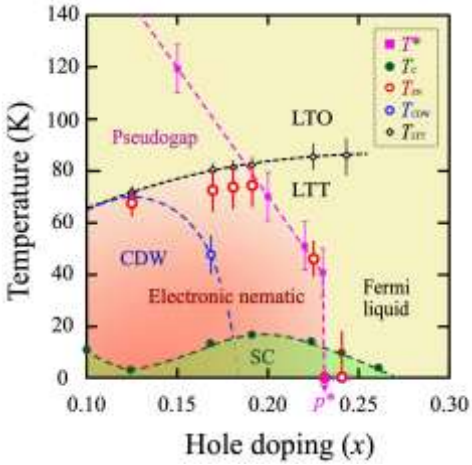

Fig. 1. Temperature-doping phase diagram of Nd-LSCO. *We measured 6 single crystal samples at different hole doping between x = 0.125 and 0.24. The red circles mark the onset of the electronic nematic order, T_{EN}. The structural phase transition from the LTO to LTT phase, T_{LTT} (black diamonds), the onset temperature of CDW order, T_{CDW} (blue circles). The pseudogap onset temperature, T* (purple squares) has been reported in Ref. (3). The quantum critical point at p* ~ 0.23 has been identified in Ref. (4). The superconducting (SC) transition temperature, T_C (green circles) has been reported in Ref. (5) on same set of samples. We find evidence for a considerable decrease in electronic nematicity beyond the pseudogap phase, either by raising the temperature through T* or increasing doping through p*.*

References

[1]. A. J. Achkar, […], D. G. Hawthorn, *Science* **351**, 576 (2016).
[2]. N. K. Gupta, […], D. G. Hawthorn, *PNAS* **118** (34), e2106881118 (2021).
[3]. C. Collignon, […], L. Taillefer, *Phys. Rev. B* **95**, 224517 (2017).
[4]. B. Michon, […], T. Klein, *Nature* **567**, 218–222 (2019).
[5]. M. Dragomir, […], B. D. Gaulin, *Phys. Rev. Mater.* **4**, 114801 (2020).

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Prof. Stefan Kaiser

Higgs spectroscopy and transient nonlinear THz response in high Tc superconductors

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The Higgs mode of a superconductor is a collective excitation of the amplitude of the superconducting order parameter [1,2,3]. In recent experiments, using a phase resolved THz-THG scheme, we have shown a coupling of external modes, likely phonon meidaed CDW fluctuastions, in different families of cuprate high-Tc superconductors [4,5]. As such the new experimental scheme lays the foundation to a full Higgs Spectroscopy of the superconducting condensate.
As a new development, here we will report on the extension of the Higgs Spectroscopy to transient states of superconductors. Non-equilibrium superconductivity typically is triggered by ultra-short tailored light pulses and applications range from ultrafast spectroscopy of the excitation dynamics of the superconducting gap [6] to light induced superconductivity by phonon or vibrational excitations in cuprates or organic superconductors [7]. Here we are going to probe such light induced states in a pump-“drive” scheme of the forced Higgs oscillations.

In the superconducting state of LSCO using a 100 fs optical pump pulse at 1.55 eV, an energy far above the superconducting gap, we have triggered such non-equilibrium dynamics breaking the long range coherence between Cooper pairs at low fluences and fully break Cooper pairs on high fluences and traced the melting dynamics of the coherent condensate and its relaxation back to the superconducting state via the transient Higgs response.

References

[1] D. Pekker and C. Varma “Amplitude/Higgs Modes in Condensed Matter Physics”, Ann. Rev. Condens. Matter Phys. **6**, 269 (2015).
[2] R. Matsunaga et al. “Higgs amplitude mode in the BCS superconductors Nb_xTi_xN induced by terahertz pulse excitation”, PRL **111**, 057002 (2013).
[3] L. Schwarz et al. “Classification and Charcterisation of Nonequilibrium Higgs Modes in Unconventional Superconductors”, Nature Communications **11**, 287 (2020).
[4] R. Matsunaga et al. “Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor”, Science **345**, 1145 (2014).
[5] H. Chu et al. “Phase-resolved Higgs response in superconducting cuprates”, Nature Communications **11**, 1793 (2020).
[6] H. Chu et al. “Fano interference of the Higgs mode in cuprate high-Tc superconductors”, arXiv preprint arXiv:2109.09971

[7] J. Demsar, “Non-equilibrium phenomena in superconductors probed by femtosecond time-domain spectroscopy”, Journal of Low Temperature Physics **201**, 676 (2020).
[8] S. Kaiser, “Light-induced superconductivity in high-Tc cuprates”, Physica Scripta **92**, 103001 (2017).

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Ayelet Zalic

Planar Van der Waals Josephson Junctions in High Parallel Magnetic Field

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Thin transition metal dichalcogenides sustain superconductivity at large in-plane magnetic fields due to atomic thickness which suppresses orbital decay, and Ising spin-orbit protection, which locks their spins in an out-of-plane orientation. We use thin exfoliated $NbSe_2$ as superconducting electrodes laterally coupled to graphene, making planar, all van der Waals two-dimensional Josephson junction devices (2DJJs) which can maintain superconducting behavior above a hitherto unexplored value of 8.5 T parallel field. Our device architecture is flexible and robust; contacts are highly transparent, and we have studied diffusive as well as ballistic and SQUID devices. In this talk I will introduce our family of novel devices, and showcase several interesting effects. In diffusive devices we explore a regime in which the Zeeman energy rivals the Thouless energy, and the physics is determined by the tuning of the Zeeman energy, along with a unique orbital effect created by ripples in an atomically thin layer. In SQUID devices we show our ability to measure an angstrom-scale misalignment in planarity; and in ballistic devices we attempt to isolate spin effects at high magnetic field. In the future our device architecture can be extended and integrated into any Van der Waals stack, e.g using different Van der Waals family superconductors as electrodes or weak links, or placing the entire junction in proximity to interesting materials. A fully planar geometry will also allow high resolution local measurements within the junction using techniques such as STM, scanning SET and scanning SQUID.

References

A. Zalic, Phys. Rev. B **103**, 115401 (2021).

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Dr. Kosuke Nakayama

ARPES observation of charge-density wave gaps and their evolution by carrier injection in a kagome superconductor CsV_3Sb_5

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Recent discovery of superconductivity with the T_c values of 0.9-2.5 K in a family of kagome metals AV_3Sb_5 (A = K, Rb, and Cs) [1–3] sparked a great deal of attention because the realization of superconductivity in kagome metals is very rare and may invoke an unconventional mechanism. Besides superconductivity, AV_3Sb_5 exhibits an unconventional charge-density wave (CDW) state below T_{CDW} = 78-103 K. A central issue is the relationship between the band structure and the mechanism of CDW and superconductivity. Another key issue is how these ordered states are affected by carrier doping. Tuning the carrier concentration is crucial for not only exploring and controlling the exotic properties but also understanding the underlying physical mechanisms. However, these key issues remain far from reaching a consensus because of the lack of experimental understanding on the CDW-gap function and an efficient carrier-doping method.

In this study, we have performed high-resolution ARPES measurements of CsV_3Sb_5 and observed strongly Fermi-surface and momentum-dependent CDW gap characterized by the larger energy gap for a band forming a saddle point, the smaller gap for a band forming massive Dirac cones, and a zero gap at the Sb-derived electron pocket [4]. In addition, we have succeeded electron doping by Cs dosing, and found that the CDW can be completely killed by electron doping accompanied with an orbital-selective band shift [5]. Our results suggest the important role of the saddle-point band and the multiorbital effect for understanding the CDW and its interplay with the superconductivity. The present result also opens a pathway toward manipulating the CDW and superconducting properties in AV_3Sb_5 through carrier tuning.

References

[1] B. R. Ortiz *et al*., Phys. Rev. Mater. **3**, 094407 (2019).
[2] B. R. Ortiz *et al*., Phys. Rev. Mater. **5**, 034801 (2021).

[3] B. R. Ortiz *et al*., Phys. Rev. Lett. **125**, 247002 (2020).
[4] K. Nakayama *et al*., Phys. Rev. B **104**, L161112 (2021).
[5] K. Nakayama *et al*., Phys. Rev. X, in press.

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Prof. Steven Anlage

Electrodynamics of UTe_2

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The recent discovery of unconventional superconductivity in UTe_2 has motivated careful studies of the electrodynamic properties of single crystals of this material [1-3].
The magnetic penetration depth shows a power-law temperature dependence at low temperatures in the superconducting state. The microwave losses show a large residual value, and its origin may be due to surface states of potentially intrinsic character. We extend the electrodynamics measurements to a new generation of UTe_2 crystals and extract the complex surface impedance and complex conductivity as a function of temperature. Recent studies [3,4] indicate that the normal state and superconducting properties of UTe_2 are anisotropic to a significant degree. The cavity perturbation measurements [2] are extended to multiple resonant modes (see Fig. 1), each of which excites microwave currents in different crystallographic directions. This allows extraction of the anisotropic electrodynamic properties as a function of frequency, as well as temperature. We will discuss the electrodynamic properties of the super- and normal-fluids in UTe_2 in light of this new data, and make connections to other measurements, as well as ongoing theoretical efforts to understand this unique material.
Acknowledgement: Electrodynamics work supported by NSF DMR2004386 (support of A.C.J.) and DOE grants No. DE-SC 0017931 (support of S.A.), DE-SC 0018788 (surface impedance measurements).

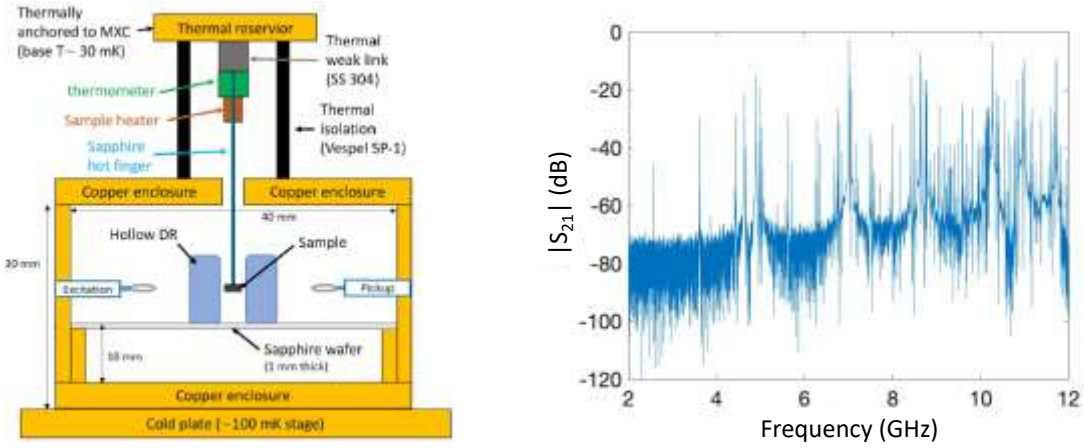

Fig. 1: *(Left) Schematic cross section of hollow cylindrical rutile resonator with sample suspended on a sapphire hot finger. Thanks to Seokjin Bae for cavity design and construction. (Right)*

Transmission spectrum of empty rutile resonator at 100 mK showing resonant modes available for cavity perturbation experiments.

References

[1] Tristin Metz, *et al*., Phys. Rev. B **100**, 220504(R) (2019).
[2] Seokjin Bae, *et al*., Nature Communications **12**:2644 (2021).
[3] K. Ishihara, *et al*., arXiv:2105.13721.
[4] Yun Suk Eo, *et al*., arXiv:2101.03102.

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Dr. Mohamed Oudah

Superconductivity and Topology in the Distorted Square-Net Antimonide $CaSb_2$

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Superconductivity in materials with non-trivial topology offers a path towards achieving topological superconductivity. The realization of non-trivial topology has been demonstrated in the family of square-net materials including those with Sb square-nets, stabilized by a particular electron filling on the Sb atoms. By varying this electron filling, these Sb square-nets are susceptible to distortions with formation of Sb-Sb zigzag chains and a reduced crystallographic symmetry. Despite the distortion in the Sb square-nets, the *M*Sb_2 family of materials appear to have persistent topological states. In particular, topology and superconductivity appear in polycrystalline $CaSb_2$ [1,2].

Here, we investigate self-flux grown single-crystals of the superconducting diantimonide $CaSb_2$ with distorted square-net by means of magnetization, electrical transport, and specific heat measurements. For $CaSb_2$, we observe type-II superconductivity with a T_c of 1.6 K (Fig. 1(a)) and an upper critical field of 24.4 mT [3]. We also observe a metal-to-insulator-like transition below ~50 K at magnetic fields larger than ~3 T, and a plateau of the resistivity below ~10 K, consistent with surface states dominating transport at low temperature, as seen in Fig. 1(b). Our non-saturating magnetoresistance up at 14 T and Hall measurements demonstrate that $CaSb_2$ is a compensated semimetal. Our experimental observations are consistent with DFT calculations, revealing an electronic structure with non-trivial topology related to the distorted Sb square nets. In this context, we discuss the implications of the Sb-distortion into zigzag chains on the topology, and discuss signatures of unconventional superconductivity in $CaSb_2$.

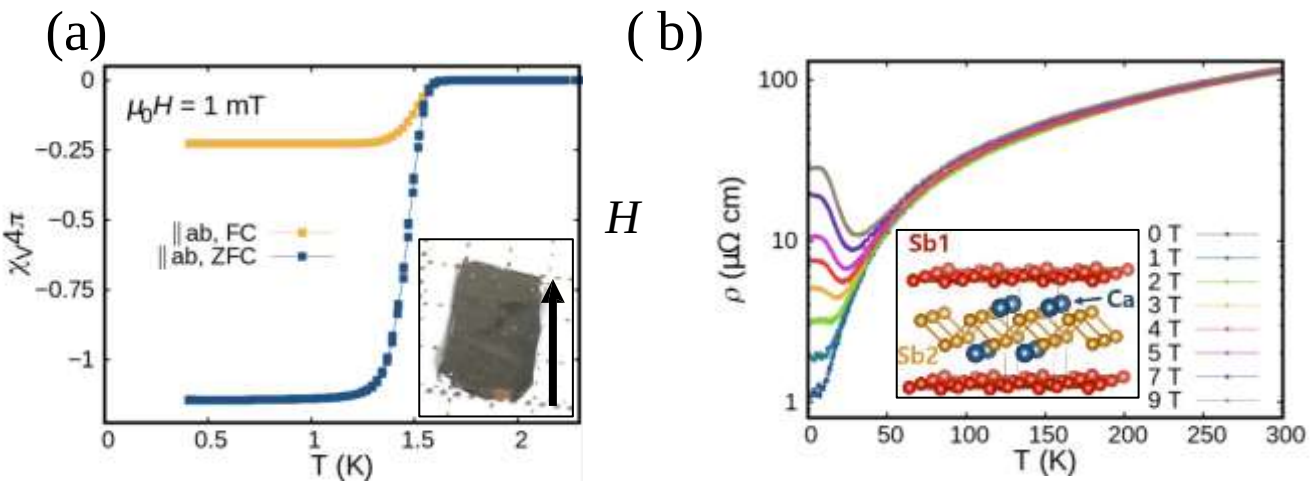

Fig. 1: (a) Temperature dependence of the dc magnetic susceptibility measured in a 1 mT field *H* // ab (along plane of crystal as shown in inset) with zero-field-cooling (ZFC) and field- cooling (FC) procedures. **(b)** Temperature dependence of the longitudinal resistivity ρ in differenct magnetic fields *H* // *c* with *I* // *ab*. Crystal structure of $CaSb_2$ shown in inset.

References

[1] K. Funada, *et al., JPSJ*, ***88***, 044711 (2019). [2] A. Ikeda, *et al., PRM*, **4**, 041801(R) (2020). [3] M. Oudah, *et al.,* arXiv:**2106**.06175 (2021).

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Andrivo Rusydi

Ferromagnetism of doped holes in cuprate heterostructures

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Elucidating magnetic and electronic correlations of doped holes within antiferromagnetically ordered Cu-O planes in copper-oxides (cuprates), a model system of high-temperature superconductors, remains highly debated after decades. The main challenge is to directly and simultaneously probe long-range order of magnetic and electronic correlations of the doped holes while being separated from localized Cu spins. Here, we report strong ferromagnetism of doped holes both within the ab-plane and along the *c*-axis of Cu-O plane in new low-dimensional-Au/*x* $La_{2-x}Ba_{0.2}CuO_4/LaAlO_3(001)$ heterostructures with *x* = 4, 8 and 12 unit cell using novel resonant soft X-ray and magnetic scattering (RSXMS) and X-ray magnetic circular dichroism (XMCD). Surprisingly, ferromagnetism is stronger at a hole doped peak (HDP) and an Upper Hubbard band (UHB) of O with a degree of spin-polarization as- high-as ~40%. For in-ab-plane spin-polarizations, the doped-hole spins in O2*p*–Cu3*d*– O2*p* are triplet states yielding strong ferromagnetism. For out-of-ab-plane spin- polarization, while the doped-hole spins in both O2*p*–O2*p* and Cu3*d*–Cu3*d* are triplet states, the spin in Cu3*d*–O2*p* is a singlet state yielding ferrimagnetism. A new ferromagnetic-(002) Bragg peak of the doped holes is found and reveals strong ferromagnetism between Cu-O layers along the *c*-axis. Our result shows, unprecedentedly, ferromagnetism of doped holes in the Cu-O plane of cuprates and demonstrates a pioneering strategy in utilizing RSXMS to reveal spin, charge, and orbital of the charge carriers in strongly correlated electron systems.

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Dr. Karol Flachbart, Nikolay Sluchanko

Dynamic Charge Stripes and Inhomogeneous Superconductivity in $Lu_xZr_{1-x}B_{12}$ with Jahn-Teller Instability

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Characteristics of the normal and superconducting states (resistivity, Hall coefficient, heat capacity, magnetization), precise X-ray diffraction (XRD) data and *μSR*- spectra of model strongly correlated electronic systems $Lu_xZr_{1-x}B_{12}$ with cooperative Jahn-Teller instability of the rigid covalent boron framework and dynamic charge stripes are investigated. It is shown that these metals are *s*-type superconductors in the dirty limit with a small mean free path of charge carriers ℓ = 5 - 140 Å, in which a non-monotonic change in the size of Cooper pairs ξ is realized in the range 500-4000 Å [1]. It is found that the dodecaboride LuB_{12} is a type-I superconductor, the substitution of Lu for Zr causes a transition to type-II superconductivity, while the Ginzburg-Landau-Maki parameter varies non-monotonically within $0.5 \leq \kappa \leq 6$. Arguments are given in favor of double-gap superconductivity in $Lu_xZr_{1-x}B_{12}$ in the concentration range x<0.3 with gaps Δ_1/k_B~12-19 K and Δ_2/k_B~5-8 K (k_B is the Boltzmann constant) with pairing in the upper band corresponding to the condition of strong coupling ($\lambda_{e\text{-}ph}$~1 and $2\Delta_1/k_BT_c$~5-6), while in the lower band the weak coupling limit is realized ($\lambda_{e\text{-}ph}$~0.1-0.4 and $2\Delta_2/k_BT_c$~2.5).
In ZrB_{12} a noticeable anisotropy of the upper band upper critical field $H_{c2}(T_c)$ is found. We estimate the coherence lengths $\xi_1(0) \approx 739$ Å and $\xi_2(0) \geq 2000$ Å providing the inequality $\xi_1(0)<\lambda<\xi_2(0)$ (with penetration depth $\lambda(ZrB_{12})$~1800 Å [2]) which is typical for type-1.5 superconductivity [3]. Very precise XRD data analysis allows to conclude that in ZrB_{12} contains conducting channels form two types of dynamic charge stripes, each in form of *grid with rhomboid cells (a checkerboard pattern)*. One of them is generated by hybridized 4*d*-2*p* orbitals and another one by 2*p* conduction band states. Note that the arrangement of the two types of plane *grids of stripes* may be considered as a factor responsible for the field-induced anisotropy of superconductivity. In $Lu_xZr_{1-x}B_{12}$, above T_c, a pseudo-gap $\Delta_{ps\text{-}gap}$ ~ 60–110 K is observed, the magnitude of which is determined by the height of the barrier in the double-well potential in the vicinity of heavy Zr/Lu ions.

References

[1]. A. Azarevich et al., Phys. Rev. B **103**, 104515(2021).
[2]. F. K. K. Kirschner et al., Phys. Rev. B **98**, 94505 (2018).
[3]. M. Silaev and E. Babaev, Phys. Rev. B **84**, 094515 (2011).

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Dr. Luke Rhodes

Checkerboard Charge Order, Nematicity and Magnetic-field Tuning of a Van Hove Singularity in the Surface Layer of Sr_2RuO_4

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Strongly correlated electron materials exhibit an intimate relation between charge, spin and structural degrees of freedom, leading to new emergent phases which seemingly break the symmetries of the underlying crystal and result in often unexpected sensitivity to external stimuli. The members of the Ruddlesden-Popper-series $Sr_{n+1}Ru_nO_{3n+1}$ exhibit a wide range of properties attributed to such physics, including unconventional superconductivity, metamagnetic quantum criticality and ferromagnetism. We show in a detailed study of the surface electronic structure of Sr_2RuO_4, an unconventional superconductor, how tiny structural distortions lead to a significant reconstruction of the Fermi surface and the low energy electronic structure. We use ultra-low temperature scanning tunnelling microscopy to establish the existence of four van Hove singularities (vHs) within 5 mV of the Fermi level, as well as checkerboard charge order and nematicity of the electronic states [1]. Including these orders into a tight-binding model, we can fully account for the four vHs. Continuum local density of states calculations which take into account the tunneling matrix elements show excellent agreement with the observed QPI patterns [2]. By applying a magnetic field up to 14 T, we observe one of the van Hove singularities to Zeeman split, with one branch extrapolated to reach the Fermi level at ~32 T – providing a text-book example of tuning towards a magnetic field-driven Lifshitz transition.

References

[1]. C. A. Marques *et al*., Adv. Mater., **33**: 2170253 (2021).
[2]. A. Kreisel *et al*., npj Quantum Mater. **6**, 100 (2021).

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Peter Hirdchfeld

Topological Electronic Structure Near Linear Defects in Iron-based Superconductors

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Recent experiments [1, 2] have suggested that topological superconducting states (TSS) in Fe-based superconductors may support Majorana zero modes near linear defects. Some studies [3] suggest that the defect constitutes an effective ferromagnetic chain, which is known to support Majorana end chain excitations when coupled to a superconductor in the presence of spin orbit coupling, whereas others suggest antiferromagnetic correlations may accomplish a similar goal. Ways to obtain TSS from singlet unconventional superconductors have also been proposed [4] via inversion symmetry breaking. Here we study realistic models of iron-based superconductors with linear defects within a spin-generalized and spin-rotationally invariant BdG framework, and discuss the defect-induced novel magnetic states and superconducting gap structures.

References

[1]. Nature Physics 16, 536-540 (2020).
[2]. Science 346, 602 (2014).
[3]. Phys. Rev. B 90, 235433 (2014).
[4]. Phys. Rev. X 11, 011041 (2021).

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Mr. Morgan Grant

Observation of the Nonlinear Meissner Effect

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The linear magnetic field dependence of the magnetic penetration depth, known as the nonlinear Meissner effect, is a key consequence of the theory of unconventional superconductivity [1]. The effect occurs due to the shifting of quasiparticle states in the presence of a field induced superfluid velocity. However, it's absence in the high temperature cuprate superconductors has been a mystery for almost 30 years [2]. Presented here are our recent measurements on LaFePO and $CeCoIn_5$ that are the first successful observations of this effect [3]. Additionally, we demonstrate a new way of analysing $\Delta\lambda(T,H)$ that can distinguish nodes from deep gap minima. These results confirm the original theory and further establish the nonlinear Meissner effect as a tool for probing the gap structure of unconventional superconductors.

References

[1] S. K. Yip & J. A. Sauls, *Phys. Rev. Lett.* **69** (1992).
[2] A. Carrington *et al.*, *Phys. Rev. B*, **59** (1999).
[3] J. A. Wilcox *et al.*, arXiv:2008.04050 (2021).

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Mr. Filippo Gaggioli

Strong Pinning Theory for a General Anisotropic Potential Landscape

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Strong pinning is characterized by the presence of bistable vortex configurations, with vortices jumping between different states, usually denoted as `pinned' and `free'; the associated jumps in energy and force determine the physical properties of the superconductor, e.g., critical currents and field penetration. Strong pinning involves a competition between the vortex lattice elasticity C and the pinning potential landscape $e_p(\mathbf{r})$: Going from a hard lattice with large C to a soft lattice with small C, strong pinning sets in at the Labusch point where curvatures in the pinning landscape $e_p(\mathbf{r})$ match C. Naturally, the study of the curvature- or Hessian-matrix of the pinning energy landscape describes the transition to and evolution of strong pinning with decreasing elasticity C or increasing Labusch parameter $\kappa = \max(-e_p'')/C$.

While previous work has focused on isotropic pinning centers, here, we extend the analysis of the weak-to-strong pinning transition to the general case of anisotropic pinning landscapes, specifically, an anisotropic defect and a 2D random potential. We express our results through two types of vortex coordinates, the vortex asymptotic coordinate **X** far away from the pins and the vortex tip coordinate **r** at the pin location. Starting at weak pinning and a compact defect potential, single stable vortex configurations exist for any value of **X**. Upon increasing κ beyond unity, bistable areas appear in **X** when strong pinning sets in and vortex tips jump across unstable areas in **r** space. For isotropic pinning centers the transition at $\kappa = 1$ involves a ring with finite trapping radius X_t and vortex tips jumping between segments of concentric circles. Furthermore, vortex configurations can be classified as pinned (for $X < X_t$) or free. On the contrary, for anisotropic defects, strong pinning sets in at an isolated point and grows from there into a banana shaped object in **X** space and corresponding ellipses in tip space **r**. A classification between pinned and free branches is no longer possible in general, as both branches asymptotically connect to the free state; this is analogous to the situation in the gas-liquid transition where no classification of phases can be done beyond the critical point. The new geometries lead to a vanishing trapping area at the transition and another critical exponent for the critical force density F_c at the weak-to-strong pinning transition: indeed, expressing the transition through the distance $\kappa - 1$ to the Labusch point, we find that $F_c \propto (\kappa - 1)^{\mu}$ with $\mu = 5/2$ replacing the previously found value $\mu = 2$ appertaining to an isotropic defect.

As the Labusch parameter κ is further increased, the unstable (in **r**) and bistable (in **X**) areas expand and change shape according to the defect's potential shape. Going to a general 2D landscape, strong-pinning ellipses appear at different points in **r** space, they expand and merge in a hyperbolic geometry, thereby dividing the plane into `unstable' and `stable/free' domains. As `unstable' areas merge to isolate out closed areas, these latter become identifiable as describing `pinned' vortex states. The three objects, ellipses, hyperbolas and holes can be identified with elements of a planar graph, with the ellipses corresponding to vertices, hyperbolas to edges, and holes to faces, thus establishing a relation between the topological properties of a strong pinning landscapes through its associated Euler characteristic.

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Ms. Barbora Budinska

Rising speed limits for fluxons via edge quality improvement in MoSi thin films

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We demonstrate that the quasiparticle energy relaxation time τ deduced from current- voltage measurements differs substantially from the intrinsic τ in superconductors unless special care was taken about their edges` quality. Our findings explain the apparent inconsistency between the deduced τ in recent works and those required for operation of superconductor microstrip single-photon detectors (SMSPDs). By using MoSi films with rough (laser cut) and smooth (focused ion beam milled) edges we demonstrate a-factor-of-3 larger critical currents, up to 20 km/s vortex velocities, and a-factor-of-40 shorter τ (Fig. 1), making accessible emerging phenomena in ultra-fast vortex dynamics and the required high-bias-current regime of SMSPDs [1].

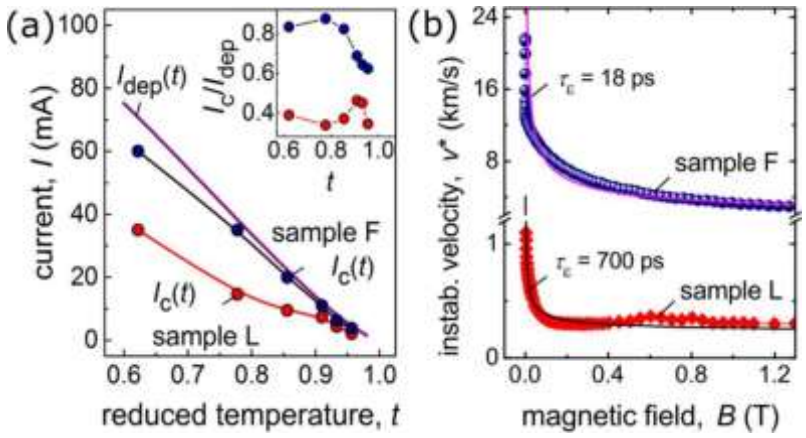

Fig. 1: (a) The experimentally measured critical current $I_c(t)$ for laser cut (sample L) and focused ion beam milled (sample F) edge in comparison with the Ginzburg-Landau depairing current. (b) The highest achieved vortex velocities for sample L and F in experiment. The energy relaxation time τ is used as the only fitting parameter of the experimental data to the Doettinger et al relation [2].

References

[1] B. Budinska et al., Preprint at http://arxiv.org/abs/2111.13431 (2021).
[2] S.G. Doettinger, R.P. Huebener, and A. Kühle, Physica C 251, 285 – 289 (1995).

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Dr. Erik van Heumen

Disentangling Carrier Density and Momentum Relaxation in Cuprate Superconductors

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One of the key mysteries in the cuprate phase diagram is the strange metallic phase, which features a variety of anomalous electronic properties. In recent years, various (magneto-) transport experiments have reported a singular behavior of the carrier density near a critical doping around p = 0.2 holes/Cu and these results have been interpreted as essential features of the strange metal response.
I will review these results considering the doping evolution of the optical conductivity across the phase diagram for the single layer material Bi2201. Whereas transport experiments only probe a combination of momentum relaxation and carrier density, the optical response enables us to disentangle the two. I will show that the doping and temperature evolution of the resistivity can be fully understood from changes in the momentum relaxation rate. At the same time, the carrier density displays a continuous and gradual evolution $n \propto p$ across the phase diagram.
I will explain how these results provide new insight in the dynamics of the strange metal phase.

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Riccardo Comin, Mr. Mingu Kang

Twofold van Hove singularity and origin of charge order in topological kagome superconductor CsV3Sb5

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The layered vanadium antimonides AV3Sb5 (A = K, Rb, Cs) are a recently discovered family of topological kagome metals that exhibit a range of strongly correlated electronic phases including charge order and superconductivity [1]. However, it is not yet understood how the distinctive electronic structure of the kagome lattice is linked to the observed many-body phases. Here, we combine angle-resolved photoemission spectroscopy and density functional theory to reveal multiple kagome-derived van Hove singularities (vHS) coexisting near the Fermi level of CsV3Sb5 and analyze their contribution to electronic symmetry breaking [3]. The vHS are characterized by two distinct sublattice flavors (p-type and m-type), which originate, respectively, from their pure and mixed sublattice characters. These twofold vHS flavors of the kagome lattice critically determine the pairing symmetry and unconventional ground states emerging in the AV3Sb5 series [4]. We establish that, among the multiple vHS in CsV3Sb5, the m-type vHS of the dxz/dyz kagome band and the p-type vHS of the dxy/dx2–y2 kagome band are located very close to the Fermi level, setting the stage for electronic symmetry breaking. The former band exhibits pronounced Fermi surface nesting, while the latter contributes via higher-order vHS. Our work reveals the essential role of kagome-derived vHS for the collective phenomena realized in the AV3Sb5 family.

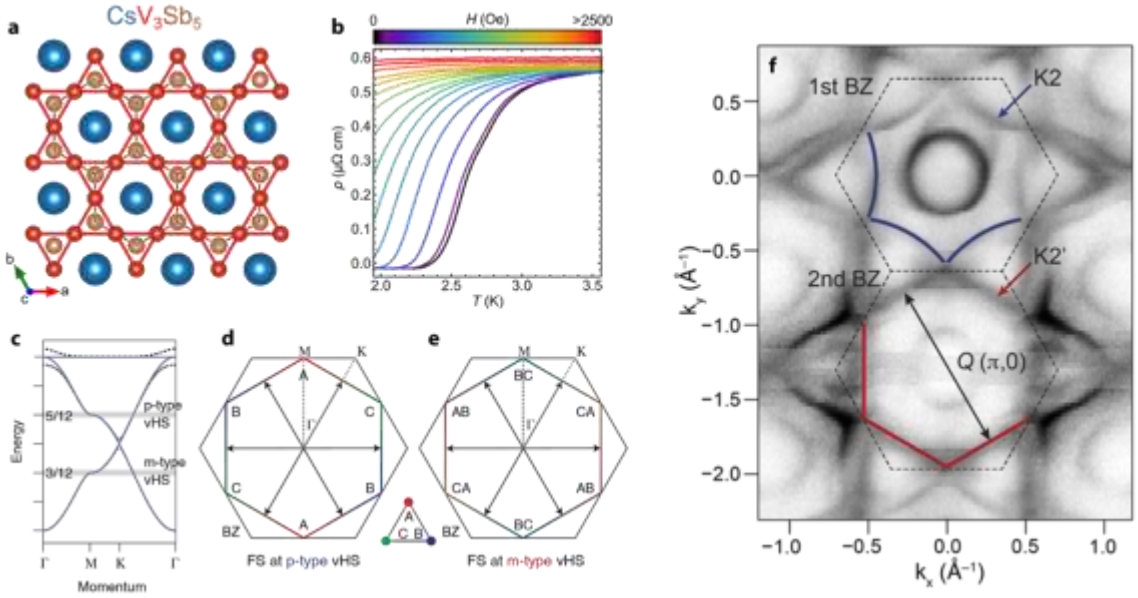

Fig. 1: a, *Top view of CsV3Sb5, with kagome sublattice highlighted.* **b,** *Superconducting transition.* **c-e**, *Fermi surface of the kagome lattice at the n=5/12 filling with p-type vHS (e) and at the n = 3/12 filling with m-type vHS (f). The nesting vector Q = (π,0) and its symmetry equivalents are marked*

with black arrows. **f,** *Fermi surface of CsV3Sb5 across the first and second Brillouin zone (BZ). The K2' band displays an almost perfectly nested Fermi surface.*

References

[1]. Ortiz, B. R., *et al.*, Phys. Rev. Mater. **3**, 94407 (2019); Phys. Rev. Lett. **125**, 247002 (2020).
[3]. M. Kang, *et al.*, Nature Physics, in press (2021).
[4]. X. Wu, *et al.*, Phys. Rev. Lett. **127**, 177001 (2021).

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Prof. Vadim Geshkenbein

Flux creep and Campbell response in type II superconductors

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Applying the strong pinning formalism to the mixed state of a type II superconductor, we study the effect of thermal fluctuations (or creep) on the current—voltage (I-V) characteristic and the penetration of an ac magnetic field as quantified by the so-called Campbell length λ_C. Within strong pinning theory, vortices get pinned by individual defects, with the jumps in the pinning energy (Δe_{pin}) and force (Δf_{pin}) between bistable pinned and free states quantifying the pinning process.

The critical current is determined by the energy jump Δe_{pin}; 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. Motivated by the observation of typical excess-current characteristics and field-scaling of critical currents, we analyze I-V curves measured on 2H-$NbSe_2$ and a-MoGe type II superconductors within the setting provided by strong pinning theory. The experimentally observed shift and rounding of the voltage-onset are in excellent agreement with the predictions of strong pinning in the presence of thermal fluctuations [1].

Analysing the evolution of the Campbell length $\lambda_C(t)$ as a function of time t, we find that it is the result of two competing effects, the change in the force jumps $\Delta f_{pin}(t)$ and a change in the trapping area $S_{trap}(t)$ of vortices; the latter describes the area around the defect where a nearby vortex gets and remains trapped. Contrary to naive expectation, we find that during the decay of the critical state in a zero-field cooled (ZFC) experiment, the Campbell length $\lambda_C(t)$ is usually non-monotonic, first decreasing with time t and then increasing for long waiting times. Field cooled (FC) experiments exhibit hysteretic effects in λ_C; relaxation then turns out to be predominantly monotonic, but its magnitude and direction depends on the specific phase of the cooling–heating cycle. Furthermore, when approaching equilibrium, the Campbell length relaxes to a finite value, different from the persistent current which vanishes at long waiting times t, e.g., above the irreversibility line. Finally, measuring the Campbell length $\lambda_C(t)$ for different states, zero-field cooled, field cooled, and relaxed, as a function of different waiting times t and temperatures T, allows to ‘spectroscopyse ’the pinning potential of the defects.

References

[1]. M. Buchacek, Z. L. Xiao, S. Dutta, E. Y. Andrei, P. Raychaudhuri, V. B. Geshkenbein, and G. Blatter, Physical Review B 100, 224502 (2019): editor’s suggestion.

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Prof. K. Tanaka

Topological Superconductivity in Quasicrystals

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Quasicrystals constitute a new class of topological materials which defy all the laws of crystallography, with aperiodic long-range order and peculiar rotational symmetry associated with higher-dimensional space group. Quasicrystals are interesting not only from the fundamental point of view, but also for technological applications due to their properties that are different from regular materials. Moreover, recent technical advances have enabled experimental studies of novel quantum phenomena in actual quasicrystals. Most notably, superconductivity has recently been discovered in a quasicrystal [1].

We propose realisation of non-Abelian topological superconductivity (TSC) in two-dimensional (2D) quasicrystals, in particular, Penrose and Ammann-Beenker quasicrystals. The model for 2D TSC with broken time-reversal symmetry [2], which has been achieved in a Pb/Co island on Si(111) [3], is generalised for 2D quasicrystals. By solving the Bogoliubov-de Gennes equations, we find that TSC is realised in both Penrose and Ammann-Beenker quasicrystals, where the Bott index is unity. The topological nature of this phase is confirmed by the existence of a zero-energy surface bound state and the chiral propagation of a wave packet projected onto the midgap bound state along the surfaces. Furthermore, we confirm the existence of a single Majorana zero mode each in a vortex at the center of the system and along the surfaces, signifying the non-Abelian character of the system when the Bott index is unity. The occurrence of TSC and topological phase transitions are explained in terms of numerically obtained band structure of quasicrystals [4].

References

[1]. K. Kamiya et al., Nat. Commun. **9**, 154 (2018).
[2]. M. Sato, Y. Takahashi, and S. Fujimoto, Phys. Rev. Lett. **103**, 020401 (2009); Phys. Rev. B **82**, 134521 (2010).
[3]. G. C. Ménard et al., Nat. Commun. **8**, 2040 (2017).
[4]. R. Ghadimi, T. Sugimoto, K. Tanaka, and T. Tohyama, Phys. Rev. B **104**, 144511 (2021).

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Prof. Devashibhai Adroja

Probing the Superconducting Gap Structure in the Noncentro symmetric Topological Superconductor ZrRuAs

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The superconducting gap structure of the topological superconductor candidate ZrRuAs with a noncentrosymmetric crystal structure has been investigated using muon-spin rotation/relaxation (μSR) measurements in transverse-field (TF) and zero field (ZF) geometries [1]. Magnetization, electrical resistivity, and heat capacity measurements reveal bulk superconductivity below a superconducting transition temperature Tc = 7.9(1) K. The temperature dependence of the effective penetration depth obtained from the TF-μSR spectra, and the electronic heat capacity in the superconducting state, are well described by an isotropic s-wave gap model. Comparison of the electronic mean free path with the superconducting coherence length suggests superconductivity in the dirty limit. ZF μSR data show there is no significant change in the muon-spin relaxation rate above and below Tc, indicating that time-reversal symmetry is preserved in the superconducting state.

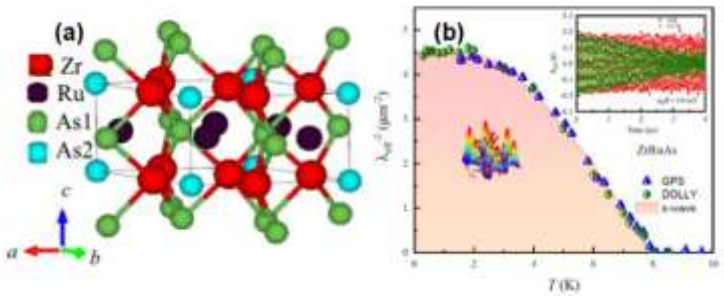

Fig. 1: (a) *Hexagonal crystal structure of ZrRuAs and, (b) Temperature dependence of* λ_{eff}^{-2} *. The solid line shows the fit to a theoretical model. The top right inset shows transverse-field (TF) μSR time spectra obtained above and below* T_c*. The bottom left inset shows the flux line lattice (FLL) probe by muons [1].*

References

[1].D. Das et al, Phys. Rev. B **103,** 144516 (2021)**.**

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Dr. Pierre Toulemonde

$LaFeSiO_{1-\delta}$: a novel superconducting member of the Fe silicides family with squeezed FeSi layers

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Since their discovery in 2008, iron-based superconducting pnictides (As, P…) and chalocgenides (Te,Se…) are now a well-established class of unconventional superconductors, spanning multiple structural families, with T_c up to 55 K in bulk materials [1]. This category of superconductors has recently been extended to other layered materials where pnictogen/chalcogen atoms are replaced by crystallogen elements: either with Ge in YFe_2Ge_2 (T_c ~ 2 K) [2] or Si in LaFeSiH (T_c ~ 10 K) [3].

First of all, in the present work, starting from LaFeSi and using decomposition of high hydrogen density materials (anthracene or ammonia borane) at high pressure and temperature in a large volume press, we were able to synthesize the superconducting tetragonal LaFeSiH silicide but also an unknown orthorhombic $LaFeSiH_{1+x}$ phase where superconductivity is suppressed.
Secondly, by oxygenation, we were able to intercalate oxygen in LaFeSi. The resulting unexpected crystallogenide, $LaFeSiO_{1-\delta}$, showed very interesting properties. Our detailed study based on complementary experimental probes reveals that this crystallogenide is superconducting with a relatively high T_c ~ 10 K, regarding its strongly squeezed Fe-Si anion height, below 1Å, challenging the usual relationship between structure and superconductivity in Fe-based compounds. Its unique crystal structure has a strong impact on its electronic properties. Just above T_c, its resistivity shows a non-Fermi liquid behavior, a signature of its electronic correlations. This correlated behavior is also visible in the NMR data. Its calculated electronic structure is significantly changed compared to the one of the canonical LaFeAsO pnictide. Its Fe-related Fermi surface, consisting almost uniquely of hole pockets, suggests another kind of electronic correlations and then a different related superconducting mechanism than the usual the s±-mechanism. Finally, the location of $LaFeSiO_{1-\delta}$ and LaFeSiH superconductors in the phase diagram points towards the existence of a new emerging superconducting dome related to Fe-silicides [4].

References

[1] H. Hosono, K Kuroki, Physica C **514**, 399 (2015).
[2] J. Chen et al., Phys. Rev. Lett. **125**, 237002 (2020). [3]
F. Bernardini et al., Phys. Rev. B **97**, 100504 (2018).
[4] M.F. Hansen et al., submitted (2021).

Xingye Lu, Dr. Wenliang Zhang, Dr. Yi Tseng, Ruixian Liu, Zhen Tao, Dr. Eugenio Paris, Dr. Panpan Liu, Dr. Tong Chen, Dr. Yu Song, Professor Rong Yu, Professor Qimiao Si, Professor Pengcheng Dai, Dr. Thorsten Schmitt

Spin-excitation anisotropy in the nematic state of detwinned FeSe

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The origin of the electronic nematicity in FeSe is one of the most important unresolved puzzles in the study of iron-based superconductors. In both spin- and orbital-nematic models, the intrinsic magnetic excitations at $\mathbf{Q}_1 = (1, 0)$ and $\mathbf{Q}_2 = (0, 1)$ of twin-free FeSe are expected to provide decisive criteria for clarifying this issue. Although a spin-fluctuation anisotropy below 10 meV between $\mathbf{Q}_1$ and $\mathbf{Q}_2$ has been observed by inelastic neutron scattering around $T_c \sim 9$ K ($<< T_s \sim 90$ K), it remains unclear whether such an anisotropy also persists at higher energies and associates with the nematic transition T_s. Here we use resonant inelastic x-ray scattering to probe the high-energy magnetic excitations of uniaxial-strain detwinned FeSe and $BaFe_2As_2$. A prominent anisotropy between the magnetic excitations along the *H* and *K* directions is found to persist to ~ 200 meV in FeSe, which is even more pronounced than the anisotropy of spin waves in $BaFe_2As_2$. This anisotropy decreases gradually with increasing temperature and finally vanishes at a temperature around the nematic transition temperature T_s. Our results reveal an unprecedented strong spin excitation anisotropy with a large energy scale well above the d_{xz}/d_{yz} orbital splitting, suggesting that the nematic phase transition is primarily spin-driven. Moreover, the measured high-energy spin excitations are dispersive and underdamped, which can be understood from a local-moment perspective. Our findings provide the much-needed understanding of the mechanism for the nematicity of FeSe and points to a unified description of the correlation physics across seemingly distinct classes of Fe-based superconductors.

References

[1]. Xingye Lu *et al.*, arXiv:2108.04484.

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Mr. Dmitry Kiselov

Theory of Superconductivity Due to Ngai's Mechanism in Lightly Doped $SrTiO_3$

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We develop a theory of superconducting pairing in low-density Strontium titanate based upon the idea of quadratic coupling of electron density to soft transverse optical phonons [1]. This coupling leads to static attractive potential between electrons which decays in real space exponentially with the length l_{eff} that scales inversely with soft optical gap ω_T . For low electron densities $n \leq 10^{18} cm^{-3}$ attraction between electrons can be considered local and superconducting transition temperature T_c is calculated using old results [2]. We use independently obtained magnitude g of the quadratic coupling strength and find $T_c(n)$ dependence in agreement with experimental data [3] for low doping. Next, we show that suppression of T_c by hydrostatic pressure [4] and strong increase of T_c due to isotope substitution $^{16}O \rightarrow ^{18}O$ observed in [5] are qualitatively explained within our theory.

References

[1] K. L. Ngai, Phys. Rev. Lett. **32**, 215 (1974)
[2] L.P.Gor'kov and T.K.Melik-Barkhudarov, Sov. Phys. - JETP **40**, 1452-1458 (1961)
[3] Xiao Lin, German Bridoux, Adrien Gourgout *et al*, Phys. Rev. Lett. **112**, 207002 (2014).
[4] Enderlein, C., de Oliveira, J.F., Tompsett, D.A. *et al*. Nat Commun **11**, 4852 (2020)
[5] Stucky, A., Scheerer, G., Ren, Z. *et al*, Sci. Rep. **6**, 37582 (2016)

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Mr. Amirreza Ataei

Electrons with Planckian Scattering Obey Standard Orbital Motion in a Magnetic Field

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In various "strange" metals, electrons undergo Planckian dissipation [1,2], a strong and anomalous scattering that grows linearly with temperature [3], in contrast to the quadratic temperature dependence expected from the standard theory of metals. In some cuprates [4,5] and pnictides [6], a linear dependence of the resistivity on magnetic field has also been considered anomalous – possibly an additional facet of Planckian dissipation. Here we show that the resistivity of the cuprate strange metals $Nd_{0.4}La_{1.6-x}Sr_xCuO_4$ [7] and $La_{2-x}Sr_xCuO_4$ [8] is quantitatively consistent with the standard Boltzmann theory of electron motion in a magnetic field, in all aspects – field strength, field direction, temperature, and disorder level. The linear field dependence is found to be simply the consequence of scattering rate anisotropy. We conclude that Planckian dissipation is anomalous in its temperature dependence but not in its field dependence. The scattering rate in these cuprates does not depend on field, which means their Planckian dissipation is robust against fields up to at least 85 T.

References

[1] J. A. N. Bruin, *et al*. *Science* **339**, 804-807 (2013).
[2] A. Legros, *et al. Nat. Phys.* **15**, 142–147 (2019).
[3] G. Grissonnanche, *et al. Nature* **595**, 667–672 (2021).
[4] P. Giraldo-Gallo, *et al. Science* **361**, 479–481 (2018).
[5] J. Ayres, *et al*. *Nature* **595**, 661–666 (2021).
[6] I.M. Hayes, *et al. Nat. Phys.* **12**, 916–919 (2016).
[7] R. Daou, *et al. Nat. Phys.* **5,** 31–34 (2009).
[8] R. A. Cooper, *et al. Science* **323**, 603–607 (2009).

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Mr. Paul Worm

Importance of electronic correlations in Nickelates

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Motivated by the recent discovery of superconductivity in the pentalayer nickelate $Nd_6Ni_5O_{12}$, we calculate its electronic structure and superconducting critical temperature. First, we analyze the compound by means of state-of-the-art density functional theory and dynamical mean field theory (DFT+DMFT) and find that electronic correlations remove the Nd pockets from the Fermi surface, which crucially changes the filling of the most relevant Ni d_{x2-y2} band. An effective single-orbital Hamiltonian can be constructed for the five layers, and we show that its properties are stunningly similar to the infinite layer case. Subsequently we solve this effective model within the dynamical vertex approximation to determine the transition temperature. We further study the related bilayer nickelate and propose a suitable dopant to achieve a doping level where superconductivity is expected.

References

[1] P. Worm, L. Si, M. Kitatani, R. Arita, J. Tomczak, K. Held, arXiv:2111.12697

Manipulation of Time Reversal Symmetry Breaking, Superconductivity in Sr_2RuO_4 by Uniaxial Stress

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Although the normal-state electronic structure of Sr_2RuO_4 is known with exceptional precision, even after two decades of research, the symmetry of its certainly unconventional superconducting state is under strong debate, e.g. the long-time favoured spin-triplet $p_x \pm ip_y$ state is ruled out by recent NMR experiments [1]. However, in general time-reversal-symmetry breaking (TRSB) superconductivity indicates complex two-component order parameters. Probing Sr_2RuO_4 under uniaxial stress offers the possibility to lift the degeneracy between such components [2]. One key prediction for Sr_2RuO_4, a splitting of the superconducting and TRSB transitions under uniaxial stress has not been observed so far. I will show results of muon spin relaxation (μSR) measurements on Sr_2RuO_4 placed under uniaxial stress, wherein a large stress-induced splitting between the onset temperatures of superconductivity and TRSB was observed [3]. Moreover, at high stress beyond the Van Hove singularity, a new spin density wave ordered phase was detected for the first time. In order to perform μSR measurements under uniaxial stress, a custom piezoelectric based pressure cell was developed [4]. This cell is going to be useful for a range of other materials, in which the Fermi surface or magnetic interaction strengths can be tuned leading to strong modifications of the electronic state. New μSR results with uniaxial pressure along <110> directions will also be presented in the context of ultrasound measurements, which altogether pose a strong constraint on the symmetry of the superconducting order parameter of Sr_2RuO_4.

References:

[1] A. Pustogow, *et al*., Nature **574**, 72 (2019);
[2] C. Hicks, *et al*., Science **344**, 283 (2014).
[3] V. Grinenko*, S. Ghosh* *et al*., Nature Physics **17**, 748–754 (2021)
[4] S. Ghosh *et al*., Review of Scientific Instruments **91**, 103902 (2020).

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Chloé Gauvin-Ndiaye

Resilient Fermi Liquid and Strength of Correlations Near an Antiferromagnetic Quantum Critical Point

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Near the antiferromagnetic quantum critical point (QCP) of electron-doped cuprate superconductors, angle-resolved photoemission experiments detect hot spots where the Fermi surface disappears [1]. Here we demonstrate, using the two-particle self-consistent theory, that in the antinodal region the Fermi liquid remains stable for a broad range of angles on the Fermi surface and for all dopings near the QCP. We show how the quasiparticle weight Z and effective mass $m*$ change and then abruptly become meaningless as the hot spots are approached. We propose a dimensionless number, easily accessible in ARPES experiments, that can be used to gauge the strength of correlations [2].

References

[1]. N. P. Armitage *et al*, Physical Review Letters **88**, 257001 (2002).
[2]. C. Gauvin-Ndiaye, M. Setrakian & A.-M. S. Tremblay, arXiv:2111.08059 (2021).

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Prof. Eduardo Da Silva Neto

Charge Order with Unidirectional Domains in Fe(Se,S)

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Strong electron correlations in cuprate high-temperature superconductors can lead to the self organization of electrons into periodic patterns known as a charge order. Despite several phenomenological parallels between the cuprates and Fe-based superconductors, a similar charge order phenomenon has not been established in the latter. We used scanning tunneling microscopy and spectroscopy to investigate the local symmetries of the electronic states in $FeSe_{1-x}S_x$. In tetragonal samples our experiments show the presence of a short-range periodic electronic pattern that breaks both translational and rotational symmetry. An analysis of the energy dependence in our spectroscopic mappings, complemented by angle-resolved photoemission spectroscopy measurements and theoretical simulations, shows that these short-range stripes coexist with quasiparticle interference patterns, similar to the charge order observed in Bi-based cuprates. We observe that this charge order appears over a narrow energy window, indicating that it likely originates from orbital-selective strong electron correlations.

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Prof. Ke Zou

Insights for pairing mechanism in high-temperature superconductor monolayer FeSe

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The physics of high-temperature superconductors is usually governed by the spin and charge degrees of freedom. For monolayer FeSe/$SrTiO_3$, one specific observation - the replica bands in the photoemission spectrum - has been taken to be of central importance as evidence of strong electron-phonon interaction. However, the essence of these spectroscopic features remains controversial. We conduct angle-resolved photoemission spectroscopy measurements on monolayer FeSe/$SrTiO_3$ using linearly polarized photons and observe high-order replica bands derived from various Fe 3*d* bands, similar to those observed on bare $SrTiO_3$. The intensity of the replica bands is unexpectedly high and different between d_{xy} and d_{yz} bands. Spin degree of freedom plays an important role in cuprates, where superconductivity is always found close to long-range antiferromagnetic order. Monolayer FeSe on $SrTiO_3$ exhibits no magnetic or nematic ordering. We grow monolayer and multilayer FeSe on antiferromagnetic $EuTiO_3$ (001) layers, to introduce a spin polarization in proximity to the superconductivity of FeSe. Our results provide new insights into the physical origin of the photoemission replica bands and the role of spin polarization in this high- temperature superconductor.

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Dr. Thorsten Schmitt

Unravelling the nature of the spin excitations disentangled from the charge contributions in the superconducting cuprate $Bi_2Sr_2CaCu_2O_{8+x}$

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The knowledge of the elementary excitations is vital for understanding the physics of superconducting cuprates. The experimental observation of the persistence of spin excitations by resonant inelastic X-ray scattering (RIXS) in the doped cuprates is one of the main unresolved issues in high-temperature superconductivity [1, 2]. It has intensively been debated, if these spin excitations in the doped cuprates are governed by localized spins or itinerant electrons from which coherent quasiparticles emerge [3, 4]. One obstacle to resolve the controversy of either localized or itinerant interpretation of the excitations measured with RIXS in doped cuprates is the fact that these excitations are usually of mixed charge and spin character, making the correct assignment of the spectral profile to individual excitations difficult [5, 6].

We present a study of the evolution of the disentangled spin and charge excitations upon doping a superconducting cuprate. To this end, we extract the spin dynamical structure factor from the Cu L_3 RIXS spectra for three distinct doping levels in $Bi_2Sr_2CaCu_2O_{8+x}$. The disentanglement of the spin and charge excitations is achieved by employing the respective scattering tensors in an azimuthal dependent analysis of the cross section [6]. The obtained spin structure factors confirm in an unambiguous manner the persistence of the collective spin excitations in large parts of the Brillouin zone, and unveil their detailed development versus momentum and hole doping. We explain the experimental results by comparing them against density matrix renormalization group (DMRG) calculations for a *t-J*-like model on a square lattice geometry. Ultimately, we conclude that the observed persistence of the collective spin excitations is due to localized spins—though solely short-range correlations between them are essential. Furthermore, we show that long-range electronic hopping plays an important role in obtaining agreement of the intensities between theory and experiment.

References

[1]. M. Le Tacon *et al*., Nature Phys. **7**, 725 (2011).
[2]. M. P. M. Dean *et al*., Nature Mater. **12**, 1019 (2013).
[3]. A. J. A. James, *et al*., Phys. Rev. B **86**, 100508(R) (2012).
[4]. Guangyong Xu *et al*., Nature Phys. **5**, 642 (2009).

[5]. Chunjing Jia *et al*., Phys. Rev. X **6**, 021020 (2016).
[6]. M. Kang *et al*., Phys. Rev. B **99**, 045105 (2019).

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Dr. David Broun

Low Energy Phenomenology of the Overdoped Cuprates: Viability of the Landau-BCS Paradigm

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Recent experiments on hole-doped overdoped cuprates, including measurements of superfluid density [1] and THz conductivity [2] in $La_{2-x}Sr_xCuO_4$, have been interpreted as implying the breakdown of the Landau–BCS paradigm in the overdoped regime. In contrast, a phenomenological model based on realistic, ARPES-derived bandstructures and Fermi-liquid renormalizations has been shown to capture essentially all aspects of the thermodynamic and transport properties [3], including superfluid density [4] and THz conductivity [5], provided the unusual effects of weak, out-of-plane dopant impurities are properly accounted for. For simplicity, this phenomenology was initially based on a mixture of Born and unitarity-limit point scatterers, a possible shortcoming of the theory. In the current work, the point scatterers are replaced by realistic impurity potentials computed using *ab-initio* DFT calculations of the defect potentials. These finite-range potentials generate strongly q-dependent scattering amplitudes, leading to significant forward scattering and vertex corrections, which have been included in the model. The van Hove singularity in $La_{2-x}Sr_xCuO_4$ also requires special treatment. What emerges is a robust and realistic model of the overdoped cuprates, showing that thermodynamic and transport properties of overdoped $La_{2-x}Sr_xCuO_4$ and Tl-2201 can be accounted for in a semi-quantitative manner using realistic impurity potentials.

References

[1]. I. Bozovic *et al.*, Nature **536**, 309 (2016).
[2]. F. Mahmood *et al.*, Phys. Rev. Lett. **122,** 027003 (2019). [3]. N. R. Lee-Hone *et al.,* Phys. Rev. R **2**, 013228 (2020). [4]. N. R. Lee-Hone *et al.,* Phys. Rev. B **96**, 024501 (2017). [5]. N. R. Lee-Hone *et al.,* Phys. Rev. B **98** 054506 (2018).

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Prof. Joachim Wosnitza

Orbital-Induced Transformation of FFLO into Abrikosov-like States in an Organic Superconductor

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The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state can emerge in superconductors for which the orbital critical field exceeds the Pauli limit. This state with modulated superconducting order parameter is well established in quasi-two-dimensional (2D) organic superconductors [1]. However, the inevitable presence of orbital effects leads to deviations of the order parameter from the original FFLO prediction. The resulting experimental signatures of the FFLO state are not well understood so far. Here, we present angular-resolved specific-heat data of the 2D organic superconductor κ-$(ET)_2Cu(NCS)_2$, focusing on the orbital suppression of the high-field FFLO state. Rotating the field away from the in-plane orientation leads to an increase of orbital effects and changes the nature of the transition from second to first order. Before orbital effects finally suppress the FFLO superconductivity, the specific-heat data indicate a transition to a further superconducting state. All observations are in line with theoretical predictions of a successive conversion of the FFLO order parameter into an Abrikosov-like one of higher-order Landau levels by increasing orbital contributions. The Abrikosov-like and FFLO states compete in 2D systems and might represent a general phenomenology of 2D Pauli-limited superconductors [2].

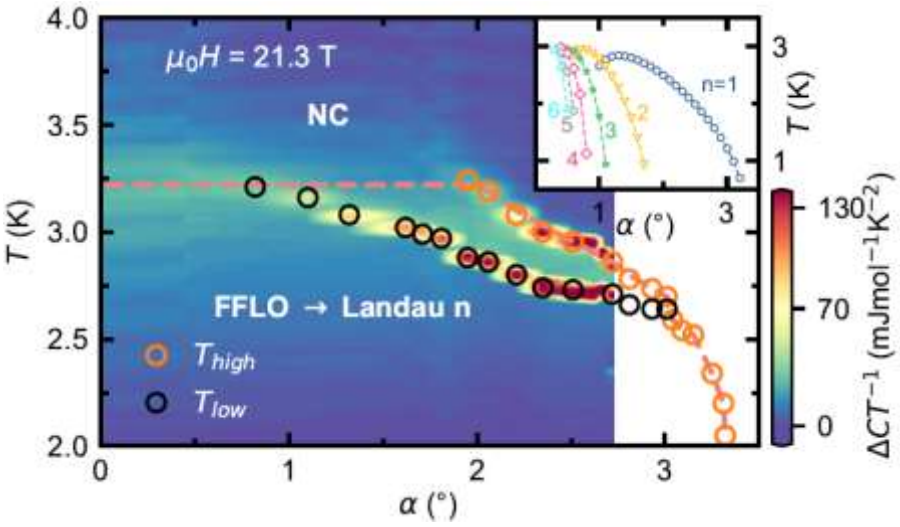

Fig. 1: *Contour plot of the specific-heat difference divided by* T *of* κ*-$(ET)_2Cu(NCS)_2$ at 21.3 T as function of* T *and angle* α*. Inset: Upper critical field at 21.3 T as function of* α *for different Landau states. The envelope of the curves marks the NC-SC transition at* H_{c2}*.*

References

[1] J. Wosnitza, Ann. Phys. **530**, 1700282 (2018).
[2] T. Kotte et al., submitted.

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Zengyi Du, Dr. Hui Li, Dr. Jiahao Yan, Dr. Genda Gu, Shane O'Mahony, Prof. Abhay Pasupathy, Dr. John Tranquada, Dr. Kazuhiro Fujita

Visualization of Electron-Lattice Interactions in the Cuprate Superconductor

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Recent studies of the resonant X-ray scattering on the cuprate superconductors have revealed a strong renormalization of the phonon dispersion, indicating that the cuprate CDW strongly couple to the lattice degree of freedom [1]. We introduce a novel Scanning Tunneling Microscopy (STM) based crystallography technique (STM crystallography) to directly visualize a local lattice distortion of the $Bi_2Sr_2CaCu_2O_{8+\delta}$. The STM crystallography revealed a spatial modulation of the lattice distortion that is strongly coupled to the unidirectional d-symmetry CDW in the pseudogap states. The direct visualization of the electron-lattice interactions here offers a new paradigm for simultaneous studies of them in strongly correlated materials. In this talk, we will present how the lattice degree of freedom is coupled to the d-symmetry CDW in the pseudogap states in $Bi_2Sr_2CaCu_2O_{8+\delta}$.

[1] W. S. Lee, K.-J. Zhou, M. Hepting, J. Li, A. Nag, A. C. Walters, M. Garcia-Fernandez, H. C. Robarts, M. Hashimoto, H. Lu, B. Nosarzewski, D. Song, H. Eisaki, Z. X. Shen, B. Moritz, J. Zaanen and T. P. Devereaux, Spectroscopic fingerprint of charge order melting driven by quantum fluctuations in a cuprate. Nature Phys. **17**, 53–57 (2021).

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Mr. Masaki Roppongi

Impurity Studies on the Pairing State of the Kagome Superconductor CsV_3Sb_5

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Kagome lattice systems have attracted much interest as they provide promising platforms for the realization of various correlated phases such as quantum spin liquids, topological order, superconductivity, charge/spin order, and Mott insulator, owing to their frustrated geometries [1-5].

The recent discoveries of superconductivity (T_c = 0.9~2.5K) and novel charge density wave (CDW) transition (T^* = 78~103K) in the Kagome metals AV_3Sb_5 (A = K, Rb Cs) have boosted tremendous attention because of its unique properties and the relationship between the CDW and superconductivity [3,4]. In particular, it has been theoretically proposed that the Kagome structure may realize unconventional superconducting states such as chiral *d*-wave states with broken time-reversal symmetry and odd-parity *f*-wave states [6,7]. To date the nature of the pairing state in CsV_3Sb_5 has been controversial; an unconventional nodal state has been suggested from the thermal conductivity measurements [8], but magnetic penetration depth, μSR, and NQR studies report fully gapped superconductivity [9-11].

However, none of these bulk measurements reported so far have included the information on the phase of the superconducting gap. In particular, if fully-gapped chiral *d*-wave states were realized, a phase-sensitive probe is required to detect the sign change of the order parameter. Here, we have tested the sign of the superconducting gap in CsV_3Sb_5 by studying how the low-energy excitations measured by the magnetic penetration depth change with introduced impurities by electron-beam irradiation. We will discuss the experimental results before and after irradiation focusing on whether the low-energy quasiparticle excitations are generated or not by Andreev bound states associated with the sign-changing order parameter in CsV_3Sb_5.

References

[1] T. H. Han *et al*., Nature **492**, 406 (2012).
[2] L. Ye *et al*., Nature **555**, 638 (2018).
[3] B. R. Ortiz *et al*., Phys. Rev. Lett. **125**, 247002 (2020).
[4] B. R. Ortiz *et al*., Phys. Rev. Mater. **3**, 094407 (2019).
[5] T. Takenaka *et al*., Sci. Adv. **7**, eabf3996 (2021).
[6] W.-S. Wang *et al*., Phys. Rev. B. **87**, 115135 (2013).

[7] M. L. Kriesel, C. Platt, and R. Thomale. Phys. Rev. Lett. **110**, 126405 (2013).
[8] C. C. Zhao *et al.*, arXiv:2102.08356 (2021).
[9] W. Duan *et al*., *Sci. China Phys. Mech. Astron*. **64**, 107462 (2021).
[10] R. Gupta *et al*., arXiv:2108.01574 (2021).
[11] C. Mu *et al*., arXiv:2104.06698 (2021).

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Prof. Eduardo Marino

A Testable Theory for High-Tc Superconductivity in Cuprates

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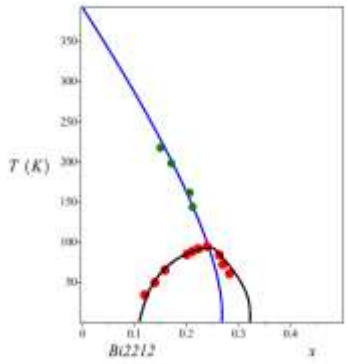
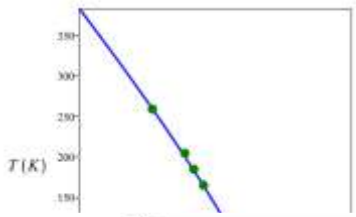
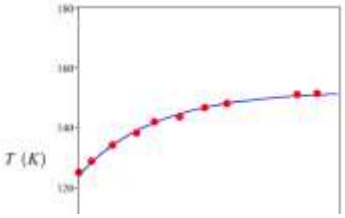
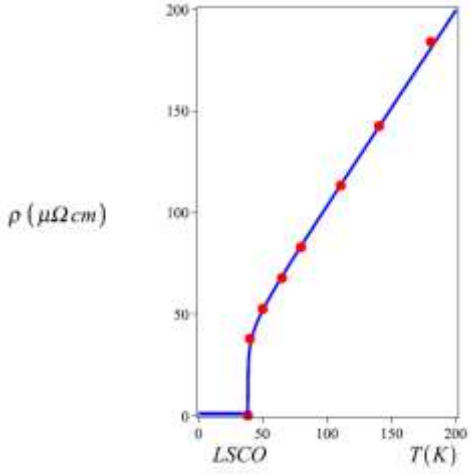
After 35 years of the discovery of superconductivity in cuprates many theories have been proposed to explain its mechanism. Almost all of them, however, fail in providing quantitative predictions that could be compared to experimental data, being, therefore not testable. We propose a theory for High-Tc superconductivity in cuprates, which makes quantitative predictions for Tc(x), T*(x), Tmax(P), ρ(T), ρ(H), among other observable quantities, some of them shown below, which compare favorably with the experimental data for several cuprate materials including LSCO, YBCO, Hg1201, Hg1212, Hg1223, Bi2201, Bi2212, Bi2213. Our theory is, therefore, testable, thus fulfilling one of the first pre-requisites of any acceptable theory. The pairing mechanism in our theory derives from the ferromagnetic fluctuations of the Kondo-like interaction between doped holes and localized Cu ions, the PG stems from the Coulomb repulsion among holes, while the main mechanism consists of resistivity hole-exciton scattering.









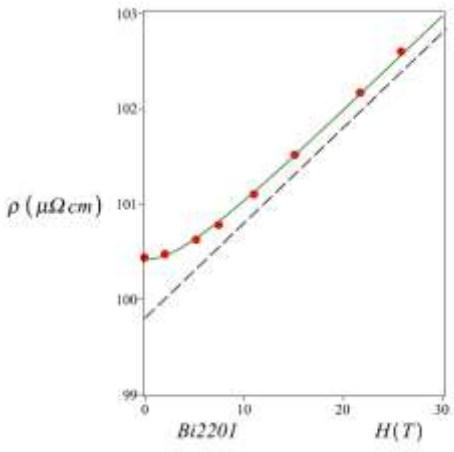


Fig1:*SC/PG Phases of **a)** Hg1201 and **b)** Bi2212. **c)** T_{max} Pressure dependence:Hg1212. **d)** Resistivity of LSCO. **e)** Magnetoresistance of Bi2201. Solid lines: obtained from our theory.*

References

[1]. E. C. Marino *et al*, Supercond. Sci. Tech. **33**, 035009 (2020).
[2]. E. C. Marino, R. Arouca, Supercond. Sci. Tech. **34**, 085008 (2021)
[3]. R. Arouca, E. C. Marino, Supercond. Sci. Tech. **34**, 035004 (2021)

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Prof. Marco Grilli

Dissipation-driven Strange Metal Behavior in High-T_c Superconducting Cuprates

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Besides the mechanism responsible for high critical temperature superconductivity, the grand unresolved issue of the cuprates is the occurrence of a strange metallic state above the so- called pseudogap temperature T*. Even though such state has been successfully described within a phenomenological scheme, the so-called Marginal Fermi-Liquid theory, a microscopic explanation is still missing. However, recent resonant X-ray scattering experiments [1] identified a new class of charge density fluctuations characterized by low characteristic energies and short correlation lengths, which are related to the well-known charge density waves. These fluctuations are present over a wide region of the temperature-vs-doping phase diagram and extend well above T*. A recent investigation showed that charge density fluctuations can explain the strange metal phenomenology [2]. Therefore, charge density fluctuations are likely the long-sought microscopic mechanism underlying the peculiarities of the metallic state of cuprates. A more recent analysis [3] also showed that the damping of these fluctuations can cast in a single and new framework the linear-in-T resistivity of cuprates, sometimes extending down to very low T, and the surprising low-temperature divergence of the specific heat occurring at a critical doping p* slightly larger than the optimal doping. Finally, an even more recent analysis [4] shows that the interplay between overdamped charge density fluctuations and diffusive electron modes due to quenched disorder can interplay to provide a microscopic generic mechanism for the above phenomenology. This scheme puts in a completely different light the strange metal issue and provides a general perspective to account for the strange metal behavior in many other system near quantum critical points, like heavy fermions, ruthenates, iron-based superconductors, and twisted bilayer graphene.

References

[1] R. Arpaia, S. Caprara, R. Fumagalli, G. De Vecchi, Y.Y. Peng, E. Andersson, D. Betto, G.M. De Luca, N.B. Brookes, F. Lombardi, M. Salluzzo, L. Braicovich, C. Di Castro, M. Grilli, and G. Ghiringhelli, Science **365**, 906 (2019)
[2] G. Seibold, R. Arpaia, Y. Y. Peng, R. Fumagalli, L. Braicovich, C. Di Castro, M. Grilli, G. Ghiringhelli, and S. Caprara, Commun. Phys. **4**, 7 (2021).
[3] S. Caprara, C. Di Castro, G. Mirarchi, G. Seibold, and M. Grilli, Commun. Phys. To appear (2022).
[4] S. Caprara, C. Di Castro, M. Grilli, and G. Seibold, in preparation.

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Jordan Baglo

High-field Thermoelectric Measurements on the Cuprate Superconductor $La_{2-x}Sr_xCuO_4$

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The enduring mystery of the exact nature of the pseudogap phase of the high temperature cuprate superconductors continues to attract much attention after three decades. While no consensus has yet emerged for a theory of its microscopic description, there is no lack of experimental evidence for its presence, its fingerprints having been seen in nearly all hole-doped cuprates and across the full gamut of measurement techniques from transport to spectroscopy.

Thermoelectric measurements have recently emerged as a new probe of the pseudogap phase: measurements of the Seebeck coefficient of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO) demonstrate clear changes across its pseudogap critical point $p^* \approx 0.23$ [1,2]. As the pseudogap phase is entered upon hole doping dropping below p^*, the magnitude of both the in- and out-of-plane Seebeck coefficients (S_a and S_c respectively) increase sharply, consistent with the drop in carrier density from $n=1+p$ to $n=p$ [1]. Perhaps more striking is a sharp sign change in S_c at low temperature from positive to negative seen just inside the pseudogap phase [2]. Much of this phenomenology of thermopower in the cuprates on either side of p^* has recently been explained within the framework of a skewed marginal Fermi liquid and the particle-hole asymmetry of its electronic properties across the Fermi level [3], but the inferred reconstruction of the Fermi surface across p^* has yet to be identified.

For further insight into these new thermoelectric signatures of the pseudogap phase, we have turned to another cuprate material, $La_{2-x}Sr_xCuO_4$ (LSCO), for which critical fields exceeding 30 T require high-field magnet facilities to access the normal state at sufficiently low temperatures.

We present the results of our high-field thermoelectric measurements on LSCO, and compare these to prior findings on Nd-LSCO.

References

[1] C. Collignon *et al.*, Phys. Rev. B **103**, 155102 (2021).
[2] A. Gourgout *et al.*, arXiv:2106.05959 (2021).
[3] A. Georges and J. Mravlje, Phys. Rev. Research **3**, 043132 (2021).

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Mr. Michael Denner

Unconventional Charge Order and Superconductivity in the Kagome Metals AV_3Sb_5

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The recent discovery of AV_3Sb_5 (A = K, Rb, Cs) has uncovered an intriguing arena for exotic Fermi surface instabilities in a kagome metal. These materials have been shown to exhibit superconductivity at low temperature and an unusual charge order at high temperature, revealing a connection to the underlying topological nature of the band structure. Specifically, the presence of multiply van Hove singularities in the vicinity of the Fermi level allows for highly unconventional pairing scenarios.
We show that the sublattice interference mechanism is central to understanding the formation of both superconductivity and charge order in these kagome metals. Starting from an appropriately chosen minimal tight-binding model with multiple van Hove singularities close to the Fermi level for AV_3Sb_5, we provide a random phase approximation analysis of superconducting instabilities. Nonlocal Coulomb repulsion, the sublattice profile of the van Hove bands, and the interaction strength turn out to be the crucial parameters to determine the preferred pairing symmetry. We highlight these implications for AV_3Sb_5, place them in the context of wider research efforts in topological physics and superconductivity, and discuss the open problems for this field.

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Dr. Hikaru Ueki

Electromagnetic Response of Niobium Superconducting Cavities

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Niobium superconducting radio-frequency (SRF) cavities have been improved in terms of the quality factor by infusing Nitrogen into the Nb surface [1], and then unprecedented quality factors have been achieved [2]. These high- cavities provide a new technology platform for quantum processors, and quantum sensors for axions, which are dark matter (DM) candidates, and the Euler-Heisenberg (EH) term of low-energy quantum electrodynamics (QED), which contributes to cubic nonlinearities in Maxwell's equations [3,4]. The sensitivity to axion DM and QED EH signals depends on the of SRF cavity. Therefore, it is important to study the impurity effects on the Nb surface of SRF cavities. To understand the fundamental limitations on of these SRF cavities, we have developed nonequilibrium theory of superconducting Nb with non-magnetic impurity disorder based on the Keldysh formalism and the coupling of the charge currents to Maxwell's equations, including numerical methods to calculate the quality factor and frequency shift of N-doped Nb cavities. We show that for strong disorder, , i.e., the dirty limit, pair breaking due to the anisotropic gap energy of Nb limits the , but for intermediate disorder, has a peak of upper convexity as a function of the quasiparticle-impurity scattering rate , suggesting that with "impurity engineering" are possible. We also present new theoretical results for the effects of inhomogeneous disorder on the transition temperature and frequency shift of SRF cavities. Our theoretical results are excellent agreement with experimental results on both the and frequency shift reported in Ref. [5], and provide a new tool for characterization of high- SRF cavities.

This research is supported by the National Science Foundation Grant PHY-1734332.

References

[1]. A. Grassellino et al., Supercond. Sci. Technol. **26**, 102001 (2013).
[2]. A. Romanenko et al., Appl. Phys. Lett. **105**, 234103 (2014).
[3]. Z. Bogorad et al., Phys. Rev. Lett. **123**, 021801 (2019).
[4]. C. Gao and R. Harnik, J. High Energ. Phys. **2021**, 53 (2021).
[5]. D. Bafia et al., arXiv:2103.10601.

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Dr. Jake Ayres

Transport Evidence for Decoupled Nematic and Magnetic Criticality in $FeSe_{1-x}S_x$

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Electronic nematicity in correlated metals often occurs alongside another instability such as magnetism. As a result, the question remains whether nematicity alone can drive unconventional superconductivity or anomalous (quantum critical) transport in such systems. In FeSe, nematicity emerges in isolation, providing a unique opportunity to address this question. Studies to date, however, have proved inconclusive; while signatures of nematic criticality are observed upon sulfur substitution, they appear to be quenched under the application of pressure due to the emergent magnetism. Here [1], we study the temperature and pressure dependence of the low-temperature resistivity of $FeSe_{1-x}S_x$ crystals at *x* values just beyond the nematic quantum critical point. Two distinct components to the resistivity are revealed; one whose magnitude falls with increasing pressure and one which grows upon approaching the magnetic state at higher pressures. These findings indicate that nematic and magnetic critical fluctuations in $FeSe_{1-x}S_x$ are completely decoupled, in marked contrast to other Fe-based superconductors, and that nematic fluctuations alone may be responsible for the transport signatures of quantum criticality found in $FeSe_{1-x}S_x$ at ambient pressure.

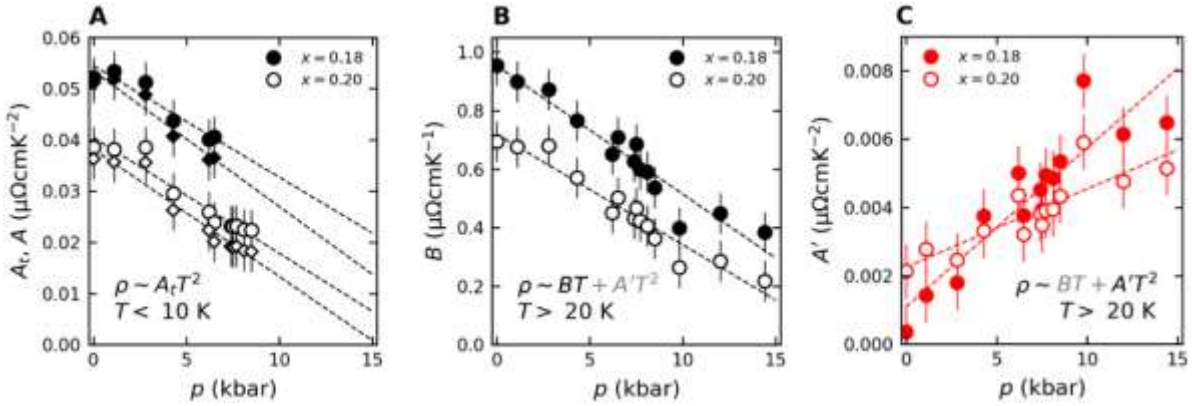

Fig. 1: *A component of the high-field resistivity ρ(T, B=35 T) that crosses from T^2 at low-T to T-linear at higher T with coefficients A and B which has previously been associated with nematic quantum criticality [2] is suppressed by hydrostatic pressure* ***(panels A and B)****. A second component that remains purely T^2 up to 40 K with coefficient A' is enhanced with pressure* ***(panel C)****.*

References

[1]. J. Ayres, arXiv:2106.08821 (2021).
[2]. S. Licciardello, Nature **567**, 213-217 (2019).

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Prof. Fabio Boschini

Non-monotonic electron interactions in the copper oxide plane

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In strongly correlated systems the strength of Coulomb interactions between electrons plays a central role in determining their emergent quantum mechanical phases. While electrons in free space have a Coulomb interaction that decays monotonically with distance, the effective Coulomb interaction in solids may be non-monotonic, with a minimum at a finite length. This general concept of how electrons interact in solids may be key to understanding the emerging electronic phases of strongly correlated quantum materials. For instance, a non-monotonic Coulomb potential may result in an attractive interaction that could lead to superconductivity or density wave order.
We performed resonant x-ray scattering on $Bi_2Sr_2CaCuO_{8+x}$, prototypical cuprate superconductor, to probe electronic correlations within the CuO_2 plane. We discovered a dynamic quasi-circular pattern in the q_x-q_y scattering plane with a wave vector radius that is determined by the minimum of the Coulomb potential [1], as shown in Fig. 1(a) and (b), respectively. Furthermore, this radius exactly matches the wave vector magnitude of the well-known static charge order patterns. Our experiments revealed a picture of charge order competing with superconductivity where short-range domains along x and y are allowed to dynamically rotate into any other in-plane direction [1]. Here I will present brand-new results showing how quasi-circular charge correlations evolve with doping, as well as how dynamical charge correlations couple with specific collective excitations (such as phonons or magnons) over the whole momentum space.

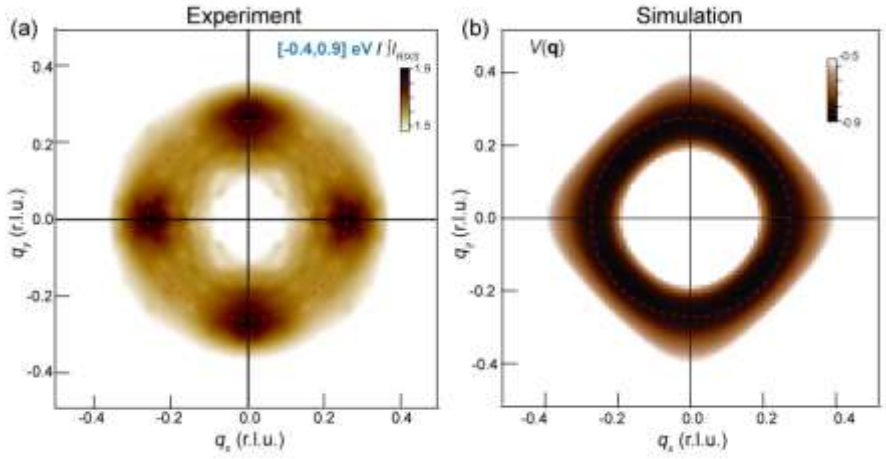

Fig. 1: *(a) RIXS intensity in the q_x-q_y plane integrated over the [-0.4,0.9] eV range and normalized to the total fluorescence. (b) The structure of the Coulomb interaction V(**q**), calculated taking into account both short- and long-range interaction [1].*

References

[1]. Boschini et al. Nature Communications 12, 597 (2021)

Dr. Genda Gu, Ruidan Zhong, J. A. Schneeloch, Yangmu Li, Prof. Qiang Li, Tonica Valla, Dr. John Tranquada

Searching for ideal topological crystalline insulators and topological superconductors in Pb-Sn-In-Te system

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The discovery of 3D topological insulator materials and topological superconductor open up a new research field in the condensed matter physics. In order to search for the topological superconductor, we have grown a large number of the single crystals of Pb-system (Pb-Sn-In-Te) topological crystalline insulator and their topological superconductor . We have measured the physical properties on these single crystals by various techniques. We have studied the effect of crystal growth condition, impurity and composition on the bulk electrical conductivity of these single crystals. We try to find out which composition and crystal growth condition is the best for the ideal topological insulator, topological crystalline insulator and topological superconductor. We have got the bulk topological superconductor with T_c=5K.

Prof. Leonardo Degiorgi

Unprecedented Optical Anisotropy in Optimally Doped Iron-Based Superconductor

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The divergent nematic susceptibility, obeying a simple Curie-Weiss power law over a large temperature interval, is empirically found to be a ubiquitous signature in several iron-based materials across their doping-temperature phase diagram. The composition at which the associated Weiss temperature extrapolates to zero is found to be close to optimal doping, boosting the debate to what extent nematic fluctuations contribute to the pairing-mechanism and generally affect the electronic structure of iron-based superconductors. Here, we offer a comprehensive optical investigation [1] of the optimally hole-doped $Ba_{0.6}K_{0.4}Fe_2As_2$ over a broad spectral range, as a function of temperature and of tunable applied stress, which acts as an external symmetry breaking field. We show (Fig. 1) that the stress-induced optical anisotropy in the infrared spectral range is reversible upon sweeping the applied stress and occurs only below the superconducting transition temperature. These findings demonstrate that there is a large electronic nematicity at optimal doping which extends right under the superconducting dome.

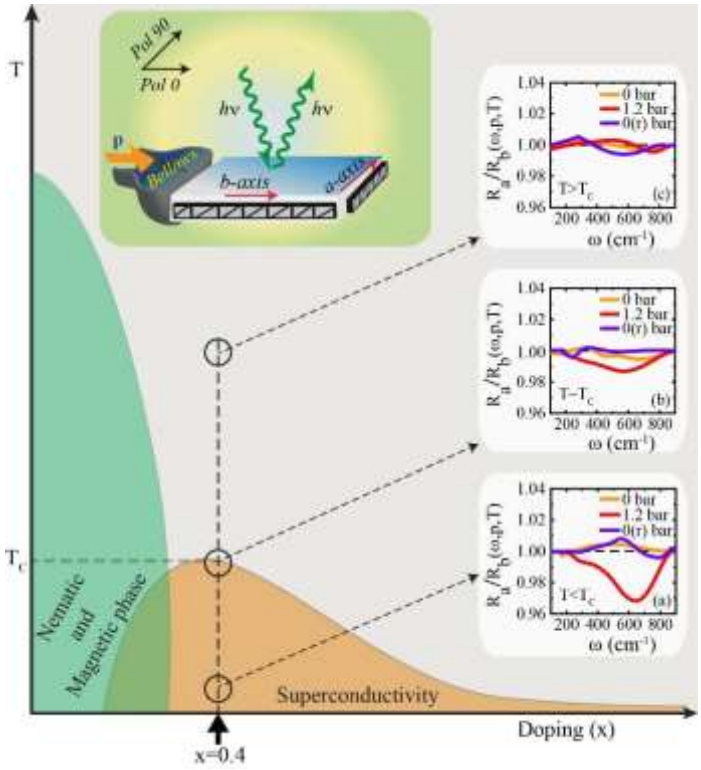

Fig. 1: *Schematic view of the experiment and flavour of the major findings within the generic phase diagram of* $Ba_{1-x}K_xFe_2As_2$.

References

1. A. Pal et al., npj Quantum Materials **4**, 3 (2019).

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Metastable States and Hidden Phase Slips in Nanobridge SQUIDs

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Phase slips – topological fluctuations of the order parameter – are an indispensable ingredient for understanding the behaviour of various superconducting nanodevices [1]. Ring-like structures like SQUIDs are particularly suitable for studying single phase slip events, due to the co-existence of multiple energy states at one specific field value. Each of these energy states corresponds to a unique value of the winding number (or vorticity) of the superconducting order parameter along the ring [2,3]. A single phase slip event modifies the vorticity of the ring, which is directly linked to a variety of macroscopic observables such as the critical current of the device. Measuring the $I_c(B)$-dependence of a SQUID thus directly translates to reading out its vorticity state. In this work, long nanobridges are used as junctions in the SQUID to introduce metastability in the SQUID energy landscape and hence $I_c(B)$-curves. A protocol to initialize the SQUID into a particular vorticity state before read-out is introduced. By comparing the vorticity in which the SQUID has been initialized with the vorticity determined upon read-out, it becomes possible to pinpoint whether phase slips have occurred during the measurement, even if these phase slips do not drive the SQUID to the normal state (“hidden phase slips”).

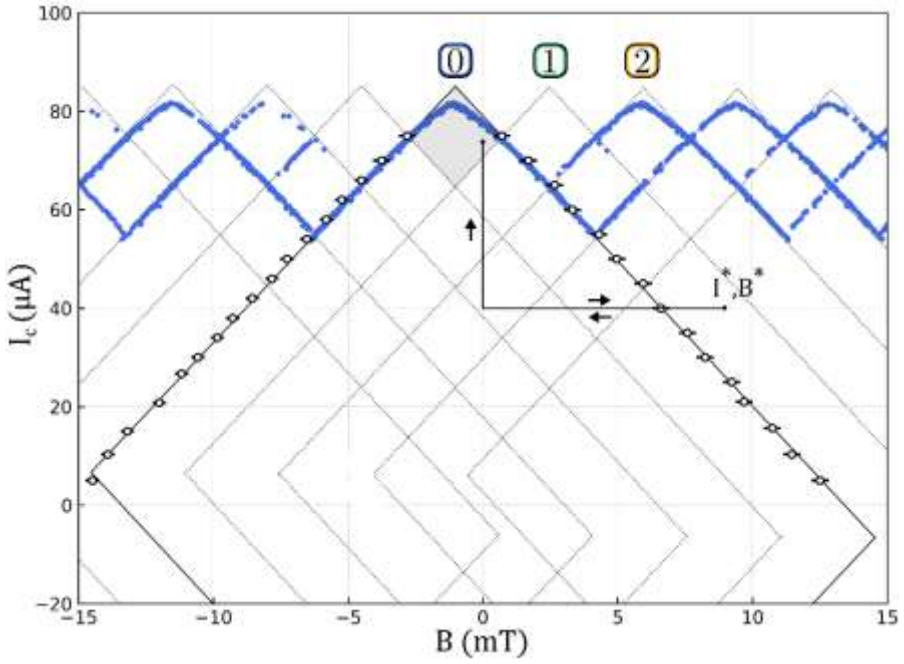

Fig. 1: *Critical currents versus applied magnetic field after preparing a SQUID in vorticity state 0 are indicated in blue. The different diamonds indicate different vorticity states, of which vorticity 0, 1 and 2 are labelled. The open black circles denote the locations of the hidden phase slips, obtained using the novel measurement protocol.*

References

[1]. X. Baumans et al., Sci. Rep. **7**, 44569 (2017).
[2]. I. Petkovic et al., Nat. Commun. **7**, 13551 (2016).
[3]. H. Dausy et al., Phys. Rev. Applied **16**, 024013 (2021)

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Prof. David Hawthorn

Response of electronic symmetry-breaking phases under uniaxial strain in cuprate superconductors

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In the cuprate superconductors, uniaxial charge density wave order co-exists and competes with superconductivity. In the $La_{2-x}M_xCuO_4$ (M = Sr, Nd, Ba, Eu) family of cuprates, the charge density wave order often onsets at or below the onset of a low-temperature tetragonal (LTT) structural phase that breaks the rotational symmetry of the CuO_2 planes. Recent resonant x-ray scattering measurements have shown electronic meta-nematic order occurs within the LTT phase. [1,2] Here we use resonant soft x-ray scattering to examine how charge density wave order (CDW) and nematic order in $La_{2-x}M_xCuO_4$ cuprates evolve under applied uniaxial strain. We show that applied compressive strain reduces both electronic nematicity and CDW order, adding insight in the relationship between CDW order, nematicity and structural phases of the cuprates.

References

[1]. AJ Achkar, M Zwiebler, Christopher McMahon, F He, R Sutarto, Isaiah Djianto, Zhihao Hao, Michel JP Gingras, M Hücker, GD Gu, A Revcolevschi, H Zhang, Y-J Kim, J Geck and DG Hawthorn. Science **351**, 576 (2016).

[2]. Naman K. Gupta, Christopher McMahon, Ronny Sutarto, Tianyu Shi, Rantong Gong, Haofei I. Wei, Kyle M. Shen, Feizhou He, Qianli Ma, Mirela Dragomir, Bruce D. Gaulin, and David G. Hawthorn. PNAS **118**(34), e2106881118 (2021).

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Tom Laurin Lacmann

Pressure-temperature phase diagram of $BaNi_2As_2$

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The normal state of the superconductor $BaNi_2As_2$ (T_c=0.6K) exhibits a variety of unconventional charge-ordered phases that have recently attracted much attention. At ambient conditions $BaNi_2As_2$ shows the same $ThCr_2Si_2$ structure type (SG: I4/mmm) as the iron-based superconductor $BaFe_2As_2$. An incommensurate charge density wave (IC-CDW) with ordering wavevector q=(0.28 0 0)$_{tet}$ forms upon cooling and the system undergoes a second order transition to an orthorhombic I/mmm phase below T=142K. This transition is shortly followed (T=137K) by a first order one into a triclinic phase (SG: P-1) in which a commensurate CDW (C-CDW) appears (q=(1/3 0 1/3)$_{tet}$) replacing the IC-CDW. [1-3]
We report a detailed high-resolution x-ray diffraction study of the crystal structure and the various charge-ordered phases as function of temperature and hydrostatic pressure (up to 13 GPa), revealing a cascade of new CDW phases.

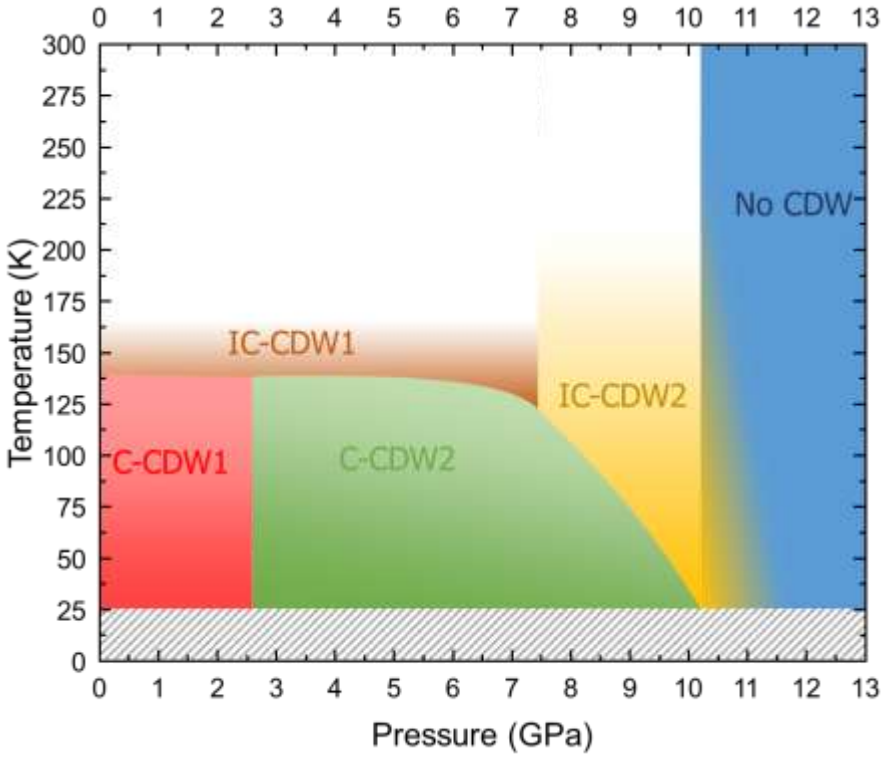

Fig. 1: Sketched p-T phase diagram of $BaNi_2As_2$ showing the different observed CDWs.

References

[1]. M. Merz et al., Phys. Rev. B **104**, 184509 (2021).
[2]. Lee et al., Phys. Rev. Lett. **122**, 147601 (2019).
[3]. Lee et al., Phys. Rev. Lett. **127**, 027602 (2021).

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Prof. Matthieu Le Tacon

Unraveling the competition between CDW and high-temperature superconductivity in the cuprates by uniaxial pressures

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We report a comprehensive resonant and non-resonant x-ray scattering study of two- and three dimensional (2D and 3D) incommensurate charge correlations in the underdoped high temperature superconductor YBa2Cu3O6+x under uniaxial compression along the two inequivalent Cu—O—Cu bond directions (a and b) in the CuO2 planes. We confirm the strong in-plane anisotropy of the 2D charge correlations and observe their symmetric response to pressure: pressure along a enhances correlations along b, and vice versa. Our results imply that the underlying order parameter is uniaxial. In contrast, for compression up to 1%, 3D long-range charge order is only observed along b in response to compression along a. Spectroscopic RXS measurements show that the 3D charge order resides exclusively in the CuO2 planes and may thus be generic to the cuprates. We discuss implications of these results for models of electronic nematicity and for the interplay between charge order and superconductivity.

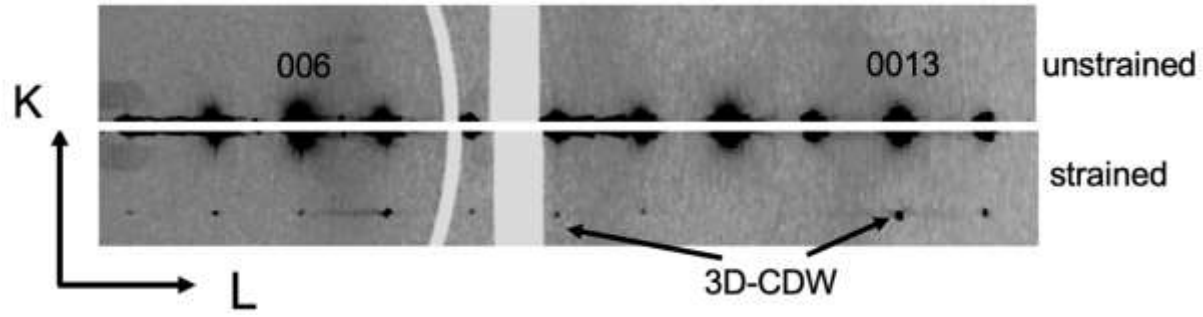

Fig. 1: *(0KL) reciprocal plane of underdoped $YBa_2Cu_3O_{6+x}$ without (upper panel) and with (lower panel) applied uniaxial pressure ($T \sim T_c$)*

References

[1]. Kim, Souliou et al. Science 362, 1040 (2018).
[2]. Kim et al. Phys. Rev. Lett. 126, 037002 (2021).
[3]. Souliou et al. in preparation (2022).

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Prof. Dirk Van Der Marel

Charged phonons and the mechanism of superconductivity in doped $SrTiO_3$ and $KTaO_3$

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$SrTiO_3$ is an insulating material close to a ferroelectric instability. This instability brings along that the frequency of one the transverse optical modes is low and approaches zero when the material is tuned through the transition into the ferroelectric phase. This is a so-called "charged phonon" [1], i.e. the oscillator strength exceeds the value expected for an ionic compound, and has been observed in buckminster-fullerene [2] and FeSi [3] and bilayer graphene [4]. In all these cases the extra oscillator strength is caused by coupling of the vibrational motion to electronic interband transitions.
When $SrTiO_3$ is doped with even a tiny density of electrons, the material becomes superconducting. However, the superconducting pairing mechanism has remained elusive due to the difficulty that the conventional electron-phonon pairing strength vanishes when the Fermi wave-vector tends to zero. Low doped $KTaO_3$ is also superconducting up to 2.2 K [5], and the insulating parent compound exhibits the charged phonon effect.
We have demonstrated that the strong charged phonon effect gives rise to a two-phonon pairing mechanism in electron doped $SrTiO_3$ [6]. Direct application of optical sum rules to the optical and soft X-ray spectra provides quantitative values for the electron-biphonon coupling in the correct range for the experimentally known Tc values. Applying the same arguments to $KTaO_3$, the electron-biphonon coupling should be even stronger in this material. This confirms the proposal of Ngai of a bi-phonon exchange mechanism [7], it provides the missing link between superconductivity and quantum ferroelectric fluctuations [8], and it explains the measured temperature dependences of resistivity and Seebeck coefficient [9].

References

[1] M. J. Rice, N. O. Lipari, and S. Strässler, *Phys. Rev. Lett*. **39**, 1359 (1977).
[2] M. J. Rice and H.-Y. Choi, *Phys. Rev. B* **45**, 10173 (1992).
[3] A. Damascelli, K. Schulte, D. van der Marel, and A. A. Menovsky, *Phys. Rev. B* **55**, R4863 (1997).
[4] E. Cappelluti, L. Benfatto, M. Manzardo, and A. B. Kuzmenko, *Phys. Rev. B* **86**, 115439 (2012).
[5] C. Liu et al, *Science* **371**, 716 (2021).
[6] D. van der Marel, F. Barantani & C. W. Rischau; *Phys. Rev. Res.* **1**, 013003 (2019)
[7] K. L. Ngai, *Phys. Rev. Lett*. **32**, 215 (1974).
[8] J. M. Edge, Y. Kedem, U. Aschauer, N. A. Spaldin, and A. V. Balatsky, *Phys. Rev. Lett.* **115**, 247002 (2015).
[9] Kh. G. Nazaryan and M. V. Feigel'man, *Phys. Rev. B* **104**, 115201 (2021).

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Prof. Nicola Pompeo

Flux-flow, pinning and creep in the vortex small oscillation regime in (Y,Gd)BCO and FeSeTe films in high dc magnetic fields

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Microwave transport properties in a dc field probe a very different dynamic regime with respect to dc, thus providing different and complementary information: small amplitude oscillations probe the quadratic pinning potential and yield the Labusch parameter k_p. By exploiting the measurement of real and imaginary parts one has access to the free-flux-flow resistivity ρ_{ff}, and performing measurements at two frequencies one has sufficient observables to estimate also the thermal creep factor χ, whence the small-displacement vortex activation energy.

We exploit a two-frequency measurement technique based on dielectric resonators operating at 15/24 GHz to obtain ρ_{ff}, k_p and χ, from the field-dependent surface impedance shift $\Delta Z(H,T)$ as measured in $FeSe_{0.5}Te_{0.5}$ (FeSeTe), $YBa_2Cu_3O_{7-x}$ (YBCO), and $(Y,Gd)Ba_2Cu_3O_{7-x}$ ((Y,Gd)BCO) thin films as a function of the temperature down to 4 K and of the magnetic field up to 12 T. In all cases we find very small activation energies, showing that the pinning potential is composed of a distribution of pinning wells and that only the smallest ones are probed in the vortex small-oscillation regime by small jumping portions, having sizes on the scale of ξ^3. The field independence of k_p points to single vortex pinning both in YBCO [1] and (Y,Gd)BCO, with a small but appreciable increase in k_p and reduction in creep χ due to Gd addition, consistently with the results in terms of critical current density which slightly improves especially at low T. The inclusion of Gd point defects in (Y,Gd)BCO does not change at all ρ_{ff}, showing that the underlying quasiparticle state is robust against this kind of defects.

On the other hand, in FeSeTe [2] k_p exhibits smaller values than YBCO and decreases appreciably when the field grows above 3-5 T. The field dependence points to a collective pinning regime, where vortex bundles are collectively pinned by weak pins. From the point of view of perspective applications, vortex pinning optimization is needed to enable FeSeTe to reach YBCO performances in high frequency regimes.

Finally, we compare the results with the observations in conventional Nb_3Sn, where the field dependence of k_p points to a collective pinning regime similar to the one observed in FeSeTe, while ρ_{ff} exhibits a nearly textbook-like Bardeen-Stephen field dependence [3].

This work was partially supported by MIUR-PRIN Project “HIBiSCUS” under Grant 201785KWLE and by MoU-FCC ADDENDUM FCC-GOV-CC-0218 (KE5084/ATS).

References

[1]. A. Alimenti et al., IEEE Instrum. Meas. Mag. **24**, 12-20 (2021). [2]. N. Pompeo et al., Supercond. Sci. Technol. **33**, 114006 (2020). [3]. A. Alimenti et al., Supercond. Sci. Technol. **34**, 014003 (2021).

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Jonathan Pelliciari

Effect of capping layer on superconducting $Nd_{1-x}Sr_xNiO_2$

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The recent discovery of superconductivity in infinite layer nickelates thin films has spurred a lot of attention in the scientific community [1]. These materials appear to be analog to the cuprates with parent compounds having a single hole in the *d* orbitals that upon hole doping become superconducting. The detection of spin excitations and charge density waves [2,3] further corroborated such similarities even if major differences such as the role of rare earth and the balance between Hubbard (U) and charge transfer energies raise questions on their actual similarity. One open question regards the role of the $SrTiO_3$ capping layer which is believed to have effect on the ground state [4].

In my talk, I will present how Resonant Inelastic X-Ray Scattering (RIXS) can unveil the role of the capping layer for the excitations in $NdNiO_2$ and optimal-doped $Nd_{1-x}Sr_xNiO_2$. In uncapped $NdNiO_2$ compound we observe hints of charge density wave and damped spin excitations resembling the one observed in the capped compound [2]. The intensity of the spin excitations is however strongly decreased compared to the capped compound indicating a renormalization of magnetism. In superconducting materials, independently of the presence of capping, we observe an overall softening of the spin excitations compared to the parent compound. Comparing the capped and uncapped $Nd_{0.8}Sr_{0.2}NiO_2$ we observe at intermediate momenta a significant difference in the dispersion of the capped sample concomitant with a significant broadening. Overall, the spin excitations spectrum is suppressed in uncapped samples indicating a strong influence of the capping layer on the magnetism in these compounds. Remarkably, the spectral weight of the Ni-Nd charge transfer is also highly suppressed. Finally, I will compare this experimental evidence in relation to previous calculations accounting for the presence or lack of the capping layer.

These pieces of evidence uncover the effect of the capping layer on magnetism and Ni-Nd hybridization which has strong implications in the understanding of nickelate superconductivity. This also represents an opportunity for heterostructuring of superconducting nickelates with other materials as a possibility to tune the delicate balance between their electronic properties.

References

[1]. D. Li et al., "Superconductivity in an Infinite-Layer Nickelate.", Nature 572, 624 (2019) [2]. H. Lu et al., "Magnetic excitations in infinite-layer nickelates", Science 373, 213 (2021) [3]. C. C. Tam et al., "Charge density waves in infinite-layer $NdNiO_2$ nickelates", arxiv 2112.04440 (2021); M. Rossi et al., "A Broken Translational Symmetry State in an Infinite-Layer Nickelate" arxiv 2112.02484 (2021)
[4]. G. Krieger et al., "Charge and spin order dichotomy in $NdNiO_2$ driven by $SrTiO_3$ capping layer", arxiv 2112.03341 (2021)

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Dr. Erik Piatti

Ion-gated molybdenum disulphide: a novel platform for tunable multi-band superconductivity

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Gate-induced superconductivity (SC) in semiconducting transition metal dichalcogenides (TMDs) has attracted a lot of attention due to the sizeable transition temperature, in-plane critical magnetic fields beyond the Pauli limit, and hints to a non-conventional nature of the pairing. Its microscopic origin hinges on the geometry of the Fermi surface (FS) hosting the Cooper pairs, which is dictated by the filling of the inequivalent valleys at the K/K' and Q/Q' points of the Brillouin zone. While it is often assumed that Cooper pairs reside only in the two electron pockets at K/K', experimental and theoretical results suggest that a multi-valley FS is associated with the SC state, involving the six electron pockets at Q/Q'. Here, I will present a combination of low-temperature electric transport and Raman spectroscopy measurements in ion-gated MoS_2 thin flakes [1] with ab-initio DFT calculations of the bandstructure [2,3] to show that a fully multi-valley FS is associated with the onset of the SC state, which does not occur until the Fermi level crosses both spin-orbit split sub-bands in the Q/Q' valleys. This allows us to map the dependence of the FS of gated MoS_2 on field-effect doping and demonstrates that the SC state is promoted by multiple Lifshitz transitions due to the simultaneous filling of multiple valleys.

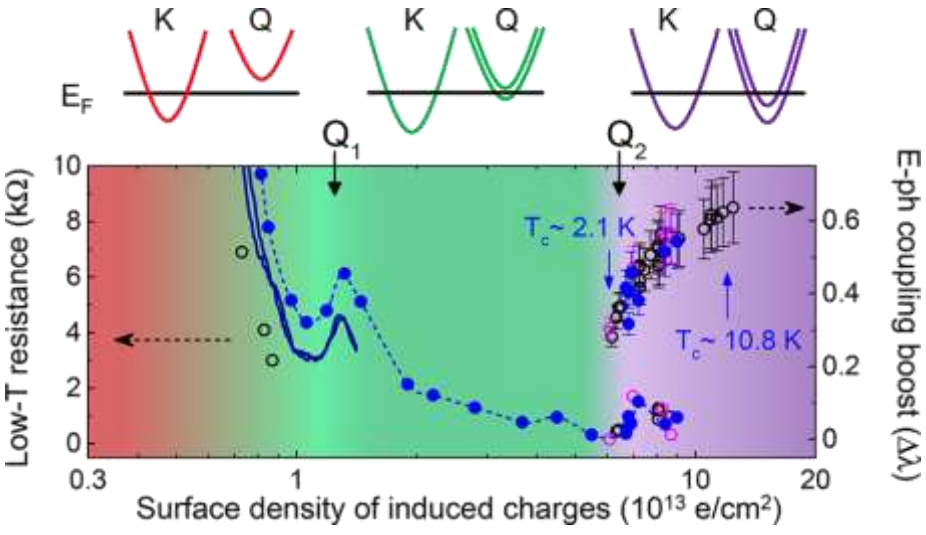

Fig. 1: *Density-dependent resistance at ~11 K, electron-phonon coupling boost, and sketch of the corresponding bandstructure of ion-gated MoS_2. Reprinted with permission from Nano Lett. 2018, 18, 8, 4821–4830. Copyright 2018 American Chemical Society.*

References

[1]. E. Piatti *et al.*, Nano Lett. **18**, 4821-4830 (2018).
[2]. E. Piatti *et al*., J. Phys. Condens. Matter **31**, 114002 (2019).
[3]. D. Romanin *et al.*, J. Appl. Phys. **128**, 063907 (2020).

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David Dawson

2D Superconductivity and the Ferrell-Glover-Tinkham Sum Rule in Thin Film Cuprate Superconductors: Comprehensive THz-IR Study

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The commonality of the layered CuO_2 plane structure to all families of copper oxide high-T_c superconductors (HTSCs) implies that understanding the effect of reduced dimensionality on superconductivity in the cuprates is key to elucidating the mechanism of HTSC. Even in the presence of strong anisotropy, the CuO_2-bilayer material $RBa_2Cu_3O_{7-\delta}$ (R = rare earth) displays critical fluctuations belonging to the 3D-*XY* universality class. Close to optimal doping the 2D-like properties of the superconducting (SC) condensate appear only within a very narrow temperature range close to T_c where uncorrelated fluctuations in adjacent CuO_2 layers are described by the Berezinskii-Kosterlitz-Thouless (BKT) vortex unbinding transition. One interesting approach to broaden the temperature range over which 2D fluctuations appear is to investigate the evolution of cuprate physics in the ultra-thin film limit where the film thickness becomes less than the *c*-axis SC coherence length. Recently, advancements in MBE growth of thin films have enabled 2D SC to be achieved in high quality cuprate films with control over doping level, disorder, and structural distortions. In this talk, I will report a study of the temperature dependence of the superfluid density as a function of thickness as well as measurements of the terahertz and infrared optical conductivity in a series of $DyBa_2Cu_3O_{7-\delta}$ SC thin films. In the ultra-thin film limit near optimal doping the temperature scaling exhibits signatures of the BKT vortex unbinding transition that is characteristic of fluctuations belonging to the 2D-*XY* universality class in the presence of moderate disorder [1]. Additionally, the broadband (THz to IR/visible) spectroscopy technique gives direct access to the full complex dielectric response. The evolution of the complex conductivity over such a wide energy range suggests that the transfer of spectral weight below T_c is conserved and the Ferrell-Glover-Tinkham sum rule is obeyed in $RBa_2Cu_3O_{7-\delta}$ films to within 0.2% accuracy.

References

[1]. R. D. Dawson *et. al.*, Physical Review Letters 125, 237001 (2020).

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Mr. Olivier Gingras

Frequency-dependent Solutions of Superconducting Strontium Ruthenate

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Recent experimental improvements have shifted the discussion on superconducting Sr_2RuO_4 away from the chiral p-wave solution, yet experiments give seemingly different pictures that are challenging to reconcile [1, 2]. In this multi-orbital system with important spin-orbit coupling, pairing mediated by electronic correlations leads to superconducting order parameters with rich structures. Taking advantage of pseudospin and inversion symmetries, we investigate the possible superconducting instabilities mediated by these spin and charge fluctuations. We find that spin-orbit coupling ubiquitously mixes even and odd contributions in orbital, spin and frequency spaces. We find two different leading inter-pseudospin symmetries depicted in the phase diagram in Fig. 1: a B_{1g}^{+} and an A_{2g}^{-} that have intra-orbital components respectively even and odd in Matsubara frequencies, consistent with a previous study neglecting spin-orbit coupling [3]. An accidental degeneracy between those could help unify experimental evidence.

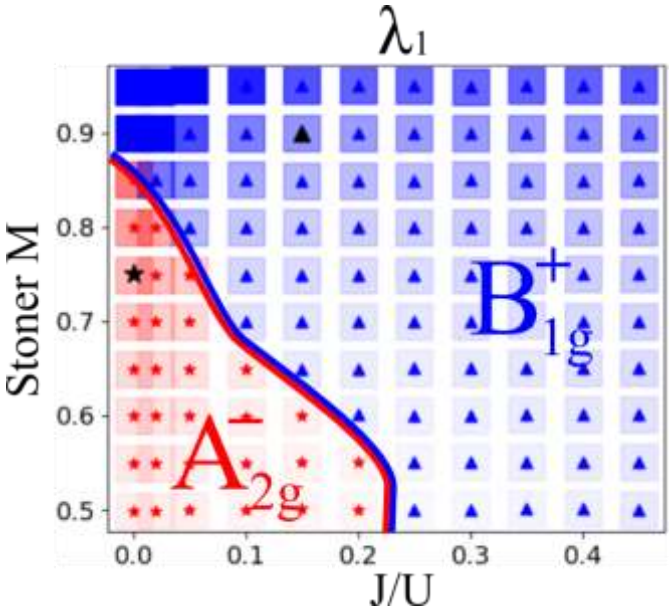

Fig. 1: *Phase diagram of the leading superconducting symmetries for strontium ruthenate in the parameter space of the two-particle interaction, namely the ratio of Hund's coupling J over the*

strength of the Hubbard repulsion U versus the proximity to a magnetic instability characterized by the magnetic stoner factor. The starting band structure is obtained from density functional theory band structure that includes spin-orbit coupling. The B_{1g}^{+} is a typical d-wave while the A_{2g}^{-} is an odd-frequency solution.

References

[1] V. Grinenko *et al.* Nat. Phys. **17**, 748–754 (2021).
[2] Y.-S. Li *et al.* Proceedings of the National Academy of Sciences **118**.10 (2021).
[3] O. Gingras *et al.* Phys. Rev. Lett. **123**, 217005 (2019).

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Dr. Mehdi Frachet

Nematicity, Charge Density Waves and Lattice Distortions in $BaNi_2(As_{1-x}P_x)_2$

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Most clearly observed in iron-based superconductors, nematicity is often thought as originating from magnetic fluctuations. Recently, an analogue to iron-based superconductors, $BaNi_2As_2$, has emerged as a promising candidate for a novel type of nematicity triggered by charge fluctuations [1,2,3].

In this talk, we discuss electrical transport measurements under strain, directly probing the nematic susceptibility of $BaNi_2(As_{1-x}P_x)_2$ with . We resolve, across the entire substitution range investigated, a well-defined response in the B_{1g} (x^2-y^2) channel. Interestingly, the temperature dependence of the B_{1g} elastoresistance in $BaNi_2(As_{1-x}P_x)_2$ markedly contrast with the one of $BaFe_2As_2$ in the B_{2g} (xy) channel, indicating important differences for the corresponding susceptibilities at temperatures above the four-fold symmetry breaking phases (see Fig. 1). Finally, our measurements indicate a close, yet complex, relationship of the strain-dependent electrical resistance with both charge ordering and structural distortions.

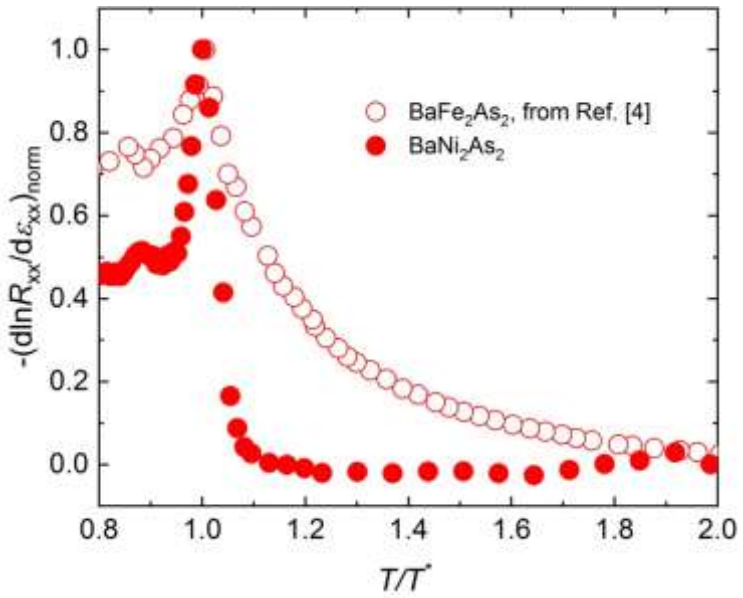

Fig. 1: *Normalized variation of the longitudinal electrical resistance with strain for $BaFe_2As_2$ (empty symbols, from Ref. [4]) and $BaNi_2As_2$ (full symbols) as a function of T/T^*, where T^* is the temperature of maximum elastoresistance*. *Note that for $BaFe_2As_2$ x//[110] while for $BaNi_2As_2$ x//[100] in tetragonal notation.*

References

[1] Lee et al., Phys. Rev. Letters **112**, 147601 (2019).
[2] Eckberg et al., Nat. Phys. **16**, 346 (2020).
[3] Merz et al., Phys. Rev. B **104**, 184509 (2021).
[4] Chu et al., Science **337**,710 (2012).

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Dr. Wan Kyu Park

Local-Moment-Involved Paring in the Heavy-Fermion Superconductor $CeCoIn_5$

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A major challenge in the superconductivity research is unraveling the microscopic pairing mechanism, which is the case for the heavy-fermion superconductor $CeCoIn_5$ despite intensive studies over the past two decades. The exact origin of the neutron spin resonance, a key experimental signature for the pairing mediated by antiferromagnetic spin fluctuations, has been debated without reaching at a consensus. Moreover, the counterpart signature in tunneling conductance is missing, unlike in the cuprate and iron-based superconductors. We have carried out tunneling spectroscopy for all three major crystallographic directions of $CeCoIn_5$ [1]. Our detailed and reproducible conductance spectra strongly indicate that: i) The pair formation begins at ~5 K, well above T_c (2.3 K); and ii) The pairing process directly involves local moments. The latter, inferred from the novel field-induced gaplike feature (Fig. 1), points to a key role played by the local physics underlying the cooperative two-channel Kondo resonance [2].

The work at the NHMFL was supported by the US NSF/DMR-1704712 & NSF/DMR-2003405 (KS, SZ, LHG, WKP), DOE EFRC DE-SC0016568 (YL, RB), and in part by the NSF/DMR-1644779 and the State of Florida. The work at UCSD was funded by the US DOE-BES DEFG02-04-ER46105 and the NSF/DMR-1810310.

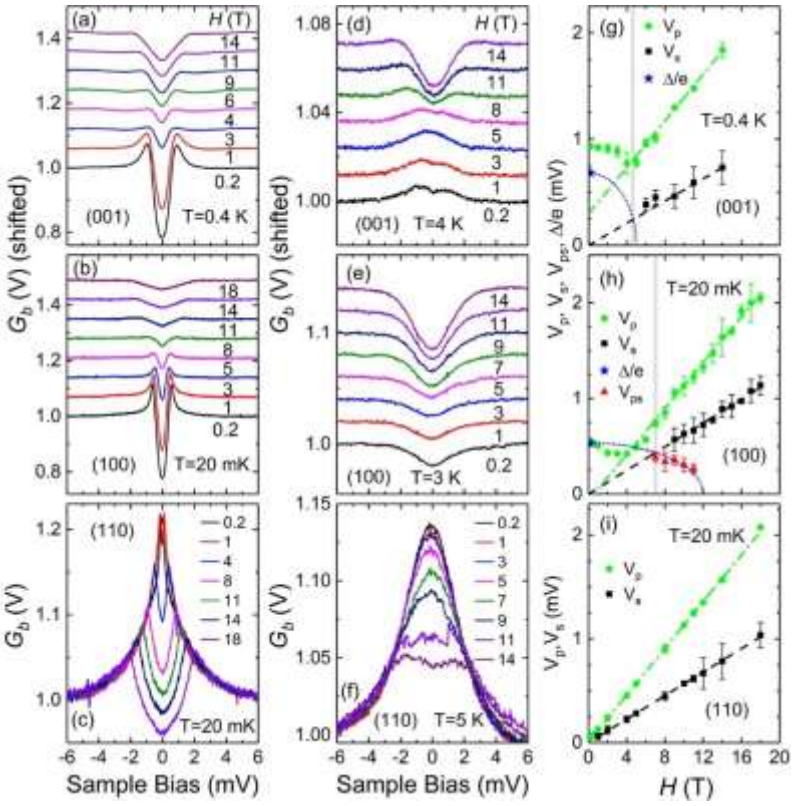

Fig. 1: Magnetic field- induced gaplike feature [1]. *(a)–(c) Field evolution of the tunneling conductance across $CeCoIn_5/AlO_x/Pb$ junctions taken well below T_c for (001), (100), and (110) directions, respectively. The coherence peaks turn into a new gaplike feature instead of dying out monotonously. (d)–(f) The same for well above T_c. (g)–(i) Field dependence of the peak position (V_p), steepest-slope point (V_s), energy gap (Δ), and slope-changing point (V_{ps}) caused by the pairing gap. From the linear field dependence of V_s, reminiscent of Zeeman splitting, the g factor is extracted as follows: 1.81±0.43, 2.14±0.22, and 1.96±0.25 for each direction.*

References

[1]. K. Shrestha et al., Phys. Rev. B **103**, 224515 (2021).

[2]. R. Flint et al., Nat. Phys. **4**, 643 (2008); Phys. Rev. Lett. **105**, 246404 (2010).

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Dr. Willem Rischau

Isotope tuning of the superconducting dome of strontium titanate

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Doped strontium titanate $SrTiO_3$ (STO) is one of the most dilute superconductors known today. The fact that superconductivity occurs at very low carrier concentrations is one of the two reasons that the pairing mechanism is not yet understood, the other is the role played by the proximity to a ferroelectric instability. In undoped STO, ferroelectric order can in fact be stabilized by substituting ^{16}O with its heavier isotope ^{18}O [1,2]. Here we explore the superconducting properties of doped and isotope-substituted $SrTi(^{18}O_y{}^{16}O_{1-y})_{3-\delta}$ for $0 \leq y \leq 0.81$ and carrier concentrations between $6x10^{17}$ and $2x10^{20}$ cm^{-3} ($\delta < 0.02$).

We show that the superconducting T_c increases when the ^{18}O concentration is increased. For carrier concentrations around $5x10^{19}cm^{-3}$ this T_c increase amounts to almost a factor 3, with T_c as high as 580mK for y=0.74. When approaching $SrTi^{18}O_3$ the maximum T_c occurs at much smaller carrier densities than for pure $SrTi^{16}O_3$. Our observations agree qualitatively with a scenario where superconducting pairing is mediated by fluctuations of the ferroelectric soft mode [3,4].

References

[1] M. Itoh et al., **82** 3540 (1999).
[2] S.E. Rowley et al., Nature Physics **10** 367 (2014).
[3] J.M. Edge et al., PRL **115** 247002 (2015).
[4] D. van der Marel et al., PRR **1** 013003 (2019).

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Prof. Jeff Sonier

Role of Disorder on the Magnetic Properties of UTe_2 Single Crystals

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Shortly after the discovery of superconductivity in the heavy fermion compound UTe_2 [1] we investigated the magnetic properties of this material by muon spin relaxation/rotation (μSR) [2]. While our initial μSR study provided evidence for ferromagnetic fluctuations coexisting with superconductivity, subsequent inelastic neutron scattering measurements have detected dominant antiferromagnetic fluctuations. These different findings have generated debate over the nature of the spin fluctuations in UTe_2 and their role in the superconducting properties. Recently, it has become apparent that sample quality is likely obstructing the elucidation of the fundamental physical properties of UTe_2 [3]. Here we report new μSR measurements of independently grown UTe_2 single crystals that expose a substantial impact of disorder on the magnetic properties. The results provide evidence for magnetically phase separated regions, including in the single crystals measured in our first μSR study of UTe_2. However, two magnetic components, including the one indicative of ferromagnetic fluctuations, are absent in higher superconducting transition temperature (T_c) single crystals exhibiting a single sharp transition in the specific heat. In these crystals we observe a slowing down of fluctuating spins below ~ 0.5 K and spin freezing below ~ 0.2 K. The higher single-T_c crystals are providing an opportunity for us to now investigate time-reversal symmetry breaking in the superconducting state by μSR. The outcome of this ongoing investigation will be presented.

References

[1]. S. Ran *et al.*, Science **365**, 684 (2019).
[2]. S. Sundar *et al.*, Phys. Rev. B **100**, 140502 (2019).
[3]. P. F. S. Rosa *et al.*, arXiv:2110.06200.

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Dr. Denis Golez

Characterizing microscopic interactions via photo-induced lifetime changes

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Understanding intertwined orders with competing degrees of freedom is one of the most challenging problems in strongly correlated systems. We present a generic procedure for quantifying the interplay of electronic and lattice degrees of freedom in photo-doped insulators through a comparative analysis of theoretical many-body simulations and time- and angle-resolved photoemission spectroscopy (TR-ARPES) of the transient response of the candidate excitonic insulator Ta_2NiSe_5. The new paradigm is that lifetime changes after a photo-excitation carry essential information about the competition between active degrees of freedom. We will exemplify the concept on the excitonic insulator candidate Ta_2NiSe_5, where the interplay between electronic and lattice degrees of freedom is a matter of hot debate. The distinction between electron-driven versus lattice-driven situations is apparent as in the former, the photo-induced lifetime changes are substantial, while in the latter, they are strongly suppressed. The quantitative comparison between experiment and theory demonstrates the pivotal (but not necessarily sole) contribution of electron-electron interactions to stabilizing the electronic gap in the material.

References

[1].D.G., S. K. Y. Dufresne et al., arXiv:2112.06298 (2021).

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Dr. Friedrich Krien

Pseudogap explained: damping and antidamping on the Fermi surface by imaginary spin scattering

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The pseudogap phenomenon in hole-doped cuprates remains one of the most controversially debated topics in condensed matter physics. Spin fluctuations have previously been discarded by many authors as a possible origin, since the antiferromagnetic correlation length drops quickly upon doping, and weak-coupling approaches fail to explain the formation of Fermi arcs. In particular, the weak-coupling picture predicts opening of a pseudogap at hot spots for large correlation length [1], whereas experiments and calculations for the single-band Hubbard model reveal Fermi arcs truncated near the magnetic Brillouin zone boundary [2].
Using a non-perturbative diagrammatic approach to the single-band Hubbard model, we show that strong coupling and particle-hole asymmetry, both hallmarks of the cuprates, give rise to a spin-fermion scattering mechanism consistent with this phenomenology [3]: a large imaginary part of the spin-fermion vertex promotes damping of antinodal fermions and, at the same time, protects the nodal Fermi arcs (antidamping). Indeed, spin fluctuations enhance the scattering rate outside of the magnetic Brillouin zone while they *diminish* it on the inside, as shown in red and blue on the top left quadrant of Fig. 1. Remarkably, for this scattering mechanism the nesting condition is lifted, as the bottom and right quadrants show. Hence, fermions interact with target states far outside (blue) or inside (red) the Fermi volume. The difference between target states of fermions inside and outside the magnetic Brillouin zone (dashed) gives rise to the nodal/antinodal dichotomy of the pseudogap.

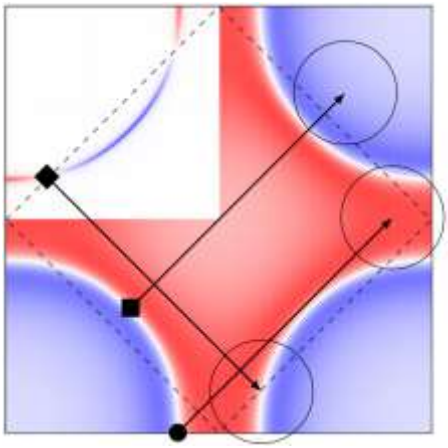

Fig. 1: *Strong-coupling mechanism of the pseudogap in the Brillouin zone. Top left quadrant: damping (red) and antidamping (blue) on the Fermi surface. Right and bottom quadrants: Blue (red) color indicates states above (below) the Fermi level (white). Filled symbols: antinode (circle), node (square), hot spot (diamond). Arrows represent the antiferromagnetic wave vector (±π, ±π). Open circles (with radius of the inverse correlation length) enclose the dominant target states; red (blue) states are occupied (unoccupied) and promote damping (antidamping). Dashed lines show the magnetic Brillouin zone.*

[1]. e.g., Vilk, PRB 55, 3870 (1997).
[2]. e.g., Shen et al., Science 307, 901 (2005).
[3]. Krien et al., arXiv:2107.06529 (2021).

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Dr. Bastien Michon

An infrared optical study across the pseudogap critical point of cuprates: quantum criticality, scaling laws and link to superconductivity

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The nature of the Pseudogap state in the phase diagram of cuprates has remained an enigma since their discovery in 1986. But recently, new experimental breakthroughs have revealed important signatures at the pseudogap critical point p*, where the pseudogap state vanishes in doping at zero temperature: 1) Transport measurements put in evidence a dramatic drop in the carrier density n - from 1+p to p - caused by a Fermi-surface reconstruction inside the pseudogap state [1-3]. 2) Normal state specific heat shows a strong effective mass m* enhancement and an unusual logarithmic divergence in temperature at p*, resulting from a quantum critical point localized at p* [4][5]. Quantum criticality was already observed in hole doped cuprates by a linear resistivity $\rho \propto T$ [6] and power law dependence in the infrared optical conductivity $\sigma(\omega,T) \propto \omega^{-\nu}$ [7], with ω the photon energy and ν the critical exponent. However, the critical exponents from optics $\nu < 1$ seem to be in direct contradiction with the linear resistivity and logarithmic specific heat giving an exponent $\nu = 1$.

In this work, we study the pseudogap critical point p* with low temperature infrared spectroscopy in $La_{2-x}Sr_xCuO_4$ and $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ cuprates. Through the extended Drude model used on the optical conductivity $\sigma(\omega,T)$, we extract the spectral weight K, the optical scattering rate $\tau(\omega,T)$ and effective mass $m^*/m(\omega,T)$ at different doping contents across p*. In parallel, we describe with a theoretical model three experimental probes: resistivity, specific heat and infrared spectroscopy using only two parameters (ν the critical exponent and the energy cutoff). With the same sample, we are able to describe and explain the experimental data and the apparent contradiction between optics and specific heat and resistivity [8]. The study of the spectral weight K in a function of doping content confirms the aforementioned behaviors of the carrier density n and the effective mass m* across p*, and reveals an intriguing relation between the electronic correlations and the superconducting critical temperature Tc [9].

References

[1] S. Badoux, W. Tabis, F. Laliberté *et al.*, Nature **531**, 210 (2016).
[2] C. Collignon, S. Badoux, S.A.A. Afshar, B. Michon *et al.*, Phys. Rev. B **95**, 224517 (2017).
[3] B. Michon, A. Ataei, P. Bourgeois-Hope *et al.*, Phys. Rev. X **8**, 041010 (2018).
[4] B. Michon, C. Girod, S. Badoux *et al.*, Nature **567**, 218 (2019).
[5] C. Girod, D. LeBœuf, A. Demuer *et al.*, Phys. Rev. B **103**, 214506 (2021).
[6] R.A. Cooper, Y. Wang, B. Vignolle *et al.*, Science **323**, 603 (2009).
[7] D. van der Marel, H.J.A. Molegraaf, J. Zaanen *et al.*, Nature **425**, 271 (2003).
[8] B. Michon, C. Berthod, C.W. Rischau *et al.*, in preparation.
[9] B. Michon, A.B. Kuzmenko, M.K. Tran *et al.*, Phys. Rev. R **3**, 043125 (20

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Marie-Eve Boulanger, Dr. Lu Chen

Thermal Hall Conductivity of Electron-Doped Cuprates

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Measurements of the thermal Hall conductivity in hole-doped cuprates showed that phonons acquire chirality in a magnetic field, both in the pseudogap phase [1,2] and in the Mott insulator state [3].

The microscopic mechanism at play is still unclear. A number of theoretical proposals are being considered, including skew scattering of phonons by various defects [4,5,6], the coupling of phonons to spins [7] and a state of loop-current order with the appropriate symmetries [8]. But more experimental information is required.

Here we present our study of the thermal Hall conductivity in the electron-doped cuprates $Nd_{2-x}Ce_xCuO_4$ and $Pr_{2-x}Ce_xCuO_4$, for dopings across the phase diagram, from x = 0, in the insulating antiferromagnetic phase, up to x = 0.17, in the metallic phase above optimal doping. We observe a large negative thermal Hall conductivity at all dopings, in both materials. Measurements with a heat current perpendicular to the CuO_2 planes confirm that phonons are responsible for this thermal Hall signal, as in hole-doped cuprates. We discuss the possibility that short-range spin correlations may be involved in the mechanism that confers chirality to the phonons.

References

[1] Grissonnanche *et al*., Nature **571**, 376 (2019).
[2] Grissonnanche *et al*., Nature Physics **16**, 1108 (2020).
[3] Boulanger *et al*., Nature Communications **11**, 5325 (2020).
[4] Guo & Sachdev, Physical Review B **103**, 205115 (2021).
[5] Flebus & MacDonald, arXiv:2106.13889 (2021).
[6] Sun, Chen & Kivelson, arXiv:2109.12117 (2021).
[7] Ye, Savary & Balents, arXiv:2103.04223 (2021).
[8] Varma, Physical Review B **102**, 075113 (2020).

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Jiajia Wen

Enhanced charge density wave with mobile superconducting vortices in $La_{1.885}Sr_{0.115}CuO_4$

J.-J. Wen[1], W. He[1,2], H. Jang[1,3], H. Nojiri[4], S. Matsuzawa[4], S. Song[1], M. Chollet[1], D. Zhu[1], Y.-J. Liu[1], M. Fujita[4], J. M. Jiang[1,2], C. R. Rotundu[1], C.-C. Kao[1], H.-C. Jiang[1], J.-S. Lee[1], Y. S. Lee[1,2]

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Superconductivity in the cuprates is found to be intertwined with charge and spin density waves. Determining the interactions between the different types of order is crucial for understanding the underlying physics. In this work, we elucidate the role of the charge density wave (CDW) in the prototypical cuprate $La_{1.885}Sr_{0.115}CuO_4$, by studying the effects of large magnetic fields up to 24 Tesla. At low temperatures, the observed CDW peaks reveal two distinct regions in the material: a majority phase with short-range CDW (labelled CDW_{SRO}) coexisting with superconductivity, and a minority phase with longer-range CDW (labelled CDW_{stripe}) coexisting with static spin density wave (SDW). With increasing magnetic field, the CDW first grows smoothly in a manner similar to the SDW. However, at high fields we discover a sudden increase in the CDW amplitude upon entering the vortex-liquid state. Our results signify strong coupling of the CDW to mobile superconducting vortices and link enhanced CDW amplitude with local superconducting pairing across the *H-T* phase diagram.

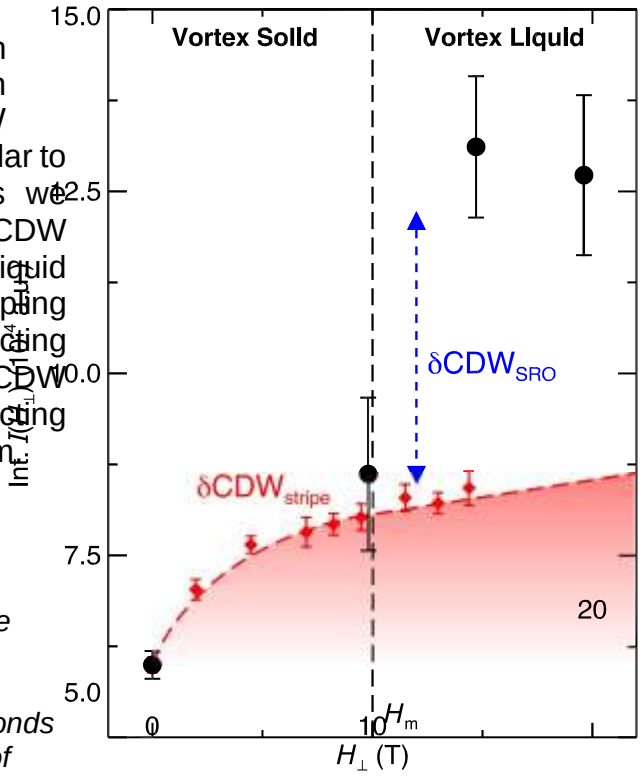

Fig. 1: *Integrated CDW intensities as a function of magnetic field measured at 6.5 K (superconducting T_c ~ 27.5 K). The vertical dashed line marks the vortex-melting field H_m deduced from in- plane resistivity measurements. The red diamonds denote the field-induced enhancement of CDW_{stripe}, deduced from field-dependent SDW intensities. The red dashed line is a guide to the eye.*

References

[1]. J.-J. Wen, *et al,* arXiv:2111.06422 (2021)

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Luca de' Medici

Quantum critical point and phase separation at finite doping in Hund metals

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"Hund metals" are multi-orbital paramagnetic metals with sizeable effects due to the intra-atomic exchange energy or Hund's coupling, and are characterized by strong, orbital-selective correlations and large fluctuating local magnetic moments. Their physics is relevant for iron-based superconductors and other materials like transition metal oxides.
A general feature found in models and realistic simulations of these materials, and corroborated by experimental data, is a frontier crossing the doping-interaction strength plane, and originating from the Mott transition point of the half-filled system, across which the aforementioned defining features are strongly enhanced.
This frontier is a cross-over at large doping while approaching half-filling it becomes a first-order transition between two metals. It features a phase separation zone ending in a quantum critical point at finite doping.
I will show that all this phenomenology is due to the first-order nature of the Mott transition and can be back-tracked to a small energy scale splitting the atomic ground-state multiplet, in this case the Hund's coupling.
I will highlight the perfect parallel with a leading scenario for the physics of the cuprates, and thus possibly a universal one for materials showing high-Tc superconductivity.

References

L. de' Medici, PRL 118, 167003 (2017)
M. Chatzieleftheriou et al. PRB 102, 205127 (2020)
T. Gorni et al. PRB 104, 014507 (2021)
P. Villar Arribi and L. de' Medici, PRB 104, 125130 (2021)
M. Chatzieleftheriou, A. Kowalski, M. Berovic, A. Amaricci, M. Capone, L. De Leo, G. Sangiovanni and L. de' Medici. (in preparation, 2021)

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Prof. Rachel Wortis

Many-body Localization in the Disordered Fermi-Hubbard Model

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The Fermi-Hubbard model is a central tool in the study of transition metal oxides and other strongly correlated systems. Because doping not only tunes the density of mobile charge carriers but also breaks translational invariance, understanding the disordered Fermi-Hubbard model is of interest. Disorder in non-interacting systems has long been known to result in localized single-particle states and the inability of an isolated system to reach thermal equilibrium. However, it has only relatively recently been understood that the absence of equilibration can persist in the presence of interactions, dubbed many-body localization. While most of the theoretical work in this area has focused on spin systems, in which there is just one local degree of freedom, the Hubbard model has two—spin and charge. To explore the spread of information between these in the presence of disorder, we compare the time dependence of the entanglement entropy with the time dependence of the charge and spin correlations, and in addition we rewrite the Hamiltonian in terms of charge and spin-specific integrals of motion, allowing us to distinguish time scales associated with charge-charge, spin-spin, and charge-spin correlations.

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Dr. Andriy Nevidomskyy

Nonunitary Triplet Pairing and Upper Critical Field in UTe_2

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The discovery of superconductivity in UTe_2 in 2019 and the identification of it likely being a triplet superconductor was one of the most tantalizing recent developments in the field of unconventional superconductivity. Despite many experimental probes, the precise nature of the superconducting order parameter remains under debate. In this talk, I will show, using a combination of phenomenological free-energy analysis and the weak-coupling BCS theory, coupled with the *ab initio* band structure calculations, that a time-reversal breaking superconducting phase, so called nonunitary state, is stabilized in UTe_2 [1]. In the past, such nonunitary states have been proposed for ferromagnetic superconductors such as UGe_2, whereas in the present proposal, the nonunitary state is predicted to be stable even in the non-magnetic phase of UTe_2. This result has a number of consequences – from chiral edge modes, recently observed in STM, to non-vanishing magneto-optical Kerr effect. Furthermore, we predict the nodal points of the gap to be topologically stable, with associated surface Majorana states and their predicted contribution to thermal Hall effect [1].

Recent studies of superconductivity under the applied hydrostatic pressure and magnetic field have revealed a complex phase diagram with what appears to be two superconducting phases whose upper critical fields are suppressed by pressure [2]. I will present a semi-phenomenological theory [2] describing the behavior of the upper critical field on pressure and the interplay between superconductivity and the meta-magnetic phase transition observed in UTe_2.

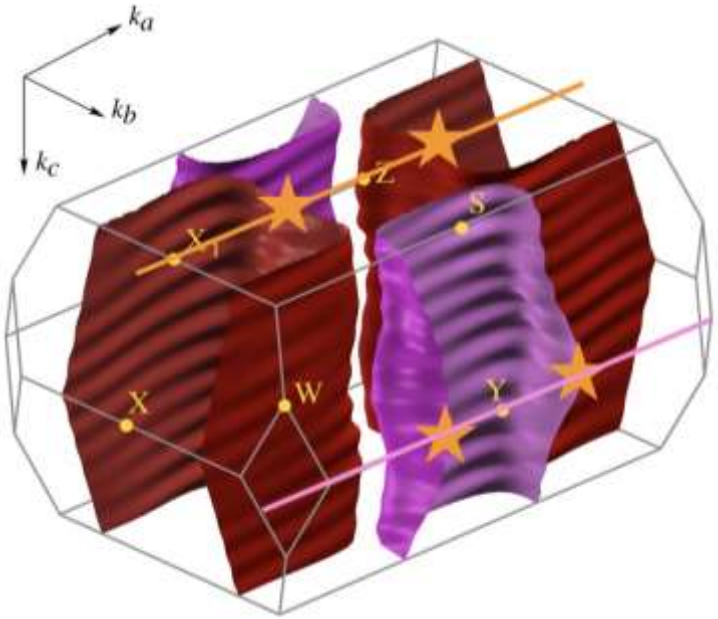

Fig. 1: *Quasi-2D Fermi surface sheets of UTe_2 with two pairs of points nodes along the a-axis (indicated by stars) predicted in the nonunitary superconducting state.*

References

[1]. A. H. Nevidomskyy, arXiv:2001.02699 (2020).
[2]. W.-C. Lin, *et al*. npj Quant. Materials **5**, 68 (2020).

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Prof. Gertrud Zwicknagl

Heavy fermions and possible quadrupole density wave in superconducting $CeRh_2As_2$

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The heavy-fermion superconductor $CeRh_2As_2$ exhibits a rich phase diagram at low temperatures. The observation of multi-phase superconductivity has been of particular interest [1]. The present contribution deals with the low-temperature normal state out of which the superconducting phases are forming. The central focus are the narrow quasiparticle bands and the electronic instabilities of the Fermi liquid state. We present calculations of the heavy quasiparticles in the heavy-fermion compound $CeRh_2As_2$. The narrow quasiparticle bands that are derived from the Ce-4f degrees of freedom are calculated by means of the Renormalized Band (RB) method. The RB scheme provides a framework for a realistic description of the coherent low-energy excitations in a Fermi liquid which combines material-specific ab-initio methods and phenomenological considerations in the spirit of the Landau theory of Fermi liquids. The central focus of the present study is the role played by the non-symmorphic lattice structure and the consequences of the Crystalline Electric Field (CEF) which removes the orbital degeneracy of the Ce 4f states. We conjecture that the quasi-quartet CEF ground state in combination with pronounced nesting features of the Fermi surface may give rise to a quadrupole density wave [2].

References

[1]. S. Khim et al., Science 373, 1012 (2021)
[2]. D. Hafner et al., arXiv:2108.06267.

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Dr. Philippe Bourges

Hidden magnetic texture in the pseudogap phase of High-Tc cuprates

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In many quantum materials, strong electron correlations lead to the emergence of new states of matter. In particular, the study in the last decades of the complex phase diagram of high temperature superconducting cuprates highlighted intra-unit-cell electronic instabilities appearing at the pseudogap temperature [1]. The observed intra-unit-cell order is breaking discrete Ising-like symmetries, while preserving the lattice translation invariance. It is currently interpreted as the magnetic hallmark of loop current order, breaking both parity and time-reversal symmetries. We perform recent polarized neutron diffraction experiments in underdoped YBa2Cu3O6.6, that indicate an hidden local magnetic quadrupling (2x2) of the unit cell at short range [2]. Together with the intra-unit-cell order, these new results suggest a real space hidden magnetic texture of the CuO2 unit cells hosting loop currents.

[1] Ph. Bourges, D. Bounoua, and Y. Sidis, Comptes Rendus Physique S22, 1-25 (2021). [2] D. Bounoua, Y. Sidis, T. Loew, F. Bourdarot, M. Boehm, P. Steffens, L. Mangin-Thro,
V. Balédent, and Ph. Bourges, https://arxiv.org/abs/2111.00525

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Yoichi Kageyama

Real-space Observation of Electronic Nematic Domains in Hole-doped (Ba,Na)Fe_2As_2 by Laser Photoemission Electron Microscopy

Yoichi Kageyama[1], Asato Onishi[1], Kousuke Ishida[1], Cédric Bareille[2], Yuta Mizukami[1], Toshiyuki Taniuchi[2], Kenichiro Hashimoto[1], Shigeyuki Ishida[3], Hiroshi Eisaki[3], Shik Shin[4], Takasada Shibauchi[1]

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The electronic nematic phase, which spontaneously breaks rotational symmetry, has been found commonly among iron-based superconductors [1]. The relationship between the electronic nematic phase and unconventional superconductivity attracted considerable attention [2]. Recently, mesoscopic nematicity wave with wavelengths more than 1000 times as long as the unit cell has been observed by the laser-photoemission electron microscopy (laser-PEEM) in FeSe and $BaFe_2(As,P)_2$ [3]. This unexpected observation of very long wavelengths implies that the electronic nematic order parameter exhibits high stiffness against real-space modulation. Here, to study the doping effect of electronic nematic domains, we report laser-PEEM observations in the hole-doped iron-based superconductor $Ba_{1-x}Na_xFe_2As$, which we compare with the previous results of FeSe and $BaFe_2(As,P)_2$ [3]. Our low-temperature laser-PEEM has a high spatial resolution (< 92 nm) and a wide field of view (5 - 40 μm) suitable to investigate the electronic nematic domains.

The electronic nematic domains in $Ba_{1-x}Na_xFe_2As_2$ are clearly observed below the structural transition temperature (Fig. 1). We analyze the domain wall by the Ginzburg-Landau theory and evaluate the domain wall thickness ξ_{nem}, which is proportional to the correlation length of the electronic nematic phase. We find that the domain wall thickness ξ_{nem} in the hole-doped $Ba_{1-x}Na_xFe_2As_2$ is much thinner than ξ_{nem} ~ 550 nm and 450 nm in FeSe and $BaFe_2(As_xP_{1-x})_2$, respectively [3]. We will discuss this difference in terms of the change in the stiffness of the nematic order parameter by the modification of the Fermi surface by hole doping. Our results suggest that the correlation length of the electronic nematic phase is sensitive to the hole doping, providing important information on the electronic nematic phase.

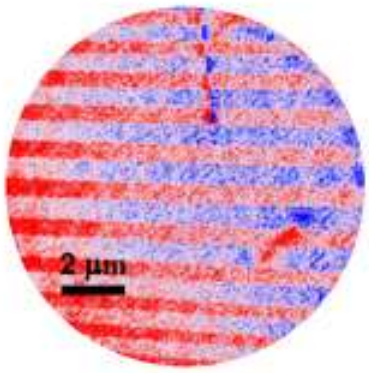

Fig. 1: *Typical laser-PEEM linear dichroism image showing electron nematic domains for $Ba_{0.82}Na_{0.18}Fe_2As_2$ obtained at 55 K.*

References

[1]. R. M. Fernandes *et al.*, Nat. Phys. **10**, 97 (2014).
[2]. K. Mukasa *et al.*, Nat. Commun. **12**, 381 (2021).
[3]. T. Shimojima *et al.*, Science **373**, 6559 (2021).

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Carolina De Almeida Marques, Dr. Luke Rhodes, Dr. Andreas Kreisel, Dr. Xiangru Kong, Dr. Tom Berlijn, Dr. Chi Ming Yim, Dr. Rosalba Fittipaldi, Dr. Veronica Granata, Dr. Andrea Gerbi, Dr. Renato Buzio, Dr. Andreas Rost, Dr. Antonio Vecchione, Professor Peter Hirschfeld, Professor Peter Wahl

Checkerboard Charge Order, Nematicity and Magnetic-field Tuning of a Van Hove Singularity in the Surface Layer of Sr_2RuO_4

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Strongly correlated electron materials exhibit an intimate relation between charge, spin and structural degrees of freedom, leading to new emergent phases which seemingly break the symmetries of the underlying crystal and result in often unexpected sensitivity to external stimuli. The members of the Ruddlesden-Popper-series $Sr_{n+1}Ru_nO_{3n+1}$ exhibit a wide range of properties attributed to such physics, including unconventional superconductivity, metamagnetic quantum criticality and ferromagnetism. We show in a detailed study of the surface electronic structure of Sr_2RuO_4, an unconventional superconductor, how tiny structural distortions lead to a significant reconstruction of the Fermi surface and the low energy electronic structure. We use ultra-low temperature scanning tunnelling microscopy to establish the existence of four van Hove singularities (vHs) within 5 mV of the Fermi level, as well as checkerboard charge order and nematicity of the electronic states [1]. Including these orders into a tight-binding model, we can fully account for the four vHs. Continuum local density of states calculations which take into account the tunneling matrix elements show excellent agreement with the observed QPI patterns [2]. By applying a magnetic field up to 14 T, we observe one of the van Hove singularities to Zeeman split, with one branch extrapolated to reach the Fermi level at ~32 T – providing a text-book example of tuning towards a magnetic field-driven Lifshitz transition.

References

[1]. C. A. Marques *et al*., Adv. Mater., **33**: 2170253 (2021).
[2]. A. Kreisel *et al*., npj Quantum Mater. **6**, 100 (2021).

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Christoph Renner, Tejas Parasram Singar

Pristine *d*-wave vortex core structure observed in a high temperature superconductor

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The electronic structure of the Abrikosov vortex cores is one among the outstanding puzzles in the understanding of high temperature superconductors (HTS). By deploying scanning tunneling spectroscopy (STS) on heavily overdoped $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi2212, $T_C \approx 52K$) at an unprecedented low magnetic field,[1] we find the long sought-after characteristic electronic vortex core signature predicted for a *d*-wave superconductor by Wang and MacDonald in 1995.[2]
Interestingly, the pristine *d*-wave electronic signature is only seen in isolated vortices probed at low fields; at fields above 1 Tesla, we observe the startling checkerboard and subgap states previously reported in optimally and underdoped crystals. While our low-field findings are consistent with the *d*-wave symmetry of the superconducting gap in Bi2212, the remarkable field dependence of the electronic vortex core structure is yet to be understood and demands further studies.

References

[1] T. Gazdić, I. Maggio-Aprile, G. Gu and Ch. Renner, Physical Review X 11, 031040 (2021)
[2] Y. Wang and A. H. MacDonald, Physical Review B 52, R3876 (1995)

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Yuxuan Wang

Symmetry-protected gates of Majorana qubits in a higher-order topological superconductor: Application to monolayer WTe_2

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We propose a platform for braiding Majorana non-Abelian anyons based on a heterostructure between a superconductor and a quantum spin-Hall insulator. It has been recently shown that such a setup leads to a pair of Majorana zero modes at corners of the sample, and thus can be regarded as a higher-order topological super- conductor. We show that upon applying a Zeeman field in the region, these Majorana modes split in space and can be manipulated for braiding processes by tuning the field and pairing phase. We show that such a setup can achieve full braiding, exchanging, and arbitrary phase gates (including the π/8 magic gates) of the Majorana zero modes, all of which are robust and protected by symmetries. We apply our theory to monolayer WTe_2, which was recently discovered to become superconducting upon gating.

References

[1]. M. F. Lapa, M. Cheng, Y. Wang, SciPost Phys. **11**, 086 (2021)

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Dr. Catherine Pépin

Charge order and Strange metals in cuprate superconductors

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Charge orders and charge fluctuations have been ubiquitously observed in the phase diagram of Cuprate superconductors. We will review the experimental status of these various observations, differentiating the under-doped region and the optimally-doped and over-doped ones. Various theories have been advanced to explain the presence of these orders and their implication for our understanding of the pseudo-gap, from the idea of "vestigial order" to the one of "fluctuating Pair Density Wave (PDW)". We will discuss these theoretical approaches in direct comparison with experiments. We will then introduce a proposal of "fractionalization of a PDW" in order to explain the pseudo-gap state. We will show that this idea produces a strong phenomenology, especially ARPES experiments, and giving a clue for the puzzling transport properties recently reported in the optimally doped and over-doped regions. We will then focus on the strange metal phase of those compounds and make a proposal for electric transport in this phase.

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Beyond BCS: An Exact Model for Superconductivity and Mottness

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High-temperature superconductivity in the cuprates remains an unsolved problem because the cuprates start off their lives as Mott insulators in which no organizing principle such a Fermi surface can be invoked to treat the electron interactions. Consequently, it would be advantageous to solve even a toy model that exhibits both Mottness and superconductivity. Part of the problem is that the basic model for a Mott insulator, namely the Hubbard model is unsolvable in any dimension we really care about. To address this problem, we point out that the overlooked Z_2 emergent symmetry of a Fermi surface is broken explicitly in the Mott state. The simplest model of this type is due to Hatsugai/Kohmoto which we show to represent a quartic fixed point for Mottness. We then show exactly[1] that this model when appended with a weak pairing interaction exhibits not only the analogue of Cooper's instability but also a superconducting ground state, thereby demonstrating that a model for a doped Mott insulator can exhibit superconductivity. The properties of the superconducting state differ drastically from that of the standard BCS theory. The elementary excitations of this superconductor are not linear combinations of particle and hole states but rather are superpositions of doublons and holons, composite excitations signaling that the superconducting ground state of the doped Mott insulator inherits the non-Fermi liquid character of the normal state. Additionally, the gap turns on at a temperature above which the pair susceptibility diverges, strong correlations of the Mott state kill the Hebel-Slichter peak and this model exhibits a superconductivity-induced transfer of spectral weight from high to low energies and a suppression of the superfluid density as seen in the cuprates. As several of these properties are observed in the cuprates, our analysis here points a way forward in computing the superconducting properties of strongly correlated electron matter.

[1] PWP, L. Yeo, E. Huang, Nature Physics, 16, 1175-1180 (2020)

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Prof. Masatoshi Sato

Majorana Fermions and Pairing Symmetries in Topological Superconductors

Masatoshi Sato

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan

Identification of Cooper pair symmetry is the first and crucial step in the investigation of unconventional superconductors. However, only a few have been established so far because of their own difficulties. In this talk, I will discuss using topological superconductivity to identify pairing symmetry [1,2]. Whereas Majorana fermions are often investigated for topological quantum computation, they are also valuable for determining the bulk pairing symmetry. For instance, they can be sensitive to the direction of d-vectors in spin-triplet superconductors. Furthermore, Majorana fermions in high-spin or nonsymmorphic superconductors may exhibit magnetic octupole responses, which directly shows these exotic superconducting states. I also would like to discuss other recent developments in the study of topological superconductors.

References

[1] Shingo Kobayashi, Yuki Yamazaki, Ai Yamakage, and Masatoshi Sato, Phys. Rev. B 103, 224504 (2021).
[2] Shingo Kobayashi, Ai Yamakage, Yukio Tanaka, and Masatoshi Sato, Phys. Rev. Lett. 123, 097002 (2019).

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Prof. Steven Johnston

The crucial role of SSH interactions in the bismuthate superconductors

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Despite decades of research, the pairing mechanism in the bismuthate family of high-temperature superconductors has yet to be conclusively identified. Proposed mechanisms include electron-phonon interactions or negative-U centers. In this talk, I will discuss recent classical and quantum Monte Carlo studies investigating the importance of Su-Schrieffer-Heeger (SSH)-like interactions for $Bi_{1-x}K_xBiO_3$ (BKBO) [1-3]. Using a state-of-the-art Hybrid Monte Carlo method, we simulate a multi-orbital model for BKBO derived from *ab initio* electronic structure calculations. This model explicitly accounts for the oxygen orbitals and is solved on three-dimensional lattices that are an order of magnitude larger than previously possible. Focusing first on the half-filled case, we observe the formation of charge order with a critical temperature in qualitative and approximate quantitative agreement with experimental results (see Fig. 1). We also present results showing enhanced pairing correlations upon doping, consistent with the emergence of high-T_c superconductivity in BKBO. Our results demonstrate that SSH-like electron-phonon interactions arising from the oxygen optical modes are sufficient to account for the phase diagram of the bismuthate superconductors.

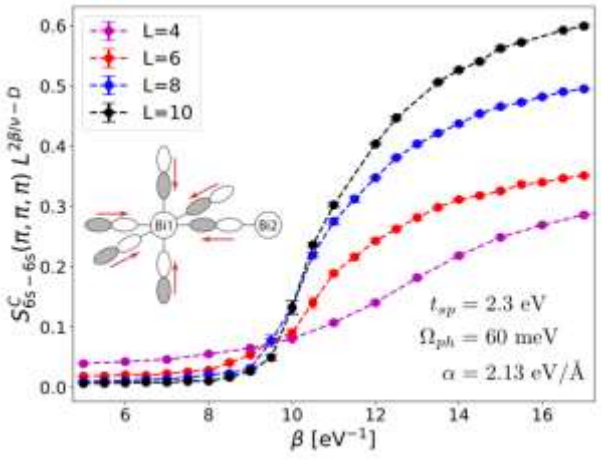

Figure 1: An Ising scaling analysis of the CDW structure factor obtained from a multi-orbital -model of the bismuthates at half-filling. The arrows in the inset sketch the oxygen breathing distortion associated with the relevant order. Using hybrid quantum Monte Carlo methods, we are able to simulate 3D lattices with unit cells, containing up to 4000 orbitals. Using parameters obtained from ab initio calculations we obtain a CDW transition temperature estimate of K.

This work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award Number DE-SC0022311.

References

[1]. S. Li and S. Johnston, npj Quantum Materials **5**, 40 (2020).
[2]. J. Mi, G. A. Sawatzky, M. Berciu, and S. Johnston, Phys. Rev. B **103**, 115129 (2021).
[3]. B. Cohen-Stead, R. Scalettar, K. Barros, and S. Johnston, in preparation.

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Emily Been

Electronic and magnetic structure of infinite-layer nickelates from first-principles and numerical modelling

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Unconventional superconductivity was given a new avenue of inquiry with the recent discovery of superconductivity in the infinite-layer nickelates. By investigating the family of infinite-layer nickelates, RNiO$_2$, with rare-earth R spanning across the lanthanide series, a new and nontrivial “knob” was introduced to tune nickelate superconductivity. Here, we discuss the strong interplay between charge transfer, bandwidth renormalization, compensation, and magnetic exchange, where compensation effects from the itinerant rare-earth 5*d* electrons present a clos analogy to Kondo lattices. We propose a microscopic Hamiltonian in the form of a Kondo- or Anderson-lattice type model using the Wannier downfolding [1]. This provides a starting point for further many-body theoretical studies examining the valence charge and spin excitations. Multi-orbital Hubbard models serve as a way to determine the fundamental building blocks for Hamiltonians that can describe the low energy properties of infinite-layer nickelates. We apply this tostudy x-ray absorption and determine the valence ground states of the parent compounds. Using exact diagonalization, we explore the doping dependence of the 2-orbital model, involving Ni and rare-earth. Taken together, such a full two-band model for infinite-layer nickelates can well describe the valence charge and spin excitations observed in experiment.

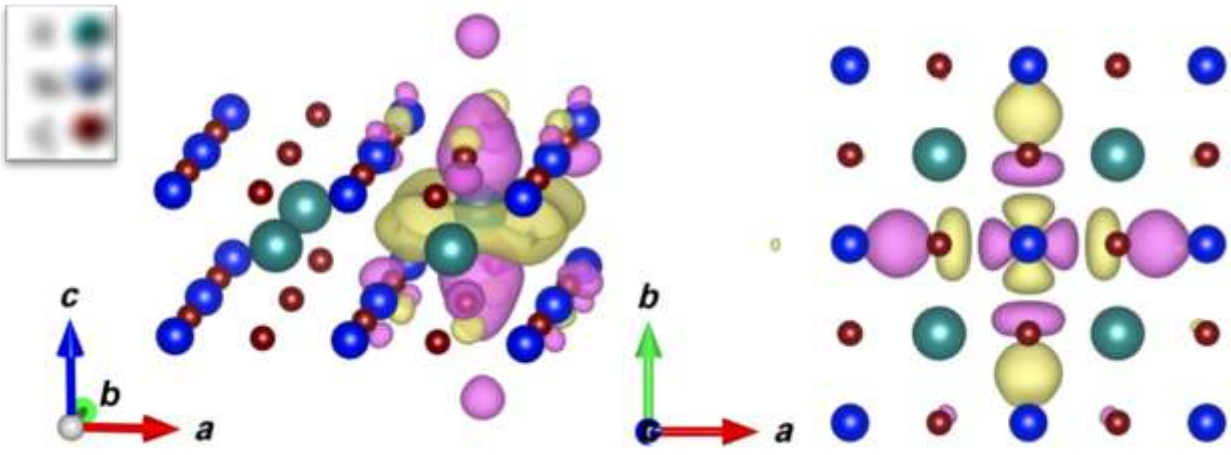

Fig. 1: *Wannier downfolding analysis to create microscopic Hamiltonian. [top] Rare-earth (R) -like and [bottom] Ni -like Wannier orbitals.*

References

[1] E. Been, et al., Phys. Rev. X **11**, 011050 (2021).

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Shane O'Mahony

On the Electron Pairing Mechanism of Copper-Oxide High Temperature Superconductivity

J.C. Séamus Davis. University of Oxford - University College Cork - Cornell University.

The elementary CuO_2 plane sustaining cuprate high temperature superconductivity occurs typically at the base of a periodic array of edge-sharing CuO_5 pyramids. Virtual transitions of electrons between adjacent planar Cu and O atoms, occurring at a rate $t/\hbar$ and across the charge-transfer energy gap , generate 'superexchange' spin-spin interactions of energy in an antiferromagnetic correlated-insulator state. However, hole doping this CuO_2 plane converts this into a very high temperature superconducting state whose electron-pairing is exceptional. A leading proposal for the mechanism of this intense electron-pairing is that, while hole doping destroys magnetic order it preserves pair-forming superexchange interactions governed by the charge-transfer energy scale . To explore this hypothesis directly at atomic-scale, we combine single-electron and electron-pair (Josephson) scanning tunneling microscopy to visualize the interplay of and the electron-pair density n_P in $Bi_2Sr_2CaCu_2O_{8+x}$. The responses of both and n_P to alterations in the distance δ between planar Cu and apical O atoms are then determined. These data reveal the empirical crux of strongly correlated superconductivity in CuO_2, the response of the electron-pair condensate to varying the charge transfer energy. Concurrence of predictions from strong-correlation theory for hole-doped charge-transfer insulators with these observations, indicates that charge-transfer superexchange is the electron-pairing mechanism of superconductive $Bi_2Sr_2CaCu_2O_{8+x.}$

Prof. Alain Sacuto, Prof. Yann Gallais, Prof. Marcello Civelli, Indranil Paul

Universal relationship between the energy scales of the quantum electronic orders in cuprates revealed by electronic Raman spectroscopy

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High-Tc cuprate superconductors are one of the iconic quantum materials. Although discovered more than 35 years ago, the complexity of their physics remains misunderstood. It calls for new concepts where the quantum electronic orders of matter are no longer independent of each other as in traditional materials. In order to understand the physics of cuprates, it is important to identify the energy scales that underlie their (*T-p*) phase diagram. Here, carrying out electronic Raman scattering measurements, we have succeeded in probing these energy scales. Our findings [1-5] provide important clues on the relationship between the different quantum electronic orders in cuprates that will be discussed in detail. In particular, an outstanding challenge in the field is to understand whether the charge density is related to the more exhaustively studied pseudogap and superconducting phases.

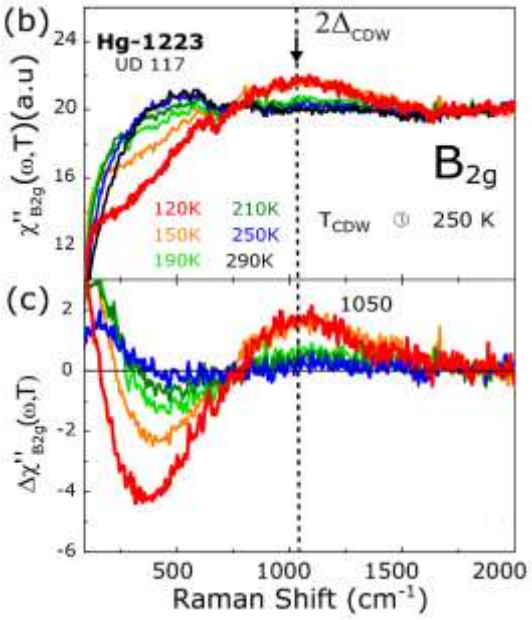

Fig. 1: *charge density wave gap Δ_{CDW} in Hg-1223 cuprate detected by Raman spectroscopy (Loret et al. Nat. Phys 15, 771, 2019).*

References

[1] N. Auvray et al. *Phys. Rev. B 103, 195130 (2021).*
[2] B. Loret et al. *Phys. Rev. B 101, 214520 (2020)*
[3] B. Loret et al. *Nature Physics 15, 771 (2019).*
[4] N. Auvray et al., *Nature Comm. 10, 5209 (2019)*
[5] B. Loret, et al. *Phys. Rev. B 97, 174521 (2018).*

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Professor Qimiao Si

Quantum Critical Metals: From Loss of Quasiparticles to High-T_c Superconductivity

Qimiao Si[1]

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Strange metals develop near quantum critical points in a variety of strongly correlated systems. A central issue is whether and how the quantum criticality goes beyond the Landau framework of order-parameter fluctuations. In the context of heavy fermion metals, the notion of Kondo destruction leads to beyond-Landau quantum criticality [1]. A defining characteristic of this strange metal is a sudden transformation of the Fermi surface from “large” to “small”, which captures a partial localization-delocalization and a complete loss of quasiparticles at the quantum critical point. Another feature is dynamical (Planckian, over) scaling in various properties including the charge responses [2,3,4], which raises the question about the implications for superconductivity. In this talk, I will present results showing that such a strange-metal state drives unconventional superconductivity with high-T_c: the transition temperature T_c reaches a few percent of the effective Fermi temperature (Fig. 1) [5]. Connections with the strange metals of other correlated electron systems –including the cuprates-- will be discussed.

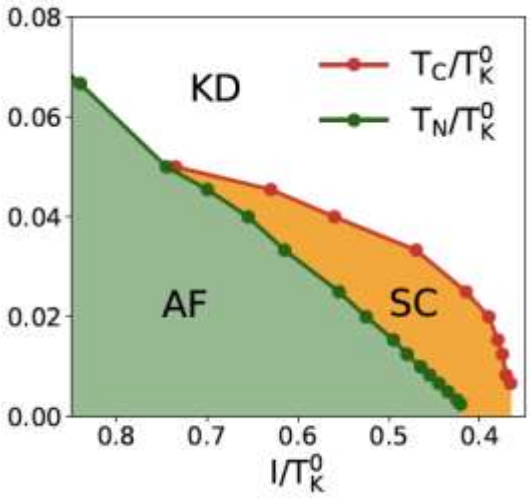

Fig. 1: *High T_c superconductivity at a Kondo-destruction quantum critical point, which goes beyond the Landau framework of order-parameter fluctuations and where quasiparticles are completely lost. From Ref. [5].*

*Supported by the NSF Grant # DMR-1920740 and the Welch Foundation Grant # C-1411.

References

[1]. S. Paschen & Q. Si, Nat. Rev. Phys. 3, 9 (2021); S. Kirchner et al, Rev. Mod. Phys. 92, 011002 (2020); Q. Si, S. Rabello, K. Ingersent, and J. L. Smith, Nature 413, 804 (2001).

[2]. A. Cai, Z. Yu, H. Hu, S. Kirchner, Q. Si, Phys. Rev. Lett. 124, 027205 (2020).
[3]. L. Prochaska, X. Li, D. C. MacFarland, A. M. Andrews, M. Bonta, E. F. Bianco, S. Yazdi, W. Schrenk, H. Detz, A. Limbeck, Q. Si, E. Ringe, G. Strasser, J. Kono, S. Paschen, Science 367, 285 (2020).
[4]. H. Hu, A. Cai, Q. Si, arXiv:2004.04679 (2020).
[5]. H. Hu, A. Cai, L. Chen, L. Deng, J. H. Pixley, K. Ingersent, Q. Si, arXiv:2109.13224.

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Oskar Vafek

Superconductivity on the Brink of Spin-Charge Order in a Doped Honeycomb Bilayer

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Using a controlled weak-coupling renormalization group approach, I plan to show how Cooper pairing and unconventional superconductivity can arise in the vicinity of spin or charge ordered states for the case of purely repulsive electrons on the Bernal stacked bilayer honeycomb lattice. While at the charge neutrality point such repulsive interactions favor excitonic order, such as a charge nematic and/or a layer antiferromagnet, upon adding charge carriers to the system, the excitonic order is suppressed, and superconductivity appears in its place, before it is replaced by a Fermi liquid. I will first focus on firmly establishing this phenomenon using the renormalization group formalism within an idealized model with parabolic touching of conduction and valence bands. Then, I will discuss the role perturbations which take the system away from the idealized limit.

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Prof. Nigel Hussey

Dual character of the cuprate strange metal

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In this presentation, I describe my group's recent studies of the (magneto)-transport properties of hole-doped cuprates across the strange metal regime in high magnetic fields up to 70 Tesla. Focussing on three distinct families of hole-doped cuprates - $Tl_2Ba_2CuO_{6+\delta}$, $La_{2-x}Sr_xCuO_4$ and La/Pb-doped $Bi_2Sr_2CuO_{6+\delta}$ – a common picture emerges of two charge sectors coexisting within the strange metal phase of overdoped cuprates, one containing coherent Landau quasiparticles, the other incoherent `Planckian' dissipators. Curiously, as the contribution from the latter grows with reduced doping, so too does the superconducting condensate. Finally, a link is established between the quadrature scaling of the magnetoresistance at high field strengths and the so-called separation of lifetimes seen at low-fields.

Dr. Thomas Maier, Peizhi Mai, Seher Karakuzu, Giovanni Balduzzi, Prof. Steven Johnston

Intertwined Spin, Charge and Pair Correlations in the Two-Dimensional Hubbard Model in the Thermodynamic Limit

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The high-temperature superconducting cuprates are governed by intertwined spin, charge, and superconducting orders. While various state-of-the-art numerical methods have demonstrated that these phases also manifest themselves in doped Hubbard models, they differ on which is the ground state. Finite cluster methods typically find dominant stripe order while embedded quantum cluster methods, which access the thermodynamic limit by treating long-range correlations with a dynamical mean field, find *d*-wave superconductivity. Here, we report the observation of fluctuating spin and charge stripes in the doped single-band Hubbard model using a quantum Monte Carlo dynamical cluster approximation (DCA) method. By resolving fluctuating spin and charge stripes using the DCA, we demonstrate that they survive in the thermodynamic limit. This discovery also provides a new opportunity to study the influence of stripe correlations on superconductivity within a unified numerical framework. Using this approach, we also find evidence for pair-density-wave correlations whose strength is correlated with that of the stripes.

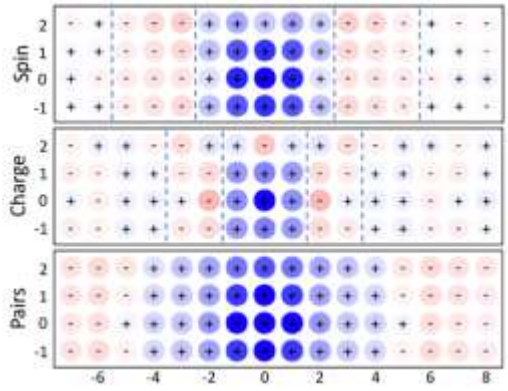

Figure 2: DCA results for the static () stripe correlations of the doped single-band Hubbard model. Results are shown for the staggered AFM spin-spin (top), density-density (middle), and d-wave projected pairing (bottom) correlations. The model parameters are , , , and .

This work was supported by the Scientific Discovery through Advanced Computing (SciDAC) program funded by the U.S. Department of Energy, Office of Science, Advanced Scientific Computing Research and Basic Energy Sciences, Division of Materials Sciences and Engineering. This research used resources of the Oak Ridge Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725.

References

[1] P. Mai, S. Karakuzu, G. Balduzzi, S. Johnston, and T. A. Maier, arXiv:2106.01944; to appear in PNAS (2021).

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Mark Dean, Yao Shen

Electronic structure and magnetic interactions in low valence nickelates

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The discovery of superconductivity in square planar low valence nickelates has ignited a vigorous debate regarding their essential electronic properties: Do these materials have appreciable oxygen charge-transfer character and superexchange akin to the cuprates or are they in a distinct Mott-Hubbard regime where oxygen plays a minimal role and superexchange is negligible? Here, we resolve this question using O K-edge and Ni L-edge RIXS measurements of the low valance nickelate $La_4Ni_3O_8$ and a prototypical cuprate $La_{2-x}Sr_xCuO_4$ (x=0.35), interpreting the results with exact diagonalization calculations [1,2]. As expected, the cuprate lies deep in the charge-transfer regime of the Zaanen-Sawatzky-Allen (ZSA) scheme. The nickelate, however, is not well-described by either limit of the ZSA scheme and is found to be of mixed charge-transfer / Mott-Hubbard character with the Coulomb repulsion U of similar size to the charge transfer energy Δ. Nevertheless, the transition-metal-oxygen hopping is larger in $La_4Ni_3O_8$ than in $La_{2-x}Sr_xCuO_4$, which leads to a significant superexchange interaction of J~70 meV and an appreciable hole occupation of the ligand O orbitals in $La_4Ni_3O_8$ despite its larger Δ. Our results clarify the essential characteristics of $d^{9-\delta}$ nickelates and put strong constraints on theoretical interpretations of superconductivity in these materials.

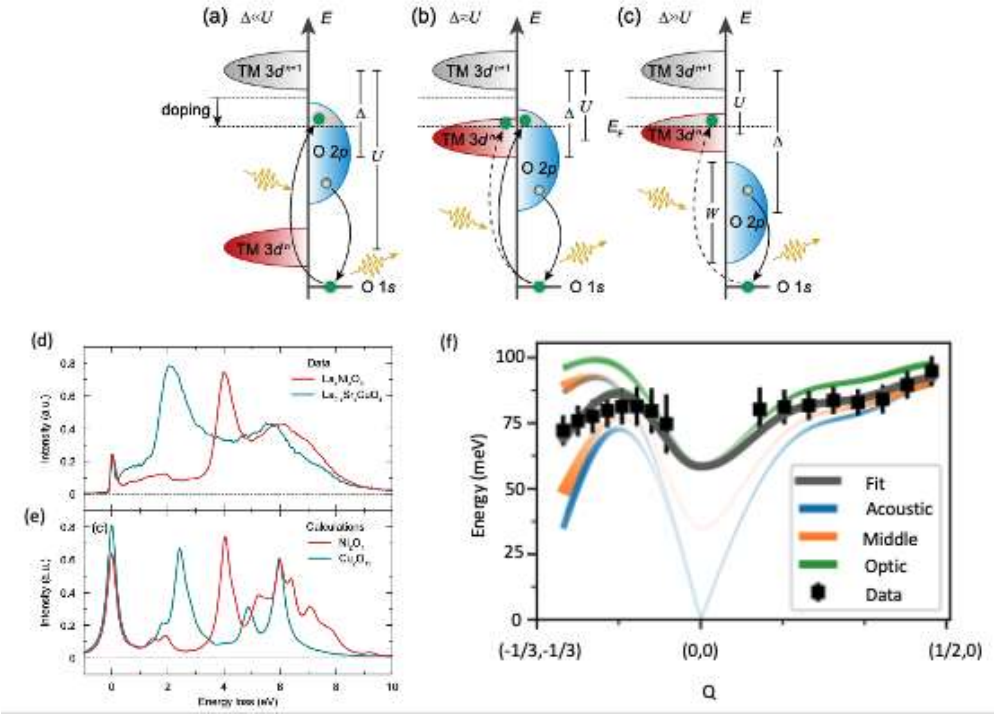

Fig. 1: *(a)-(c) Different regimes in the ZSA scheme for electronic structure classification: (a) Charge transfer, (b) Mixed Charge transfer Mott Hubbard (c) Mott Hubbard. (d)-(e) O K-edge RIXS data and calculations for $La_{2-x}Sr_xCuO_4$ and $La_4Ni_3O_8$ which have charge transfer and mixed charge transfer Mott Hubbard electronic character, respectively [2]. Ni K-edge data and spin wave theory for $La_4Ni_3O_8$, which was used to extract the magnetic exchange interaction of 70 meV [1].*

References

[1]. J. Q. Lin, P. Villar Arribi, G. Fabbris, A. S. Botana, D. Meyers, H. Miao, Y. Shen, D. G. Mazzone, J. Feng, S. G. Chiuzbaian, A. Nag, A. C. Walters, M. Garcia-Fernandez, Ke-Jin Zhou, J. Pelliciari, I. Jarrige, J. W. Freeland, Junjie Zhang, J. F. Mitchell, V. Bisogni, X. Liu, M. R. Norman, and M. P. M. Dean, Phys. Rev. Lett. 126, 087001 (2021)

[2]. Y. Shen, J. Sears, G. Fabbris, J. Li, J. Pelliciari, I. Jarrige, Xi He, I. Bozovic, M. Mitrano, Junjie Zhang, J. F. Mitchell, A. S. Botana, V. Bisogni, M. R. Norman, S. Johnston, and M. P. M. Dean, Role of oxygen states in square planar $d^{9-\delta}$ nickelates, arXiv:2110.08937 (2021)

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Prof. Srinivas Raghu

Reentrant superconductivity has been observed in the candidate spin-triplet superconductor UTe_2 as a function of magnetic field applied along the hard axis. Resistivity measurements have shown, a broadened superconducting transition appears near the minimal T_c, highlighting the importance of superconducting fluctuations in this regime. We present a phenomenological study assuming a field-driven first-order transition between two superconducting states. We show that with quenched randomness, inhomogeneity-enhanced superconducting fluctuations near the transition could nat- urally account for both the reentrant superconductivity as well as the broadened superconducting transition.

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Prof. Nandini Trivedi

We show that while orbital magnetic field and disorder, acting individually weaken superconductivity, acting together, they produce an intriguing evolution of a two-dimensional type-II s-wave superconductor. For weak disorder, the critical field Hc at which the superfluid density collapses is coincident with the field at which the superconducting energy gap gets suppressed. However, with increasing disorder these two fields diverge from each other creating new Bose metal and pseudogap phases. The nature of vortices also transform from Abrikosov vortices with a metallic core for weak disorder to Josephson vortices with gapped and insulating cores for higher disorder. Our results naturally explain the gigantic magnetoresistance peak observed as a function of magnetic field in thin disordered superconducting films.

Ref: [1] Anushree Datta, Anurag Banerjee, Nandini Trivedi, and Amit Ghosal, arXiv:2101.00220
[2] Mason Swanson, Yen Lee Loh, Mohit Randeria, and Nandini Trivedi,
Phys. Rev. X 4, 021007

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Prof. Thomas Devereaux

Ubiquitous fluctuating charge and spin order in the Hubbard model

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The single-band Hubbard model contains many signatures resembling aspects of the rich cuprate phase diagram[1,2]. In this talk I will present results from unbiased numerical simulations of the Hubbard model at zero and finite temperatures using density matrix renormalization group and determinant quantum Monte Carlo techniques on various cluster sizes and shapes. While “strange metallic” behavior can be seen across the phase diagram at elevated temperatures[3], at lower temperatures charge and spin order in the form of unidirectional stripes are ubiquitous[4-7]. The results indicate that superconductivity at lower temperatures, if it exists in this simple model in the thermodynamic limit, evolves from strong stripe correlations and not a simple “strange metal”.

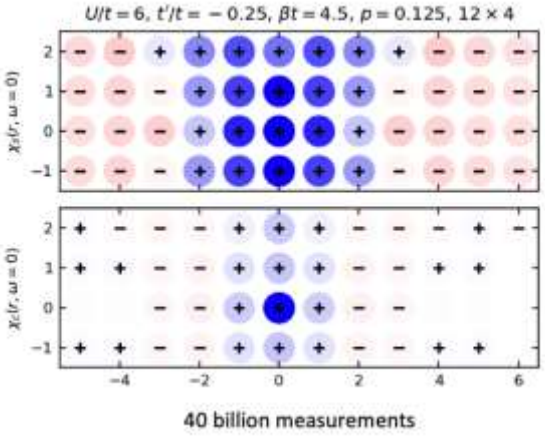

Fig. 1: Static *spin (top) and charge (bottom) susceptibilities revealing anti-phase antiferromagnetic domains separate by charge domain walls. Results are obtained from quantum Monte Carlo for the parameters given.*

References

[1]. Daniel P. Arovas, Erez Berg, Steven Kivelson, Srinivas Raghu, arXiv:2103.12097.
[2]. E. W. Huang, W. O. Wang, J. K. Ding, T. Liu, F. Liu, X.-X. Huang, B. Moritz, T. P. Devereaux, J. Phys. Soc. Jpn. **90**, 111010 (2021).
[3]. Edwin W. Huang, Ryan Sheppard, Brian Moritz, & Thomas P. Devereaux, Science **366**, 987 (2019).
[4]. Y. Jiang, J. Zaanen, T. P. Devereaux, & H.-C. Jiang, Phys. Rev. Res. **2**, 033073 (2020).
[5]. Hong-Chen Jiang and Thomas P. Devereaux, Science **365**, 1424 (2019).
[6]. Edwin W. Huang, Christian B. Mendl, Hong-Chen Jiang, Brian Moritz, & Thomas P. Devereaux, NPJ Quantum Materials **3**, 22 (2018).
[7]. Hong-Chen Jiang, Steven A. Kivelson, arXiv:2105.07048.

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Douglas Scalapino

Separating the two-fermion vertices that enter the one-electron self-energy and particle-particle Bethe-Salpeter equations into contributions from a particle-hole spin (S = 1) exchange and a remainder, we examine the contributions of spin-fluctuations to the low-energy single particle spectral weight A(k; 0) and the d-wave pairing eigenvalue lamba_d(T) of an electron doped t-t'-U Hubbard model. Analysis shows that antiferromagnetic spin-fuctuations are responsible for the suppression of the spectral weight A(k; 0+) which is observed near the nodal regions and for the increase of the d-wave pairing eigenvalue lambda_d(T) as the temperature is lowered (1).

1. Steven Johnston, Thomas A. Maier, D.J. Scalapino; to be published.

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Dr. Daniel Mayoh

Exploring Superconductivity in Time-Reversal Symmetry Breaking Hexagonal Noncentrosymmetric Superconductors.

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For all superconductors, the topology of the electronic band structure, along with the underlying crystal structure, play a vital role in determining the superconducting properties of the material. Systems lacking a centre of inversion exhibit a nonuniform lattice potential, giving rise to a Rashba-type antisymmetric spin-orbit coupling which allows for an admixture of singlet and triplet pairs. This may lead to exotic superconducting band structures, time-reversal symmetry breaking and magnetoelectric effects such as upper critical fields that exceed the Pauli limit. Broken time-reversal symmetry is still a relatively rare phenomena in noncentrosymmetric superconductors; it has been detected in $LaNiC_2$, some rhenium based materials with an α-Mn structure, and tetragonal α-V_3S-type Zr_3Ir. Time-reversal symmetry breaking has now also been observed in polycrystalline La_7Ir_3 [1], La_7Rh_3 [2], La_7Pd_3 [3] and La_7Ni_3 [4] while further characterisation of these materials has indicated mostly conventional nodeless superconducting properties. The nature of the pairing states in these superconductors continues to be a puzzling and challenging question. Here we discuss some of the recent progress in studying the hexagonal noncentrosymmetric La_7X_3 superconductors.

Single crystals of these noncentrosymmetric superconductors are highly desirable to understand the nature of the electron pairing mechanism. We will highlight the successful synthesis of large single crystals of La_7Ir_3 which can now be used to more closely examine the unusual superconducting state of this material [5]. Furthermore, we show the presence of a robust electronic upper critical field, that diverges from the upper critical field derived from heat capacity in these single crystals of La_7Ir_3, which is the hallmark of surface superconductivity.

References

[1] J. A. T. Barker, Phys. Rev. Lett. **155**, 267001 (2015). [2]
D. Singh, Phys. Rev. B **103**, 134511 (2020).
[3] D. A. Mayoh, Phys. Rev. B **103**, 024507 (2021). [4]
Arushi, Phys. Rev. B **103**, 174502 (2021).
[5] D. A. Mayoh, Phys. Rev. Mat. **5**, 114803 (2021).

8

Prof. Liling Sun

Quantum superconducting phase transition and 2D-3D superconductivity crossover in pressurized bismuth-based cuprates

Liling Sun

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Copper oxide superconductors have been continually fascinating the communities of condensed matter physics and material sciences because they host the highest ambient-pressure superconducting transition temperature (T_c) and mysterious physics. Searching for the universal correlation between the superconducting state and its normal state or neighboring ground state is believed to be an effective way for finding clues to elucidate the underlying mechanism of the superconductivity. One of the common pictures for the copper oxide superconductors is that a metallic phase will present after the superconductivity is entirely suppressed by chemical doping or application of the magnetic field. In this talk, I will present two interesting phenomena discovered by our recent high-pressure studies. One is the universal quantum phase transition from a superconducting state to an insulating-like state in the under-, optimally- and over-doped superconductors with two CuO_2 planes per unit cell (Bi2212), as well as in the superconductors with one CuO_2 plane (Bi2201) and three CuO_2 planes (Bi2223) [1], the other is a pressure-induced crossover from 2D to 3D superconducting states in optimally-doped Bi2212 bulk superconductors [2].

I would like to extend my thanks to Profs. Genda Gu, Xingjiang Zhou, Chengtian Lin, Qi Wu, Jiangping Hu and Tao Xiang for significant contributions to these works.

References

[1]. Y Zhou and L Sun *et al*, arXiv 2012 07523.

[2]. J. Guo and L. Sun *et al*, Nature Physics **16**, 295 (2020).

12

Jan Zaanen

Quantum supreme matter and the strange metals.

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Quantum supreme matter refers to forms of matter that are densely many-body entangled with the ramification that the quantum supremacy of the quantum computer is required to enumerate the way it works. The evidence is mounting that the AdS/CFT (holographic) correspondence of the string theorist, augmented by progress with SYK type models, yields a mathematical view on generic properties of such states of matter. This revolves around a particular “covariant” renormalization group flow revealed by holography showing how the Fermi-liquid generalizes into a densely many-body entangled affair [1]. Guided by these insights, substantial progress has been made in recognizing various of these traits in experiments on the strange metal states of the high Tc superconductors.

References

[1]. J. Zaanen, arXiv:2110.00961 (2021).

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Carmen Rubio Verdú

Twisted graphene: topological edge states and nematic order

Carmen Rubio-Verdú[1], Alexander Kerelsky[1], Simon Turkel[1], Larry Song[1], Lennart Klebl[2], Rhine Samajdar[3], Mathias S. Scheurer[3,4], Jörn F. Venderbos[5,6], Lei Wang[1], Dorri Halbertal[1], Nathan Finney[7], Kenji Watanabe[8], Takashi Taniguchi[9], Héctor Ochoa[1], Lede Xian[10], Dante M. Kennes[2,10], James Hone[7], Cory Dean[1], Dmitri Basov[1], Rafael M. Fernandes[11], Ángel Rubio[10,12,13], Abhay N. Pasupathy[1]

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Atomically thin van der Waals materials stacked with an interlayer twist are an excellent platform towards achieving gate-tunable correlated phenomena linked to the formation of flat electronic bands. We demonstrate the formation of emergent correlated phases in twisted double bilayer graphene (tDBG) in two regimes of twist angle: minimally twisted (<0.1°) and 1.1°. Minimally twisted tDBG hosts large regions of uniform rhombohedral four-layer (ABCA) graphene where scanning tunneling spectroscopy reveals unprecedentedly sharp flat band of 3-5 meV half-width [1]. We demonstrate that, when this flat band straddles the Fermi level, a correlated many-body gap emerges. Moreover, under certain experimental conditions, topological helical edge states appear at the natural interface between rhombohedral and Bernal graphene. On the other hand, scanning tunneling microscopy on tDBG at a regime of twist angles (~1.1°) at which moiré physics play an important role, reveals the presence of van Hove singularities whose spatial distribution within the moiré unit cell is determined by the inequivalent stacking sites [2]. Tuning the electron filling as well as the displacement field reveals broken C_3 symmetry that emerges when the Fermi level is brought in the flat band. This symmetry breaking is manifested as long-range commensurate stripes along a high-symmetry moiré crystallographic direction, distinctive of nematic correlations of electronic origin. Comparing our experimental data with a combination of microscopic and phenomenological modeling, we show that the nematic instability is not associated with the local scale of the graphene lattice, but is an emergent phenomenon at the scale of the moiré lattice, pointing to the universal character of this ordered state in flat band moiré materials.

References

[1] Kerelsky*, Rubio-Verdú* *et al., Moiréless correlations in ABCA graphene*, PNAS **118** e2017366118 (2021)
[2] Rubio-Verdú *et al., Universal moiré nematic phase in twisted graphitic systems,* Nat. Phys. (2021)

4

Prof. Louis Taillefer

New experimental signatures of the pseudogap phase in cuprates

L. Taillefer[1,2]

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The pseudogap phase of cuprate superconductors is arguably the most enigmatic phase of quantum matter. We aim to shed new light on this phase by investigating the non-superconducting ground state of several cuprate materials at low temperature, by suppressing superconductivity with a magnetic field [1].

Hall effect and thermal conductivity measurements across the pseudogap critical doping p^* reveal a sharp drop in carrier density n from $n = 1 + p$ above p^* to $n = p$ below p^* [2], signaling a major transformation of the Fermi surface. From specific heat measurements, we observe the classic thermodynamic signatures of quantum criticality: the electronic specific heat shows a sharp peak at p^*, where it varies in temperature as $-T \log T$ [3]. At p^* and just above, the electrical resistivity is linear in T at low T, with an inelastic scattering rate that obeys the Planckian limit [4]. Finally, the pseudogap phase is found to have a large negative thermal Hall conductivity, as a result of phonons acquiring chirality in a magnetic field [5].

Understanding the mechanisms responsible for these various new signatures will help elucidate the nature of the pseudogap phase.

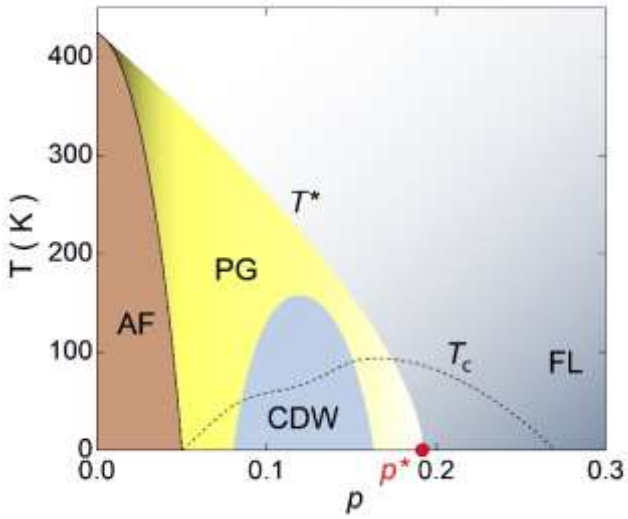

Fig. 1: *Phase diagram of cuprates. In zero field, superconductivity exists in a dome below T_c (dashed line). When it is removed by a magnetic field, various underlying ground states are revealed: doped Mott insulator with antiferromagnetic order (AF, brown); pseudogap phase (PG, yellow) below a temperature T*, ending at a T = 0 critical point p* (red dot); charge-*

density wave phase (CDW, blue), contained inside the PG phase; a strange metal region just above p, which gives way to a Fermi liquid state (FL, gray region) at highest doping.*

References

[1] Proust & Taillefer, Annu. Rev. Condens. Matter Phys. **10**, 409 (2019).
[2] Badoux *et al*., Nature **531**, 210 (2016); Collignon *et al*., Phys. Rev. B **95**, 224517 (2017).
[3] Michon *et al*., Nature **567**, 218 (2019).
[4] Legros *et al*., Nat. Phys. **15**, 142 (2019); Grissonnanche *et al*., Nature **595**, 667 (2021).
[5] Grissonnanche *et al*., Nature **571**, 376 (2019); Nat. Phys. **16**, 1108 (2020).

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Prof. Philip Kim

Toward realization of novel superconductivity based on twisted van der Waals Josephson junction in cuprates

S. Y. F. Zhao[1], N. Poccia[1], X. Cui[1], P. A. Volkov[2], H. Yoo[1], R. Engelke[1], Y. Ronen[1], R. Zhong[3], G. Gu[3], S. Plugge[4], T. Tummuru[4], M. Franz[4], J. H. Pixley[2], P. Kim[1]

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Twisted interfaces between stacked van der Waals cuprate crystals enable tunable Josephson coupling, utilizing anisotropic superconducting order parameters. Employing a novel cryogenic assembly technique, we fabricate high-temperature Josephson junctions with an atomically sharp twisted interface between Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ crystals. The critical current density J_c sensitively depends on the twist angle. While near 0° twist, J_c nearly matches that of intrinsic junctions, it is suppressed almost 2-orders of magnitude but remained finite near 45°. J_c also exhibits non-monotonic behavior \textit{vs} temperature due to competition between two supercurrent contributions from nodal and anti-nodal regions of the Fermi surface. Near 45° twist angle, we observe two-period Fraunhofer interference patterns and fractional Shapiro steps at half integer values, a signature of co-tunneling Cooper pairs necessary for high temperature topological superconductivity.

References

[1]. S. Y. F. Zhao et. al, arXiv:2108.13455

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Robert Cava

Finding New Superconducting Materials – a Chemical Perspective
R. Cava Department of Chemistry, Princeton University

Finding new materials that are of interest to materials physicists is, in my opinion, best done by using the insights and tools of solid state chemistry to direct exploratory synthesis towards finding materials with potentially new electronic and magnetic properties; superconductivity being one of the properties of most general interest. Although recent trends in materials chemistry seem to say that searches for materials with properties like superconductivity should be directed by calculations based on density functional theory, I am too old-fashioned to share that view, thinking that states like superconductivity arise in materials through a balance of competing forces that remain beyond the current ability of modifications or extensions of DFT-based computer programs to model. Electron counting, relative ionicities and atomic masses come from a basic understanding of chemistry and physics and so I don't get the uniqueness of "predictions" such as those have been claimed for superconductors containing hydrogen for example. All that being said to be controversial, in this talk I plan to describe the superconducting materials that we have worked on in recent years in several different chemical families, including oxides and intermetallics. The work has been done by my graduate students and postdocs. I hope that you will find some of the materials to be interesting.

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Dr. Richard Harris

Title: Quantum magnetism on a chip

Abstract: D-Wave Systems produces superconducting quantum processing units (QPUs) that instantiate the quantum annealing algorithm for solving hard optimization problems. However, these QPUs have also proved to be an interesting platform for studying quantum magnetism within the context of the so-called transverse field Ising model. For slow evolution, one can probe near-equilibrium paramagnetic-to-spin glass phase transitions and Kosterlitz-Thouless physics as a function of the transverse degree of freedom. In contrast, fast evolution can be used to probe the physics of dynamical phase transitions with the engineered quantum system decoupled from its environment, thus exposing the coherent regime. This lecture will provide a review of interesting quantum magnetism results obtained to date and a discussion of how those physics results pertain to use of D-Wave's technology in a practical setting.

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Prof. Ryo Shimano

Higgs Mode Responses in Photoexcited Unconventional Superconductors

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With the development of ultrafast spectroscopy techniques, it has now become possible to control the superconducting order parameter in a non-thermal way. Even though the phenomena are mostly restricted in a transient time scale within a few to a few tenth ps, the technique can allow one to elucidate the interplay between competing orders, and disentangle the intertwining degree of freedoms, thereby providing deep insights into the mechanism of emergent superconductivity. To study the nonequilibrium dynamics of superconductivity, however, it is crucial to probe the superconducting order parameter itself with ultrafast time resolution. To this end, we shed light on the observation of the Higgs mode, i.e. the amplitude oscillation of superconducting order parameter [1]. We report our study on the nonequilibrium dynamics of unconventional superconductors induced by the phtoexcitation, including both cuprates and iron chalcogenides [2]. We compare the transient behavior of optical conductivity in the gap energy scale with the transient behavior of the Higgs mode measured by THz-third-harmonic generation (THG) and pump-probe spectroscopy.

References

[1]. R. Shimano and N. Tsuji, Ann. Rev. Cond. Mat. Phys. **11**, 103 (2020).
[2]. K. Isoyama, N. Yoshikawa, K. Katsumi, J. Wong, N. Shikama, Y. Sakishita, F. Nabeshima, A. Maeda and R. Shimano, Commun. Phys. **4**, 160 (2021).

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Anand Bhattacharya

Tuning Superconductivity at interfaces of $KTaO_3$

Anand Bhattacharya

Abstract:

In this talk I will discuss the recently discovered superconducting electron gas at interfaces between $KTaO_3$ (KTO) and insulating overlayers of either EuO or $LaAlO_3$. The superconducting T_c can be as high as 2.2 K, about an order of magnitude higher than in the $LaAlO_3/SrTiO_3$ system. Critical field and current-voltage measurements indicate that the superconductivity is two-dimensional. Using transmission electron microscopy and resonant x-ray scattering, we establish the presence of substitutional defects and oxygen vacancies at the KTO interface that can act as donors of electrons, and may lead to the formation of the interfacial electron gas. Furthermore, we have uncovered several unusual properties of the superconducting state, including its orientation selectivity, anisotropy in transport properties, and dependence on chemical doping and electric field-effect gating. These properties point to a highly tunable two-dimensional interfacial superconductor. I will present these results, and discuss their implications for the nature of superconductivity at $KTaO_3$ interfaces.

Ref.: C. Liu et al., *Science* 2021. DOI: 10.1126/science.aba5511

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Aharon Kapitulnik

EXPERIMENTAL STUDIES OF UNCONVENTIONAL SUPERCONDUCTIVITY: COMPOSITE ORDER PARAMETERS AND VESTIGIAL ORDER

Aharon Kapitulnik

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It is common to describe unconventional superconductors as materials that display superconductivity but that do not conform to BCS or Migdal-Eliashberg theories. BCS theory of conventional superconductivity describes pairing of spin-singlet time-reversed states, and is characterized by an order parameter which breaks U(1)-gauge symmetry leading to basic superconducting properties, such as the Meissner effect, persistent current and flux quantization. By contrast, unconventional superconductors exhibit internal degrees of freedom within the pair-wavefunction, which often lead to additional broken symmetries, and thus distinct superconducting phases with unique properties. Concentrating on time-reversal symmetry breaking (TRSB), we discuss the variety of ways that it is manifested in unconventional superconductors and some unique ways to detect it. While TRSB must conform to the point group symmetry and the representations of each material system, its discrete nature originating from a multi-component order parameter may also allow for vestigial phases valid in the vicinity of the superconducting transition.

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Alex Frano

Highly anisotropic three-dimensional charge order stabilized through interplanar orbital hybridization in $Pr_xY_{1-x}Ba_2Cu_3O_{6+\delta}$

Alejandro Ruiz,[1,2] Brandon Gunn,[1] Yi Lu,[3] Kalyan Sasmal,[1] Rourav Basak,[1] Hai Huang,[4] Jun-Sik Lee,[4] Fanny Rodolakis,[5] Timothy J. Boyle,[6,7] Morgan Walker,[6] Yu He,[8] Santiago Blanco-Canosa,[9,10] Eduardo H. da Silva Neto,[6,7,11] M. Brian Maple,[1] and Alex Frano[1]

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In the copper oxides, two-dimensional (2D) charge order (CO) is a universal phase that competes with superconductivity but is only a short-range phenomenon primarily due to disorder. Three-dimensional (3D) CO can emerge by applying magnetic field or strain, but a 2D CO component remains present and the out-of-plane correlation lengths remain shortened by disorder. We report Cu-L_3 and Pr-M_5 resonant x-ray scattering experiments and band structure calculations on $Pr_xY_{1-x}Ba_2Cu_3O_{6+\delta}$ showing that, through the hybridization between the Pr 4f orbital and the CuO 2 electronic states, 3D CO can be stabilized with the highest reported out-of-plane correlation length. At the onset of superconductivity, the 3D CO shows a suppression which is more pronounced on the Cu 3d states than on the Pr 4f states. Further, the in-plane reciprocal space structure of the 3D CO peak reveals an anisotropy that has not been observed in other cuprate compounds. Importantly, we do not detect any evidence of 2D CO. These results provide the first observation of a fully stabilized anisotropic 3D CO phase that can be achieved by tuning the orbital character of the electronic structure.

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Marta Zonno

Tracking the Low-Energy Electrodynamics of Bi-based Cuprates by TR-ARPES

M. Zonno[1,2,3], F. Boschini[1,4], A. Damascelli[1,2]

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The phase diagram of cuprates hosts numerous intertwined phases as disparate as high-temperature superconductivity, charge order and the pseudogap (PG). This makes the precise description of each separate phase challenging. In this regard, the recent development of time-resolved techniques has offered a novel venue for investigating dynamical properties of quantum phases. Among them, time- and angle-resolved photoemission spectroscopy (TR-ARPES) stands out owing to its ability to directly access the momentum-resolved electronic dynamics and interactions on sub-picosecond timescales. Here we employ TR-ARPES to investigate the transient evolution of the low-energy electrodynamics of Bi-based cuprates, both along the gapless nodal direction and in the near-nodal superconducting gap region [1-3].

First, we discuss the temperature-dependent breakdown of the nodal coherent spectral weight (CSW) and show that its suppression upon increasing temperature is not only ubiquitous across single- and bi-layer Bi cuprates but also uncorrelated to superconducting and PG onset temperatures. Instead, our results indicate that the evolution of the nodal CSW naturally stems from the temperature and energy dependence of the Fermi-Liquid electron self-energy, thus establishing the key role played by the normal state electrodynamics in the description of nodal quasiparticles [1,2].

We then focus on the study of the near-nodal region and confirm the dominant role played by phase coherence in the emergence of high-temperature superconductivity. In particular, we demonstrate that while the gap dynamics and amplitude are locked to the evolution of the electronic occupation, *i.e.* the electronic temperature, the transient filling of the superconducting gap reflects non-thermal pair-breaking phenomena. Our observations of similar gap-filling dynamics for different doping levels and compounds (single- and bi-layer alike) points towards a universal mechanism for the superconducting-to-normal state phase transition in Bi-based cuprates [2,3].

To conclude, we showcase how TR-ARPES can be exploited to gain insights also into the electron-doped side of the cuprates phase diagram. By tracking the temperature evolution of the PG spectral features in the optimally doped $Nd_{2-x}Ce_xCuO_4$, we reveal a filling and not closing of the PG similar to the case of the superconducting gap in hole-doped cuprates, but now associated with the evolution of the spin correlation length. This finding provides evidence for the primary role of antiferromagnetic correlations in determining the PG in electron-doped cuprates [4].

References

[1] M. Zonno*, F. Boschini* et al., PRB **103**, 155109 (2021)
[2] M. Zonno et al., J. Electron Spectrosc. Relat. Phenom. **251**, 147091 (2021)
[3] F. Boschini et al., Nat. Mater. **17**, 416 (2018)
[4] F. Boschini*, M. Zonno* et al., npj Quantum Mater. **5**, 6 (2020)

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Prof. Zhi-xun Shen

Electronic Phase Diagram of Cuprate Superconductors – a Balancing Act

Zhi-Xun Shen
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Stanford University
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High-temperature superconductivity in cupper based materials, with critical temperature well above what was anticipated by the BCS theory, remains a major unsolved physics problem more than 30 years after its discovery. The problem is fascinating because it is simultaneously simple - being a single band and ½ spin system, yet extremely rich - boasting d-wave superconductivity, pseudogap, spin and charge orders, and strange metal phenomenology. For this reason, cuprates emerge as the most important model system for correlated electrons – stimulating conversations on the physics of Hubbard model, quantum critical point, Planckian metal and others.

Heart of this challenge is the complex electronic phase diagram consisting of intertwined states with unusual properties. Angle-resolved photoemission spectroscopy has emerged as the leading experimental tool to understand the electronic structure of these states and their relationships. In this talk, I will describe our recent results on the subjects: i) the incoherent metal sharply bounded by a critical doping and quantum critical point[1]; ii) the breaking up of the superconducting transition into two distinct steps of pairing and phase condensation[2], as well as the role of flat-band for phase fluctuation in the overdoped regime[3]. Time permits, I will also discuss the benchmarking of 1D Hubbard model and the necessity of an additional attractive term to describe the cuprates[4], and the enhanced superconductivity as a result of interplay of electron-electron and electron-phonon interactions[5]. The rich phenomenology suggests that a delicate balance between local Coulomb interaction and electron-phonon interaction holds the key to cuprate physics.

[1] S. Chen et al. Science 366, 6469 (2019)
[2] S. Chen et al., Nature, 2022 (in press)
[3] Yu He et al., Phys. Rev. X 11, 031068
[4] Z.Y. Chen, Science 373, 6560 (2021)
[5] Yu He et al., Science, 362, 62 (Oct. 2018)

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Steven Kivelson

What is needed to achieve high temperature superconductivity in the Hubbard model?

Steven Kivelson

The repulsive Hubbard model plays a central role in discussions of the mechanism of unconventional superconductivity, and especially of high temperature superconductivity (HTSC). It can be shown to exhibit low temperature SC when U is small but it primarily exhibits ferromagnetism for very large U. Various approximate approaches to the problem have suggested HTSC occurs robustly at intermediate U. However, a consensus has recently developed, based on controlled DMRG studies of relatively broad Hubbard cylinders, that the "pure" model on a square lattice with intermediate U and only nearest-neighbor hopping is not superconducting at all due to a ferocious competition with charge-density-wave order. This focusses attention on the question: What, if any, specific changes in the microscopic electronic structure (e.g. band parameters) allows HTSC to emerge? Two specific examples of deformations of the pure model that have been shown to spectacularly enhance superconductivity are magnetic frustration (i.e. intuitively corresponding to a doped spin-liquid) and a form of stripe order (i.e. intuitively corresponding to an array of doped two-leg ladders). General lessons concerning the destructive effect of antiferromagnetic order and the essential role of short-range singlet correlations will be discussed.

Optical control of electric and magnetic polarization through the crystal lattice

A.S. Disa[1,2]

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The ability to manipulate symmetry breaking order parameters, such as spontaneous electric polarization and magnetization, underpins many current and future information storage and processing technologies. A key challenge for realizing next-generation optical/photonic computing paradigms, offering improved efficiency and speed, is to robustly control such macroscopic order with light. In this talk, I will describe how optical control of electric and magnetic polarization can be achieved by taking advantage of the coupling to the crystal structure [1-3]. We make use of tailored THz pulses to resonantly drive large amplitude atomic distortions, providing a tool to engineer the structure and functionality of materials, often beyond what's possible in equilibrium. I will focus on a recent experiment illustrating the application of this approach to dynamically enhance magnetism in a strongly correlated ferromagnet, $YTiO_3$ (T_c = 27 K) [2]. At low temperatures within the ferromagnetic phase, we find that the magnetization can either be transiently increased or decreased through selective phonon excitation. For a specific driven lattice distortion, the non-equilibrium ferromagnetism can be optically stabilized up to ~100 K, nearly three times the equilibrium T_c. These results demonstrate novel THz light-induced functionalities that can be extended to other materials systems.

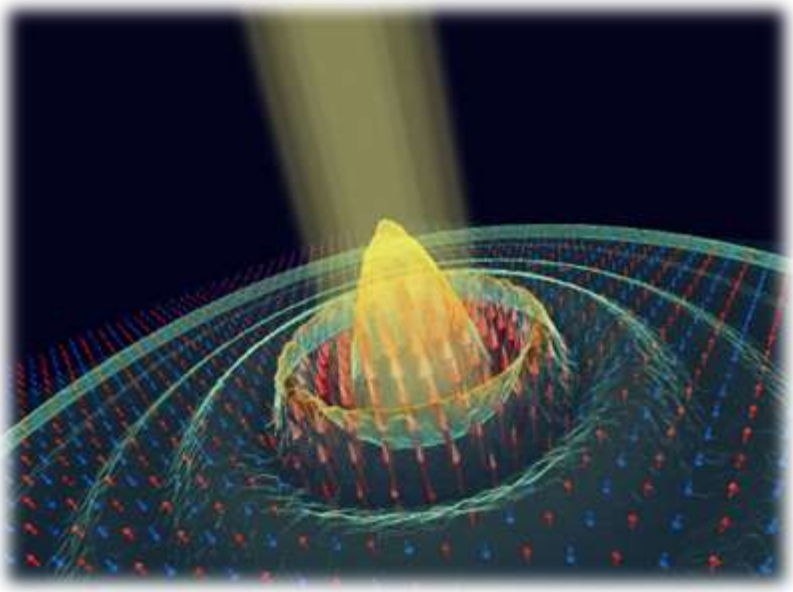

Fig. 1: *Artistic depiction of the use of optical excitation to control magnetism – creating ferrimagnetic order in an antiferromagnetic compound [3].*

References

[1] A.S. Disa, T.F. Nova, and A. Cavalleri, Nature Physics 17, 1087 (2021)
[2] T.F. Nova, A.S. Disa, M. Fechner, A. Cavalleri, Science 364, 1075 (2019)
[2] A.S. Disa, et al., Nature Physics 16, 937 (2020)
[3] A.S. Disa, et al., arXiV:2111.13622

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Dr. Marc-Henri Julien

The Charge Density Wave of $YBa_2Cu_3O_y$: NMR Insights

M.-H. Julien[1]

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Our NMR studies of $YBa_2Cu_3O_y$ [1-6] show that long-range CDW order is observed above a doping-dependent onset field that anti-correlates with the strength of superconductivity, consistent with a competing order nucleated in the vortex cores. The CDW is oxygen-centered, unidirectional and has a commensurate period 3, implying that the incommensurability observed in xray scattering studies arises from phase slips (discommensurations). The normal-state/zero-field CDW is interpreted as CDW fluctuations pinned by disorder, an effect documented in many CDW materials. This normal state CDW is still present at optimal doping, it shows some degree of planar anisotropy and it contributes to the pseudogap seen in the magnetic susceptibility.

References

[1]. T. Wu *et al.* Nature 477, 191 (2011).
[2]. T. Wu *et al.* Nat. Commun. 4, 2113 (2013).
[3]. T. Wu *et al.* Nat. Commun. 6**,** 6438 (2015)
[4]. R. Zhou *et al*. PRL 118, 017001 (2017).
[5]. I. Vinograd *et al.* Nat. Commun. 12, 3274 (2021).
[6]. R. Zhou et al., in preparation.

Dragana Popovic

High-Field Normal State of Stripe-Ordered Cuprates

D. Popović[1]

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In underdoped cuprates, the relationship between the pseudogap, superconductivity, and charge and spin ordering has been of key interest. Since high magnetic fields (*H*) perpendicular to CuO_2 layers are commonly used to suppress superconductivity and probe the nature of this unusual normal state, one of the central issues is to understand the interplay of superconductivity with charge and spin orders in the limit of high *H*. Time permitting, this talk will describe the main results (Fig. 1) of the comprehensive series of experiments [1-3] performed using several complementary electrical transport techniques on underdoped La-214 cuprates in which charge and spin orders appear in the form of stripes near *x*~1/8 doping. Our results a) establish a robust phase diagram for superconducting (SC) vortices in underdoped cuprates [1], b) provide much-needed transport signatures of the elusive pair-density wave (PDW) state in stripe-ordered cuprates in the regime where superconductivity is destroyed by quantum phase fluctuations [2], and c) reveal striking, novel properties of the normal state of cuprates, such as the vanishing of the Hall response [3]. The broader relevance of our findings to cuprate physics will be also discussed.

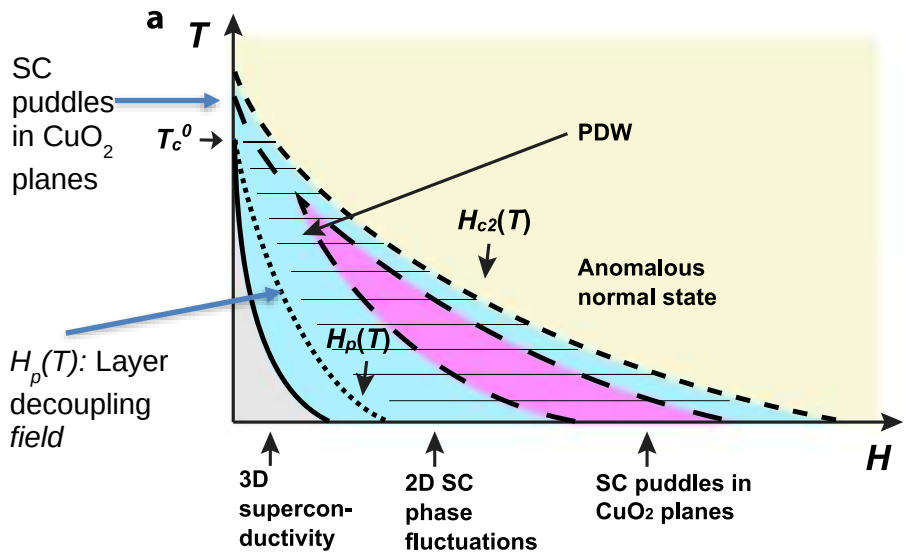

Fig. 1: *Schematic (T, H) phase diagram of stripe-ordered Eu-LSCO and Nd-LSCO. Strong SC phase fluctuations persist in the planes up to $H_{c2}(T)$. Evidence of PDW correlations is found in the region marked by thin hatched lines.*

References

[1]. Z. Shi, P. G. Baity, T. Sasagawa, D. Popović, Sci. Adv. **6**, eaay8946 (2020).
[2]. Z. Shi, P. G. Baity, J. Terzic, T. Sasagawa, D. Popović, Nat. Commun. **11**, 3323 (2020).

[3]. Z. Shi, P. G. Baity, J. Terzic, B. K. Pokharel, T. Sasagawa, D. Popović, Nat. Commun. **12**, 3724 (2021).

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Prof. Amit Keren

Stiffness and coherence length measurements of ultra-thin superconductor using a Stiffnessometer

A. Keren[1], N. Blau[1], N. Gavish[2], O. Kenneth[1]

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We use an applied rotor-free vector potential $\mathbf{A}$, and measurements of current density $\mathbf{J}$ with a SQUID, to determine 2D and 3D superconducting stiffness ρ_s, and coherence length ξ, as defined by the London equation $\mathbf{J} = -\rho_s \mathbf{A}$ and it's range of validity[1]. The method is applied to ultra-thin, ring shaped, superconducting MoSi films. We find that ξ is a function of the film thickness d with a jump at $\xi \sim d \sim 5$ nm, as depicted in Fig. 1. At base temperature, the superconducting 3D stiffness is an increasing function of T_c. Similar behavior, known as the Uemura plot, exist in bulk layered superconductors, but with doping as an implicit parameter.

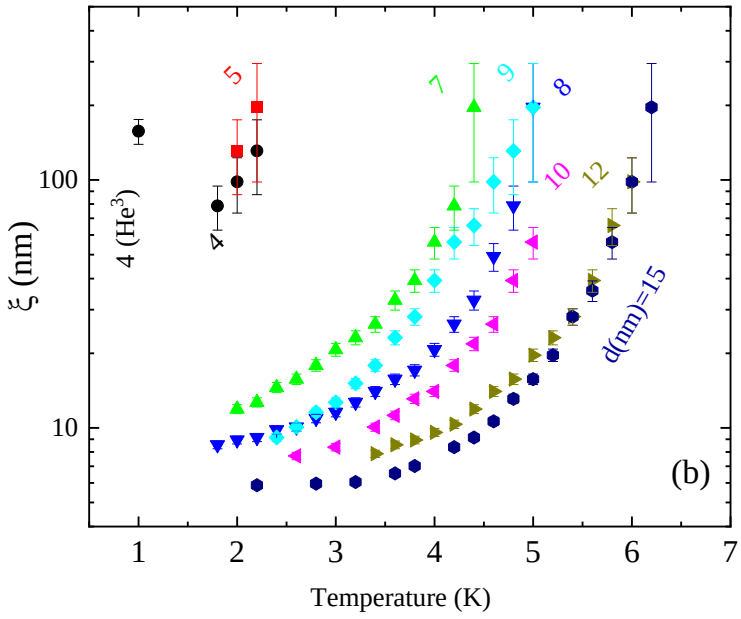

Fig. 1: *Coherence length ξ as a function of thickness and temperature measured by an external field free experiment.*

References

[1]. A. Keren et al., submitted to Phys. Rev. B **20**.

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Ming Yi[1,2],

Correlation-Driven Electronic Reconstruction in Iron Chalcogenides

M. Yi[1,2], J. Huang[1], R. Yu[3], Z. Xu[2,4], J.-X. Zhu[5], J. S. Oh[1,2], Q. Jiang[6], M. Wang[7], H. Wu[1], T. Chen[1], J. D. Denlinger[8], S.-K. Mo[8], M. Hashimoto[9], M. Michiardi[10,11], T. M. Pedersen[12], S. Gorovikov[12], S. Zhdanovich[10,11], A. Damascelli[10,11], G. Gu[13], P. Dai[1], J.-H. Chu[6], D. Lu[9], Q. Si[1], R. J. Birgeneau[2,14]

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Electronic correlation is of fundamental importance to high temperature superconductivity. While the low energy electronic states in cuprates are dominantly affected by correlation effects across the phase diagram, observation of correlation-driven changes in fermiology amongst the iron-based superconductors remains rare. Here we present experimental evidence for a correlation-driven reconstruction of the Fermi surface tuned independently by two orthogonal axes of temperature and Se/Te ratio in the iron chalcogenide family. We demonstrate that this reconstruction is driven by the de-hybridization of a strongly renormalized d_{xy} orbital with the remaining itinerant iron 3d orbitals in the emergence of an orbital-selective Mott phase. Our observations are further supported by our theoretical calculations to be salient spectroscopic signatures of such a non-thermal evolution from a strongly correlated metallic phase into an orbital-selective Mott phase in d_{xy} as Se concentration is reduced.

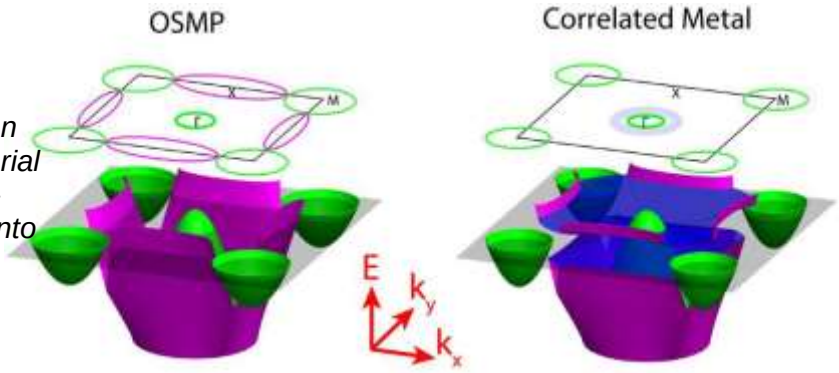

Fig. 1: *Illustration showing the observed electronic reconstruction and effect on the fermiology as the material transitions from a strongly-correlated metallic phase into an orbital- selective Mott phase (OSMP).*

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Prof. André-Marie Tremblay

Oxygen Hole Content, Charge Transfer Gap, Superexchange and the Mechanism of Superconductivity in Cuprates

N. Kowalski[1,2], S.S. Dash[1,2], Patrick Sémon[1,2], D. Sénéchal[1,2], A.-M.S. Tremblay[1,2]

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Using cluster generalizations of dynamical mean-field theory for the three-band Hubbard model, we explain three apparently unrelated experiments that suggest how to optimize T_c in cuprates: i) NMR experiments that show that T_c is optimized by maximizing oxygen hole content [1] ii) Scanning Tunneling spectroscopy that shows that T_c is optimized by decreasing the charge transfer gap [2] and iii) neutron experiments that show that T_c is optimized by increasing superexchange [3]. The unified explanation of these three experiments that we offer also explains the mechanism for superconductivity in cuprates. The results suggest new avenues to discover compounds that superconduct at even higher temperature [4].

References

[1] Rybicki D, et al. Nature Communications 7:11413 (2016)
[2] Ruan W, et al., Science Bulletin 61(23):1826–1832 (2016)
[3] Wang L, et al. arXiv:2011.05029
[4] Nicolas Kowalski, Sidhartha Shankar Dash, Patrick Sémon, David Sénéchal, and André-Marie Tremblay, PNAS (Proceedings of the National Academy of Sciences) **118** (40) e2106476118 (2021).

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Prof. Liang Fu

Superconductivity in doped insulators: ZrNCl, WTe2 and more

L. Fu[1]

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I will present a novel mechanism for unconventional superconductivity in doped band insulators, where short-ranged pairing interaction arises from Coulomb repulsion due to virtual interband or excitonic processes. Remarkably, electron pairing is found upon infinitesimal doping, giving rise to BEC-BCS crossover at low density. Our theory explains puzzling behaviors of superconductivity and predicts spin-triplet pairing in electron-doped ZrNCl and WTe$_2$.

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Milan Allan

Measuring local moiré lattice heterogeneity of twisted bilayer graphene

Milan P. Allan
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It was proposed that superconductivity can emerge in moiré lattices even if it is absent in their building blocks [1,2], and several materials have been discovered recently where this is the case. These real-world materials differ from the ideal case, and are often thought to be rather heterogenous. In this talk, I will present a new method to continuously map inhomogeneities of a moiré lattice and apply it to large-area topographic images we measure on open-device twisted bilayer graphene (TBG). We show that the variation in the twist angle of a TBG device, which is frequently conjectured to be the reason for differences between devices with a supposed similar twist angle, is about 0.08° around the average of 2.02° over areas of several hundred nanometers, comparable to devices encapsulated between hexagonal boron nitride slabs [3]. We distinguish between an effective twist angle and local anisotropy and relate the latter to heterostrain. Our results imply that for our devices, twist angle heterogeneity has an effect on the electronic structure roughly equal to that of local strain. The method introduced here is applicable to results from different imaging techniques and on different moiré materials.

References

[1] R. Bistritzer and A. H. MacDonald, Moiré bands in twisted double-layer graphene, Proc. Natl. Acad. Sci. USA 108, 12233 (2011).
[2] MP Allan, MH Fischer, O Ostojic, A Andringa. SciPost Phys. 3, 010 (2017)
[3] T Benschop , TA de Jong, P Stepanov*, Xiaobo Lu, V Stalman, SJ van der Molen, DK Efetov, MP Allan. Phys. Rev. Research 3, 013153 (2021)

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James Analytis, Nikola Maksimovic

Strongly correlated itinerant ferromagnetism in NiTa4Se8 on the boundary of superconductivity

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We report on the growth of a novel magnetic metal NiTa$_4$Se$_8$ (or Ni$_{1/4}$TaSe$_{2}$) with a Curie temperature of 58 Kelvin. Structurally, the material is composed of 2H-TaSe$_2$ layers with a hexagonal lattice of nickel atoms between each layer. Its saturated low-temperature magnetic moment (0.7μ_{B}) is significantly smaller than the effective fluctuating moment (2.1μ_{B}), putting this material in the class of weak itinerant ferromagnets. In analogy to other materials of this type, strong electron-electron correlations lead to an enhanced electron effective mass and Kadowaki-Woods ratio. This systems lies on the boundary of a superconducting dome, which appears to be consistent with a nodal order parameter.

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Dr. Gaël Grissonnanche

Chiral phonons in quantum materials

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The thermal Hall effect has been proposed as a powerful tool to probe exotic topological excitations in quantum spin liquids, with the spectacular report of a half-quantized thermal Hall effect in the Kitaev material α-$RuCl_3$ [1,2].

Here we report measurements of the thermal Hall conductivity κ_{xy} in the normal state of four different cuprates and show that a large negative κ_{xy} signal is a property of the pseudogap phase, appearing with the onset of that phase at the critical doping p^*. It is also a property of the Mott insulator at $p \approx 0$, where κ_{xy} is the largest, so it cannot come from mobile electrons. To identify the heat carriers responsible for this negative κ_{xy} from heat transport in the CuO_2 planes, we turn to transverse heat transport along the c-axis: κ_{zy}. We find that the thermal Hall conductivity at $p = 0$ is roughly isotropic, being nearly the same for heat transport parallel and normal to the CuO_2 planes, *i.e.* $\kappa_{zy}(T) \approx \kappa_{xy}(T)$. Because only phonons can travel between the CuO_2 planes, this demonstrates that the negative thermal Hall response must come from phonons.

Now. it is becoming surprisingly apparent that phonons can also produce a large thermal Hall effect across a wide range of quantum materials, from cuprate superconductors [3,4] to the titanates [5] and frustrated magnets [6]. A significant phonon Hall effect is also suspected in α-$RuCl_3$ [7]. While phonons carry no charge and are common low energy excitations in solids, the origin of the handedness that gives rise to a phonon Hall effect in a magnetic field remains an enigma. Besides, the present ubiquity of the phonon Hall effect calls for caution when interpreting the results of quantum spin liquids candidates.

References

[1] Kasahara *et al.* Nature **559**, 277 (2018).
[2] Yokoi *et al.* Science **373**, 6554 (2021).
[3] Grissonnanche *et al.* Nature **571**, 376 (2019).
[4] Grissonnanche *et al.* Nat. Phys. **16**, 1108 (2020).
[5] Li *et al.* PRL **105**, 225901 (2020).
[6] Hirokane *et al.* PRB **99**, 134419 (2019).
[7] Lefrançois *et al.* arXiv:2111.05493

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Andrew Potter, Professor Shyam Shankar, Yuxuan Zhang, Ameya Riswadkar

Josephson parametric amplifiers for rapid, high-fidelity measurement of solid-state qubits

Presenter: Shyam Shankar
Affiliation: Electrical and Computer Engineering, University of Texas at Austin
Abstract: Quantum physics puts a limit on how small the noise added by an amplifier can be. Limiting this extra noise, which causes unavoidable signal degradation, is an essential requirement for the measurement of weak electromagnetic signals in various areas of science and engineering. In particular, a nearly-quantum-limited microwave amplifier is a key tool for performing rapid, high-fidelity measurement of solid-state qubits. In this talk, I will review how we build a microwave measurement system using Josephson parametric amplifiers (JPAs) that adds only the minimum amount of noise required by quantum physics. I will discuss how, over the past half-decade, we have improved the performance of these amplifiers to achieve greater power handling and information throughput, necessary for realizing large-scale quantum information processors. Finally, I will discuss recent work to realize JPAs with a new element, a Josephson Junction Field Effect Transistor (JJFET) made from InAs-Al superconductor-semiconductor heterostructures.

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Prof. Hadar Steinberg

Gap stability in ultrathin $NbSe_2$ at high magnetic fields

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Superconducting two-dimensional transition metal dichalcogenides (TMDs) exhibit outstanding stability towards in-plane magnetic fields. This is a consequence of a strong Ising-type spin-orbit term which locks the spins to an out-of-plane orientation. Remarkably, the combined effect of the spin orbit and in-plane magnetic field are expected to cause the emergence of triplet order due to tilting of the spins, which acquire an in-plane component [1]. We report the fabrication and measurement of tunnel junctions, realized by placement of thin barriers on top of $NbSe_2$. These junctions allow probing of the spectrum at high resolution, revealing clear signatures of the quasiparticle structure and of the sub-gap features [2-4]. Specifically, we find that in finite thickness $NbSe_2$, the tunnel spectra exhibit the signatures of two gaps, and in-plane field reveals distinct depairing dynamics of these different gaps. Tracking the spectra all the way to the ultrathin limit, we find the signatures of the two-gap physics disappear. Here, the application of in-plane magnetic field up to 30 T, reveals a surprising stability of the gap [5]. We discuss possible origins of the added stability and its relation to the emergence of a sub-dominant equal-spin-triplet order parameter. Our work suggests that the study of TMD superconductors at high in-plane fields is a promising avenue for searching for exotic superconductivity.

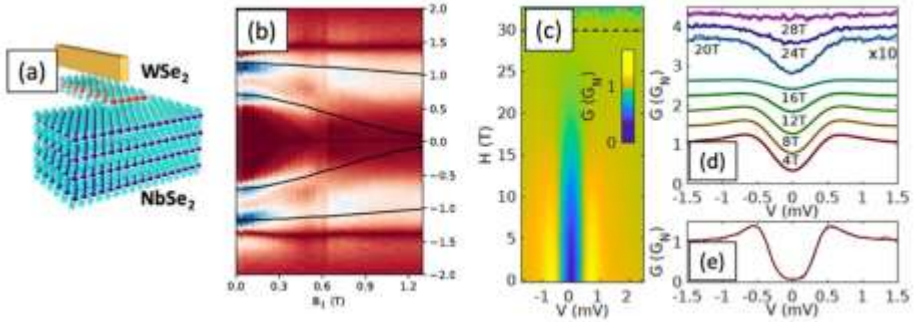

Fig. 1: *(a) Schematic of vdW-assembled tunnel device. (b) d^2I/dV^2 vs. Bias and in-plane magnetic field of a 20-nm thick $NbSe_2$ flake, showing the distinct evolution of the two gaps (c) dI/dV vs. bias and in-plane field, of a 2-layer flake, showing the superconducting gap survives well above 20 T. (d) line scans of selected field in the dataset in (c), showing the stability of the gap above 20 T. (e) Tunnel spectrum of same device at 20 mK, B = 0.*

1. Möckli, D. and M. Khodas, *Robust parity-mixed superconductivity in disordered monolayer transition metal dichalcogenides.* Physical Review B, 2018. **98**(14): p. 144518.
2. Dvir, T., et al., *Spectroscopy of bulk and few-layer superconducting $NbSe_2$ with van der Waals tunnel junctions.* Nature Communications, 2018. **9**(1): p. 598.

3. Dvir, T., et al., *Zeeman Tunability of Andreev Bound States in van der Waals Tunnel Barriers.* Physical Review Letters, 2019. **123**(21): p. 217003.
4. Dvir, T., et al., *Tunneling into the Vortex State of $NbSe_2$ with van der Waals Junctions.* Nano Letters, 2018. **18**(12): p. 7845-7850.
5. Kuzmanović, M., et al., *Tunneling spectroscopy of few-monolayer $NbSe_2$ in high magnetic field: Ising protection and triplet superconductivity.* arXiv: 2104.00328, 2021.

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Prof. Shanti Deemyad

Quantum grounds states under pressure: Pressure-induced superconductivity in charge density wave material $BaSbTe_{2.1}S_{0.9}$

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Restricting the volume of a material, through application of pressure, changes the dominance of interactions within the material, and exposes unnatural states of matter not found in our predominantly adiabatic universe. High pressure studies are particularly important in understanding the electronic quantum states caused by electron-phonon interactions such as conventional superconductivity and charge density waves (CDW). In this talk, I will provide an overview of the pressure effects on superconductivity and other electronic orders in materials. I will present some of our recent studies on exploring competitive ground states of materials at extreme conditions and discuss our studies on the interplay between the CDW and superconducting states in 2D material $BaSbTe_{2.1}S_{0.9}$ under pressure.

Prof. Elena Hassinger

Two-Phase Superconductivity in $CeRh_2As_2$

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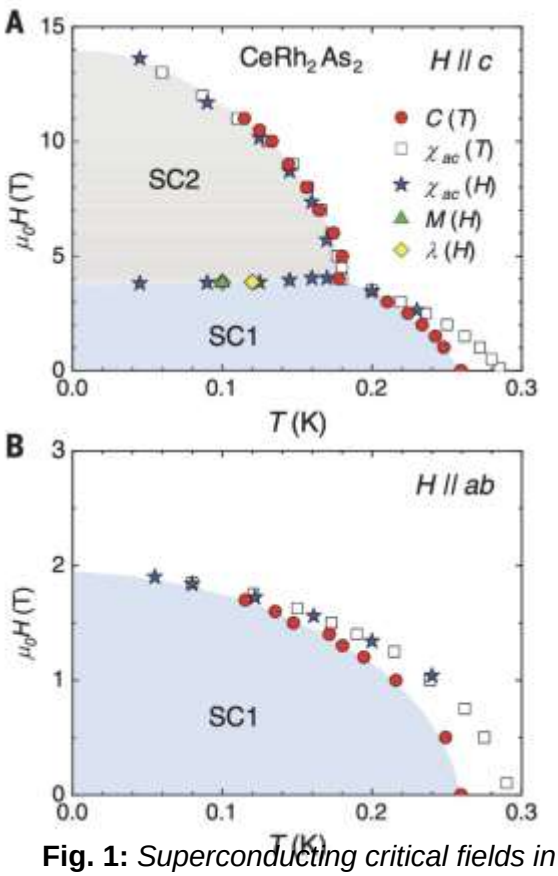

We report the discovery of two-phase unconventional superconductivity in $CeRh_2As_2$ [1]. Using thermodynamic probes, we establish the highly anisotropic critical field phase diagram (Fig. 1). The superconducting state appearing at low fields is characterised by an enhanced and anisotropic Pauli limit. Furthermore, a c-axis field drives a transition to a second superconducting state that seems to be purely orbitally limited with a critical field as high as 14 T, remarkable in a material whose transition temperature is 0.26 K. In spite of the fact that CeRh2As2 is globally centrosymmetric, local inversion-symmetry breaking at the Ce sites would naturally enable Rashba spin-orbit coupling to dominate the critical fields and drive a transition from even to odd parity super- conductivity. The angular dependence of the critical fields confirms that the high-field state is an odd-parity state.

Fig. 1: *Superconducting critical fields in $CeRh_2As_2$ for magnetic fields H || c (***A***) and H || a (***B***)*

References

[1]. S. Khim, J. Landaeta, Science **737**, 1012–1016 (2021).

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Prof. Takasada Shibauchi

Nematicity and Exotic Superconductivity in FeSe-based Superconductors

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The interplay among magnetism, electronic nematicity, and superconductivity is the key issue in strongly correlated materials including iron-based, cuprate, and heavy-fermion superconductors. Magnetic fluctuations have been widely discussed as a pairing mechanism of unconventional superconductivity, but recent theory predicts that quantum fluctuations of electronic nematicity, which is characterized by rotational symmetry breaking, may also promote high-temperature superconductivity. FeSe-based superconductors are suitable to study this issue [1], because FeSe exhibits a nonmagnetic nematic order that can be suppressed by S or Te substitution for Se. I will review recent studies of FeSe-based superconductors, which show quite exotic superconducting states. In $FeSe_{1-x}S_x$ superconductors, the nematic order can be completely suppressed at x=0.17, above which the superconducting properties change drastically with a significantly reduced critical temperature T_c [2,3]. From recent muon spin rotation (μSR) measurements [4], we find evidence for a novel ultranodal pair state with broken time reversal symmetry [5]. In the Te substitution case, however, we find quite different behavior; the suppression of nematic order leads to an enhancement of T_c, which is likely associated with quantum critical fluctuations of nematicity [6].

References

[1] See, for a review, T. Shibauchi, T. Hanaguri, and Y. Matsuda, J. Phys. Soc. Jpn. **89**, 102002 (2020).
[2] Y. Sato *et al.*, Proc. Natl. Acad. Sci. USA **115**, 1227-1231 (2018).
[3] T. Hanaguri *et al.*, Sci. Adv. **4**, eaar6419 (2018).
[4] K. Matsuura *et al.*, preprint.
[5] C. Setty, S. Bhattacharyya, Y. Cao, A. Kreisel, and P. J. Hirschfeld, Nat. Commun. **11**, 523 (2020).
[6] K. Mukasa *et al.*, Nat. Commun. **12**, 381 (2021).

New Material Systems for Superconducting Qubits

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Many platforms for quantum technologies are limited by noise and loss arising from uncontrolled defects at surfaces and interfaces, including superconducting qubits, color centers in diamond, trapped ions, and semiconductor quantum dots. I will describe our recent efforts to tackle noise and microwave losses in superconducting qubits. Building large, useful quantum systems based on transmon qubits will require significant improvements in qubit relaxation and coherence times, which are orders of magnitude shorter than limits imposed by bulk properties of the constituent materials. This indicates that relaxation likely originates from uncontrolled surfaces, interfaces, and contaminants. Previous efforts to improve qubit lifetimes have focused primarily on designs that minimize contributions from surfaces. However, significant improvements in the lifetime of planar transmon qubits have remained elusive for several years. We have fabricated planar transmon qubits that have both lifetimes and coherence times exceeding 0.3 milliseconds by replacing niobium with tantalum in the device [1]. Following this discovery, we have parametrized the remaining sources of loss in state-of-the-art devices using systematic measurements of the dependence of loss on temperature, power, and geometry. This parametrization, complemented by direct materials characterization, allows for rational, directed improvement of superconducting qubits.

References

[1]. A.M. Place *et al*, Nature Communications 12, 1779 (2021).

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Dr. Jonathan Ruhman

"Zero density" superconductivity in polar Dirac metals at their quantum critical point

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In this talk I will discuss the fate of a Dirac liquid coupled to a ferroelectric order parameter at its quantum critical point. Based on the renormalization group technique I will show that the coupling between the fermions and the quantum-critical fluctuations is relevant, rendering the transition a strong coupling problem. Using Eliashberg theory, I will show that this strongly coupled problem avoids the critical point through a first order transition from a Dirac liquid to a "zero-density" superconductor coexisting with ferroelectric order. Furthermore, I will show the ferroelectric state is a non-uniform wave, which we dub a "ferroelectric density wave". Given that this theory predicts a finite superconducting transition temperature at charge neutrality, where the charge density and density of states are zero, this result contributes to our understanding of how superconductivity emerges in doped materials such as the rocksalt alloy $Sn_xPb_{1-x}Te$.

Dr. Shigeru Kasahara

Fulde-Ferrell-Larkin-Ovchinnikov States in the BCS-BEC-Crossover Superconductor FeSe

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The iron-chalcogenide FeSe is argued as a strong candidate superconductor located in the crossover regime between the weakly coupled BCS and the strongly coupled BEC limits [1,2]. Its extremely small and shallow Fermi pockets, large superconducting gap, and consequently a large Maki parameter suggest that FeSe offers an ideal platform to study the potential Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superconducting state, in which a new pairing (***k***, -***k***+***q***) with nonzero q is formed. Here, we present several pieces of evidence for the emergence of distinct high-field superconducting phases in FeSe. For ***H*** || *ab*, our state-of-the-art high-field thermal transport up to 33 T shows a discontinuous downward jump within the superconducting state, indicating a first-order phase transition to a distinct high-field superconducting phase [3]. For ***H*** || *c*, the presence of a high-field phase is shown by an anomalous kink of the heat capacity, which occurs well below the irreversibility field. We attribute these high-field superconducting phases to the FFLO superconducting states. We also point out the importance of the multi-band nature and the orbital dependent pairing for the formation of the FFLO phase in FeSe.

This work has been done in collaboration with Y. Sato, Y. Suzuki, Y. Masuda (Kyoto Univ.), T. Shibauchi (Univ. of Tokyo), T. Hanaguri, T. Machida (RIKEN), S. Licciardello, M. Čulo, N. E. Hussey (Radboud Univ. and HFML Nijmegen), S. Arsenijević, J. Wosnitza (HZDR), J. Böker, I. Eremin (Ruhr-Universität Bochum).

References

[1] S. Kasahara et al., Proc. Natl. Acad. Sci. USA **111**, 16309 (2014).
[2] T. Shibauchi, T. Hanaguri, Y. Matsuda, J. Phys. Soc. Jpn. **89**, 102002 (2020).
[3] S. Kasahara et al., Phys. Rev. Lett. **124**, 107001 (2020).

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Cyril Proust

Engineering Competing Orders in Multi-layered Cuprate Superconductors

V. Oliviero[1], S. Benhabib[1], I. Gilmutdinov[1], B. Vignolle[2], L. Drigo[1], M. Massoudzadegan[1], M. Leroux[1], G.L.J.A. Rikken[1], A. Forget[3], D. Colson[3], D. Vignolles[1] and C. Proust[1]

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Multilayered cuprates possess not only the highest superconducting temperature transition but also offer a unique platform to study disorder-free CuO_2 planes and the interplay between competing orders with superconductivity [1]. After a short introduction on multi-layered cuprate superconductors, I'll present a recent study of quantum oscillation and Hall effect in magnetic field up to 88 T in the underdoped trilayer cuprate $HgBa_2Ca_2Cu_3O_{8+\delta}$. A careful analysis of the complex spectra of quantum oscillations strongly supports the coexistence of multiple competing orders [2]. In particular, our interpretation implies that a metallic antiferromagnetic state extends deep inside the superconducting phase, a key ingredient that supports magnetically mediated pairing interaction in cuprates [3].

References

[1]. H. Mukuda *et al.*, J. Phys. Soc. Jpn **81**, 011008 (2012).
[2]. V. Oliviero *et al*., arXiv: 2111.03589 (2021).
[3] D.J. Scalapino, Mod. Phys. **84**, 1383 (2012).

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Amit Kanigel

Unconventional superconductivity in 4Hb-TaS_2

A. Kanigel

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Low dimensional materials have been a major subject of interest in recent years. In particular, the transitions metal dichalcogenides (TMDs), quasi-2D layered materials with weak van der Waals coupling between layers, received a lot of attention. TMDs exhibit strong electron-electron and electron-phonon interactions that lead to complicated phase diagrams showing a variety of ground states

A fascinating frontier, largely unexplored, is the stacking of strongly correlated phases of TMDs. We study 4Hb-TaS_2, which naturally realizes an alternating stacking of 1T-TaS_2 and 1H-TaS_2 structures. The former is a well-known Mott insulator, which has recently been proposed to host a gapless spin-liquid ground state. The latter is a superconductor known to also host a competing charge density wave state. This raises the question of how these two components affect each other when stacked together.

We find a superconductor with a T_c of 2.7 Kelvin and anomalous properties. Using Muon Spin Relaxation, we show that 4Hb-TaS_2 breaks time-reversal symmetry, abruptly at the superconducting transition [1].
Using scanning superconducting quantum interference device (SQUID) microscopy we found a spontaneous vortex phase whose vortex density depends on the magnetic history of the sample above Tc.
In addition, using scanning tunneling spectroscopy we find spectroscopic evidence for the existence of topological surface superconductivity. These include edge modes running along the 1H-layer terminations as well as under the 1T-layer terminations, where they separate between superconducting regions of distinct topological nature [2].

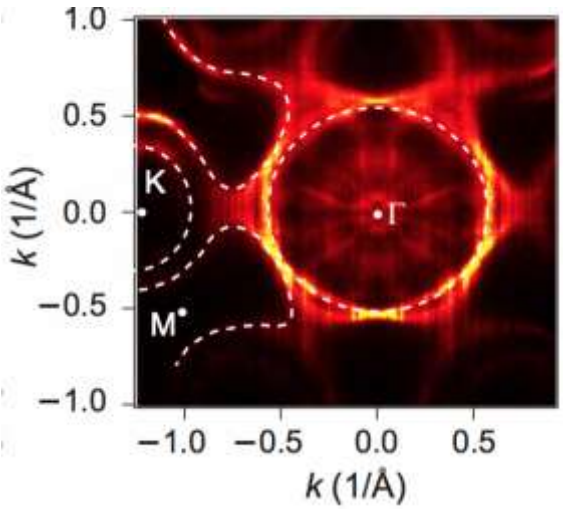

Fig. 1: *Fermi surface of 4Hb-TaS2.*

References

[1]. A. Ribak *et al*., *Sci. Adv.* **6,** eaax9480 (2020).
[2]. A.K.Nayak *et al*., Nature Phys., (2021).

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Dr. Aline Ramires

Deconstructing Sr_2RuO_4: insights from a microscopic perspective

Aline Ramires

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Sr_2RuO_4 has long been thought to host a spin-triplet chiral p-wave superconducting state. However, recent spin-susceptibility measurements cast serious doubts on this pairing state. Together with the evidence for broken time-reversal symmetry and a jump in the shear modulus c_{66} at the superconducting transition temperature, the available experiments point towards an even-parity chiral superconductor with E_g symmetry. This state has consistently been dismissed based on the quasi-two-dimensional electronic structure of this material. In this talk, I discuss how the orbital degree of freedom can encode the two-component nature of the E_g order parameter, allowing for a local orbital-antisymmetric spin-triplet state that can be stabilized by on-site Hund's coupling [1]. In addition, I will highlight recent strain experiments and show how this specific order parameter seems to naturally reconcile the surprising behaviour of the evolution of the critical temperature under strain along different directions. In particular, we can semi-quantitatively account for the asymmetric splitting of the critical temperatures for compressive strain along the 100 direction, and the reduction of the critical temperatures for compressive strain along the 001 and 110 directions with a single free parameter [2].

References

[1]. H. G. Suh et al., Phys. Rev. Research **2**, 032023(R) (2020)
[2]. S. Beck et al., arXiv.2111.13506

A Moiré Superlattice on the Surface of a Topological Insulator

Jennifer Cano[1,2], Shiang Fang[3], J. H. Pixley[3], and Justin H. Wilson[3]

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Twisting van der Waals heterostructures to induce correlated many-body states provides a novel tuning mechanism in solid-state physics. In this work, we theoretically investigate the fate of the surface Dirac cone of a three-dimensional topological insulator subject to a superlattice potential. Using a combination of diagrammatic perturbation theory, lattice model simulations, and ab initio calculations we elucidate the unique aspects of twisting a single Dirac cone with an induced moiré potential and the role of the bulk topology on the reconstructed surface band structure. We report a dramatic renormalization of the surface Dirac cone velocity as well as demonstrate a topological obstruction to the formation of isolated minibands. Due to the topological nature of the bulk, surface band gaps cannot open; instead, additional satellite Dirac cones emerge, which can be highly anisotropic and made quite flat. We discuss the implications of our findings for future experiments.

References

[1]. J. Cano, S. Fang, J. H. Pixley and Justin H. Wilson, Phys. Rev. B 103, 155157 (2021)

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Prof. Ashvin Vishwanath

Skyrmion superconductivity - A topological mechanism for strong coupling superconductivity in twisted bilayer graphene and beyond

A.Vishwanath[1]

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I will describe a strong coupling approach to flavor-ordered insulators and superconductivity in twisted bilayer graphene (TBG), in which the quantum geometry of the electronic bands and topological textures like skyrmions play a central role. I will also discuss how we can bridge real space and momentum space descriptions in the limit of small skyrmions, and report on numerical studies which confirm aspects of this theory. I will also explain how these insights point to a promising new family of moiré materials - the alternating twist multilayer graphene along with their associated magic angles - and highlight special features of these multilayer structures which are currently under active experimental study.

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Prof. Ming Shi

Rich Nature of Van Hove Singularities in Kagome Superconductor CsV_3Sb_5

M. Shi[1]

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The recently discovered layered kagome metals AV_3Sb_5 (A=K, Rb, Cs) exhibit diverse correlated phenomena, which are intertwined with a topological electronic structure with multiple van Hove singularities (VHSs) in the vicinity of the Fermi level. As the VHSs with their large density of states enhance correlation effects, it is of crucial importance to determine their nature and properties. Here, we combine polarization-dependent angle-resolved photoemission spectroscopy with density functional theory to directly reveal the sublattice properties of 3d-orbital VHSs in CsV_3Sb_5. Four VHSs are identified around the M point and three of them are close to the Fermi level, with two having sublattice-pure and one sublattice-mixed nature. Remarkably, the VHS just below the Fermi level displays an extremely flat dispersion along MK, establishing the experimental discovery of higher-order VHS. The characteristic intensity modulation of Dirac cones around K further demonstrates the sublattice interference embedded in the kagome Fermiology. The crucial insights into the electronic structure, revealed by our work, provide a solid starting point for the understanding of the intriguing correlation phenomena in the kagome metals AV_3Sb_5.

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Andrew Mackenzie

Some recent developments in Sr_2RuO_4

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I will describe the results of a number of experiments, done with many collaborators, investigating both the normal state and superconducting properties of the unconventional superconductor Sr_2RuO_4. Among other things, I will describe developments in establishing its phase diagram, the role played by the van Hove singularity in its underlying physics and rapid progress in understanding its superconducting order parameter.

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Frank Marsiglio, Prof. Jorge Hirsch

High-Pressure Hydrides: Experimental Questions and Theoretical Thoughts

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Room-temperature superconductivity was reported in October, 2020, after 5 years of discovery of superconducting hydrides in the 200 - 250 K range. This talk will critically review the experimental evidence for superconductivity. At the time of this writing, there are big resistivity drops, but no compelling measurements of the Meissner effect or flux trapping. We also provide a basic review of our current understanding of the electron-phonon interaction in relation to superconductivity. It is hard to see how high-temperature electron-phonon superconductivity can be theoretically supported.

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Dr. John Tranquada

Charge Stripes in Cuprates: Where Holes Go to Pair

J. M. Tranquada

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Charge stripes are typically associated with a depression of bulk superconducting order; nevertheless, they may be key to understanding the pairing mechanism in cuprates. For example, the pair-density-wave order proposed [1] to explain the decoupled superconducting layers observed in $La_{2-x}Ba_xCuO_4$ at $x = 1/8$ [2] has now been experimentally confirmed [3]. That means that pairing must occur within the charge stripes, which, in this case, are confined by antiphase spin stripes. A proposal [4], based on the spin excitation spectrum determined by neutron scattering, is that the charge stripes have the character of hole-doped two-leg spin ladders [5], with the spins decoupled from the surrounding spin stripes by geometric frustration (see Fig. 1). Josephson coupling between the charge stripes [6] must be antiphase to minimize interaction with the spin stripes. To get a uniform phase coupling, one must get the antiphase spin-stripe correlations out of the way. Indeed, experiment shows that the incommensurate spin gap provides an upper limit on the coherent uniform *d*-wave gap [7]. I will present the evidence that supports this story.

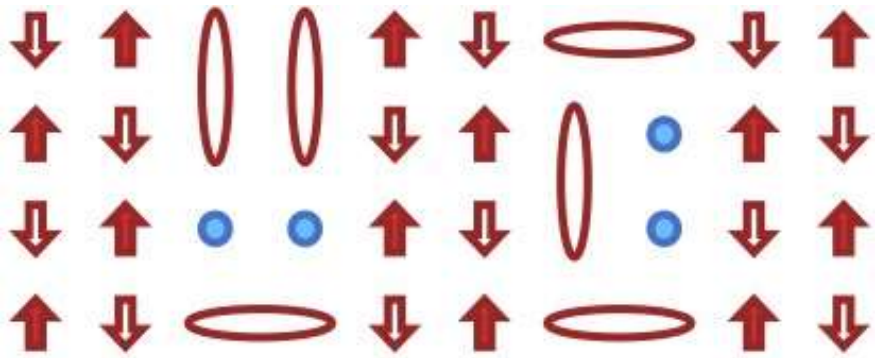

Fig. 1: *Cartoon of spin stripe order (arrows indicate S = ½ on Cu) defining charge stripes as two-leg ladders in which holes pair for energies below the singlet-triplet excitation (~ 50 meV, correspond-ding to the spin gap at the antiferromagnetic wave vector); ellipses represent singlet correlations.*

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References

[1]. E. Berg *et al*., Phys. Rev. Lett. **99**, 127003 (2007).
[2]. Q. Li *et al*., Phys. Rev. Lett. **99**, 067001 (2007).
[3]. P. M. Lozano *et al*., arXiv:2110.05513 (2021).
[4]. J. M. Tranquada, Adv. Phys. **69**, 437 (2020).
[5]. E. Dagotto and T. M. Rice, Science **271**, 618 (1996).
[6]. V. J. Emery, S. A. Kivelson, and O. Zachar, Phys. Rev. B **56**, 6120 (1997).
[7]. Y. Li *et al*., Phys. Rev. B **98**, 224508 (2018).

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Stephen Wilson

'AV_3Sb_5 (A=K, Cs, Rb): a new class of kagome metals with intertwined charge density wave and superconducting orders '

Stephen D. Wilson[1]

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Kagome metals are compelling materials platforms for hosting electronic states that feature an interplay between topologically nontrivial electronic states and correlated electron phenomena. These two features can, for instance, arise from the Dirac points, flatbands, and saddle-points endemic to the kagome lattice type in simple tight-binding models. In this talk, I will present some of our recent work exploring the electronic properties of a new class of kagome metals with Z2 topology and saddle points close to Fermi energy. Specifically, I will discuss our work studying the compounds AV_3Sb_5 (A=K, Cs, Rb) [1] which exhibit an unusual charge density wave order proposed to break time reversal symmetry as well as a low temperature superconducting ground state [2,3]. Data will be presented arguing that these two order parameters are intertwined in an unconventional manner, and the possibility of unconventional superconductivity in these materials will be discussed.

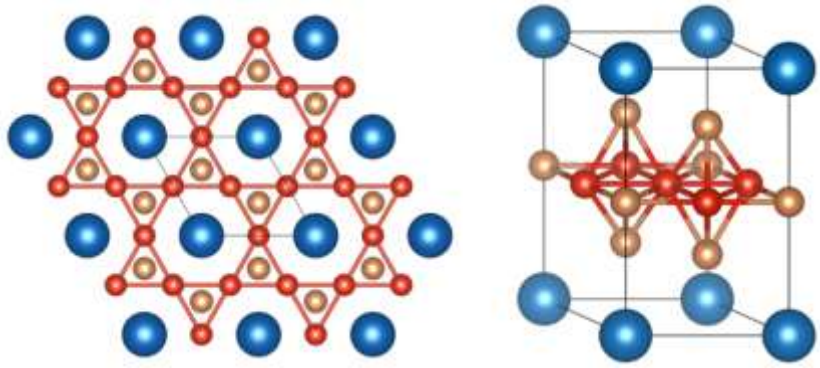

Fig. 1: *Lattice structure of AV_3Sb_5 compounds. (left) View of the lattice structure as seen looking down the long, out-of-plane axis. (right) Isometric view of the unit cell showing the layered nature of the compound. Vanadium ions (red) form a kagome net coordinated by Sb cations (orange), which are then separated by alkali metal ions (blue).*

References

[1] Brenden R. Ortiz, Lídia C. Gomes, Jennifer R. Morey, Michal Winiarski, Mitchell Bordelon, John S. Mangum, Iain W. H. Oswald, Jose A. Rodriguez-Rivera, James R. Neilson, Stephen D. Wilson, Elif Ertekin, Tyrel M. McQueen, and Eric S. Toberer, "New kagome prototype materials: discovery of KV_3Sb_5, RbV_3Sb_5, and CsV_3Sb_5" Physical Review Materials 3, 094407 (2019).

[2]. Brenden R. Ortiz, Samuel M. L. Teicher, Yong Hu, Julia L. Zuo, Paul M. Sarte, Emily C. Schueller, A. M. Milinda Abeykoon, Matthew J. Krogstad, Stephan Rosenkranz, Raymond Osborn, Ram

Seshadri, Leon Balents, Junfeng He, and Stephen D. Wilson “CsV3Sb5: A Z2 Topological Kagome Metal with a Superconducting Ground State” Physical Review Letters 125, 247002 (2020).

[3]. Brenden R. Ortiz, Samuel M. L. Teicher, Linus Kautzsch, Paul M. Sarte, Noah Ratcliff, John Harter, Jacob P. C. Ruff, Ram Seshadri, and Stephen D. Wilson “Fermi Surface Mapping and the Nature of Charge-Density-Wave Order in the Kagome Superconductor CsV_3Sb_5” Phys. Rev. X 11, 041030 (2021).

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Prof. Ilya Eremin

Nematicity and Bardasis-Schriffer mode in nonequilibrium dynamics of unconventional superconductors

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The recent technological development of THz spectroscopy makes it possible to probe properties of quantum matter, which cannot be observed in equilibrium. This is of considerable interest in the field of unconventional superconductivity, where controlled probing of the relaxation dynamics yields access to understanding ground state properties of the underlying system.

Motivated by the recent development of terahertz pump-probe experiments, I will discuss in my talk the short-time dynamics in superconductors with multiple attractive pairing channels and competing nematic instability. Studying a single-band and multiband superconductors, we analyze the signatures of collective excitations of the pairing symmetries (known as Bardasis-Schrieffer modes) as well as the order parameter amplitude (Higgs mode) in the short-time dynamics of the spectral gap and quasiparticle distribution after an excitation by a pump pulse. We show that the polarization and intensity of the pulse can be used to control the symmetry of the non-equilibrium state as well as frequencies and relative intensities of the contributions of different collective modes[1-2].

Finally, I address the question of whether pump-probe technique can be used to reveal an interplay between various collective modes visible in the superconducting state and to distinguish the Pomeranchuk nematic collective mode from the BS mode due to the subdominant Cooper-pairing channel[3-4].

References

[1] Marvin A. Müller, Pavel A. Volkov, Indranil Paul, Ilya M. Eremin, Phys. Rev. B 100, 140501(R) (2019)
[2] Marvin A. Müller, Pavel A. Volkov, Indranil Paul, Ilya M. Eremin, Phys. Rev. B 103, 024519 (2021)
[3] Marvin A. Müller and Ilya M. Eremin, Phys. Rev. B 104, 144508 (2021).
[4] Luke C. Rhodes, Jakob Böker, Marvin A. Müller, Matthias Eschrig and Ilya M. Eremin, npj Quantum Mater. 6, 45 (2021)

The M2S 2022 Conference will not issue proccedings.

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Prof. Xingjiang Zhou

Hidden Symmetry Breaking and High Temperature Superconductivity Pairing at 83K in FeSe-Based Superconductors

Xingjiang Zhou[1]

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We will report our recent angle-resolved photoemission (ARPES) studies on iron- based superconductors [1-3]. We observed highly anisotropic Fermi surface and extremely anisotropic superconducting gap in the nematic state of the FeSe superconductor [1]. We identified two hole-like Fermi surface sheets around the Brillouin zone center, and the splitting of the associated bands, in the nematic state of FeSe [2]. These indicate that, in addition to nematic order and spin-orbit coupling, there is an additional order in FeSe that breaks either inversion or time-reversal symmetries. Finally, we present spectroscopic evidence of superconductivity pairing at 83 K in single-layer FeSe/$SrTiO_3$ films [3]. We find that the superconductivity pairing state can be divided into two temperature regions of 64-83 K and below 64 K. These results indicate that either Tc as high as 83 K is achievable in iron-based superconductors, or there is a pseudogap formation from superconductivity fluctuation in single-layer FeSe/$SrTiO_3$ films.

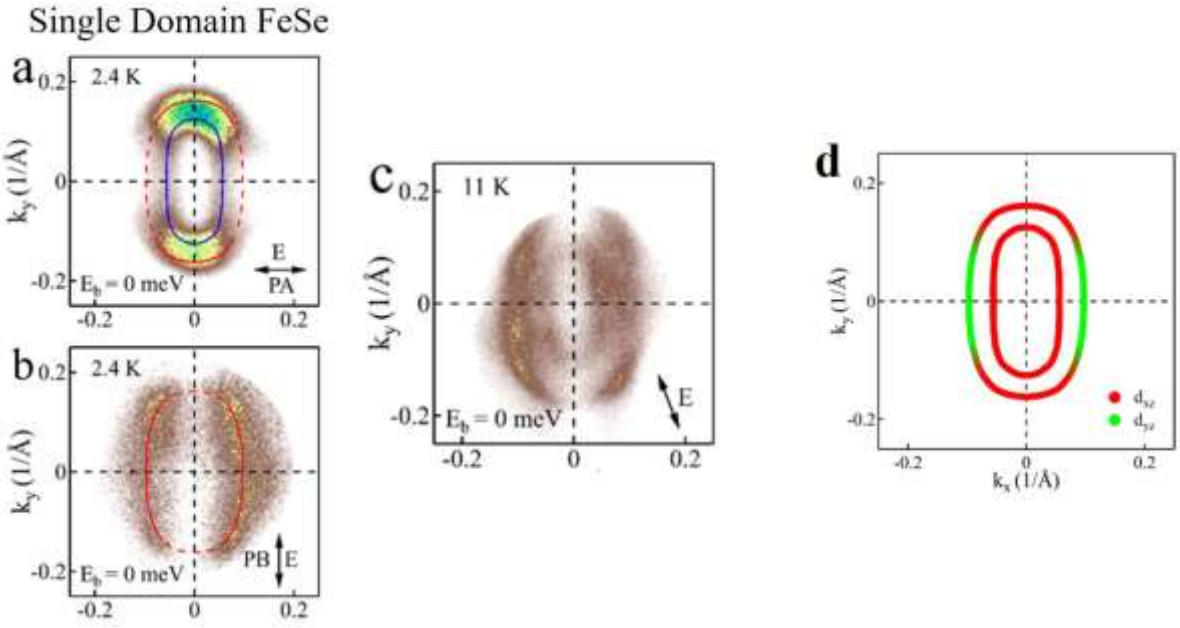

Fig. 1: *Observation of two hole-like Fermi surface sheets in FeSe around* Γ

References

[1]. Defa Liu, Cong Li, Jianwei Huang, X. J. Zhou et al., Phys. Rev. X 8, 031033 (2018). [2]. Cong Li, L. Zhao, X. J. Zhou et al., Phys. Rev. X 10, 031033 (2020).
[3]. Yu Xu, L. Zhao, X. J. Zhou et al., Nature Communications 2, 2840 (2021).

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Sergey Frolov

Hybrid superconductor-semiconductor devices

S.M. Frolov[1]

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Research into the generation, confirmation and manipulation of Majorana zero modes has brought heightened interest to hybrid materials systems made of fairly conventional components such as s-wave superconductor metals and semiconductors. The game in this arena is to carefully tailor the properties of an electronic device to make possible the observation of exotic physics such as topological superconductivity. The main lesson that we have learned is that the path to any plausible discovery lies through painstakingly careful and very deep understanding of the materials properties and device fabrication conditions. This being true for such a standard set of materials, the lesson certainly applies to more exotic compounds.

In this talk I will briefly summarize the status of the search for Majorana modes in superconductor-semiconductor hybrid devices. I will also highlight other unusual phenomena that arise in these systems such as higher order Josephson effects, time-reversal symmetry broken Josephson current phase relations. I will also show how these materials can be used to build quantum circuits with enhanced functionality, not necessarily arising from topological protection.

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Prof. Valla Fatemi

Andreev Bound State Quantum Devices

V. Fatemi[1], P. Kurilovich[1], M. Hays[1], D. Bouman, T. Connolly[1], S. Diamond[1], N. E. Frattini[1], V. D. Kurilovich[1], P. Krogstrup, J. Nygard, A. Geresdi, L. I. Glazman[1], M. H. Devoret[1]

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Andreev bound states (ABSs), the quantum many-body electronic states that are localized at Josephson weak-links, provide a platform to explore the interplay of superconductivity, spin-orbit interaction, Coulomb interaction, and magnetism, including in topological regimes. A feature of ABSs is that they carry supercurrent, which imbues the states with routable long-ranged electrodynamics. ABSs are thus suited to being probed by the well-developed circuit quantum electrodynamics (cQED) toolset, which offers microwave-domain measurement and manipulation of quantum states. In this talk, I will describe our implementation of cQED to reveal the spectrum, susceptibilities, dynamics, and potential applications of discrete ABSs hosted in Josephson semiconductor nanowires.

References

[1]. V. Fatemi, et al. arXiv:2112.05624
[2]. P. D. Kurilovich, et al. Phys. Rev. B 104, 174517 (2021)
[3]. M. Hays, et al. Science 373, 6553 (2021)

Dr. Dirk Manske

Higgs Spectroscopy of Superconductors

D. Manske

Max Planck Institute for Solid State Research, Stuttgart, Germany

Higgs spectroscopy is a new and emergent field [1-3] that allows to classify and determine the superconducting order parameter by means of ultra-fast optical spectroscopy. There are two ways to activate the Higgs mode in superconductors, namely a single-cycle 'quench' or an adiabatic, multicycle 'drive' pulse, both illustrated in Figure 1. In the talk I will review and report on the latest progress on Higgs spectroscopy, in particular on the role of the third-harmonic-generation (THG) [4-6] and the possible IR-activation of the Higgs mode by impurities or external dc current [7,8]. I also provide new predictions for time-resolved ARPES experiments in which, after a quench, a continuum of Higgs mode is observable and a phase information of the superconducting gap function would be possible to extract [9]. Finally, I show that the Higgs mode can solve the 25-years-old A_{1g}-puzzle in equilibrium Raman scattering on high-T_c cuprates [10].

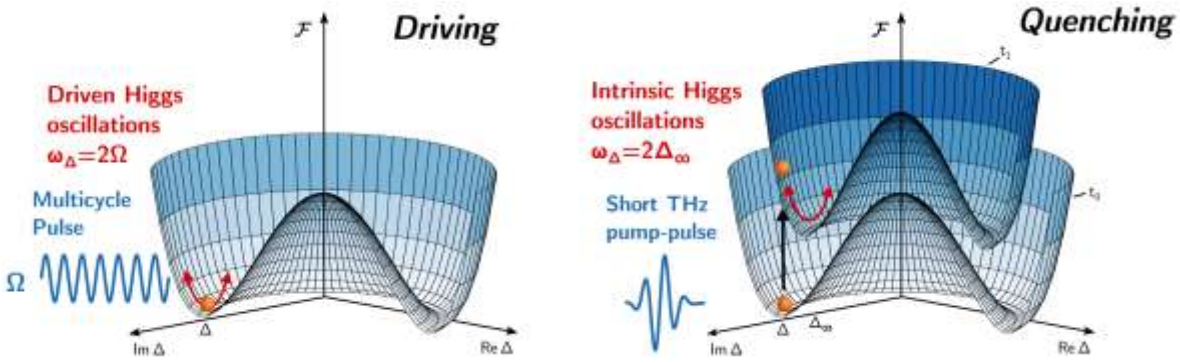

Fig. 1: *Two ways to activate the Higgs mode in superconductors: 'Driving' or 'Quenching'. A driven superconductor in steady-state non-equilibrium becomes resonant at the eigenfrequency of the Mexican hat and leads to third harmonic generation (THG).'In the non-adiabatic case, in which a single-cycle THz pulse shrinks suddenly the Mexican hat, one can observe Higgs oscillations directly in various quantities.*

References

[1]. L. Schwarz, D. Manske *et al*., Nat. Commun. **11**, 287 (2020).
[2]. L.Schwarz and D. Manske, Phys. Rev. B **101**, 184519 (2020).
[3]. H.Chu, S. Kaiser, D. Manske *et al*., Nat. Commun. **11**, 1793 (2020).
[4]. L. Schwarz. R. Haenel, and D. Manske, Phys. Rev. B **104**, 174508 (2021).

[5]. H.Chu, S. Kaiser, D. Manske *et al*., arXiv:2109.09971, submitted to Nature Materials (2021).
[6]. M.-J. Kim, S. Kaiser, D. Manske *et al*., submitted to Nature Photonics (2021).
[7]. M. Puviani, L. Schwarz, X.-X. Zhang, S. Kaiser, and D. Manske, Phys. Rev. B **101**, 220507 (2020).
[8]. R. Haenel, P. Froese, D. Manske, and L. Schwarz, Phys. Rev. B **104**, 134504 (2021).
[9]. L.Schwarz, B. Fauseweh, and D. Manske, Phys. Rev. B **101**, 224510 (2020).
[10]. M. Puviani, R. Hackl, D. Manske *et al*., Phys. Rev. Lett. **127**, 197001 (2021).

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Johan Chang

Electron-phonon coupling and charge stripe order symmetry in the cuprates

J. Chang[1], Q. Wang[1], K. von Arx[1], J. Küspert[1], J. Choi[1], M. Horio[1], M. Janoschek[1], D. J. Mukkattukavil[2], Y. Sassa[2] , T. Schmitt[3] , A. Nag[4] , M. Garcia-Fernandez[4], Ke-Jin Zhou[4], S. Pyon[5], T. Takayama[5], H. Takagi[5], N. B. Christensen[6], T. Kurosawa[7], N. Momono[7], M. Oda[7], O. Ivashko[8], M. v. Zimmermann[8]

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Charge order is universal to all hole-doped cuprates. Yet, the driving interactions remain an unsolved problem. Electron-electron interaction is widely believed to be essential, whereas the role of electron-phonon interaction is unclear. In this talk, we report an ultrahigh-resolution resonant inelastic x-ray scattering (RIXS) study of the electron-phonon coupling in stripe-ordered cuprates. We find an enhancement of the electron-phonon coupling around the charge-stripe ordering wave vector upon cooling into the low-temperature tetragonal structure phase. These results suggest that, in addition to electronic correlations, electron-phonon coupling contributes substantially to the emergence of long-range charge-stripe order in cuprates [1]. Finally, the symmetry of the crystal structure and stripe order is addressed by x-ray diffraction experiments carried out under uniaxial pressure [2-4].

References

[1] Q. Wang et al., Science Advances **7**, 27 (2021)
[2] J. Choi et al., https://arxiv.org/abs/2009.06967
[3] Q. Wang et al., Submitted to Nature Communications 2021
[4] R. Frison et al., In preparation

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Prof. Antoine Georges

Heating and Illuminating Planckian Metals

Antoine Georges
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I will discuss the remarkable implications of a `Planckian' T-linear scattering rate for
thermoelectric and optical properties, and confront these predictions to
measurements of the Seebeck coefficient and optical response of cuprates in the strange metal regime.
I will also review recent works which support the existence of a quantum phase transition
at a critical doping doping between two metallic phases
in a random t-J model related to Sachdev-Ye-Kitaev models. At this quantum critical point, the Fermi surface
undergoes a volume change and `Planckian' behaviour is found.

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Prof. Dai Aoki

Multiple Superconducting Phases and Field Induced Superconductivity in UTe_2

D. Aoki[1,2]

[1] *IMR, Tohoku University, Oarai, Japan*

We present our recent results on the novel spin-triplet superconductor UTe_2, which is a heavy fermion paramagnet [1]. The superconducting transition temperature is about 1.7K, but the upper critical field is huge up to 35T for the field along b-axis in the orthorhombic structure, highly exceeding the Pauli limit with field-reentrant behavior. The huge upper critical field resembles those observed in ferromagnetic superconductors URhGe and UCoGe with spin-triplet state. The ferromagnetic fluctuations are, however, not established in UTe_2, instead the antiferromagnetic fluctuations with the incommensurate q-vector are experimentally detected. Another remarkable point in UTe_2 is the multiple superconducting phases under pressure. The unusual enhancement of the upper critical field at low temperatures is linked to the multiple superconducting phases, which is a key signature of spin-triplet superconductivity due to the spin-degree of freedom. Just above the critical pressure at which superconductivity is suppressed, field-induced superconductivity is detected at high field above 10T. These totally unusual superconducting properties are most likely related to the multiple fluctuations such as ferromagnetic, antiferromagnetic, valence fluctuations and Fermi surface instabilities.

References

[1]. D. Aoki, J. P. Brison, J. Flouquet, K. Ishida, G. Knebel, Y. Tokunaga, and Y. Yanase, arXiv:2110.10451.

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Erez Berg

Exotic Superconductivity in Graphene Multilayers

Erez Berg[1,2], Areg Ghozaryan[1,2], Tobias Holder, Maksym Serbyn, Eyal Cornfeld, Mark Rudner[1,2], Shubhayu Chatterjee, Taige Wang, and Michael Zaletel

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Abstract: Recently, graphene multilayers have emerged as a rich platform to study quantum many-body physics. I will describe recent experiments in rhombohedral trilayer graphene (RTG), where superconductivity was recently discovered at the boundary between states with different patterns of spin and valley symmetry breaking. I will argue that several key experimental facts can be explained if the superconductivity is unconventional, and will present several theoretical routes to achieving such states in RTG. Motivated by the fact that one of the superconducting phases is a fully spin polarized triplet state, I will analyze the properties of this exotic phase. The topology of its order parameter space, that intertwines the phase of the superconducting condensate with the spin polarization, can lead to unusual phenomena, such as anomalous supercurrent dissipation and a fractional-period ac Josephson effect.

References

[1]. A. Ghazaryan, T. Holder, M. Serbyn, E. Berg, arXiv:2109.00011.
[2]. S. Chatterjee, T. Wang, E. Berg, M. Zaletel, arXiv: 2109.00002.
[3]. E. Cornfeld, M. Rudner, E. Berg, arXiv:2006.10073.

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Daniel Agterberg

Pseudospin-triplet pairing in $CeRh_2As_2$ and UTe_2

D.F. Agterberg[1], P.M.R. Brydon[2], D.C. Cavanagh[2], T. Shishidou[1], H. Suh[1], and M. Weinert[1]

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Recent measurements suggest that $CeRh_2As_2$ has field induced odd-parity superconductivity and that UTe_2 is an odd parity Weyl superconductor. Here, after an overview of recent experimental developments, I will discuss how the underlying crystal structure links closely to superconductivity in both these materials. Specifically, I will argue that the local inversion symmetry breaking of the Ce and U atomic sites provides a natural framework with which to understand the origin of odd-parity superconductivity.

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Prof. Kamran Behnia

The Nernst response of mobile superconducting vortices

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At the beginning of the present century, it was generally assumed that a BCS superconductor cannot produce a Nernst signal far above its critical temperature. This assumption was contradicted by subsequent experiments, which detected a transverse thermoelectric response generated by short-lived Cooper pairs deep in the normal state [1]. A recent surprise [2] is that the entropy carried by a mobile superconducting vortex in superconducting strontium titante is much smaller than what is stocked in the vortex core. Experimental data across different superconductors with vastly different critical temperatures indicate that the irreducible entropy of a superconducting vortex is of the order of k_B per layer. This may be the signature of an information barrier surrounding a topological singularity.

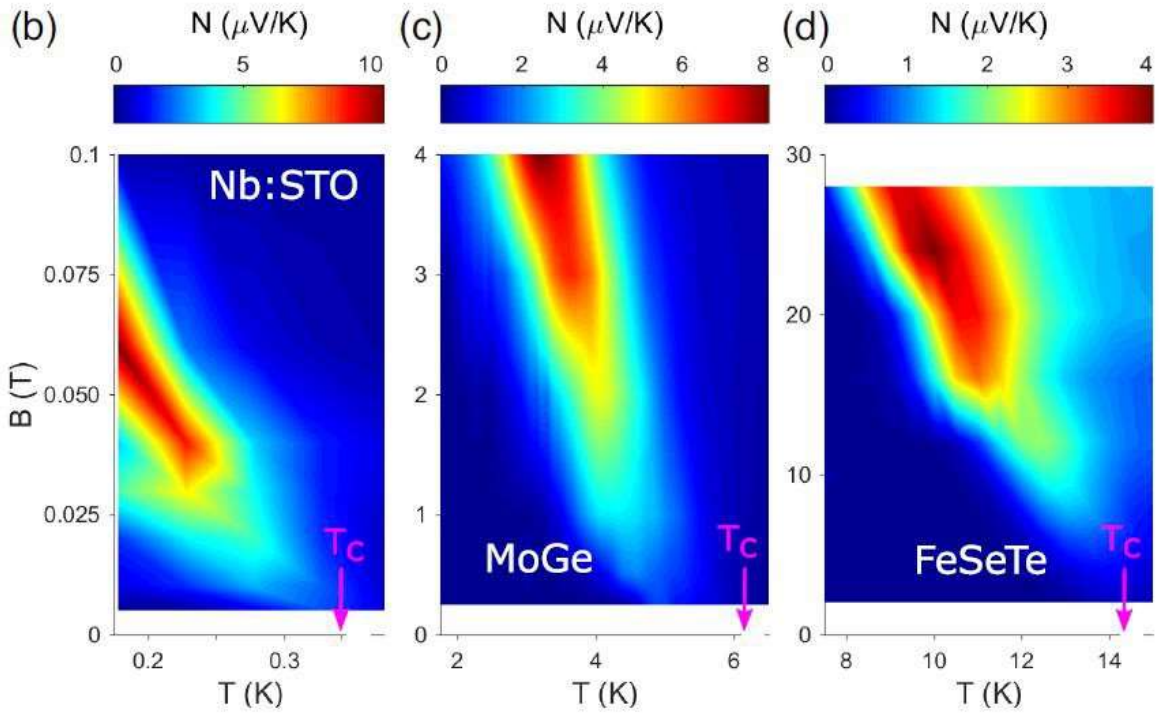

Fig. 1: *Nernst signal in three different superconductors in the (B,T) plane. The maximum Nernst signal, combined with flux flow resistivity yields the entropy per vortex per layer.*

References

1. K. Behnia & H. Aubin, Rep. Prog. Phys. **79**, 046502 (2016)
2. C. W. Rischau *et al*., Phys. Rev. Lett. **126**, 077001 (2021)

Prof. Lara Benfatto

Generalized plasma waves in layered cuprates and their spectroscopic signatures

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In a layered and strongly anisotropic superconductor the hybrid modes provided by the propagation of electromagnetic waves in the matter identify two well separated energy scales connected to the large in-plane plasma frequency and to the soft out-of-plane Josephson plasmon. Despite the wide interest in their detection and manipulation by means of different experimental protocols, ranging from strong-field THz spectroscopy to EELS, a unified description of plasma waves valid at arbitrary energy and momentum, and a critical discussion of their interplay with other collective modes, as e.g. the Higgs mode, is still lacking. Here I will review our recent progresses in the theoretical description of the nature and the spectroscopic visibility of generalized plasma waves in layered cuprates. First, I will show how a gauge-invariant description in terms of the superconducting phase[1] allows one to identify two intertwined hybrid light-matter modes with mixed longitudinal and transverse character, while a purely longitudinal plasmon is only recovered for wavevectors larger than the crossover scale set in by the plasma-frequencies anisotropy. Second, I will discuss how these excitations emerge in different spectroscopies, sensible either to the density response or to the propagation of electromagnetic waves in thin films. In particular, I will critically revisit[2] recent experiments with strong THz field polarized either perpendicular or parallel to the CuO_2 planes. In this context I will show that in the case of cuprates attributing a main role to the field-induced response of the Higgs mode is theoretically unjustified. Indeed the Higgs-mode contribution turns out to be a relatively small effect as compared to quasiparticle excitations[2] and anisotropic plasma waves[3].

References

[1] F. Gabriele, C. Castellani, L. Benfatto, arXiv:2110.06772
[2] M. Udina *et al.* preprint 2022
[2] G. Seibold, M. Udina, C. Castellani and L. Benfatto, Phys. Rev. B 103, 014512 (2021)
[3] F. Gabriele, M. Udina and L. Benfatto, Nat. Comm. 12, 752 (2021)

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Prof. Marina Putti

Iron Based Superconductors: development of conductors for high field generation

M. Putti[1], M. Iebole[1], M. Meinero[1], V. Braccini[2], E. Bellingeri[2], C. Bernini[2], M. Cialone[2], G. Grimaldi[2], A. Leo[2], A. Malagoli[2], A. Martinelli[2], I. Pallecchi[2], L. Piperno[2], L. Gozzelino[3], M. Fracasso[3], R. Gerbaldo[3], G. Ghigo[3], F. Laviano[3], A. Napolitano[3], D. Torsello[3], E. Silva[4], A. Alimenti[4], N. Pompeo[4], E. Silva[4], K. Torokhtii[4], G. Celentano[5], A. Vannozzi[5]

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Iron-based superconductors (IBS) with critical temperatures up to 55 K, upper critical field exceeding 50 T, high critical current density, can represent a breakthrough to overcome the limits of low-Tc Nb3Sn and the extreme material complexity of cuprate high-Tc superconductors (HTS), which leads to articulated and expensive processes for conductor fabrication.
The talk will review of the state of the art of the development of technical conductors based on IBS, then will present the results obtained by the project HIBiSCUS. HIBiSCUS aims at developing new fabrication processes for CCs based on Fe(SeTe), relying on the advanced technologies developed in the last decades for HTS-CCs, but focusing on the possibility of simplifying the template to drastically reduce fabrication costs and times. We are focusing on biaxially textured metallic substrates, either commercially available and home-made [1], covered with simple buffer layers able to promote the epitaxial growth of the film and to avoid diffusion of Ni – mainly CeO2 based buffer layers grown via chemical deposition techniques – on which Fe(Se,Te) films are deposited via Pulsed Laser Ablation [2]. The optimization of IBS-CCs and their suitability for specific applications will be addressed by the combined use of complementary techniques including microstructure and superconducting properties on the local and macroscopic scale [3]. In parallel, a deep investigation of Fe(Se,Te) thin films grown on single crystalline substrate is carried out by transport and microwave measurements to assess the limitations set by the weak links between the grains and the mechanisms of flux pinning [4]. Irradiations with ions are also carried out with the twofold goal of investigating the possible degradation of CCs in view of their use in locations with potential radiation hazard and of tuning their pinning properties [5].
This work was partially supported by MIUR-PRIN Project “HIBiSCUS” under Grant 201785KWLE.

References

[1]. G. Sylva et al., Supercond. Sci. Technol. 33 (2020) 114002.
[2]. A. Vannozzi et al., Supercond. Sci. Technol. 33 (2020) 084004. [3].
M. Scuderi et al., Sci. Rep. 11 20100 (2021)
[4]. N. Pompeo et al., Supercond. Sci. Technol. **33**, 114006 (2020)
[5]. G. Sylva et al., Supercond. Sci. Technol. 31 (2018) 054001; D. Torsello et al., IEEE Trans Appl. Supercond., submitted

The Retention of High-Pressure-Induced Superconducting and Non-Superconducting Phases in HTS and Possibly in RTS at Ambient for Science and Technology

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The search for high-temperature superconductivity (HTS) and room temperature superconductivity (RTS) in hydrogen and hydrogen-rich compounds under high pressure has a long history. Recently, several reports[1–4] of high T_c up to 288 K in hydrides under pressure of up to 267 GPa have appeared. The ultrahigh pressure needed to create the HTS in hydrides has hampered the detailed study of the phenomenon, as well as any potential applications. To lower the required pressure, even to zero, we have developed a pressure-quench process (PQP) and have demonstrated it successfully in stabilizing at ambient the high-pressure-induced HTS phase and other phases in FeSe and Cu-doped FeSe[5]. as shown in Fig. 1. It is not inconceivable that the PQP may be adapted for hydrides with T_c approaching room temperature for science and technology. The results will be presented, and both the opportunities and challenges will be discussed.

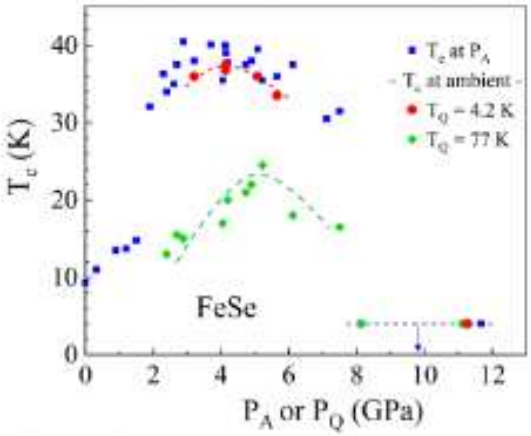

Fig. 1: *T_c as a function of applied pressure (P_A) or quenching-pressure (P_Q) for single-crystalline FeSe. High-pressure T_c (P_A) at P_A (blue squares), and T_c (P_Q) at ambient pressure for FeSe pressure-quenched at P_Q and quenching-temperature (T_Q) of 4.2 K (red circles) and 77 K (green diamonds)[5].*

The work is supported in part by AFOSR, TLL Temple Foundation, JJ&R Moores Endowment, and TCSUH; and at Rice by DOE.

References

[1]. A. P. Drozdov *et al.*, Nature **525**, 73 (2015).
[2]. M. Somayazulu *et al.*, Phys. Rev. Lett. **122**, 027001 (2019).
[3]. E. Snyder *et al.*, Nature **586**, 373 (2020).
[4]. D. V. Semenok *et al.*, Materials Today **33**, 36 (2020).
[5]. L. Z. Deng *et al.*, PNAS USA **118**, e2108938118 (2021).

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Prof. Takeshi Kondo

Doped Mott states in clean CuO_2 planes of high-T_c cuprates

Takeshi Kondo

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The critical temperature of superconductivity (T_c) in cuprates is sensitive to the number of CuO_2 layers per unit cell. The magnitude of T_c reaches the maximum in trilayer compounds among the homologous series. The highest T_c in cuprates is obtained in $HgBa_2Ca_2Cu_3O_{8+d}$ (Hg1223), which is a trilayer compound. While the intriguing relation between T_c and the number of layers per unit cell was found shortly after the discovery of high-T_c cuprates, its mechanism has not been understood yet and still been under huge debate. In solving this long-standing issue, it is particularly important to clarify the electronic properties distinctive for the many-layered cuprates.

Anomalous features of trilayer $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi2223) were revealed by angle-resolved photoemission spectroscopy (ARPES) using the low energy photons, which allow bulk sensitive measurements [1,2]. While this compound exhibits multibands reminiscent of those in Bi2212, the different bands in Bi2223 show different magnitudes of the superconducting gap. This situation is in stark contrast to that of Bi2212 consisting of the bonding and antibonding bands with the same gaps. The multiple bands of Bi2223 are attributed to be each for the inner and outer planes with different carrier concentrations; that is, Bi2223 has a non-uniform distribution of charges over the triple CuO_2 layers, differently from Bi2212 with evenly doped double layers. The charge nonuniformity is a common intriguing feature of the compounds with three or more layers. Furthermore, inner CuO_2 planes are protected from the dopant layers, realizing homogeneous electronic state. This is another fascinating aspect of multi-layered cuprates.

In my presentation, I will introduce our recent ARPES studies of multi-layered cuprates $Ba_2Ca_{n-1}Cu_nO_{2n}(F,O)_2$. These compounds have clean, thus ideal CuO_2 planes in the inner layers [3], thus they may reveal the phase diagram, which is inherent for cuprates but has not been unveiled so far. Most surprisingly, we found small Fermi surface pockets around $(\pi/2,\pi/2)$ consistently by ARPES and quantum oscillation measurements [4]. The formation of small Fermi pockets has been predicted in the doped Mott state since the discovery of a high-T_c superconductor in cuprates. Yet, this structure had not been detected, even though it could be a key element in relating high-T_c superconductivity to the Mott physics. We also find that the *d*-wave superconducting gap opens along the pocket, thus the superconductivity and antiferromagnetic order coexists in the same CuO_2 sheet. Our data further indicate that the superconductivity can occur without contribution from the states near the antinodal region, which are shared by other competing excitations such as the charge density wave and pseudogap states. These findings will have significant implications for understanding the superconductivity and puzzling Fermi arc phenomena in cuprates.

References

[1] S. Ideta et al., Phys. Rev. Lett. 104, 227001 (2010).
[1] S. Kunisada et al., Phys. Rev. Lett. **119**, 217001 (2017).
[2] S. Shimizu et al., Phys. Rev. B **85**, 024528 (2012).
[3] S. Kunisada et al., Science **369**, 833 (2020).

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Jan Jaroszynski

Rapid assessment of REBCO CC angular critical current $I_c(B,T,\theta)$ using torque magnetometry up to 45 tesla

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Simple magnetometer allows measurement of the torque and assessment of $I_c(B,T,\theta)$ over the full angular range and temperatures up to 50 K. It works flexibly in both superconducting and resistive magnets at the NHMFL. Recently it was scaled to run in the 45 T hybrid magnet. It uses large samples (13x4 mm^2), so contributions of the reversible magnetization from vortices and from the return currents at the sample ends can be neglected. This size also enables the study of the entangled electromagnetic and mechanical properties in samples of the full width. $I_c(B,T,\theta)$ derived from the torque agrees well with the transport data [1]. The measurements are very fast and consume very little LHe.

After testing dozens of samples we found that $I_c(B,T,\theta=90) \propto \exp(-B/B_0)$ rather than to power function. At B=30T, I_c varies from ~ 400 to ~1400 A, while FWHM of the **ab** I_c peak spans from ~ 7 to ~ 32deg. Such rich diversity of ReBCO tapes makes selection of proper conductor for different part of the magnet possible. Temperature dependence and data parameterization will be also discussed.

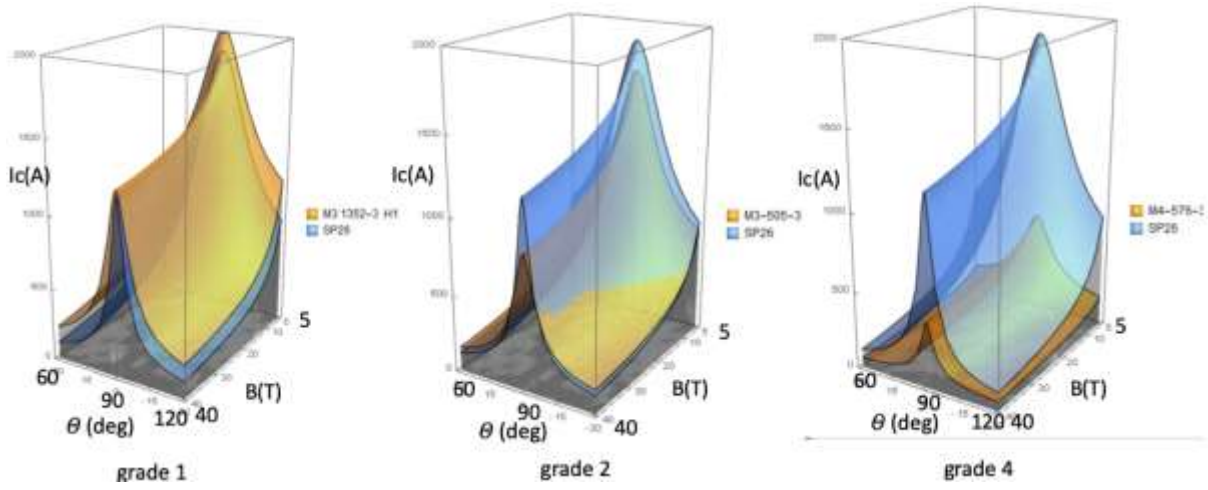

Fig. 1: *$I_c(B,T=4.2\ K,\theta)$ for three recent graded samples (yellow surfaces) compared with the vintage SP26 [1] sample (blue). Surfaces were calculated from fits to the data for 5<B<30 T and extrapolated beyond 30 T.*

References

[1] A. Xu, V. Braccini, J. Jaroszynski, Y. Xin, D. Larbalestier, Phys. Rev. B86, 115416 (2012).

Prof. Matteo Mitrano

Ultrafast manipulation of electronic interactions in quantum materials

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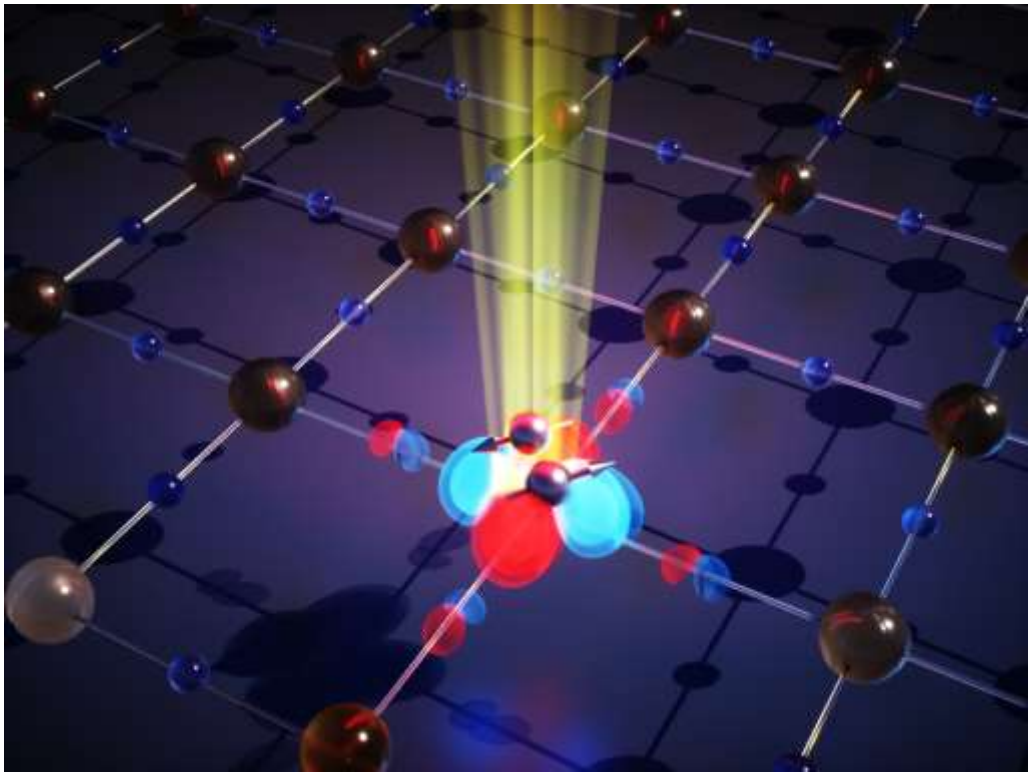
Intense ultrashort electromagnetic fields are an increasingly important tool to realize and control novel emergent phases in quantum materials. Among a variety of nonthermal excitation pathways, a particularly intriguing route is represented by the direct light-engineering of effective many-body interactions, such as electron hopping amplitudes and electron-electron repulsion. Achieving a light-induced dynamical renormalization of the screened onsite Coulomb repulsion ("Hubbard *U*") would have far-reaching implications for high-harmonic generation, attosecond spectroscopy and ultrafast magnetism in the solid state. However, experimental evidence for a dynamically controlled Hubbard *U* remains scarce. In this talk, I will present a recent demonstration of light-induced renormalization of the Hubbard *U* in a high-temperature superconductor, $La_{2-x}Ba_xCuO_4$, [1] and discuss its implications for the control of superconductivity, magnetism, as well as to the realization of other long-range-ordered phases in light-driven quantum materials. Further, I will discuss the application of these methods to the control of quasi-1D correlated electron systems with long-ranged Coulomb interaction, such as Sr_2CuO_3.

Fig. 1 – Light-induced renormalization of the onsite Coulomb repulsion between electrons in the CuO_2 plane



of the prototypical high-temperature superconductor $La_{2-x}Ba_xCuO_4$.

References

[1] D. R. Baykusheva et al. *Phys. Rev. X* **12**, 011013

Prof. Ion Errea

When are Hydrogen-Based Superconductors High-T_c Compounds?

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By analyzing structural and electronic properties of more than a hundred predicted hydrogen-based superconductors, we determine that the capacity of creating an electronic bonding network between localized units is key to enhance the critical temperature in hydrogen-based superconductors. We define a magnitude named as the networking value, which correlates with the predicted critical temperature better than any other descriptor analyzed thus far. By classifying the studied compounds according to their bonding nature, we observe that such correlation is bonding-type independent, showing a broad scope and generality. Furthermore, combining the networking value with the hydrogen fraction in the system and the hydrogen contribution to the density of states at the Fermi level, we can predict the critical temperature of hydrogen-based compounds with an accuracy of about 60 K, as shown in Fig. 1. Such correlation is useful to screen new superconducting compounds and offers a deeper understating of the chemical and physical properties of hydrogen-based superconductors, while setting clear paths for chemically engineering their critical temperatures.

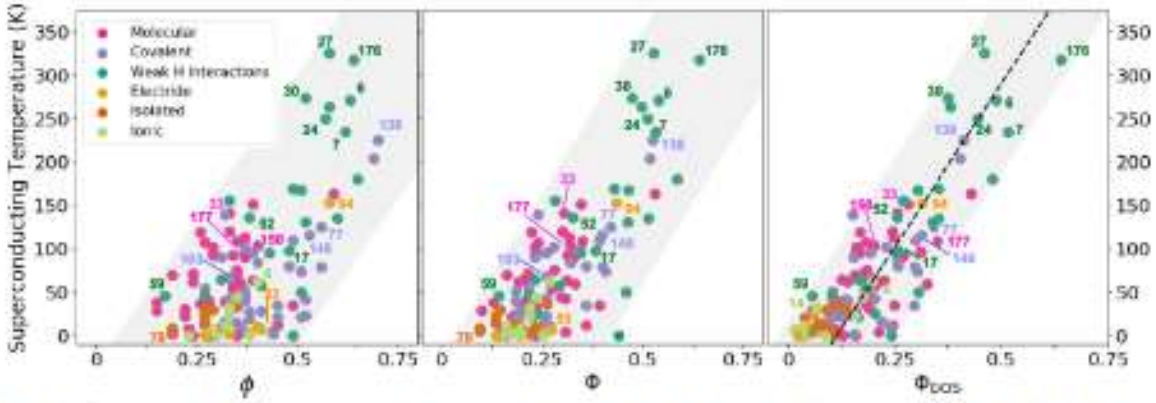

Fig. 1: *Correlation between the networking value (ϕ) and the critical temperature for many predicted hydrides. The correlation is also shown for the networking value multiplied by the fraction of hydrogen in the system (Φ), as well as the latter times the hydrogen fraction of the density of states at the Fermi level (Φ_{DOS}). Figure taken from Ref. [1].*

References

[1]. F. Belli, T. Novoa, J. Contreras-García, I. Errea, Nat. Commun. **12**, 5381 (2021).

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Igor Mazin

Ising superconductors: role of magnetism and defects

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Recent studies on superconductivity in monolayer NbSe2 have demonstrated a giant anisotropy in the superconducting critical field. This phenomenon was quite well understood in terms of the so-called “Ising superconductivity”, where the spins of Cooper pairs are strictly aligned with one particular crystallographic direction. Besides the (formally infinite) critical field, anisotropy Ising superconductors (IS) have demonstrated a number of unusual and seeming exotic phenomena. In the first part of my talk I will briefly review the physics of IS in terms accessible for general audience.
In the second part I will make, in terms of DFT calculations, a quantitative connection with the specific material in which most of the IS studies are being performed, monolayer $NbSe_2$; in particular, I will show that, contrary to a common misconception, $NbSe_2$ is close to a magnetic instability (specifically, an incommensurate magnetic spiral) and this fact cannot be ignored when discussing IS. In the next part I will present several important ramification, and will also discuss new phenomena emerging upon interfacing IS with a ferromagnet, and the nontrivial role played by magnetic and nonmagnetic defects in recent experiments. If time allows, I will present the results of *ab initio* Eliashberg calculations accounting for coupling with both phonons and spin fluctuation.

This talk will be based on published [1-4] and unpublished work with my collaborators Darshana Wickramaratne, Maxim Khodas, Roxana Margine, Dan Agterberg, Suvadip Das, and Menashe Haim.

References

[1]. Ising superconductivity and magnetism in $NbSe_2$. D. Wickramaratne, S. Khmelevskyi, D.F. Agterberg, I.I. Mazin, Phys. Rev. X 10, 041003 (2020).
[2]. Magnetism-driven unconventional effects in Ising superconductors: Role of proximity, tunneling, and nematicity. D. Wickramaratne, M. Haim, M. Khodas, and I.I. Mazin, PRB Letters, B104, L060501 (2021)
[3]. Quantitative assessment of the role of spin fluctuations in 2D Ising superconductor NbSe2, S. Das and I. I. Mazin, Comp. Mater. Sci. 200, 110758 (2021)
[4]. Ising superconductivity in monolayer niobium dichalcogenide alloys. D. Wickramaratne, I. I. Mazin, arXiv:2108.05426 (2021)

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Michael Eisterer

Understanding and Retarding the Degradation of Fusion Magnets due to Neutron Radiation

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Fusion magnets, in particular the toroidal field coils, will be exposed to neutron radiation arising from the nuclear reactions in the burning plasma. The high energy neutrons induce a variety of defects which have two competing effects on superconductivity. They increase flux pinning that favors high critical currents but reduce the superconducting transition temperature and the density of superconducting charge carriers. The adverse effect dominates at high defect concentrations leading to a degradation of the magnet and possibly limiting its lifetime.
Neutron irradiation was performed in a fission research reactor to increase the defect density in Nb_3Sn wires and REBCO coated conductors. In both cases, the critical current first increases, reaches a maximum and finally degrades at high fluences. The size and the density of the introduced defects can be influenced by the applied fluence, the neutron energy distribution and thermal treatments to distinguish between the positive and negative effects of the radiation and identify the responsible defects. We aim at both, the development of radiation robust conductors and thermal annealing of the magnets to enhance the maximum fluence they can be exposed to during operation.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Dr. Tetsuo Hanaguri

Superconductivity, Nematicity and Topology in Fe(S,Se,Te)

T. Hanaguri[1]

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In FeSe, superconductivity and electronic nematicity coexist [1]. S and Te substitutions suppress the electronic nematicity, whereas superconductivity is observed all the way except near the Te end. Here we show that Fe(S,Se,Te) hosts at least three distinct superconducting phases and argue the relation among superconductivity, nematicity, and topology. We performed spectroscopic-imaging scanning tunneling microscopy to reveal the spectroscopic features of the superconducting gap and to investigate the band structure from the quasiparticle interference effect. In Fe(Se,S), we found that the superconducting gap suddenly shrinks above 17 % S substitution, which is the nematic endpoint. In the tetragonal phase above the nematic endpoint, a large residual density of states appears at the Fermi level (Fig. 1) [2]. These results indicate the relation between nematicity and superconductivity and suggest that a so-called Bogoliubov Fermi surface emerges in the tetragonal phase [3]. The electronic nematicity is also suppressed by Te substation but survives up to 45 % substitution. Topological superconductivity and a possible Majorana quasiparticle in the vortex core have been suggested at high Te substitutions [4,5,6]. We investigated the electronic-state evolutions in the low Te substitution regime. We found that the anisotropic superconducting gap shrinks with Te substitution and changes to the isotropic one at about 25 % Te substitution (Fig. 1). The band structure also changes at the same substitution. If these changes inside the nematic phase represent the topological transition, nematicity plays a minor role in the topological nature.

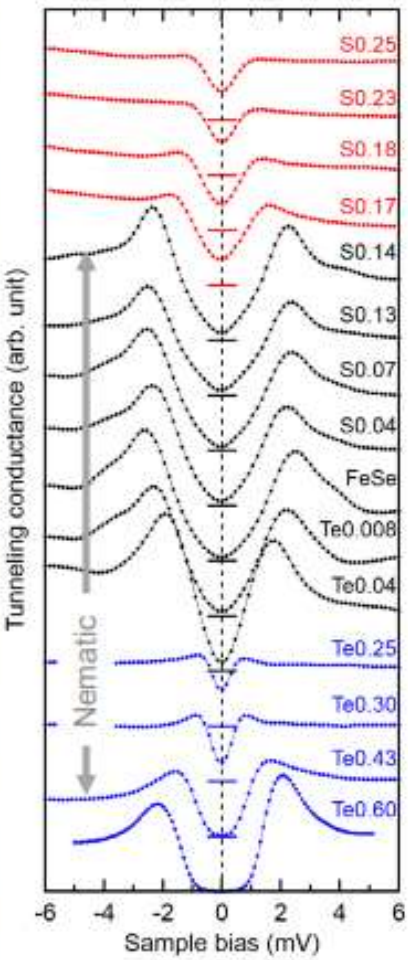

Fig. 1: *Superconducting-gap spectra of Fe(S,Se,Te) at 1.5 K*

This work has been done in collaboration with Y. Matsuda group (Kyoto Univ.), T. Shibauchi group (Univ. Tokyo), and T. Tamegai group (Univ. Tokyo).

References

[1]. T. Shibauchi, T. Hanaguri, and Y. Matsuda, J. Phys. Soc. Jpn. **89**, 102002 (2020).
[2]. T. Hanaguri *et. al.*, Sci. Adv. **4**, eaar6419 (2018).
[3]. C. Setty *et. al.*, Nat. Commun. **11**, 523 (2020).
[4]. Z. Wang *et. al.*, Phys. Rev. B **92**, 115119 (2015).
[5]. P. Zhang *et. al.*, Science **360**, 182 (2018).
[6]. T. Machida *et. al.*, Nat. Mater. **18**, 811 (2019).

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Prof. Peter Armitage

THz cyclotron resonance experiments in the cuprates

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Using time-domain terahertz spectroscopy in pulsed magnetic fields up to 31 T, we measure the terahertz optical conductivity in an optimally doped thin film of the high-temperature superconducting cuprate $La_{2-x}Sr_{2-x}CuO_4$ over a broad doping range. We observe systematic changes in the circularly polarized complex optical conductivity that are consistent with cyclotron absorption of p-type charge carriers characterized and a scattering rate that increases with magnetic field. These results open the door to studies aimed at characterizing the degree to which electron-electron interactions influence carrier masses in cuprate superconductors.

References

[1]. K. W. Post, A. Legros, D. G. Rickel, J. Singleton, R. D. McDonald, Xi He, I. Božović, X. Xu, X. Shi, N. P. Armitage, and S. A. Crooker, Phys. Rev. B 103, 134515 (2021).

Prof. Hanno Weitering

Chiral d-wave Superconductivity on a Reconstructed Silicon Surface

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Chiral superconductors represent an exotic and heavily pursued state of matter where the Cooper pairing symmetry is unconventional and parity and time-reversal symmetries are broken. While there are several candidates for the realization of chiral superconductors, including e.g. NaxCoO2, and hole-doped graphene, conclusive evidence for the existence of chiral superconductivity has yet to be established. Here we present evidence for the existence of chiral d-wave superconductivity in a monatomic Sn layer on the Si(111) surface. This single-band Mott insulator becomes superconducting upon hole doping [1], with a critical temperature close to 8 Kelvin. Importantly, chirality produces a unique feature in STM quasi-particle interference imaging below the superconducting Tc, while the experimental edge state spectra are fully consistent with the calculated edge states for a chiral d-wave order parameter. Whereas most candidates for chiral superconductivity are complex materials, the simplicity and experimental control of simple adsorbate systems provide a powerful testbed for theoretical models and discovery of elusive phases of quantum matter.

*In collaboration with F. Ming, K. Wang, and S. Johnston.

References

[1] X. Wu, F. Ming, T. S. Smith, G. Liu, Fei Ye, K. Wang, S. Johnston, and H. H. Weitering, Phys. Rev. Lett. **125**, 117001 (2020).

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Prof. Andrey Chubukov

Interplay Between Superconductivity and Non-Fermi Liquid at a QCP in a Metal

Andrey V Chubukov

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I discuss the interplay between non-Fermi liquid behaviour and pairing near a quantum-critical point (QCP) in a metal. These tendencies are intertwined in the sense that both originate from the same interaction mediated by gapless fluctuations of a critical order parameter. The two tendencies compete because fermionic incoherence destroys the Cooper logarithm, while the pairing eliminates scattering at low energies and restores fermionic coherence. I discuss this physics for a class of models with an effective dynamical interaction $V(\Omega) \sim 1/|\Omega|^{\gamma}$ (the γ-model). This model describes, in particular, the pairing at a 2D Ising-nematic critical point (γ=1/3), a 2D antiferromagnetic critical point (γ=1/2) and the pairing by an Einstein phonon with vanishing dressed Debye frequency (γ=2). I argue the pairing wins, unless the pairing component of the interaction is artificially reduced, but because of fermionic incoherence in the normal state, the system develops pseudogap behaviour in the temperature range between the onset of the pairing at Tp and the onset of phase coherence at the actual superconducting Tc. The ratio Tc/Tp decreases with γ and vanishes at g =2. I present two complementary arguments of why this happens. One is the softening of longitudinal gap fluctuations, which become gapless at γ =2. Another is the emergence of a 1D array of dynamical vortices, whose number diverges at γ =2. I argue that a fundamentally novel superconducting ground state emerges at γ >2.

References

[1]. Shang-Shun Zhang, Yi-Ming Wu, Artem Abanov, and Andrey V. Chubukov, Phys. Rev. B 104, 144509 (2021).

[2]. The interplay between superconductivity and non-Fermi liquid at a quantum-critical point in a metal, Andrey V. Chubukov, Artem Abanov, Yuxuan Wang, and Yi-Ming Wu, Annals of Physics, 417, 168142 (2020).

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Prof. Yann Gallais

Nematic quantum criticality and electron-lattice coupling in iron-based superconductors: Raman and elasto-Raman scattering results

S. Chibani[1], J.-C. Philippe[1], J. Faria[1], P. Massat[1], D. Farina[1], M. Cazayous[1], S. Houver[1], A. Sacuto[1], S. Karlsson[2], P. Strobel[2], P. Toulemonde[2], T. Urata[3], Y. Tanabe[3,9], K. Tanigaki[3], A. E. Bohmer[4,5,8], P. C. Canfield[5,6], M. Merz[4], A. Forget[7], D. Colson[7], I. Paul[1] and Y. Gallais[1]

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[8] Experimentalphysik IV Ruhr-Universität Bochum, Bochum, Germany
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In my talk I will discuss insights from Raman scattering measurements on nematic quantum criticality, and its potential role in promoting superconductivity in iron-based superconductors (Fe SC). In sulfur doped FeSe ($FeSe_{1-x}S_x$), the low energy Raman spectra display clear fingerprint of critical nematic fluctuations throughout its phase diagram. However, a Curie–Weiss analysis of the associated nematic susceptibility indicates a substantial effect of nemato-elastic coupling, which shifts the location of the nematic QCP. I will argue that this lattice-induced shift likely explains the absence of any enhancement of the superconducting transition temperature at the QCP in this compound [1].
I will then describe Raman scattering measurements under uni-axial strain (« elasto-Raman scattering» [2]) on optimally Co-doped $BaFe_2As_2$ (T_c=24K), both in its normal and superconducting state. I will demonstrate that uni-axial strain efficiently suppresses nematic fluctuations, consistently with uni-axial strain acting as a symmetry breaking field for Ising nematicity [3]. The observed concomitant and drastic suppression of both the superconducting T_c and the nematic fluctuations under strain for a role of nematic fluctuations in enhancing T_c in Co-$BaFe_2As_2$. I will conclude by discussing the key ingredients governing the interplay between nematic quantum criticality and superconductivity in Fe SC.

[1] S. Chibani et al. npj Quantum Materials 6, 37 (2021)
[2] J.-C. Philippe et al. arXiv: 2110.06175 (2021)
[3] J.-C. Philippe et al. in preparation

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Rafael Fernandes

Impact of Lattice Disorder on the Electronic Nematic Phase of Iron-Based Superconductors

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Defects commonly found in crystals can have a profound impact on electronic nematicity, since strain couples linearly to the nematic order parameter. In the case of iron-based superconductors, the large nemato-elastic coupling further enhances these lattice-disorder effects, which must be considered for a more realistic description and a full understanding of nematic phenomena in these compounds. In this talk, we will discuss how surface defects and inhomogeneities in the bulk crystal lattice can fundamentally change the character of the nematic phase transition. In particular, we show that step-like defects present at a crystal's surface shift the maximum of the nematic instability towards a finite wave-vector. This gives rise to an electronic smectic phase that onsets before the emergence of bulk nematic order, and that is localized near the surface. We also investigate the interplay between nematicity and random strain generated by lattice defects in the bulk of the crystal. Because nematic order in iron pnictides is a composite order intertwined with the underlying antiferromagnetic stripe state, random strain acts both as a random nematic field and as a random magnetic bond, rendering a description in terms of the random-field Ising model incomplete. To capture this dual role of random strain, we propose a description in terms of the Ashkin-Teller model with a random Baxter field. Numerical simulations of this model reveal that the random strain generates new correlations between the magnetic degrees of freedom, which are absent in both the clean Ashkin-Teller model and in the random-field Ising model. These correlations are associated with the emergence of two different domain break-up lengths, as well as of two different relaxation time scales. We discuss the implications of these results for several puzzling experimental observations in iron-based superconductors.

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David LeBoeuf

Hidden magnetism at the pseudogap critical point of $La_{2-x}Sr_xCuO_4$

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Hole-doped cuprates are highly correlated materials well-known for their structural, charge, magnetic and superconducting properties. Their temperature vs. hole-doping phase diagrams have been scrutinized but much remains unknown, especially at low temperature where superconductivity hides the normal (i.e. non-superconducting) ground state. The application of large magnetic fields has proven to be an efficient way to overcome this problem. Here we use ultrasound measurements up to 80 T, in order to probe the doping dependence of the low temperature ground state of the lanthanum-based cuprate $La_{2-x}Sr_xCuO_4$ (LSCO) [1,2]. The phase diagram of LSCO hosts a glassy antiferromagnetic (AFM) phase, which, in zero magnetic field, exists from a doping level $p = 0.02$ up to $p \approx 0.135$. We show that, once superconductivity is sufficiently suppressed by a magnetic field, this AFM glass actually exists up to a much higher doping level. We find that the AFM glass disappears at the critical doping level $p^* \approx 0.19$ where the pseudogap ends. This means that the AFM-glass phase exists from the doped Mott insulator at $p = 0.02$ up to $p^* \approx 0.19$, which provides a connection between the pseudogap and the physics of the Mott insulator.

References

[1]. M. Frachet, I. Vinograd *et al.,* Nature Physics **16** 1064 (2020)
[2]. M. Frachet *et al.,* Physical Review B **103** 115133 (2021)

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Dr. Keenan Avers

Crystal Growth, Metallurgy, and Sample Quality of the Ferromagnetic Superconductor UCoGe

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The impact of sample quality and metallurgy on unconventional superconductors is a long explored discipline, and has made it prudent to investigate a given material grown using a variety of techniques in order to optimize its superconducting properties. In particular, the uranium containing ferromagnetic superconductors UGe_2, UCoGe, URhGe and UTe_2 can exhibit widely varying properties depending on details of how they are made. Unlike congruently melting superconducting systems like UPt_3, the UCoGe crystal structure remains stable off the ideal 1:1:1 stoichiometry and has a small peritectic decomposition temperature range, which has complicated single crystal growth quality and control. This motivated our attempt to grow single crystals of UCoGe using an ultra-high vacuum electron-beam floating-zone refining system, as shown in Fig. 1 [1]. After our UCoGe single crystals were annealed at 900 C for two weeks they exhibit well defined signatures of superconductivity and ferromagnetism in resistivity, heat capacity and magnetization, which is consistent with high-quality samples grown by other methods [2]. Using scanning electron microscopy, we observed that annealing caused an off-stoichiometric uranium rich phase of UCoGe to liquefy and flow through cracks and voids in the crystal, which induced damage and disorder at the surface that manifests in resistivity, but not heat capacity and magnetization. Fortuitously, polishing away the damaged surface eliminates the discrepancies in resistivity, which suggests that all future electrical transport on UCoGe should be done on polished surfaces to ensure better comparison across multiple publications. Our results also support the notion that the exact stoichiometry of the UCoGe crystal is vital for optimizing the superconducting and ferromagnetic transition temperatures [3].

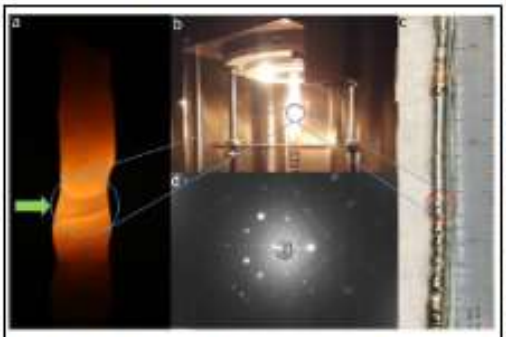

Fig. 1: The UCoGe ingot during zone refining (a and b), after zone refining (c), and Laue X-ray pattern taken near [010] orientation (d). Adapted from Ref. [1].

References

[1]. K. E. Avers *et al.*, Phys. Rev. Materials 5, 054803 (2021).
[2]. D. Aoki and J. Flouquet, J. Phys. Soc. Japan 83, 061011 (2014).
[3]. J. Pospisil *et al.*, J. Phys. Soc. Japan 80, 084709 (2011).

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Prof. Ali Yazdani

Correlations, topology, and unconventional superconductivity in magic angle twisted bilayer graphene

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We have explored magic angle twisted bilayer graphene's (MATBG) electronic properties using variety of spectroscopic methods with the scanning tunneling microscope (STM). Beside unraveling signatures of strong correlations [1] driving a cascade of transitions [2] in the electronic properties of MATBG, we have shown that such correlations also drive formation of topological Chern insulators stabilized with weak magnetic fields[3]. Most recently, we have focused our attention on the nature of superconducting state that forms near half filling of MATBG's valance flat band. [4] Our experiments show signatures of nodal superconductivity with tunneling gap to transition temperature ratio that far exceeds the BCS limit. Moreover, we find superconductivity emerges from a pseudogap phase, which might be indication of either preformed pairs or the formation of some ordered state that makes superconductivity possible. Remarkably, we find that samples in which MATBG is in perfect alignment with the hexagonal BN substrate, both the pesudogap phase and superconductivity are suppressed.

References

[1]. Y. Xie. et al. Nature 572, 101 (2019).
[2]. D. Wong, et al. Nature 582, 198 (2020).
[3]. K. Nuckolls et al. Nature 588, 610-615 (2020).
[4]. M. Oh et al. to appear in Nature (2021). https://doi.org/10.1038/s41586-021-04121-x

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Dr. Kazuhiro Fujita

Visualizing the Cuprate Pair Density Wave State

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The defining characteristic[1,2] of Cooper pairs with finite center-of-mass momentum is a spatially modulating superconducting energy gap D(***r***). Recently, this concept has been generalized to the pair density wave (PDW) state without an applied magnetic field that is predicted to exist in cuprates[3,4]. Although the signature of a cuprate PDW has been detected in Cooper-pair tunneling[5], the distinctive signature in single-electron tunneling of a periodic D(***r***) modulation has never been observed. Here, by using the Spectroscopic Imaging Scanning Tunneling Microscopy technique (SI-STM), we report strong D(***r***) modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ that have eight-unit-cell periodicity or wavevectors ***Q***~2p/a_0(1/8,0); 2p/a_0(0,1/8). Simultaneous imaging of the local-density- of-states *N*(***r***,*E*) reveals electronic modulations with wavevectors ***Q*** and 2***Q***, as anticipated when the PDW coexists with superconductivity. Finally, by visualizing the topological defects in these *N*(***r***,*E*) density waves at 2***Q***, we discover them to be concentrated in areas where the PDW spatial phase changes by p, as predicted by the theory of half-vortices in a PDW state[6,7]. Overall, this is a compelling demonstration, from multiple single-electron signatures, of a PDW state coexisting with superconductivity in the canonical cuprate $Bi_2Sr_2CaCu_2O_{8+\delta}$(*Nature* **580** 65-70 (2020)). In this talk, we will discuss recent developments of the cuprate PDW studies and how the PDW is related to other electronic degrees of freedom (*J. Phys. Soc. Jpn.* **90***,*
111003 (2021)). We will also discuss how a bosonic degree of freedom is involved in these situations. This work was done in collaboration with Zengyi Du, Hui Li Sanghyun Joo, Elizabeth P. Donoway, Jinho Lee, J. C. Séamus Davis, Genda D. Gu, and Peter D. Johnson.

References

[1]. P. Flude, and R. A. Ferrel, *Phys. Rev.* **135**, A550 (1965).
[2]. A. I. Larkin, and Yu. N. Ovchinnikov, *Sov. Phys. JETP* **20**, 762 (1965).
[3]. E. Fradkin, S. A. Kivelson, J. M. Tranquada, *Rev. Mod. Phys*. **87**, 457 (2015).
[4]. D. F. Agterberg *et al.*, *Annual Review of Condensed Matter Physics* **11** 231-270 (2020). [5]. M. H. Hamidian, *Nature* **532**, 343-347 (2016).
[6]. D. F. Agterberg, and H. Tsunetsugu, *Nature Phys*. **4**, 639-642 (2008).
[7]. E. Berg, E. Fradkin, S. A. Kivelson, *Nature Phys.* **5**, 830-833 (2009).

Johnpierre Paglione

Superconducting Phases of UTe_2

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An unconventional superconducting state was recently discovered in uranium ditelluride (UTe_2), in which spin-triplet superconductivity emerges from the paramagnetic normal state of a heavy-fermion material. The coexistence of magnetic fluctuations and superconductivity, together with the crystal structure of this material, suggests that a distinctive set of symmetries, magnetic properties, and topology underlie the superconducting state. We will discuss experiments designed to probe the superconducting gap structure and symmetry of UTe2, including thermal conductivity, heat capacity, microwave penetration depth and polar Kerr effect. Our observations of low-energy quasiparticle excitations, together with evidence for a double superconducting transition and nonzero polar Kerr effect, suggest that the superconductivity in UTe_2 is characterized by a two-component order parameter that breaks time-reversal symmetry. These data place constraints on the symmetries of the order parameter and inform the discussion on the presence of topological superconductivity in UTe_2.

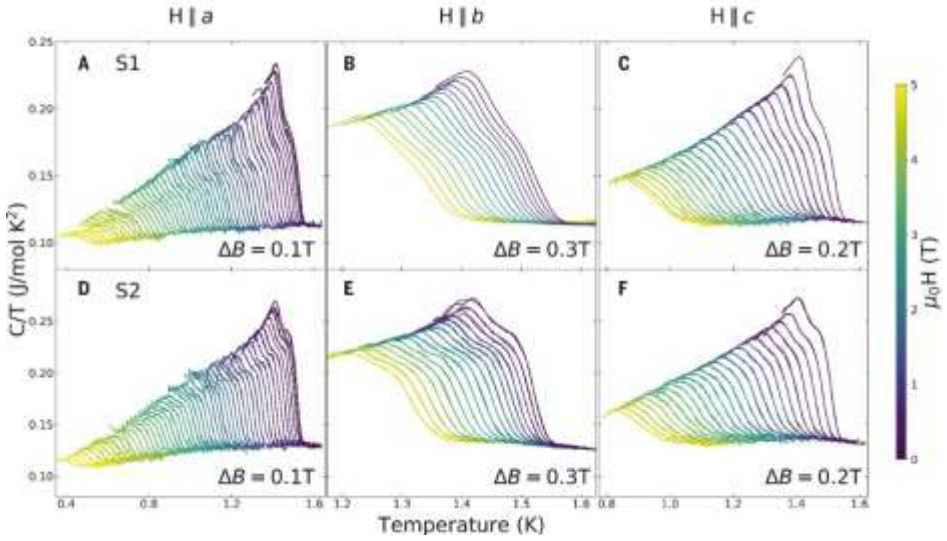

Fig. 1: *Magnetic field evolution of the split superconducting transition of UTe2*

References can also be given in the abstract (see sample below). Abstract text can flow around the graph/figure.

References

[1]. S. Ran et al. Science 365, 684–687 (2019).
[2]. T. Metz et al., Phys. Rev. B 100, 220504 (2019).

[3]. S. Bae et al. Nature Comm. 12, 2644 (2021).
[3]. I. M. Hayes et al., Science 373, 797 (2021).

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Prof. Assa Auerbach

Hall Anomalies in Strongly Correlated Metals and Superconductors

Assa Auerbach

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Hall and Thermal coefficients are commonly used to characterize the carriers of electrical and thermal currents. However, weak-scattering Fermi-liquid and Boltzmann transport theory has failed to explain ‘’Hall anomalies’’, such as unexpected divergences and sign changes, which are observed in underdoped cuprates, and in vortex liquids (flux flowing superconducting films). I will review recent simplifications of the Hall Kubo formulas[1,2,3,4] which enables us to compute the Hall coefficients of the t-J model at high temperatures, narrow gapped semimetals, and thermal Hall coefficients of flexo-electric insulators.
Hall anomalies in superconducting films are explained[5] by Ginzburg-Landau steady-state theory of flux flow The Hall conductivity contains an additional term which is 2e/h times the moving vortex charge. Quantitative predictions of the moving vortex charge are obtained, and awaiting independent experimental confirmation.
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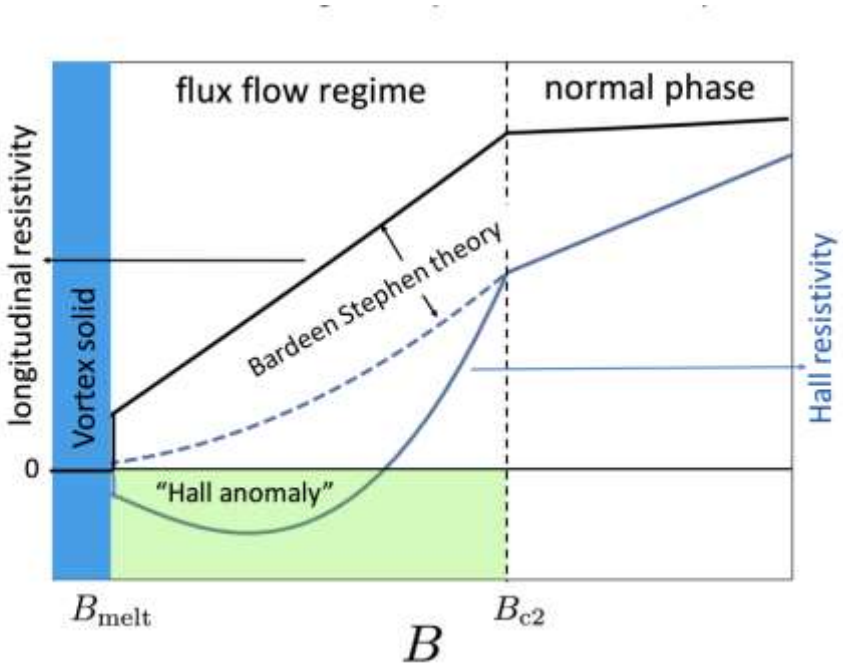

Fig. 1:
Bardeen Stephen theory and Hall anomaly in the flux flow regime. For this illustration, vortex cores are assumed to obey Drude theory of metals. The deviation of Hall resistivity from Bardeen Stephen theory, and its sign reversal, are ascribed to moving vortex charge.

References

[1] A. Auerbach, Phys. Rev. Lett. 121, 066601 (2018).

1. A. Auerbach, Phys. Rev. B 99, 115115 (2019).
2. A. Samanta, D. P. Arovas, and A. Auerbach, Phys. Rev. Lett. 126, 076603 (2021)
3. N. Bashan, A.Auerbach, arXiv:2108.11372
4. A. Auerbach, D. P. Arovas, SciPost Phys. 8, 061 (2020).

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Dr. Mathieu Taupin

Unconventional Superconductivity and Extreme Strange Metal Behavior in $YbRh_2Si_2$

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The heavy fermion compound $YbRh_2Si_2$ is a highly versatile platform to investigate quantum criticality [1]. It has been used to demonstrate a jump in the Fermi volume at the quantum critical point [2] and dynamical energy-over-temperature scaling in the THz conductivity associated with it, with a linear temperature exponent that directly relates to the linear-in-temperature “strange metal” electrical resistivity [3]. Both clearly point to the beyond-order-parameter nature of the quantum criticality. Recently, superconductivity has been uncovered at very low fields but its relation to the quantum critical point at much larger fields remained unclear [4], making $YbRh_2Si_2$ a highly prominent case where strange metal behavior remains uncovered by superconductivity. To get to the bottom of this situation, we have performed sub-milli-Kelvin electrical resistivity measurements and discovered superconductivity condensing directly out of the strange metal state, which now extends over 3.5 orders of magnitude in temperature [5]. The shape of the superconducting phase in the temperature—magnetic field phase diagram suggests that two different order parameters might be at play [5]. These results will be discussed in the context of other strange metal superconductors.

References

[1] S. Paschen and Q. Si, Nat. Rev. Phys. **3**, 9 (2021).
[2] S. Paschen et al., Nature **432**, 881 (2004); S. Friedemann et al., PNAS **107**, 14547 (2010).
[3] L. Prochaska et al., Science **367**, 285 (2020).
[4] E. Schubert et al., Science **351**, 485 (2016).
[5] D. H. Nguyen et al., Nat. Commun. **12**, 4341 (2021). Featured article, https://www.nature.com/collections/rcdhyvxytb (Aug 11, 2021).

Andrea Caviglia

Coherent spin-wave transport in an antiferromagnet

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Magnonics is a research field complementary to spintronics, in which the quanta of spin waves (magnons) replace electrons as information carriers, promising lower dissipation. The development of ultrafast, nanoscale magnonic logic circuits calls for new tools and materials to generate coherent spin waves with frequencies as high and wavelengths as short as possible. Antiferromagnets can host spin waves at terahertz frequencies and are therefore seen as a future platform for the fastest and least dissipative transfer of information. However, the generation of short-wavelength coherent propagating magnons in antiferromagnets has so far remained elusive. Here we report the efficient emission and detection of a nanometre-scale wavepacket of coherent propagating magnons in the antiferromagnetic oxide dysprosium orthoferrite using ultrashort pulses of light. The subwavelength confinement of the laser field due to large absorption creates a strongly non-uniform spin excitation profile, enabling the propagation of a broadband continuum of coherent terahertz spin waves. The wavepacket contains magnons with a shortest detected wavelength of 125 nm that propagate into the material with supersonic velocities of more than 13 km s–1. This source of coherent short-wavelength spin carriers opens up new prospects for terahertz antiferromagnetic magnonics and coherence-mediated logic devices at terahertz frequencies [1].

[1] J.R. Hortensius, D. Afanasiev, M. Matthiesen, R. Leenders, R. Citro, A.V. Kimel, R.V. Mikhaylovskiy, B.A. Ivanov, A.D. Caviglia Coherent spin-wave transport in an antiferromagnet Nature Physics 17, 1001 (2021).

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Prof. Amalia Coldea

Fermi surfaces and quasiparticle effective masses in the high-pressure phase of superconducting iron-chalcogenides, $FeSe_{1-x}S_x$

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Electronic nematic and spin-density wave phases of FeSe family of iron-chalcogenides superconductors can be intertwined and difficult to assess their relevance on superconductivity. A tuning parameter, like applied pressure and chemical pressure [1,2], are versatile tuning parameters that can be used to explore their relative importance. In my talk, I will present quantum oscillations studies under high applied hydrostatic pressure in $FeSe_{1-x}S_x$ using magnetotransport and tunnel diode oscillator experiments [3,4]. I will discuss the evolution of the Fermi surface and electronic correlations away from the nematic phases inside the high-pressure phase where superconductivity is enhanced. I will also present the changes in the upper critical field as a function of applied chemical and applied pressure and discuss the nature of the high-pressure phase of $FeSe_{1-x}S_x$.

References

[1]. A. I. Coldea, Frontiers in Phys. **8**, 594500 (2021).
[2]. A. I. Coldea et al., npj Quantum Materials, **4**, 2 (2019). [2].
P. Reiss et al, Nature Physics, **16**, 89 (2020).
[3]. Z. Zajicek et al., in preparation (2021).

Primary Pair Density Wave Order in a Magnetic Pnictide Superconductor

Speaker: Abhay Pasupathy, Brookhaven National Laboratory and Columbia University

In superconductors with spin-split Fermi surfaces, it is possible to stabilize a state where the superconductivity is modulated in real space, termed a pair density wave. In this talk, I will describe scanning tunneling microscopy measurements on an iron pnictide superconductor that also features in-plane ferromagnetic order at low temperature. Our spectroscopy measurements show that the superconductivity is modulated in real space in this system with a period of several lattice constants. I will show that all real space modulations in this system disappear when either the ferromagnetic order disappears (with elevated temperature) or the superconducting order is suppressed (in superconducting vortices). These measurements show that the pair density wave seen in this system is a primary order, distinct from other recent examples of modulated superconductivity seen in the cuprates and in other charge density wave materials. We propose a phenomenological explanation for our data in terms of exchange splitting of the FeAs derived Fermi surfaces in the presence of ferromagnetic order.

Thermal Hall Effect in Quantum Materials

Ashvini Vallipuram[1], L. Chen[1], É. Lefrançois[1], M-E. Boulanger[1], G. Grissonnanche[2], L. Taillefer[1,3]

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The thermal Hall effect is the thermal analog of the classical electric Hall effect. Here, we send a heat current and measure temperature differences instead of sending an electric current and measuring differences in voltages. This technique lets us characterize materials by gaining information on the heat carriers that are present in a given system. It is possible to characterize various quantum materials such as cuprates, magnetic insulators and Kitaev candidate materials. In this poster, I will show recent thermal Hall data obtained in our group at Sherbrooke in those three categories. These all point to phonons as the carriers responsable for the thermal Hal effect.

Poster Presentations

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Ms. Ji-Hye Kim, Mr. Ji-Sol Jeong, Hyo-Sang Choi

Derivation of arc frequency calculation formula for circuit with superconducting LC divergent vibration DC circuit breaker

Ji-Hye Kim, Sang-Yong Park, Ji-Sol Jeong, Geon-Woong Kim, Hyo-Sang Choi

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The proportion of new and renewable energy is increasing, and DC power transmission technology is becoming an issue. Fault current interrupting technology is required to secure the reliability and stability of the system. Therefore, this research team proposed a superconducting LC divergence oscillation DC circuit breaker. The proposed circuit breaker is composed of a superconducting current limiter and the LC divergence oscillation circuit breaker. When the superconducting current limits the rapid growth of the fault current, the LC divergence oscillation circuit breaker reliably interrupts an arc. The arc occurs at the same time as the opening starts, and has an unspecified frequency and high resistance. When the fault current flows through the LC divergence oscillation path, an oscillation is generated in the fault current by the inductor and capacitor. The fault current can have an artificial current zero-point by amplitude. At this time, the fault current level varies according to the superconducting current limiter capacity and a load capacity. L and C capacities should be varied according to the level of fault current. However, the formula for selecting the appropriate L and C capacities that limit the fault current has not been studied so far. Therefore, we try to derive an equation for calculating the arc frequency. For this, the frequency response characteristics of the arc were analyzed. And an analysis model based on the results was derived. In addition, the arc frequency was calculated by changing the superconducting current limiter capacity. The L and C capacities according to the arc frequency were calculated, and a resulting interrupt time was confirmed by simulation. If we deviate from the conventional method of estimating L and C capacities, it is expected that the commercialization time of LC divergence oscillation DC circuit breaker will be accelerated.

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Oguzhan Can

Title: Topological superconductivity in twisted cuprates

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Abstract:
We predict that structures composed of two monolayer-thin d-wave superconductors with a twist angle near 45 degrees form a fully gapped topological phase with spontaneously broken time-reversal symmetry and protected chiral edge modes. These structures can be realized by mechanically exfoliating van der Waals-bonded high-critical-temperature copper oxide materials, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$. Our symmetry arguments and microscopic modelling suggest that this phase will form for a range of twist angles in the vicinity of 45°, and will set in at a temperature close to the bulk superconducting critical temperature.

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Prof. Robert Markiewicz

Cuprate Pseudogap as Antiferromagnetic Order with Domain Walls

R.S. Markiewicz and A. Bansil
Northeastern University

While magnetic fields generally compete with superconductivity, a type II superconductor can persist to very high fields by confining the field in topological defects, namely vortices. We propose that a similar physics underlies the pseudogap phase in cuprates, where the relevant topological defects are the antiphase domain walls of an underlying antiferromagnetic (AFM) order. A key consequence of this scenario is that the termination of the pseudogap phase should be quantitatively described by the underlying AFM model. We demonstrate that this picture can explain a number of key experimentally observed signatures of the pseudogap phase and how it collapses in the cuprates.

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Shiro Sakai

Superconductivity in quasicrystals: Multifractal or hyperuniform?

S. Sakai

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Quasicrystal is a crystal without periodicity: Its structure is characterized by an unusual rotational symmetry and self-similarity. Because of the aperiodicity, electrons distribute inhomogeneously but still orderly in quasicrystals. Accordingly, various local quantities show nontrivial spatial patterns, which depend on the quantity of interest. These inhomogeneous but orderly spatial patterns may originate interesting properties unreachable with periodic crystals.

The Penrose tiling is a prototypical structure of the quasicrystals. Previous theoretical studies of the tight-binding model on the Penrose tiling have revealed that the distribution of the electron wavefunctions show multifractality [1]. On the other hand, the distribution of the charge density does not generally show the multifractality [2]. The latter instead shows hyperuniformity [3], which has a vanishing long-range fluctuation of the charge-density distribution.

Here, we study the distribution of the superconducting order parameter for the attractive Hubbard model on the Penrose tiling [4], partly motivated by the recent experimental discovery of a quasicrystalline superconductor [5]. We find that, even though the superconducting order parameter is determined by the electron states around the Fermi level, its distribution is not multifractal unlike the wave functions of the tight-binding model. Instead, we find that the distribution of the superconducting order parameter is hyperuniform. As the distribution of the order parameter changes with the model parameters (like chemical potential and interaction strength), we will discuss how such changes are quantified in terms the order metric of the hyperuniformity.

References

[1]. T. Tokihiro, T. Fujiwara, and M. Arai, Phys. Rev. B **38**, 5981 (1988). [2].
S. Sakai, R. Arita, and T. Ohtsuki, Phys. Rev. B **105**, 054202 (2022). [3]. S.
Torquato, Phys. Rep. **745**, 1 (2018).
[4]. S. Sakai, N. Takemori, A. Koga, and R. Arita, Phys. Rev. B **95**, 024509 (2017). [5].
K. Kamiya *et al*., Nature Commun. **9**, 154 (2018).

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Prof. Sergey Kubatkin

'Devices Made of Wafer Scale Epitaxial Two-Dimensional Superconductor TaC, Protected by Graphene, for Quantum Technology.'

S. Kubatkin1, K-H. Kim1, N. Shetty1, J. Ekman1, S. Lara-Avila1, D. Montemurro1, F.

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Quantum information technology puts stringent demands on the quality of materials and interfaces in the pursuit of increasing the device coherence. Superconducting quantum devices suffer from the 1/f noise, affecting both the device coherence times and often the basic quantum bit parameters. Little is known about the chemical structure and origins of paramagnetic impurities that produce flux/charge noise causing the decoherence of the fragile quantum states and impeding the progress towards large- scale quantum computing. However, it is a common belief that they are residing on the device interface and originate both from imperfections of crystalline structure and from the results of chemical interactions between the surface oxide and the ambient. Therefore, there is a strong need for crystalline epitaxial superconducting films with interfaces protected from the environment.

We demonstrate the growth of epitaxial, ultra-thin TaC (3nm) films on SiC with their surface protected (encapsulated) by graphene over entire 7 mm x 7 mm substrates. Evidence of this composite system is provided by a variety of surface science techniques including SPM, LEEM, LEED, ARPES, HR-TEM, XPS and XRD.
The method of producing graphene-encapsulated TaC devices combines top-down approaches for patterning of as-deposited TaC films, with self-ordering (epitaxy) of TaC and bottom –up growth of graphene. As a result, we demonstrate all-epitaxial, crystallographically perfect epitaxial TaC nanowires (down to 50 nm wide) with the top surface protected by graphene.
The composite TaC/graphene film has a superconducting transition temperature Tc~10K and critical magnetic fields Bc~1.5T (perpendicular) and B>14T (parallel). From technological point of view, encapsulation by graphene protects TaC from ambient oxidation, resulting in samples which are remarkably stable over time, allowing to study numerous properties of TaC. It is worth saying that little is known about TaC thin films up to now.
Our transport measurements on this material are consistent with the notion of 2D superconductor, in which the Ginzburg-Landau coherence length ~15 nm is greater than the film thickness (3 nm). Together with the estimated London penetration depth

~60 nm, we calculate the upper limit of depairing current about 2x108 A/.cm2 The narrowest nanowires of 50 nm show six times less critical current density =3x107 A/ cm2 , perhaps due to current crowding effects.
We discuss the prospects for this novel material, graphene-encapsulated TaC, for quantum information technologies, where protection by graphene eliminates the oxide, common to most superconducting films and bringing new surface chemistry, possibly improving coherence in superconducting devices.

Ms. Marina Raboni Ferreira

Growth and Characterization of Superconducting $Mo_{1-x}Re_x$ Thin Films for the Study of Unconventional Superconductivity Through Synchrotron Radiation Techniques

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Binary $Mo_{1-x}Re_x$ alloys are known to be low-temperature (up to $T_c \approx 13K$) superconductors for $0 \leqslant x \leqslant 1$. Some interesting properties of these materials include the existence of electronic topological transitions (ETTs)[1], time-reversal symmetry breaking (TRSB) in both centrosymmetric and non-centrosymmetric structures[2], at critical Re concentrations (x), and evidence of two-gap superconductivity[3]. These features make them great candidates for the study of unconventional superconductivity.

With that in mind, in this work we intend to correlate the changes observed in the superconducting properties of $Mo_{1-x}Re_x$ thin films, as a function of the samples' Re percentage, with their electronic and magnetic structures, mainly through X-ray absorption spectroscopy techniques such as X-ray Absorption Near Edge Structure (XANES) and X-ray Magnetic Circular Dichroism (XMCD).

We grew several Mo-rich thin film alloys with stoichiometries ranging from $Mo_{60}Re_{40}$ to $Mo_{85}Re_{15}$. The obtained films are type-II superconductors with high critical fields (up to $H_{C2} \approx 5T$) and critical temperatures between $8.4K$ and $12K$. Furthermore, X-ray diffraction measurements revealed that the samples presented two different structural phases: $\beta - W$ $(A15)$ and $BCC - W$. Preliminary XANES measurements at the Re $L-$edge showed a change in the white line intensity and in the calculated branching ratio above and below the superconducting critical temperature, as may be observed in Fig. 1. Further XANES analysis will be presented.

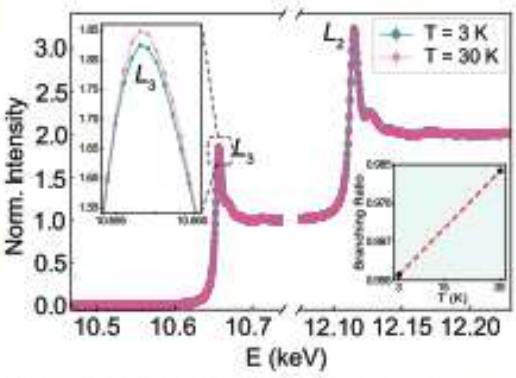

Fig. 1: *XANES data at the Re L_2 and L_3 absorption edges for a $150\ nm$-thick $Mo_{80}Re_{20}$ film.* ***Upper left:*** *L_3 absorption peaks.* ***Lower right:*** *calculated branching ratio as a function of temperature.*

References

[1] L. S. S. Chandra, S. Sundar, S. Banik et al. J. Appl. Phys. **127**, 163906 (2020).
[2] T. Shang, C. Baines, L. J. Chang et al. npj Quantum Mater. **5** 76 (2020).
[3] V. Tarenkov, A. Dyachenko, V. Krivoruchko et al. J. Supercond. Nov. Magn. **33** 569–574 (2020).

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Olga Ivanenko, Dr. Kirill Mitsen

Cluster Structure of Superconducting Phase and the Nature of Peaks in the Doping Dependences of the London Penetration Depth in Iron Pnictides

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Earlier in [1], we showed that the features of the phase diagrams of heterovalently doped cuprate and pnictide HTSCs can be understood within the framework of an approach that assumes the self-localization of doped carriers. At such approach doped carrier locally deforms the electronic structure of the crystal, leading to the formation of so-called CT plaquettes in the cells adjacent to the localization area of the doped carrier (CuO_4 cells in cuprates and $AsFe_4$ cells in pnictides). Due to the influence of the dopant on these plaquettes, the gap Δ for the transitions between the states of the anion and the cation in this plaquette is reduced to the value $0<\Delta^*<E_{ex}$ - the binding energy of the CT exciton. It is shown that the proposed model, despite its simplicity and neglect of the features of the electronic structure, makes it possible not only to accurately calculate the positions of superconducting domes on the phase diagrams of specific HTSC compounds, but also to explain the nature and position of sharp Your abstract text needs to be submitted in the official conference language, **English**.
Note that the abstract with all information should not exceed **one page** with margins being 2.5 cm top, bottom, left and right. The title should be written in '**Title Case**', i.e., capitalize the first letters of each word except the conjunctions such as *and*, *or*, *at*, *in*, *for*, *the*). Underneath the title, please list the **author(s) name(s) and affiliation(s)**. The next line should be blank. After this line, the abstract text starts with Arial 12pt, justified, 1.0 line spacing. If your abstract includes tables and/or figures, please place them as shown below. Please pay attention that all text is legible and the figure is saved with high resolution. Coloured figures are welcome. Caption text font is Arial 11pt with the caption title (Fig. 1) being bold (see sample below).
in cuprates and pnictides.

References

[1]. K. V. Mitsen, O. M. Ivanenko, Phys. Usp. **60**, 402 (2017).

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Prof. Jorge Hirsch

How Arxiv's self-righteousness damages the scientific enterprise

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On October 2020, the discovery of room temperature superconductivity in a hydride under high pressure was announced [1]. On December 1, 2021, R. P. Dias and A. Salamat, authors of ref. [1], uploaded to Arxiv raw data [2] underlying the ac magnetic susceptibility data reported in [1] as a "superior test for superconductivity". On December 8, 2021, I attempted to upload two papers to Arxiv [3], [4] reporting my analysis of those raw data and my conclusion that they were incompatible with the published data. Arxiv blocked the posting of those papers, as well as another with further analysis that I submitted in January [5]. As a consequence, physicists that could have benefitted from that information were prevented from learning about it. Arxiv blocked other papers I submitted thereafter in collaboration with D. van der Marel [6], while posting a paper by Dias and Salamat [7] "explaining" their data. Several weeks later, Nature took action to warn readers of concerns with [1]. Physicists that in the intervening period had devoted valuable efforts, resources and time in research assuming the validity of results reported in [1] and [2] would have benefitted from the information that Arxiv self-righteously blocked for reasons they never explained.

[1] E. Snider et al, Nature **586**, 373–377 (2020).
[2] R. P. Dias and A. Salamat, arXiv:2111.15017 (2021).
[3] J. E. Hirsch , https://www.preprints.org/manuscript/202112.0115/v2
[4] J. E. Hirsch , https://www.preprints.org/manuscript/202112.0188/v2
[5] J. E. Hirsch, https://www.preprints.org/manuscript/202201.0003/v1; Europhys. Lett. doi.org/10.1209/0295-5075/ac50c9 (2022).
[6] D. Van der Marel and J. E. Hirsch, arXiv:2201.07686 (2022); *Preprints* **2022**, 2022020005.
[7] R. P. Dias and A. Salamat, arXiv:2201.11883 (2022).

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Pedro Lozano, Prof. Qiang Li

Angular resolved c-axis transport properties of the stripe ordered cuprates under in-plane magnetic field

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To understand the interplay of charge order, spin stripe orders, and pair-density-wave (PDW) order in cuprates, we performed angular resolved c-axis magneto-transport measurements in $La_{2-x}Ba_xCuO_4$ single crystals with x=0.125 and 0.095. We observed strong dependence of c-axis resistivity (Fig. 1) and supercurrent on the orientation of an in-plane magnetic field with respect to Cu-O bonds. This observation may have direct implications for the superconducting pairing mechanism and the formation of PDW in cuprates.

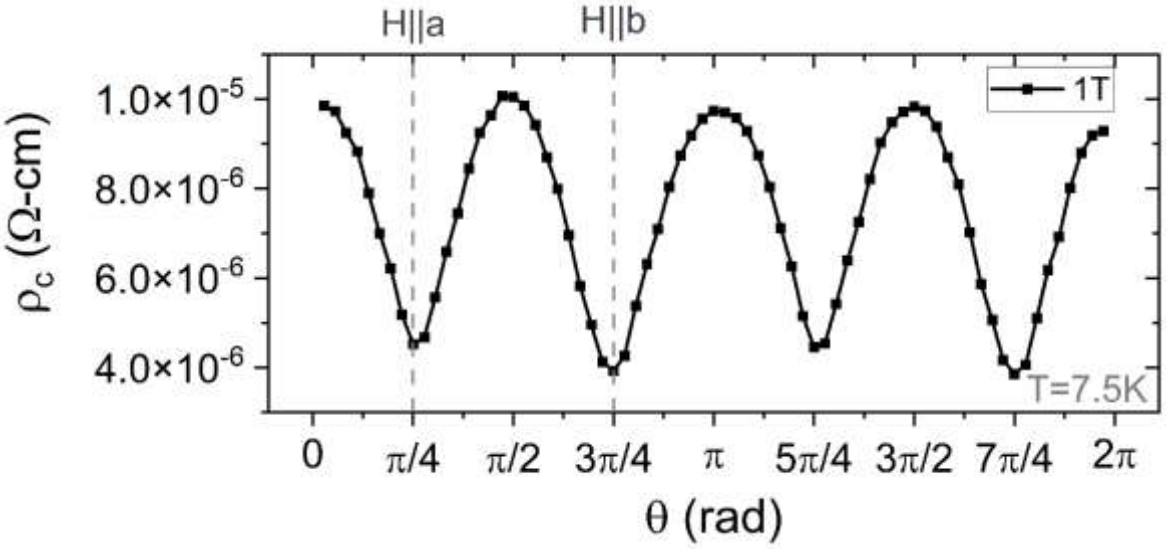

Fig. 1: A typical angle-resolved c-axis resistivity of $La_{2-x}Ba_xCuO_4$ single crystals with x=1/8 at B = 1T, T = 7.5 K. depends on the angle between the in-plane magnetic field and crystal a-, or b-axis (Cu-O bond direction).

Manuel Nunez-Regueiro

Possible high temperature superconducting transitions in bulk twisted graphite S. Layek[1], M. Monteverde[2], G. Garbarino[3], M-A. Méasson[1], A. Sulpice[1], N. Bendiab[1], P. Rodière[1], A. Hadj-Azzem[1], J-L. Hodeau[1], M. Núñez-Regueiro[1]

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We have de-intercalated by soft chemistry at room temperature samples of KC_8. X-rays studies show mainly a KC_{72} structure, with orientational disorder. The six AB slabs have facing AA separations twisted at variable angles, certainly including "magic angles". The K atoms show only short-range order, implying a variable local doping. Thus the samples presumably scan both angles and dopings. Magnetization measurements show a ferromagnetic response, corresponding to $1m_B$ per 10^5 carbon atoms, at high temperature with T_0=420K. And transitions to diamagnetic states at T_c=110K, T_c=240K and T_c=320K. We obtain diamagnetic hysteresis cycles similar to superconducting ones that decrease in size as the temperature increases, disappearing at T_c. However, the amount of perfect diamagnetism measured from the field dependence of the magnetization at 5K (inset Fig.a) is small, 0.001%, and zero resistance has not been attained (best result showed on Fig.c). Although within a Moiré superconducting hypothesis it is obvious that a very small number of crystallites will have the magic angles, and that the volume of both the eventual superconductivity and ferromagnetism will be tiny, more work is necessary to increase their fraction and confirm the existence of superconductivity in bulk twisted graphite.

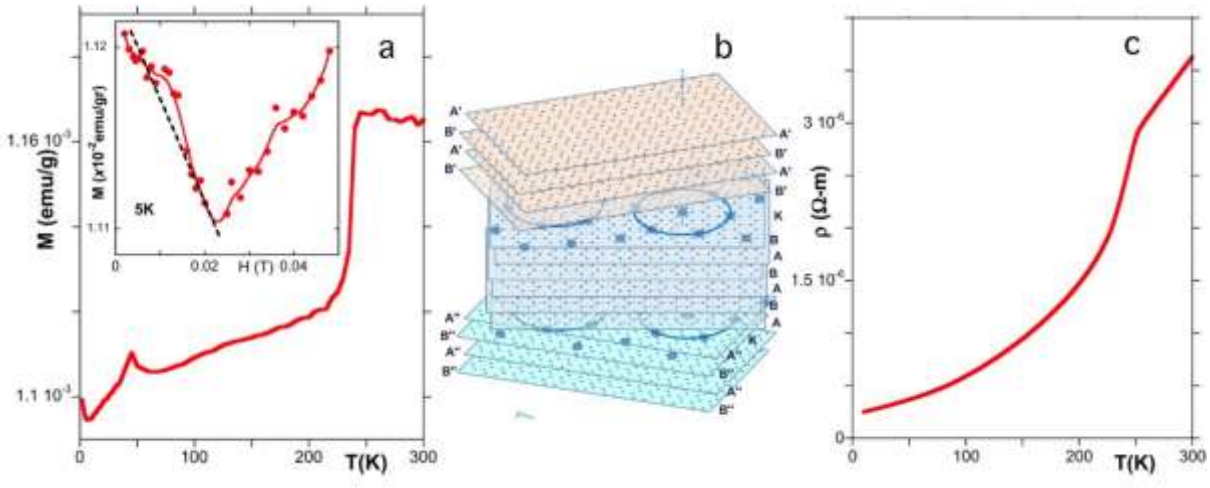

Fig. 1: *(a) Magnetization showing a diamagnetic transition at T_c=240K. Inset: evolution of magnetization with field at 5K. (b) Stacking of stage 6 AB planes with random rotations in between. (c) Electrical resistivity jump at T_c=240K.*

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Mr. Yuta Watanabe

Quantum and temperature effects on crystal structure of superhydride: A path integral molecular dynamics study

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Hydrogen-rich materials under high pressure are attracting attention as candidates of high-T_c superconductors [1]. One of those materials, LaH_{10}, shows a distinctively high critical temperature [2,3]. It was revealed that the quantum effect of hydrogen atoms plays a crucial role in LaH_{10} to stabilize its structure [4]. However, the accurate *P-T* phase diagram of the crystal structure has not been made up to now. We performed molecular dynamics (MD) and path integral molecular dynamics (PIMD) simulations to consider the influence of temperature in addition to the quantum effect [5]. Fig. 1 shows the results of XRD simulations for the crystal structures obtained from the MD and PIMD simulations. The two peaks in classical calculation at 200 K merge when the quantum effect is considered. The peak also merges at 300 K without the quantum effect. The space group analysis revealed that space group of the crystal structure is Fm-3m when only single peak appears. On the other hand, when peak splits, the space group is R-3m, which is lower than Fm-3m. These results indicate that both classical and quantum atomic fluctuation symmetrize the crystal structure.

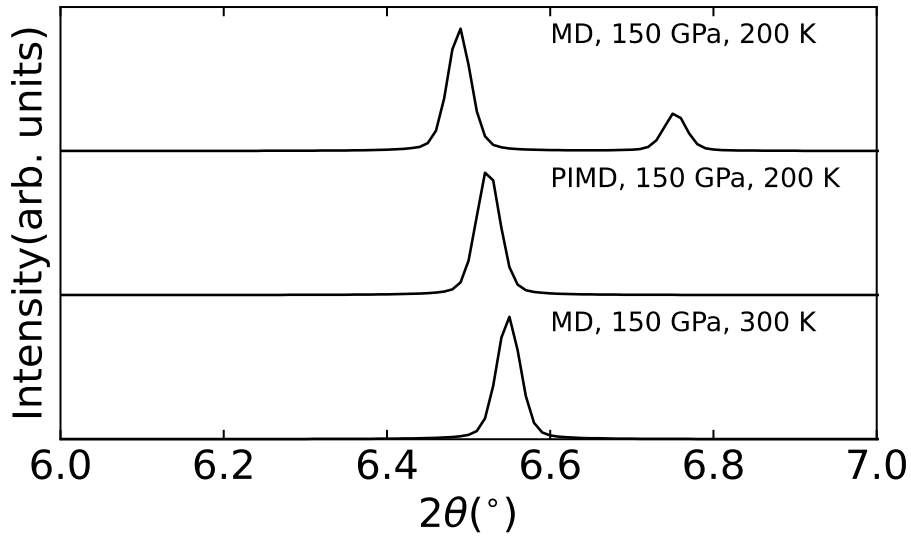

Fig. 1: *X-ray diffraction patterns of LaH_{10} crystal obtained from molecular dynamics (MD) and path integral molecular dynamics (PIMD) simulation. A weak signal besides the one distinct peak appears when the symmetry of the crystal structure is low.*

References

[1]. J. A. Flores-Livas, et al., Physics Reports 78 (2020).
[2]. A. P. Drozdov, et al., Nature **569**, 528 (2019).
[3]. M. Somayazulu, et al., Phys. Rev. Lett. **122**, 027001 (2019).
[4]. I. Errea, et al., Nature **578**, 66 (2020).
[5]. M. Shiga, PIMD (2020). See https://ccse.jaea.go.jp/software/PIMD/index.en.html for further information.

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Mr. Prosper Reulet

The Influence of the Growth Path on the Electronic Properties of $Pr_{2-x}Ce_xCuO_{4-\delta}$

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The electron-doped cuprates become superconductors ~~when even~~only after a tiny proportion of oxygen atoms ~~are~~ is removed from the crystal structure. The mechanism behind this strong influence of the oxygen vacancies created during the reduction process ~~during the reduction process~~ or the removal of interstitial oxygen during the reduction process ~~remains~~remains ~~misunderstood~~ unexplained [1]. There are still several competing scenarios that have been proposed for this mechanism, including the removal of interstitial oxygen defects on their apical site, generating new defects by the removal of oxygen atoms in their copper-oxygen planes or the repair of defects (filling oxygen vacancies) in the crystal structure.

In this study, ~~two samples~~thin films of $Pr_{1.85}Ce_{0.15}CuO_{4-\delta}$ (PCCO 15%) ~~having the same critical temperature (T_c) but different electronic properties are~~ are deposited by PLD ~~obtained~~ by taking ~~two~~ different growth paths.

~~These thin films are deposited by PLD, where~~ Ttheir growth is controlled by the oxygen partial pressure in a mixed ~~n~~ atmosphere of N_2O and O_2 and by the reduction time. ~~Next,~~ Rresistivity and Hall effect measurements are performed to determine T_c, to study the impact of crystal defects and to probe the carrier density. These ~~results~~ properties are used to compare the effect of the growth path on the electronic properties of PCCO.

For example, two samples deposited ~~with~~ using different atmospheres and *in situ* reduction times can have the same T_c and a similar resistivity, but a different Hall effect. On the other hand, t~~T~~wo ~~other~~ samples having ~~a~~ different T_c ~~–~~'s but the same Hall effect ~~are~~ can be obtained.

These results imply that the oxygen defects, either vacancies or interstitials, are not the same depending on the growth path. The Fermi surface and the carrier density are affected by the type of oxygenation achieved during the growth and not only by the reduction time. ~~This~~ The presence of very different oxygen defect populations would explain the variability in the ~~results~~ physical properties of electron-doped cuprates ~~coming~~ often noted ~~from~~ when comparing closely the samples~~different groups on electron-doped cuprates,~~ obtained by various groups using different growth methods. It suggests that the phase diagram of the electron-doped cuprates is a complex relationship between Tc, the Ce doping and the "site occupational" oxygen stoichiometry.

References

[1]. N. P. Armitage, P. Fournier, R. L. Greene, Rev. Mod. Phys. **82**, 2421 (2010).

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Dr. Fabian Jerzembeck

The Superconductivity of Sr_2RuO_4 Under c-Axis Uniaxial Stress

Fabian Jerzembeck[1], Henrik S. Røising[2], Alexander Steppke[1], Helge Rosner[1], Dmitry A. Sokolov[1], Naoki Kikugawa[3], Thomas Scaffidi[4], Steven H. Simon[5], Andrew P. Mackenzie[1,6], and Clifford W. Hicks[1,7]

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In-plane uniaxial pressure has been proven to be capable of tuning the electronic structure of strongly correlated low dimensional systems dramatically. Applying *a*-axis pressure to the unconventional superconductor Sr_2RuO_4 can tune the largest Fermi surface (the gamma sheet) through a Lifshitz transition at a single point in *k* space, which results in enhancement of T_c and H_{c2} by a factor of 2.3 and 20, respectively. *c*- axis uniaxial pressure is expected to drive the gamma sheet to a Lifshitz transition at two *k*-space points simultaneously, leading to an even stronger divergence in the density of states, and so potentially an even stronger enhancement of the superconductivity.

Here, we present uniaxial pressure data under up to 3.2 GPa compression along the c-axis of Sr_2RuO_4. This is a record value for bulk Sr_2RuO_4, achieved by using a focused ion beam as a novel sample preparation technique. We observe that H_{c2} increases, as is expected from an increasing DOS. However, against expectations, T_c decreases. We present three-dimensional weak-coupling calculations and find that no single order parameter can explain the contrasting effect of *a*-axis versus *c*-axis uniaxial stress. For Sr_2RuO_4, these new results strongly constrain any theory of superconductivity.

References

[1] Steppke et al. Science (2017)
[2] Jerzembeck et al. arXiv:2111.06228 (2021)

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Dr. Ricardo Donizeth Dos Reis

Evidence of ferromagnetism collapse and a valence instability in the EuB_6 at high pressures

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Rare earth heaxaborides compounds have attracted research interest over the last few decades due to their rich and complex phase diagram besides their simple crystal structural, what gives to this family a wide spectrum of potential applications as well make them ideal prototypical materials to explore new physical phenomena. Despite the fact that the majority of related research focuses on the topological insulator candidate SmB_6, recently proposed of non-trivial band topology on the parent compounds YbB_6, and EuB_6, are provoking strong interest in the possibility of tuning the hexaborides in order to induce new topological phases. Here, by combining X-ray Absorption and Synchrotron Mossbauer spectroscopies we find that application of pressures higher than 20 GPa dramatically suppress the magnetic ordering of the material and induces an increase on their main valence from pure divalent at ambient pressure to 2.2 at 28 GPa. The observed tunability of the electronic and magnetic phases of the EuB6 material might provides important insights into the interplay between structural, magnetic and electronic degrees of freedom in correlated electron material and topological physics.

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Mr. Ashutosh Mukund Bhudia

Novel Kinetic-Inductance Based On-Chip Microwave Filters for Quantum Computation

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Quantum computers based on superconducting qubits and emerging spin-based qubits employ planar on-chip microwave resonators for qubit measurement and qubit coupling. Often, the on-chip control circuits for qubits cause parasitic losses in the planar resonators, due to their proximity to them. In such systems, filters on the control lines can be used to reflect photons back into the resonator, lowering the loss. Here we design and demonstrate novel high kinetic inductance distributed element (DE) filters and lumped element (LE) filters that employ the kinetic inductance of disordered nanometer-scale superconductors in the dirty limit. We enhance the kinetic inductance effects by using a thin NbTiN film with high sheet inductance per square, and miniaturizing device features to the nanometer scale. In contrast to previous efforts, our filters are simpler and more compact[1][2]. The DE filters can be an order of magnitude smaller than LE filters. The devices were fabricated

on sputtered 10nm NbTiN films on silicon wafers using electron beam lithography, followed by reactive ion etching. Measurements of the LE filter were carried out in a 4 Kelvin liquid helium dunker using a vector network analyzer. The results show that the rolloff of the attenuation matches well with the theory, indicating that the filters are indeed acting as a shunt capacitor and series inductor network. The typical parasitic effect for low pass filters is avoided, showing that the capacitor is well grounded. The real inductance differs from what was predicted, evidenced by a shift in cutoff frequency. These compact filters display favorable performance that arises from exploiting kinetic inductance.

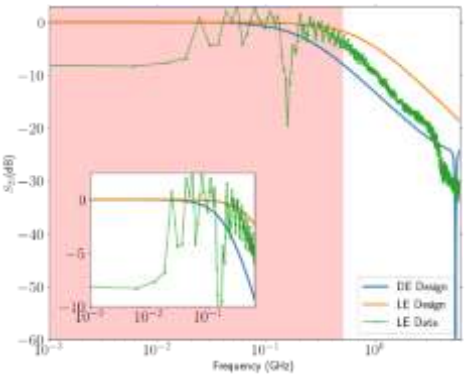

Fig. 1: *Comparison of filter responses on a log-log plot of the transmitted signal versus the signal frequency.*

References

[1]. Mi, X., et al. "Circuit quantum electrodynamics architecture for gate-defined quantum dots in silicon." Applied Physics Letters 110.4 (2017): 043502.

[2]. Harvey-Collard, Patrick, et al. "On-chip microwave filters for high-impedance resonators with gate-defined quantum dots." Physical Review Applied 14.3 (2020): 034025.

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Mr. Geon-Woong Kim, Mr. Sang-Yong Park, Hyo-Sang Choi

Experiment and Simulation of Bifilar-Meander type R-SFCL

Geon-Woong Kim, Sang-Yong Park, Ji-Sol Jeong, Ji-Hye Kim, Hyo-Sang Choi

Dept. of Electrical engineering, University of Chosun, Gwangju, South Korea

Currently, multi-terminal HVDC and microgrids connected to renewable energy are in the spotlight all over the world. Accordingly, the protection method of the DC system is a very important topology. Many loads and sources are connected in multi-terminal and microgrid systems, so when a fault occurs, the fault current spreads to the connected equipment and adversely affects them [1]. Among the protection methods of the DC system, the SFCL device limits the fault current by quenching when a fault occurs. When the system is in steady state, SFCL is in a superconducting state, so its resistance is almost zero. However, if the fault current exceeds the critical value of the superconducting material in the fault state, it changes from the superconducting state to the normal resistance state within a very short time. This resistance can effectively limit the level of the fault current to protect the equipment connected to the system. Generally, resistive SFCLs are non-inductive, and they can be found in diverse shapes meander, multifilar pancakes, spiral or bars, and coils [2]. The conventional meander- type SFCL has a structure that cancels the magnetic field, but it still has parasitic inductance. We proposed an improved winding method of R-SFCL to wind more superconducting tape and lower the inductance. In this method, up to 4 tapes are adjacent, and the currents in all adjacent tapes are reversed. The proposed resistive SFCL was analyzed by FEM and tested in a 500V experimental environment. After that, the data obtained from the tests are applied to the resistive SFCL modeled with PSCAD. VSC-HVDC characteristics are considered in PSCAD to describe environments similar to real systems when the fault occurs. As a result, the bifilar- meander type resistive SFCL effectively limited the fault current in the tests and simulations.

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This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2021R1H1A2095768).

References

[1]. R. Marquardt, “Modular multilevel converter topologies with DC-short circuit current limitation." 8th International Conference on Power Electronics-ECCE Asia. IEEE, 2011.
[2]. M. Farokhiyan, M. Hosseini, “Current density distribution in resistive fault current limiters and its effect on device stability,” Vol. 580, Jan. 2021

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Prof. Kamran Behnia

On the dynamic distinguishability of nodal quasi-particles in overdoped cuprates

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The concomitant emergence of linear resistivity and a superconducting ground state below a critical doping in cuprates is a longstanding puzzle. Here, I begin by noticing that the electron-electron collision rate in the Fermi liquid above the doping threshold is unusually large. Therefore, the scattering time of nodal quasi-particles is close to the threshold for dynamic indistinguishibality, which is documented in liquid 3He at its zero-temperature melting pressure. Failing this requirement of Fermi-Dirac statistics will exclude nodal electrons from the Fermi sea. Becoming classical, they will scatter other carriers within a phase space growing linearly with temperature.

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Local Transformation of the Electronic Structure and Generation of Free Carriers in Cuprates and Ferropnictides under Heterovalent and Isovalent Doping

K. Mitsen[1], O. Ivanenko[1]

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We have previously shown [1] that most of the anomalies in the superconducting characteristics of cuprates and ferropnictides observed at dopant concentrations within the superconducting dome, as well as the position of the domes in the phase diagrams, do not require knowledge of the details of their electronic structure for explanation, but can be understood and calculated with high accuracy within the framework of a simple model describing the cluster structure of the superconducting phase. This fact suggests a change in the paradigm that forms our understanding of HTSC. In this paper, we propose a unified view on the transformation of the electronic structure of cuprates and ferropnictides upon heterovalent and isovalent doping, based on the assumption of self-localization of doped carriers. In this representation, in undoped cuprates and ferropnictides, which initially have different electronic structures (Mott insulator and semimetal), local doping forms percolation clusters with the same electronic structure of a self-doped excitonic insulator where a specific mechanism of superconducting pairing is implemented, which is genetically inherent in such a system. The proposed model includes a mechanism for generating additional free carriers under heterovalent and isovalent doping and makes it possible to predict their sign, which, in the general case, does not coincide with the sign of doped carriers.

References

[1]. K. Mitsen, O. Ivanenko, Results in Physics **32** 105156 (2022).

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Prof. Harold Hwang

Superconductivity in the Infinite-Layer Nickelates

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Since its discovery, unconventional superconductivity in cuprates has motivated the search for materials with analogous electronic or atomic structure. We have used soft chemistry approaches to synthesize superconducting infinite layer nickelates from their perovskite precursor phase, using topotactic reduction. We will present the synthesis and transport properties of the nickelates, observation of a doping-dependent superconducting dome, and our current understanding of the electronic and magnetic structure.

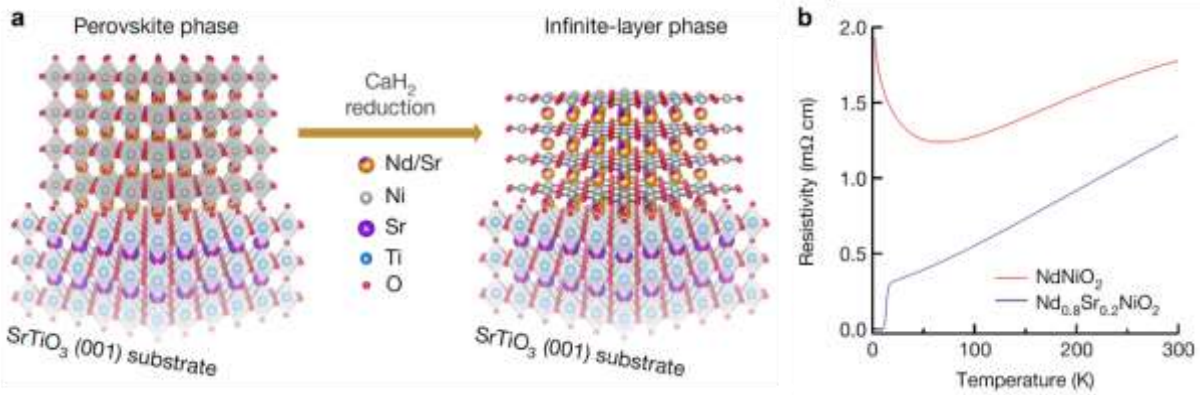

Fig. 1: *(a) Illustration of the topotactic reduction of perovskite $Nd_{0.8}Sr_{0.2}NiO_3$ (left) to infinite-layer $Nd_{0.8}Sr_{0.2}NiO_2$, for films grown on $SrTiO_3$. (b) Resistivity vs. temperature plot of $NdNiO_2$ (red) and $Nd_{0.8}Sr_{0.2}NiO_2$. Superconductivity emerges upon hole doping by strontium.*

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Vidya Madhavan

STM studies of the heavy fermion superconductor UTe_2

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[2]NIST Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
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A particularly interesting manifestation of triplet pairing is a chiral p-wave state which is topologically non-trivial and a natural platform for realizing Majorana edge modes. Triplet pairing is however rare in solid state systems. The best-known example of chiral spin-triplet paring is the superfluid ^{3}He-A phase and over the last few decades, there has been an intensive search for potential spin-triplet superconductors in solid-state systems. Since pairing is most naturally mediated by ferromagnetic spin fluctuations, uranium based heavy fermion systems containing *f*-electron elements that can harbor both strong correlations and magnetism are considered ideal candidate spin-triplet superconductors. In this work I will present scanning tunneling microscopy data on the heavy fermion superconductor, UTe_2 with a T_{SC} of 1.6 K. I will show signatures of coexisting Kondo effect and superconductivity which show competing spatial modulations within one unit-cell. STM spectroscopy at step edges show signatures of chiral in-gap states, predicted to exist at the boundaries of a topological superconductor. Combined with existing data indicating triplet pairing, the presence of chiral edge states suggests that UTe_2 is a candidate material for chiral-triplet topological superconductivity.

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Prof. Brad Ramshaw

The Planckian Limit: a Fundamental Bound on Electron Scattering

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Certain quantities in Nature are bounded at a fundamental level: nothing can travel faster than the speed of light, for example, and Heisenberg's uncertainty principle sets how precisely an object's position and momentum can be specified. These bounds motivate new discoveries and serve as guardrails when making predictions. Recently, it was conjectured that there is a fundamental bound on how often electrons can collide with each other in a metal, with the collision rate set by Planck's constant. This "Planckian" bound, if it were shown to be true, would unify our understanding of a host of seemingly disparate systems, including high-temperature superconductors and twisted bilayer graphene, and even connect their properties to the physics of black holes. The difficulty has been finding experimental proof for this conjecture. We recently developed a new technique for measuring electron scattering rates and found that the Planckian bound not only holds, but it holds in a way that was entirely unexpected: it is independent of the electron's momentum [1]. I will review the history of how this bound came to be proposed, what we have learned so far, and what still needs to be resolved to establish the Planckian bound as a fact grounded both in experiment and in theory.

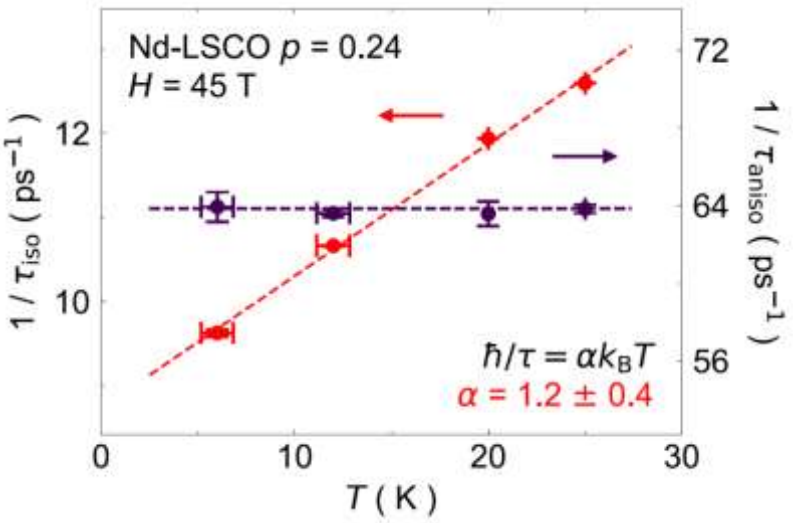

Fig. 1: Temperature dependence of the scattering rate of Nd-LSCO at p = 0.24. The purple points are the anisotropic part of the scattering rate, which varies strongly around the Fermi surface. This component is temperature-independent, suggesting elastic scattering from disorder. The red points are the isotropic part of the scattering rate, which is momentum independent. This scattering rate saturates the Planckian bound, with

References

[1] G. Grissonnanche et al. Linear-in temperature resistivity from an isotropic Planckian scattering rate, Nature 595, 667-672 (2021)

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Prof. Stuart Brown

'Unconventional Superconductivity, Van Hove Physics, and Magnetism in Stressed Sr_2RuO_4'

Stuart Brown

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The stoichiometric transition metal oxide Sr_2RuO_4 is widely considered a model unconventional superconductor, owing to clear evidence for a strongly correlated, Fermi liquid normal state, and to the emergence of superconductivity at T_c=1.5 K. Although our recent ^{17}O NMR Knight shift measurements are inconsistent with the prior prevailing understanding of an odd-parity (*p*-wave) superconductor [1,2], the symmetry of the even-parity ground state remains unresolved [3]. To that end, and initially motivated by indications for a two-component order parameter (recently confirmed [4,5]), and the expected splitting of the transition under stressed conditions, we examined the normal and superconducting states of Sr_2RuO_4 while subjected to variable (B_{1g}) stress. The magnetic response is initially dominated by strain-induced passing of the Fermi energy through a van Hove singularity, which manifests in a strongly nonlinear low-temperature spin susceptibility and a logarithmic temperature dependence that persists over 100s K [6]. Recent μSR^+ [7] measurements report a magnetic transition at still higher stresses. NMR spectroscopy and relaxation measurements examining the nature of the magnetic phase, and its relationship to the proximate superconducting state are underway.

References

[1]. A. Pustogow, *et al.*, Nature **574**, 72-75 (2019).
[2]. A. Chronister, *et al.*, Proc. Natl. Acad. Sci. U.S.A. **118**, e2025313118 (2021).
[3]. S. A. Kivelson, *et al.*, npj Quantum Mater. **5**, 43 (2020).
[4]. S. Ghosh, *et al.*, Nature Phys. **17**, 199-204 (2021).
[5]. S. Benhabib, *et al.*, **17**, 194-198 (2021).
[6]. A. Chronister, *et al.*, arXiv:2111.05570 (2021).
[7]. V. Grinenko, *et al.*, Nature Phys. **17**, 748-754 (2021).

Allan Macdonald[1], Chunli Huang[1], Pawel Potasz[1], Nemin Wei[1], Tobias Wolf[1], Ming Xie[1], Jihang Zhu[1]
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Magnetism and Superconductivity in Strongly Correlated Graphene

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Band states in graphene multilayers have a 4-fold spin x valley flavor degeneracy. Recent experiments have demonstrated that ground states that break flavor degeneracy without breaking translational symmetry are common in the absence of a magnetic field when correlations are strong, just as they are in the quantum Hall regime. Strong correlations are realized in magic angle twisted multilayers [1] and in some epitaxial multilayers at large displacement fields. These states can be viewed as generalized ferromagnets in which electron spin is replaced by a four-component spin/valley flavor spinor. The broken symmetries are responsible for large Fermi surface reconstructions that are revealed [2] by magnetic oscillations and weak-field Hall effects. I will discuss properties of these flavor ferromagnets, commenting on the soft collective modes that they produce [3] and on the relationship between magnetism and superconductivity [4].

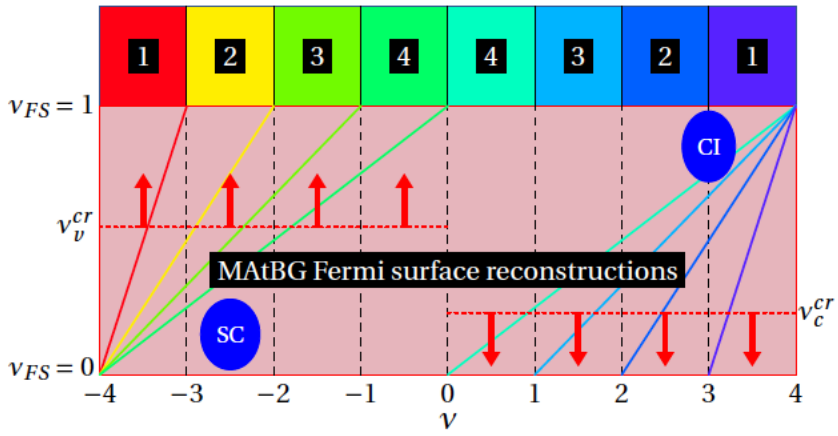

Fig. 1: The pattern of flavor symmetry breaking in magic angle twisted bilayer graphene keeps the filling factors of partially occupied moiré bands small, by completely filling conduction bands or completely emptying valence bands for some flavors.

References

[1] Bistritzer R, MacDonald AH. Moiré bands in twisted double-layer graphene. Proceedings of the National Academy of Sciences. 2011 Jul 26;108(30):12233-7.
[2] Xie M, MacDonald AH. Weak-Field Hall Resistivity and Spin-Valley Flavor Symmetry Breaking in Magic-Angle Twisted Bilayer Graphene. Physical review letters. 2021 Nov 2;127(19):196401.
[3] Kumar A, Xie M, MacDonald AH. Lattice collective modes from a continuum model of magic-angle twisted bilayer graphene. Physical Review B. 2021 Jul 8;104(3):035119.
[4] Huang C, Wei N, Qin W, MacDonald A. Pseudospin Paramagnons and the Superconducting Dome in Magic Angle Twisted Bilayer Graphene. arXiv preprint arXiv:2110.13351. 2021 Oct 26.

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Dr. Andrew Millis

Mechanisms of superconductivity: what do we know, what do we think we know, and what would we like to know

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[2] Center for Computational Quantum Physics, Flatiron Institute, 162 5th Avenue New York NY 10010 USA

This talk presents an overview of beyond-BCS mechanisms for superconductivity in unconventional materials. I will discuss the theory of electron-phonon coupled materials in and beyond Migdal-Eliashberg theory, touching on both a conventional (one loop RPA) theory including phonons and the coulomb interaction and stronger coupling effects leading to Bose condensation of polarons. Next I will consider the superconductivity observed in the layered rare earth nickelates in comparison to the superconductivity observed in the high-Tc cuprates, focusing on the similarities and differences of the electron-electron interactions. I will finally turn to the spin fluctuation theory of electronically mediated superconductivity, using numerically exact results obtained from dynamical mean field theory to infer general conclusions about the superconductivity in the Hubbard model and in other models of correlated electrons. This talk is a general summary of work performed in collaboration with M. Katsnelson, M. Roesner and Yann in t'Veld (ME theory); John Sous, David Recihman, Nikolay Prokofev and Mona Berciu (polarons); alex Hample and Jonathan Karp (nickelates) and Xinyang Dong and Emanuel Gull (spin fluctuations).

Dr. Roser Valenti

Topological Phenomena in Fe-based superconductors: The case of $CaKFe_4As_4$

Roser Valentí[1,]

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The realization of topological phenomena in iron-based superconductors has opened a route to elucidate the interplay between topology, electronic correlations, and unconventional superconductivity. Indeed, a band inversion involving an As/Se p_z band and a pair of Fe d_{xz} /d_{yz} bands along the Γ-Z line of the Brillouin zone has been observed in several compounds, such as $FeTe_{1-x}Se_x$, $LiFe_{1-x}Co_xAs$, and $CaKFe_4As_4$. With the help of symmetry analysis, low-energy modeling, and *ab initio* simulations we will show in this talk that another nontrivial topological phenomenon— Weyl points—can be realized in the iron-based superconductor $CaKFe_4As_4$ in a magnetic field [1]. We will then discuss how the presence of such Weyl points (Fig. 1) in iron-based materials may open the door to investigate the interplay between Weyl fermions and other types of electronic orders not usually present in the currently studied Weyl semimetals.

This work has been done in collaboration with N. Heinsdorf, M. H. Christensen, M. Iraola, S.-S. Zhang, F. Yang, T. Birol, C. D. Batista, and R. M. Fernandes.

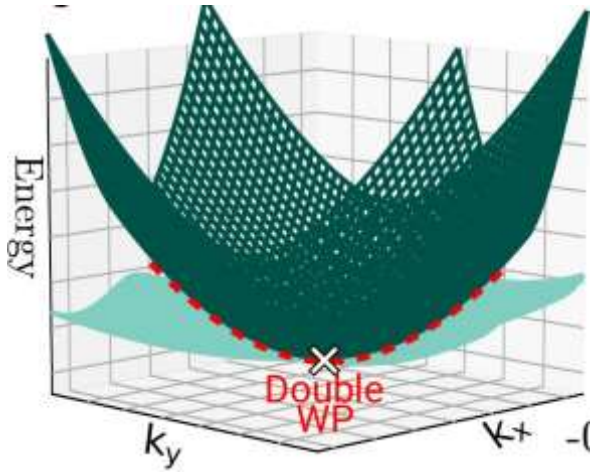

Fig. 1: *Energy dispersion of the two bands in $CaKFe_4As_4$ forming the Weyl point.*

References

[1] N. Heinsdorf et al. Phys. Rev. B **104**, 075101 (2021).

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Prof. Pablo Jarillo-Herrero

The Magic of Moiré Quantum Matter

P. Jarillo-Herrero[1]

[1] *Dept. of Physics & Astronomy, University of British Columbia, Vancouver, BC, Canada*

The understanding of strongly-correlated quantum matter has challenged physicists for decades. The discovery three years ago of correlated phases and superconductivity in magic angle twisted bilayer graphene led to the emergence of a new materials platform to investigate strongly correlated physics, namely moiré quantum matter. These systems exhibit a plethora of quantum phases, such as correlated insulators, superconductivity, magnetism, Chern insulators, and more. In this talk I will review some of the recent advances in the field, focusing on the newest generation of moiré quantum systems, where correlated physics, superconductivity, and other fascinating phases can be studied with unprecedented tunability. I will end the talk with an outlook of some exciting directions in this emerging field.

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Nicholas Butch

New experimental insights into the spin triplet superconductor UTe_2

Nicholas P. Butch[1,2], S. Ran[1,2,3], J. Paglione[1,2], S. R. Saha[1,2]

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Uranium ditelluride hosts an unusual form of superconductivity that exhibits signatures of spin-triplet pairing, multiple order parameters, time-reversal symmetry breaking, and in-gap chiral surface states. Additional reentrant superconductivity appears at fields greater than 40T. In this talk, I will discuss the dependence of the multiple ordered phases on magnetic field and applied pressure. In addition, I will highlight recent experimental developments.

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Prof. Marcel Franz

High-temperature topological superconductivity in twisted double-layer copper oxides

O. Can[1,2], T. Tummuru[1,2], R.P. Day[1,2], I. Elfimov[1,2], A. Damascelli[1,2], M. Franz[1,2]

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As an application of the twist paradigm, we predict that structures composed of two monolayer-thin d-wave superconductors with a twist angle close to 45° form a robust, fully gapped topological phase with spontaneously broken time-reversal symmetry and protected chiral edge modes [1]. These structures can be realized by mechanically exfoliating van der Waals-bonded high-critical-temperature copper oxide materials, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$. Our symmetry arguments and detailed microscopic modelling suggest that this phase will form for a range of twist angles in the vicinity of 45°, and will set in at a temperature close to the bulk superconducting critical temperature of 90 K. Therefore, this platform may provide a long-sought realization of a true high-temperature topological superconductor. Experimentally observable signatures of the T-broken topological phase, including the polar Kerr effect [2], anomalous Josephson effect and various spectroscopies will also be discussed.

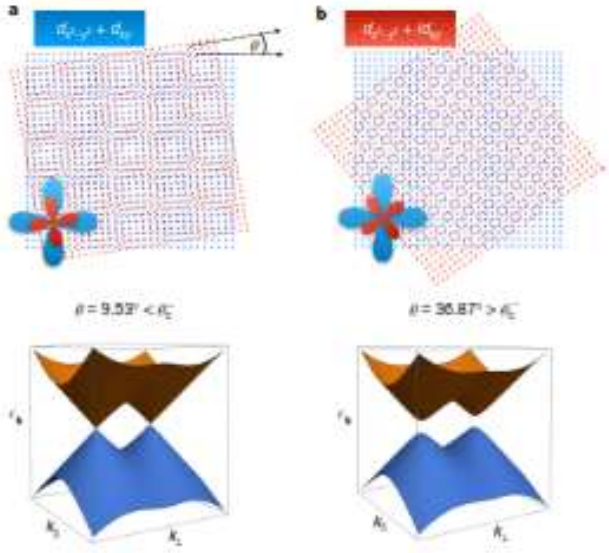

Fig. 1: ***Twisted double-layer d-wave superconductor.*** *a, Illustration of the lattice geometry at small twist angle θ < θc , where the free energy is minimized for interlayer phase difference φ = 0. This results in a gapless spectrum with weakly split Dirac points. b, For twist angles θ > θc , the preferred state has φ ≠ 0. It breaks time reversal and is fully gapped as indicated by the massive Dirac spectrum.*

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Dr. Jisun Kim

Interplay between Charge Balance and Surface Structure on Superconducting Properties of $Ca_{10}(Pt_4As_8)(Fe_2As_2)_5$

Jisun Kim[1], Tiffany Matthé[1], Seokhwan Choi[1], Amy Qu[1], Brandon Stuart[1], James Day[1],Silu Huang[2], Rongying Jin[2], D. A. Bonn[1], and S. A. Burke[1]

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$Ca_{10}(Pt_4As_8)(Fe_2As_2)_5$ contains both superconducting building blocks (Fe_2As_2 layers) and conducting spacers (Pt_4As_8 layers), unlike the insulating spacers in other Fe-based superconductors. Prior work using scanning tunneling microscopy and spectroscopy (STM/STS) showed the important role played by the charge environment and surface structure in this material's superconducting properties: evidence for superconductivity is absent in the bare Pt_4As_8 surface but recovers when Ca atoms are on top, and different surface reconstructions also lead to different superconducting features [1]. I will describe our recent STM/STS results on the role of charge balance and surface structure in superconductivity in this compound. Cleaving at room temperature provides two terminations: Pt_4As_8 layer with clustered Ca atoms and disordered Ca layer on top of Fe_2As_2 layer, whose superconducting features have not yet been probed. Compared to the ordered surfaces studied in the previous work, Ca clusters and disordered Ca alter not only the surface structure but also charge balance of the surface, which results in local changes in spectral features. I will discuss the delicate balance between charge and order on surface superconductivity based on STS results taken at various temperatures.

References

[1]. J. Kim *et al.*, Sci. Rep. **6**, 35365 (2016).

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Mr. Tomoki Kobayashi

Superconductivity in Ultrathin Films of FeSe on $SrTiO_3$ Grown by the PLD Technique

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Iron chalcogenide superconductor, FeSe, has attracted much attention because monolayer FeSe on $SrTiO_3$ (STO) shows much higher superconducting transition temperature (T_c) than that of bulk FeSe [1]. High T_c in the monolayer FeSe/STO is attributed to the interfacial effects such as electron doping from STO substrate and electron-phonon interaction with phonons of STO substrate. Although ARPES measurements have reported T_c of 65 K [2], almost all resistivity measurements have reported the onset T_c (T_c^{onset}) of about 40 K and much lower zero-resistance T_c (T_c^{zero}) [1,3,4]. The origin of the discrepancy in reported values of T_c is under debate. We have worked on the growth of FeSe thin films by a pulsed laser deposition (PLD) [5] and found even only electron doping increases T_c^{zero} up to 46 K [6]. This is the highest value of T_c^{zero} among all reported values of T_c by resistivity measurements in FeSe, except for the singular report [7]. Thus, it is intriguing how this T_c changes as the thickness of FeSe is reduced. In order to investigate that, we further optimized the growth condition to realize the interface superconductivity in FeSe/STO by PLD, while the interface superconductivity in FeSe/STO had been observed only for films grown by molecular beam epitaxy so far. In this work, we report the first successful growth of FeSe/STO ultrathin films that show interface superconductivity by the PLD technique.

Prior to the deposition, the STO substrates were thermally treated to obtain step and terrace structure on the surface. This is very important to obtain films with good superconducting properties. We fabricated three films of FeSe/STO with different thicknesses. As shown in Fig.1, all films show superconductivity with T_c^{onset} much higher than that for bulk FeSe. The 11-nm-thick film shows the highest T_c^{onset} = 26 K and T_c^{zero} = 11 K. The T_c^{onset} values of the films are exceptionally high in terms of the effect of in-plane strain for bulk superconductivity in FeSe [8]. In addition, the T_c^{onset} increases as the thickness of film is reduced. This behavior is in good agreement with those of MBE-grown films [9]. These results indicate that the mechanism of the superconductivity includes interface effects other than lattice strain.

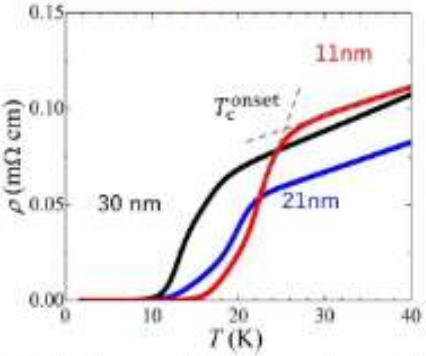

Fig.1 *Temperature dependence of resistivity of three films*

References

[1]. Q. Y. Wang *et al.*, CRL **29**, 037402 (2012).
[2]. S. He *et al.*, Nat. Mater. **12**, 605 (2013)
[3]. A. K. Pedersen *et al.*, PRL **124**, 227002 (2020)
[4]. B. D. Faeth *et al.*, PRX **11** 021054(2020)
[5]. Y. Imai, F. Nabeshima, A. Maeda Condens. Matter **2**, 25 (2017)
[6]. N. Shikama *et al.*, Appl. Phys. Express **13**, 083006 (2020)
[7]. J. F. Ge *et al.*, Nat. Mater. **14**, 285 (2014)
[8]. F. Nabeshima *et al.*, JJAP **57**, 120314 (2018)
[9]. Q. Wang *et al.*, 2D Mater. **2**, 044012 (2015)

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Dr. Martin Bluschke

Non-equilibrium dynamics of electronically driven C_4-rotational symmetry breaking in the CuO_2 planes of LESCO observed with time-resolved resonant x-ray scattering

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Understanding the interplay between charge, nematic, and structural ordering tendencies in cuprate superconductors is critical to unraveling their complex phase diagram. Using pump-probe time-resolved resonant x-ray scattering (tr-RXS) on the (0 0 1) Bragg peak at the Cu L_3 and O K resonances, we investigate the dynamics of (Q_a = Q_b = 0) C_4-rotational symmetry breaking and its association with charge density wave (CDW) order in $La_{1.65}Eu_{0.2}Sr_{0.15}CuO_4$. For measurements probing the apical oxygen we detect a slow response to optical pumping, characteristic of lattice dynamics. This response is vanishingly small in the low-fluence regime (approx. F < 100 $\mu J/cm^2$) as shown in Fig. 1. In contrast, for measurements of copper or planar oxygen (in the CuO_2 plane), we detect a large and fast response to pumping, clearly distinct from the structural dynamics. The temperature dependence of the fast (001) peak dynamics at Cu L_3 and planar O K resonances is correlated with the onset of CDW order. This indicates that CDW order, typically evidenced by translational symmetry breaking, includes a significant Q = 0 (electronic nematic) component [1].

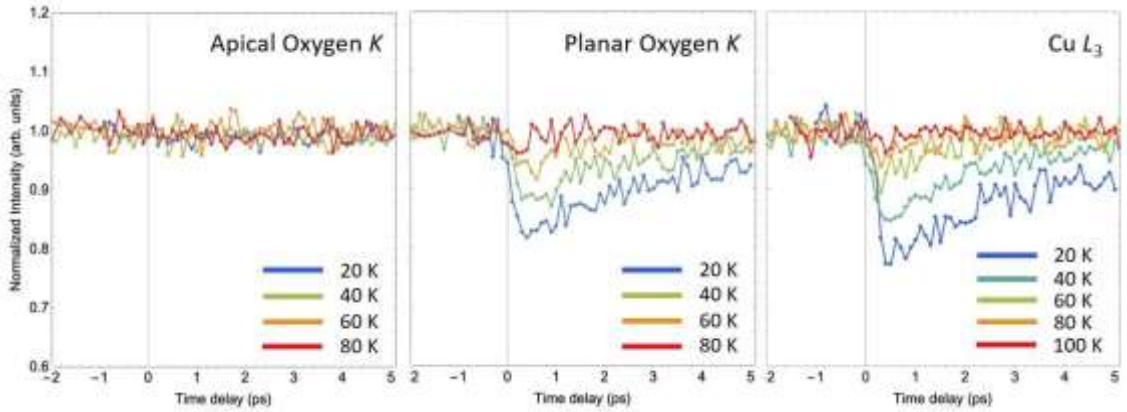

Fig. 1: *Q=(001) RXS intensity as a function of pump-probe delay in LESCO x=0.15 (T_{CDW} ≈* 75 K*). The planar O K and Cu L_3 resonances are sensitive to pump-induced nematicity dynamics in the CDW phase. In contrast, the RXS intensity at the apical O K resonance, sensitive only to structural distortions, is unperturbed by the 50 μJ/cm², 1.55 eV optical pump.*

References

[1] A. J. Achkar et al., Science **351**, 576 (2016).

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Mr. Dušan Kavický

Model-independent Determination of the Gap Function of Nearly Localized Superconductors

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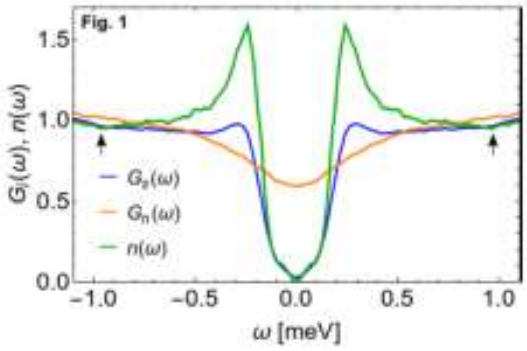
The gap function $\Delta(\omega)$ carries information on both, pair-generating and pair-breaking processes in a superconductor. In superconductors with a constant density of states (DoS) in the normal state, $N_n(\omega)$, the function $\Delta(\omega)$ can be obtained from the tunneling conductance in the superconducting state, $G_s(\omega)$. However, if $N_n(\omega)$ is not constant, e.g. in nearly localized superconductors, the standard procedure for extraction of $\Delta(\omega)$ cannot be applied. Here, we introduce a model-independent method [1] that makes it possible to extract $\Delta(\omega)$ also in this case. The procedure starts with the measured conductance in the normal and superconducting states $G_n(\omega)$, $G_s(\omega)$, and consists of three consecutive steps: (i) Extraction of $N_n(\omega)$, $N_s(\omega)$ not by fitting, but instead by a direct inversion of the finite-temperature data for $G_n(\omega)$, $G_s(\omega)$. (ii) Determination of the superconducting DoS-function $n(\omega)$ in which the influence of the non-constant $N_n(\omega)$ on the superconducting DoS, $N_s(\omega)$, is eliminated. (iii) Extraction of $\Delta(\omega)$ from $n(\omega)$. The feasibility of the procedure is demonstrated on the tunneling data for the disordered thin films of TiN [2]. Our results show an unconventional feature of $\Delta(\omega)$, see arrows in Figs.1,2, which suggests that the electrons are coupled to a pair-breaking mode at 1 meV [3].



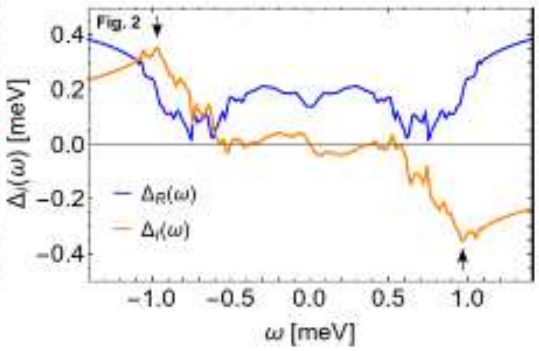


Fig. 1: *Experimental input: symmetrized conductance of the TiN films [2] in the superconducting ($G_s(\omega)$, blue) and normal ($G_n(\omega)$, orange) states. $G_n(\omega)$ was extrapolated from the B=4 T and 7 T data. Output: the DoS-function $n(\omega)$ (green).*

Fig. 2: *Complex gap function $\Delta(\omega)=\Delta_R(\omega)+i\Delta_I(\omega)$ extracted from the DoS-function $n(\omega)$ (Fig. 1). The peaks in $\Delta_I(\omega)$ (see arrows) indicate that the electrons couple to a pair-breaking mode at the same energy [3].*

References

[1]. D. Kavický, F. Herman, and R. Hlubina, in preparation.
[2]. S. V. Postolova et al., Phys. Rev. Research **2**, 033307 (2020).
[3]. T. Bzdušek and R. Hlubina, Philos. Mag. **95**, 609 (2015).

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Leandro Rodrigues De Faria

Field-Reentrant Superconducting Behavior in Tb-Doped $ZrTe_3$ Single Crystals

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$ZrTe_3$ is a good example of a material that exhibits a clear coexistence between superconductivity and Charge Density Waves (CDW). While a filamentary superconducting transition occurs at 2.0 K along with CDW instability near 63 K in pristine crystals, the transition temperature may be raised through doping (Cu or Ni) or disorder while CDW is suppressed. In this work, terbium-doped $ZrTe_3$ single crystals were grown through chemical vapor transport and bulk superconductivity was found near 5.0 K for the composition $Tb_{0.01}ZrTe_3$. A departure from the zero-resistivity state followed by a reentrance into the superconducting state is observed as a bump in resistivity inside the superconducting state for fields above 500 Oe on the RxT and the RxH curves. We show in this work that this reentrant behavior it is a clear signature of coexistence between some magnetic order into the superconducting state.

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Ms. Meng-Jung Hsieh

The Magnetic Phase Diagram of CuB_2O_4

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Copper metaborate CuB_2O_4 attracts researcher's concerns due to the particular magnetic structures and other physical properties. CuB_2O_4 was known to have complex magnetic orderings at both T_1 = 21 K and T_2 = 10 K, especially for the lower temperature one. [1] The nature of both ordering remains not fully elucidated. Very recently, the isotope effect on the electronic structure of CuB_2O_4 has been revealed. [2] Therefore, a deep understanding of CuB_2O_4 is called for to further manipulate the ground state of CuB_2O_4. In this work, we utilize the heat capacity and magnetic measurements to investigate the magnetic orderings at zero and in applied magnetic fields. The preliminary heat capacity data in low fields in Fig. 1 reveal that the ordering at T_2 is of the antiferromagnetic nature. Furthermore, a magnetic crossover below T_2 at zero field has the tendency to have a field-induced long range ordering. More comprehensive results will be presented to have a complete picture of magnetic phase diagram of CuB_2O_4.

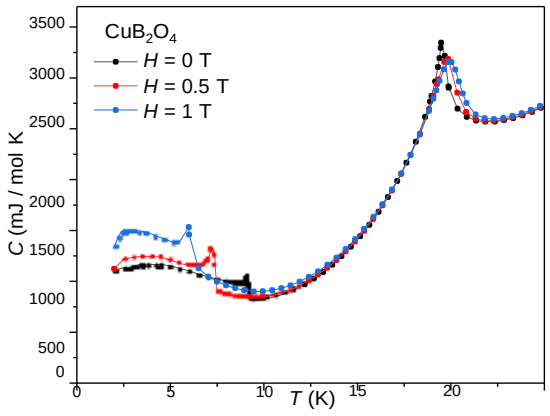

Fig. 1 *The heat capacity of CuB_2O_4 at zero field, 0.5 T, and 1 T.*

References

[1] M. Boehm et al., Phys. Rev.B **68**, 024405 (2003).

[2] Rea Divina Mero et al., ROYAL SOCIAL OF CHEMISTRY Adv. **10**, 41891–41900 (2020).

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Dr. Krzysztof Wohlfeld

Origin of the fundamental differences between ARPES of 1D and 2D cuprates

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We study the origin of the fundamental differences found in the ARPES spectra of the 1D and 2D copper oxides [1]. To this end, we consider the motion of a single hole in a 1D antiferromagnet and express this problem *exactly* in the magnon basis [2]. This enables us to express the 1D problem in the language that is typically used to treat the 2D problems and therefore understand the intrinsic contrasts between the 1D and 2D cuprate physics. Ultimately, we solve the (reformulated) 1D *t-J* model problem using the state-of-the-art exact diagonalisation on 28 sites in the magnon basis.

The main result shows how the spin polaron quasiparticle, which is well-known from the studies of a single hole in the 2D antiferromagnet [3], is destroyed in 1D by the magnon-magnon interactions, leading to spin-charge separation. Nevertheless, we observe some surprising similarities between the ARPES spectra obtained with and without magnon-magnon interactions. This indicates that some of the key features of the spin polaron physics are still preserved in the 1D cuprates and thus suggests a remarkable "robustness" of the spin polaron picture—-which can be used in the future to better understand the ARPES spectra of the doped 2D cuprates.

References

[1]. J. A. Sobota, Y. He, and Z.X. Shen, Rev. Mod. Phys. **93**, 025006 (2021). [2].
P. Wrzosek and K. Wohlfeld, Phys. Rev. B **103**, 035113 (2021).
[3]. B. I. Shraiman and E. D. Siggia, Phys. Rev. Lett. **60**, 740 (1988).

Dr. Rina Tazai

Non-Trivial Interplay between Unconventional CDW and Superconductivity in Kagome Metal AV_3Sb_5

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Recently, unconventional charge density-wave (CDW) and exotic superconductivity in geometrically frustrated kagome metal AV_3Sb_5 attract increasing attention. This discovery sparked lots of theoretical studies, such as the first principles studies, renormalization group theories, and mean-field theories. However, the microscopic origins of these exotic orders and their nontrivial interplay have not been understood in the previous studies.

Here, we focus on the novel “paramagnon interference”. This interference process originates from the many body effects beyond mean-field approximation. The importance of this process has been verified by functional renormalization group (fRG) studies [1], while it has not been studied in previous theories. Based on the paramagnon interference, we explained the emergence of triple-Q bond-order [2], which corresponds to 2×2 David-Star CDW [3] in Fig.1 (b).Moreover, the origin of the bond-order is the interference of two-spin fluctuations as shown in Fig.1 (a).

In addition, we reveal the novel interplay between CDW and superconductivity. The development of bond-order fluctuations give sizable beyond-Migdal pairing glue for the exotic superconductivity as explained in Fig.1 (c). Its driving force is the paramagnon interference, which provides large backward and umklapp scattering among different van-hove singularity points. For this reason, both the triplet p-wave pairing and the singlet anisotropic s-wave pairing states are obtained as shown in Fig.1 (d). Thus, we uncover the novel mechanism that bond-fluctuation enhance the T_c of both p-wave and s-wave superconductivity.

In the presentation, we further discuss the possibility of time-reversal symmetry (TRS) breaking under the CDW transition at $T<T_{cdw}$ and dome structure of the superconductivity under the pressure.

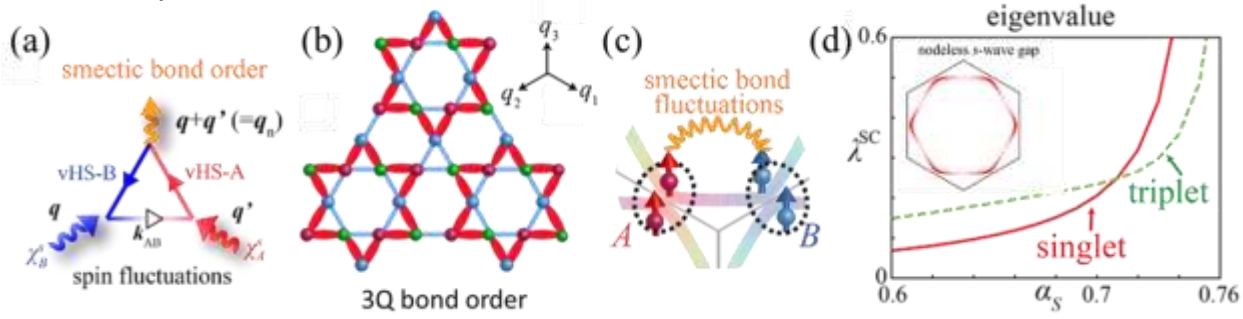

Fig. 1: (a) Magnon interference mechanism that induce 2×2 David-Star bond-order. Spin fluctuations at van-Hove singularity of A-site and B-site induces bond order. (b) Obtained David-star type bond order. Hopping modulation is enlarged/suppressed at the red/blue colored region.(c) Novel mechanism of the superconductivity induced by the bond-order fluctuations. (d) Both triplet p-wave and singlet s-wave superconducting states appear.

References

[1] Rina Tazai, Y. Yamakawa, and H. Kontani, Phys. Rev. B **103**, L161112 (2021).
[2] R. Tazai et al., arXiv: 2107.05372.
[3] Jiang, YX *et al.,* **20**, 1353 *Nat. Mater* (2021).

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Niclas Heinsdorf

Topological Superconductivity in the nodal-plane material RhGe

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We find a symmetry-enforced nodal plane in the noncentrosymmetric crystal RhGe that was reported to become superconducting below 4.5K in 2015 [1]. The degeneracy at the boundaries of the Brillouin zone is stabilized by the combined effect of a nonsymmorphic screw rotation and time-reversal symmetry.
Since the nodal plane is close to the Fermi level, we suspect it to play an important role in the emergence of superconductivity and potentially enhance interband pairing effects.
Density Functional Theory predicts this material to be a weak ferromagnet. Starting from our own ab-inito calculations, we construct an effective low-energy model and calculate the susceptibility within the Random Phase Approximation.
Lastly, we analyze the spin-fluctuation mediated paring symmetry as a function of filling and intra- and inter-band interactions.
We find a number of different superconducting phases with non-trivial toplogies, and discuss implications for experiments on RhGe.

References

[1]. A. B. Tsvyashchenko et al., Journal of Alloys and Compounds 686:431–437 (2016).

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Chaitanya Murthy

Quantum-Critical Dynamics of a Josephson Junction at the Topological Transition

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Superconducting quantum wires with broken time-reversal and spin-rotation symmetries recently emerged as a basis for a topological qubit. By varying the applied magnetic field and chemical potential such wires may be tuned through a quantum critical point into a topological phase in which Majorana zero modes are localized at the ends of the wire. We investigate signatures of this topological transition in the finite-frequency admittance $Y(\omega)$ of a nanowire Josephson junction. The dependence of the admittance on frequency ω and temperature T at the critical point is universal and determined by the symmetries of the system. Despite the absence of a spectral gap at the transition, the dissipative response may remain weak at low energies: $\mathrm{Re}\,Y(\omega) \propto \max(\omega,T)^2$. This behavior is strikingly different from the electromagnetic response of a normal metal. Away from the critical point, the scaling functions for the dependence of the admittance on frequency and temperature are controlled by at most two parameters.

References

[1]. V. D. Kurilovich, C. Murthy, P. D. Kurilovich, B. van Heck, L. I. Glazman, and C. Nayak, Phys. Rev. B **104**, 014509 (2021).
[2]. C. Murthy, V. D. Kurilovich, P. D. Kurilovich, B. van Heck, L. I. Glazman, and C. Nayak, Phys. Rev. B **101**, 224501 (2020).

Mr. Ivan Jakovac

Effects of In-plane Stress on the Spin Order and Dynamics in Stoichiometrically Doped $La_{1.875}Ba_{0.125}CuO_4$

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Although static spin and charge stripes are ubiquitous in the cuprate superconductors, the coupling of the stripe formation mechanism to the low-temperature orthorhombic to tetragonal transition is drastically different. While the charge order (CO) in Eu-doped LSCO sets in well below [1], in 1/8-doped LBCO CO transition is decoupled only by hydrostatic pressure [2]. Remarkably, there is no insight into the spin order (SO) coupling mechanism, although the transition manifests clearly in NMR [3]. The orthorhombic distortion also has a profound effect on the cuprate superconductivity [4, 5] which makes NMR under uniaxial strain a unique method to resolve some of the outstanding questions.

We report an extensive ^{139}La and ^{17}O NMR study of the spin dynamics under uniaxial strain with the external magnetic field aligned along [001] direction to avoid breaking the four-fold symmetry of the CuO_2 planes. We find that even the moderate strain along [110] direction induces orthorhombic distortion which is detrimental to the formation of both SO and CO in the system . The ^{139}La NMR spin-lattice relaxation rate consequently decreases. The system also exhibits unusual scaling with the applied strain. In contrast, no discernible change in either or is found when the strain is applied in [100] direction.

We propose a free-energy model where the stripe formation is directly coupled to the orthorhombic distortion. We also applied a magnetic field in [110] direction to quench the spin degrees of freedom in CuO_2 plane. The field expectedly couples to the spin system and the observed effect of the [110] orthorhombic strain is substantially diminished.

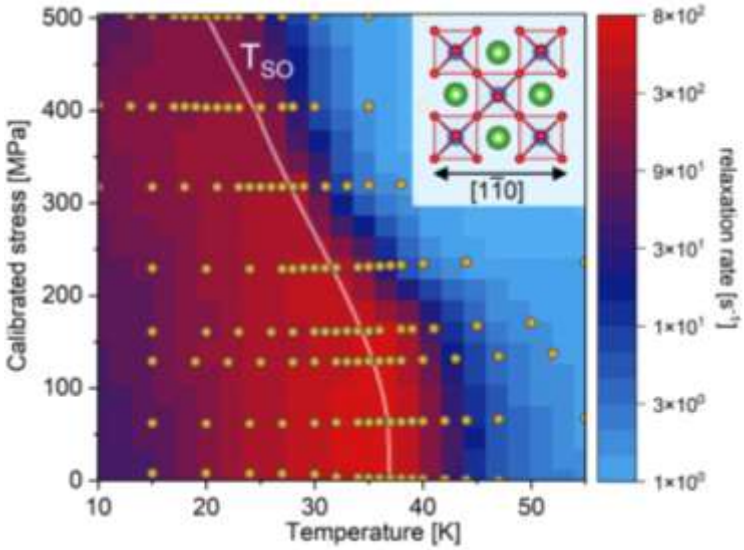

Fig. 1: *The interpolation of measured ^{139}La NMR relaxation rates (yellow points) in vicinity of the spin order transition.*

References

[1]. A. J. Achkar et al., Science **351**, 6273 (2016).
[2]. M. Hücker et al., Phys. Rev. Lett. **104**, 057004 (2010).
[3]. S.-H. Baek et al., Phys. Rev. B **92**, 155144 (2015).
[4]. N. Takeshita et al., J. Phys. Soc. Jpn. **73**(5), 1123 (2004).
[5]. Z. Guguchia et al., Phys. Rev. Lett. **125**, 097005 (2020).

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Dr. Giorgio Levy

Determination of a realistic tight-binding description of the electronic structure of $YBa_2Cu_3O_{6+\delta}$ from Angle-Resolved Photoemission Spectroscopy.

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The description of the normal state electronic structure of copper-based high temperature superconductors is challenging owing to the strong electronic correlations present in these materials. Indeed, Density Functional Theory (DFT) predicts a metallic behavior at half-filling (i.e. at zero hole doping); instead a ground state corresponding to a charge transfer insulator is observed. As the hole doping is increased, the discrepancy between the DFT electronic structure and the corresponding experimental one from Angle-resolved Photoemission Spectroscopy (ARPES) appears to improve. Despite this, a quantitative description by DFT is not completely achieved even in the overdoped regime, where Fermi-liquid-like behavior is observed, due to the strong renormalization still affecting band dispersion and quasiparticle excitations.

Starting from DFT [1], ~~Starting from DFT and the ARPES data presented in Ref. 1~~we~~, we~~ derive a set of Wannier orbitals~~–~~ to generate an effective tight-binding model that describes the band structure related to the CuO_2 planes as well as the CuO chains in $YBa_2Cu_3O_{6+\delta}$. Then b~~B~~ased on the ARPES electronic structure acquired on the charge-compensated polar surface of $YBa_2Cu_3O_{6+\delta}$ ~~[~~presented in Ref. 2~~]~~, we adjust the tight-binding parameters to obtain a realistic description starting from the very overdoped regime. We follow the doping evolution of the features associated to CuO_2 planes and CuO chains well into the underdoped regime, to extract the detailed variation of the model parameters. Our model could serve as a ~~realistic~~ springboard~~tarting point~~ for the quantitative interpretation of transport results.

References

[1] E. Pavarini, I. Dasgupta, T. Saha-Dasgupta, O. Jepsen, and O. K. Andersen, Phys. Rev. Lett. **87**, 047003 (2001).
[2] D. Fournier, G. Levy, Y. Pennec, J.L. McChesney, A. Bostwick, E. Rotenberg, R. Liang, W.N. Hardy, D.A.Bonn, I.S. Elfimov, and A. Damascelli ~~*et al.*~~, Nature Physics 6, 905 (2010).

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Dr. John Sous

Bipolaronic High-Temperature Superconductivity

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We present a simple model for phonon-mediated high-T_c superconductivity based on condensation of light bipolarons into a superfluid [1]. In contrast to the Holstein model in which phonons modulate the electron's onsite energy, we investigate the effects of phonons on electron hopping within the bond-Peierls model in which phonons on the bonds modulate electron hopping between sites. We employ a recently developed sign-problem-free quantum Monte Carlo approach [2] in order to compute bipolaron properties from which we calculate T_c in two dimensions, finding that it generically exceeds the upper bound based on Eliashberg theory. This establishes principles towards the design of high-T_c superconductors.

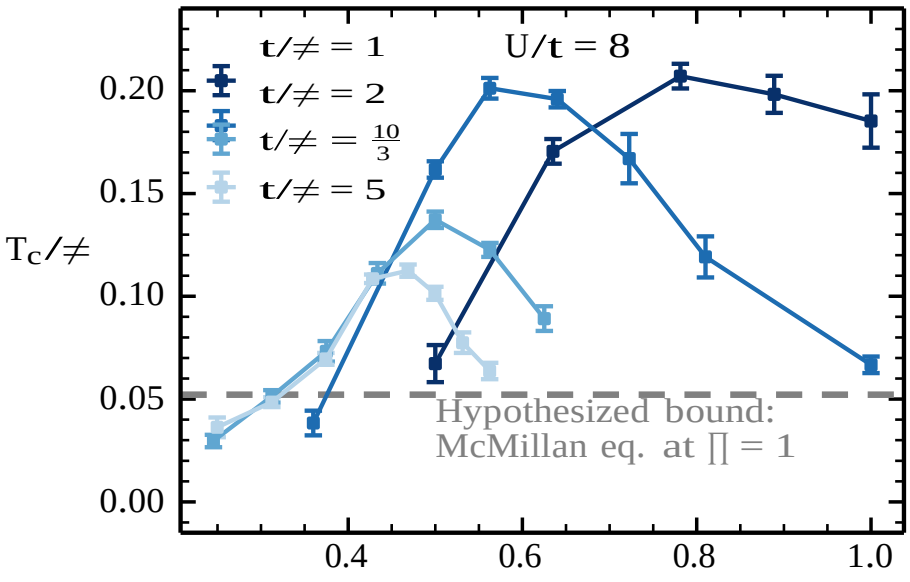

Fig. 1: *T_c in units of the phonon frequency Ω for different adiabaticity t/Ω at a Hubbard repulsion U = 8t as a function of the electron-phonon coupling λ computed from QMC simulations. We contrast the behavior of the bipolaronic superconductivity obtained in the Peierls model against the upper bound on T_c predicted from McMillan's phenomenological theory of strong-coupling superconductivity at the largest coupling, λ = 1, it is valid for (dashed gray line). This comparison illustrates that T_c of the bipolaronic superconductor exceeds the upper bound hypothesized for phonon-mediated superconductivity in the majority of the parameter space.*

References

[1]. C. Zhang, J. Sous, D. R. Reichman, M. Berciu, A. J. Millis, N. V. Prokof'ev, and B. V. Svistunov, to be submitted.

[2]. C. Zhang, N. V. Prokof'ev, and B. V. Svistunov, arXiv:2108.06725 (2021).

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Dr. Karol Flachbart

Search for Superconductivity in High Entropy Alloy Hydrides and Transition Metal Oxy-hydrides

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Superconductivity in hydrogen and hydrogen containing materials (hydrides) continues to attract researchers since many decades. Hydrogen, the lightest element of the periodic table, was predicted to be a room-temperature superconductor, albeit only at very high pressure, already in 1968. The same prediction is applicable to pressurized hydrogen-rich materials. The reason for this is that in some metal hydrides the chemical pre-compression from metal atoms combines with the experimentally applied pressure and enables to reach hydrogen densities in a range where its metallization can occur. In this context sulphur hydride, lanthanum hydride and carbonaceous sulphur hydride have very recently attracted a great deal of attention due to record high transition temperatures T_C reaching values up to room temperature at pressures above 250 GPa [1]. Superconductivity in this case arises due to the existence of hydrogen-dominated high-frequency vibrations (phonons) and their strong (electron-phonon) coupling to conduction electrons, and is therefore of conventional BCS-type. But, attempts to find hydrides with a high T_C at ambient pressure have not been successful. The highest T_c's observed in hydrides of Pd and Pd alloys do not exceed temperatures of the order of 15 - 17 K. And, as regards superconducting transition metals (M = Ti, V, Zr, Nb, Hf e.g.), it was shown that adding hydrogen into these metals usually leads to a reduction of their *Tc*. Moreover, to prepare hydrides with a higher H concentration, generally high hydrogen pressure has to be applied.
On the other hand, it has been reported that e.g. TiVZrNbHf high entropy alloys (HEA) are able to absorb rather large amounts of H, reaching a H/M ratio of ~2 [2]. Moreover, many of HEA based on Ti, V, Zr, Nb and Hf, exhibit superconductivity (see e.g. [3]). Thus, the influence of hydrogen on the superconducting properties of HEA, which are also promising hydrogen storage materials, represents an interesting subject of research. The same seems to apply for transition metal oxy-hydrides which can be prepared with different ratios of transition metal, hydrogen and oxygen (see e.g. [4]).
In our contribution we will present the influence of hydrogenation of TiVZrNbHf - based high entropy alloys on their superconducting properties, as well as the low temperature transport properties of yttrium and gadolinium based oxy-hydride thin films. The obtained experimental results will be analysed and discussed.

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References

[1]. E. Snider et al., Nature **586**, 373 (2020).
[2]. G. Ek et al., Inorganic Chem. **60**, 1124 (2021).
[3]. L. Sun, R. J. Cava, Phys. Rev. Mat. **3**, 090301 (2019).
[4]. A. Pishtshev et al., Crystal Growth and Design **19**, 2574 (2019).

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Mr. Nassim Derriche

Exploration of the Effect of Inter-orbital Hybridization on Lattice Instabilities

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Fermi surface nesting effects have largely been acclaimed as the mechanism resulting in lattice instabilities and the formation of charge and spin density waves as temperature is decreased. These concepts are mainly based on the discontinuities in the charge susceptibility represented by the bands crossing the Fermi energy. In 1D, this results in the familiar Peierls instability for a wave vector equal to 2kf. According to Peierls' work, the ground state of one-dimensional chains of hydrogen atoms at half filling is dimerized. In its original form, this argument should apply to other species such as lithium which also has a single half filled band crossing the Fermi energy, but ab initio density functional calculations predict that equally-spaced Li in a chain is not susceptible to lattice instabilities. We show that the root cause of this apparent failing of the Peierls model is due to its disregard of the form of the charge carrier wavefunction, notably of the presence of interatomic orbital hybridization. Calculating the charge density susceptibility for these systems while fully taking inter-orbital hybridization into account through a tight binding model leads to an elimination of the divergence in the charge susceptibility usually indicative of a lattice instability in 1D half filled band systems (shown in Figure 1 below). We also argue that this inter-orbital hybridization will in general strongly modify the charge susceptibility from the one obtained from considering only nesting conditions in higher dimensions.

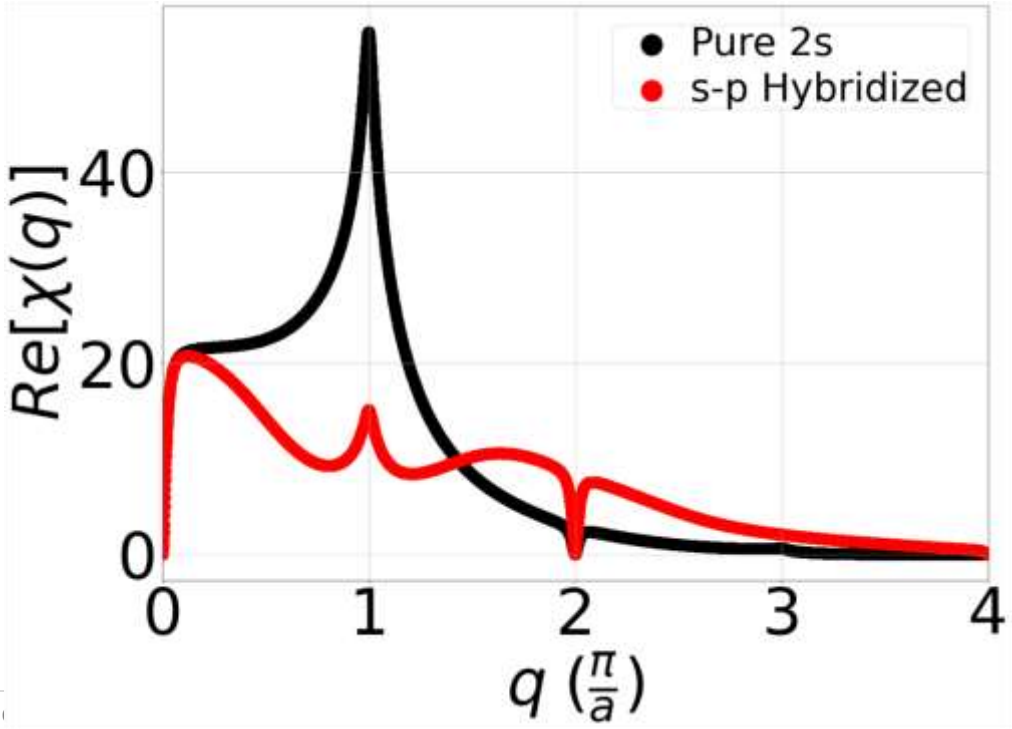

Fig. 1: *Real part of the charge susceptibility of an equally spaced, relaxed 1D chain of lithium using a tight binding model fitted to DFT band data. The black curve represents the susceptibility for a pure 2s state and the red curve results from the full expression of the susceptibility assuming an s-p hybridized wavefunction*

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Bernd Aichner

Vortex Matching Effects Above 2 T in YBCO Thin Films with Ultra-Dense Defect Patterns Created by Focused Helium Ion Irradiation

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The high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) combines intriguing electronic properties with low demands in cooling. One drawback in the fabrication of electronic devices from this material is its sensitivity to surface damage, limiting the application of conventional lithography techniques. A promising method to realize patterns smaller than 100 nm in YBCO is locally suppressing the critical temperature T_c by focused helium ion beam irradiation.
Various pinning landscapes are fabricated in YBCO thin films and their point defect profiles simulated with the program SRIM/TRIM. These defect densities are matched to experimentally determined critical temperature values, providing a local T_c landscape that can anchor magnetic flux quanta.
Experimentally, the collective vortex pinning can be identified by maxima of the critical current and minima of the resistivity at the matching field, at which every defect is occupied by one flux quantum.
Unprecedented high matching fields above 2 Tesla show the high resolution of this method, and its efficiency is revealed by angle-resolved electronic transport measurements [1]. Additionally, this technique enabled us to fabricate a complex structure based on a kagomé tiling that leads to magnetic caging of vortices and allows us to switch between two stable vortex configurations by changing the temperature. The experimental results are corroborated by molecular dynamic simulations [2].
Focused ion-beam irradiation in a helium ion microscope is an innovative method for realizing ultra-dense and complex nanostructures in high-T_c superconductors that can be used to pin and manipulate vortices. These findings may be a further step on the path to low-dissipative superconducting electronics.

References

[1]. B. Aichner, K. L. Mletschnig, B. Müller, M. Karrer, M. Dosmailov, J. D. Pedarnig, R. Kleiner, D. Koelle, W. Lang, Low Temp. Phys. **46**, 331 (2020).

[2]. B. Aichner, B. Müller, M. Karrer, V. Misko, F. Limberger, K. L. Mletschnig, M. Dosmailov, J. D. Pedarnig, F. Nori, R. Kleiner, D. Koelle, and W. Lang, ACS Appl. Nano Mater., **2**, 5108 (2019).

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Mrs. Lucas Correa, Msc Pedro Ferreira, Msc Leandro de Faria, Guilherme Bocalon, Thiago Francisco, Dr Mario da Luz, Dr Zachary Fisk, Dr. Milton Torikachivili, Dr Luiz Eleno, Dr Antonio Jefferson

Multiband superconductivity in the Pt-intercalate $ZrTe_2$

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Since the discovery of superconductivity in $ZrTe_2$ with copper intercalation and transition temperature (T_c) close to 9.7 K [1], a lot of interest has been given due to its multiband nature. In this work, we show results which suggest the existence of the new superconductor with platinum intercalation. Preliminary results show that it is possible to grow high quality crystals of with general stoichiometries of Pt_xZrTe_2 and the crystallographic and chemical qualities were attested by X-ray diffraction and energy dispersive spectroscopy (EDS) measurements. The crystal of composition $Pt_{0.02}ZrTe_2$ presents superconductivity with T_c close to 3.7 K. The results reveal the same behavior resembling a multiband nature observed in the Cu-intercalated compound. Results of magnetization as a function of temperature, resistivity and specific heat confirm this observation.

Reference

[1] - A. J. S. Machado, N. P. Baptista, B. S. De Lima, et al. Physical Review B 95, 144505 (2017).

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Superconductor-Metal-Insulator transitions in Y_xSi_{1-x} thin films.

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We report on the low temperature study of a-Y_xSi_{1-x} films. In these disordered thin films, transport properties are governed by the interplay between localization, Coulomb interactions and superconductivity.

Thick amorphous Y_xSi_{1-x} films (300 to 600 Å) were synthetized by electron-beam co-deposition from two separate sources under ultrahigh vacuum. As shown by AFM, SEM and EDX measurements, these films are very homogeneous both in composition and thickness with a film roughness of about 3 – 4 Å.

Furthermore, we have studied the temperature dependence of the resistance as a function of the stoichiometry of the alloy. It was observed that Y_xSi_{1-x} can exist in various states: insulating, metallic and superconducting. We have determined a preliminary phase diagram for the 3D Y_xSi_{1-x} alloy.

On the superconducting side, T_c evolves from 200 mK to 990 mK when the composition is varied from 22% to 32%. a-Y_xSi_{1-x} therefore belongs to this class of disordered superconductors that are of interest both to understand the fundamental mechanisms at play in these systems [1] and to engineer high kinetic inductance devices that can be used in quantum circuits [2,3]. On the insulating side, our preliminary results indicate a strong electron-phonon decoupling, which could be the signature of many-body localized states in this system (Fig. 1). a- Y_xSi_{1-x} is an interesting material to probe this theoretically-predicted new state and possibly evidence a finite-temperature insulator [4].

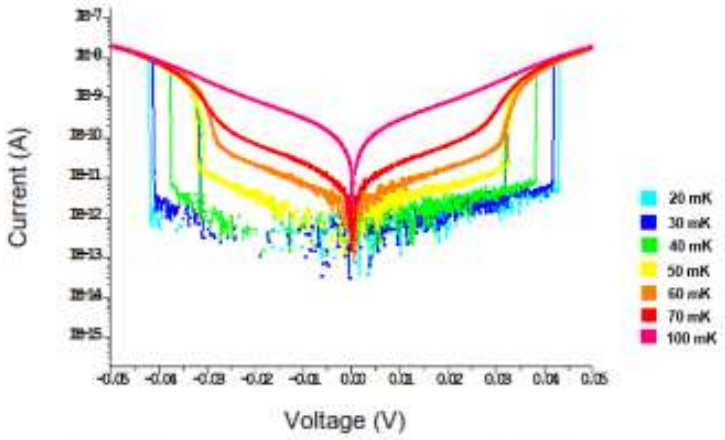

Fig. 1: *Hysteretic jumps in current-voltage characteristics at different temperatures.*

References

[1] Sacépé, B., Feigel'man, M. & Klapwijk Nature Physics volume 16, pages 734–746 (2020).
[2] B Douçot and L B Ioffe 2012 Rep. Prog. Phys. 75 072001.
[3] Benjamin A. Mazin, AIP Conference Proceedings1185, 135 (2009).
[4] D. M. Basko, I. L. Aleiner, and B. L. Altshuler, (2007). Phys. Rev. B 76, 052203 (2007)

Nathan Bassot, Dr. Pierre Toulemonde

Absence of superconductivity in bulk layered Ni^{+} doped nickelates

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The discovery of superconductivity below T_c ~ 15 K in thin films of doped infinite layer $Nd_{1-x}Sr_xNiO_2$ nickelate two years ago has generated an enormous interest in the condensed matter community because of their great similitude with cuprates [1]. Then, superconductivity was also shown with other rare earth elements, i.e. in La and Pr based systems with maximal T_c of 10 K and 14 K respectively [2,3]. And very recently, the quintuple-layer oxide $Nd_6Ni_5O_{12}$, with five NiO_2 layers separated with rare-earth fluorite blocking slabs and not doped with Sr or Ca, was successfully grown in thin films and found superconducting at T_c ~ 13 K [4].

In parallel with other groups in the world, we have studied the analogous bulk materials of such systems. We have synthesized good quality polycrystalline samples of $(Nd_{1-x}Sr_x)NiO_2$, $(Pr_{1-x}Sr_x)NiO_2$ series and more recently the $(Nd_{1-x}Ca_x)NiO_2$ series, doped with calcium (see left fig.), where the filling varies from d^9 to $d^{8.7}$. Using the same topotactic chemical process, we have also obtained the reduced forms of the n = 3 members of the $La_{n+1}Ni_nO_{3n+1}$ Ruddlesden-Popper series with Ln = Nd and Pr, i.e. $Nd_4Ni_3O_8$ and $Pr_4Ni_3O_8$ oxides. Those tri-layers systems have a lower bidimensional character and present a higher doping level at $d^{8.67}$. No superconductivity was found in any of these compounds but a spin-glass like and insulating behavior were observed at low temperature (see right fig.).

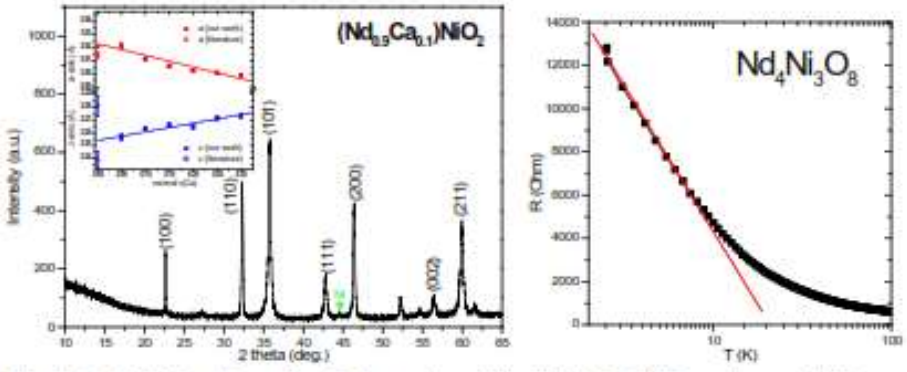

Fig. 1: *Left: XRD pattern of x=0.1 member of the $(Nd_{1-x}Ca_x)NiO_2$ series and lattice parameters versus x(Ca) doping (inset). Right: Temperature dependence of electrical resistivity of $Nd_4Ni_3O_8$ showing a Ln(T) behavior below 10 K.*

References

[1] Li, D. et al. Nature **572**, 624 (2019).
[2] M. Osada et al. Adv. Mater. **33**, 2104083 (2021) ; S.W. Zeng et al. arXiv: 2105.13492 (2021).
[3] M. Osada et al. Phys. Rev. Materials **4**, 121801(R) (2020).
[4] G.A. Pan et al. Nature Materials DOI: 10.1038/s41563-021-01142-9 (2021).

Mrs. Anita Eka Putri

Nano-Size Effect of Magnetic Properties on La_2CuO_4

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We are going to report the nano-size effect on magnetic and superconducting properties of the mother system of Cu-based high-T_C superconducting oxide, La_2CuO_4 (LCO), from the magnetic susceptibility measurement. LCO nanoparticles were synthesized by controlling the temperature and time. Figure 1 shows an example of the TEM image measured on the LCO nanoparticle, showing the size of the particle to be around 60 nm. Figure 2 shows the temperature dependence of the magnetic susceptibility measured on some LCO nanoparticles by using a Superconducting Quantum Interference Device (SQUID). No clear anomaly related to the antiferromagnetic transition of Cu spins was observed in the temperature dependence of the magnetic susceptibility. Instead, the Curie-Weiss up turn behavior at low temperatures was observed. In our presentation, more detailed characterizations of superconducting and magnetic properties of LCO nanoparticles will be reported [1].

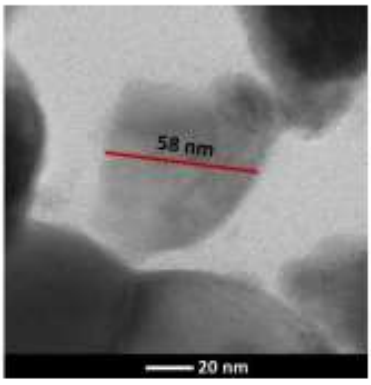

Fig. 1: *TEM images of La_2CuO_4 nanoparticles which synthesized using the sol-gel method.*

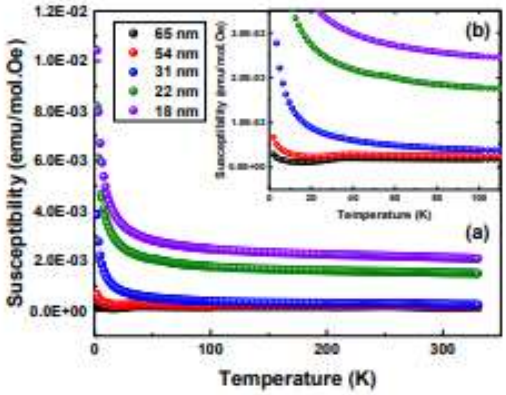

Fig. 2: *(a) Magnetic susceptibility of the temperature dependences on La_2CuO_4 with various particles size (H=1T; ZFC) (b) Insert figure which show the superconducting state.*

References

[1]. A. E. Putri *et al*. Mater. Sci. Forum, 1028, 44-49 (2021).

Dr. Amir-Abbas Haghighirad

Crystal Growth of Pnictide Superconductors with Novel Electronic Order and Elastic Response

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In this contribution, I will focus on three families of materials, $BaNi_2(As_{1-x}P_x)_2$ [1], $FeSe_{1-x}S_x$ [2] and $CrAs_{1-x}P_x$ [3], that show rich phase diagrams containing nearly degenerate electronic states. In these materials the electronic properties (e.g. nematicity, charge- and magnetic ordering) can be altered by tuning the interplay between the structural and electronic degrees of freedom, for instance by chemical doping or by applying hydrostatic pressure. The prerequisite for detailed experimental exploration, is the design and crystal growth of high-quality singly crystals.

We have been implementing chemical vapour transport and crystallisation by flux for the growth of the selected materials enabling us to study the phenomena of interest under well-controlled conditions. A series of high-quality single crystals of $BaNi_2(As_{1-x}P_x)_2$, $FeSe_{1-x}S_x$ and $CrAs_{1-x}P_x$ have been grown and characterised by chemical analysis, x-ray diffraction and magnetic measurements (see Figure 1). Furthermore, we have carefully monitored the doping dependence of various electronic phases in these materials and tracked the pressure-temperature dependent changes in the crystal structure.

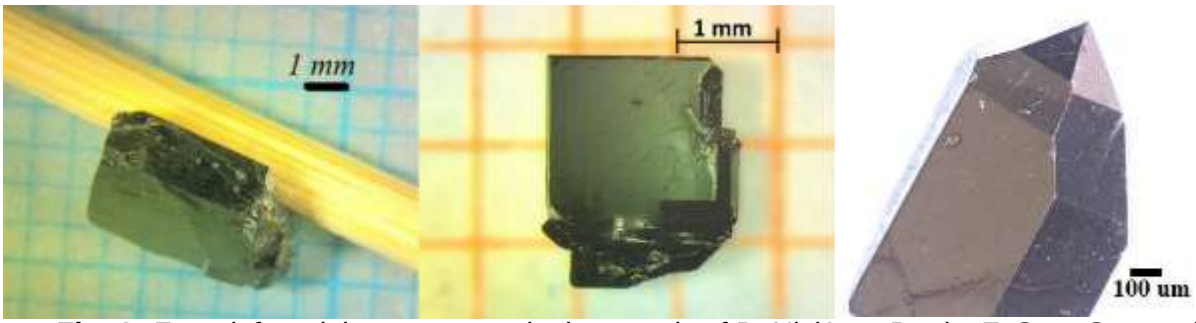

Fig. 1: *From left to right: as-grown single crystals of $BaNi_2(As_{0.94}P_{0.06})_2$, $FeSe_{0.88}S_{0.12}$ and $CrAs_{0.97}P_{0.03}$, respectively.*

References

[1]. Y. Yao et al., submitted (2021).
[2]. M. Watson et al., New Journal of Physics **19**, 103021 (2017).
[3]. K. Sen et al., Physical Review B **100**, 104301 (2019).

Dr. Thomas Baker

Tensor Network Simulation Methods for Superconducting Circuits

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Methods to simulate superconducting circuits for use as qubits in a quantum computer with tensor network solvers are discussed here. A new multi-targeted DMRG algorithm [1] is used to completely solve the fluxonium circuit [2]. The method is capable of handling hundreds of sites and scales well with the number of excitations solved for. This vastly outperforms exact diagonalization studies of the same systems. The method can be extended to other cases of interest and these will be discussed given time with the latest results.

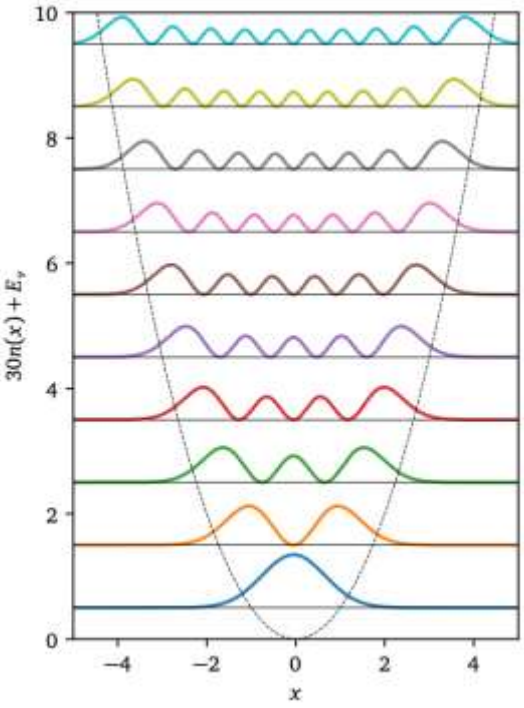

Fig. 1: ***Excitations from multi-targeted DMRG —*** *One-body density (shifted, dilated) of the excitations derived from the tensor network algorithm in [1] for the quantum harmonic oscillator. The algorithm performs equally well for superconducting circuits and their excitations [2].*

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T.E.B. thanks funding provided by the postdoctoral fellowship from Institut quantique (Université de Sherbrooke) and Institut Transdisciplinaire d'Information Quantique (INTRIQ). This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund (CFREF).

References

[1] T.E. Baker, et. al., “Direct solution of multiple excitations in a matrix product state with block Lanczos”, arxiv:2109.14114 (2021).

[2] A. Di Paolo, T.E. Baker, et. al. “Efficient modeling of superconductring quantum circuits with tensor networks” *npj Quantum Information* **7**, 11 (2021).

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Mr. Joern Bannies

Superconductivity and semimetallicity in rare-earth diantimonides

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The coexistence of superconductivity and semimetallicity in a single material is an intriguing yet rarely found combination of properties because superconductivity is conventionally related to a high density of states and electron-phonon coupling. Semimetals with their low carrier density defy the conventional BCS paradigm and may realize unconventional superconductivity. This connection is particularly interesting considering that the band structure of many semimetals is topologically non-trivial, possibly opening a way to realize topological superconductivity.
Recently, it was found that $CaSb_2$ is a superconducting semimetal [1]. Here, we investigate the related material $YbSb_2$, which was found to be superconducting below 1.3 K in previous studies [2,3] (see Fig. 1(a)). Using high-quality single crystals grown from self-flux, we focus on the electrical transport behavior in the context of semimetallicity (Fig. 1(b)). Based on magnetoresistance and Hall measurements, we find that $YbSb_2$ is a semimetal. Supported by DFT calculations, we relate the semimetallicity to the presence of distorted Sb square-nets in the crystal structure. The distorted Sb square-nets also lead to a non-trivial character of the low-energy electronic structure. In this regard, $YbSb_2$ closely resembles $CaSb_2$ and $LaSb_2$, both known to be superconducting semimetals. The occurrence of distorted Sb square-nets in all three materials suggests a crucial role of this structural feature for the coexistence of superconductivity and semimetallicity.

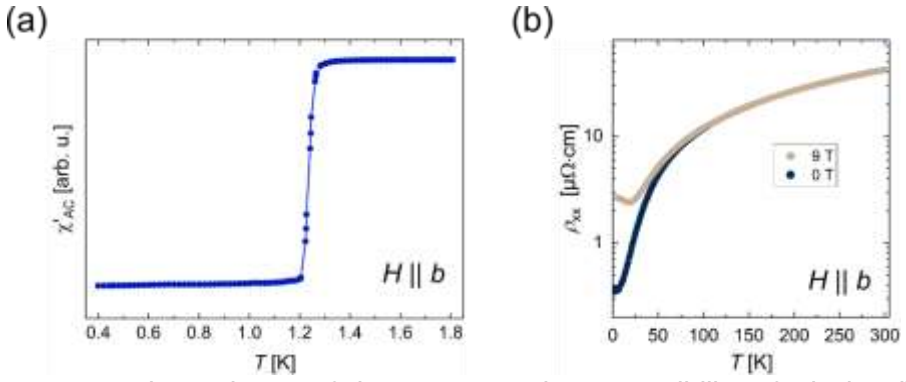

Fig. 1: (a) Temperature dependence of the ac magnetic susceptibility of $YbSb_2$. (b) Longitudinal resistivity ρ_{xx} as function of temperature in zero field and 9 T.

References

[1] M. Oudah, J. Bannies, D. A. Bonn and M. C. Aronson, arXiv:2106.06175 (2021).
[2] Y. Yamaguchi, S. Waki, and K. Mitsugi, J. Phys. Soc. Jpn. 56, 419 (1987).

[3] L. L. Zhao, S. Lausberg, H. Kim, M. A. Tanatar, M. Brando, R. Prozorov, and E. Morosan, Phys. Rev. B 85, 214526 (2012).

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Mr. Masahiro Hori

Quasicrystalline Topological Superconducting States in Ammann-Beenker Lattice

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Topological superconductivity (TSC) results in a non-trivial superconducting state characterized by a nonzero topological invariant in the bulk. The bulk-edge correspondence implies the existence of edge modes, which are zero-energy Majorana fermions appearing along the edges of the system in the case of TSC. There has been an experimental report on detecting Majorana fermions along the surfaces of a two-dimensional (2D) topological superconductor [1]. Theoretically, self-consistent studies of TSC have only been made for periodic crystals such as square lattice systems [2]. In such systems with translational symmetry, wavenumber is a good quantum number and Bloch's theorem can be utilized.

Recently, superconductivity has been experimentally realized in a quasicrystal [3]. We investigate TSC in 2D quasicrystals, Ammann-Beenker lattice (Fig. 1). The Ammann-Beenker lattice consists of a square and a rhombus, colored by red and blue, respectively, in Fig. 1. It has local eight-fold rotational symmetry and self-similarity. Due to the long-range order of the Ammann-Beenker lattice, there are Bragg peaks in pseudo-wavenumber space. Whether a stable TSC phase can exist in quasicrystals is not obvious, because of their aperiodic and self-similar structure.

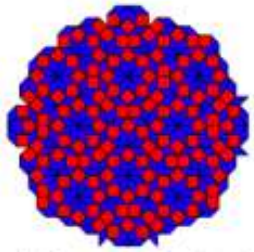

Fig. 1: *Ammann-Beenker lattice*

We solve the Bogoliubov-de Gennes equations on the tight-binding model for 2D TSC [4] generalized for quasicrystals self-consistently [2]. This model [4] describes 2D TSC with broken time-reversal symmetry as experimentally realized [1], whose topological nature is governed by the first Chern number. For quasicrystals, we calculate the Bott index as the topological invariant of the system, which is equivalent to the first Chern number in the absence of translational symmetry [5].

By solving for the superconducting order parameter self-consistently, we have found topological phase transitions in the Ammann-Beenker lattice for various electron density including half filling. There is a certain pseudo-wavenumber that is associated with the topological phase transition at half filling. Furthermore, the value of the pseudo-wavenumber is characterized by the self-similarity, local eight-fold rotational symmetry, and mirror symmetry of the Ammann-Beenker lattice.

References

[1]. G. C. Ménard *et al.*, Nat. Comm. **8**, 2040 (2017).
[2]. S. L. Goertzen, K. Tanaka, Y. Nagai, Phys. Rev. B **95**, 064509 (2017).
[3]. K. Kamiya *et al.*, Nat. Comm. **9**, 154 (2018).
[4]. M. Sato *et al.*, Phys. Rev. B **82**, 134521 (2010).
[5]. R. Ghadimi, T. Sugimoto, K. Tanaka, T. Tohyama, Phys. Rev. B **104**, 144511 (2021).

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Ms. Karin von Arx

The Fate of Charge Order in Overdoped La-based Cuprates

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To understand the mechanisms of superconductivity in strongly correlated systems, it is vital to consider the surrounding phases and their interplay. When the suppression of the superconducting transition temperature at the famous 1/8 doping was discovered by an appearance of charge order in hole doped cuprates, superconductivity and charge order were understood as adversaries [1]. However, since then charge order has been detected far away from 1/8 doping, even exceeding the doping associated to a pseudogap quantum critical point [2]. So far, the connection between superconductivity, charge order and the pseudogap phase remain unclarified. In La-based cuprates, several studies on the charge and spin order have recently lead to controversial results in the overdoped regime [2-4]. At the same time, resonant inelastic x-ray scattering (RIXS) has made it possible to detect weak charge correlations above its REXS onset temperature [5]. To address the open questions on the origin of charge order, its connection to the tentative pseudogap critical point and the spin order, we performed a thorough RIXS study of charge order in $La_{2-x}Sr_xCuO_4$ and $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ samples with dopings up to x = 0.25. The results provide a comprehensive and a systematic overview of the charge order in La-based cuprates and sheds light on the doping evolution of the incommensurability and correlation length, as well as the temperature dependence.

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Dr. Philip Dee

Multiorbital FLEX-Migdal Formalism for Superconductivity with Applications

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Several recent efforts[1-6] have aimed to describe aspects of iron-based and cuprate superconductivity using state-of-the-art implementations of self-consistent many-body approaches. For the iron-based systems, the focus has been on the combined roles of spin fluctuations and electron-phonon coupling as it pertains to the symmetry of the superconducting gap. Typically, resource requirements constrain calculations to just one or two orbitals leaving out valuable information in systems where three or more orbitals may be necessary, such as iron-based compounds. We present a multi-orbital implementation of a combined self-consistent FLEX+Migdal approximation where electrons and phonons are treated on equal footing. We will discuss the capabilities of such an approach, its limitations, and some of the results obtained thus far.

References

[1]. L. Rademaker *et al.*, New J. Phys **18**, 022001 (2016).
[2]. P. M. Dee *et al*., Phys. Rev. B **99**, 024514 (2019).
[3]. F. Schrodi *et al.*, Phys. Rev. B **102**, 180501(R) (2020).
[4]. L. Rademaker *et al*., Phys. Rev. B **103**, 144504 (2021).
[5]. F. Schrodi *et al.*, Phys. Rev. B **102**, 024503 (2021).
[6]. F. Schrodi *et al.*, Phys. Rev. B **104**, L140506 (2021).

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Prof. Peter Samuely

Ising Superconductivity in 3D Heavily Doped Transition Metal Dichalcogenides

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Recently, a new type of superconducting interaction – the Ising pairing – has been discovered in the atomically thin $NbSe_2$ [1]. The lack of crystal inversion symmetry in monolayer combined with strong spin-orbit coupling leads to an effective spin-orbit magnetic field which locks spins in the Cooper pairs and hinders the spin pair-breaking. This leads to anomalously high in-plane upper critical fields $B_{c2//ab}$ strongly violating the Pauli limit B_p. In the pure $NbSe_2$ the Ising superconductivity is strong only in the case of atomic monolayer, while adding layers rapidly suppress $B_{c2//ab}$ due to restoration of the inversion symmetry.
Here, we show that even more extreme in-plane $B_{c2//ab}$ fields exist in fully 3-dimensional misfit layer $(LaSe)_{1.14}(NbSe_2)$ and $(LaSe)_{1.14}(NbSe_2)_2$ single crystals with T_c = 1.23 K and 5.7 K, respectively [2]. Both misfits are characterized by a strong charge transfer from LaSe to $NbSe_2$. Our quasiparticle interference QPI STM measurements and DFT calculations show [3] that $(LaSe)_{1.14}(NbSe_2)_2$ is electronically equivalent to the highly doped $NbSe_2$ monolayer. Also the spin split Fermi surfaces around *K* and *K'* points in the Brillouin zone pointing to Ising superconductivity are observed. In the case of $(LaSe)_{1.14}(NbSe_2)$ compound even larger charge transfer happens as the electronic donor LaSe is supplying not two $NbSe_2$ layers but just one. It leads to further rigid band shift as compared with $(LaSe)_{1.14}(NbSe_2)_2$, pushing the Fermi surface more to the top of the $NbSe_2$ hole band with a larger spin splitting and proportionally larger Ising coupling. This explains extreme in-plane upper critical fields violating Pauli B_p ten times. The reason why the Ising coupling survives in our 3D crystals consisting of alternating insulating LaSe and (super)conducting $NbSe_2$ atomic layers will be discussed.

References

[1] X. Xi et al., Nat. Phys. **12**, 139 (2016).
[2] P. Samuely et al., Phys. Rev. B, accepted.

[3] R. T. Leriche et al., Adv. Funct. Mat. 2020, 2007706.
[4] O. Šofranko et al., to be published.

Thermodynamics and Order Parameter Fluctuations in the 2D t-J Model

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Thermodynamic properties of the 2D *t-J* model have been calculated for the full range of densities at *J/t* = 0.4 by using a 12th order high temperature expansion. For the thermodynamic properties the primary calculation is for the entropy[1]. From the entropy calculation other thermodynamic properties can be found from standard thermodynamic relations by taking density or temperature derivatives, or by integrating over temperature and using the known high temperature behavior from the high temperature series. Of most interest are the second derivatives of the free energy, particularly the density derivative of the entropy, , and quantities that can be calculated using that derivative. The thermodynamic properties match up with the parameter ranges where antiferromagnetic and d-wave pair fluctuations are found[2].

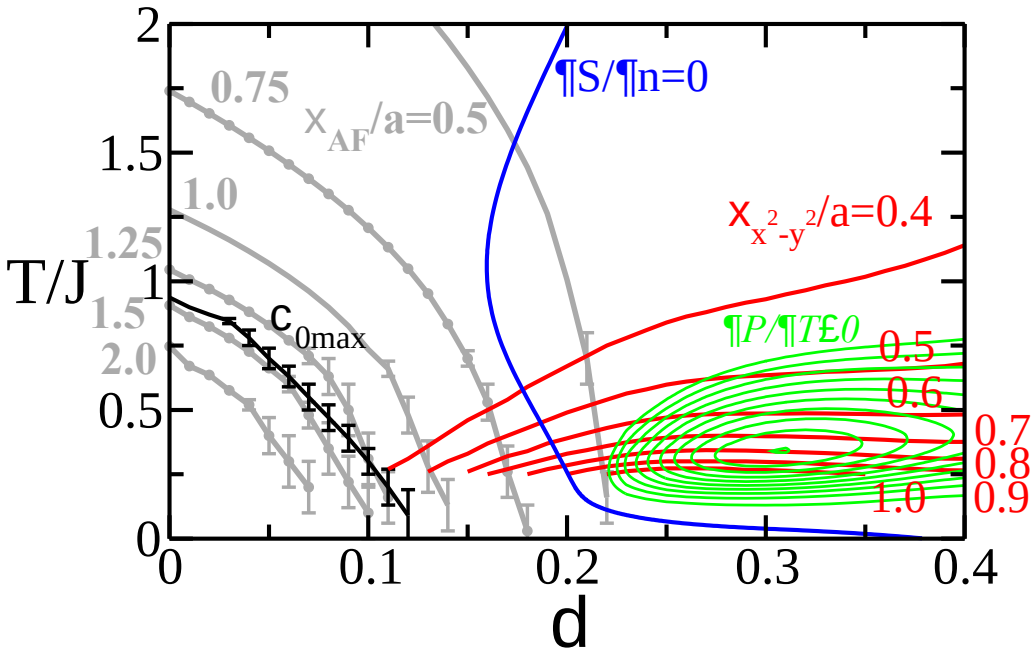

Fig. 1: Phase diagram, temperature vs. doping, for the 2D t-J model with J/t=0.4. The red curves are contours of fixed d-wave pair correlation length, the gray curves are contours of fixed antiferromagnetic correlation length. For both the scale is the lattice spacing. The black curve is the temperature maximum of the uniform spin susceptibility, a proxy for the pseudogap boundary. The green contours are where the temperature derivative of the pressure is negative, equivalent to a negative thermal expansion. The blue curve is where the entropy is a maximum as a function of density. At high temperatures where the entropy is purely configurational this is a line at . For

temperatures there is substantial deviation towards lower hole densities showing the effects of interactions and increasing correlations.

References

[1]. W. O. Putikka, J. Phys.: Conf. Series **640**, 012046 (2015).
[2]. W. O. Putikka and M. U. Luchini, Phys. Rev. Lett. **96**, 247001 (2006).

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Dr. Dita Puspita Sari

Superconductivity Nearby Quantum Spin Liquid States in Doped Organic Metal

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The hole-doped organic superconductor k-$(ET)_4Hg_{2.89}Br_8$ (k-HgBr) has been an important *bridge* between triangular ½-filled organics and squared doped cuprates system. Both k-HgBr and optimum-doped cuprate superconductor has the non-Fermi- liquid region above T_c. But, due to its triangular lattice, k-HgBr has been suspected as quantum spin liquid Mott insulator before being doped [1]. The pairing symmetry in the hole-doped ⬚-type organic superconductors, which is generally an anisotropic triangular lattice, were theoretically suggested as *d*-wave, like the cuprate's, but close to extended-*s*+*d* wave region [2]. Accordingly, we are going to report superconductivity in k-HgBr and possible spin liquid state in the sister Mott insulator compound, k- $(ET)_4Hg_{2.78}Cl_8$ (k-HgCl), by muon spin relaxation (μ^+SR). Figure 1 shows the good quality of our sample, measured by SQUID and μ^+SR. The superconducting sample has almost full-volume fraction. Before the zero-field μ^+SR, a transverse field of 25 Oe was applied for ~10 minutes to destroy the shielding field. This causes an increase of muon spin relaxation rate from the pinned vortices when the field is turned off, relating to the lower critical field, H_{c1}. Furthermore, the zero-field λ is temperature-independent down to 0.3 K. The μ^+ Knight-shift study in k-HgCl is going to be presented for the first time, compared with that of k-HgBr, discussing the high spin-fluctuations in the metallic state nearby superconductivity.

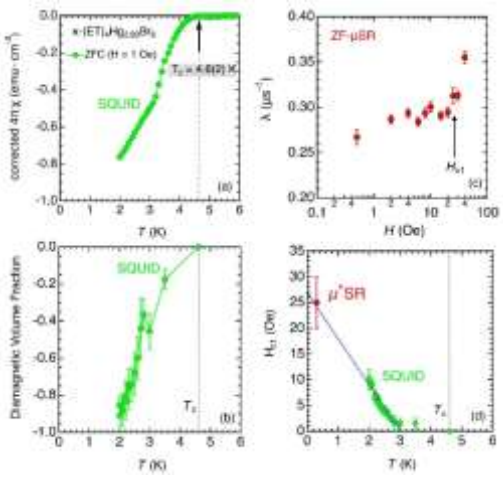

Fig. 1: (a) *Temperature dependence of diamagnetism and (b) SC volume fraction measured by SQUID. (c) Relaxation rate of ZF-μ^+SR time spectra after applying and then cutting off several transverse fields, H, from 2 to 40 Oe. (d) Temperature dependence of H_{c1} measured by SQUID down to 2 K compared with that from the μ^+SR measurement.*

References

[1]. H. Oike, et al., Nat. Com. **8**, 756 (2017).
[2]. H. Watanabe et al., Nat. Com. **10**, 3167 (2019).

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Miss Jixun Ding

Transport in the Hubbard Model: Critically Examining the Cuprates

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The normal state of hole-doped cuprate superconductors is host to a wide variety of anomalous thermodynamic, magnetic, and transport properties. Particularly mysterious and universal is the strange metal phase, which exhibits T-linear resistivity exceeding the MIR bound, strongly temperature- and doping-dependent Hall conductivity, and scale-invariant magnetoresistance. Strange metal phenomenology indicates the breakdown of Fermi liquid theory and Boltzman transport, and calls into question the nature of charge and heat carriers in the absence of long-lived quasiparticles. Therefore, it is important to investigate transport and scrutinize Fermi liquid predictions in strongly correlated systems.

We use the numerically exact and unbiased determinant quantum Monte Carlo (DQMC) method to study the single-band Hubbard model on a two-dimensional square lattice, and directly obtain thermal and electronic transport coefficients using the Kubo formula without simplifying assumptions. We find a correspondence between the sign of the Hall coefficient and the location of the spectral peak A(k,w=0) [1,2], clarify the nature of heat transport at half-filling [3], and uncover qualitatively discrepant behavior between the charge diffusivity and thermal diffusivity in the strange metallic regime. Finally, we include effects of an orbital magnetic field, and investigate thermodynamic [4] and magneto-transport properties of the resulting model. We discuss the implications of our results for future theoretical and experimental efforts on cuprate superconductors.

References

[1]. W. O. Wang, *et al.*, npj Quantum Materials 5, 51 (2020).
[2]. W. O. Wang, *et al.*, Phys. Rev. Research 3, 033033 (2021).
[3]. W. O. Wang, *et al.*, arXiv:2109.01119 (2021).
[4]. J. K. Ding, *et al.*, arXiv:2111.09258 (2021).

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Mr. Timothy Branch

Microwave Response of Strongly Demagnetized Anisotropic Superconducting Samples

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Understanding the electromagnetic response of superconducting samples in magnetic fields is necessary to interpret the results of radio and microwave frequency experiments. A common geometry used involves aligning a platelet sample perpendicular to the applied field; this, however, induces strong demagnetizing effects that are still the subject of ongoing study because of the difficulty of modelling field concentrations near sharp edges and corners. Furthermore, in superconductors exhibiting non-local electrodynamics[1], the surface impedance associated with each face may be different, meaning the weighted contributions from different sample faces to the apparent surface impedance become harder to disentangle.

To support the interpretation of such spectroscopic measurements, the microwave magnetic response of strongly demagnetized superconducting samples was studied[2] using numerical simulations in COMSOL Multiphysics. Here we present the results from these studies, and how they can be used to determine the face-dependent surface impedances of superconducting samples from microwave spectroscopy measurements.

References

[1] Kosztin, PRL 79, 135 (1997)
[2] Branch T., Master's Thesis (2021)

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Dr. Byung-Hyuk Jun

Effects of Electron Beam Irradiation on the Critical Current Characteristics of MgB_2 Superconductor

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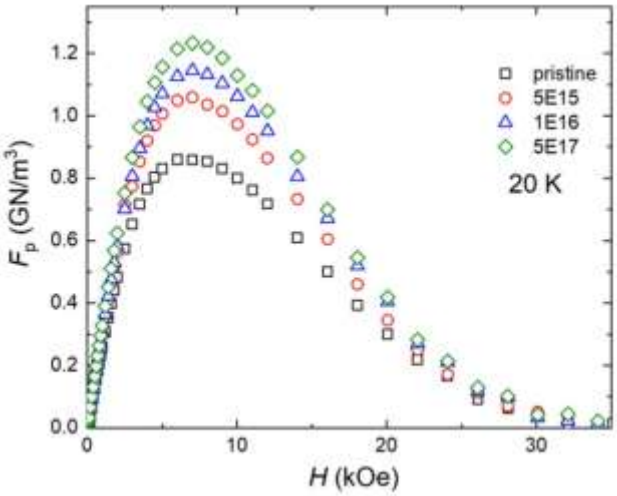
When a defect is generated inside the superconductor through neutron, proton, electron and ion irradiation etc., critical current characteristics under the magnetic field can be improved. When the radiation particles are irradiated to the superconductor, fine defects acting as a magnetic flux pinning center are uniformly generated. Among these radiation particles, electrons have the advantage of having no radiation problem and being able to have a large capacity, so they are suitable for commercialization purposes to improve critical current.

This research investigated the changes in critical current characteristics by irradiating MgB_2 superconductors (wire, bulk) using an electron beam. The electron beam energy was 2.5 MeV (@ 5 mA), and the irradiation dose was changed from 1E15 to 5E17 e/cm^2. For MgB_2 wire, the critical current density tended to increase in all magnetic field areas as the dose increased. The critical current density by MPMS at the dose of 5E17 e/cm^2 and magnetic field of 2 T increased from 108.8 to 156.5 kA/cm^2 (44% increase) and from 14.9 to 20.9 kA/cm^2 (40% increase), respectively, at 4.2 and 20 K. In addition, it was found that as the dose increased, the magnetic flux pinning force density (F_p) increased. That is, the maximum $F_{p,max}$ increased from 2.66 to 3.75 GN/m^3 and from 0.86 to 1.23 GN/m^3, respectively, at 4.2 and 20 K. This shows that irradiation defects are formed in MgB_2 by electron beam irradiation, thereby blocking the movement of the voltex inside MgB_2 and increasing the critical current density. As the radiation dose increased, the maximum value of the flux pinning force density increased, and at the same time, the critical current density increased. As the dose increased, the full width at half maximum (FWHM) tended to increase. Such an increase in FWHM is caused by a deterioration in crystallinity due to an increase in fine defects in the superconductor by the irradiation, thereby improving critical current characteristics. These results show that irradiation defects generated by electron beam can act as magnetic flux pinning points that can improve the critical current density of the MgB_2 superconductor.



This work was supported by the National Research Foundation Grant (No. 2020M2D8A2047959) from the Ministry of Science and ICT (MSIT) of Republic of Korea. The manufacturing of MgB_2 wire for irradiation and the measurement of critical characteristics were performed by Sam Dong Co., Ltd. and Sungkyunkwan University, respectively, which are joint research institutes.

Fig. 1: *Flux pinning force density versus magnetic field at 20 K depending on irradiation dose.*

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Mr. Greg Wallace

Investigating the Competing Orders of the Cuprates Using Hydrostatic and Uniaxial Pressure

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Chemical doping is widely used to tune the relative strengths of the competing orders (superconductivity (SC), charge density wave (CDW), pseudogap (PG)) present in the cuprates. The primary effect is the addition of holes to the CuO_2 planes. Both hydrostatic pressure and uniaxial strain can also be used to tune the strengths of the competing orders, but the mechanism for how they do so is unclear. One effect of increased hydrostatic pressure is an increase in charge transfer from the CuO_2. However, changes in structure and Fermiology are likely to have a significant impact on competing orders as well. For example, the increased orbital overlap caused by hydrostatic pressure should push the system away from the insulating state, reducing its 'Mottness'. Here the effect of charge transfer on the doping of $YBa_2Cu_3O_{6+x}$ (Y123) is studied by measuring the thermopower under hydrostatic pressure up to 3 GPa. The additional impact of chain oxygen ordering on the charge transfer process is determined by measuring the thermopower over time after pressurisation and depressurisation.

In the underdoped cuprates a sign change in the Hall coefficient is observed that is believed to be caused by a reconstruction of the Fermi Surface. However, the origin of this reconstruction is unclear. One possibility is that the reconstruction is driven by one of the observed CDWs; there is a biaxial 2D CDW and an additional uniaxial 3D CDW that emerges in a high magnetic field. Recently, it was shown, using x-ray scattering, that uniaxial pressure along the *a*-axis could be used to reduce T_c as well as stabilize the uniaxial 3D CDW when T_c was sufficiently suppressed. Here the effect of uniaxial strain on the Hall effect has been measured in high magnetic fields up to 35 T in order to shed light on the relationship between the 3D CDW, the sign change in the Hall coefficient, and T_c.

Mrs. Sylwia Gutowska

Phonon Engineering and Superconductivity in Laves Phases

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The Laves phase compounds is a widespread family of AB_2 compounds characterized by the complex *fcc* ($MgCu_2$-type) or hexagonal layered crystal structure. Their physical properties like high hardness or corrosion resistance lead to the possible applications in industry and the question why this specific type of crystal structure is so popular among the intermetallic compounds is still a matter of study.

Here we focus on superconductivity of those materials on the example of $SrIr_2$ and $SrRh_2$ *fcc* Laves compounds with critical temperatures T_c=6.1 K and 4.6 K respectively. What caught our attention is that their crystal structure can be seen as the *fcc* structure of Ir or Rh with half of close-packed atomic tetrahedrons replaced by Sr (Fig. 1.). Despite of this similarity, the question arises, why their critical temperature is much higher than of Ir and Rh (T_c=0.3 K and 0.003 K respectively)?

In order to find the answer, we study the $SrIr_2$ and $SrRh_2$ in both experimental and theoretical ways. The experimentally measured large jump of heat capacity at T_c shows a strong electron-phonon coupling (EPC) in those materials, in contrast to weakly-coupled Ir and Rh, which is also confirmed in our calculations of the phonon linewidths and EPC functions. Moreover, the transition from weak to strong coupling is not due to the changes in the electronic structure, but is induced by the changes in propagation of phonons, having much lower frequency than in metallic Ir/Rh. But what is the origin of this lowering of frequency?

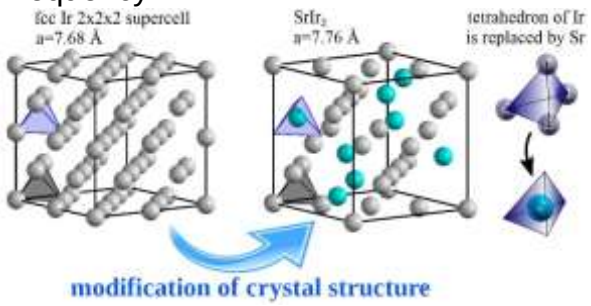

Fig. 1.

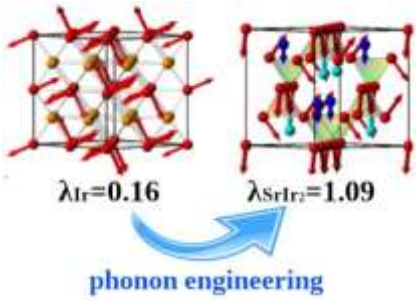

Fig. 2.

By analysis of phonon modes and force constants in real space we found that it is due to changes in the geometry of Ir tetrahedron network (Fig. 1) which affects phonon displacement patterns (Fig. 2), weakens restoring force leading to lower frequency of phonons. This effect, labelled as phonon engineering, leads to T_c much higher than in the case of Ir. In addition, we explain why $SrIr_2$ has a higher T_c than $SrRh_2$ and reveal the key role of spin-orbit coupling in stability of these compounds.

Finally, we examine the proposed mechanism in the case of hexagonal Laves phases using Osmium-based compounds as an example.

The research was supported by the National Science Center (Poland), Project No. 2017/26/E/ST3/00119 and by the EU Project POWR.03.02.00-00-I004/16.

References

[1] Sylwia Gutowska, et al. Phys. Rev. B **104**, 05450 (2021)

Dr. Tadashi Machida

Zeeman effects on Yu-Shiba-Russinov states

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A magnetic impurity in a superconductor locally disrupts the superconductivity due to the exchange interaction between the impurity spin and an itinerant electron, forming so-called Yu-Shiba-Russinov (YSR) bound states in the superconducting gap. Upon increasing the exchange interaction, the YSR state undergoes a quantum phase transition from the spin-doublet to the singlet ground states [1,2]. Although vigorous scanning tunneling microscopy (STM) experiments have been performed to distinguish these two states [3-6], an unambiguous way has not yet been established because tunneling spectra are indistinguishable between the two states. Here we demonstrate that these two ground states exhibit distinct Zeeman effects in a magnetic field. By using ultra-low temperature STM [7], we investigated a tunneling junction between Cu(111) surface and a superconducting niobium tip decorated by a single Fe atom. Depending on the condition of the Fe adsorbate, the YSR state either splits or shifts, signifying the singlet or doublet ground states, respectively (Fig. 1). We also found that the magnetic field dependence of the Zeeman shift systematically deviates from the linear behavior depending on the YSR-state energy at 0 T. These findings make it possible to discriminate the two different YSR states and pave the way for high-resolution spin-polarized spectroscopy [8] and quantum computations [9].

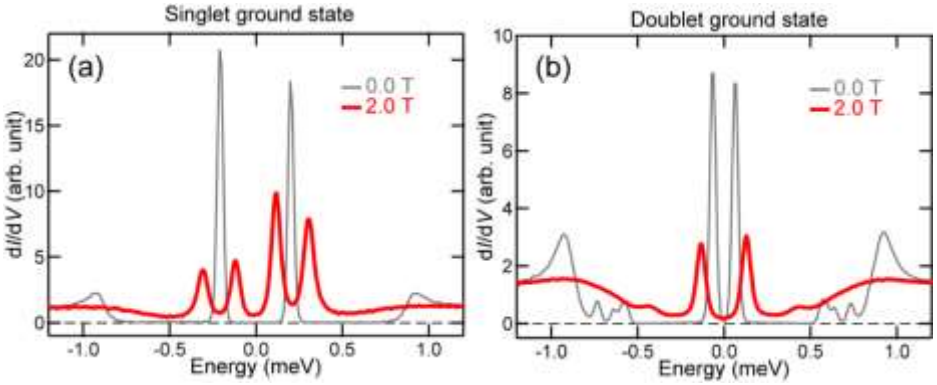

Fig. 1: *Tunneling spectra in the singlet (a) and doublet (b) ground states. Gray and red lines represent the spectra at 0 T and 2 T, respectively.*

References

[1] T. Matsuura, Prog. Theor. Phys., **57**, 1823 (1977).

[2] K. Satori, *et al*, J. Phys. Soc. Jpn. **61**, 3239 (1992).
[3] K. J. Franke, *et al*, Science **332**, 940 (2011)
[4] Y.-h. Zhang, *et al*., Nat. Commun. **4**, 2110 (2013)
[5] N. Hatter, *et al*., Nat. Commun. **8**, 2016 (2017)
[6] H. Huang, *et al*., Commun. Phys. 3, 199 (2020)
[7] T. Machida, *et al*, Rev. Sci. Instrum. **89**, 093707 (2018).
[8] L. Schneider, *et al*, Sci. Adv. **7**, eabd7302 (2021).
[9] A. Mishra, *et al*, arXiv:2106.01188 (2021).

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Dr. Alberto Nocera

Liquids of Peierls bipolarons offer an alternative route to high-T_c superconductivity

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The search for alternative microscopic mechanisms for high-T_c superconductivity has recently stimulated a renewed interest in the study of bipolarons—bound states of two polarons, where a polaron is an electron dressed by a cloud of phonons—in the presence of different forms of electron-lattice coupling [1]. Using the density matrix renormalization group (DMRG) method in one dimensional clusters, I show that the Peierls electron-phonon coupling, which describes the modulation of the electron hopping by lattice distortions (Fig.1a), gives rise to a liquid of strongly bound bipolarons which remain stable against phase separation up to finite electronic densities and strong electron-phonon interaction strengths (Fig.1b) [2]. This behavior is in striking contrast with the more studied Holstein and Fröhlich models, where bipolarons become increasingly heavy at stronger couplings and phase separation sets in at weak electron-phonon couplings for low electronic densities. Finally, I will show that similar results hold in coupled chain clusters, suggesting that Peierls bipolaron liquids can open a viable path to high-T_c superconductivity based on a bipolaronic mechanism in higher dimensions [3].

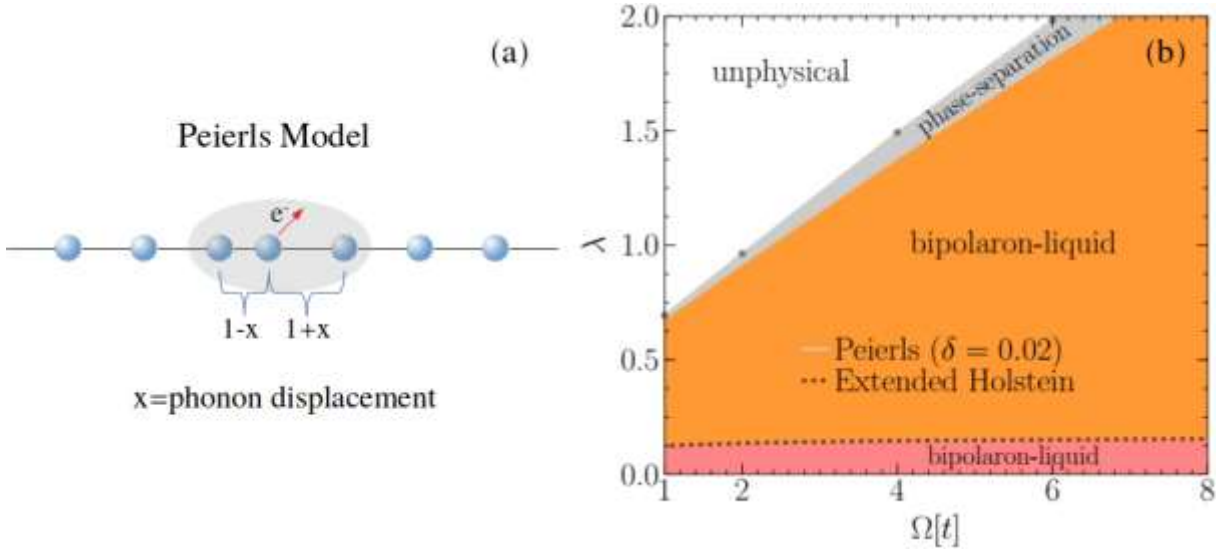

Fig. 1: (a) Peierls model of electron-phonon coupling. (b) Phase Diagram as a function of electron-phonon interaction strengths λ and phonon frequencies Ω at finite electron concentration obtained using the DMRG method.

References

[1] J. Sous *et al.*, Phys. Rev. Lett. **121**, 247001 (2018).
[2] A. Nocera *et al.*, Phys. Rev. B **104**, L201109 (2021).
[3] M. Naamneh et al. arXiv:1808.06135 [cond-mat.supr-con] (2018)

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Prof. Jiunn-Yuan Lin

An Emergent Quasi-2D Metallic State Derived from the Mott Insulator Framework

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Recent quasi-2D systems with judicious exploitation of the atomic monolayer or few-layer architecture exhibit unprecedented physical properties that challenge the conventional wisdom on condensed matter. Here we show that infinite layer $SrCuO_2$ (SCO), a topical cuprate Mott insulator, can manifest an unexpected metallic state in the quasi-2D limit when SCO is simply grown on TiO_2-terminated $SrTiO_3$ (STO) substrates. The sheet resistance does not comform to Landau's Fermi liquid paradigm. Hard x-ray core-level photoemission spectra demonstrated a definite Fermi level of the hole doped metal, and the soft x-ray absorption spectroscopy revealed features analogous to those of a doped Mott insulator. The key element of hole doping is not at the interface between SCO and STO, but comes from an emergent transient layer(s) between the chain-type and planar-type structures within the SCO sector as implied by an energy scan of x-ray Laue nano-diffraction.

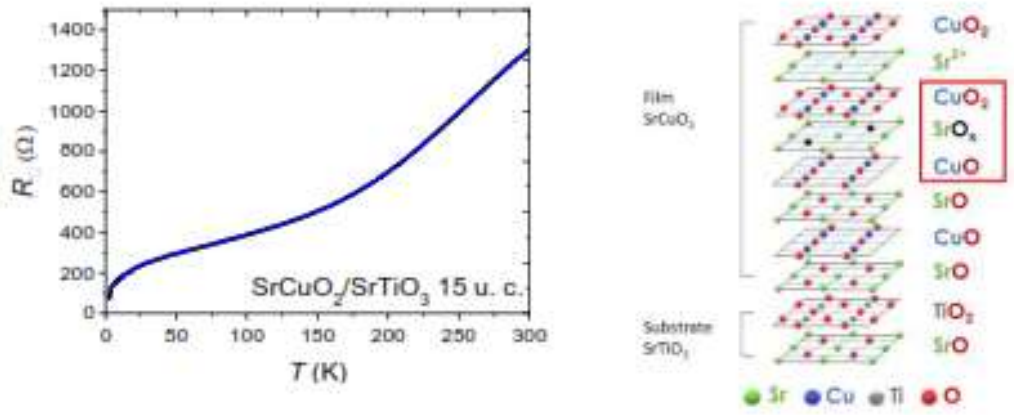

Fig. 1: *Left: Sheet resistance $R_\square(T)$ of a 15 u. c. SCO/STO. Right:* ***Origin of the metallic state.*** *Schematic of layered SCO/STO structure. The metallic region and the doping mechanism are highlighted with the block.*

Ms. Arushi .

Type-I Superconductivity in a Topological Superconductor, Pb_2Pd

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In recent years, the discovery and study of unconventional superconductors have seen a surge from both experimental and theoretical perspectives. Among different unconventional superconductors, topological superconductors form an essential subclass as they are proposed to possess unconventional, odd parity superconducting gap function. It not only enriches the existing theoretical framework of unconventional superconductivity but also provides a background for investigations on low energy excitations, Majorana fermions which have potential applications in fault-tolerant quantum computation [1]. In order to realize a topological superconducting state, strong spin-orbital coupling (SOC) is considered one of the necessary ingredients [2]. Superconducting compounds containing heavy atomic number (Z) elements are known to have strong SOC since the strength of SOC is proportional to Z^4. Such superconducting materials can also be of potential importance to realize the most desired, intrinsic topological superconductivity.
In this regard, we have thoroughly investigated the superconducting properties in a single crystal of Pb_2Pd consisting of high SOC (due to the presence of two heavy elements Pb, Pd) and is proposed as a topological superconducting candidate based on the Z_2 invariant of normal state band structure [3]. Pb_2Pd demonstrate type I superconductivity, and until now, this feature remained unexplored, although superconductivity has been known in this compound since 1962 [4]. Electrical transport, magnetization and specific heat measurements confirm bulk superconductivity below the transition temperature, T_C = 3.0 ± 0.1 K. To confirm the type I nature of Pb_2Pd, a microscopic technique known as muon spin rotation and relaxation (μSR) was employed together with the magnetization measurements. Zero- field measurements confirm the presence of time-reversal symmetry (TRS) on entering the superconducting state of Pb_2Pd. Therefore, the microscopic measurement suggests type I nature with TRS preserved topological superconductivity in Pb_2Pd.

References

[1] J. Alicea, Y. Oreg, G. Refael, F. von Oppen, M. P. A. Fisher, Nature Physics 7, **412** (2011). [2] M. Sato, Y. Ando, Rep. Prog. Phys. 80, **076501** (2017).
[3] http://www.physics.rutgers.edu/~dhv/pubs/archive/nv_pdpb/pap.pdf
[4] M. F. Gendron, R. E. Jones, J. Phys. Chem. Solids 23, **405** (1962).

Allan Gonzaga, Fellipe Carneiro, Eduardo Bittar

Peak Effect in the Superconductor $La_3Co_4Sn_{13}$

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The $R_3T_4X_{13}$ family of superconductors, where R is a rare-earth or alkaline element, T a transition metal, and X a group-III or group-IV element, is known to exhibit reentrant superconductivity in the presence of an external magnetic field [1,2]. This reentrant superconductivity, also called peak effect, is characterized by an electrical resistivity peak caused by the increase in critical density current within the superconducting state near the upper critical field H_{c2}. In this work, we study the peak effect in $La_3Co_4Sn_{13}$ single crystals through electrical transport measurements. Electrical resistivity measurements were performed as a function of temperature, magnetic field, and angle variation in different crystalline orientations (Fig. 1). We study this phenomenon based on the Lorentz forces that will act on the magnetic vortices for each measured conformation.

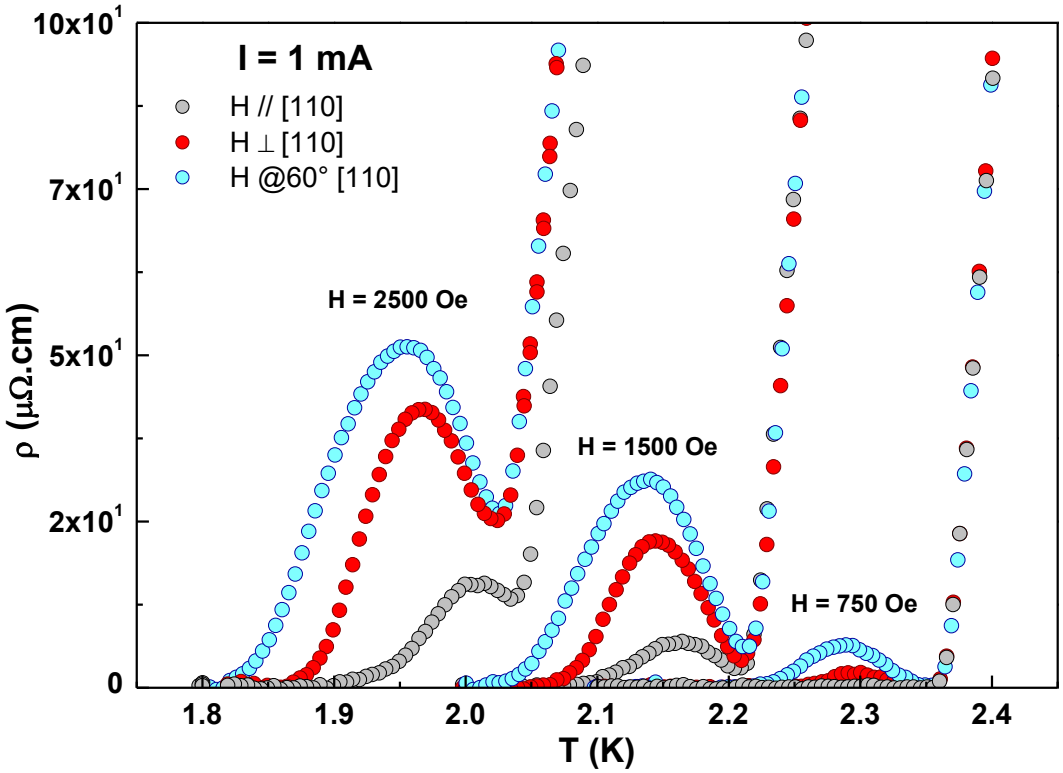

Fig. 1: *Temperature-dependent electrical resistivity of $La_3Co_4Sn_{13}$ single-crystal at different magnetic fields and orientations.*

References

[1] C. V. Tomy, G. Balakrishnan, and McK. Paul, Phys. Rev. B **56**, 8346 (1997).
[2] Z. F. Weng, M. Smidman, G. M. Pang, O. Prakash, Y. Chen, Y. J. Zhang, S. Ramakrishnan, and H. Q. Yuan, Phys. Rev. B 95, 184501 (2017).

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Mr. Prashant Chauhan

Abstract Title: Low Energy Spectroscopy of Topological Superconductor Candidates

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Topological superconductors can host Majorana modes which have possible applications in quantum information processing. Most of the topological superconductor candidates superconduct at low temperatures, which puts their superconducting gap in the microwave and THz range making the spectroscopic tools at these scales very useful for studying them. Here, I review our work in the Armitage lab utilizing low-energy optical spectroscopy techniques like time-domain-THz spectroscopy and microwave cavity resonators to study the properties of various topological superconductor candidates. Terahertz spectroscopy was used to elaborate on the nature of the superconducting gap and the origin of superconductivity in a time-reversal symmetry-breaking superconductor Bi/Ni bilayer heterostructure. Similarly, crystalline $PdPb_2$ shows anomalous transport properties and unusual temperature dependence of microwave surface impedance measured using a cavity resonator. By ruling out disorder as an origin of this behavior through extensive sample characterization, we determine $PdPb_2$ to be a candidate topological superconductor with a fully gapped bulk and normal fluid surface, consistent with Majorana surface states. Lastly, we study normal and superconducting state properties of two-dimensional electron gas (2DEG) in InAs quantum well proximitized by aluminum which is a promising platform for topological qubits based on Majorana zero modes using magneto-terahertz spectroscopy.

References

[1]. Chauhan *et al.* Phys. Rev. Lett. 122, 017002 (2019)

Charge transfer of the FeSe monolayer and $SrTiO_3$

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The FeSe monolayer on $SrTiO_3$ (STO) has a higher superconducting T_c than its bulk counterpart and exhibits many unique characteristics such as missing hole pockets at the Brillouin zone center and replica bands in photoemission experiments, implying a distinct low-energy physics occurring in the FeSe overlayer. Despite a decade of rigorous research, the reason for the monolayer T_c increase remains mysterious. One consensus reached to date is that the modulation doping of FeSe by impurities in the STO substrate is critical. Monitoring the T_c change with a variable carrier density would provide valuable information for the electron pairing itself and the importance of interlayer interactions. However, varying the carrier density via the modulation doping method is challenging, and many groups have reported similar doping levels. We have developed the theory underlying the charge transfer at the FeSe/STO interface and discovered the key factor limiting the FeSe doping level, which provides an experimental pathway to control the carrier density of the FeSe monolayer via the modulation doping. Besides the electron doping, we also find that the induced electric field crossing the interface breaks the inverse symmetry of the FeSe overlayer and interacts strongly with the Fe spin depending on the FeSe magnetic structure type.

References

[1]. F. Li, I. Elfimov, and G. Sawatzky, to be published.

Prof. Enrique Munoz

Monopole versus spherical harmonic superconductors: Topological repulsion, coexistence, and stability

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The monopole harmonic superconductor (SC), proposed in doped Weyl semimetals as a pairing between the Fermi surfaces enclosing the Weyl points, is rather unusual, as it features the monopole charge inherited from the parent metallic phase. However, this state can compete with more conventional spherical harmonic pairings, such as an *s* wave. We here demonstrate [1], within the framework of the weak-coupling mean- field BCS theory, that the monopole and a conventional spherical harmonic SC quite generically coexist, while the repulsion can take place when the absolute value of the monopole charge matches the angular momentum quantum number of the spherical harmonic. As we show, this feature is a direct consequence of the topological nature of the monopole SC, and we dub it *topological repulsion*. We illustrate the above principle with the example of the conventional *s*- and (*px* ± *i py*)-wave pairings competing with the monopole SC $Y_{-1,1,0}(\theta,\varphi)$, which coexist in a finite region of the parameter space and repel, respectively. Furthermore, the *s*-wave pairing is more stable both when the chemical potentials at the nodes are unequal and in the presence of pointlike charged impurities. Since the phase transition is discontinuous, close to the phase boundary, we predict that the Majorana surface modes at the interfaces between domains featuring the monopole and the trivial phases, such as an *s*-wave, will be the experimental signature of the monopole SC.

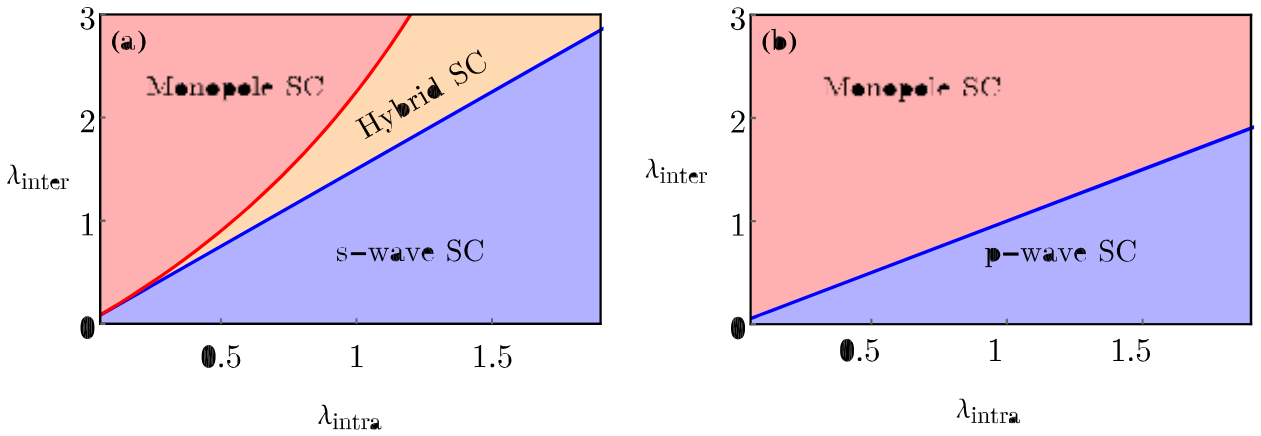

Fig. 1: *Zero-temperature phase diagram of the Weyl superconductor (SC) with the inter- and intra-Fermi surface pairings tuned by the couplings λ_{inter} and λ_{intra}, respectively [1]. (a) Monopole versus the s-wave pairing. (b) Monopole versus the p±-wave SC*

References

[1]. E. Muñoz, R. Soto-Garrido and V. Juricic, Phys. Rev. B **102**, 195121 (2020).

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Bill Atkinson

Magneto-Thermal Conductivity Oscillations in Spin-Orbit-Coupled Nodal Superconductors

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We describe a mechanism by which the longitudinal thermal conductivity, measured in an in-plane magnetic field, oscillates as a function of field angle in layered nodal superconductors. These oscillations occur when the spin-orbit splitting at the nodes is larger than the nodal scattering rate, and are complementary to vortex-induced oscillations identified previously. In sufficiently anisotropic materials, the spin-orbit mechanism may be dominant. As a particular application, we focus on the cuprate high-temperature superconductor $YBa_2Cu_3O_{6+x}$. This material belongs to the class of Rashba bilayers, in which individual CuO_2 layers lack inversion symmetry although the crystal itself is globally centrosymmetric. We show that spin-orbit coupling endows the thermal conductivity with a characteristic dependence on magnetic field angle that should be easily detected experimentally, and argue that for underdoped samples the spin-orbit contribution is larger than the vortex contribution. A key advantage of the magneto-thermal conductivity is that it is a bulk probe of spin-orbit physics, and therefore not sensitive to inversion breaking at surfaces.

References

W.A.A. and A.P.K, Phys. Rev. Research **3**, 023023 (2021)

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Dr. Marc Gali Labarias

Effect of spread in HTS Josephson junction parameters on SQUID array response

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Superconducting quantum interference device (SQUID) arrays have been widely investigated to extend the functionality of a single SQUID. The larger set of parameters that define the arrays allows for more optimization options compared to a single SQUID, however spreads in the parameters of each of the SQUIDs can decrease the overall array performance.

Despite the existence of models for SQUID arrays at low-temperatures [1-3], these models fail to include the effects of thermal noise to better predict the response of arrays operating at higher temperatures, as is the case for high-temperature superconductors (HTS) at 77K.

Here we will use a new model capable of simulating the response of 2D SQUID arrays operating at finite temperatures [4, 5] for which we extend the mathematical framework further to allow for variations in Josephson junctions characteristics, more commonly associated with HTS junctions [6].

Using this new model, we will investigate theoretically how the spread in Josephson junction characteristics affects the flux to voltage response of small one- and two-dimensional SQUID arrays operating at finite temperatures. We will study the effects of parameter spread on the voltage modulation depth, maximum transfer function and current-voltage characteristics.

References

[1]Oppenlander et al. PRB 63, 2 (2000) [2]Berggren et al. European Phys. J. 87, 4(2014) [3]Dalichaouch et al. SUST 27, 6, (2014)

[4]M.A. Galí Labarias et al., *arxiv.org/abs/2106.11439*, submitted to *Physical Review Applied*, (2021).

[5] M.A. Galí Labarias et al.,accepted, *IEEE Trans. Appl. Superconduct. Dec. 2021*.

[6]S.K.H. Lam et al. SUST 27, 5 (2014)

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Mr. Ji-Sol Jeong, Mr. Geon-Woong Kim, Mr. Sang-Yong Park, Ms. Ji-Hye Kim, Hyo-Sang Choi

Operating characteristics of a transformer-type superconducting current-limiting module applied with a normal-resistor

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DC must be interrupted at high voltage and current since it has no frequency. Therefore, many solutions for stable DC interruption have been proposed, and superconductors are being a lot of applied. However, there are few solutions to protect superconductors that are applied for DC interruption. We proposed a method to protect the superconducting element on the secondary side of the transformer type superconducting current-limiting module. It consists of the normal-resistor connected in parallel to the transformer secondary side superconducting element. When the superconducting element is quenched and reaches high resistance under transient conditions, the fault current flows through the normal-resistor connected in parallel. Therefore, the normal-resistor reduces the consumption power of the superconducting element through quenching of the superconducting element. In this paper, we designed DC simulation circuit and transformer-type superconducting current-limiting module using the PSCAD/EMTDC. In addition, we simulated short-circuit to confirm the operating characteristics of the transformer-type superconducting current-limiting module to which the normal-resistor is applied.

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Prof. Haruhisa Kitano

Depairing J_c Measurements of Iron Chalcogenide Superconductors with FIB-Fabricated Microbridges

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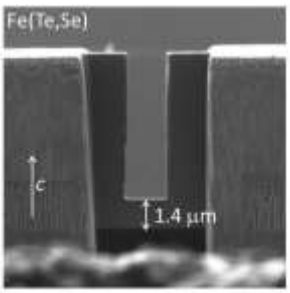
The critical current density, J_c, in the depairing limit provides crucial information on the critical velocity of the Cooper pairs and the collapse of the superconducting state. The depairing limit is usually interrupted by the vortex flow, occurring when the Lorentz force exceeds the pinning force of vortices. Such a difficulty can be overcome by reducing the cross sectional area of the superconducting strip, since the critical field to expel vortices can be enhanced by the reduction of the strip width [1].

Here, we present a systematic study on the depairing J_c measurements for high-quality single crystals of iron chalcogenide (Fe*Ch*) superconductors. Fe*Ch* attracts much attention in terms of the novel superconducting states such as the topological superconductivity in Fe(Te,Se) and the ultranodal pair state with Bogoliubov Fermi surface in Fe(Se,S) [2]. By using focused ion beam (FIB) techniques, we fabricated the single-crystal bridge structure of Fe(Te,Se) and FeSe with the lateral sizes which were comparable to or smaller than the Pearl length $\Lambda(\equiv 2\lambda^2/t)$, as shown in Fig.1. Here, λ is the penetration depth and t is a height of the bridge, respectively.

We confirmed the achievement of the depairing limit in both J_c^{ab} and J_c^{c} [3], based on the following results; (i) The measured J_c is an order of magnitude larger than the depinning J_c, obtained from the magnetization [4]. (ii) The measured J_c is increased with decreasing the lateral sizes of the bridge. (iii) The temperature dependence of J_c agrees with the theoretical curves (GL theory and Kupriyanov-Lukichev theory) at least down to $T=0.7T_c$. (iv) External magnetic fields, both parallel and perpendicular to the *ab* plane, do not suppress the measured J_c^{ab} of FeSe at least up to B=1 T (at T=4 K). These results strongly suggest that the depairing limit is accessible even for high-crystalline and clean superconductors, by using the FIB fabrication techniques. This enables us to perform new experiments which explore unknown phenomena induced by the ultrafast motion of Cooper pairs.



In addition, by further decreasing the lateral sizes of the bridge using the FIB pick-up method [5], we observed a crossover from the depairing limit to the Josephson limit, where the current-voltage curves show a characteristic behavior dominated by the effectively-enhanced Josephson current in the non-equilibrium state [6].

Fig. 1: *Scanning ion microscopy image of the fabricated Fe(Te,Se).*

References

[1] G. Stan *et al*., Phys. Rev. Lett. **92**, 097003 (2004).
[2] T. Shibauchi, T. Hanaguri, and Y. Matsuda, J. Phys. Soc. Jpn. **89**, 102002 (2020).
[3] On the *c*-axis depairing J_c of Fe(Te,Se), Y. Sun *et al*., Phys. Rev. B **101**, 134516 (2020). [4] Y. Sun *et al*., Supercond. Sci. Technol. **28**, 044002 (2015); Y. Sun *et al*., Phys. Rev. B **92**, 144509 (2015).
[5] T. Miyazawa *et al*., J. Phys.: Conf. Ser. **1975**, 012010 (2021).
[6] M. Octavio *et al*., Phys. Rev. B **17** 159 (1978).

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Mr. Simon Klein

Collective Modes' Contributions in Third-Harmonic Generation in Non-centrosymmetric Superconductors

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Recent interest for collective amplitude (Higgs) and phase (Leggett) excitations in single- and multi-band superconductors have led to various studies focused on third-harmonic generation (THG) experiments, both for singlet *s*- and *d*-wave gap structure. A resonance in the THG intensity appears, when matching the driving frequency to the energy of the corresponding investigated mode, leading to a phase jump at the resonance frequency. We extend these studies to superconductors without an inversion symmetry, which can be effectively described by a two-band model with an order parameter, consisting of spin singlet (even parity) and spin triplet (odd parity) components. In our work, we use both an effective action approach as well as a diagrammatic description of the processes. We calculate the THG signal for the non-centrosymmetric compound $CePt_3Si$, showing that it contains contributions from three distinguishable sources, namely the Higgs mode, the Leggett mode and quasiparticles. In the clean limit, only diamagnetic Raman-like processes contribute to the THG signal, whereas the quasiparticle contributions dominate the collective modes for all singlet-triplet ratios of the gap structure. In the dirty limit, we find a significant enhancement of the Higgs mode contributions to the THG signal, due to the inclusion of non-vanishing paramagnetic diagrams. We notice a significant change in the phase jump, which helps to differentiate between diamagnetic and paramagnetic results and thus between clean and dirty superconductors.

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Dr. Roland Willa

Inhomogeneous Time-Reversal Symmetry Breaking in Strontium Ruthenate

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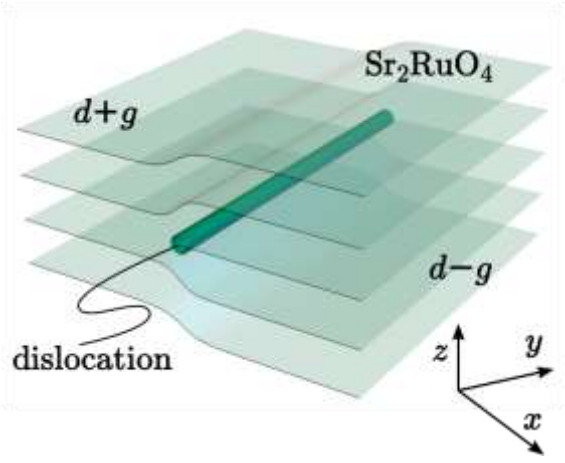
We show that the observed time-reversal symmetry breaking (TRSB) of the superconducting state in Sr_2RuO_4 can be understood as originating from inhomogeneous strain fields near edge dislocations of the crystal. Specifically, we argue that, without strain inhomogeneities, Sr_2RuO_4 is a single-component, time-reversal symmetric superconductor, likely with a $d_{x^2-y^2}$ symmetry. Due to the strong strain inhomogeneities generated by dislocations, a slowly-decaying sub-leading pairing state contributes to the condensate in significant portions of the sample. As it phase winds around the dislocation, time-reversal symmetry is locally broken. Global phase locking and TRSB occur at a sharp Ising transition that is not accompanied by a change of the single-particle gap and yields a very small heat capacity anomaly. Our model thus explains the puzzling absence of a measurable heat capacity anomaly at the TRSB transition in strained samples, and the dilute nature of the time-reversal symmetry broken state probed by muon spin rotation experiments. We propose that plastic deformations of the material may be used to manipulate the onset of broken time-reversal symmetry.



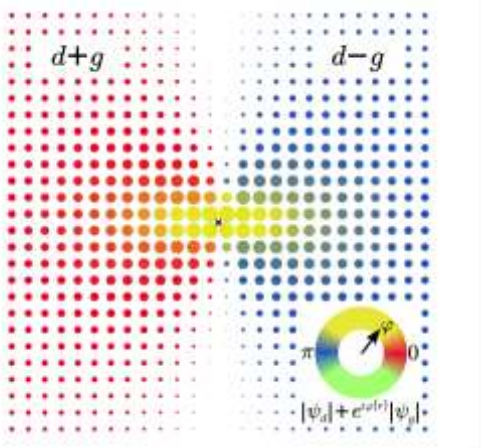


Fig. 1: Inhomogeneous strain near crystallographic dislocations (left) induces a subleading *g*-wave superconducting state in the superconducting *d*-wave state of strontium ruthenate. As the direction of the phase winding (Z_2 Ising variable) orders, the global TRSB transition is accompanied by a very small specific heat anomaly.

References

[1]. R. Willa, M. Hecker, R.M. Fernandes, J. Schmalian, Phys. Rev. B **104**, 024511 (2020).

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Andrew Macfarlane

β-detected NMR of $LaNiO_3$ and $LaNiO_3/LaAlO_3$ Superlattices

V.L. Karner[1,2], E. Benckiser[3], A.V. Boris[3], A. Chatzichristos[2,4], G. Cristiani[3], D.L. Cortie[1,2,4], M.H. Dehn[2,4], O. Foyevtstov[2,4], K. Foyevtstova[2,4], D. Fujimoto[2,4], B. Keimer[3], R.F. Kiefl[2,4,5], C.D.P. Levy[5], R. Li[5], G. Logvenov[3], R.M.L. McFadden[1,2], J.F. Mitchell[6], G.D. Morris[5], M.R. Pearson[5], M. Stachura[5], J.O. Ticknor[1,2], F. Wrobel[3], J. Zhang[6], W.A. MacFarlane[1,2,5]

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Using implanted ^{8}Li beta-detected NMR, we have studied the strongly correlated perovskite oxide metal $LaNiO_3$ in the form of single crystal, thin film and ultrathin layers in superlattices with $LaAlO_3$. We find evidence[1,2] for electronic phase separation in the biexponential form of the spin-lattice relaxation function. In the bulk, both phases appear metallic, but in ultrathin layers the behaviour of one diverges appearing magnetic at low temperature.

[1] V.L. Karner et al, Phys. Rev. B 100, 165109 (2019)
[2] V.L. Karner et al, Phys. Rev. B **104**, 205114 (2021)

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Dr. Oliver Dicks

Searching for Exciton Mediated Superconductors

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The search for high temperature superconductors has been ongoing for the past 60 years, with constant developments in both experimental and theoretical arenas. The original microscopic theoretical description of superconductivity by Bardeen, Cooper and Schrieffer[1] (BCS theory), which combined the pairing of electrons into Cooper pairs to form Bose-Einstein condensates with a phonon coupling mechanism that allowed an attractive potential between electrons, described early conventional superconductors but could not predict the newly discovered high temperature superconductors. Eliashberg[2] was able to go a step further and include a more accurate treatment of electron-electron interactions allowing for prediction of higher T_c superconductors in the strong coupling regime.

However, phonons are not the only bosons capable of mediating the attractive electron-electron interaction. Exciton and exciton-polariton interactions have also been posited to allow superconducting pairs to form, and due to their increased binding energy, offer a path to higher transition superconducting critical temperatures.

In my talk I will outline potential pathways to search for and find potential novel exciton mediated superconducting materials using beyond-DFT theoretical calculations. Identifying key calculable properties is crucial to allow computational screening of enough materials to discover new high temperature superconductors.

[1] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957)
1. G.M. Eliashberg, Zh. Eksp. Teor. Fiz. 38 (1960) 966; Soviet Phys. JETP 11 (1960) 696–702

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Mr. Vincent Oliviero

Magnetotransport Signatures of Antiferromagnetism Coexisting with Charge Order in a High T_c Superconductor

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Antiferromagnetic order close to unconventional superconductivity is a general feature of strongly correlated superconductors. In cuprates, the role of antiferromagnetism in the pairing mechanism is still under debate mainly because of the presence of the pseudogap and other competing orders. Multilayered cuprates provide a proving ground to study such orders: they possess disorder-free CuO_2 planes and an extended antiferromagnetic phase, stabilized by interlayer coupling. I will present our recent study of quantum oscillations and Hall effect in magnetic fields up to 88 T in the underdoped tri-layered cuprate $HgBa_2Ca_2Cu_3O_{8+\delta}$, the cuprate with the highest superconducting temperature transition (T_c = 133 K). The analysis of the complex spectra of quantum oscillations strongly supports the coexistence of multiple competing orders. Our interpretation implies that a metallic antiferromagnetic state extends deep inside the superconducting phase, a key ingredient that supports magnetically-mediated pairing interaction in cuprates.

Yipeng Cai

μSR study of non-centrosymmetric superconductor $NbGe_2$

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The time-reversal and inversion symmetry are particularly important for a superconducting state and the absent of such two symmetry will likely result in an unconventional superconducting pairing symmetry. Only few superconductors have been confirmed with time reversal symmetry breaking (TRSB) and even less superconductors with topological properties. Recent studies on non-centrosymmetric $NbGe_2$ show superconducting property around 2 K, it also exhibits a crossover from type-I to type-II upon decreasing temperature. Meanwhile, a large surface superconductivity critical field was also observed which was proposed related to the topological state. Further measurements of the penetration depth and TRSB are valuable to gain additional insight into the superconducting state of $NbGe_2$, where muon spin rotation is the ideal technique. As a result, our zero field μSR measurements shows no clear signature of TRSB, as shown in Fig.1(a),(b), that the ZF relaxation rate are mainly due to the nelcear dipoles. Further study on transverse field μSR measurements suggest $NbGe_2$ at low temperatures to be a type-II conventional s-wave superconductor, as shown in Fig.1(c),(d). These features are overall consistent with describing $NbGe_2$ as an isotropic fully gapped single-band superconductor.[1,2,3]

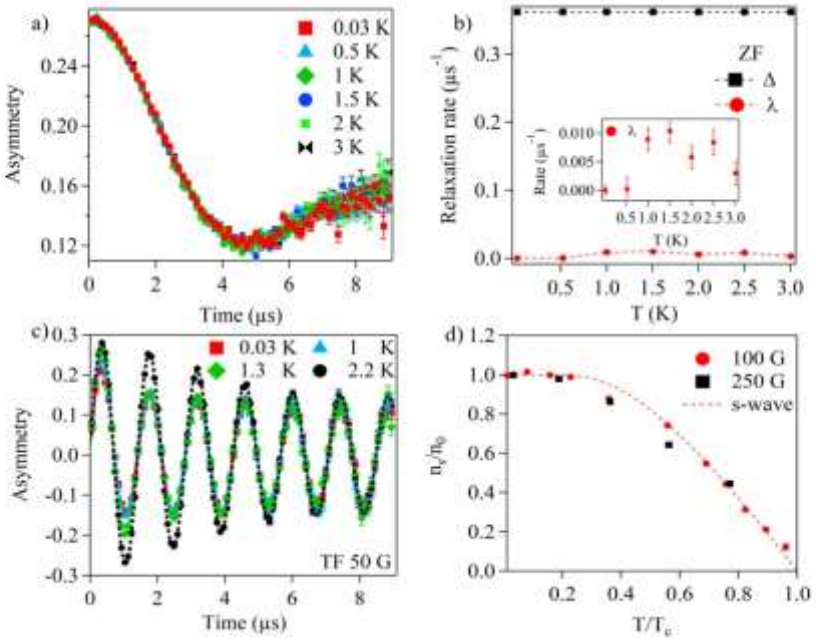

Fig. 1: *ZF-μSR spectra at selected temperatures, b) T-dependent ZF relaxation rates, c) The TF-μSR spectra, above and below Tc at 50 G, d) The T-dependent superfluid density*

References

[1]. B. Lv, Phys. Rev. B **102**, 064507 (2020).
[2]. E. Emmanouilidou, Phys. Rev. B **102**, 235144 (2020).
[3]. D. Zhang, Phys. Rev. B **103**, 214508 (2021).

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Antiferromagnetic order close to unconventional superconductivity is a general feature of strongly correlated superconductors. In cuprates, the role of antiferromagnetism in the pairing mechanism is still under debate mainly because of the presence of the pseudogap and other competing orders. Multilayered cuprates provide a proving ground to study such orders: they possess disorder-free CuO_2 planes and an extended antiferromagnetic phase, stabilized by interlayer coupling. I will present our recent study of quantum oscillations and Hall effect in magnetic fields up to 88 T in the underdoped tri-layered cuprate $HgBa_2Ca_2Cu_3O_{8+\delta}$, the cuprate with the highest superconducting temperature transition (T_c = 133 K). The analysis of the complex spectra of quantum oscillations strongly supports the coexistence of multiple competing orders. Our interpretation implies that a metallic antiferromagnetic state extends deep inside the superconducting phase, a key ingredient that supports magnetically-mediated pairing interaction in cuprates.

Ms. Victoria Karner

β-detected NMR of La_2CuO_4 and $La_2CuO_4/LaNiO_3$ Superlattices

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We report β-detected NMR of ion-implanted ^{8}Li in a thin film of La_2CuO_4 and novel hybrid $La_2CuO_4/LaNiO_3$ superlattices. The Mott insulator La_2CuO_4, the parent compound of the 214 cuprate superconductors, orders antiferromagnetically below a $T_N \approx 300$ K which is extremely sensitive to doping. In a La_2CuO_4 film, spin-lattice relaxation measurements reveal fast but measurable NMR spin-lattice relaxation rate $1/T_1$ for the implanted radioisotope ^{8}Li. We see emergence of magnetic order in the film from a gradual loss of signal amplitude beginning at 140 K. We attribute the suppression of T_N and the breadth of the transition to inhomogeneous hole doping in the film, either due to the substrate or to variation in oxygen stoichiometry. Below 40 K, an upturn in $1/T_1$ suggests freezing of mobile holes in the more doped regions. The behaviour in the superlattices is similar and does not appear to depend on the number of intervening metallic $LaNiO_3$ layers.

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Mr. Gabriel Kuderowicz

Electronic Structure, Electron-Phonon Coupling and Superconductivity in Noncentrosymmetric $ThCoC_2$ from *Ab Initio* Calculations

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In noncentrosymmetric superconductors (NCS), due to the lack of an inversion center, presence of the antisymmetric spin-orbit coupling allows for the mixture of spin-singlet and spin-triplet symmetry of Cooper pairs. $ThCoC_2$ is an example of NCS, in which non-BCS properties were reported, like the non-exponential temperature dependence of the electronic specific heat [1]. Moreover, Ni substation for Co greatly enhanced superconductivity as the critical temperature increased to 12 K for $ThCo_{0.6}Ni_{0.4}C_2$ compared to 2.5 K for the undoped sample [2]. Finally, based on the μSR measurements, superconductivity in $ThCoC_2$ was proposed to have a nodal d-wave gap and pairing mediated by spin fluctuations [3].

In this work we aim to discuss the pairing mechanism in $ThCoC_2$ using *ab initio* calculations [4] and isotropic Eliashberg equations. Strong spin-orbit coupling was found, with the average band splitting of about 150 meV. Calculated electron-phonon coupling constant $\lambda = 0.59$ remains in decent agreement with the experimental estimate, suggesting the phonon-based pairing [5]. However, calculated temperature dependence of magnetic penetration depth and electronic specific heat do not follow experimental ones which supports non-s-wave character of superconductivity. Electron-phonon mechanism is further supported by our studies of Ni doping effect [6] as λ was found to increase with Ni concentration. Finally, we simulate isotope effect on carbon and the pressure evolution of T_c as these experiments should help to determine the pairing mechanism in $ThCoC_2$.

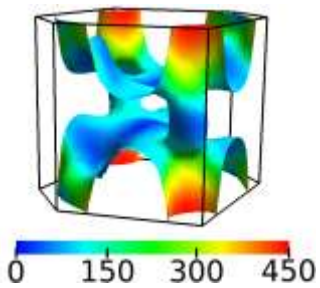

Fig. 1: *k-dependent distribution of Fermi surface splitting due to SOC in $ThCoC_2$ [5].*

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References

[1]. T. Grant et al., Supercond. Sci. Technol. 27, 035004 (2014).
[2]. T. Grant et al., Phys. Rev. B 96, 014507 (2017).

[3]. A. Bhattacharyya et al., Phys. Rev. Lett. 122, 147001 (2019).
[4]. P. Giannozzi et al., J. Phys.: Condens. Matter 29, 465901 (2017).
[5]. G. Kuderowicz et al., Phys. Rev. B 104, 094502 (2021).
[6]. G. Kuderowicz et al., J. Magn. Magn. Mater. 168688 (2021).

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Multiband superconductivity and charge density waves in the Ni-intercalate $ZrTe_2$

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In previous works carried out with intercalation of cooper in $ZrTe_2$, yielding superconductivity with T_c ~ 9.7K[1]. The superconducting behavior deviates from BCS an it is consistent with multiband superconductivity. Based on this finding, this work investigated the possibility of the new superconductor in Ni-intercalate in $ZrTe_2$. High quality $Ni_{0.04}ZrTe_{1.89}$ single crystals show a coexistence of charge density waves with superconductivity at 287 K, suggested by heat capacity and resistivity measurements. Both temperature lower (H_{c1}) and upper (H_{c2}) critical magnetic fields deviate significantly from the behaviors expected in conventional single-gap superconductors. The behaviors of the normalized superfluid density $\rho_s(T)$ and H_{c2} (T) can be described well using a two-gap model for the Fermi surface, in a manner consistent with conventional multiband superconductivity.

Reference

[1] - A. J. S. Machado, N. P. Baptista, B. S. De Lima, et al. Physical Review B 95, 144505 (2017).

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Dr. Hyeok Yoon

The conductance spectroscopy in the superconducting states of UTe_2

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Uranium ditelluirde (UTe_2) is a strong candidate for spin-triplet superconductors, evidenced by the enormous upper critical field far exceeding the Pauli-limit, the temperature-insensitive Knight shift down to superconducting states [1], the broken time-reversal symmetry observed in polar Kerr effect [2]. It has been suggested that the superconducting order parameter of UTe_2 is chiral with the non-trivial topology. However, the spectroscopic studies for the superconductivity has been limited to the easy-cleave surface so far [3]. Here, we examine the conductance spectra in UTe_2 using the planar junction structure, consisting of the metallic electrode on the polished surface of UTe_2, with the various surface orientations. We will discuss features in the conductance spectra below T_c that are consistent with the superconducting gap energy of 0.25 meV, as well as the features of superconducting order parameters which explain the observed spectra.

References

[1] S. Ran, C. Eckberg, Q.-P Ding, Y. Furukawa, T. Metz, S. R. Saha, M. Zic, H. Kim, J. Paglione, N. P. Butch, Science **365**, 684-687 (2019)
[2] I. M. Hayes, D. S. Wei, T. Metz, J. Zhang, Y. S. Eo, S. Ran, S. R. Saha, J. Collini, N. P. Butch, D. F. Agterberg, A. Kapitulnik, J. Paglione, Science **373**, 797-801 (2021)
[3] L. Jiao, S. Howard, S. Ran, Z. Wang, J. O. Rodriguez, M. Sigrist, Z. Wang, N. P. Butch, V. Madhavan, Nature **579**, 523-527 (2020)

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Hilary Noad

Stress-Strain Relation in Sr_2RuO_4

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Stress-strain measurements are well established in materials science and engineering for characterizing the elastic properties of structural materials. They are promising for the study of superconducting and other quantum materials as a method of obtaining information about the free energy under strain, but until now, they have not been applied to quantum materials because the measurement conditions are more difficult: samples are small and often brittle, temperatures are usually cryogenic, and space is limited. Through focused ion beam micromachining of mm-scale samples and using a new cryo-compatible uniaxial pressure cell [1], we have developed a method to do these measurements accurately and reliably under the required conditions. Applying this technique to Sr_2RuO_4, we clearly resolve the signatures of a uniaxial-pressure-tuned electronic transition [2], track its behavior across the superconducting transition, and quantitatively reconstruct the Young's modulus as a function of strain. We find that the 4 K Young's modulus decreases by ~10% at the Lifshitz transition; the onset of superconductivity only weakly alters this softening. We anticipate that cryogenic stress-strain measurements will be useful in a wide variety of quantum materials.

References

[1] M.E. Barber, A. Steppke, A.P. Mackenzie, C.W. Hicks, Rev. Sci. Instrum. **90**, 023904 (2019).
[2] V. Sunko, E. Abarca Morales, I. Marković, M. E. Barber, D. Milosavljević, F. Mazzola, D. A. Sokolov, N. Kikugawa, C. Cacho, P. Dudin, H. Rosner, C. W. Hicks, P. D. C. King, A. P. Mackenzie, npj Quantum Mater. **4**, 46 (2019).

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Dr. Hiroshi Watanabe

Unified Description of Cuprate Superconductors Using a 4-band *d-p* Model

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Since the discovery of cuprate superconductors, we have not yet reached a unified understanding of their properties, including their material dependence of the transition temperature T_c [1]. The preceding studies have provided an overall picture of the phase diagram, and some important parameters for the T_c, such as the contribution of Cu d_{z^2} orbital to the Fermi surface [2] and the site-energy difference between the Cu $d_{x^2-y^2}$ and O p orbitals Δ_{dp} [3]. However, they are somewhat empirical and limited in scope, and do not provide a comprehensive view of the series of cuprates. Here we propose a four-band *d-p* model as a minimal model to study material dependence in cuprates. Using the variational Monte Carlo calculations, we study the superconducting correlation functions for the La_2CuO_4 and $HgBa_2CuO_4$ systems (Fig. 1). Our results comprehensively account for the empirical correlation between T_c and model parameters [4]. We also discuss the heavily-overdoped region where superconductivity vanishes. The local moment is enhanced through the Hund's coupling between Cu $d_{x^2-y^2}$ and d_{z^2} orbitals, and a multiorbital character becomes apparent there.

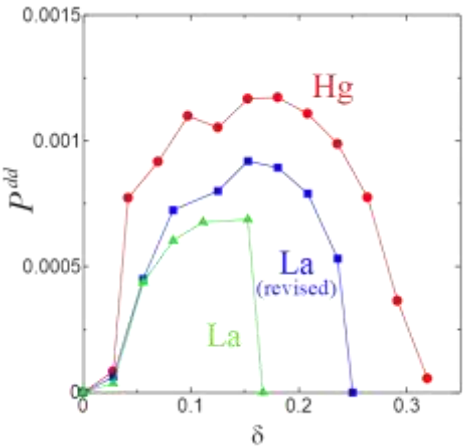

Fig. 1: *Superconducting correlation functions versus hole doping rate δ for La and Hg systems.*

References

[1] E. Pavarini *et al*., Phys. Rev. Lett. **87**, 047003 (2001).
[2] H. Sakakibara *et al*., Phys. Rev. Lett. **105**, 057003 (2010).
[3] C. Weber *et al*., Europhys. Lett. **100**, 37001 (2012).
[4] H. Watanabe *et al*., Phys. Rev. Research **3**, 033157 (2021).

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Mr. Rodrigo Arouca

Characterization of Exceptional Points in Non-Hermitian Unconventional Superconductors

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Non-Hermitian physics is currently a very active area of research because it naturally allows to describe open systems, extending the Altland-Zirnbauer classification of topological phases, and giving rise to unique effects that do not exist in Hermitian setups [1]. For instance, they host energy level degeneracies, also known as exceptional points [2], where eigenvalues and eigenvectors coalesce. Exceptional points are not only a mathematical curiosity that appears in these systems, but also have deep physical consequences. For instance, it was recently shown that, in a non-Hermitian superconductor, odd-frequency is the only possible pairing at exceptional points [3], thus revealing a truly unusual superconducting state.

Motivated by the rich physics occurring when combining superconductivity and non-Hermitian physics, we study non-Hermitian unconventional p-wave superconductors and characterize the emerge of exceptional points. In particular, we consider the non-Hermitian Kitaev model [4], where non-Hermitian properties emerge by adding a non-reciprocal hopping to the celebrated Hermitian Kitaev model, relevant for topological superconductivity and quantum computation. Furthermore, we investigate the consequences of exceptional points on the properties of Green's function associated to the non-Hermitian Kitaev model and explore the presence of ordered states in this system.

References.

[1] E. J. Bergholtz, J. C. Budich, and F. K. Kunst, Reviews of Modern Physics 93, 015005 (2021).
[2] M. V. Berry, Czechoslovak journal of physics 54, 1039 (2004).
[3] J. Cayao and A. M. Black-Schaffer, arXiv:2107.04445.
[4] Y. Cao, arXiv: 2103.17157.

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Prof. Ruggero Vaglio

Nonlinear surface impedance of HTS superconductors in high magnetic fields

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Recent envisaged high temperature (HTS) superconductor's applications rely on their rf properties in very high magnetic fields. As an example, coating of surfaces facing particle beams with HTS for reducing the beam coupling impedance is being considered for the next generation of hadron colliders, such as the FCC-hh at CERN, where HTS would be exposed to the high-frequency wakefields generated by the particle bunches and to the strong field (16T) of the steering magnets [1]. Other considered applications are rf cavities for axion detection [2] as well as capture cavities for muon colliders**.** In these applications, it is important to keep under control the level of the nonlinear effects, always-present using superconductors.
In this frame, we present a simple model for the calculation of the rf behavior of HTS exposed to a strong external magnetic field, which takes into account the nonlinearity of the pinning potential of the vortex lattice. In particular, following our recent work on the same topic [3] we calculate the amplitude of the third-harmonic components in the electric field produced by vortex oscillation, as a function of the nonlinearity level of the assumed potential (see Fig.1). The implications of the estimated effect on the considered applications will be finally discussed.

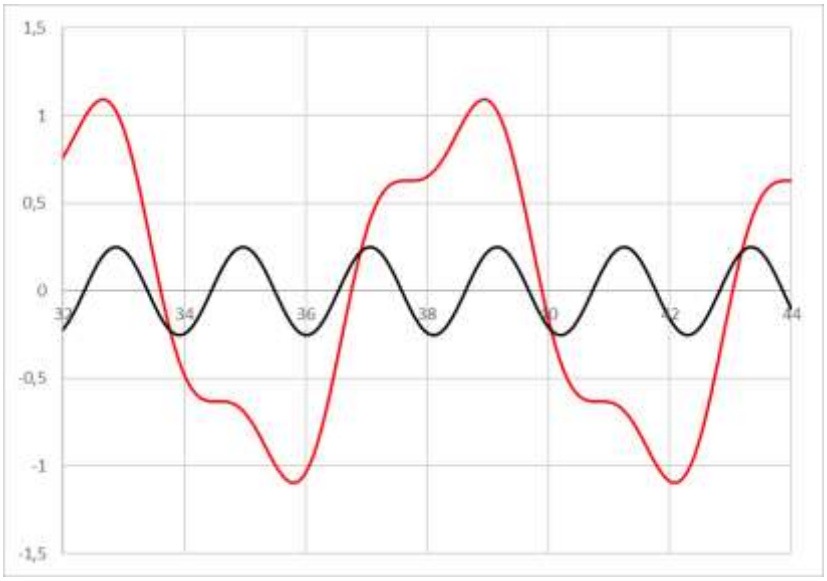

Fig. 1: *Example of the calculated first order perturbation term of the electric field generated by a nonlinear potential as a function of time (red curve). The third harmonic term is represented by the black curve (both electric field and time are in arbitrary units).*

References

[1]. S. Calatroni, IEEE Trans. Appl. Supercond. 26 (2016) 3500204.
[2]. D. Ahn, O. Kwon, W. Chung, W. Jang, D. Lee, J. Lee, S. Woo Y., D. Youm, Y. K. Semertzidis, https://arxiv.org/abs/ 2002.08769.
[3]. S.Calatroni, R. Vaglio, IEEE Trans. Appl. Supercond. 31 (2021) 3500208.

Dr. Kristin Willa

Short-rang magnetic correlations in UTe_2 by thermodynamic measurements

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The recent discovery of superconductivity in the heavy fermion UTe_2 [1] has led to an enormous interest in this material. It hosts various unusual phenomena like metamagnetism, field reentrant superconductivity and pressure-induced magnetic and superconducting phases [2]. There are still many open questions especially concerning the magnetic properties of the normal state. While no ordered magnetic moment has been observed, a mixture of ferromagnetic, anti-ferromagnetic and valence fluctuations has been proposed. In this talk, I will present our thermodynamic (thermal-expansion, specific-heat, magnetostriction and susceptibility) measurements on the normal state of UTe_2 [3]. In In all of these quantities, clear evidence for a broad Schottky-like anomaly around T*=12K is observed with a calculated entropy of roughly Rln2. Combining our thermodynamic measurements with previously published high magnetic-field transport data [4] allows us to construct an H - T phase diagram which resembles that of the ferromagnetic superconductor URhGe. From our thermodynamic data, we calculate the electronic Grüneisen parameter related to T*. It is found to be comparable in magnitude to that of the metamagnetic field indicating a common origin. Finally, enhanced Wilson and Korringa ratios suggest that the existence of short-range ferromagnetic fluctuations cannot be ruled out, although no direct evidence for their existence has been found to date.

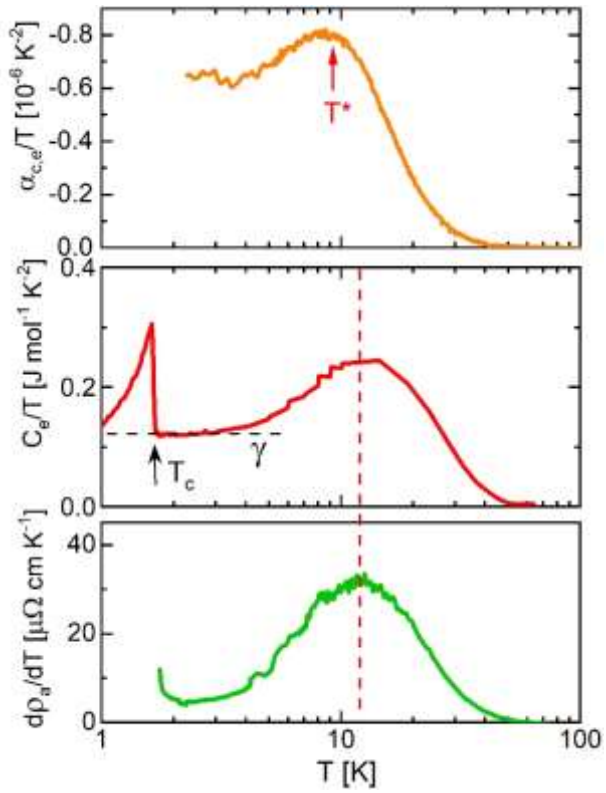

Fig. 1: *Electronic contribution to c axis thermal expansion and specific heat together with the temperature derivative of the a-axis resistivity of UTe_2. The arrow and the red dashed line indicate the position of the crossover temperature T.*

References

[1]. S. Ran, et al., Science 365, 684 (2019).
[2]. Braithwaite, et al., Communications Physics 2 (2019).
[3]. Willa, et al., PRB 104, 205107 (2021).
[4]. Knafo, et al., JPSJ 88, 063705 (2019).

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Prof. Pieralberto Marchetti

A FL* Solution to the FL /NFL Dichotomy in the Cuprates

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One amazing characteristic of hole-doped cuprates is that some of their physical quantities qualitatively behaves almost like in a Fermi liquid (FL), especially at sufficiently large doping and temperature, but still exhibiting FL features even at lower values of such parameters, whereas in the same range of parameters other quantities behave in a completely non-FL (NFL) fashion.
For example, in the "pseudogap" region of the doping-temperature phase diagram, although in ARPES experiments gapless Fermi arcs are clearly seen, the behavior of in-plane resistivity is completely NFL, even exhibiting a metal-insulator crossover at a temperature basically not influenced by added disorder which provides only an offset of the resistivity curves, excluding a simple explanation in terms of disorder-induced localization. In NMR experiments although the uniform susceptibility [Knight shift] at high T and doping approaches a FL response, the magnetic susceptibility [$^{63}T_1$] remains quite NFL in nature in the same range of parameters. In the superconducting phase below the "pseudogap" region in the doping-temperature phase diagram although the superconducting gap near the nodes is well described by a d-wave BCS theory, the superfluid density has definitely a non-BCS behavior, resembling that of a 3D XY model.
We argue that this phenomenology is due to the FL* nature of the cuprates, where using the terminology of [1] we denote by FL* an exotic FL in which, besides standard electrons (or better holes for the cuprates) carrying charge and spin, the quasi-particle excitations are the holons carrying only charge and the spinons carrying only spin.
The electron is then a bound state, or in general a resonance, made of holon and spinon and the corresponding Landau quasi-particle is the true low-energy excitation,
holon and spinon being well defined particle-like excitations only far away from the region of small energy close to the electron Fermi surface.
In our FL* formalism [2] for hole-doped cuprates, based upon a 2D t-J model expressed in terms of gapped spinons and semionic holons with Fermi surface lower in energy than that of the hole [3], all the experimental dichotomies FL/NFL mentioned above are qualitatively well reproduced [4] and the NFL features appear when the response is dominated by spinons whereas the FL features appear when the response is dominated by the hole resonance.

References

[1]. T. Senthil, S. Sachdev, and M. Vojta, Phys. Rev. Lett. **90**, 216403 (2003); A. Paramekanti and A. Vishwanath, Phys. Rev. B **70**, 245118 (2004).
[2]. P.A. Marchetti, F. Ye, Z.-B. Su and L. Yu, Phys. Rev. B **100**, 035103 (2019); paper in preparation.

[3]. P.A. Marchetti, Z. B. Su, and L. Yu, J. Phys.Condens. Matter **19**, 125212 (2007); P.A. Marchetti, Condens. Matter **5**, 12 (2020).
[4]. P.A. Marchetti, L. De Leo, G. Orso, Z. B. Su, and L. Yu, Phys. Rev. B **69**, 024527 (2004); P.A. Marchetti, F. Ye, Z. B. Su, and L. Yu, Phys. Rev. B **84**, 214525 (2011); P.A. Marchetti and G. Bighin, Europhys. Lett. 110, 37001 (2015), J. Low Temp. Phys. **185**, 87 (2016); paper in preparation.

Prof. Jeff Tallon

Field-dependent thermodynamic studies of overdoped cuprates

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Overdoped cuprate superconductors have proved to be as enigmatic as underdoped cuprates but for different reasons. Despite increasing carrier concentration the superfluid density falls with increasing doping [1,2] where it is expected to increase. Field-dependent specific heat studies allow the superconducting gap and superfluid density to be deduced. We report such data for a number of cuprates and demonstrate essentially conventional behaviour in the condensation energy where the BCS ratio is preserved across a large part of the overdoped regime. But in each cuprate the superfluid density immediately falls on closure of the pseudogap with doping and the detailed behaviour seems to be universal (see Figure). In this sense the antinodal pseudogap seems to protect the superfluid which immediately starts to collapse with the pseudogap's demise. This data places strong constraints on the various models for the anomalous overdoped behaviour including strong scattering, multiple bands and phase separation.

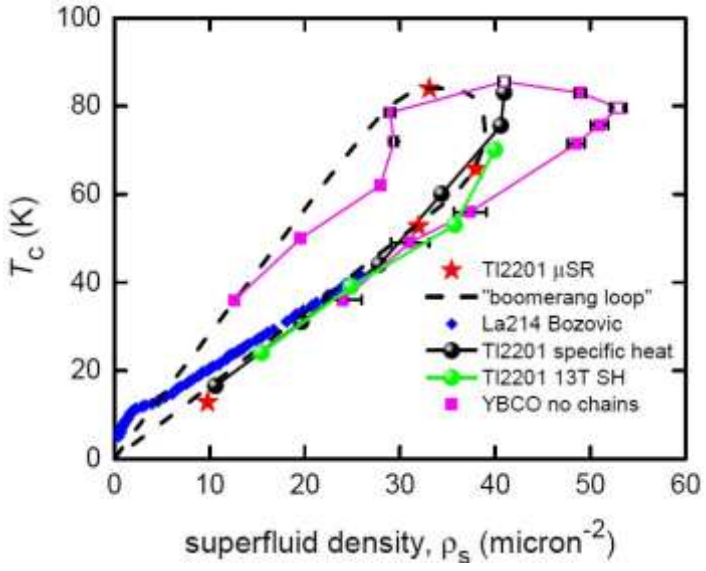

Fig. 1: *A 'Uemura plot'of T_c versus superfluid density showing the original 'boomerang curve' for Tl-2201 (dashed), the muon spin relaxation data for Tl-2201 [1], the data of Božović et al [2] for La214, data from field-dependent specific heat (black and green circles) and YBCO with the chain contribution subtracted. There seems to be a unniiversal collapse of superfluid density on the overdoped side.*

References

[1] Ch. Niedermayer *et al*., *Phys. Rev. Lett.* **71**, 1764-1767 (1993).
[2] I. Božović, X. He, J. Wu and A. T. Bollinger, Nature 536, 309-311 (2016).

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Mr. Francesco Barantani

Experimental observation of electron-exciton coupling in high-T_c cuprates

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Explaining the mechanism of superconductivity in the high-T_c cuprates requires an understanding of what causes electrons to form Cooper pairs. Pairing can be mediated by phonons, the screened Coulomb force, spin or charge fluctuations, excitons, or by a combination of these [1,2,3,4]. An excitonic pairing mechanism has been postulated [4,5], but experimental evidence for coupling between conduction electrons and excitons in the cuprates is sporadic [6].
Here we use resonant inelastic x-ray scattering (RIXS) to monitor the temperature dependence of the dd exciton spectrum of $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) crystals with different charge carrier concentrations. We observe a significant change of the dd exciton spectra when the materials pass from the normal state into the superconductor state: in the proximity of T_c the dd excitons peak first moment shows a change of slope in its temperature dependence, which changes sign as function of doping. From theoretical modelling we determine the strength of the coupling between the electrons and the excitons for the momentum values investigated in this study.

References

[1]. D. J. Scalapino, Rev. Mod. Phys., **84**, 1383 (2012)
[2]. W. Anderson, Science, **235**, 1196 (1987)
[3]. A. J. Leggett, Proc. Nat. Acad. Sci. USA, **96**, 8365 (1999)
[4]. W. A. Little, Phys. Rev., **134**, A1416 (1964).
[5]. W. Weber, A. L. Shelankov, X. Zotos, Physica C, 153-155, 1305 (1988)
[6]. M. J. Holcomb, J. P. Collman, W. A. Little, Phys. Rev. Lett., **73**, 2360 (1994)

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Mrs. Seyedeh Sara Ghotb, PhD Maxime Dion, PhD Guillaume Hardy, Professor Patrick Fournier

Non-Linear Hall Effect in PCCO Electron-Doped Cuprate

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The Hall effect has been one of the most important tools used to explore the numerous differences between the p-type and n-type cuprates. In the conventional transport theory of metallic materials, the Hall resistivity is simply linear in field with the slope, the Hall coefficient, related to the density of charge carriers. Studying the evolution of the Hall coefficient as a function of temperature and doping in cuprates gave some crucial information on their major trademarks, about the charge carrier sign, the density but also the presence of major changes in their Fermi surface morphology. The Hall effect in electron-doped cuprates shows non-trivial behavior as a function of doping and temperature with a marked transition at $x^* \sim 0.17$[1]. Another intriguing feature is the observation of two sign changes in $R_H(T)$ at two different temperatures of 40 and 260 K for $Pr_{2-x}Ce_xCuO_4$ (PCCO) at $x = 0.17$. One can use a two-carrier model to explain minimally, but not accurately, this temperature dependence of the Hall coefficient [2-4].
To extract even more information from the transport properties, we present a quantitative analysis of the non-linear field dependence of the Hall effect for PCCO thin films as a function of doping. High quality PCCO thin films are deposited by pulsed laser deposition and Hall bars are fabricated by photolithography. The structural characterization is done mostly using X-ray diffraction while the transport properties are carried out using a resistivity option of a PPMS. Hall resistivity as a function of magnetic field shows a non-linear behavior, easily evidenced at temperatures where $R_H \sim 0$, but present also at all temperatures. This non-linear contribution grows rapidly with decreasing temperature and is present for several doping levels around $x = 0.17$. By considering higher orders in the field dependence of $\rho_{xy} = AH + BH^3 + CH^5 + \ldots$ we extract B as a function T and doping and relate it to parameters of the two-carrier model. Results show that one needs to go beyond this simplistic model to improve our understanding of the band structure of these materials and the impact of the Fermi surface transformation as a function of doping.

References

[1] Armitage, N. P., Fournier, P. & Greene, R. L. (2010). Progress and perspectives on electron-doped cuprates. Rev. Mod. Phys. **82**, 2421-2487.
[2] Fournier, P., Jiang, X., Jiang, W., Mao, S. N., Venkatesan, T., Lobb, C. J. & Greene, R. L. (1997).Thermomagnetic transport properties of $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ films: Evidence for two types of charge carriers. Phys. Rev. B **56**, 14149.
[3] Wang, Z. Z., Chien, T. R., Ong, N. P., Tarascon, J. M., & Wang, E. (1991). Positive Hall coefficient observed in single-crystal $Nd_{2-x}Ce_xCuO_{4-\delta}$ at low temperatures. Physical Review B, **43**(4), 3020.
[4] Greene, R. L., Mandal, P. R., Poniatowski, N. R., & Sarkar, T. (2020). The strange metal state of the electron-doped cuprates. Annual Review of Condensed Matter Physics, **11**, 213-229.

Dr. Yoshikazu Mizuguchi, Mr. Md. Riad Kasem, Dr. Aichi Yamashita, Dr. Yuki Nakahira, Dr. Chennan Wang

Superconductivity of high-entropy-alloy-type compounds

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Since the discovery of superconductivity in a high-entropy alloy Ti-Zr-Hf-Nb-Ta [1], exploration of new HEA superconductors has been a growing topic in the field of superconductivity [2]. The common strategy to design HEA is alloying five or more elements with a range of 5-35% in concentration of each element. Our focus has been material development of new compound superconductors having a HEA-type site; the examples are shown in Fig. 1(b-e), where one of crystallographic sites is high-entropy-alloyed with different five elements [3-5]. Since the introduction of a HEA-type site in compounds result in highly disordered chemical bonds and electronic states. To find out new pathway to designing novel unconventional superconductors or high-performance practical-use materials, clarification of the effects of the HEA-site on superconductivity are highly desired. We have investigated the effects of the presence of HEA-type site on superconducting properties for various compounds [3-7]. Through our reserch, we found that the HEA effects on superconducting properties are depending on dimensionality of crystal structure. For some cases, positive effects, such as an increase in critical current density and an improvement of bulk nature of superconductivity. In addition, unexpected modification of supercondcuting states were found in specific heat experiments in $TrZr_2$. In this presentation, we will show an overview on superocnducting properties of HEA-type compound superconductors and recent results on superconducting properties in the HEA-type compounds.

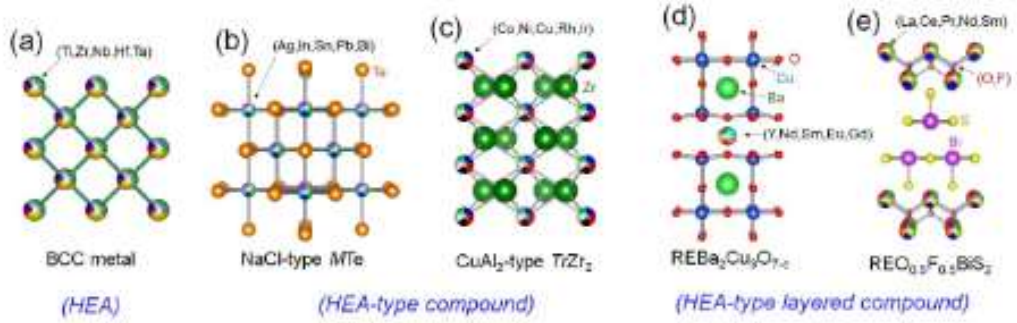

Fig. 1: *Crystal structure of HEA-type compound superconductors. (a) conventional HEA, (b) HEA-type metal telluride MTe, (c) HEA-type transition-metal zirconide $TrZr_2$, (d) HEA-type cuprate $ReBa_2Cu_3O_{7-\delta}$, (e) HEA-type layered BiS_2-based system $RE(O,F)BiS_2$.*

References

[1]. P. Koželj et al., Phys. Rev. Lett. **113**, 107001 (2014).
[2]. L. Sun, R. J. Cava, Phys. Rev. Mater. **3**, 090301 (2019).
[3] R. Sogabe, Y. Goto, Y. Mizuguchi, Appl. Phys. Express **11**, 053102 (2018).
[4] Y. Mizuguchi, A. Yamashita, IntechOpen: 10.5772/intechopen.96156.
[5] Md. R. Kasem et al., Appl. Phys. Express **13**, 033001 (2020).
[6] R. Sogabe et al., Solid State Commun. 295, **43** (2019).
[7] Md. Riad Kasem et al., Supercond. Sci. Technol. **34**, 125001 (2021).

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PhD Guillaume Hardy

Interface and Strain Effects in $Pr_{1.83}Ce_{0.17}CuO_4$ and $LaFeO_3$ Bilayers

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We report structural studies, resistivity and Hall effect measurements on bilayers made of the antiferromagnetic oxide $LaFeO_3$ (LFO) as bottom layer and the electron-doped cuprate $Pr_{1.83}Ce_{0.17}CuO_4$ (PCCO) as a top layer grown by pulsed laser deposition (PLD). These bilayers contain PCCO layers of various thicknesses and are grown on $SrTiO_3$ (STO), $(LaAlO_3)_{0.3}$-$(Sr_2AlTaO_6)_{0.7}$ (LSAT) and $SrLaGaO_4$ (SLGO) substrates. The samples were produced to further the study of a reported charge transfer between $LaFeO_3$ and electron-doped cuprates[1]. While superconductivity is observed for the thickest top layers of PCCO, a marked suppression is observed as the PCCO top layer becomes thinner. This is paired with increasing resistivity and Hall effect measurements that show a drop in charge carrier density. The decrease in T_c, the increase in resistivity and the vanishing carriers represent the exact opposite trend compared to what was originally expected if a charge transfer is playing a role. Upon further analysis, we observe that, despite the LFO buffer layer between the substrate and PCCO, the threshold PCCO thickness below which this occurs depends on the underlying substrate. X-ray diffraction shows that the LFO layer is fully strained by the substrate over its whole thickness, while the PCCO structure is only strained near the interface with LFO. The thickness of this strained region in PCCO is greater for lower structural mismatch between the substrate and PCCO. We demonstrate that the strained region in PCCO is correlated with that of a highly resistive interface region. We hypothesize that the structural strain reduces the mobility of oxygen ions that are normally removed during a reduction annealing, thus resulting in a nonuniform oxygen reduction in the PCCO layer, which fixed the oxygen concentration obtained during the deposition near the interface.

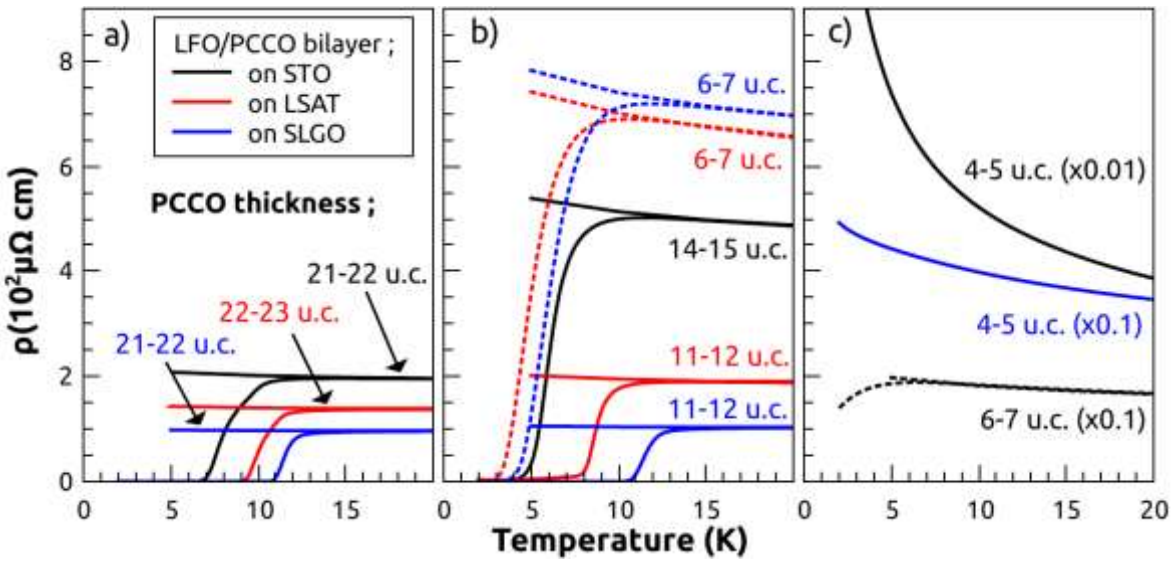

Fig. 1: *Resistivity of PCCO and LFO bilayers for various substrates and thicknesses of the PCCO layer.*

References

[1]. F. Y. Bruno *et al.*, Advanced Materials **25**, 1468 (2013).

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Dr. Timur Kim

Superconductivity and Magnetism in RbEuFe4As4: Electronic Structure of the Iron-Based Superconductor with Helical Antiferromagnetic Order

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We have studied the novel iron-based material $RbEuFe_4As_4$ where superconducting order of Fe 3d states co-exist with peculiar magnetic order of Eu 4f states. Using synchrotron-based angle-resolved photoemission spectroscopy (ARPES) measurements we observed full three-dimensional electronic structure and compared it with Density Functional Theory (DFT) results. Moreover, we distinguished multiple superconducting gaps on various sheets

of the Fermi surface. Utilizing high resolution resonant photoemission (ResPES) we revealed magnetic ordering of Eu 4f states deep into superconducting state. By performing detailed temperature dependence of Fe and Eu derived stated we discovered that superconductivity and magnetism are fully decoupled from each other. Our results unambiguously confirm that Fe-based superconductivity and long-range magnetic order of Eu independently coexist in $RbEuFe_4As_4$, bring vital information regarding the electron pairing in this unconventional superconductor.

References

[1]. T. K. Kim et al., Phys. Rev. B **103**, 174517 (2021).

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Prof. Carmen Almasan

Quantum criticality in $Ce_{1-x}Sm_xCoIn_5$*

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Motivated by the possibility of observing the co-existence between magnetism and unconventional superconductivity in heavy-fermion $Ce_{1-x}Sm_xCoIn_5$ alloys, we studied how the samarium substitution on the cerium site affects the magnetic field-tuned- quantum criticality of stoichiometric $CeCoIn_5$ by performing specific heat and resistivity measurements. By applying an external magnetic field, we have observed Fermi-liquid to non-Fermi-liquid crossovers in the temperature dependence of the electronic specific heat normalized by temperature and of the resistivity. We obtained the magnetic-field-induced quantum critical point (QCP) by extrapolating to zero temperature the temperature - magnetic field dependence at which the crossovers take place. Furthermore, a scaling analysis of the electronic specific heat is used to confirm the existence of the QCP. We have found that the magnitude of the magnetic-field- induced QCP decreases with increasing samarium concentration. Our analysis of heat capacity and resistivity data reveals a zero-field QCP for x_{cr} = 0.15, which falls inside the region where Sm ions antiferromagnetism and superconductivity co-exist.

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Manel Mezidi

Exploration of Electronic Orders by Raman Scattering in Cuprates

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Raman spectroscopy is the inelastic light scattering by elementary excitations of the matter. We have performed linear and circular polarized Raman measurements on hole doped cuprates in a large energy range up to 1eV with different excitation lines (488nm, 530 nm and 562nm). We have also carried out Raman measurements as function of temperature.

We have investigated single, double and triple-layer cuprates over a wide range of doping from very under-doped to over-doped regime. The single crystals are the bismuth $BiSr_2Ca_2Cu_2O_{4+\delta}$ (Bi-2212 double layers) and the family of mercurates $HgBa_2CuO_{4+\delta}$ (Hg-1201 single layer) and $HgBa_2Ca_2Cu_3O_{4+\delta}$ (Hg-1223 triple layers).

The aim of our studies is to identify from the pure polarizations of the Raman spectra, the underlying electronic orders of the cuprate phase diagram and bring a better understanding of the pseudo-gap phase.

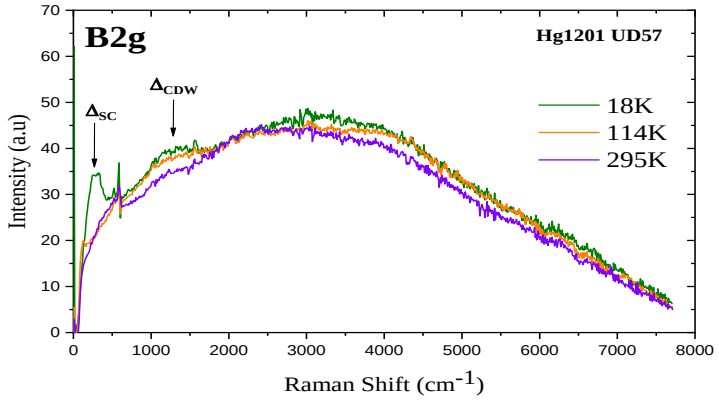

Fig1.: Symmetry-resolved Raman response of an underdoped Hg1201 (UD57) single crystal.

References :

[1]. Loret *et al.,* Phys. Rev. B **101,** 214520 (2020).

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Rafael Haenel

Spectroscopy of Superconducting Collective Modes: Theory

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Superconducting condensates hosts a zoo of collective modes, the most prominent ones being Higgs modes and quantized relative phase or Leggett fluctuations. They may be observed in non-linear THz spectroscopic experiments or yield a Raman signature in the visible optical regime.
Here, we theoretically discuss the bosonic mode spectrum and experimental signatures of collective modes in superconductors with multiple order parameters and in the presence of impurities. We focus on two scenarios: (a) materials with two superconducting bands such as MgB2 and (b) multi-component order parameters transforming under 2d irreducible representations that spontaneously break time-reversal symmetry.
Measurement of the characteristic collective mode signatures may be used as a tool to identify the nature of the underlying superconducting state.

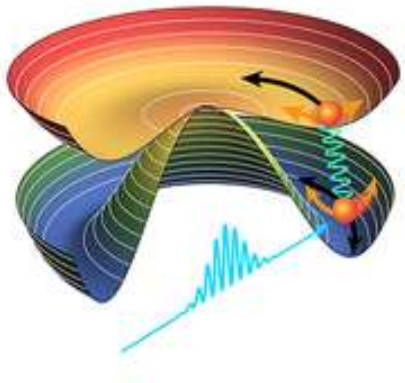

Fig. 1: *Visualization of the free energy of a two-band superconductor.*

References

[1] R. Haenel, P. Froese, D. Manske, L. Schwarz, Phys. Rev. B **104**, 134504 (2021).
[2] L. Schwarz, R. Haenel, D. Manske, Phys. Rev. B **104**, 174508 (2021).

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Dr. Tae-ho Park, Han-Yong Choi

Maximal superconducting T_c for phonon mediated superconductors

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The question of maximal superconducting critical temperature T_c due to the phonon mediated pairing is ever more important since the realization of the record T_c close to room temperature in superhydrides under high pressure. Theoretically, the high T_c of hydrogen-rich materials has been estimated or expected from McMillan's or Allen and Dynes' T_c formula by calculating the dimensionless electron-phonon coupling constant in terms of the density functional theory (DFT) based phonon calculation. However, those formulae were obtained empirically based on the perturbative framework so called Eliashberg theory, which may break down in the limit of very large electron-phonon coupling g or antiadiabatic limit where the phonon frequency (ω_0) is larger than the Fermi energy (ε_F). We calculated the superconducting T_c of the Holstein model in non-perturbative way by employing the dynamical mean-field theory in combination with the numerical renormalization group technique. Interestingly, the maximum superconducting T_c^{max} occurs at the lower critical value g_{c1} of the first order metal-insulator transition in the normal state. Underlying physics is the balance between the enhanced electron-phonon coupling and the decrease of the average phonon frequency caused by the soft mode emerging along the phase boundary associated with the enhanced quantum fluctuation. Implications of T_c^{max} calculations will be discussed in comparison with a variety of ways to estimate T_c bounds using the electron-phonon coupling spectra of the normal state.

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Dr. Isao Watanabe

Quantum Distributions of Magnetic Moment in La_2CuO_4 Revealed by Density Functional Theory Calculations and Muon Spin Relaxation Measurement

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We are going to demonstrate a new way to reveal quantum electronic states of the Cu spin in the mother material of the Cu-based high-T_C superconducting oxide, La_2CuO_4 (LCO), from both density functional theory (DFT) calculations and the muon spin relaxation (μSR) measurement. Three positions were found as initial muon-stopping sites from the static electric potential calculations as shown in Fig. 1(a). By using those positions, quantum distributions of the electronic orbitals of Cu deformed by the injected muon were revealed from DFT calculations as displayed in Fig. 1(b).

In the antiferromagnetic ordered state, clear muon-spin precession behavior was observed. This internal field can be simulated by using the DFT results of the quantum distribution of the Cu spin on the basis of the dipole-dipole interaction between the muon and each component of the distributed Cu spin. Adjusting both DFT and μSR results, we succeeded to estimate the final muon positions, the on-site Coulomb potential, U, and the minimum charge transfer energy between the upper Hubbard band and the O2p band to be 4.87(4) eV and 1.24(1) eV, respectively.

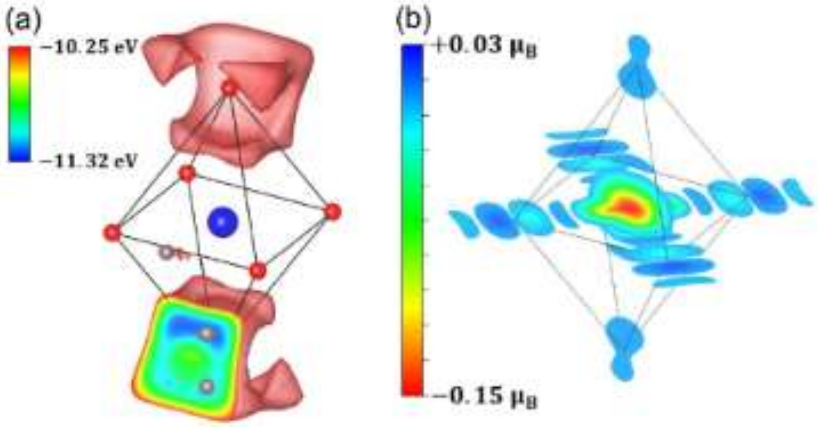

Fig. 1: *(a) DFT calculation result of the electro-static potential around the CuO_6 octahedra of La_2CuO_4. The red area shows the iso-surface with the 1.0 eV higher energy from the minimum potential. Black marks are possible initial stopping positions for the injected muon. (b) DFT calculation result of the quantum distribution of the Cu spin in the CuO_6 octahedra.*

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Edwin Huang

Incipient order in the strange metal of the Hubbard model

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The Hubbard model is the paradigmatic model of strongly correlated electron systems. Over the past several years, advanced numerical techniques have led to considerable progress in determining the ground state phases of the model, revealing spin stripe order, charge stripe order, and d-wave superconductivity as the dominant players at low energies. I will discuss numerically exact determinantal quantum Monte Carlo calculations demonstrating how the interplay of these orders persists well above the onset of the pseudogap [1]. In particular, I will focus on the nature of fluctuating spin [2,3] and charge stripes in the model, and show that they remain mutually commensurate at temperatures where the model exhibits bad metallic transport [4]. I will also discuss connections between these results to recent X-ray scattering experiments on cuprates that find fluctuating charge order over an extended region of the phase diagram [5].

References

[1]. E. W. Huang et al, J. Phys. Soc. Jpn. **90**, 111010 (2021).
[2]. E. W. Huang et al, Science **358**, 1161 (2017).
[3]. E. W. Huang et al, npj Quantum Materials **3**, 22 (2018).
[4]. E. W. Huang et al, Science **366**, 987 (2019).
[5]. S. Lee, EWH, T. A. Johnson et al, submitted to PNAS, arXiv:2110.13991.

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Mr. Sam Cross

Superconductivity in YH_4 Films at Very High Pressures

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The discovery of the hydride superconductor H_3S in 2015 with a T_c record of 203K at 155GPa has been a cornerstone for the research on hydride at high pressures and the quest for room temperature superconductivity [1]. Since several other superhydride compounds have been synthesized, such as YH_6 [2] and YH_9 [3, 4], exhibiting superconductivity close to room temperature under megabars pressures. While theoretical works are paving the way to realize new hydrides superconductors, their synthesis within the laboratory remains very challenging. Here we demonstrate a new approach to synthesize YH_4 from an elemental yttrium film directly evaporated on the diamond anvil and ammonia borane (NH_3BH_3) as a hydrogen donor [5]. This method allows a more accurate control of the sample size and helps to reach high hydrogen content in the synthesis. The critical superconducting temperatures observed for YH_4 films are consistent with those reported by other independent groups in YH_4 bulk [2, 3, 6]. Resistivity measurements up to 34T allow us to extract $H_{c2}(T)$ and estimate $H_{c2}(T=0)$ at 40-55T using the Werthamer–Helfand–Hohenberg model [7]. We will also present x-ray diffraction and Raman spectroscopy measurements and discuss the crystal structure of YH_4 films.

References

[1]. A. P. Drozdov, et al., Nature **525**, 73 (2015).
[2]. I. A. Troyan et al., Advanced Materials **33**, 2006832 (2021). [3].
P. P. Kong et al., Nature Communications **12**, 5075 (2021).
[4]. E. Snider et al., Physical Review Letters **126**, 117003 (2021).
[5]. Buhot et al., Physical Review B **102**, 104508 (2020). [6]. M.
Shao et al., Physical Review B **104**, 174509 (2021).
[7]. N. R. Werthamer et al., Physical Review **147**, 295 (1966).

Mr. Kazuhisa Hoshi

Extremely High Upper Critical Field for the $BiCh_2$-Based Superconductor

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$BiCh_2$-based superconductor was discovered in 2012 [1]. The crystal structure has a layered structure composed of blocking layers and $BiCh_2$ conducting layers, which is similar to that of cuprate and iron-based superconductor. Theoretical works suggest that unconventional superconductivity, such as extended *s*-wave, d_{x2-y2}-wave, *g*-wave superconductivity, is realized in $BiCh_2$-based superconductor [2]. In the experimental aspect, angle-resolved photoemission spectroscopy (APRES) study found the anisotropic superconducting gap and absence of isotope effect was observed [2]. Recently, local inversion symmetry breaking has much attention. The $BiCh_2$-based system has local inversion symmetry breaking in the $BiCh_2$ layer and Rashba-type spin polarization was theoretically predicted [3]. The spin polarization due to the Rashba-type spin-orbit coupling was observed by spin-ARPES [4]. The Rashba-type spin texture can lead to high upper critical fields such as non-centrosymmetric superconductors. Thus, we investigate upper critical fields for the $BiCh_2$-based superconductor $LaO_{0.5}F_{0.5}BiS_{2-x}Se_x$ (x = 0.22 and 0.69) by using high magnetic field. We found that huge upper critical fields were observed in fields parallel to the *ab*-plane direction. The results indicate that the Rashba-type spin-orbit coupling plays an important role in the superconductivity and also a parity-mixed state can be realized in the $BiCh_2$-based superconductor. I will discuss the relationship between the paring mechanism and local inversion symmetry breaking in my presentation.

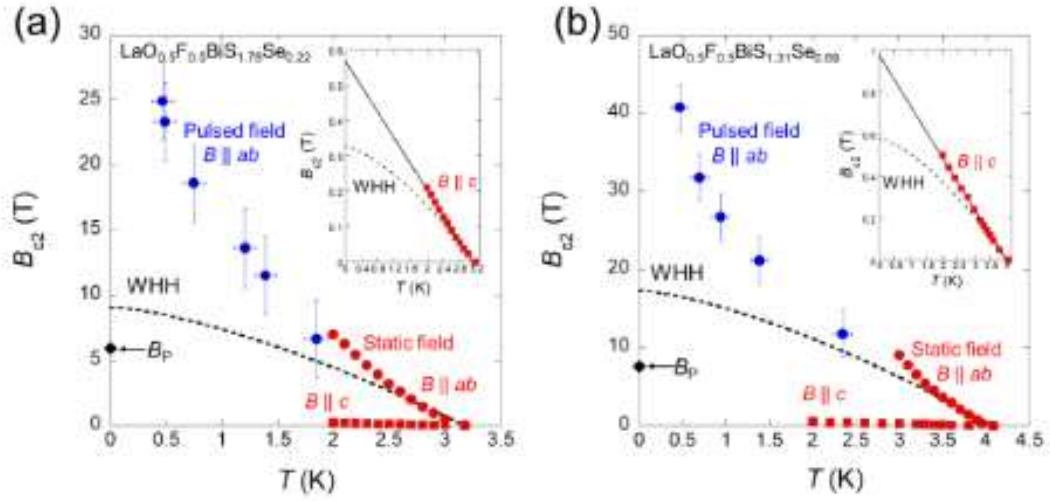

Fig. 1a *Upper critical fields as a function of temperature for (a) $LaO_{0.5}F_{0.5}BiS_{1.78}Se_{0.22}$ and (b) $LaO_{0.5}F_{0.5}BiS_{1.31}Se_{0.69}$.*

References

[1] Y. Mizuguchi, J. Phys. Soc. Jpn. **88**, 041001 (2019).
[2] K. Suzuki *et al.*, J. Phys. Soc. Jpn. **88**, 041008 (2019).
[3] X. Zhang *et al.*, Nat. Phys. **10**, 387 (2014).
[4] S. L. Wu *et al.*, Nat. Commun. **8**, 1919 (2017).

Pierre-olivier Downey

Pseudogap Formation in the Half-Filled Hubbard Model on the Triangular Lattice

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Although the pseudogap in the weak interaction regime is mostly understood, in the strong interaction regime it still poses an important challenge for the understanding of hole-doped cuprates. It has been proposed that short-range antiferromagnetic (AFM) correlations are part of the mechanism involved in its formation [1]. The main objection to this proposal is that since the conclusion is based on the solution of a square 2x2 cluster with cluster dynamical mean-field theory, long-range AFM could also be responsible for its formation. To resolve this issue, we solve the Hubbard model using the dynamical cluster approximation on a larger triangular cluster where long-range AFM fluctuations are prohibited by geometrical frustration. We prove that pseudogaps exist in such systems at half-filling and that neither short nor long-range AFM correlations are involved in the formation of this pseudogap, which is instead mediated by short-range spiral-order fluctuations.

References

[1]. G. Sordi, K. Haule, and A.-M. S. Tremblay. Phys. Rev. B, **84** :075161, (2011).

Mr. Yuta Watanabe

Quantum and temperature effects on crystal structure of superhydride: A path integral molecular dynamics study

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Hydrogen-rich materials under high pressure are attracting attention as candidates of high-T_c superconductors [1]. One of those materials, LaH_{10}, shows a distinctively high critical temperature [2,3]. However, the accurate *P-T* phase diagram of the crystal structure has not been made up to now. It was revealed that the quantum effect of hydrogen atoms plays a crucial role in LaH_{10} to stabilize its structure [4]. We performed molecular dynamics (MD) and path integral molecular dynamics (PIMD) simulations to consider the influence of temperature in addition to the quantum effect [5]. Fig. 1 shows the results of XRD simulations for the crystal structures obtained from the MD and PIMD simulations. The two peaks in classical calculation at 200 K merge when the quantum effect is considered. The peak also merges at 300 K without the quantum effect. Moreover, the inclusion of the quantum effect does not symmetrize the crystal structure at 125 GPa with 200 K, while the symmetrized structure is stable at 300 K with the same pressure. These results show that the temperature effect is essential in determining the crystal structure. We also performed the calculations on YH_{10}, which is suggested to have a higher T_c than LaH_{10}. Through our calculation, H-H bond elongations were observed both in LaH_{10} and YH_{10} due to the quantum nuclear effect, which might be a key for maintaining the symmetric crystal structure.

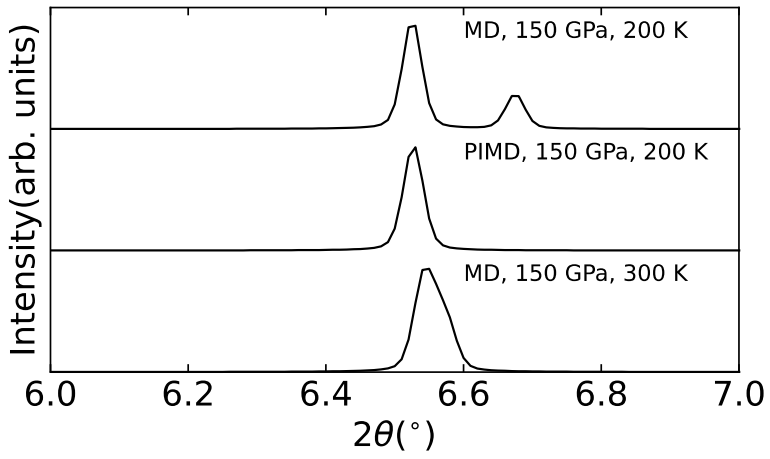

Fig. 1: *X-ray diffraction patterns of LaH_{10} crystal obtained from molecular dynamics (MD) and path integral molecular dynamics (PIMD) simulation. A weak signal besides the one distinct peak appears when the symmetry of the crystal structure is low.*

References

[1]. J. A. Flores-Livas, et al., Physics Reports 78 (2020).
[2]. A. P. Drozdov, et al., Nature **569**, 528 (2019).

[3]. M. Somayazulu, et al., Phys. Rev. Lett. **122**, 027001 (2019).
[4]. I. Errea, et al., Nature **578**, 66 (2020).
[5]. M. Shiga, PIMD (2020). See https://ccse.jaea.go.jp/software/PIMD/index.en.html for further information.

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Mr. Archie Morfoot

The Effect of Electronic Correlations on the Nematic Electronic Phase of $FeSe_{1-x}Te_x$

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Orbitally-dependent electronic correlations can play an important role in the stabilization of the nematic and superconducting states of iron-chalcogenides. In FeSe nematicity is supressed using isoelectronic substitution of sulphur and tellurium, but the increase in bandwidths only occurs with sulphur substitution leading to reduced correlations [1,2,3]. Here we will present a study of the electronic structure of the nematic superconductors $FeSe_{1-x}Te_x$ using ARPES to understand the role of orbitally- dependent correlations on the nematic electronic state with tellurium substitution. We assess the degree of band renormalisation by comparing our ARPES data to DFT band structure calculations. From the linewidths and band velocities of the energy dispersions we access information of the self-energy, corresponding to the quasiparticle lifetime and renormalisation. Next, we extract the size of the Fermi surface and its k_z-dependence and compare these findings to previous studies on $FeSe_{1-x}S_x$. Lastly, by using deep energy cuts, we discuss the formation of a Hubbard- like band in $FeSe_{1-x}Te_x$ as compared with FeSe [4].

References

[1]. P. Reiss et al., Phys. Rev. B **96**, 121103(R) (2017).
[2]. M. D. Watson et al. Phys. Rev. B **92**, 121108(R) (2015). [3].
A. I. Coldea, Front. Phys. **8**, 594500 (2021).
[4]. M. Watson et al., Phys. Rev. B **95**, 081106 (2017).

Acknowledgements

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Mr. Sang-Yong Park, Mr. Geon-Woong Kim, Mr. Ji-Sol Jeong, Ms. Ji-Hye Kim, Hyo-Sang Choi

Operation characteristics of a mechanical DC circuit breaker using a multi-meander type superconducting element

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The scale of use of DC systems is expanding as the supply of new and renewable energy sources and the increase in demand for digital loads. Accordingly, the breaking capacity of the DC system is increased, and a method for effectively cutting off the fault current in the line transient state is required. We proposed a mechanical DC circuit breaker with a multi-meander type superconducting element. The multi-meander type superconducting element is composed of multi-layers and has a structure in which the inductance is offset by designing the current direction of each wire in the opposite direction. Mechanical DC circuit breaker has a structure in which a mechanical high-speed switch, an LC divergence oscillation circuit, and a surge arrester are connected in parallel. It has a stable cut-off technology using the fast-current limiting operation of the superconducting element and the divergence oscillation current of the mechanical DC circuit breaker. In this paper, design parameters of superconducting elements and mechanical DC circuit breakers were designed through simulation, and prototypes were manufactured and tested. We analyzed the DC blocking characteristics by applying the multi-meander-type superconducting element model and the mechanical DC circuit breaker model through the above experiment. As a result, it was confirmed that the current limiting characteristics of about 43 % were confirmed in the multi-meander type superconducting element, and the cut-off time was improved by about 17 % by the divergence oscillation current of the mechanical DC circuit breaker.

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References

[1]. S. Y. Park, H. S. Choi, Operation characteristics of mechanical DC circuit breaker combined with LC divergence oscillation circuit for high reliability of LVDC system, Energies, vol. 14, pp. 5097 (2021) [2]. S. J. So, S. Y. Lee, S. Y. Park, H. S. Choi, K. D. Choi, W. S. Kim, HTS FCL module with voltage of 500 V for DC circuit breaker, vol. 31, no. 5, pp. 5601504 (2021)

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Dr. Fuyuki Nabeshima

Growth and Transport Properties of FeSe Thin Films under Chemical Pressure

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Iron chalcogenide superconductor FeSe is an ideal material to investigate the interplay between nematicity, magnetism and superconductivity in iron-based superconductors because it shows a nematic transition at 90 K without accompanying magnetic transition, different from other iron-based compounds. Much research has been focused on FeSe and S-substituted FeSe because of successful growth of single crystalline samples with high quality by a chemical vapor transport technique. S substitution for Se shrinks the lattice of FeSe, resulting in positive chemical pressure. However, growth of single crystals of $FeSe_{1-x}S_x$ for $x > 0.2$ is very difficult and only a limited region of composition is available. As for another isovalent substitution by Te, which corresponds to negative chemical pressure, few systematic investigations of Te-substituted FeSe have been conducted because the systematic synthesis of bulk $FeSe_{1-y}Te_y$ had, until recently, been hindered by the phase separation region.

We succeeded in growing thin films of $FeSe_{1-x}S_x$ for $0 \le x \le 0.43$ and $FeSe_{1-y}Te_y$ in a whole range of y by pulsed laser deposition[1]. The obtained electronic phase diagram is shown in Fig. 1. The nematic transition was suppressed by both S and Te substitution. The superconducting transition temperature, T_c, shows a drastic increase at a composition where the nematic transition disappears for Te substitution, while T_c decreases monotonically with increasing x for S substitution. This contrastive behavior of T_c at the nematic end point between S and Te substitution suggests that the nematicity does not play a primary role on the superconductivity in iron chalcogenides.

We investigated magneto-transport properties of these films in the normal state. From analysis with a two-carrier model, we found that carrier density drastically increased for Te-substituted samples, while no significant change in carrier density was observed for S-substituted samples[2]. This composition dependence of carrier density well-corresponds to the T_c behaviors, which suggests a correlation between T_c and the carrier densities. In addition, proportionality between superfluid density n_s and T_c was observed irrespective of the presence or absence of nematic order[3]. Combining these results with DFT calculation, we propose that the change in Fermi surfaces associated with nematic transition is the primary factor influencing the change of T_c at the nematic end point.

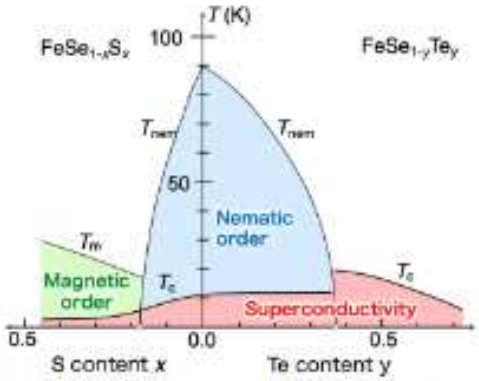

Fig. 1: *Phase diagram for $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ thin films.*

References

[1]. F. Nabeshima *et al.*, J. Phys. Soc. Jpn. **87**, 073704 (2018).
[2]. F. Nabeshima *et al.*, Phys. Rev. B **101**, 184517 (2020).
[3]. H. Kurokawa et al., Phys. Rev. B **104**, 014505 (2021).

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Akshat Pandey

Strong Correlation Effects in SNS Junctions and Failed Superconductors

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A wide variety of well characterized experimental systems exhibit anomalous metallic states in which current is carried by large superconducting quantum fluctuations that remain uncondensed to the lowest accessible temperatures. As a first step toward a theory of such a state, we revisit the case of a single SNS junction, but taking into account interaction effects in the normal metal portion of the junction. In particular, we identify circumstances in which magnetic fluctuations lead to dynamical variations in the sign of the Josephson coupling - i.e. in the sign of the local superfluid density. This has important implications for the theory of the anomalous metal more generally.

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Dr. Chen Lu

Two-orbital model for possible superconductivity pairing mechanism in nickelates

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The newly synthesized strontium doped RNiO2 (R=Nd, Pr, La) superconductors have stimulated extensive interests in understanding their pairing mechanism and pairing nature. Here we study the pairing mechanism in this family from a two-orbital model comprising the Ni- 3dx2-y2 - and 3dxy- orbitals, equipped with extended Hubbard interactions and induced low-energy effective superexchange interactions. We then study the pairing symmetry in this system by using large scale variational Monte Carlo approach. Our results yield the intraorbital dx2-y2-wave singlet pairing as the leading pairing symmetry in the nickelates, which is analogous to the cuprates. However, there exist two important differences between the physical properties of the two families due to the fact that at the low Sr-doping regime, while the Ni-3dx2-y2 orbitals remain half-filled and singly-occupied to form a Mott-insulating background, the Ni-3dxy orbitals accommodate nearly all the extra doped holes, which move freely on this background. The first difference lies in the single-particle aspect: while the 3dx2-y2 degree of freedom remains Mott insulating with spectra weight pinned down at zero at low dopings, the 3dxy one behaves as Fermi liquid with spectra weight near 1. The second difference lies in the pairing aspect: while the huge intra-3dx2-y2 -orbital pairing gap is actually a pseudo gap which has nothing to do with the SC, the small intra-3dxy-orbital pairing gap serves as the true superconducting pairing gap, which is related to the Tc via the BCS relation. Both differences can be verified by the angle-resolved photo-emission spectrum.

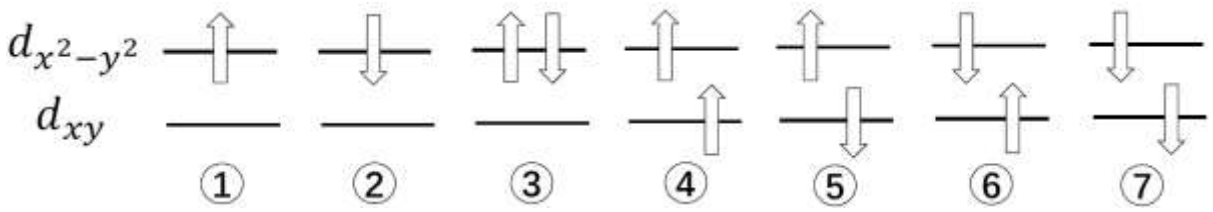

Fig. 1: *The seven configurations on each site with single holes and doublons in the strong coupling limit.*

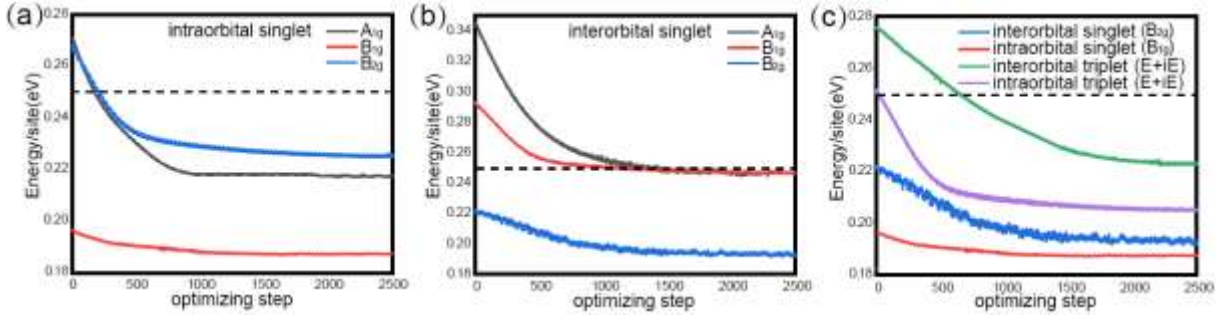

Fig. 2: *The optimizing-step dependences of the energies for the different pairing symmetries in (a) the intraorbital singlet-pairing channel and (b) the interorbital singlet-pairing channel. (c) The results for the leading pairing symmetries in all the four spin-orbital channels put together for comparison. In all the three figures, the horizontal dotted lines denote the minimized energy of the non-superconducting normal state.*

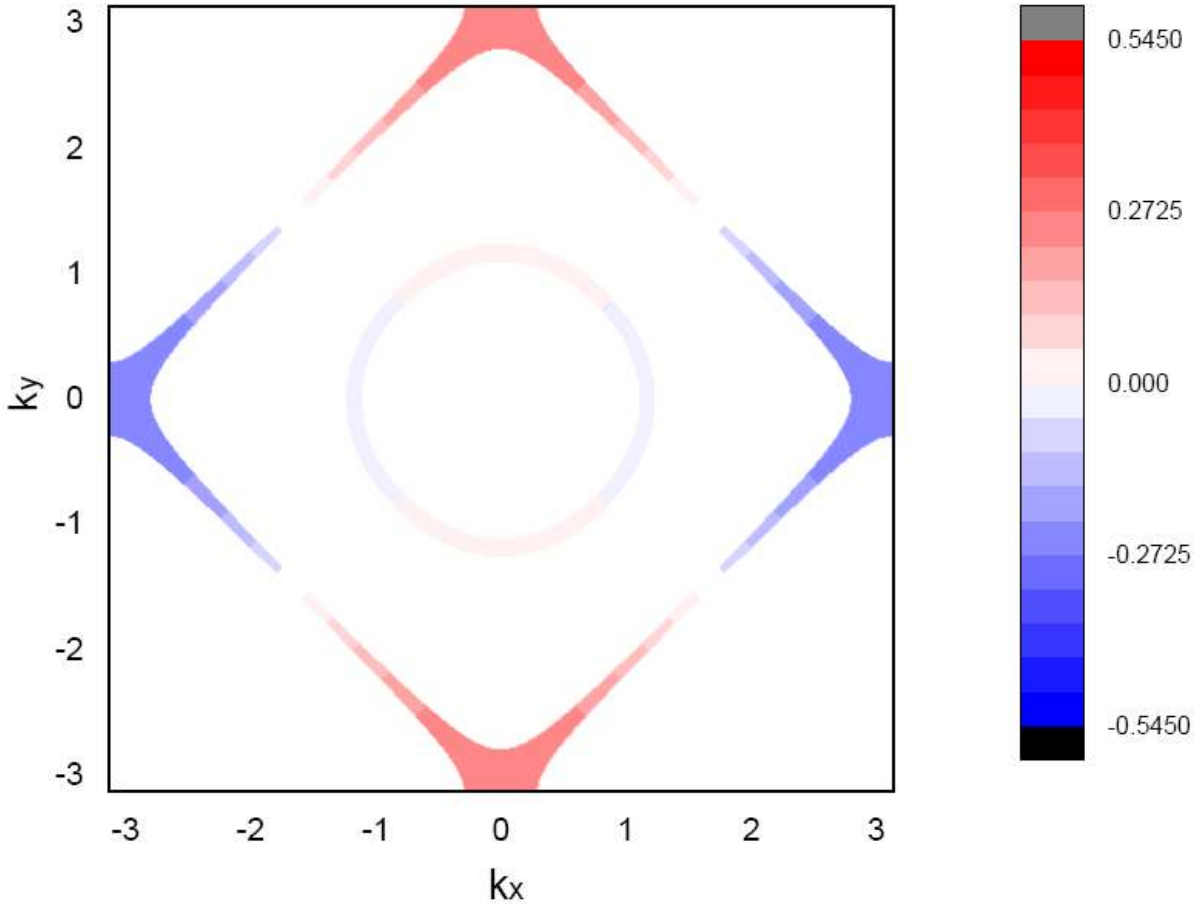

Fig. 3: *Distribution of the leading pairing gap function on the FSs for the intraorbital B_{1g} pairing symmetry obtained for the doping level δ=0.2. The color represents the value of the pairing gap function in unit of eV. Obviously, this gap function possesses the $d_{x^2-y^2}$ symmetry. The dominant orbital component of the outer Fermi pocket is $3d_{x^2-y^2}$, whose gap function is much larger than that of the inner Fermi pocket whose main orbital component is $3d_{xy}$. However, the gap on the outer Fermi pocket is actually a pseudo-gap, which is not related to the real SC.*

References

[1] C. Lu, L.-H. Hu, Y. Wang, F. Yang, C. Wu arXiv:2112.02610, (2021).

Dr. Aichi Yamashita, Dr. Yoshikazu Mizuguchi

Possible pairing mechanism switching driven by structural symmetry braking in $BiCh_2$-based superconductors

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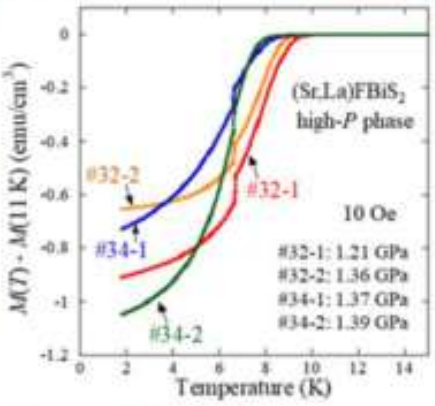
$BiCh_2$-based (Ch: chalcogen) superconductors have attracted much attention as a new layered superconducting family since the discovery in 2012 [1]. Recent theoretical and experimental study suggest the unconventional superconducting mechanism in tetragonal structural phase. To investigate the intrinsic physical properties and superconducting paring mechanisms, we have performed isotope effects for $BiCh_2$-based superconductors. The isotope effect is a direct probe for the importance of phonons for superconductivity. Recently, we have reported two unconventional isotope effects in La(O,F)BiSSe [2] and $Bi_4O_4S_3$ [3]. These unconventional superconductors have tetragonal structures. On the other hand, the superconducting mechanism in the high-pressure phase, which has the highest T_c in $BiCh_2$-based, have not been unveiled so far.

In this study, we performed the isotope effect in the high-pressure phase of $(Sr,La)FBiS_2$. Conventional shifts in superconducting transition temperature indicate the importance of phonons for the pairing. From those results, we concluded that the structural symmetry breaking caused by a structural transition is a conventional-unconventional switch of pairing mechanisms for the $BiCh_2$-based superconductors [4].



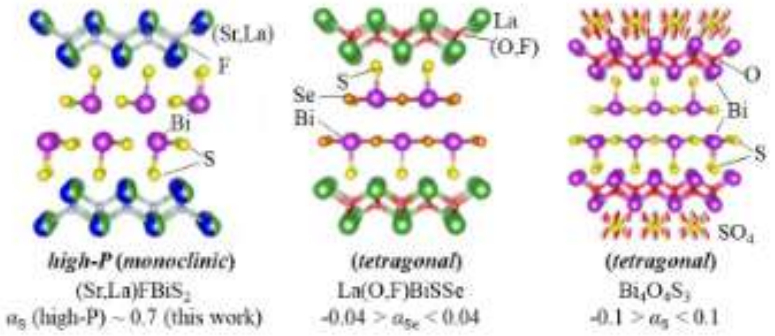


Fig. 1: *(Top)Temperature dependence of magnetization for the high-P phases. (Bottom) Schematic images of crystal structure of the high-P (monoclinic) of $(Sr,La)FBiS_2$ and tetragonal phases of La(O,F)BiSSe and $Bi_4O_4S_3$.*

References

[1]. Y. Mizuguchi et al., J. Phys. Soc. Jpn. **81**, 114725 (2012).
[2]. K. Hoshi et al., Phys. Rev. B **97**, 094509 (2018).
[3]. R. Jha et al., Appl. Phys. Express **13**, 093001(1-5) (2020).
[4]. A. Yamashita et al., Sci. Rep. **11**, 230 (2021).

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Prof. Tadashi Adachi

Ferromagnetic Fluctuations in Heavily Overdoped Bi-2201 cuprates

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It has been theoretically proposed that a ferromagnetic (FM) phase exists and is related to the suppression of superconductivity in the heavily overdoped (HOD) regime of the hole-doped high-T_c cuprates [1]. In non-superconducting HOD La-214 cuprate, three-dimensional FM fluctuations have been suggested from muon-spin-relaxation (μSR) and transport measurements [2]. The FM fluctuations/order have also been suggested in HOD Bi-2201 from RIXS [3] and in heavily electron-doped $La_{2-x}Ce_xCuO_4$ from transport and magnetic measurements [4]. In this talk, we review our results of the two-dimentional FM fluctuations in HOD Bi-2201 cuprates [5,6].

We found in HOD Bi-2201 that the magnetization curve tended to be saturated in high magnetic fields at low temperatures, suggesting the precursor phenomenon toward a possible FM transition at a lower temperature. μSR measurements revealed that spin fluctuations are developed at low temperatures in HOD Bi-2201. The ab- plane electrical resistivity, specific heat and magnetic susceptibility χ of HOD Bi-2201 exhibited temperature dependences characteristic of a metal with two-dimensional FM fluctuations. All these results suggest that two-dimensional FM fluctuations exist in the HOD regime of Bi-2201, suggesting the universality of FM fluctuations in the HOD regime of the high-T_c cuprates.

We also investigated the Fe-substitution effects on FM fluctuations in HOD Bi-2201 [6]. The χ exhibited hysteresis between the zero-field and field cooling at low temperatures, suggesting the formation of spin-glass state. The muon-spin relaxation rate and χ were enhanced by the Fe substitution. The effective Bohr magneton estimated from χ was larger than that of a bare Fe^{3+} spin, suggesting the Fe-induced enhancement of FM fluctuations. We propose the formation of FM spin clusters around each Fe, which is in contrast to antiferromagnetic spin clusters suggested in Fe- substituted Bi-2201 in the overdoped regime [7].

The origin of FM fluctuations in the HOD regime of the hole-doped cuprates would be the itinerant ferromagnetism due to the Fermi-surface nesting and the large density of

states or would be the localized ferromagnetism due to the double exchange interaction relating to the Cu3d$_{x2-y2}$ and Cu3d$_{3z2-r2}$ orbitals.

References

[1] A. Kopp *et al*., Proc. Natl. Adad. Sic. USA **104**, 6123 (2007).
[2] J. E. Sonier *et al*., Proc. Natl. Adad. Sic. USA **107**, 17131 (2010). [3]
Y. Y. Peng *et al*., Phys. Rev. B **98**, 144507 (2018).
[4] T. Sarkar *et al*., Science **368**, 532 (2020).
[5] K. Kurashima *et al*., Phys. Rev. Lett. **121**, 057002 (2018). [6]
Y. Komiyama *et al*., J. Phys. Soc. Jpn. **90**, 084701 (2021).
[7] H. Hiraka *et al*., Phys. Rev. B **81**, 144501 (2010).

Prof. Robert Markiewicz, Prof. Bahadur Singh, Dr. Christopher Lane, Prof. Arun Bansil

Roles of High-order Van Hove Singularities in Cuprates

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High-order Van Hove singularities (VHSs) – i.e., VHSs with power-law instead of logarithmic singularities – have been found in twisted-bilayer materials including graphene[1], attracting considerable attention. Over the past 35 years, they have also shown up in the superconducting cuprates, in a number of distinct contexts. Here we provide an overview of the roles they play in cuprates, illustrating a number of subtle issues that are likely to crop up in other materials as well.
Among our findings, we note that (1) by extending the definition of high-order VHSs, we find a close connection to flat band physics; (2) the power law exponent increases with decreasing dimensionality of the *electronic* dispersion, even in a structurally three-dimensional material, e.g., cubic; (3) the VHS instability manifests itself at two distinct q-vectors in the susceptibility, not just in the q=0 susceptibility, or density-of-states (DOS), and these two instabilities compete with each other – as in the Hubbard model, where near half filling the (π,π) VHS controls the Mott gap; (4) cuprates display a clear correlation between the strength of a high-order VHS and the superconducting critical temperature Tc, Fig. 1.[2]

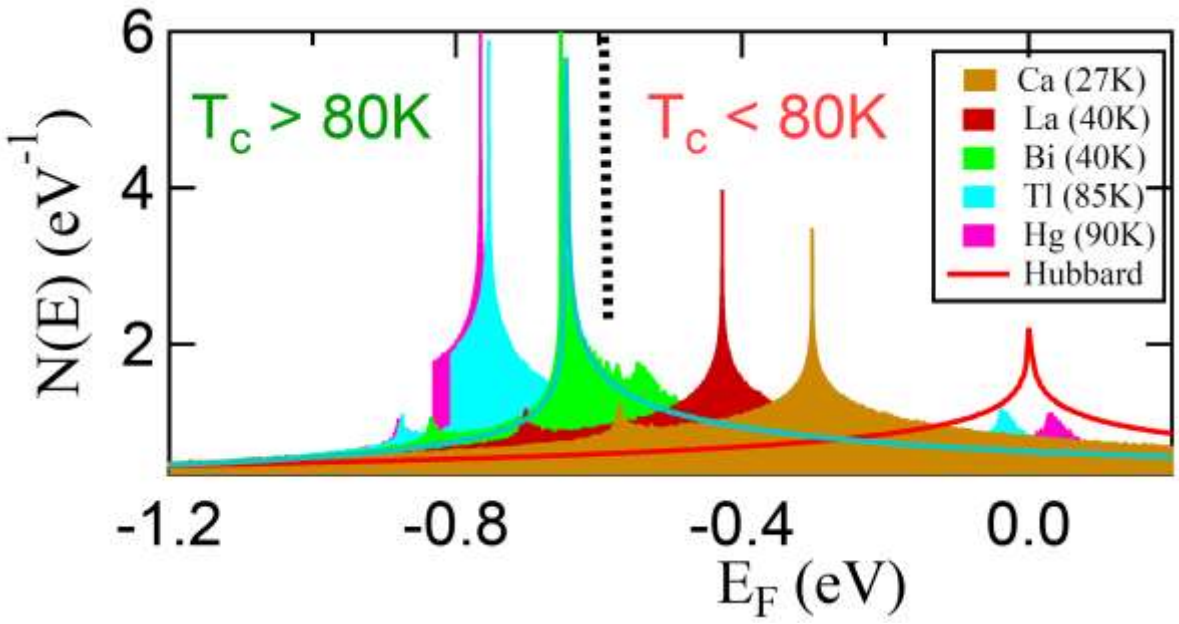

Fig. 1: *DOS of monolayer cuprates at the VHS, compared to Hubbard model.*

References

[1]. F. Noah, Q. Yuan, Hiroki Isobe, and Liang Fu, Nat. Commun. 10, 5769 (2019).
[2]. R.S. Markiewicz, B. Singh, C Lane, and A. Bansil, arXiv:2105.04546.

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Mr. Yau Chuen Yam

Interplay between hole-magnon and hole-phonon couplings on the effective mass of the quasiparticle of strongly underdoped cuprate layers

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It is generally believed that in cuprates, the CuO2 plane captures the most relevant electronic properties. The lowest-energy state in the presence of a doped hole has long been thought to be the so-called Zhang-Rice singlet, derived from the large U_dd limit of a three-band charge transfer gap model, which could then be further simplified to a one-band t-J model. It was found that hole-magnon interactions strongly influence the quasiparticle dispersion in this model. Later, a less simplified three-band model, which can better describe the interaction between the holes and the magnons and the propagation of a doped hole through the lattice, was studied. It was found that the quasiparticle continues to be a spin polaron, however the background spin fluctuations do not affect its dynamics, questioning the validity of the simple t-J model. However, neither of these models takes phonons into account, despite experimental evidence that they may play an important role. In this work, we study the influence of electron phonon coupling of Peierls type (rather than the conventionally used Holstein type) on the quasiparticle of the three-band model.

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Dr. Alexei Tsvelik

'Superconductivity from Spin Liquid – Order Fractionalization, Statistics Transmutation and Topology'

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The idea that by doping spin liquid state with mobile carriers may facilitate superconductivity is well accepted in theory of high temperature superconductivity. However, a scarcity of models allowing a rigorous treatment of spin liquids hampers the progress. In our study we take advantage of exact solvability of a class of such models, the so-called Yao-Lee ones [1], and consider the situation when the local spins of spin liquid interact with conduction electrons via antiferromagnetic exchange interaction. The Yao-Lee model is similar to the famous Kitaev model; it is equivalent to the theory of Majorana fermions coupled to a static Z_2 gauge field, with that essential difference that the number of Majorana species is three and the spin excitations are gapless. The Kondo exchange generates an effective hybridization between conduction electrons carrying charge *e* and spin ½ and neutral Majorana fermions which carry spin 1. This topologically robust mismatch of the quantum numbers serves as a mechanism for the transmutation of statistics: the order parameter – the hybridization matrix element Z_σ, - is a complex bosonic spinor with charge *e* and spin ½. This order is fractionalized; although the gauge invariant object includes two Z-spinors at different space locations connected by the string of the gauge fields, but since the gauge field is static and the string tension is zero, the Z-quanta can be taken apart as far as necessary and hence can be treated as independent.

We discuss the concept of fractionalized order and illustrate it with model calculations for two- and three-dimensional Kondo-Yao-Lee models.

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under Contracts No. DE-SC0012704 (AMT) and DE-FG02-99ER45790 (PC).

References

[1]. H. Yao and D.-H. Lee, "Fermionic Magnons, Non-Abelian Spinons, and the Spin Quantum Hall Effect in an Exactly Solvable Spin-1/2 Kitaev Model with SU(2) symmetry", Phys. Rev. Lett. 107, 087205 (2011).

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Ryota Mizuno

A novel impurity solver in dynamical mean field theory:

Iterative perturbation theory combined with the parquet equations

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Although several impurity solvers in dynamical mean field theory (DMFT) [1] have been proposed, there are practical difficulties arising from a trade-off between numerical costs and reliability, especially in multi-band systems. In this study, we re-interpret the iterative perturbation theory (IPT) [2] as an approximation that captures the strong correlation effects by mimicking the particular frequency structures of the exact two-particle vertex. From this insight, we extend IPT, by combining it with the parquet equations, such that it has efficiency and reliability simultaneously. We apply this method to several models to evaluate the validity. We confirm that our method shows good agreement with the numerically exact continuous-time quantum Monte Carlo method (CT-QMC)[3], not only in single- band systems, but also in multi-band systems. In this presentation, we will explain the details of the method and show the results of benchmarks.

References

[1] A. Georges, et al.: Rev. Mod. Phys. 68 (1996)13. [2] H.
Kajueter et al.: Phys. Rev. Lett. 77 (1996) 131.
[3] A. N. Rubtsov, et al.: Phys. Rev. B 72, 035122 (2005).
[4] R. Mizuno, M. Ochi, K. Kuroki: Phys. Rev. B 104, 035160 (2021).

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Matthias Hecker, Rafael Fernandes

Phonon-induced rotation of the electronic nematic director in superconducting doped Bi_2Se_3

Nematic superconductivity has been directly observed in the doped topological insulator $A_xBi_2Se_3$, with $A = \{Cu, Nb, Sr\}$, as manifested by a two-fold symmetric in-plane critical field H_{c2}. The orientation of the elliptically-shaped in-plane H_{c2} is set by the electronic nematic director, which is parametrized by an angle α. Since the nematic order parameter follows the Z_3-Potts model, the angle α naturally aligns with one of the three high-symmetry directions of the trigonal lattice of Bi_2Se_3. We find that the inclusion of acoustic phonons changes this phenomenology in a fundamental way in trigonal systems, but not in hexagonal ones. Trigonal systems have an additional elastic constant c_{14}, stemming from the fact that the in-plane and out-of-plane shear strain doublets belong to the same irreducible representation. We show that, when c_{14} is large enough, the contribution to the nematic action coming from the coupling to the acoustic phonons makes the nematic director unlock from the high-symmetry directions. We discuss the implication of this rotation of the nematic director in H_{c2} measurements, as well as the applicability of these results to doped Bi_2Se_3.

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Mr. Takahiro Sawahara

Superconductivity in In-doped (Ag*M*Bi)$_{(1-x)/3}$In$_x$Te (*M* = Sn, Pb) with electronic band inversion

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NaCl-type SnTe has been a hot material because of the characteristics of a topological-crystalline insulator [1]. When In was doped for the Sn site, superconductivity with a transition temperature T_c ~ 4 K is observed [2], and the material, In-doped SnTe, has been studied as a candidate system of a topological superconductor. In our recent study, we found that systematic lattice compression is achieved by the substitution of Sn^{2+} site by $(Ag_{0.5}Bi_{0.5})^{2+}$, and the lattice-compressed phases exhibited band inversion, which suggests the possibility of topologically protected electronic states in (Ag,Sn,Bi)Te [3].
To investigate the effects of In doping in (Ag,Sn,Bi)Te, the (Ag,In,Sn,Bi)Te polycrystalline samples were synthesized by high-pressure synthesis. Superconductivity was induced by In doping in (Ag,Sn,Bi)Te with a NaCl-type structure (Fig. 1a). The highest T_c was observed for x = 0.4 (Fig. 1b) [3]. Since In-doped PbTe is also a superconductor system [4], we investigated the effects of lattice compression and In doping in (Ag,Pb,Bi)Te. In the presentation, we will show the crystal structure, electronic structure, and superconducting properties of In-doped (Ag*M*Bi)$_{(1-x)/3}$In$_x$Te (*M* = Sn,Pb).

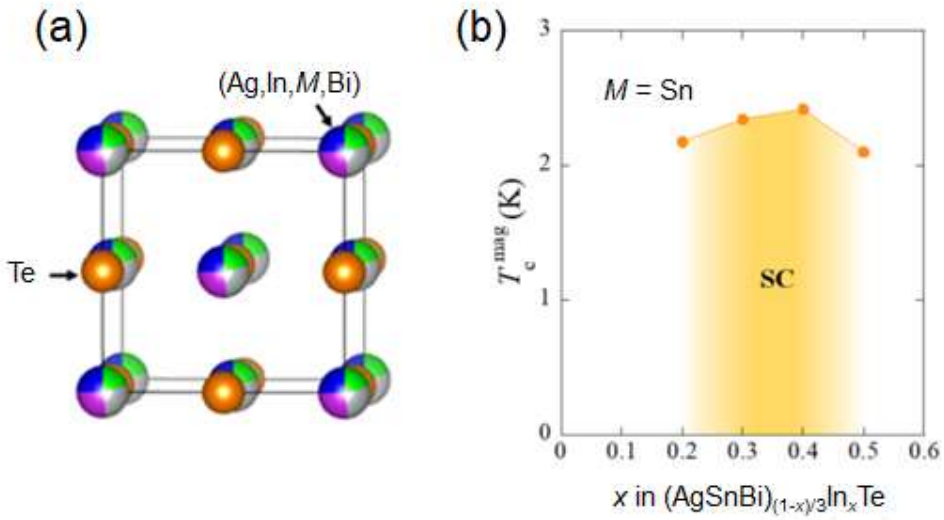

Fig. 1: (a) Schematic image of NaCl-type crystal structure of $(AgMBi)_{(1-x)/3}In_xTe$ (drawn by VESTA). (b) Superconductivity phase diagram for *M* = Sn.

References

[1] T. H. Hsieh *et al.,* Nat. Commun. **3**, 982 (2012).
[2] G. Balakrishnan *et al.,* Phys. Rev. B **87**, 140507 (2013).
[3] T. Mitobe *et al.*, Sci. Rep. **11**, 22885 (2021).
[4] M. Katsuno *et al.,* Condens. Matter **5**, 14 (2020).

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Paul Froese

Superconducting Gap Symmetry of a Microscopic Model for Underdoped Cuprates

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We use a BCS approach to investigate the symmetry of the superconducting state that arises in a microscopic model for underdoped cuprates. The starting point assumes that the doped holes move on the O sublattice while interacting with spins at the Cu sites, forming a spin-polaron quasiparticle with the correct dispersion [1,2]. Exchange of magnons between the doped holes leads to an effective attraction of an unusual type, whereby both holes hop around a common Cu site and flip their spins [3]. We investigate the possible superconducting states and their symmetries for this effective multi-band model of quasiparticles subjected to this effective magnon-mediated interaction.

References

[1]. B. Lau, M. Berciu and G. A. Sawatzky, Phys. Rev. Lett. **106**, 036401 (2011).
[2]. H. Ebrahimnejad, G. A. Sawatzky and M. Berciu, Nature Physics **10**, 951-955 (2014).
[3]. M. M. Moeller, C. P.J. Adolphs and M. Berciu, Phys. Rev. B **100**, 165118 (2019) .

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Mr. Morihiko Nishida

Transient Terahertz Optical Response of Stripe-ordered Superconductor $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$

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High- cuprate superconductors are known to generally have charge- and spin-ordered phases, whose interplay between superconductivity is much of interest. Especially in La-based cuprates, lattice distortion stabilizes stripe-like ordering of charge and spin, referred to as stripe orders. Recently, melting of the distortion and the stripe orders by optical pumping [1,2] or static pressure [3] were revealed to increase superconducting transition temperature. Although these results indicate the competition between stripe orders and superconductivity, the microscopic mechanism remains to be resolved.
Here, we performed optical-pump terahertz (THz)-probe spectroscopy of stripe-ordered cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (x=0.12). In this compound Nd^{3+} ions are substituted for La^{3+}, causing lattice distortion which pins stripe orders.
The dynamics and the temperature dependence of *c*-axis reflectivity change in the THz frequency range after photo-excitation are represented in Fig.1(a) and 1(b). At 9 K, a plasma edge-like structure appears just after photo-excitation (0.8 ps), followed by low-frequency shift within a few ps. This plasma edge-like structure was observed up to around charge-stripe ordering temperature , suggesting that coherent *c*-axis transport was recovered by melting of charge-stripe. We will discuss the origin of this *c*-axis THz response.

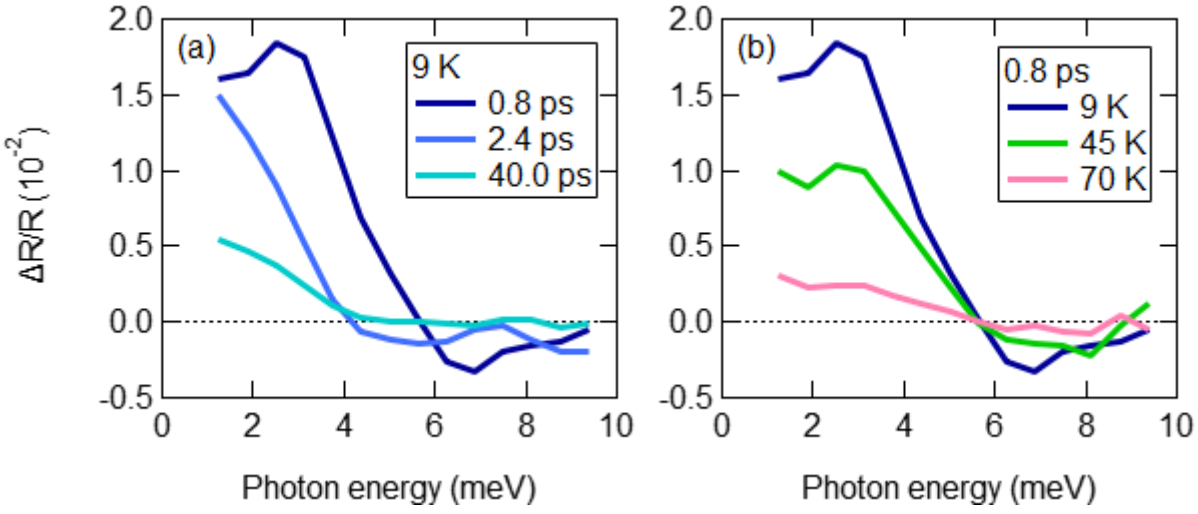

Fig. 1: *c-axis transient reflectivity change after photo-excitation* (*a*) *and its temperature dependence* (*b*). .

References

[1]. D. Fausti *et al*., Science **331**, 189-191 (2011).
[2]. D. Nicoletti *et al*., Phys. Rev. B **90**, 100503(R) (2014).
[3]. Z. Guguchia *et al*., Phys. Rev. Lett. **125**, 097005 (2020).

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Professor Pengcheng Dai

Abstract Title Resonance from antiferromagnetic spin fluctuations for superconductivity in UTe_2

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Superconductivity originates from the formation of bound (Cooper) pairs of electrons that can move through the lattice without resistance below the superconducting transition temperature T_c. While electron Cooper pairs in most superconductors form anti-parallel spin-singlets with total spin $S=0$, they can also form parallel spin-triplet Cooper pairs with $S=1$ and an odd parity wavefunction. Spin-triplet pairing is important because it can host topological states and Majorana fermions relevant for quantum computation. Since spin-triplet pairing is usually mediated by ferromagnetic (FM) spin fluctuations, uranium based materials near a FM instability are considered ideal candidates for realizing spin-triplet superconductivity. Indeed, UTe_2, which has a T_c ~1.6 K, has been identified as a candidate for chiral spin-triplet topological superconductor near a FM instability, although it also has antiferromagnetic (AF) spin fluctuations. Here we use inelastic neutron scattering (INS) to show that superconductivity in UTe_2 is coupled with a sharp magnetic excitation, termed resonance, at the Brillouin zone (BZ) boundary near AF order. Since the resonance has only been found in spin-singlet unconventional superconductors near an AF instability, its discovery in UTe_2 suggests that AF spin fluctuations may also induce spin-triplet pairing or that electron pairing in UTe_2 has a spin-singlet component [1].

[1]. Chunruo Duan et al., Nature **DOI :** 10.1038/s41586-021-04151-5 (2021).

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Dr. Mikhail Eremets

Recent Progress in High-Temperature Conventional Superconductivity

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Room-temperature superconductivity became realistic as a result of dramatic progress in conventional superconductivity. Soon after the discovery of high critical temperature T_c = 203 K in hydrogen sulfide at about 150 GPa [1], many novel hydrogen-rich superconducting compounds were revealed. These compounds have a clathrate or cage-like structure, in which a metal atom inside the cage acts as an electron donor, while hydrogen atoms form weak covalent bonds with each other within the cage. Such crystal lattices are favourable for both high-frequency phonons and strong electron-phonon coupling – the necessary condition of high-temperature conventional superconductivity – and exhibit even higher T_cs, e.g. 243 K in YH_9 at about 200 GPa [2] and 250 K in LaH_{10} at about 170 GPa [3-6]. Interestingly, these superhydrides can be considered as doped atomic hydrogen and close realization of superconducting metallic hydrogen.

In contrast to the superhydrides, in the crystal structure of H_3S each hydrogen atom is connected with the two neighbouring sulfur atoms by a strong covalent bond. The strong bonding provides large electron-phonon coupling and enhanced superconductivity. The covalent metals are most promising ambient pressure superconductors. We will emphasize our recent studies of magnetic properties of the conventional superconductors.

1. Drozdov, A.P., et al., *Conventional superconductivity at 203 K at high pressures.* Nature 2015. **525**: p. 73.
2. Kong, P.P., et al., *Superconductivity up to 243 K in the yttrium-hydrogen system under high pressure.* Nature Comm., 2021. **12**: p. 5075.
3. Drozdov, A.P., et al., *Superconductivity at 250 K in lanthanum hydride under high pressures* Nature, 2019. **569** p. 528.
4. Somayazulu, M., et al., *Evidence for Superconductivity above 260 K in Lanthanum Superhydride at Megabar Pressures.* Phys. Rev. Lett., 2019. **122** p. 027001.
5. Sun, D., et al., *High-temperature superconductivity on the verge of a structural instability in lanthanum superhydride.* Nature Communications, 2021.
6. Minkov, V., et al., *Experiments on superconductivity in S-C-H system at high pressure. Raman. X-ray and electrical studies.* 2021.

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Prof. Mohit Randeria

Bounds on Tc for strongly correlated and flat band superconductors

Mohit Randeria

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I will first describe exact upper bounds on the BKT Tc in 2D superconductors that are expressed in terms of the optical sum rule spectral weight. These general results are valid for multi-band systems independent of pairing strength or mechanism, with the only assumption that the vector potential couples to the kinetic energy and not the interactions. I will show that the bounds are particularly useful for strongly correlated superconductors where mean field theory fail, and then discuss applications to a variety of materials including Li:ZrNCl, monolayer FeSe/STO, and magic angle twisted bilayer graphene. I will then generalize these results to flat-band models, where we need to bound the low-energy optical spectral weight for which we cannot use the usual Peierls' substitution. I will present bounds on Tc for both topologically trivial and non-trivial flat bands that are related to the quantum geometry of the flat band Wannier functions.

Prof. Bernhard Keimer

Strain as exploratory tool for cuprate superconductors

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We will discuss how strain tuning can open up new regimes of the phase diagram of cuprate high-temperature superconductors. Elastic and inelastic x-ray scattering experiments $YBa_2Cu_3O_{6+x}$ have demonstrated that uniaxial strain enhances two-dimensional charge order and induces a three-dimensional charge density wave that competes strongly against superconductivity [1,2]. We will also show initial results of measurements designed to establish a correspondence between the atomic-scale charge correlations and the macroscopic transport properties under uniaxial strain [3]. Finally, we will show that stabilization by epitaxial strain allows the synthesis of highly overdoped $La_{2-x}Ba_xCuO_4$ films with lower levels of disorder than in other "214" superconductors [4]. The persistence of superconductivity beyond the superconducting "dome" in the phase diagram of other 214 compounds suggests that doping-induced disorder is the leading cause of the disappearance of superconductivity at high doping levels.

References

[1]. H.-H. Kim, S. M. Souliou, M. E. Barber, E. Lefrançois, M. Minola, M. Tortora, R. Heid, N. Nandi, R. A. Borzi, G. Garbarino, A. Bosak, J. Porras, T. Loew, M. König, P. M. Moll, A. P. Mackenzie, B. Keimer, C. W. Hicks, M. Le Tacon, Science 362, 6418, 1040 (2018)

[2] H.-H. Kim, E. Lefrançois, K. Kummer, R. Fumagalli, N. B. Brookes, D. Betto, S. Nakata, M. Tortora, J. Porras, T. Loew, M. E. Barber, L. Braicovich, A. P. Mackenzie, C. W. Hicks, B. Keimer, M. Minola, and M. Le Tacon, Phys. Rev. Lett. 126, 037002 (2021).

[3] S. Nakata et al., to be published.

[4] G. Kim, K. S. Rabinovich, A.r V. Boris, A. N. Yaresko, Y. E. Suyolcu, Y.-M. Wu, P. A. van Aken, G. Christiani, G. Logvenov, B. Keimer, PNAS 118, e2106170118 (2021)

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Prof. Giacomo Ghiringhelli

Charge order, fluctuations and excitations of cuprates across *T*c and *T** studied by RIXS

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High Tc superconductors are stubbornly eluding our understanding due to the complex landscape of interactions, where localization and collective phenomena get entwined. Strong electronic correlation provides the robust antiferromagnetic scaffold and the persistent *d*-wave symmetry of the electronic structure, including the superconducting gap. Although nearest neighbor interactions are indeed shaping the orbital and spin physics, wider range hopping terms cannot be neglected and lead to significant spin and orbital phenomena already in the parent compounds [1]. Charge density modulations, in the form of charge density waves (CDW), occasionally coupled to spin order to form stripes, and charge density fluctuations (CDF) are manifestations of charge density instability pervading a large part of the phase diagram [2,3]. Their relations with transport properties, such as CDW competition with superconductivity, CDF influence on strange metal resistivity in the normal state and CDW/CDF intermixing with phonons, must encourage us to enquire their ultimate role on the very superconductivity of cuprates.
Resonant inelastic x-ray scattering (RIXS) spectra offer an exceptional opportunity to study the entanglement of charge, spin orbital and lattice properties in curates as they simultaneously provide the all corresponding excitations. Thanks to the recent progress in resolution and sensitivity of RIXS instrumentation at ESRF and DLS, the temperature dependence of charge order, charge density fluctuations and particle-hole excitations have become possible with unprecedented accuracy. I will present recent results on YBCO, Bi2212 and other hole doped cuprates where the crossing of the significant temperatures such as T_c, T_{CDW} and T^* is reflected into the low energy RIXS spectral function, dominated by the particle-hole excitations and by charge density fluctuations. These results provide a fresh insight on the very nature of the pseudogap phenomenon in cuprates.

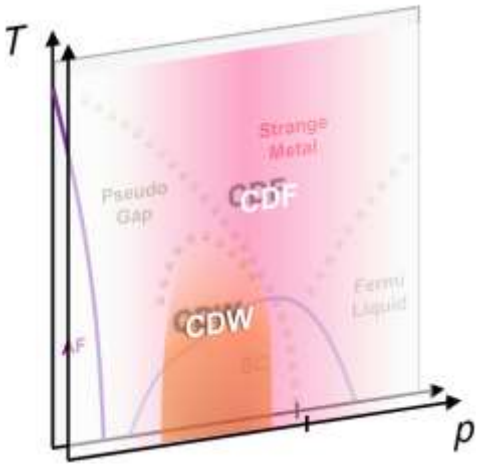

Fig. 1: *The phase diagram of hole doped cuprates: RIXS results have added the CDW/CDF layer on the previously established antiferromagnetism-pseudogap-strange metal-superconductivity scenario (from Ref [2]).*

References

[1]. L. Martinelli, D. Betto, K. Kummer, R. Arpaia, L. Braicovich, D. Di Castro, N. B. Brookes, M. Moretti Sala, and G. Ghiringhelli, arXiv:2110.06666 (2021).
[2]. R. Arpaia and G. Ghiringhelli, J. Phys. Soc. Japan, **90**, 111005 (2021).
[3]. W.-S. Lee, K.-J. Zhou, M. Hepting, [...], J. Zaanen, and T. P. Devereaux, Nat. Phys. **17**, 53 (2021).

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Prof. Joerg Schmalian

Superconductivity without quasiparticles: Quantum critical Eliashberg theory and its holographic dual

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Superconductivity is abundant near quantum-critical points, where fluctuations suppress the formation of Fermi liquid quasiparticles and the Bardeen-Cooper- Schrieffer theory no longer applies. Two very distinct approaches have been developed to address this issue: quantum-critical Eliashberg theory and holographic superconductivity. The former includes a strongly retarded pairing interaction of ill- defined fermions, the latter is rooted in the duality of quantum field theory and gravity theory. We demonstrate that both are different perspectives of the same theory. We derive holographic superconductivity in form of a gravity theory with emergent space- time from a quantum many-body Hamiltonian - the Yukawa SYK model - where the Eliashberg formalism is exact. Exploiting the power of holography, we then determine the dynamic pairing susceptibility of the model. Our holographic map comes with the potential to use quantum gravity corrections to go beyond the Eliashberg regime.

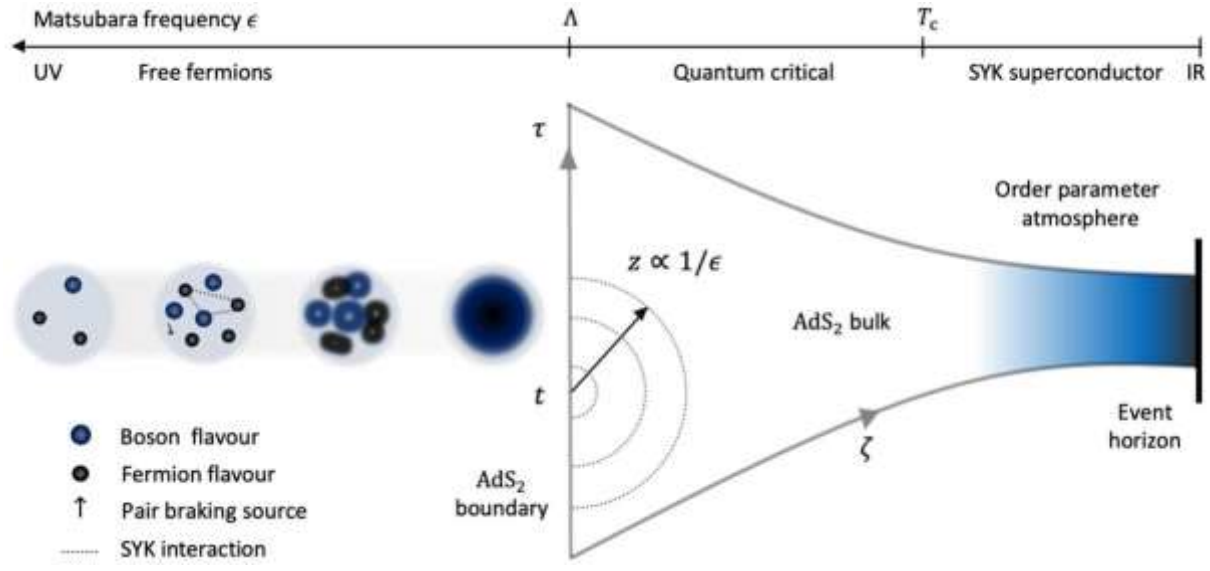

Fig. 1: T*he emergence of the dual holographic theory from the SYK superconductor. Below the UV scale Λ, a strongly coupled quantum-critical fluid forms out of interacting fermions and bosons. Below this scale the fluctuating order parameter becomes a scalar field with emergent AdS2 gravity and forms an atmosphere around a black hole event horizon.*

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Possibility of field-induced Bogoliubov Fermi surfaces in $FeSe_{1-x}S_x$

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The layered iron-chalcogenide superconductor FeSe has attracted a great deal of attention due to its unique features. FeSe is a compensated semimetal with extremely small Fermi surfaces, which undergoes a structural phase transition from tetragonal to orthorhombic, or, nematic transition at 90K. In contrast to other iron-based superconductors, no magnetic transition is observed. Substitution of Se with S suppresses the nematic transition temperature, and the nematic quantum critical point (QCP) is believed to be located at S content x~0.17 [1].

The superconducting gap structure is highly anisotropic, and a BCS-BEC crossover-like behavior is observed. In the high magnetic field region, there appears a novel superconducting phase, indicative of the FFLO phase. In the vicinity of the nematic QCP, the pairing state is likely a chiral state with broken time-reversal symmetry [1]. This state has been phenomenologically studied in the context of the Bogoliubov Fermi surface (BFS) [2]. However, it is unclear whether such a chiral state can be explained from the microscopic viewpoint. It is not yet conclusive whether the high-field phase is the well-known FFLO state. It will be interesting to consider the relationship between the BFS state and the high-field phase.

Here, we would like to consider the possibility of a field-induced BFS state. First, we construct a BCS model consistent with the original j=3/2 model [3] and studied the evolution of BFS under a magnetic field. Figure 1 shows the BFS under in-plane/out-of-plane fields. We found that the size of the BFS increases under the magnetic field, in contrast to the temperature dependence, and curious islands of BFS appear in the in-plane field. Next, we investigate the instability of the BFS state due to the remaining interaction [4]. In the presentation, we will show the H-T phase diagram, and discuss its relationship to the putative FFLO state.

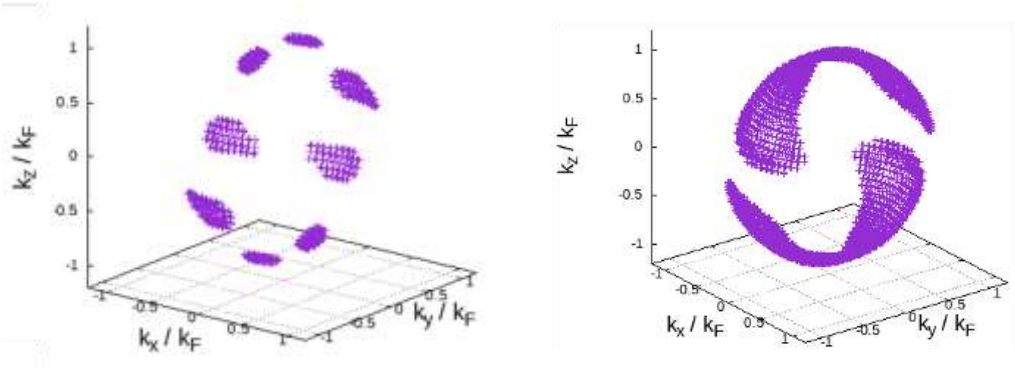

Fig. 1: Bogoliubov Fermi surface under the in-plane field (Left) and the out-of-plane field (Right).

References

[1] T. Shibauchi et al, J. Phys. Soc. Jpn. **89**, 102002 (2020).
[2] C. Setty et al, Nat Commun **11**, 523 (2020).
[3] D. F. Agterberg, P. M. R. Brydon, and C. Timm, Phys. Rev. Lett **118**, 127001 (2017).
[4] S.-T. Tamura, S. Imura, and S. Hoshino, Phys. Rev. B **102**, 024505 (2020).

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From Mott to Not: Phenomenology of the Overdoped Cuprate Superconducting State

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Recent experimental data on superfluid density and terahertz conductivity of overdoped LSCO have exhibited behavior incompatible with a clean BCS superconductor [1]. However, it has also been suggested that the properties observed are however compatible with “dirty d-wave theory” assuming weak scattering by dopant atoms [2,3]. These calculations were extended to specific heat and thermal conductivity data on LSCO, as well as another overdoped cuprate, Tl-2201. The latter system was thought to be quite clean since it exhibits quantum oscillations, low residual resistivities and small superconducting state Sommerfeld coefficients. Nevertheless, the same phenomenological behavior is observed, and captured by the dirty d-wave theory. Here we attempt to place this theory on a more quantitative basis by performing ab-initio calculations of dopant impurity potentials for LSCO and Tl-2201. These potentials are more complex than the pointlike impurity models considered previously, and require calculation of forward scattering corrections to transport properties. Including realistic, ARPES-derived bandstructures and Fermi liquid renormalizations, we show that the theory can explain semiquantitatively a wide variety of results on the two most studied overdoped materials, and make predictions for future measurements. We conclude that overdoped cuprates can be described semiquantitatively by dirty d-wave theory, subject to significant Fermi liquid renormalizations, without introducing physics beyond the Landau-BCS paradigm.

[1] I. Bozovic, X. He, J. Wu and A. T. Bollinger, Nature 536, 309 (2016). F. Mahmood, X. He, I. Bozovic, and N. P. Armitage, Phys. Rev. Lett. 122, 027003 (2019).

1. N. Lee-Hone, J. S. Dodge, and D. M. Broun, Phys. Rev. B 96, 024501 (2017).
2. N. Lee-Hone, V. Mishra, D. Broun and P.J. Hirschfeld, Phys. Rev. B 98, 054506 (2018).
3. N. R. Lee-Hone, V. Mishra, U. Őzdemir, D. M. Broun, and P. J. Hirschfeld, Phys. Rev. Res.2, 013228 (2020).