Superconductivity at low carrier density

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I will discuss some aspects of superconductivity at low density of carriers. I first discuss how to compute T_c with the exact prefactor for the case of a dynamical electron-phonon interaction, and show that there is a qualitative difference between this case and a static interaction. I then discuss the computation of T_c and the gap function for the case when both electron-phonon and electron-electron interaction are present, and show a similarity to nodal topological superconductivity.

Enhanced superconductivity in plastically deformed strontium titanate

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The properties of quantum materials are commonly tuned using experimental variables such as pressure, magnetic field and doping. Here we explore a different approach: irreversible, plastic deformation of single crystals. We show for the archetypal unconventional superconductor $SrTiO_3$ that compressive plastic deformation induces low-dimensional superconductivity significantly above the superconducting transition temperature (T_c) of undeformed samples. We furthermore present evidence for unusual normal-state transport behaviour that suggests superconducting correlations at temperatures two orders of magnitude above the bulk T_c. The superconductivity enhancement is correlated with the appearance of self-organized dislocation structures, as revealed by diffuse neutron and X-ray scattering. These results suggest that Tc in $SrTiO_3$ is strongly influenced by strain, consistent with a theory of superconductivity enhanced by soft polar fluctuations. More broadly, our results demonstrate the promise of plastic deformation and dislocation engineering as tools to manipulate electronic properties of quantum materials.

Low-density superconductivity in $SrTiO_3$ bounded by the adiabatic criterion

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The dilute oxide semiconductor $SrTiO_3$ exhibits superconductivity over a wide range of carrier densities (10^{19}-10^{21} cm^{-3}). Across this range, the Fermi level traverses a number of vibrational modes in the system, making it an ideal choice to study the physics of dilute superconductivity. Here we use high-resolution planar-tunneling spectroscopy to probe superconductivity in chemically- doped $SrTiO_3$ across the superconducting dome. The over-doped superconducting boundary aligns, with surprising precision, to the Fermi energy crossing the Debye energy. Superconductivity emerges with decreasing density, throughout which it maintains the gap to transition-temperature ratio of the BCS weak-coupling limit, despite being in the anti-adiabatic regime. At lowest superconducting densities, the lone remaining adiabatic phonon van Hove singularity is the anomalously soft transverse-optic mode, which is associated with the ferroelectric instability.

Superconducting domes from finite-range interactions in BCS theory

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Many properties of superconductors are universal and thus insensitive to details on the underlying model. For this reason, one can often work with simplified models. One standard such simplification in BCS theory is to assume that the pairing interaction is local. However, non-universal properties like the superconducting critical temperature, T_c, depend on model details.

In this talk I present a method to reliably take into account a non-trivial spatial dependence of the superconducting pairing interaction. Our results show that non-local pairing interactions always lead to superconducting domes: a non-monotonic dependence of T_c as a function of the carrier concentration, n.

Based on work in collaboration with C. Triola and A.V. Balatsky, Phys. Rev. Lett. 122, 157001 (2019) arXiv:1810.03349

The enigmatic susceptibility peak in magnetic and dielectric materials

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The field-induced polarization in many nearly ferromagnetic or ferroelectric materials is initially enhanced by thermal fluctuations at low temperatures. The origin of this phenomenon, sometimes described in terms of the idea of “order by disorder”, remains in certain cases mysterious. We review origins that have been proposed and present a model that provides a quantitative description of this phenomenon in displacive quantum paraelectrics in particular [1,2].

1.“Ferroelectric quantum criticality”, S. E. Rowley, L. J. Spalek, R. P. Smith, M. P. M. Dean, M. Itoh, J. F. Scott, G. G. Lonzarich and S. S. Saxena, Nature Physics, 10, 367-372 (2014)

2. “Quantum critical phenomena in a compressible displacive ferroelectric”, M. J. Coak, C. R. S. Haines, C. Liu, S. T. Rowley, G. G. Lonzarich and S. S. Saxena, PNAS, 117 (23) 12707-12712 (2020)

Superconductivity mediated by ferroelectric modes in systems with spin-orbit coupling

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Recent experimental and theoretical works suggest an interplay between ferroelectricity and superconductivity in $SrTiO_3$. Motivated by these studies, we study superconductivity mediated by odd-parity ferroelectric modes. We consider a Rashba-like coupling between the electrons and ferroelectric fluctuations, present in systems with spin-orbit coupling, and solve the linearized gap equation away from quantum criticality. A procedure to compute the Rashba-like coupling functions of the electronic bands with the polar modes will also be discussed.

Multiferroic Quantum Criticality

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The zero-temperature limit of a continuous phase transition is marked by a quantum critical point, which can generate exotic physics that extends to elevated temperatures [1]. Magnetic quantum criticality is now well known, and has been widely explored [2]. Ferroelectric quantum critical behavior has also been recently established in $SrTiO_3$, motivating a flurry of research investigating its consequences [3]. In this talk, I will present the concept of multiferroic quantum criticality - in which both magnetic and ferroelectric quantum criticality occur in the same system - that we have recently proposed [4]. I will describe the phenomenology of multiferroic quantum critical behavior and its emergence in complex transition metal perovskite oxides.

[1] S. Sachdev, Quantum phase transitions (Cambridge University Press, Cambridge, 2011).
[2] P. Gegenwart, Q. Si, and F. Steglich, Nature Physics 4, 186 (2008).
[3] S. Rowley et al., Nature Physics 10, 367 (2014).
[4] A. Narayan, A. Cano, A. V. Balatsky, and N. A. Spaldin, Nature Materials 18, 223 (2019).

Novel Metallicity near Polar Quantum Critical Points

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Quantum criticality in metallic systems leads to a variety of exotic behaviors that depend sensitively on the type of the quantum phase transition involved. Motivated by recent experiments on doped strontium titanate, we ask whether metals close to polar quantum critical points can develop strongly interacting novel phases. The case of a polar transition in a metal, structurally identical to a ferroelectric transition in an insulator, is challenging because the critical mode, a transverse optical phonon, does not couple easily to the electronic degrees of freedom. In our work we show there exists a robust coupling not requiring spin-orbit coupling between the critical polar mode and electrons in multiband metals. We identify and characterize several novel interacting phases, including non-Fermi liquids, when band crossings are close to the Fermi level so that particle-hole excitations are gapless. Experimental signatures that probe these emergent behaviors will be discussed, and we'll conclude with implications for existing materials.

P.A. Volkov and P. Chandra, "Multiband Quantum Criticality of Polar Metals," Physical Review Letters 124, 237601 (2020)

TBA

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Scanning SQUID imaging of $LaAlO_3/SrTiO_3$ conductivity near the metal-insulator transition

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Tetragonal domain patterns in $SrTiO_3$ are known to locally modify the electronic properties of $SrTiO_3$ based systems. In my talk, I will show how the introduction of such patterns interferes with the gate driven metal-insulator transition (MIT) in the $LaAlO_3/SrTiO_3$ interface. We used scanning SQUID microscopy to map current paths in $LaAlO_3/SrTiO_3$ devices tuned through the MIT. We found that the emergence of metallicity is strongly correlated with the $SrTiO_3$ tetragonal domain patterns, emerging at quasi-1D channels formed by domain boundaries. I will discuss the relationship between the local observations and the critical behavior of the system.

T^2 and T^n resistivity in $SrTiO_3$ films and titanate heterostructures

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One of the notable gaps in our understanding of $SrTiO_3$ is the mechanism for T^2 resistivity, which is the dominant scattering rate for this material in the intermediate cryogenic temperature range (approximately 10-150 K). This talk will present an overview of the experimental trends in this scattering rate, based on systematic studies of uniformly doped thin $SrTiO_3$ films and $SrTiO_3$ /$RTiO_3$ (R = Gd, Sm) heterostructures with two-dimensional doping from polar discontinuity [1-3]. While the T^2 scaling is traditionally associated with electron-electron interactions in a Fermi liquid, this assignment is challenged by the persistence of this scattering up to near-room temperatures, and low carrier densities where momentum dissipation through Umklapp scattering is impossible. This calls for a theoretical reevaluation of the microscopic description to account for persistence of this scattering rate across wide ranges of temperature and carrier density. Additionally, it needs to allow for a certain degree of universality, given the widespread observations of T^2 resistivity in three and two-dimensional metallic perovskites. Another hint at universality comes from the studies of quantum well titanate heterostructures [3, 4], where the normal state resistance takes on aspects of cuprate-like physics: non-Fermi liquid behavior and scattering rate separation. As a function of 2DEG confinement in a quantum well, the power law T^n resistivity evolves from n = 2 into an anomalous n = 1.6 scaling near a quantum phase transition, while the T^2 scaling is maintained in the Hall angle. This directly parallels the lifetime separation phenomenon, extensively documented in the cuprates.

[1] E. Mikheev, B. Himmetoglu, A. P. Kajdos, P. Moetakef, T. A. Cain, C. G. Van de Walle, S. Stemmer. Limitations to the room temperature mobility of two- and three-dimensional electron liquids in $SrTiO_3$ .Applied Physics Letters 106 (6), 062102, 2015.
[2] E. Mikheev, S. Raghavan, J. Y. Zhang, P. B. Marshall, A. P. Kajdos, L. Balents, S. Stemmer. Carrier density independent scattering rate in $SrTiO_3$ -based electron liquids. Scientific Reports 6 (1), 1-8, 2016
[3] E. Mikheev, C. R. Freeze, B. J. Isaac, T. A. Cain, S. Stemmer. Separation of transport lifetimes in $SrTiO_3$-based two-dimensional electron liquids. Physical Review B 91 (16), 165125, 2015.
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T-square resistivity in dilute metals without Umklapp scattering

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The electrical resistivity of Fermi liquids (FLs) displays a quadratic temperature (T) dependence because of electron-electron (e-e) scattering. For such collisions to decay the charge current, there are two known mechanisms: interband scattering (identified by Baber) and Umklapp events. However, dilute metallic strontium titanate ($SrTiO_3$) was found to display T^2 resistivity in absence of either of these two mechanisms. The presence of soft phonons in $SrTiO_3$ and their possible role as scattering centers raised the suspicion that T-square resistivity in $SrTiO_3$ is not due to e-e scattering. Hereafter, we present another case: Bi_2O_2Se, a layered semiconductor with hard phonons, which becomes a dilute metal with a small single-component Fermi surface upon doping. It displays T-square resistivity well below the degeneracy temperature where neither Umklapp nor inter-band scattering is conceivable. We observe a universal scaling between the prefactor of T^2 resistivity and the Fermi energy in $SrTiO_3$ and Bi_2O_2Se and across various FLs, which is an extension of the Kadowaki-Woods plot. Our results imply the absence of a satisfactory theoretical basis for the ubiquity of e-e driven T-square resistivity in Fermi liquids.

Quasiparticle and non-quasiparticle transport in doped quantum paraelectrics

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Charge transport in doped quantum paralectrics (QPs) presents a number of puzzles, including a pronounced T^2 regime in the resistivity. We analyze charge transport in a QP within a model of electrons coupled to a soft transverse optical (TO) mode via a two-phonon mechanism. For T above the soft-mode frequency but below some characteristic scale (E_0), the resistivity scales with the occupation number of phonons squared, i.e., as T^2. The T^2 scattering rate is not affected by a crossover between degenerate and non-degenerate regimes, in agreement with the experiment. Temperatures higher than E_0 correspond to a non-quasiparticle regime, which we analyze by mapping the Dyson equation onto a problem of supersymmetric quantum mechanics. The combination of scattering by two TO phonons and by a longitudinal optical mode explains the data quite well.

Specific Heat of Doped $SrTiO_3$

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In this talk I will review two contributions to the understanding of the structural and electronic properties of doped and substituted $SrTiO_3$, achieved via measurements of specific heat [1,2]. I will first briefly review quantitative rationalization of the variation of the temperature of the antiferrodistortive transition (T_a) with substitution in $SrTiO_3$ [1]. Valence mismatch between the substituent and host is shown to play the key role, providing quantitative understanding of T_a for all known substitutions [1]. Lower temperature lattice dynamic contributions to specific heat can also be understood, in terms of the established phonon density-of-states and soft mode behavior [2]. Electronic contributions to specific heat are then analyzed vs. electron doping across the two Lifshitz transitions [2]. Quantitative agreement with quantum oscillation data and calculated band structure is achieved, establishing a doping-independent mass enhancement factor of 2.0 [2]. Finally, with the doping-dependent Sommerfeld coefficient determined for the first time, in combination with the doping-dependent T^2 resistivity prefactor, Kadowaki-Woods scaling can be rigorously tested. This scaling is violated at low doping [2], but obeyed at high x in $Sr_{1-x}La_xTiO_3$. Implications of these results will be briefly discussed.

[1] McCalla, Walter and Leighton, Chem. Mater 28, 7973 (2016)

[2] McCalla, Gastiasoro, Cassuto, Fernandes and Leighton, Phys. Rev. Mater. 3, 022001(R) (2019)