Magneto-transport near a quatum critical point

Analytis, James
(University of California, Berkeley, USA)

The physics of quantum critical phase transitions connects to some of the most difficult problems in condensed matter physics, including metal-insulator transitions, frustrated magnetism and high temperature superconductivity. Near a quantum critical point (QCP) a new kind of metal emerges, whose thermodynamic and transport properties do not fit into the unified phenomenology with which we understand conventional metals - the Landau Fermi liquid (FL) theory - characterized by a low temperature limiting T-linear specific heat and a T^2 resistivity [1]. Studying the evolution of the T dependence of these observables as a function of a control parameter leads to the identification both of the presence and the nature of the quantum phase transition in candidate systems. In this study we measure the transport properties of \basp\, at $T<T_c$ by suppressing superconductivity with high magnetic fields. At sufficiently low temperatures, the resistivity of all compositions ($x \geq 0.31$) crosses over from a linear to a quadratic temperature dependence, consistent with a low temperature FL ground state. As compositions with optimal T_c are approached from the overdoped side, this cross-over becomes steeper, consistent with models of quantum criticality where the effective Fermi temperature T_F goes to zero.

Universal Fermi-liquid scattering rate throughout the phase diagram of the cuprates

Barišić, Neven
(Technische Universität Wien,)

The enigmatic “strange-metal” phase of the cuprates remains one of the major puzzles in condensed matter physics. Numerous unconventional electronic scattering mechanisms have been proposed, and it has been suggested by many that Landau’s remarkably successful quasiparticle paradigm should be abandoned. In a series of papers, we demonstrated that, deep in the pseudogap (PG) regime, the nature of charge carriers is in fact best described as a Fermi liquid (FL): the scattering rate is quadratic in both temperature [1] and frequency [2], and Kohler’s rule for the magnetoresistance is obeyed [3]. Starting from this well-documented PG/FL state, we subsequently demonstrated that the transport scattering rate remains quadratic in temperature even in the strange-metal phase and, importantly, that this quantity is doping and compound independent, and hence universal [4]. We have thus been able to quantitatively connect the well-accepted FL properties at high doping with those recently established deep in the PG phase, and to demonstrate that the strange-metal phase hosts hidden FL behaviour and is not so strange after all. When interpreted in a simple, logical manner, our findings have several significant implications [4]: (i) the well-known temperature dependence of the Hall effect in the strange-metal phase mandates a conventional interpretation, namely a temperature-dependent carrier density; (ii) the PG phenomenon signifies the gradual localization of one hole per unit cell upon cooling; (iii) the mysterious T-linear resistive behaviour in the strange-metal phase is the result of a FL T^2 scattering rate combined with a T-linear increase in carrier density.

[1] N. Barišić et al., Proc. Natl. Acad. Sci. U.S.A. 110, 12235 (2013)
[2] S. I. Mirzaei et al., Proc. Natl. Acad. Sci. U.S.A. 110, 5774 (2013)
[3] M. K. Chan et al., Phys. Rev. Lett. 113, 177005 (2014)
[4] N. Barišić et al., arXiv: 1507.07885 (2015)

The role of Hund’s coupling in the nematicity of iron superconductors

Bascones, Elena
(CSIC, Instituto de Ciencia de Materiales de Madrid, Departamento de Teoría y Simulación de Materiales, Madrid, Spain)

The origin and properties of the nematic state, is one of the less understood problems in the field of iron superconductors. The two most popular mechanisms to explain the transition invoke ferro-orbital ordering and spin fluctuations. The instabilities of a system are directly connected with the nature of the correlations present in it. It is by now clear that Hund's coupling plays a key role in setting the correlations in these materials. In the talk I will discuss the role of Hund's coupling in the nematicity of iron superconductors. I will show that for the interaction parameters relevant in iron superconductors, and especially FeSe, the correlations induced by Hund's coupling strongly suppress ferro-orbital ordering. Nevertheless, we have found that the correlations show a strongly enhanced response to anisotropic perturbations. This enhanced nematic response has importance consequences on the experimental observables. In particular it modifies the amplitude and sign of the splittings at the symmetry points between zx/yz bands which are measured by ARPES and other spectroscopic probes. Not to include these effects in the analysis of the experimental measurements can lead to qualitatively wrong interpretations.

Nematicity and spin-orbit interaction in iron-based superconductors.

Borisenko, Sergey
(IFW Dresden, Dresden, Germany)

Spin-orbit coupling is a fundamental interaction in solids that can induce a broad range of unusual physical properties, from topologically non-trivial insulating states to unconventional pairing in superconductors. In iron-based superconductors its role has, so far, not been considered of primary importance, with models based on spin- or orbital fluctuations pairing being used most widely. Using angle-resolved photoemission spectroscopy, we directly observe a sizeable spin-orbit splitting in all the main members of the iron-based superconductors. We demonstrate that its impact on the low-energy electronic structure and details of the Fermi surface topology is stronger than that of possible nematic ordering. The largest pairing gap is supported exactly by spin-orbit coupling-induced Fermi surfaces, implying a direct relation between this interaction and mechanism of high-temperature superconductivity [1].

1. Sergey Borisenko et al. Nature Physics (in press).

Polarons and Orbitals in Fe based superconductors

Büchner, Bernd
(IFW Dresden, Institut für Festkörperforschung, Dresden, Germany)

Magnetic field controlled charge density wave coupling in underdoped $YBa_{2}Cu_{3}O_{6+x}

Chang, Johan
(University of Zurich, Department of Physics, Switzerland)

Recently, it has become widely accepted that charge ordering is a universal property of hole doped high-temperature cuprate superconductors [1-8]. This talk presents recent hard x-ray experiments on $YBa_{2}Cu_{3}O_{6+x}$ in high magnetic fields. In particular, the recent discovery of field-induced 3-dimensional CDW order [8,9] will be discussed. Connections to ultrasound [6], NMR [1] and thermal Hall effect [11] experiments will be made.

[1] T. Wu et al., Nature 477, 191 (2011)
[2] G. Ghiringhelli et al., Science 337, 821 (2012)
[2] E. Blackburn et al., Physical Review Letters 110, 137004 (2013)
[3] J. Chang et al., Nature Physics 8, 871 (2012)
[4] S. Blanco-Canosa et al., Physical Review Letters 110, 187001 (2013)

[6] D. LeBoeuf et al., Nature Physics 9, 79 (2013)
[7] R. Comin et al., Science 343, 390-392 (2014)
[8] E. H. da Silva et al., Science 343, 393-396 (2014)
[9] S. Gerber et al., Science 350, 949-952 (2015)
[10] J. Chang et al., arXiv:1511.06092 (to appear in Nat. Comm. 2016)
[11] G. Grissonnanche et al., arXiv :1508.05486

Superconductivity near a quantum-critical point

Chubukov, Andrey
(University of Minnesota, Physics, Minneapolis, USA)

Tuning electronic structure of FeSe with chemical pressure

Coldea, Amalia
(Oxford University, Clarendon Laboratory, Physics, Oxford, United Kingdom)

FeSe is a unique and intriguing superconductor which can be tuned into a high temperature superconducting state using applied pressure, chemical intercalation and surface doping. In the absence of magnetism, the structural transition in FeSe is believed to be electronically driven, with the orbital degrees of freedom playing an important role [1]. This scenario supports the stabilization of a nematic state in FeSe, which manifests as a Fermi surface deformation in the presence of strong interactions and display an enhanced nematic susceptibility to applied in-plane strain [1]. Isovalent Sulphur substitution onto the Selenium site constitutes a chemical pressure, which subtly modifies the electronic structure of FeSe, suppressing the structural transition without inducing high temperature superconductivity [3]. I will present the evolution of the electronic structure with chemical pressure in FeSe, as determined from quantum oscillations [1,2] and ARPES studies [3] and I will discuss the suppression of the nematic electronic state and the role of electronic correlations.

[1] Phys. Rev. B 91, 155106 (2015);
[2] Phys. Rev. Lett. 115, 027006 (2015);
[3] Phys. Rev. B 92, 121108 (2015).

Resonant X-ray scattering of charge order in hole- and electron-doped cuprates.

da Silva Neto, Eduardo
(The University of British Columbia, Department of Physics and Astronomy, Vancouver, Canada)

Selective correlations and heavy-fermionic behaviour in Iron-based superconductors

de' Medici, Luca
(European synchrotron radiation facility (esrf), France)

The matching between recent experimental evidences from various probes and realistic theoretical calculations highlights the coexistence, in the normal phase of Fe-based superconductors, of strongly correlated and weakly correlated electrons. This peculiar situation can be backtracked to the influence of Hund’s coupling exchange interaction between the conduction electrons in these materials, and can be controlled to some degree. In some of these compounds this differentiation can get quite extreme and gives rise to heavy-fermionic behaviour.
We will speculate that these and similar d-electron materials could constitute a new ballpark for the exploration of heavy-fermionic physics, and of its applications. A new possible application of the strong thermomagnetic properties that can in principle be found in heavy-fermions is proposed: self-cooling of

high-current cables.

L. de' Medici, G. Giovannetti and M. Capone, PRL 112, 177001 (2014)
L. de' Medici, "Weak and strong correlations in Fe superconductors", in "Iron-based Superconductivity", Springer Series in Materials Science Volume 211, 2015, pp 409-441
L. de' Medici, "A thermomagnetic mechanism for self-cooling cables", Physical Review Applied (in press) - ArXiv:1506.01674

Spin excitations in iron-based superconductors in presence of the spin-orbit coupling

Eremin, Ilya
(Ruhr-Universität Bochum, Theoretische Physik III, Fakultät für Physik und Astronomie, Bochum, Germany)

We analyze the magnetic excitations in Sr2RuO4 and iron-based superconductors in presence of spin-orbit coupling. Based on several tight-binding parametrizations of the 3d electron states we show how the spin-orbit coupling introduces the anisotropy of the magnetic excitations of paramagnetic states of both compounds. The orientation of the spin fluctuations is determined by the contribution of the xy, xz, and yz orbitals to the electronic states near the Fermi level. In iron based superconductors we find that within an itinerant approach the magnetic ordering is most favorable along the wavevector of the striped AF state. This appears to be a natural consequence of the spin-orbit coupling in the striped AF state where the ferro-orbital order of the xz and yz orbitals is only a consequence of the striped AF order. We further analyze the role of spin-orbit coupling for the Sr2RuO4 and contrast its behavior to the spin excitations in iron-based superconductors.

Nematicity and superconductivity in FeSe

Fernandes, Rafael
(University of Minnesota, School of Physics and Astronomy, Minneapolis, USA)

Charge nematic fluctuations in FeSe

Gallais, Yann
(Université Paris Diderot-Paris 7, MPQ, Paris, France)

In the context of nematicity FeSe is peculiar system: while a structural transition is observed at \$T_S\sim\$ 90K, no magnetic ordering is found at ambient pressure, a clear departure from the conventional behavior observed in other Fe SC where magnetism and nematicity are closely tied. Furthermore while both the lattice distortion and the elastic softening are comparable with other Fe SC, NMR and neutrons measurements do not detect sizable low energy spin fluctuations above \$T_S\$ putting into question the spin-nematic scenario.
Up to now however there is no evidence for charge or orbital nematic fluctuations in the tetragonal phase of FeSe. To what extend nematicity is fundamentally different in FeSe with respect to other Fe SC remains therefore an open question.

In my talk, I will report polarization resolved electronic Raman scattering showing clear evidence for charge nematic fluctuations with d-wave or \$B_{1g}\$ symmetry in the tetragonal phase of FeSe. The associated \$B_{1g}\$ charge nematic susceptibility follows Curie-Weiss like behavior down to \$T_S\$ before collapsing in the orthorhombic phase. The behavior of the charge nematic susceptibility in FeSe scales remarkably well with the one observed in 122 systems suggesting the same driving force behind nematicity in both systems despite the absence of low energy spin fluctuations in FeSe. I will show that the energy spectrum of nematic fluctuations consists of two components which might be linked to intra and interband processes, the former being critical close to \$T_S\$ while the latter only mildly enhanced towards \$T_S\$. Finally I will show that the observed charge nematic fluctuations can account for the lattice softening observed in elastic modulus measurements.

Charge Order and the Pseudogap in the Electron-doped Cuprates: Relation with Tc?

Greene, Richard
(University of Maryland, Center for Nanophysics and Advanced Materials (CNAM), Department of Physics, College Park, Maryland, USA)

The origin of high-Tc superconductivity in the strongly correlated cuprates is still a mystery, 30 years after its discovery. In the hole-doped cuprates a "pseudogap phase" is found in the underdoped part of the phase diagram and this is believed to be related to the cause of the high-Tc superconductivity. A few years ago, charge order was found in the hole-doped cuprates and this was thought to be the cause of the quantum oscillations found in the "pseudogap" region and perhaps related to the origin of the high-Tc superconductivity. Here I discuss the recent observation of charge order (CO) in the electron-doped cuprates from resonant x-ray scattering experiments1,2. This is an unexpected result since the electron-doped cuprates do not have a "pseudogap phase" and their physics is believed to be dominated by antiferromagnetism and its associated spin fluctuations. Moreover, the temperature onset of the CO is unusual and is not related to the onset of the spin fluctuations or to the quantum oscillations. The CO is incommensurate, short ranged (as found in hole-doped cuprates), and has an unusual doping dependence. It appears to be unaffected by the onset of superconductivity or magnetic field up to 10T. Since the origin of the high-Tc superconductivity is the same in all the cuprates (both p- and n-types), the CO found in the n-doped cuprates suggests that neither the "pseudogap" nor the CO are related to the origin of the high-Tc superconductivity in the cuprates.
1. E. Silva Neto et al., Science 347, 282 (2015).
2. E. Silva Neto et al, submitted (2016)

Dynamical charge density waves rule the phase diagram of cuprates

Grilli, Marco
(University of Rome , Department of Physics, Rome, Italy)

The idea that charge density waves (CDWs) are present in underdoped high-temperature superconducting cuprates and disappear with a quantum critical point (QCP) in the optimally doped region is rather old. This QCP is buried underneath the superconducting dome and, except under special circumstances, like high magnetic fields suppressing superconductivity, the CDWs do not appear as a truly long ranged phase because of low-dimensionality (the layered structure of cuprates), competition with superconducting pairing, and disorder. Nevertheless, the strong tendency of the charge to order strongly affects the dynamical and thermodynamical properties of these systems [1]. In the last three years a wealth of experimental results from transport, nuclear magnetic resonance, tunneling, and X-ray spectroscopies not only added compelling evidence to the presence of CDWs, but also provided a great deal of information, that can be exploited for a theoretical understanding of these systems. Despite the wealth of experimental data there are many unsolved issues related to a) the origin of the CDW, b) the number and nature of the QCPs, which seem to proliferate and depend on experimental probes, c) the doping dependence of the CDW critical vector, ...

The purpose of this work is to exploit the recent experimental data (mostly on YBCO systems), to build up a coherent theoretical scenario rationalizing the above issues on the basis of one single idea: The pivotal role of a CDW-QCP near optimal doping and of the accompanying dynamical quantum critical fluctuations. More specifically we show that CDW may arise from a frustrated phase-separation mechanism where instantaneous nearly local interactions drive an electronic phase separation, which is prevented by the Coulombic repulsion. The resulting wavevector of the CDW is poorly related to nesting features of the Fermi surface and tends to increase when doping is reduced as a natural consequence of reduced screening. The strong momentum and doping dependence of the effective interaction mediated by the fluctuating CDW also accounts for the rapid changes in transport (Hall) properties occurring in YBCO between doping 0.16 and 0.19 [3].

The main general outcome is that the dynamics of the CDW accounts for the different CDW onset temperatures revealed by different probes and seemingly extrapolating to different zero-temperature QCPs. The different dynamical properties of CDW in the strongly underdoped and in the weakly-underdoped and optimally-doped regions as well as the emergence of a nematic state as a ``vestigial CDW'' in the strongly underdoped region are discussed.

[1] For a review see, e.g., G. Seibold, M. Grilli, and J. Lorenzana, Physica C 481, 132 (2012).
[2] S. Caprara, C. Di Castro, G. Seibold, and M. Grilli, in preparation.
[3] S. Badoux et al. arXiv:1511.08162

Direct Visualization of Cooper-Pair Density Wave in Cuprates

Hamidian, Mohammad
(Harvard University, Physics Department, Cambridge, USA)

Towards a complete Fermi surface in underdoped high Tc superconductors*

Harrison, Neil
(Los Alamos National Laboratory, National High Magnetic Field Laboratory, Los Alamos, USA)

The discovery of magnetic quantum oscillations in underdoped high Tc superconductors raised many questions, and initiated a quest to understand the origin of the Fermi surface the like of which had not been
seen since the very first discovery of quantum oscillations in elemental bismuth. While studies of the Fermi
surface of materials are today mostly assisted by computer codes for calculating the electronic band structure, this was not the case in the underdoped high Tc materials. The Fermi surface was shown to reconstructed into small pockets, yet there was no hint of a viable order parameter.
Crucial clues to understanding the origin of the Fermi surface were provided by the small value of the observed Fermi surface cross-section, the negative Hall coefficient and the small electronic heat capacity at
high magnetic fields. We also know that the magnetic fields were likely to be too weak to destroy the pseudogap and that vortex pinning effects could be seen to persist to high magnetic fields at low temperatures. I will show that the Fermi surface that appears to fit best with the experimental observations is
a small electron pocket formed by connecting the nodal "Fermi arcs" seen in photoemission experiments, corresponding to a density-wave state with two different orthogonal ordering vectors. The existence of such
order has subsequently been detected by x-ray scattering experiments, thereby strengthening the case for charge ordering being responsible for reconstructing the Fermi surface. I will discuss new efforts to understand the relationship between the charge ordering and the pseudogap state, discussing the fate of the
quasiparticles in the antinodal region and the dimensionality of the Fermi surface.
The author acknowledges contributions from Suchitra Sebastian, Brad Ramshaw, Mun Chan, Yu-Te Hsu, Mate Hartstein, Gil Lonzarich, Beng Tan, Arkady Shekhter, Fedor Balakirev, Ross McDonald, Jon Betts, Moaz
Altarawneh, Zengwei Zhu, Chuck Mielke, James Day, Doug Bonn, Ruixing Liang, Walter Hardy.
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Contrasting criticalities in the cuprate and pnictide superconductors

Hussey, Nigel E.
(Radboud University Nijmegen, High Field Magnet Laboratory, Nijmegen, Netherlands)

The iron-based high temperature superconductors share a number of similarities with their copper-based counterparts, such as reduced dimensionality, proximity to states of competing order, and a critical role for 3d electron orbitals. Their respective temperature-doping phase diagrams also contain certain commonalities that have led to claims that the metallic and superconducting properties of both families are governed by their proximity to a quantum critical point (QCP) located inside the superconducting dome. In this talk, we critically examine these claims and highlight significant differences in the bulk physical properties of both systems. We argue that the opening of the normal state pseudogap in cuprates, so often tied to a putative QCP, is in fact a manifestation of the anisotropic breakdown of quasiparticle coherence that is in turn linked to their proximity to the Mott insulating state at half filling. Finally, a new phase diagram for the cuprates is presented, based on this picture of anisotropic quasiparticle decoherence.

NMR studies of charge order in YBCO

Julien, Marc-Henri
(Centre National de la Recherche Scientifique, Laboratoire National des Champs Magnétiques Intenses, Grenoble, France)

In 2011, the NMR discovery that superconductivity competes, and coexists, with charge-density-wave (CDW) order in YBa2Cu3Oy was argued to strongly support the, hitherto controversial, view that underdoped cuprates are generically unstable towards CDW formation [1]. While this affirmation is now unanimously accepted, the exact nature of the CDW is not. In this talk, I will discuss insights into charge order from our NMR studies in both the normal and superconducting states of YBa2Cu3Oy [1-4].

Work performed with R. Zhou, T. Wu, M. Hirata, I. Vinograd, H. Mayaffre, S. Krämer, M. Horvatić, C. Berthier (LNCMI Grenoble), P.L. Kuhns, A.P. Reyes (NHMFL, Tallahassee, USA), W.N. Hardy, R. Liang, D. A. Bonn (University of British Columbia, Vancouver, Canada), T. Loew, J. Porras, B. Keimer (MPI Stuttgart, Germany).

[1] T. Wu et al. Nature 477, 191 (2011).
[2] T. Wu et al. Nature Commun. 4, 2113 (2013).
[3] T. Wu et al. Nature Commun. 6, 6438 (2015).
[4] M. Hirata et al., R. Zhou et al., in preparation.

Optical Studies of Time-reversal Symmetry in the Normal and Superconducting States of the Cuprates

Kapitulnik, Aharon
(Stanford University, SIMES, Departments of Physics and Applied Physics, Stanford, USA)

While Kerr effect has been used extensively for the study of magnetic materials, it is only recently that its has shown to be a powerful tool for the study of more complex quantum matter. Since such materials tend to exhibit a wealth of new phases and broken symmetries, it is important to understand the general constraints on the possibility of observing a finite Kerr effect. In this talk we will review the consequences of reciprocity on the scattering of electromagnetic waves. In particular we concentrate on the possible detection of Kerr effect from chiral media with and without time-reversal symmetry breaking. We show that a finite Kerr effect is possible only if reciprocity is broken. Introducing the utilization of the Sagnac interferometer as a detector for breakdown of reciprocity via the detection of a finite Kerr effect, we argue that in the linear regime, a finite detection is possible only if reciprocity is broken. A finite Kerr effect detected in the pseudogap regime of the cuprates, persisting into the superconducting phase is analyzed in view of the above discussion. Possible consequences of these observations are discussed.

Interplay and competition between the magnetism, superconductivity and orbital order in Fe-based superconductors

Khodas, Maxim
(The University of Iowa, Department of Physics & Astronony, USA)

p-Orbital Density Wave with d-Symmetry in High-Tc Superconductors Predicted by the Renormalization-Group + Constrained-RPA Study

Kontani, Hiroshi
(Nagoya University, Physics, Nagoya, Japan)

In the charge-density-wave formation in high-T_c cuprate superconductors, the many-body effects beyond the mean-field-level approximations, called the vertex corrections, play essential roles. Toward solving this problem, it is required to analyze the twodimensional Hubbard model by applying a reliable unbiased numerical method. In this paper, we employ the recently-developed functional renormalization-group method, by which we can calculate the higher-order vertex corrections in a systematic way with high numerical accuracy. We discover the critical development of the p-orbital-density-wave (p-ODW) instability in the strong-spin-fluctuation region. The obtained p-ODW state possesses the key characteristics of the charge ordering pattern in Bi- and Y-based superconductors, such as the wavevector parallel to the nearest Cu-Cu direction, and the d-symmetry form factor with the antiphase correlation between p_x and p_y orbitals in the same unit cell. In addition, from the observation of the beautiful scaling relation between the spin susceptibility and the p-ODW susceptibility, we conclude that the main driving force of the density wave is the Aslamazov-Larkin vertex correction that becomes very singular near the magnetic quantum-critical point.

Non-Equilibrium momentum dependent dynamic of unconventional superconductors

Lanzara, Alessandra
(University of California, Berkeley, Physics Department, Berkeley, USA)

Understanding how superconductivity emerges from other competing phases and how this balance evolves through the phase diagram is one of the biggest challenges in the field of high Tc superconductors. By using high resolution time- and angle- resolved photoemission spectroscopy (tr-ARPES) we are able to directly probe the effects of optical excitation on the electronic structure of cuprate superconductors, and study the resulting quasiparticles, superconducting gap, and Cooper pair formation dynamics near their natural time- scales. Direct measurements of these and other non-equilibrium spectral phenomena through the phase diagram further illustrate the power of this unique time- and momentum-resolved spectroscopy. These results reveal new windows into the nature of the pairing interaction in high Tc superconductors.

CDW and phonon anomalies in underdoped cuprates

Le Tacon, Mathieu
(Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany)

High resolution inelastic x-ray scattering was used to observe of a quasi-elastic ‘central peak’ in underdoped YBa2Cu3O6.6, demonstrating the static nature of the CDW correlations, attributed to the pining of CDW nanodomains on defects. Low energy phonons also exhibit anomalously large superconductivity induced renormalizations close to the CDW ordering wave vector, providing new insights regarding the long-standing debate of the role of the electron-phonon interaction, a major factor influencing the competition between collective instabilities in correlated-electron materials. Relationship to the well-known anomalies in reported in the higher energy phonon branches will be discussed. Finally, dependence of these effects with pressure will be reported.

Non-Fermi liquid behavior near a nematic quantum critical point: a Monte Carlo study

Lederer, Samuel
(Massachusetts Institute of Technology, Physics, Cambridge, USA)

The Ising nematic quantum critical point (QCP) associated with the breaking of fourfold rotational symmetry in a zero temperature metal is an exemplar of metallic quantum criticality. We have carried out a minus sign-free quantum Monte Carlo study of this QCP for a two dimensional lattice model with sizes up to 24×24 sites. The nematic boson propagator exhibits scaling behavior over the accessible ranges of temperature, (imaginary) time, and distance. This scaling behavior has remarkable similarities with recently measured properties of the Fe-based superconductors near their putative nematic QCP. For sufficiently strong coupling between the fermions and the nematic bosons, high temperature superconductivity emerges near the QCP. This superconductivity condenses out of a metallic normal state largely devoid of coherent quasiparticles, and with transport properties inconsistent with Fermi liquid theory.

What makes the T_c of $FeSe/SrTiO_3$ so high ? -- a sign problem free quantum Monte-Carlo study

Lee, Dung-Hai
(University of California, Berkeley, Physics, Berkeley, USA)

Single unit cell thick FeSe films grown on SrTiO$_3$ substrate [(FeSe)$_1$/STO] show superconducting gap and gap closing T_c which are almost an order of magnitude larger than those of the bulk FeSe. This large enhancement of superconductivity is unique among all FeSe-based superconductors. This fact and the angle-resolved photoemission spectroscopy observation of ``replica" bands in (FeSe)$_1$/STO suggest that the interaction between FeSe electrons and STO phonons is the mechanism responsible for the T_c enhancement.
Here we study the cooperation between electron-phonon and pure electron mechanisms of pairing by unbiased sign-problem-free quantum Monte Carlo computation on effective models capturing the low energy physics of (FeSe)$_1$/STO. Our results clearly indicate that irrespective to the pure electronic driving force of Cooper pairing and the resulting pairing symmetry, nematic fluctuations and especially forward-focusing electron-phonon couplings significantly enhance the superconductivity.

Resilient broken symmetries in the presence of quenched disorder in cuprates

Lorenzana, José
(Consiglio Nazionale delle Ricerche, Istituto dei Sistemi Complessi, Dip. di Fisica, Sapienza, Roma, Italy)

Empirical evidence in heavy fermion, pnictide and other systems suggests that unconventional superconductivity appears associated to some form of real-space electronic broken symmetry. For the cuprates, despite several proposals, the emergence of order in the phase diagram between the commensurate antiferromagnetic state and the superconducting state is not well understood. Here we show that in this regime doped holes assemble in ‘electronic polymers’. Within a Monte Carlo study, we find that in clean systems by lowering the temperature the polymer melt condenses first in a smectic state and then in a Wigner crystal both with the addition of inversion symmetry breaking. Disorder blurs the positional order leaving a robust inversion symmetry breaking and a nematic order (called ferronematic), accompanied by vector chiral spin order and with the persistence of a thermodynamic transition. Such electronic phases, whose properties are reminiscent of soft-matter physics, produce charge and spin responses in good accord with experiments.

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G Seibold, M Capati, C Di Castro, M Grilli, J Lorenzana
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Spin excitations of ferronematic order in underdoped cuprate superconductors
G Seibold, C Di Castro, M Grilli, J Lorenzana
Scientific reports 4,5319 (2014)

Electronic polymers and soft-matter-like broken symmetries in underdoped cuprates
M Capati, S Caprara, C Di Castro, M Grilli, G Seibold, J Lorenzana
Nature communications 6,7691 (2015).

Strain tuning of superconductivity in Sr_2RuO_4

Mackenzie, Andrew
(Max-Planck-Institut für Chemische Physik fester Stoffe, Physics of Quantum Materials, Dresden, Germany)

I will discuss on-going experiments in which uniaxial pressures in excess of 1 GPa are applied to the unconventional superconductor Sr_2RuO_4, resulting in lattice parameter changes along the pressured direction of approximately 1%. This has a striking effect on the superconductivity of Sr_2RuO_4, increasing T_c by a factor of 2.3 and the c-axis upper critical field by over a factor of twenty. As well as discussing the implications of our work for the superconductivity of Sr_2RuO_4, I will mention the possibility of extending it to the cuprates and other correlated electron systems.

Collaborators: Clifford Hicks, Alexander Steppke, Mark Barber, Lishan Zhao, Thomas Scaffidi, Steve Simon, Helge Rosner, Alexandra Gibbs and Fabian Jerzembek

Fully gapped s-wave pairing of a prototypical heavy-fermion superconductor in the very edge of magnetic instability

Matsuda, Yuji
(Kyoto University, Physics, Kyoto, Japan)

In exotic superconductors including cuprates, iron-pnictides, and heavy-fermions, purely electronic, spin-fluctuation mechanisms of Cooper-pairing under strong Coulomb repulsions have long been primarily considered instead of the conventional attractive electron-phonon interactions. This trend was initiated by the 1979 discovery of heavy-fermion superconductivity in $CeCu_2Si_2$, which exhibits strong antiferromagnetic fluctuations. The hallmark of such unconventional pairing is the sign change of the superconducting order parameter, which often leads to gap nodes in certain crystal directions. Here, we show low-temperature specific heat, thermal conductivity and penetration depth measurements in

$CeCu_2Si_2$, demonstrating the absence of gap nodes in the whole Fermi surface. Moreover, electron-irradiation experiments reveal considerably small pair-breaking effect, which contradicts a sign-changing order parameter. These results strongly imply that, contrary to the long-standing belief, heavy-electrons can condense into a fully-gapped s-wave superconducting state usually driven by on-site attractive interactions, despite extremely strong on-site Coulomb repulsions. This urges to reconsider the notion of simple magnetically-mediated superconductivity in strongly correlated electron systems.

Incommensurate magnetic order and superconductivity in the 2D Hubbard model

Metzner, Walter
(Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany)

We analyze the competition of magnetism and superconductivity in the two-dimensional Hubbard model with a moderate interaction strength, including the possibility of incommensurate spiral magnetic order [1]. Using the functional renormalization group, fluctuation driven order is captured without any bias for a specific instability. Charge, spin, and pairing channels are treated on equal footing.
Away from half-filling, magnetic order coexists with superconductivity, as a consequence of a Cooper instability in electron or hole pockets. In the presence of a next-to-nearest neighbor hopping amplitude, both magnetism and superconductivity exhibit a pronounced particle-hole asymmetry. On the hole-doped side, superconductivity has larger maximal gaps, and it coexists with incommensurate magnetism at moderate doping. The incommensurate magnetic order is however "gossamer-like" in the sense that it is stabilized only by a tiny energy gain with respect to a purely superconducting state. Suppressing superconductivity by a strong magnetic field would stabilize that order. Indeed, in a very recent high field experiment a Hall coefficient consistent with hole-pockets arising from possible spin-density waves was observed in YBCO at much higher doping than previously expected [2].

[1] H. Yamase, A. Eberlein, and W. Metzner, Phys. Rev. Lett. 116, 096402 (2016).

[2] S. Badoux et al., Nature 531, 210 (2016).

Monolayer FeSe on $SrTiO_3$: charge transfer, electron-phonon coupling and superconductivity

Millis, Andrew
(Columbia University, Department of Physics, New York, USA)

Monolayer films of FeSe grown on $SrTiO_3$ substrates are electron doped relative to bulk and exhibit a significantly enhanced superconducting transition temperatures, which has been suggested to arise from coupling to polar phonons in the $SrTiO_3$. We present density functional calculations and a modified Schottky model incorporating the strong paraelectricity of $SrTiO_3$ which demonstrate that the doping may be due to charge transfer from $SrTiO_3$ impurity bands driven by work function mismatch. A remarkable doping dependence of the FeSe electronic structure is noted. The coupling of electrons in FeSe to polar phonons in the depletion regime of the $SrTiO_3$ is calculated and the interplay with the Coulomb interaction in the FeSe is determined. The plasmon spectrum is computed and preliminary calculations of the superconducting transition temperature are presented. Problematic aspects of the resulting physical picture are discussed.

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Pseudo gap, charge order and excitonic patches in under doped curates

Pépin, Catherine
(CEA Saclay, Institutde Physique Théorique, Gif-sur-Yvette, France)

Not yet ready !

Metallic critical points with finite BCS couplings

Raghu, Srinivas
(Stanford University, Department of Physics, USA)

The problem of superconductivity near quantum critical points (QCPs) remains a central topic of modern condensed matter physics. Near a QCP, there is a competition between the enhanced pairing tendency due to the presence of long-range attractive interactions near criticality, and the suppression of superconductivity due to the destruction of Landau quasiparticles. I will describe some recent work that addresses these competing effects in the context of a solvable model of a metallic quantum critical point. I will show that the two effects - namely the enhanced pairing and the destruction of Landau quasiparticles - can offset one another, resulting in stable "naked" quantum critical points without superconductivity. However, the resulting quantum critical metal exhibits strong superconducting fluctuations on all length scales.

Reference: S.R., Gonzalo Torroba, and Huajia Wang, arXiv1507.06652, PRB(2015).

Strong Superconducting Fluctuations leading to a Giant Phonon Anomaly in the Pseudogap Phase of Underdoped Cuprates

Rice, T. Maurice
(ETH Zurich, Theoretical Physics, Zurich, Switzerland)

As the hole density decreases and the Mott insulator is approached, umklapp scattering processes increase in importance. Analogies between the well studied D-Mott Insulator state in Hubbard 2-leg ladders, and the underdoped cuprates shows that these processes can gap the 2-particle spectrum and transform a superconducting gap into an insulating pseudogap, starting at antinodal. Long range ordered superconductivity is then confined to 4 anisotropic pockets centered on the nodal directions. A consistent description of the break up the Fermi surface observed in ARPES experiments follows, as proposed earlier by Yang, Rice & Zhang. The Fermi surface surface breakup in turn leads to a breakup of the superconducting d-wave order parameter into two subband amplitudes along (1,1) & (1,-1) directions and to a low energy Leggett mode due to phase fluctuations between them. This leads to a large increase in the temperature range of superconducting fluctuations with an overdamped Leggett mode. Almost resonant forward scattering of intersubband phonons to a state with a pair of Leggett modes, causes anomalously strong phonon damping at wavevectors connecting the ends of the pockets. A close connection in both temperature and hole density between these anomalously strong superconducting fluctuations and the Giant Phonon Anomaly reported by Le Tacon et al. {Nature Physics 2014} follows.
Y.H. Liu, R. Konik, T.M. Rice & F.C. Zhang
Nature Communications 7, 10378, (2016)

Quantum entanglement and the phases of matter

Sachdev, Subir
(Harvard University, Department of Physics, Cambridge, USA)

Many modern materials involve phases with long-range quantum entanglement between the electrons. This is especially so for certain quantum "critical" states: remarkably, these turn out to have a holographic connection to physics near the horizon of a charged black hole. I will describe recent experimental observations on graphene, and on the copper-based high temperature superconductors, and interpret them using theories of quantum criticality.

Pseudogap in hole doped high-Tc cuprates and its interplay with the Superconducting Gap

Sacuto, Alain
(Université Paris Diderot-Paris 7, Paris, France)

Much of the current research on the pseudogap phase of high-temperature cuprate superconductors is dominated
by the quest to understand its microscopic origin and how it is related to the superconducting gap. Here we report Electronic Raman scattering measurements on cuprates both in the normal and superconducting states.

We reveal in the first part how the pseudogap manifests itself in the normal state Raman response [1,2] and why it disppears at high doping level in the cuprate phase diagram. More precisely we show that the pseudogap is sensitive to the Fermi surface topology [3].

In the second part our study focus on the superconducting state. Our main finding is that the superconducting pair-breaking peak is
associated with a dip on its higher-energy side, disappearing together at Tc . We are able to interpret this observation as a new interplay between the pseudogap and the superconducting gap coexisting below Tc. The pseudogap and the superconducting gap share the same electronic states below the Fermi level but compete for the same electrons above the Fermi level. This non trivial scenario sheds new light on the long-standing debate
about the role of the pseudogap in the unconventional pairing mechanism of cuprate superconductors [4].

[1] New insights into the phase diagram of the copper oxide superconductors from electronic Raman scattering, Rep. Prog. Phys. 76, 022502 (2013).
[2] Raman-Scattering Measurements and Theory of the Energy-Momentum Spectrum for Underdoped Bi2Sr2CaCuO8þ Superconductors: Evidence of an s-Wave
Structure for the Pseudogap, Phys. Rev. Lett. 111, 107001 (2013)
[3] Collapse of the Normal-State Pseudogap at a Lifshitz Transition in the Bi2Sr2CaCu2O8+d Cuprate Superconductor, S.Benhabib et al.
Phys.Rev. lett. 114, 147001 (2015).

[4] Unconventional high-energy-state contribution to the Cooper pairing in under-doped copper-oxide superconductor HgBa2Ca2Cu3O8+d,
Bastien Loret et al. submitted in february arXiv:1602.00123 (2016).

Tracing the pairing glue via inelastic tunnelling

Schmalian, Jörg
(Karlsruher Institut für Technologie, Institut für Theorie der Kondensierten Materie, Karlsruhe, Germany)

Scanning tunneling microscopy (STM) has been shown to be a powerful experimental probe to detect electronic excitations and further allows to deduce some fingerprints of bosonic collective modes. Here, we demonstrate that the inclusion of inelastic tunnel events is crucial for the interpretation of tunneling spectra and allows to directly probe bosonic excitations via STM. We develop a model describing both the elastic tunneling current, which displays the electronic spectral function, and the inelastic current, that contains the information about the bosonic spectrum, in the superconducting state. Adopting this extended tunneling formalism we can naturally reproduce the tunneling spectra of various unconventional superconductors and trace the occurring features back to an opening of a spin gap in the superconducting state. More generally, our approach is a strong argument in favour of a collective mode mediating the pairing state in particular in iron-based systems. In particular, we conclude that the debated pairing mechanism in LiFeSe is also of electronic origin with sign-changing pairing symmetry.

Direct observation of the pseudogap quantum critical point in cuprate superconductors

Taillefer, Louis
(Université de Sherbrooke, Département de Physique, Sherbrooke, QC, Canada)

The pseudogap is a partial gap that opens in the normal state of cuprate superconductors whose origin is a long-standing puzzle. Its connection to the Mott insulator at low doping p remains ambiguous and its relation to the charge order that reconstructs the Fermi surface at intermediate p is still unclear. I will report measurements of the Hall coefficient in magnetic fields up to 88~T, performed at the LNCMI in Toulouse, which reveal that Fermi-surface reconstruction by charge order in YBCO ends sharply at a critical doping $p = 0.16$, distinctly lower than the pseudogap critical point at $p^\star = 0.19$ [1]. This shows that pseudogap and charge order are separate phenomena. I will also report measurements of the Seebeck coefficient in magnetic fields up to 45~T, performed at the LNCMI in Grenoble and the NHMFL in Tallahassee, which reveal a similar separation in LSCO, a very different cuprate [2].
In YBCO, we find that the Hall number changes from $n_{\rm H} = 1 + p$ at high p to $n_{\rm H} = p$ at low p, starting right at $p^\star$ [1] -- a new signature of the pseudogap quantum critical point. I will present a detailed study, performed at the HFML in Nijmegen, of resistivity and Hall effect in Nd-LSCO, a cuprate whose pseudogap critical point is precisely known [3,4]. We observe the same drop in Hall number as in YBCO, from from $n_{\rm H} = 1 + p$ to $n_{\rm H} = p$ at $p^\star$, accompanied by a major increase in resistivity, showing that the change is due to a drop in carrier density n, with $n = n_{\rm H}$ [5]. The excellent agreement between our Hall data [1,5] and recent calculations of the Hall coefficient in cuprates [6] suggest that the underlying mechanism is a reconstruction of the Fermi surface by the onset of a new periodicity at $p^\star$, with wavevector $Q = (\pi, \pi)$, akin to the antiferromagnetic order in electron-doped cuprates.

[1] Badoux et al., Nature (2016); doi:10.1038/nature16983 (arXiv:1511.08162).

[2] Badoux et al., arXiv:1512.00292 (2015).

[3] Daou et al., Nature Physics 5, 31 (2009).

[4] Matt et al., Physical Review B 92, 134524 (2015).

[5] Collignon et al., to be published.

[6] Storey, Europhysics Letters 113, 27003 (2016).

D-wave superconductivity in the iron pnictides

Thomale, Ronny
(Universität Würzburg, Theoretische Physik I, Würzburg, Germany)

We will reflect on recent results in investigating the possibility of d-wave superconducting order in the iron pnictides. Our work focusses on the 122 pnictide family where the pairing propensity towards d-wave can be significantly enhanced due to hole doping by potassium. We will connect our theoretical findings to experimental evidence from thermal conductivity measurements and Raman scattering.

Berry phases and the intrinsic thermal Hall effect in high temperature cuprate superconductors

Vafek, Oskar
(National High Magnetic Field Lab and Florida State University, Tallahassee, USA)

Bogolyubov quasiparticles (qps) move in a practically uniform magnetic field in the vortex state of high temperature cuprate superconductors. When set in motion by an externally applied heat current, jQ, the qps' trajectories may bend, causing a temperature gradient perpendicular to jQ, and the applied field H, and resulting in the thermal Hall effect. Here we relate this effect to the Berry curvature of qp magnetic sub-bands, and calculate
the dependence of the intrinsic thermal Hall conductivity on T, superconductor's temperature, H, and Δ, the amplitude of the d-wave pairing. The intrinsic contribution to the thermal Hall conductivity collapses onto a scaling function. It also displays a rapid onset with increasing T, which compares favorably with existing experiments at high H on the highest purity samples. Because such temperature onset is related to Δ, this finding may help to settle a much-debated question of the bulk value of the pairing strength in cuprate superconductors in magnetic field.

[1] Vladimir Cvetkovic and Oskar Vafek, Nature Communications 6, 6518 (2015)
[2] Oskar Vafek Phys. Rev. B 92, 174508 (2015)

Singular Fermi-liquid due to Quantum Critical Fluctuations

Varma, Chandra
(University of California, Riverside, Physics, Riverside, CA 92521, USA)

Metallic states of weakly doped Mott insulators

Vojta, Matthias
(Technische Universität Dresden, Institut für Theoretische Physik, Dresden, Germany)

Spin-fermion model with overlapping hot spots and charge modulation in cuprates

Volkov, Pavel
(Ruhr-Universität Bochum, Theoretische Physik III, Bochum, Germany)

We study particle-hole instabilities in the framework of the spin-fermion (SF) model. In contrast to previous studies, we assume that adjacent hot spots can overlap due to a shallow dispersion of the electron spectrum in the antinodal region. In addition, we take into account effects of a remnant low energy and momentum Coulomb interaction. We demonstrate that at sufficiently small values $|\varepsilon(\pi,0)-E_F|\lesssim\Gamma$, where E_F is the Fermi energy, $\varepsilon(\pi,0)$ is the energy in the middle of the Brillouin zone edge, and Γ is a characteristic energy of the fermion-fermion interaction due to the antiferromagnetic fluctuations, the leading particle-hole instability is a d-form factor Fermi surface deformation (the Pomeranchuk instability) rather than the charge modulation along the Brillouin zone diagonals predicted within the standard SF model previously. At lower temperatures, we find that the deformed Fermi surface is further unstable to formation of a d-form factor charge density wave (CDW) with a wave vector along the Cu-O-Cu bonds (axes of the Brillouin zone). We show that the remnant Coulomb interaction enhances the d-form-factor symmetry of the CDW. These findings can explain the robustness of this order in the cuprates. The approximations made in the paper are justified by a small parameter that allows one to implement an Eliashberg-like treatment. Comparison with experiments suggests that in many cuprate compounds the prerequisites for the proposed scenario are indeed fulfilled and the results obtained may explain important features of the charge modulations observed recently.

Charge-density-wave and pair-density-wave orders in under-doped cuprates

Wang, Yuxuan
(University of Illinois at Urbana-Champaign, Institute of Condensed Matter Theory (ICMT), Department of Physics, Urbana, USA)

Recent experiments have provided strong evidence that there exist incommensurate static charge-density-wave (CDW) order with momenta (Q,0) and (0,Q) in underdoped cuprates. In the same doping range and at higher temperatures, there are evidence for broken rotational symmetry and broken time-reversal symmetry. In this talk we argue that magnetically-mediated interaction, which is known to give rise to d-wave superconductivity, can also lead to the CDW order. We then discuss the interplay between different charge order parameters and show that rotational symmetry and time-reversal symmetry are both broken in the ground state. Going beyond mean-field analysis we show that these discrete symmetries get broken at higher temperatures than the CDW onset temperature. We consider the feedback effect from d-wave superconductivity on different components of the charge order.

In the second part, we show an SU(2) particle-hole symmetry of the model leads to the coexistence of CDW order and a pair-density-wave (PDW) order, the latter defined as a superconducting order with a finite total Cooper pair momentum. The PDW order has been argued to exist in the pseudogap region, and we show the coexistence of CDW and PDW explains ARPES data. We make specific predictions for experiments.