TT 41: Unconventional Superconductors

Time: Wednesday 15:00–19:00 Location: HSZ 201

Invited Talk TT 41.1 Wed 15:00 HSZ 201

Probing unconventional superconductivity using the field dependent magnetic penetration depth — •Joseph A. Wilcox — H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom

In the field of unconventional superconductivity, one of the key efforts has been to investigate the momentum space structure of the superconductor energy gap due to its close relation to the underlying pairing mechanism. The temperature dependence of the magnetic penetration depth $\lambda(T)$ has long been used to perform such investigations and, in-particular, to identify the presence or absence of gap nodes. However, in certain cases it is not possible to distinguish between different scenarios that could give rise to the same observed behaviour, e.g. gap nodes with small amounts of impurities and large gap anisotropy with very deep gap minima, but no nodes.

A solution to this issue is that the temperature dependence of the magnetic penetration depth should change in the presence of a weak magnetic field. This effect was searched for extensively in cuprates but was not clearly observed, possibly because of other competing effects. Here we show that the magnetic field dependence of λ is strongly enhanced in low-T_c unconventional superconductors and that $\lambda(B,T)$ can be used as a tool with which to distinguish nodal pairing states from those where there is a small residual gap. We show data for $CeCoIn_5$ and LaFePO which show the effect of a nodal gap and for KFe_2As_2 which is consistent with a small but finite gap.

TT 41.2 Wed 15:30 HSZ 201

Sr_2RuO_4 under uniaxial pressure along the c-axis — •Fabian Jerzembeck[1], Alexander Steppke[1], Dmitry Sokolov[1], Naoki Kikugawa[2], Helge Rosner[1], Andrew Mackenzie[1,3], and Clifford Hicks[1] — [1]Max Planck Institute for Chemical Physics of Solids — [2]National Institute for Material Science, Tsukuba, Ibaraki — [3]School of Physics and Astronomy, University of St. Andrews

The unconventional superconductor Sr_2RuO_4 has been extensively studied under in-plane uniaxial pressure. a-axis pressure deforms one of the Fermi surfaces elliptically, so that at a compressive strain of $\varepsilon_{xx} = -0.44$ %, one of the Fermi surfaces undergoes a Lifshitz transition at a single point in k-space, dramatically altering the low-temperature electronic properties. Here, we investigate the consequences of pressure along the c-axis. c-axis pressure causes charge transfer from the d_{xz} and d_{yz} to the d_{xy}-orbital, resulting in an expansion of the main Fermi surface and finally in Lifshitz transitions at the X and Y points simultaneously. DFT calculations suggest that this occurs at $\varepsilon_{zz} \approx -2.5$ %. We present data for strains up to -2 %, finding that, surprisingly, T_c decreases even as the density of states increases.

TT 41.3 Wed 15:45 HSZ 201

Muon spin relaxation studies of time reversal symmetry breaking superconductivity in Sr_2RuO_4 by the application of uniaxial pressure — •Shreenanda Ghosh[1], Vadim Grinenko[1,2], Rajib Sarkar[1], Felix Brückner[1], Jean-Christophe Orain[3], Artem Nikitin[3], Joonbum Park[4], Mark Barber[4], Naoki Kikugawa[5], Jake Bobowski[6,7], Dmitry Sokolov[4], Takuto Miyoshi[6], Matthias Elender[3], Yoshiteru Maeno[6], Andrew Mackenzie[4], Hubertus Luetkens[3], Clifford Hicks[4], and Hans-Henning Klauss[1] — [1]IFMP, Technische Universität Dresden — [2]IFW, Dresden — [3]Paul Scherrer Institute, Switzerland — [4]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [5]National Institute for Material Science, Japan — [6]Department of Physics, Graduate School of Science, Kyoto University, Kyoto, Japan — [7]University of British Columbia, Kelowna, Canada

After more than two decades of extensive research, the idea regarding the symmetry of the superconducting order parameter of Sr_2RuO_4 is still lacking a consensus. One key prediction for Sr_2RuO_4, a splitting of the superconducting and time-reversal symmetry breaking(TRSB) transitions under uniaxial pressure have not been observed. Here, we report a large stress-induced splitting between the onset temperatures of superconductivity and TRSB transitions observed by muon spin relaxation (μSR) measurements on Sr_2RuO_4 placed under uniaxial pressure. In order to perform these technically challenging experiments, a customized uniaxial pressure cell was developed, which will be introduced.

TT 41.4 Wed 16:00 HSZ 201

Nematicity and checkerboard order in the surface layer of Sr_2RuO_4 — •Carolina A. Marques[1], Luke C. Rhodes[1], Veronica Granata[2], Rosalba Fittipaldi[2], Antonio Vecchione[2], Andreas W. Rost[1], and Peter Wahl[1] — [1]SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS, United Kingdom — [2]CNR-SPIN, UOS Salerno, Via Giovanni Paolo II 132, Fisciano, I-84084, Italy.

Superconductivity in strongly correlated systems is often found near exotic electronic phases, such as antiferromagnetism and electronic nematicity. These phases can be highly sensitive to minor changes in the crystal structure, induced by doping or strain. In the unconventional superconductor Sr_2RuO_4, a 6° rotation of the RuO_6 octahedra at the surface seems to suppress its superconducting state and, additionally, pushes a van Hove singularity below the Fermi energy.

Using ultra-low temperature Scanning tunnelling microscopy (STM), we study the low energy electronic properties of the reconstructed surface of Sr_2RuO_4. Our measurements show clear signatures of C4 symmetry breaking, together with the appearance of a checkerboard order. This order is associated with a peak in the tunnelling spectrum, which splits in a magnetic field, revealing a charge nature. Tight binding calculations show that a nematic order parameter coexisting with a modulation of the charge-density reproduces the observed low energy density of states. Understanding the underlying physics at this surface provides a new platform to study the strongly correlated phases of Ruthenate materials.

TT 41.5 Wed 16:15 HSZ 201

Stabilizing even-parity chiral superconductivity in Sr_2RuO_4 — Han G. Suh[1], Henri Menke[2], Philip M. R. Brydon[2], Carsten Timm[3], •Aline Ramires[4,5,6], and Daniel F. Agterberg[1] — [1]Department of Physics, University of Wisconsin, Milwaukee, WI 53201, USA — [2]Department of Physics and MacDiarmid Institute for Advanced Materials and Nanotechnology, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand — [3]Institute of Theoretical Physics, Technische Universität Dresden, 01062 Dresden, Germany — [4]Max Planck Institute for the Physics of Complex Systems, Dresden, 01187, Germany — [5]ICTP-SAIFR, International Centre for Theoretical Physics, South American Institute for Fundamental Research, Sao Paulo, SP, 01140-070, Brazil — [6]Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, SP, 01140-070, Brazil

Sr_2RuO_4 has long been thought to host a spin-triplet chiral p-wave superconducting state. However, the singlet-like response observed in recent Knight shift measurements casts serious doubts on this pairing state. The available experimental results seem to point towards an even-parity chiral superconductor, a pairing state which has been systematically neglected given the quasi-2D electronic structure of Sr_2RuO_4. Here we show how the orbital degree of freedom can encode the two component nature of the E_g order parameter, allowing for an s-wave orbital-antisymmetric spin-triplet state which can be stabilized by Hund's coupling.

TT 41.6 Wed 16:30 HSZ 201

Direct observation of a uniaxial stress-driven Lifshitz transition in Sr_2RuO_4 — •Edgar Abarca Morales[1,2], Veronika Sunko[1,2], Igor Markovic[1,2], Mark Barber[1], Dijana Milosavljevic[1], Federico Mazzola[2], Dmitry Sokolov[1], Helge Rosner[1], Clifford Hicks[1], Philip King[2], and Andrew Mackenzie[1,2] — [1]Max Planck Institute for Chemical Physics of Solids, Nöthnitzer Strasse 40, 01187, Dresden, Germany — [2]SUPA, School of Physics and Astronomy, University of St. Andrews, St. Andrews KY16 9SS, UK

Application of uniaxial pressure has recently been shown to more than double the transition temperature of the unconventional superconductor Sr_2RuO_4, leading to a peak in T_c versus strain whose origin is still under debate. Here we develop a simple and compact method to apply large uniaxial pressures in a way compatible with angle-resolved photoemission. We directly visualise how uniaxial stress drives a Lifshitz transition of the γ-band Fermi surface, pointing to the key role of strain-tuning its associated van Hove singularity to the Fermi level in mediating the peak in T_c. Our measurements provide stringent constraints for theoretical models of the strain-tuned electronic structure evolution of Sr_2RuO_4. Furthermore, our experimental approach opens the door to future studies of strain-tuned phase transitions where large pressure cells or piezoelectric-based devices may be difficult to implement.

15 min. break.

TT 41.7 Wed 17:00 HSZ 201

Uniaxial stress dependence of the critical temperature of $YBa_2Cu_3O_{6.67}$ — •Clifford Hicks[1], Mark Barber[1], Marcin Konczykowski[2], Bernhard Keimer[3], and Andrew Mackenzie[1] — [1]Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany — [2]École Polytechnique, Paris, France — [3]Max-Planck-Institut für Festkörperforschung

We use piezoelectric-based uniaxial pressure apparatus and GaAs/AlGaAs-based susceptometers to measure the stress dependence of the critical temperature of $YBa_2Cu_3O_{6.67}$. T_c of the unstressed material is 65 K, and with compression along the a axis T_c decreases steadily. At a pressure of 1 GPa, long-correlation-length charge density wave order appears, and strong competition between this order and superconductivity causes a rapid suppression of T_c.

TT 41.8 Wed 17:15 HSZ 201

Spiral magnetic order in high-T_c cuprates - a ground state candidate at high magnetic fields — •Johannes Mitscherling, Pietro Maria Bonetti, Demetrio Vilardi, and Walter Metzner — Max Planck Institute for Solid State Research, Stuttgart

The normal state beneath the superconducting dome determines the fluctuations that govern the anomalous properties of cuprate superconductors in a wide range of their phase diagram. Recent experiments at very high magnetic fields shed new light on the phenomenology of the high field ground state: A drastic change in the carrier density at the onset of the pseudogap observed in various cuprate compounds, thermodynamic signatures of a quantum critical point at this doping and, very recently, NMR and ultrasound experiments indicated glassy antiferromagnetic order up to the pseudogap onset.

We present incommensurate spiral magnetic order as a potential ground state candidate at high magnetic fields [1,2]. Previous theoretical work suggests that suppression of superconductivity leads to such a ground state [3]. We present quantitative results for magnetic order in the Hubbard model at strong coupling using dynamical mean-field theory [4]. We show that experimental signatures as the Fermi arcs, nematicity and a drastic drop in both the DC conductivity and the Hall number can be understood within this framework.

[1] A. Eberlein *et al.*, PRL **117**, 187001 (2016)
[2] J. Mitscherling *et al.*, PRB **98**, 195126 (2018)
[3] H. Yamase *et al.*, PRL **116**, 096402 (2016)
[4] P. M. Bonetti *et al.*, in prep.

TT 41.9 Wed 17:30 HSZ 201

A hydrodynamical description for magneto-transport in the strange metal phase of cuprates — Andrea Amoretti[1,2], •Martina Meinero[1,3], Daniel Brettan[2], Federico Caglieris[4], Enrico Giannini[5], Christian Hess[4], Bernd Buechner[4], Nicodemo Magnoli[1,2], and Marina Putti[1,3] — [1]DIFI-Università di Genova, via Dodecaneso 33, 14146 Genova, Italy — [2]INFN-Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy — [3]CNR-SPIN, corso Perrone 24, 16152 Genova, Italy — [4]Leibniz IFW Dresden, Helmholtz str. 20, 10169 Dresen, Germany — [5]University of Geneva, 24 Quai Ernst Ansermet, 1211 Geneva, Switzerland

High temperature superconductors are strongly coupled systems which present a complicated phase diagram with many coexisting phases. This makes it difficult to understand the mechanism which generates their singular transport properties. Hydrodynamics, which mostly relies on the symmetries of the system without referring to any specific microscopic mechanism, constitutes a promising framework to analyze these materials. In this paper we show that in the strange metal phase of the cuprates, a whole set of transport coefficients are described by a universal hydrodynamic framework once one accounts for the effects of quantum critical charge density waves. We corroborate our theoretical prediction by measuring the DC transport properties of Bi-2201 close to optimal doping, proving the validity of our approach. Our argument can be used as a consistency check to understand the universality class governing the behavior of high temperature cuprate superconductors.

TT 41.10 Wed 17:45 HSZ 201

The source of spontaneous currents in BTRS superconductors — •V. Grinenko[1,2], S. Ghosh[1], R. Sarkar[1], F. Brückner[1], H. Luetkens[3], K. Kihou[4], C.H. Lee[4], P. Chekhonin[1,2], W. Skrotzki[1], R. Hühne[2], K. Nielsch[2], S.-L. Drechsler[2], V.L. Vadimov[5], M.A. Silaev[6], P. Volkov[7,8], I. Eremin[7], J. Park[9], M.E. Barber[9], N. Kikugawa[10], D.A. Sokolov[9], J.S. Bobowski[11,12], T. Miyoshi[11], Y. Maeno[11], A. P. Mackenzie[9,13], C. Hicks[9], and H.-H. Klauss[1] — [1]TU Dresden — [2]IFW Dresden — [3]PSI, Switzerland — [4]AIST, Japan — [5]IPM, Russia — [6]University of Jyväskylä, Finland — [7]Ruhr-Universitat Bochum — [8]Rutgers University — [9]MPI CPFS — [10]NIMS, Japan — [11]Kyoto University — [12]University of British Columbia — [13]University of St. Andrews

Recently, the superconductivity that breaks time-reversal symmetry (BTRS) attracts a lot of attention in the scientific community. However, there is no general agreement among the researches whether the evadible experimental data provide convincing support for the theoretical predictions. In particular, the nature of the spontaneous currents in the BTRS state remains mysterious. Here, we verify the proposal that spontaneous currents in the BTRS superconducting state appear due to spatial inhomogeneities of the superconducting order parameter. We study the effect of disorder on the strength of the spontaneous currents in the BTRS state in two superconducting systems: Sr_2RuO_4 and $Ba_{1-x}K_xFe_2As_2$. Our available data indicates that non-magnetic impurities indeed affect noticeably the strength of the spontaneous magnetization measured by muon spin rotation/relaxation technique.

TT 41.11 Wed 18:00 HSZ 201

Field-induced change of the superconducting state in the locally non-centrosymmetric heavy fermion $CeRh_2As_2$ — •Javier Landaeta, Seunghyun Khim, Daniel Hafner, Jacinta Banda, Manuel Brando, Robert Küchler, Christoph Geibel, and Elena Hassinger — Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany

$CeRh_2As_2$ is a new heavy fermion superconductor with a $CaBe_2Ge_2$-type crystalline structure, which lacks inversion symmetry locally at the Ce site. A weak phase transition is observed in the specific heat at T_0=0.4 K with possibly quadrupolar origin and below T_c= 0.27 K the material becomes superconducting. Here, we present a comprehensive study of the low temperature AC magnetic susceptibility in a single crystal of $CeRh_2As_2$ up to 15 T. We did not detect any additional transition above T_c, supporting that the specific heat anomaly might be caused by a quadrupolar order. The superconducting upper critical field is strongly anisotropic with $\mu_0 H_{c2} = 13$ T for $B \parallel c$ and $\mu_0 H_{c2} =$ 2 T for $B \perp c$, which exceed the Pauli limit. The large H_{c2} and their anisotropy are reminiscent of non-centrosymmetric superconductors such as $CePt_3Si$, $CeRhSi_3$, $CeIrSi_3$. What makes $CeRh_2As_2$ stand out is its unique superconducting phase diagram with a pronounced kink at 4 T for $B \parallel c$ reproducible in heat capacity, resistivity and AC susceptibility measurements. Moreover, isothermal AC susceptibility and magnetostriction reveal a sharp phase transition inside the superconducting phase at 4 T independent of temperature. Therefore, two different superconducting states exist for $B \parallel c$ in $CeRh_2As_2$.

TT 41.12 Wed 18:15 HSZ 201

Uranium-based superconducting materials — •Eteri Svanidze — Max Planck Institute for Chemical Physics of Solids

A rather large number of uranium-based materials are exotic - they show complex magnetic orders, coexistence of superconductivity with magnetism, enhanced effective electron masses, quantum critical behavior, and topological states [1-3]. All of these peculiar phenomena are thought to arise from electrons' dual nature, which is also believed to lie at the origin of high-temperature superconductivity. From a condensed matter point of view, the most intriguing uranium-based materials are in fact superconductors - UBe13, URu2Si2, and UPt3. In this talk, I will provide a brief historic overview of superconductivity in uranium-based systems, and address several pertinent questions: Is superconductivity in uranium-based materials always unconventional? Why are superconducting temperatures in uranium-based compounds so low, compared to other compounds, based on actinide or lanthanide elements? Is there a way to pinpoint crystallographic motifs, which are favorable for the emergence of superconducting state? I will then provide a number of empirical features that should be targeted in the search for new uranium-based superconductors [4].

[1] J. C. Griveau and É. Colineau, Comptes Rendus Phys. 15, 599 (2014)

[2] B. D. White et al., Phys. C Supercond. its Appl. 514, 246 (2015)
[3] H. R. Ott and Z. Fisk, Encycl. Inorg. Bioinorg. Chem. (2018)
[4] E. Svanidze, Handbook Phys. Chem. Rare Earths 56, 163 (2019)

TT 41.13 Wed 18:30 HSZ 201

Low-Temperature Phase of the $Cd_2Re_2O_7$ Superconductor: Ab initio Phonon Calculations and Raman Scattering — •Reinhard K. Kremer[1], Konrad J. Kapcia[2], Andrzej Ptok[2], Przemysław Piekarz[2], Fereidoon S. Razavi[3], Maureen Reedyk[3], Mojtaba Hajialamdari[3], and Andrzej M. Oleś[4] — [1]MPI für Festkörperforschung, Stuttgart, Germany — [2]Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland — [3]Dep. of Physics, Brock University, St. Catharines, Canada — [4]Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

Using an *ab initio* approach, we report a phonon soft mode in the tetragonal structure described by the space group $I4_122$ of the 1 K $5d$ superconductor $Cd_2Re_2O_7$. It induces an orthorhombic distortion to a crystal structure described by the space group $F222$ which hosts the superconducting state. This new phase has a lower total energy than the other known crystal structures of $Cd_2Re_2O_7$. Comprehensive temperature dependent Raman scattering experiments on isotope enriched samples, $^{116}Cd_2Re_2{}^{18}O_7$, not only confirm the already known structural phase transitions but also allow us to identify a new characteristic temperature regime around $\sim$ 80 K, below which the Raman spectra undergo remarkable changes with the development of several sharp modes and mode splitting. Together with the results of the *ab initio* phonon calculations we take these observations as strong evidence for another phase transition to a novel low-temperature crystal structure of $Cd_2Re_2O_7$.

TT 41.14 Wed 18:45 HSZ 201

Local spin susceptibility in the FFLO state of an all-organic conductor — •S. Molatta[1,2], H.H. Wang[3], G. Koutroulakis[3], J.A. Schlueter[4], S.E. Brown[3], J. Wosnitza[1,2], and H. Kühne[1] — [1]Hochfeld-Magnetlabor Dresden (HLD-EMFL), HZDR, Dresden, Germany — [2]Institut für Festkörper- und Materialphysik, TU Dresden, Germany — [3]Department of Physics and Astronomy, UCLA, Los Angeles, USA — [4]Materials Science Division, Argonne National Laboratory, Argonne, USA

The phenomenology of the superconducting Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, initially proposed in 1964, was experimentally confirmed in several organic conductors during the last years. A spatial modulation of the superconducting order parameter and spin susceptibility, caused by a strong population imbalance of a multi-component Fermi liquid, is a hallmark of the FFLO state. We report on recent results of ^{13}C nuclear magnetic resonance (NMR) measurements of the material β''-$(ET)_2SF_5CH_2CF_2SO_3$, which probe the inhomogeneous spatial distribution of the static and dynamic spin susceptibility across the transition from normal into the FFLO state. The NMR results reveal a low-temperature onset and increase of the inhomogeneous spectral line broadening and related superconducting gap amplitude. Further, increased spin fluctuations in the regime of the thermodynamic phase boundary indicate a complex interplay of FFLO superconductivity, reduced dimensionality, and inter-plane coherence.