TT 67: Unconventional Superconductors

Time: Thursday 9:30–13:15 Location: H 3007

Invited Talk TT 67.1 Thu 9:30 H 3007

Giant lattice softening at a uniaxial-pressure-tuned Lifshitz transition in the unconventional superconductor Sr_2RuO_4 — •Hilary M. L. Noad — Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

In the unconventional superconductor Sr_2RuO_4, properties such as the transition temperature, the upper critical field, and the in-plane normal-state resistivity depend strongly on uniaxial pressure along the [100] direction. Underlying this behaviour is a pressure-tuned Lifshitz transition, at which there is a change in topology of one of the three quasi-two-dimensional Fermi surfaces. We investigated the influence of this electronic transition on the lattice by using a piezo-based uniaxial pressure cell to measure the stress-strain relation of Sr_2RuO_4 across the Lifshitz transition, revealing a large and strongly temperature dependent softening of the [100] Young's modulus at the Lifshitz transition [1]. Through thermodynamic considerations and comparison to a tight-binding model, we show that the softening is indeed driven by conduction electrons. Moreover, the model describing this effect exhibits quantum critical elasticity, raising intriguing questions about the relationship between the superconductivity of Sr_2RuO_4 and the electronically driven softening of the lattice.

[1] H.M.L. Noad, K. Ishida, Y.-S. Li, E. Gati, V. Stangier, N. Kikugawa, D.A. Sokolov, M. Nicklas, B. Kim, I.I. Mazin, M. Garst, J. Schmalian, A.P. Mackenzie, C.W. Hicks, *Science* **382** (2023) 447.

TT 67.2 Thu 10:00 H 3007

Measurements of the elastocaloric effect on strained Sr_2RuO_4 in magnetic fields. — •Aleksei Frolov[1], You-Sheng Li[1], Naoki Kikugawa[2], Andreas W. Rost[3], Andrew P. Mackenzie[1,3], and Michael Nicklas[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany. — [2]National Institute for Materials Science, Japan. — [3]Scottish Universities Physics Alliance, School of Physics and Astronomy, University of St Andrews, St Andrews, UK

Recently, elastocaloric measurements under uniaxial stress have been shown to be a powerful tool for exploring the intriguing properties of the unconventional superconductor Sr_2RuO_4[1]. The results revealed an entropy peak in the normal state coinciding with the optimal superconducting T_c at the Van Hove strain, and traced an adjacent magnetic phase transition at higher strains. To study their interplay, thermodynamic measurements under magnetic field are highly desirable.

The aim of the present study was twofold: i) to investigate the phase diagram of the unconventional superconductor Sr_2RuO_4 in magnetic fields by thermodynamic means; ii) to extend the scope of the method for measuring the elastocaloric effect under uniaxial stress to high magnetic fields and to lower temperatures.

We have obtained high-resolution data on the elastocaloric effect in magnetic fields up to 16 T in a wide temperature range down to less than 1 K, providing new insights into the intriguing phase diagram of Sr_2RuO_4. We discuss the effect of the magnetic field on the superconducting and on the magnetic phase as well as their relationship.

[1] Y. S. Li *et al.*, Nature 607 (2022) 276

TT 67.3 Thu 10:15 H 3007

Evidence for vertical line nodes in Sr_2RuO_4 from nonlocal electrodynamics — •Javier Landaeta[1,2], Konstantin Semeniuk[2], Joost Aretz[2], Ismardo Bonalde[3], Jörg Schmalian[4], Andrew Mackenzie[2], and Elena Hassinger[1] — [1]Institute of Solid State and Materials Physics, TU Dresden, 01069, Dresden, Germany — [2]Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany — [3]Centro de Física, Instituto Venezolano de Investigaciones Científicas, Caracas 1020-A, Venezuela — [4]Institute for Theoretical Condensed Matter Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

By determining the superconducting lower and upper critical fields $H_{c1}(T)$ and $H_{c2}(T)$, respectively, in a high-purity spherical Sr_2RuO_4 sample via ac-susceptibility measurements, we obtain the temperature dependence of the coherence length ξ and the penetration depth λ down to $0.04\,T_c$. Given the high sample quality, the observed T^2 dependence of λ at low temperatures cannot be explained in terms of impurity effects. Instead, we argue that the weak type-II superconductor Sr_2RuO_4 has to be treated in the non-local limit. In that limit, the penetration depth data agree with a gap structure having vertical line nodes of the superconducting gap, while horizontal line nodes cannot account for the observation.

TT 67.4 Thu 10:30 H 3007

Identification of the magnetic phase of Sr_2RuO_4 under uniaxial pressure through a.c. Young's modulus measurements — •C.I. O'Neil[1,2], Z. Hu[1,2], N. Kikugawa[3], D.A. Sokolov[1], A.S. Gibbs[2,4,5], A.P. Mackenzie[1,2], H.M.L. Noad[1], and E. Gati[1] — [1]MPI - CPfS, Dresden, Germany — [2]University of St Andrews, UK — [3]National Institute for Materials Science, Japan — [4]ISIS Pulsed Neutron and Muon Source, UK — [5]MPI - FKF, Stuttgart, Germany

Pressure tuning allows one to explore the link between electronic and lattice degrees of freedom in quantum materials. In this respect, Sr_2RuO_4 has recently been established as an important model system [1]. Here, under [1 0 0] strain, an electronic Lifshitz transition drives a giant lattice softening, giving rise to a strongly changing Young's modulus, $E(\epsilon)$. To further explore non-linear elasticity in quantum materials, we developed an a.c. technique to measure $E(\epsilon)$. Owing to its improved resolution, we can clearly identify a response of the lattice to a magnetic transition, which has been reported to occur on the high-stress side of the Lifshitz transition [2]. Through the combination of the a.c. $E(\epsilon)$ and a.c. elastocaloric measurements, we can revisit the phase diagram under [1 0 0] compression and discuss the interplay of magnetism with other electronic phases in Sr_2RuO_4. Furthermore, we can resolve a change in lattice relaxation upon entering this magnetic phase, extracted from the imaginary part of the a.c. response.

Work is supported by the DFG through TRR288 (Elasto-Q-Mat).

[1] Noad *et al.*, Science **382** (2023) 6669
[2] Grinenko *et al.*, Nat. Phys. **17** (2021) 748

TT 67.5 Thu 10:45 H 3007

Non-local electronic correlations and spin excitations in Sr_2RuO_4 — •Maria Chatzieleftheriou[1], Silke Biermann[1,2,3], Yvan Sidis[4], and Evgeny Stepanov[1,2] — [1]Ecole Polytechnique, Palaiseau, France — [2]Collège de France, Paris, France — [3]ETSF, Palaiseau, France — [4]CEA/CNRS, Gif-sur-Yvette, France

In this work we study the effect of non-local correlations on the electronic properties of Sr_2RuO_4. We go beyond the state-of-the-art single-site description of Dynamical Mean-Field Theory (DMFT) [1] by deploying the D-TRILEX [2-4] self-consistent diagrammatic expansion method. We calculate the magnetic susceptibility and find that accounting for spatial fluctuations indeed leads to a very good agreement with the experimental evidence. In particular, we find an accurate description of the static spin susceptibility and observe a dome-like structure centred around the Γ point, in agreement with the experimental evidence and in contrast to previous theoretical studies. Moreover, we observe the quasi-ferromagnetic fluctuations reported in the experimental work [5] upon increasing the Hund's exchange coupling.

[1] A. Georges et al., Rev. Mod. Phys. 68 (1996) 13
[2] E. A. Stepanov et al., Phys. Rev. B 100 (2019) 205115
[3] V. Harkov et al., Phys. Rev. B 103 (2021) 245123
[4] M. Vandelli et al., SciPost Phys. 13, 0366
[5] P. Steffens et al. Phys. Rev. Lett. 122 (2022) 047004 (2019)

TT 67.6 Thu 11:00 H 3007

Field-induced compensation of magnetic exchange as the possible origin of reentrant superconductivity in UTe_2 — •Toni Helm[1], Motoi Kimata[2], Kenta Sudo[2], Atsuhiko Miyata[1], Markus Koenig[3], Ilya Sheikin[4], Alexandre Pourret[5], Georg Knebel[5], Dai Aoki[2], Jochen Wosnitza[1], and Jean-Pascal Brison[5] — [1]Dresden High Magnetic Field Laboratory, Helmholtz-Zentrum Dresden-Rossendorf, Germany — [2]IMR, Tohoku University, Japan — [3]Max Planck Institute CPfS Dresden, Germany — [4]LNCMI Grenoble, France — [5]CEA, University des Alpes, Grenoble, France

The potential spin-triplet heavy-fermion superconductor UTe_2 exhibits signatures of multiple distinct superconducting phases. For field aligned along the b axis, a metamagnetic transition occurs at $\mu_0 H_m = 35\,T$. It is associated with magnetic fluctuations that may be beneficial for the field-reinforced superconductivity surviving up to H_m. Once the field is tilted away from the b towards the c axis, a reentrant superconducting phase emerges just above H_m. We conducted magnetic-torque and magnetotransport measurements in pulsed mag-

netic fields. We determine the record-breaking upper critical field of $\mu_0 H_{c2} \approx 73\,\mathrm{T}$ and its evolution with angle. Furthermore, the normal-state Hall effect experiences a drastic suppression indicative of a reduced band polarization above H_m in the angular range around 30° caused by a partial compensation between the applied field and an exchange field. This promotes the Jaccarino-Peter effect as a likely mechanism for the reentrant superconductivity above H_m.

TT 67.7 Thu 11:15 H 3007

The rich superconducting phase diagram of UTe_2 — •Alexander Eaton[1], Zheyu Wu[1], Theodore Weinberger[1], Friedrich Malte Grosche[1], Andrej Cabla[2], and Michal Valiska[2] — [1]Cavendish Laboratory, University of Cambridge, UK — [2]Department of Condensed Matter Physics, Charles University, Prague, Czech Republic

Few materials manifest two or more distinct superconducting phases. Under various conditions of applied pressure and magnetic field tilt angle, the heavy fermion paramagnet UTe_2 has been observed to host up to five separate superconducting states. Several of these show numerous characteristics indicative of spin-triplet pairing, which may have important technological applications in the field of quantum computing. This talk will review recent developments in our knowledge of the UTe_2 phase diagram, attained from measurements on a new generation of pristine quality crystals grown in a molten salt flux. Our recent high field and high pressure experiments have uncovered new anomalous regions of the multi-dimensional phase space not previously observed in lower quality samples. A discussion will be given as to how these new observations may help point towards possible microscopic theories to reconcile the diverse array of exotic physical phenomena at play in UTe_2.

15 min. break

TT 67.8 Thu 11:45 H 3007

Thermodynamic transitions and topology of spin-triplet superconductivity: Application to UTe_2 — Henrik S. Røising, Max Geier, •Andreas Kreisel, and Brian M. Andersen — Niels Bohr Institute, University of Copenhagen, DK-2200 Copenhagen, Denmark

The discovery of unconventional superconductivity in the heavy-fermion material UTe_2 has reinvigorated research of spin-triplet superconductivity. We perform a theoretical study of coupled two-component spin-triplet superconducting order parameters and their thermodynamic transitions into the superconducting state. With focus on the behavior of the temperature dependence of the specific heat capacity, we find that two-component time-reversal symmetry breaking superconducting order may feature vanishing or even negative secondary specific heat anomalies. The origin of this unusual specific heat behavior is tied to the non-unitarity of the composite order parameter. Additionally, we supply an analysis of the topological surface states associated with the different possible spin-triplet orders: single-component orders host Dirac Majorana surface states in addition to possible bulk nodes. A second component breaking time-reversal symmetry gaps these surfaces states producing chiral Majorana hinge modes. DFT+U band-structure calculations support that these topological phases are realized in UTe_2 when introducing weak superconducting pairing. Our topological analysis suggests measurable signatures for surface-probe experiments to acquire further evidence of the superconducting pairing symmetry.

TT 67.9 Thu 12:00 H 3007

Quantum interference between quasi-2D Fermi surface sheets in UTe_2 — •Theodore Weinberger[1], Zheyu Wu[1], David Graf[2], Yurii Skourski[3], Andrej Cabala[4], Michal Vališka[4], F. Malte Grosche[1], and Alexander Eaton[1] — [1]Cavendish Laboratory, University of Cambridge, Cambridge, UK — [2]NHMFL, Tallahassee, Florida, USA — [3]HLD-EMFL, Dresden, DE — [4]Department of Condensed Matter Physics, Charles University, Prague, CZ

Superconductivity in UTe_2 exhibits extreme resilience to applied magnetic field, with critical fields exceeding 60 T. This, alongside the observation of distinct superconducting states in different regions of the phase diagram suggest unconventional, likely triplet pairing states. If a chiral pairing state were realised, this would mean that UTe_2 could host topologically protected Majorana surface states. Quantum oscillation studies resolving the precise nature of the Fermi surface in UTe_2, enabled by a new generation of high-quality crystals, provide valuable input for a full theoretical understanding of the topology of the pairing state. Here, we present and discuss high field contactless resistivity data, in which oscillations are observed with frequencies and effective masses that differ markedly from prior de Haas-van Alphen effect studies. These magnetoconductance oscillations can be understood as a quantum interference effect from quasiparticles tunnelling across quasi-2D Fermi surface sheets at high magnetic fields. A large variation in the apparent effective masses for the various interference paths yields valuable insight into the electronic bandstructure underpinning unconventional superconductivity in UTe_2.

TT 67.10 Thu 12:15 H 3007

Exposing quantum criticality and odd-parity superconductivity in $CeRh_2As_2$ with hydrostatic pressure — •Konstantin Semeniuk[1], Meike Pfeiffer[2,1], Javier Landaeta[2,1], Seunghyun Khim[1], and Elena Hassinger[2,1] — [1]MPI CPfS, Dresden, Germany — [2]TU Dresden, Germany

The locally non-centrosymmetric Kondo-lattice system $CeRh_2As_2$ hosts a multi-phase superconductivity ($T_c = 0.4$ K), a state "Phase I" of currently unknown origin ($T_0 = 0.5$ K), and displays antiferromagnetic ordering below T_c. At the magnetic-field-induced transition between the superconducting (SC) states SC1 and SC2, the parity of the SC order parameter has been proposed to change from even to odd. This idea is supported by the field-temperature phase diagram, but is yet to be verified directly. Alternatively, Phase I or magnetic order could play a role in the phenomenon. Other pertinent questions include the origin of the non-Fermi-liquid behavior, and the impact of the staggered Rashba interaction on the ordered states.

By tuning $CeRh_2As_2$ with hydrostatic pressure, we investigated the interplay of Phase I and the SC states. Measurements of resistivity and heat capacity show that Phase I is fully suppressed at $P_0 = 0.5$ GPa, terminating in a quantum critical point (QCP), which is responsible for the non-Fermi-liquid physics and the colossal quasiparticle masses. The SC phase forms an unusually broad dome around the QCP, remaining robust at 2.7 GPa with $T_c = 0.2$ K. Crucially, the two SC states still exist for $P > P_0$, definitively excluding the involvement of Phase I in the SC1-SC2 switching.

TT 67.11 Thu 12:30 H 3007

Evidence of finite-momentum pairing in a centrosymmetric bilayer — •Dong Zhao, Lukas Debbeler, Matthias Kühne, Sven Fecher, Nils Gross, and Jurgen Smet — Max Planck Institute for Solid State Research, Stuttgart

A phase characterized by a spatially modulated order parameter is counter-intuitive because of the entropy penalty that the modulations incur. Its possible existence in superconductors was first proposed under the condition that the formation of Cooper pairs is limited to some segments of the Fermi surface and that the Cooper pairs carry momentum above the Pauli limit. This prediction motivated experimental efforts to identify such non-uniform superconducting states in organic superconductors, heavy fermion compounds and cuprates. Here we report evidence of another type of finite-momentum pairing that manifests below the Pauli limit. It is driven by the orbital effect and does not rely on Fermi surface segmentation. We have evidence of this spatially modulated superconducting state in a hexagonal MoS2 bilayer through remote intercalation that offers both balanced doping and firm out-of-plane coherence across both layers.

TT 67.12 Thu 12:45 H 3007

Local probe of the effective charge of a nodal superconductor — •Maialen Ortego Larrazabal[1], Jiasen Niu[2], Jian-Feng Ge[2], Genda Gu[3], Ingmar Swart[1], and Milan P. Allan[2] — [1]Debye Institute for Nanomaterials Science, Utrecht University, 3508 TA Utrecht, The Netherlands — [2]Leiden Institute of Physics, Leiden University, 2333 CA Leiden, The Netherlands — [3]Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, NY 11973 Upton, USA

Shot-noise is a powerful tool for determining the effective charge of the carriers of mesoscopic systems. This method provides unique information about a broad range of materials such as superconductors and fractional quantum Hall systems [1,2]. We combine scanning tunnelling microscopy with shot-noise spectroscopy in order to get local information with atomic resolution [3]. In a s-wave BCS superconductor, we observe shot-noise doubling inside of the superconducting gap due to Andreev reflection processes [4]. For superconductors with d-wave pairing symmetry, however, things get more complicated, as the nodal quasiparticles change the situation. Here, I will discuss first

results of local shot-noise measurements on the unconventional superconductor $Bi_2Sr_2Ca_2Cu_1O_{8+p}$.
[1] Y. Ronen et al., Proc. Natl. Acad. Sci. U. S. A. 113 (2016) 1743
[2] R. de-Picciotto et al., Nature 389 (1997) 162
[3] K. M. Bastiaans et al., Rev. Sci. Instrum. 89 (2018) 093709
[4] K. M. Bastiaans et al., Phys. Rev. B 100 (2019) 104506

TT 67.13 Thu 13:00 H 3007

Superconductivity with high upper critical field in Ta-Hf Alloys — •Pavan Kumar Meena, Sonika Jangid, Roshan Kumar Kushwaha, and Ravi Prakash Singh — Indian Institute of Science Education and Research Bhopal

Recently, there has been considerable interest in exploring superconducting alloys for potential applications in superconducting devices [1-4]. In this study, I will present our findings on superconductivity in TaxHf1-x alloys, utilizing magnetization, electrical resistivity, and specific heat measurements on polycrystalline samples [5]. The crystal structures of these alloys are composition dependent. Notably, when we substituted Hf (a Type-I superconductor with a critical temperature, T_c, of 0.12 K) with Ta (also a Type-I superconductor with a T_c of 4.4 K), a remarkable enhancement in TC was observed, along with a transition to Type-II superconductivity featuring high upper-critical fields. This transition is of particular interest from the perspective of materials science. Our specific heat measurements provided evidence of strong coupling superconductivity, aligning with conventional principles of superconductivity. These metallic alloys exhibit both metallic properties and a high upper-critical field, making them highly promising for practical superconducting devices like SQUID and qubits.
[1] T. G. Berlincourt et al., Phys. Rev. 131 (1963) 140
[2] J. K. Hulm et al., Phys. Rev. 123 (1961) 1569
[3] K. M. Wong et al., Phys. Rev. B 30 (1984) 1253
[4] A. P. Place et al., Nat. Commun. 12 (2021) 1779
[5] P. K. Meena et al., arXiv: 2305.19253 (2023)