TT 3: Correlated Electrons: Heavy Fermions

Time: Monday 9:30–13:15 Location: H 3005

TT 3.1 Mon 9:30 H 3005

Elusive Fulde-Ferrell-Larkin-Ovchinnikov state: Evolution of quasi-particle entropy in high-field superconducting phase in $CeCoIn_5$ — •Yoshi Tokiwa — I. Physik. Institut, Georg-August Universität Gottingen, Friedrich-Hund-Platz 1, 37077 Göttingen

We have performed a "smoking gun" experiment for Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state for $CeCoIn_5$. Entropy as a function of field is expected to show a steep increase at the transition field from BCS to FFLO superconducting (SC) state, because of the additional quasi-particles in the nodal parts of FFLO SC gap structure. We obtained electronic entropy of $CeCoIn_5$ by measuring magnetocaloric effect and specific heat at low temperatures down to 100mK and high fields up to 12T. In the high-field SC state for the field along [100], we observed a reduction of entropy, $\sim$8 mJ/mol·K, which is consistent with a spin density wave (SDW) order without the formation of FFLO state. The anomaly for the SDW transition in magnetocaloric effect and specific heat disappears, when the field is tilted 18° towards [001] from [100] in agreement with the neutron scattering experiment. Our experiment shows negative results for the formation of FFLO state in $CeCoIn_5$ for all the studied field directions, $H \parallel$[100], 18° and [001]. Although the numerous efforts for the experimental realization of FFLO state have been made since its prediction 40 years ago, an unambiguous observation in a solid state system still remains as a challenge in the field of condensed matter physics. This work is done by the collaboration with P. Gegenwart and E. Bauer and supported by DFG through research unit 960 (Quantum phase transitions).

TT 3.2 Mon 9:45 H 3005

Superconducting gap symmetry from the quasiparticle interference in the heavy fermion superconductor $CeCoIn_5$ — •Alireza Akbari[1], Peter Thalmeier[1], and Ilya Eremin[2] — [1]Max Planck Institute for the Chemical Physics of Solids, 01187 Dresden, Germany — [2]Theoretische Physik III, Ruhr-Universität Bochum, 44780, Bochum, Germany

One of the most difficult issues in the heavy Fermion superconductors like the 115 compounds $CeMIn_5$ (M = Co, Ir, Rh) is the identification of the symmetry of superconducting order parameter. The ambiguity between d_{xy} and $d_{x^2-y^2}$ symmetry remained from earlier specific heat and thermal transport investigations has been resolved in favor of the latter by the observation of a spin resonance that can occur only in $d_{x^2-y^2}$ symmetry. However these methods are all indirect and depend considerably on theoretical interpretation. We presented the theory for the quasiparticle interference (QPI) in the heavy Fermion superconductor $CeCoIn_5$ as a direct method to confirm the d-wave gap symmetry. We calculate the QPI pattern for both magnetic and non-magnetic impurities. By comparing the effect of the possible d-wave superconducting order parameters on QPI, the characteristic differences are found which may be identified by STM method. Our results propose that quasiparticle interference (QPI) and scanning tunneling microscopy (STM) can give a direct fingerprint of the superconducting gap in real space which may lead to a definite conclusion on its symmetry for $CeCoIn_5$ and related 115 compounds.

[1] A. Akbari, P. Thalmeier, I. Eremin, Phys. Rev. B 84, 134505 (2011).

TT 3.3 Mon 10:00 H 3005

Resonant magnetic exciton mode in the heavy-fermion antiferromagnet CeB_6 — G. Friemel[1], Y. Li[1], A. V. Dukhnenko[2], N. Y. Shitsevalova[2], N. E. Sluchanko[3], A. Ivanov[4], V. B. Filipov[2], B. Keimer[1], and •D. S. Inosov[1] — [1]MPI für Festkörperforschung, Stuttgart, Germany. — [2]Institute for Problems of Material Sciences, Kiev, Ukraine. — [3]General Physics Institute, Moscow, Russia. — [4]Institut Laue-Langevin, Grenoble, France.

Resonant magnetic excitations are widely recognized as hallmarks of unconventional superconductivity in copper oxides, iron pnictides, and heavy-fermion compounds. Model calculations have related these modes to the microscopic properties of the pair wave function, but the mechanisms of their formation are still debated. Here we report the discovery of a similar resonant mode in the non-superconducting antiferromagnetic heavy-fermion metal CeB_6. Unlike conventional magnons, the mode is non-dispersive and is sharply peaked around a wave vector separate from those characterizing the antiferromagnetic order. The magnetic intensity distribution rather suggests that the mode is associated with a coexisting antiferro-quadrupolar order parameter, which has long remained "hidden" to the neutron-scattering probes. The mode energy increases continuously below the onset temperature for antiferromagnetism, in parallel to the opening of a nearly isotropic spin gap throughout the Brillouin zone. These attributes bear strong similarity to those of the resonant modes in unconventional superconductors, indicating the dominance of itinerant spin dynamics in the ordered low-temperature phases of CeB_6.

TT 3.4 Mon 10:15 H 3005

Lattice dynamical Properties of the non-centrosymmetric Superconductor $CePt_3Si$ — •Sven Krannich[1], Frank Weber[1], Rolf Heid[1], Klaus-Peter Bohnen[1], Daniel Lamago[1,2], Ludwig Klam[3], Dirk Manske[4], and Hilbert von Löhneysen[1,5] — [1]Karlsruhe Institute of Technology, Institute of Solid State Physics, Karlsruhe, Germany — [2]Laboratoire Léon Brillouin, CEA-Saclay, Gif sur Yvette Cedex, France — [3]ETH Zürich, Institute for Theoretical Physics, Zürich, Switzerland — [4]Max Planck Institute for Solid State Research, Department Metzner, Stuttgart, Germany — [5]Karlsruhe Institute of Technology, Physics Institute, Karlsruhe, Germany

The order parameter of superconductors is usually classified as either a spin singlet (even parity) or a spin triplet (odd parity) by the Pauli exclusion principle. A necessary prerequisite for such a classification is, however, the existence of an inversion center. Something of a stir has been caused by the discovery of bulk superconductivity in $CePt_3Si$ which lacks inversion symmetry. In such systems the existence of an antisymmetric potential gradient causes a parity-breaking antisymmetric spin-orbit coupling (ASOC) that leads to a splitting of the Fermi surface and, moreover, gives rise to the unique possibility of having admixtures of spin-singlet and spin-triplet pairing states. Model calculations including ASOC predict anomalous lattice dynamics even in the non-superconducting state. Here we report on first measurements of the phonon dispersion using inelastic neutron scattering at T= 10 K. Experimental results are compared to DFT calculations including the Ce 4f electrons.

TT 3.5 Mon 10:30 H 3005

Resistivity, specific heat, and pressure dependent magnetization of multiple-transition antiferromagnet $CeAu_2Ge_2$ — •Chien-Lung Huang[1,2], Veronika Fritsch[1], Wolfram Kittler[1], and Hilbert von Löhneysen[1,2] — [1]Karlsruher Institut für Technologie, Physikalisches Institut, 76031 Karlsruhe, Germany — [2]Karlsruher Institut für Technologie, Institut für Festkörperphysik, 76021 Karlsruhe, Germany

The resistivity and specific heat of a $CeAu_2Ge_2$ single crystal grown from Au-Ge flux were measured between 1.8 and 200 K. Two transitions were observed in the specific heat at 11.5 and 14.5 K, confirming our recent susceptibility results[1]. We observe three field-induced transitions in the magnetoresistance measured at 1.6 K in accordance with the $B-T$ phase diagram constructed from magnetization. In addition, we have measured the magnetization under pressure. The antiferromagnetic transition temperature T_N is linearly enhanced by pressure with a small rate of 0.067 K/kbar, which suggests that, if attributed to a pure volume effect, this compound is close to the maximum transition temperature of the Doniach phase diagram. The transition fields B_M between the field-induced phases increase linearly upon applying pressure. The comparable Grüneisen parameters of T_N and B_M indicate that the energy scale depending on the sample's volume is determined by the antiferromagnetic correlations.

[1] V. Fritsch, P. Pfundstein, P. Schweiss, E. Kampert, B. Pilawa, and H. v. Löhneysen, Phys. Rev. B 84, 104446 (2011).

TT 3.6 Mon 10:45 H 3005

Superconductivity in an intermediate valence Ce compound with a quasi-two-dimensional structure — •Thomas Gruner[1], Miss. Anupam[2], Zakir Hossain[2], and Christoph Geibel[1] — [1]MPI for Chemical Physics of Solids, 01187, Dresden, Germany — [2]Department of Physics, IIT Kanpur, 208016, Kanpur, India

Binary rare earth - transition metal metallographic phase diagrams show a large immiscibility gap for early transition metals (i.e. from the left side of the periodic table). As a result, no binary compound forms

and only very few ternary compounds have been reported. Among them $CeRe_4Si_2$ presents an interesting structure: a stacking of Re_2Si and Ce layers results in a quasi-two-dimensional character. The preparation of this compound is challenging because of the high melting point of Re (3180 °C) and the fact that $CeRe_4Si_2$ likely forms in a solid-state reaction. We developed an appropriate synthesis process and obtained almost phase pure polycrystalline samples. Results of electrical resistivity, magnetic susceptibility and specific heat measurements show that Ce is in an intermediate valence state and that the compound becomes superconducting below $T_c \approx 3.2$ K. $CeRe_4Si_2$ is thus one of the very few intermediate valence Ce-based superconductors. The properties of this superconducting state will be discussed.

TT 3.7 Mon 11:00 H 3005

Shubnikov-de Haas Oscillations in $LuRh_2Si_2$ — •Sven Friedemann[1], Swee K Goh[1], F Malte Grosche[1], Zachary Fisk[2], Michael Sutherland[1], Patrick Rourke[3], and Gertrud Zwicknagl[4] — [1]Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, CB3 0HE Cambridge, United Kingdom — [2]Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA — [3]H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, UK — [4]Institute for Mathematical Physics, TU Braunschweig, Mendelssohnstrasse 3, 38106 Braunschweig, Germany

We present measurements of the Shubnikov-de Haas effect on $LuRh_2Si_2$ in conjunction with electronic band structure calculations. These electronic structure investigations can help understand the peculiar temperature dependence of the Hall effect. In addition, $LuRh_2Si_2$ represents the non-magnetic reference compound to $YbRh_2Si_2$, a prototypical heavy-fermion system featuring an unconventional quantum critical point. In $YbRh_2Si_2$, an orbitally selective Mott transition occurs from a large Fermi surface configuration including f electrons to a small configuration with conduction electrons only. $LuRh_2Si_2$ resembles the small Fermi surface configuration of $YbRh_2Si_2$. We detect oscillations of the resistivity with a large number of frequencies and discuss the angular dependency. We compare the detected orbits with those predicted for the three sheets by band structure calculations and discuss implications for the interpretation of quantum oscillation measurements on $YbRh_2Si_2$.

15 min. break.

TT 3.8 Mon 11:30 H 3005

Ferromagnetic correlations in Yb based heavy fermions probed by NMR relaxation: $YbNi_4P_2$ vs. $Yb(Rh,Ir)_2Si_2$ — •M. Baenitz, R. Sarkar, P. Khuntia, C. Krellner, C. Geibel, and F. Steglich — Max - Planck Institute of Chemical Physics of Solids, 01187 Dresden, Germany.

Intersite correlations in Ce-based heavy fermion systems close to the quantum critical point separating the magnetic ordered state from the paramagnetic Kondo lattice are in almost all cases predominantly antiferromagnetic (AFM) in nature. The NMR relaxation of these systems show an evolution from localized fluctuations with $1/T_1$ nearly constant above the Kondo temperature T_K, to a linear in T Korringa- like behavior with a constant and enhanced $(1/T_1T)$- value below T_K. We report on ^{31}P-NMR results on the ferromagnetic (FM) quantum critical system $YbNi_4P_2$ over a wide range in temperature (2-300 K) and field (0.2 - 9 T). Here, $^{31}(1/T_1T)(T)$ does not show such a signature at T_K, instead a continuous increase of $(1/T_1T)$ down to lowest T is observed. A similar behavior has been reported for $YbRh_2Si_2$, which also exhibits strong FM correlations evidenced by ^{29}Si - NMR and an enhanced Wilson ratio. Furthermore, in CeFePO, which is likely unique among Ce-based quantum critical system because of its strong FM correlations, $(1/T_1T)$ also diverges continuously for $T \longrightarrow 0$. This suggests that the difference in the relaxation between most of the Ce systems and the Yb systems is predominantly related to a change from AFM to FM intersite correlations. NMR-results (shift, line width, T_1) are analyzed and discussed in diffrent models (Korringa, Moriya).

TT 3.9 Mon 11:45 H 3005

High-field thermoelectric transport in $YbRh_2Si_2$ — R. Daou, •H. Pfau, M. Brando, C. Krellner, C. Geibel, and F. Steglich — MPI CPfS, Nöthnitzer Str. 40, 01187 Dresden, Germany

The heavy fermion compound $YbRh_2Si_2$ has attracted much interest providing an example of an unconventional quantum critical point that can be approached using very small magnetic fields. However, there are also anomalous features at higher fields that have not been well explored, and these may give us further insights into the electronic state of this unusual material. We report thermopower measurements on the best available single crystals of $YbRh_2Si_2$ at temperatures down to 0.1 K and magnetic fields up to 12 T applied along the ab-plane. We find two step-like features in the field dependence at 9 T and 11 T, the region where a suppression of the heavy fermion state was reported [1]. Additionally, another step appears at 3.5 T. These steps in thermopower correspond to features found in electrical transport [2]. The experimental results are supported by recently published renormalized bandstructure calculations [3] which show two features in the field dependent quasiparticle density of states at around 4 T and at 10 T. In these calculation, the anomalies at 10T in various quantities are caused by a van-Hove-type singularity below the Fermi energy. However, the separation into two features in thermopower and in resistivity remains unexplained as well as the origin of the clear 3.5 T-signature.

[1] P. Gegenwart et al., New. J. Phys. **8**, 171 (2006).
[2] HR. Naren et al., *This conference*.
[3] G. Zwicknagl, J. Phys.: Condens. Matter **23**, 094215 (2011).

TT 3.10 Mon 12:00 H 3005

High-field study of the heavy-fermion material URu_2Si_2 — •Gernot Werner Scheerer[1], William Knafo[1], Dai Aoki[2], Geraldine Ballon[1], Cyril Jaudet[1], Alain Mari[3], Cyril Proust[1], David Vignolles[1], and Jacques Flouquet[2] — [1]Laboratoire National des Champs Magnétiques Intenses, UPR 3228, CNRS- UJF-UPS-INSA, Toulouse, France — [2]Institut Nanosciences et Cryogénie, SPSMS, CEA-Grenoble, France — [3]Laboratoire de Chimie de Coordination, Toulouse, France

URu_2Si_2 is known for its "hidden-order" state below T_0=17.5 K, where the order parameter is still not identified [1]. A magnetic field along the **c**-axis induces a cascade of low-temperature phase transitions between 35 and 39 T from the "hidden order" to a polarized paramagnetic state. We have performed electrical transport and magnetization measurements in pulsed magnetic fields on ultra clean URu_2Si_2 samples. We established the H-T-phase diagram for $\mathbf{H} \parallel c$ in extended scales up to 60 T and 60 K. The vanishing of a high-temperature crossover at around 40-50 K, presumably related to intersite electronic correlations, precedes the polarization of the magnetic moments, as well as the destabilization of the "hidden-order" phase. Strongly sample-quality dependent magnetoresistivity confirms the Fermi surface reconstructions in a high magnetic field along **c** and at T_0 [2,3]. Shubnikov-de Haas quantum oscillations will also be presented.

[1] J. A. Mydosh and P. M. Oppeneer, arXiv:1107.0258
[2] E. Hassinger et al.: Phys. Rev. Lett. **105** (2010) 216409
[3] M.M. Altarawneh et al.: Phys. Rev. Lett. **106** (2011) 146403

TT 3.11 Mon 12:15 H 3005

Fermi surface and magnetic order in UPt_2Si_2 — •Zübeyir Cakir and Gertrud Zwicknagl — Institut f. Mathemat. Physik, TU Braunschweig, Germany

U intermetallic compounds exhibit highly complex phase diagrams at low temperatures with unusual and often enigmatic orders. The high sensitivity with respect to variations in external parameters like pressure or magnetic field reflect the strong correlations within the U 5f-shell. The present contribution focusses on the tetragonal compound UPt_2Si_2. We calculate the magnetic-field dependence of the Fermi surface for itinerant and partially localized U 5f-electrons and discuss consequences for field-induced instabilities.

TT 3.12 Mon 12:30 H 3005

Finite-temperature spectra and quasiparticle interference in Kondo lattices: From light electrons to coherent heavy quasiparticles — •Adel Benlagra[1], Thomas Pruschke[2], and Matthias Vojta[1] — [1]Institut für theoretische physik, TU Dresden, Germany — [2]Institut für theoretische physik, Universität Göttingen, Germany

Recent advances in scanning tunneling spectroscopy performed on heavy-fermion metals provide a window onto local electronic properties of composite heavy-electron quasiparticles. Here we theoretically investigate the energy and temperature evolution of single-particle spectra and their quasi- particle interference caused by point-like impurities in the framework of a periodic Anderson model. By numerically solving dynamical-mean-field-theory equations, we are able to access all temperatures and to capture the crossover from weakly interacting c and f electrons to fully coherent heavy quasiparticles. Remarkably, this crossover occurs in a dynamical fashion at an energy-dependent

crossover temperature. We study in detail the associated Fermi-surface reconstruction and characterize the incoherent regime near the Kondo temperature. Finally, we link our results to current heavy-fermion experiments.

TT 3.13 Mon 12:45 H 3005

Metamagnetism and Lifshitz transitions in models for heavy fermions — •Martin Bercx and Fakher F. Assaad — Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Am Hubland, 97074 Würzburg

We investigate metamagnetic transitions in models for heavy fermions by considering the metallic Kondo lattice model in two dimensions. Results are obtained within the framework of dynamical mean field and dynamical cluster approximation. Universal magnetization curves for different temperatures and Kondo couplings develop upon scaling with the lattice coherence temperature. Furthermore, the coupling of the local moments to the magnetic field is varied so as to take into account the different g-factors between localized and itinerant electrons. Competition between lattice coherence scale and Zeeman energy scale allow for two interpretations of the metamagnetism in heavy fermions: Kondo breakdown or Lifshitz transitions. By tracking the single particle residue through the transition and showing that it does not vanish at the transition, we can uniquely conclude in favour of the Lifshitz transition scenario.

TT 3.14 Mon 13:00 H 3005

Ring Exchange Periodic Anderson Model for Bilayer ^{3}He — •Jan Werner and Fakher Assaad — Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Würzburg, Deutschland

A unique feature of experiments on bilayer ^{3}He[1] is that the second layer starts growing before the first solidifies. The fermions in the first layer close to solidification are thus slow, whereas the fermions in the second layer are light. This combination of slow and light fermions which can hybridize with each other is the basic ingredient of the Anderson model, and the experiment has been interpreted in terms of heavy fermion physics. However in contrast to the Anderson model, magnetism in the 3He first layer is dominated by three body ring exchange. We present a simple model, which captures all above features, including an independent scale for the ring exchange and the strict constraint of no double occupancy in the first layer. We solve this model using CDMFT with a hybridization expansion CT-QMC algorithm as impurity solver. Our results show remarkable similarities with the experiments: a suppression of the coherence temperature upon approaching the solidification point of the first layer accompanied by the onset of ferromagnetic correlations within the first layer.

[1] M. Neumann, J. Nyeki, B. Cowan, und J. Saunders, Science 317, 1356 (2007)