TT 41: Correlated Electrons: Quantum-Critical Phenomena

Time: Wednesday 9:30–13:00 Location: HSZ 204

TT 41.1 Wed 9:30 HSZ 204

Quantum criticality with a twist: interplay of strong correlations and Kohn anomalies in three dimensions — •Thomas Schäfer[1], Andrey A. Katanin[2], Karsten Held[1], and Alessandro Toschi[1] — [1]Institute of Solid State Physics, TU Wien, 1040 Vienna, Austria — [2]Institute of Metal Physics, 620990, Kovalevskaya str. 18, Ekaterinburg, Russia; Ural Federal University, 620002, Mira str. 19, Ekaterinburg, Russia

Quantum critical points (QCPs) are among the most interesting phenomena in condensed matter systems and can emerge by exploiting a non-thermal parameter to suppress finite-temperature phase transitions. Although the limit of zero temperature cannot be reached experimentally, the existence of a QCP can severely influence the system's excitation spectrum. In spite of the intrinsic interest, a consistent theory for QCPs has not been established yet, due to the associated intermingling of temporal and spatial correlations. In this talk, quantum critical properties of the fundamental model of electronic correlations, the Hubbard model in three dimensions, are studied by means of a diagrammatic extension of the dynamical mean field theory, the dynamical vertex approximation (DΓA). The model's magnetic phase diagram is computed upon doping and its critical regions and exponents are analyzed. Quite unexpectedly, the quantum critical properties are found to be driven by the model's Fermi surface properties (Kohn points), even in presence of strong correlations, contradicting the predictions of the conventional Hertz-Millis-Moriya theory.

[1] T. Schäfer et al., arXiv:1605.06355 (2016).

TT 41.2 Wed 9:45 HSZ 204

Critical spin dynamics in $YbCo_2Si_2$ — A. Hannaske[1], K. Schmalzl[2], C. Geibel[1], and •O. Stockert[1] — [1]Max-Planck-Institut CPfS, Dresden, Germany — [2]JCNS at ILL, Grenoble, France

The strongly correlated compound $YbCo_2Si_2$ is the antiferromagnetically ordered sister compound to quantum critical $YbRh_2Si_2$. The magnetic order in $YbCo_2Si_2$ with $T_N = 1.7\,K$ can be continuously suppressed upon application of a magnetic field with a critical field of $B_c = 2\,T$. We performed detailed inelastic neutron scattering experiments on single-crystalline $YbCo_2Si_2$ to study the spin dynamics at B_c. A critical slowing down of the magnetic response is observed as function of temperature at B_c with slightly sublinear temperature dependence of the relaxation rate of the critical spin fluctuations. Moreover, as inferred from measurements at finite momentum transfer, away from the antiferromagnetic ordering wave vector, the paramagnons soften and their lifetime decreases with temperature. Our results will be compared with theoretical calculations.

TT 41.3 Wed 10:00 HSZ 204

Microstructured $YbRh_2Si_2$ and $YbNi_4P_2$: Magnetoresistance at low temperatures — •Alexander Steppke[1], Sandra Hamann[1], Markus König[1], Andrew P. Mackenzie[1], Kristin Kliemt[2], Cornelius Krellner[2], Heike Pfau[3], Ramzy Daou[4], and Manuel Brando[1] — [1]MPI for Chemical Physics of Solids, Noethnitzer Str. 40, 01187 Dresden — [2]Goethe-Universität Frankfurt, Max-von-Laue Strasse 1, 60438 Frankfurt am Main — [3]Stanford Institute for Materials and Energy Science, 2575 Sand Hill Road Menlo Park, California 94025, USA — [4]Normandie Univ, ENSICAEN, CNRS, CRISMAT, 14000 Caen, France

With electrical transport measurements providing valuable information about novel phases or topological changes of the Fermi surface we investigated the properties of $YbRh_2Si_2$ and $YbNi_4P_2$. In the Kondo lattice $YbRh_2Si_2$ the recent discovery of a strong change in the ac susceptibility indicates a superconducting state below 2 mK [1]. Yet data of resistive transitions at these temperatures are still absent, due to the challenge of measuring resistances with minimal dissipation. Furthermore magnetoresistance measurements can be used to detect field induced Lifshitz transitions in both systems. Here we show that by modifying the geometry of clean bulk samples using focused ion beam the resistance can be increased by several orders of magnitude without influencing the magnetic or electronic properties. This opens a path to resistance measurements at ultra low temperatures.

[1] E. Schuberth et al. Science 351, 485 (2016)

TT 41.4 Wed 10:15 HSZ 204

Angle-dependent electron spin resonance measurements on $YbRh_2Si_2$ down to 1.6 K using superconducting planar resonators — •Linda Bondorf[1], Manfred Beutel[1], Markus Thiemann[1], Kristin Kliemt[2], Jörg Sichelschmidt[3], Cornelius Krellner[2], Martin Dressel[1], and Marc Scheffler[1] — [1]1. Physikalisches Institut, Universität Stuttgart, Germany — [2]Goethe-Universität, Frankfurt am Main, Germany — [3]Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany

$YbRh_2Si_2$ is a tetragonal heavy-fermion system with strong magnetic anisotropy. Its antiferromagnetic order below 70 mK can be suppressed by an in-plane magnetic field of 60 mT, which leads to a quantum critical point. Experimental challenges, e.g. for neutron spectroscopy have so far prohibited a full understanding of the antiferromagnetism of YbRh2Si2. Here, angle-dependent electron spin resonance (ESR) could be an alternative method. However, conventional ESR spectrometers are limited in frequency (typically 9 GHz, corresponding to 200 mT for YbRh2Si2) and temperature (down to 2 K).

To overcome these limitations, we use superconducting planar microwave resonators, and we have performed angle-dependent ESR measurements with in-situ rotation of $YbRh_2Si_2$ single crystals inside a ^{4}He cryostat down to 4.4 GHz and 1.6 K. We present the ESR g-factor as a function of angle, which is consistent with results of previous measurements at higher temperatures and frequencies. Angle-dependent ESR investigations inside the antiferromagnetic phase of $YbRh_2Si_2$ can now be addressed experimentally.

TT 41.5 Wed 10:30 HSZ 204

Grüneisen ratio divergence at the structural quantum critical point in $(Ca_{0.9}Sr_{0.1})_3Rh_4Sn_{13}$ — •Rudra Sekhar Manna[1], Andreas Wörl[1], Swee K. Goh[2], Kazuyoshi Yoshimura[3], and Philipp Gegenwart[1] — [1]EP VI, EKM, Augsburg University, 86159 Augsburg, Germany — [2]Dept. of Physics, The Chinese University of Hong Kong, Hong Kong, China — [3]Dept. of Chemistry, Kyoto University, Kyoto 606-8502, Japan

Quasi-skutterudite compound $Sr_3Rh_4Sn_{13}$ shows a second-order structural phase transition at 138 K which can be tuned to 0 K either by applying hydrostatic pressure or by chemical pressure in $(Ca_xSr_{1-x})_3Rh_4Sn_{13}$. At the critical concentration, $x_c = 0.9$, specific heat shows a pronounced enhancement (compared to the x = 0) of the low-temperature phonon (T^3) contribution, possibly related to the softening of an optical mode [1]. We have performed high-resolution thermal expansion and specific heat measurements on single crystal of x = 0 and a lump of small $(Ca_{0.9}Sr_{0.1})_3Rh_4Sn_{13}$ crystals. Thermal expansion also detects a strongly enhanced phonon contribution at the critical concentration. Importantly, the effective Grüneisen parameter $\Gamma_{eff} = \beta \cdot V_{mol}/\kappa_T \cdot C$ diverges from 20 K down to below 1 K, providing evidence for quantum criticality.

[1] S. K. Goh, D. A. Tompsett, P. J. Saines, H. C. Chang, T. Matsumoto, M. Imai, K. Yoshimura, and F. M. Grosche, PRL **114**, 097002 (2015).

TT 41.6 Wed 10:45 HSZ 204

Magnetic and structural phase transitions in $CeCu_{6-x}Au_x$ — •Sebastian Kuntz[1], Kai Grube[1], Lothar Pintschovius[1], Frank Weber[1], Peter Schweiss[1], Oliver Stockert[2], Veronika Fritsch[3], Sebastian Bachus[3], Yasuyuki Shimura[3], Philipp Gegenwart[3], and Hilbert von Löhneysen[1,4] — [1]Institut für Festkörperphysik, Karlsruher Institut für Technologie, D-76021 Karlsruhe, Germany — [2]Max-Planck-Institut für Chemische Physik fester Stoffe, D-01187 Dresden, Germany — [3]Experimentalphysik VI, Center for Electronic Correlations and Magnetism, Augsburg University, 86159 Augsburg, Germany — [4]Physikalisches Institut, Karlsruher Institut für Technologie, D-76049 Karlsruhe, Germany

The heavy-fermion compound $CeCu_{6-x}Au_x$ is a model system for unconventional quantum criticality. At small Au contents $CeCu_{6-x}Au_x$ reveals a structural transition from an orthorhombic to a monoclinic crystal symmetry while at higher x an antiferromagnetic phase appears. To shed light on the interplay between quantum critical magnetic and structural fluctuations we performed neutron scattering experiments and thermodynamic measurements on samples with varying Au concentration between $x = 0$ and 0.3. The application of hydrostatic and chemical pressure allows to separate the magnetic from the

structural transition and demonstrates that the unconventional quantum criticality is based on the magnetic fluctuations and not influenced by the monoclinic distortion.

TT 41.7 Wed 11:00 HSZ 204

Coherent Emergence of a Quantum Critical Heavy Fermion Groundstate — •Christoph Wetli[1], Johann Kroha[2], Oliver Stockert[3], Hilbert von Löhneysen[4], Kristin Kliemt[5], Cornelius Krellner[5], and Manfred Fiebig[1] — [1]Department of Materials, ETH Zürich — [2]Institute of Physics, Bonn University — [3]MPI for Chemical Physics of Solids, Dresden — [4]Institute of Solid State Physics, KIT — [5]Institute of Physics, Goethe University Frankfurt

Kondo quasiparticles in heavy-fermion metals have an outstandingly long lifetime. However, near a quantum phase transition, the quasiparticles may disintegrate and give way to an exotic state of matter where the very concept of a particle breaks down. We investigate the emergence of this quantum critical behavior in a time-resolved Terahertz reflection experiment. Due to the non-ionizing nature of Terahertz radiation, we directly monitor the formation dynamics of a strongly correlated groundstate in a time-resolved experiment, while simultaneously monitoring the spectral weight and the Kondo temperature. In the quantum critical $CeCu_{5.9}Au_{0.1}$ compound, the heavy-fermion state reconvenes after 5.8 ps under the emission of a temporally delayed, yet phase-coherent reflex. When the temperature is lowered, the changing dynamics indicates the emergence of the unconventional quantum critical state. A decrease in amplitude and an increase in delay of the reflex reveals that the quasiparticle weight collapses while the Kondo temperature reduces but remains finite.

15 min. break.

TT 41.8 Wed 11:30 HSZ 204

Quantum oscillations in the pressure-metallised Mott insulator NiS_2 — •Konstantin Semeniuk[1], Hui Chang[1], Sven Friedemann[2], Jordan Baglo[1], Monika Gamza[3], Pascal Reiss[4], Alix McCollam[5], Inge Leermakers[5], Patricia Alireza[1], Audrey Grockowiak[6], William Coniglio[6], Stanley Tozer[6], and Malte Grosche[1] — [1]Cavendish Laboratory, University of Cambridge, UK — [2]HH Wills Laboratory, University of Bristol, UK — [3]Jeremiah Horrocks Institute, University of Central Lancashire, UK — [4]Clarendon Laboratory, University of Oxford, UK — [5]High Field Magnet Laboratory, Nijmegen, The Netherlands — [6]NHMFL, Tallahassee, Florida, USA

The metallic state on the threshold of Mott localisation represents one of the most fundamental examples of correlated electron physics. The 3D Mott insulator NiS_2 can be tuned into the metallic state by moderate hydrostatic pressure of about 30 kbar, enabling quantum oscillation measurements in close proximity to the Mott transition.

We present the results of a comprehensive Fermi surface study of NiS_2 performed in magnetic fields of up to 35 T, using a tunnel diode oscillator technique with 0.01ppm frequency resolution in combination with liquid medium high pressure anvil cells. The evolution of the Fermi surface and the effective carrier masses of NiS_2 has been tracked from 33 to 55 kbar, and a rotation study has been carried out to resolve the 3D geometry of the principal Fermi surface sheet. Our results are interpreted in the context of the canonical Brinkman-Rice picture of Mott localisation.

TT 41.9 Wed 11:45 HSZ 204

Quantum Tricritical Points in $NbFe_2$ — •Sven Friedemann[1,2], Max Hirschberger[2,4], Thomas Bauer[3], Robert Kuechler[3], Andreas Neubauer[4], Manuel Brando[3], Christian Pfleiderer[4], and F Malte Grosche[2] — [1]HH Wills Laboratory, University of Bristol, UK — [2]Cavendish Laboratory, University of Cambridge, Cambridge, UK — [3]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [4]Physik Department E21, TU München, Garching, Germany

Quantum critical points (QCPs) in ferromagnetic (FM) metals impose a long-standing challenge including seemingly incompatible temperature dependencies in transport and thermodynamic properties. In many of these systems, the FM QCP is avoided through a change to 1st order. Here, we present results on a second class of FM quantum critical metals in which the QCP is avoided through an intervening spin-density-wave (SDW) phase. We show that the phase diagram of $NbFe_2$ can be modelled with a two-order-parameter theory in which the FM QCP is buried within a SDW phase, as proposed by Moriya and Usami [1]. This model reproduces detailed magnetisation measurements on high-purity single crystals for a series of samples tuned across the buried FM QCP via variations in the composition. We establish the presence of quantum tricritical points at which both the uniform and finite wavelength susceptibility diverge, which may explain the incompatible temperature dependencies.

[1] Sol State Com, **23** 935 (1977)

TT 41.10 Wed 12:00 HSZ 204

Effect of tuning parameters on the partially frustrated magnetic order in CePdAl — •Stefan Lucas[1,2], Zita Hüsges[3], Veronika Fritsch[4], Jens-Uwe Hoffmann[3], Karel Prokeš[3], Manfred Reehuis[3], Hilbert von Löhneysen[5], and Oliver Stockert[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]Institute of Solid State Physics, TU Dresden, Dresden, Germany — [3]Helmholtz-Zentrum Berlin, Berlin, Germany — [4]EP 6, Electronic Correlations and Magnetism, Augsburg University, Augsburg, Germany — [5]Karlsruhe Institute of Technology, Institute for Solid State Physics, Karlsruhe, Germany

The heavy-fermion system CePdAl is a model system to investigate magnetic frustration in a metallic material. An arrangement of the Ce moments on a distorted kagomé lattice in the basal plane together with a strong Ising anisotropy leads to geometric frustration. This results in a complex interplay with the RKKY and Kondo interaction, where only two thirds of the magnetic moments are long-range ordered, whereas the remaining third is frustrated and/or screened by the Kondo effect below the antiferromagnetic ordering temperature of 2.7 K. Using different in-plane tuning parameters like magnetic fields and especially uniaxial pressure, we investigated the stability of the complex magnetic order. Thereby, we were able to stabilize the magnetic order under moderate uniaxial pressures of up to 1 kbar.

TT 41.11 Wed 12:15 HSZ 204

Signature of frustrated moments in quantum critical $CePd_{1-x}Ni_xAl$ — Akito Sakai[1], Stefan Lucas[2], Zita Huesges[2], Kai Grube[3], Philipp Gegenwart[1], Oliver Stockert[2], Hilbert v. Löhneysen[3], and •Veronika Fritsch[1] — [1]EP 6, Electronic Correlations and Magnetism, Augsburg University, Germany — [2]Max Planck Insitute for Chemical Physics of Solids, Dresden, Germany — [3]Institute for Solid State Physics and Physics Institute, Karlsruhe Institute of Technology, Germany

Magnetic frustration suppresses long-range magnetic order despite the presence of strong magnetic couplings. This results in exotic ground states, where the spins can fluctuate down to zero temperature. However, metallic materials that simultaneously exhibit magnetic frustration and a strong coupling between the magnetic moments and the conduction electrons, are quite scarce.

The here presented CePdAl is a system were the Kondo effect and magnetic frustration coexist. It can be tuned across a quantum critical point by substitution of Pd with approximately 14% of Ni. Furthermore, field-induced quantum criticality can be observed in $CePd_{1-x}Ni_xAl$. We have investigated single crystals with Ni concentrations $0 \leq x \leq 0.16$. In addition to the generic signatures of quantum criticality a unique thermodynamic feature of the frustrated moments, i.e. an additional contribution to the magnetic Grüneisen paramter, is discovered [1].

[1] A. Sakai *et al.*, ArXiv:1609.00816 [cond-mat.str-el] (2016).

TT 41.12 Wed 12:30 HSZ 204

$YbNi_4(P_{1-x}As_x)_2$: Single crystal growth and characterization — •Kristin Kliemt[1], Philipp Ross[1], Oliver Stockert[2], Manuel Brando[2], and Cornelius Krellner[1] — [1]Goethe-University Frankfurt, Institute of Physics, 60438 Frankfurt, Germany — [2]MPI CPfS, 01187 Dresden, Germany

The low lying Curie temperature, $T_C = 0.17$ K, of the heavy-fermion compound $YbNi_4P_2$ can be further suppressed by substituting P by As and the rare case of a ferromagnetic quantum critical point occurs in the substitution series $YbNi_4(P_{1-x}As_x)_2$ at $x \approx 0.1$ [1,2].

Here, we present the growth of $YbNi_4(P_{1-x}As_x)_2$ single crystals with As concentrations from $0 \leq x \leq 1$ using the Czochralski method from a levitating melt. Recently, this crucible free growth method was successfully implemented to obtain cm-sized oriented single crystals of the unsubstituted compound $YbNi_4P_2$ [3]. The samples were characterized by electrical transport, heat capacity and magnetization measurements and we will give details about these results. Furthermore, we determined their crystal structure by powder X-ray diffraction and investigated the homogeneity of the As distribution in the crystals us-

ing energy dispersive X-ray spectroscopy. In addition, the crystallinity of the samples was checked by neutron Laue backscattering.

[1] C. Krellner et al., New J. Phys. 13, 103014 (2011)
[2] A. Steppke et al., Science 339, 933 (2013)
[3] K. Kliemt, C. Krellner, J. Cryst. Growth 449, 129 (2016).

TT 41.13 Wed 12:45 HSZ 204

Magneto-acoustic investigations of field-induced quantum criticality in Cs_2CuCl_4 — •Bernd Wolf[1], Lars Postulka[1], Yeekin Tsui[1], Pham Thang Cong[1,2], Natalia van Well[1,3], Franz Ritter[1], Cornelius Krellner[1], and Michael Lang[1] — [1]Physics Institute, Goethe University Frankfurt, D-60438 Frankfurt(M) — [2]Dresden-HFFL, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden — [3]Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institute, CH-5232 Villigen

Magnetoelastic investigations of the frustrated triangular-lattice antiferromagnet Cs_2CuCl_4 were performed for the longitudinal modes c_{11}, c_{22} and c_{33} in magnetic fields up to 10 T and down to 0.032 K. Acoustic anomalies have been found both in the temperature and in the field dependence of these modes. For temperatures 0.8 K $> T >$ 2.0 K in the 1D-regime of Cs_2CuCl_4, the magnetoelastic behaviour can be well described with a microscopic theory. The field-dependent measurements for $T > T_N$ around the quantum-critical point (QCP) at $B_s \sim 8.5$ T display two distinct anomalies which are attributed to the transition into long-range afm order and signatures of the preceding spin-liquid state. At the lowest temperatures of our experiment c_{33}(B) can be well described by a Landau free energy model with a very small magnetoelastic coupling constant $G/k_B = 2.8$ K. The observation of rather classical behaviour at lowest temperatures and the deviations from the classical behaviour at somewhat higher temperatures are assigned to the opening of a small gap in the magnetic excitations spectrum for $B < B_s$ which drives the system away from quantum criticality.