TT 35: Correlated Electrons: Quantum-Critical Phenomena - Experiment I

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

TT 35.1 Tue 9:30 HSZ 204

Optical non-Fermi-liquid behavior in $CeCoIn_5$ — •Marc Scheffler[1], Uwe S. Pracht[1], Martin Dressel[1], Masaaki Shimozawa[2], Ryota Endo[2], Takahito Terashima[3], Takasada Shibauchi[2], and Yuji Matsuda[2] — [1]1. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany — [2]Department of Physics, Kyoto University, Kyoto, Japan — [3]Research Center for Low Temperature and Materials Science, Kyoto University, Kyoto, Japan

The non-Fermi-liquid metallic state of the heavy-fermion superconductor $CeCoIn_5$ is interpreted as a consequence of a nearby quantum-critical point. Spectroscopic studies of quantum-critical heavy fermions have yielded valuable information, but are experimentally challenging. This also holds for optical techniques: the required low energies, both in temperature and frequency, are hard to reach. We overcome these difficulties by combining high-quality thin films of $CeCoIn_5$ with THz transmission spectroscopy. We cover frequencies 0.2-1.1 THz at temperatures down to 3 K, i.e. matching energy scales.

The THz spectra of $CeCoIn_5$ indicate metallic behavior with unconventional features. Upon cooling, the transport relaxation rate decreases through our frequency window, but we never find a simple Drude response. Instead, at low temperatures we observe a strongly frequency-dependent relaxation rate which is clearly inconsistent with Fermi-liquid predictions and which we attribute to electronic correlations in this non-Fermi-liquid phase. We further address the frequency- and temperature-dependent effective mass, and we discuss possible scaling behavior in the quantum-critical regime.

TT 35.2 Tue 9:45 HSZ 204

Exploring new LuT_2In compounds: Evidence for a structural quantum critical point — •Thomas Gruner, Dongjin Jang, Raul Cardoso, Manuel Brando, Gerhard Fecher, and Christoph Geibel — MPI CPfS, 01187 Dresden, Germany

Finding novel compounds with unconventional properties is one of the most appealing tasks in modern solid state physics. We recently studied the compounds $LuPt_2In$ and $LuPd_2In$ and discover that they present an exceptional opportunity for studying a structural quantum critical point (QCP). Up to now QCPs have been intensively studied in magnetic systems, while structural QCPs are rather scarce.
We synthesized both compounds to study their structural and electronic properties. We found that at high temperatures both compounds crystalize in the simple cubic Heusler structure. While $LuPd_2In$ retains this structure down to lowest T, in $LuPt_2In$ susceptibility $\chi(T)$, resistivity $\rho(T)$ and T-dependent powder XR diffraction evidence a charge density wave type transition at about 450 K to a yet undetermined low T structure. The T dependence of the anomalies in $\chi(T)$ and $\rho(T)$ indicate a 2^{nd} order type transition. Substituting Pd for Pt in $Lu(Pt_{1-x}Pd_x)_2In$ results in a continuous decrease of T_{trans}, indicating a structural QCP at $x_{\text{QCP}} \approx 0.55$. Most interestingly we observed bulk superconductivity in the whole alloy series, with a clear maximum in the SC transition temperature at x_{QCP}. Furthermore we found that the phonon contribution to the specific heat at low T also presents a clear maximum at x_{QCP}, suggesting critical phonon softening. These results provide new insight into structural QCPs.

TT 35.3 Tue 10:00 HSZ 204

The Spin-1/2 XXZ Chain System Cs_2CoCl_4 in a Transverse Magnetic Field — •Oliver Breunig[1], Markus Garst[2], Eran Sela[2,3], Benjamin Buldmann[2], Petra Becker[4], Ralf Müller[1], and Thomas Lorenz[1] — [1]II. Physikalisches Institut, Universität zu Köln — [2]Institut für Theoretische Physik, Universität zu Köln — [3]Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University — [4]Institut für Kristallographie, Universität zu Köln

Cs_2CoCl_4 consists of $CoCl_4$ tetrahedra that form chains along the crystallographic b axis. Due to a strong single-ion anisotropy the Co^{2+} orbital S=3/2 ground state is split into two Kramers doublets. Thus, at low temperatures a description of the lower doublet in terms of an effective spin-1/2 with an additional easy-plane anisotropy arises. By comparing measurements of specific heat and thermal expansion to exact finite-size diagonalization, we show that Cs_2CoCl_4 at temperatures below 2 K realizes the spin-1/2 XXZ chain in a transverse field [1]. Our data indicate a quantum phase transition at a critical field of ~ 2 T before around 3.5 T the description in terms of an effective spin-1/2 chain becomes inapplicable. Considering both thermal as well as virtual excitations of higher crystal field states, we find that the spin chain is in the XY-limit with an anisotropy $J_z/J_\perp \approx 0.12$ substantially smaller than previously believed. This work has been supported by the Deutsche Forschungsgemeinschaft via SFB 608 and FOR 960.
[1] O. Breunig *et al.*, PRL **111**, 187202 (2013)

TT 35.4 Tue 10:15 HSZ 204

Anomalous quantum critical behavior in a 3d itinerant magnet $Sr_{1-x}Ca_xRuO_3$ — •Chien-Lung Huang[1,2], Dirk Fuchs[2], Markus Wissinger[2], Jörg Schmalian[3], Rudolf Schneider[2], Meng-Chieh Ling[3], and Hilbert von Löhneysen[1,2] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, 76128 Karlsruhe, Germany — [2]Institut für Festkörperphysik, Karlsruher Institut für Technologie, 76021 Karlsruhe, Germany — [3]Institut für Theorie der Kondensierten Materie, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany

The magnetization M and the specific heat C of polycrystalline $Sr_{1-x}Ca_xRuO_3$ were investigated as a function of the Ca substitution x. The Curie temperature $T_C = 162$ K of $SrRuO_3$ decreases linearly with increasing x. Long-range ferromagnetic (FM) order is completely suppressed above the critical concentration $x_c \sim 0.7$ at which quantum critical behavior was observed. That behavior cannot be described by the conventional Hertz-Millis-Moriya thoery for an FM quantum critical point, nor by the existence of a Griffiths phase. Nevertheless, the electronic and magnetic specific heat $\delta C_{em}/T = (C_{em}(B) - C_{em}(0))/T$ after subtraction of the phonon contribution and the scaled magnetization M/T^β collapse onto single scaling functions $\mathcal{F}(B/T^{1.25})$ and $\mathcal{F}(B/T^{1.7})$, respectively. The anomalous critical behavior will be discussed in terms of magnetic inhomogeneity.

TT 35.5 Tue 10:30 HSZ 204

Frustration and Quantum Criticality in Ni-doped CePdAl — •Veronika Fritsch[1], Zita Huesges[2], Oliver Stockert[2], Christian Taubenheim[1], Wolfram Kittler[1], Chien-Lung Huang[1], Kai Grube[1], and Hilbert v. Löhneysen[1] — [1]Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany — [2]Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany

In heavy-fermion systems, magnetic quantum phase transitions (QPT) usually arise from the competition between RKKY and Kondo interaction. For large Kondo interactions the $4f$ states hybridize strongly with the conduction electrons, thus suppressing the magnetic ordering temperature to zero. Magnetic frustration is an alternative way to suppress the magnetic order, while keeping the local moments intact. Recently theoretical models were developed discussing additional frustration-induced fluctuations for heavy-fermion metals. We will examine the role of magnetic frustration at the QPT in the heavy fermion system CePdAl, which crystallizes in a hexagonal ZrNiAl-type structure, where the magnetic Ce-ions form a distorted kagomè lattice. The magnetic order, as revealed through previous neutron scattering experiments, is partially frustrated with one third of the Ce-ions not participating the long-range magnetic order. An external magnetic field turns the system toward a Fermi-liquid state. The substitution of Pd by Ni yields a QPT accompanied by non-Fermi-liquid behavior. We will present our recent experiments on single-crystalline $CePd_{1-x}Ni_xAl$, namely measurements of specific heat, thermal expansion, electrical resistivity and magnetization, as well as neutron scattering experiments.

TT 35.6 Tue 10:45 HSZ 204

Frustrated magnetic order in $CePd_{1-x}Ni_xAl$ studied by neutron diffraction — •Z. Huesges[1], S. Woitschach[1], O. Stockert[1], V. Fritsch[2], M.-H. Lemée-Cailleau[3], S. Capelli[3], S. Matas[4], K. Prokes[4], B. Pedersen[5], and H. von Löhneysen[2] — [1]Max Planck Institute CPfS, Dresden, Germany — [2]Karlsruhe Insitute of Technology, Germany — [3]Institut Laue-Langevin, Grenoble, France — [4]Helmholtz Zentrum Berlin, Germany — [5]FRM2, Technical University München, Germany

The heavy-fermion compound CePdAl might be a model system to study the influence of frustration on quantum criticality, which has recently become a much-discussed topic in theoretical condensed matter physics. The quantum critical point can be accessed by Ni doping

on the Pd site, which reduces the Néel temperature from 2.7 K in the pure compound to zero for 14 % Ni substitution. The magnetic order of undoped CePdAl has previously been investigated by powder neutron diffraction, which revealed that only two thirds of the Ce spins order, while the ordered moment of the remaining third is zero even at very low temperatures. This frustration can be related to the quasi-Kagomé lattice of the Ce ions in the hexagonal basal plane. We have performed single crystal neutron diffraction for different alloys of the doping series $CePd_{1-x}Ni_xAl$. We found that the ordering vector remains unchanged upon doping and that the ordered moment is gradually suppressed. Furthermore, we observed short-range magnetic order which co-exists with the long-range order signal. The length scale of these fluctuations becomes much shorter on approaching the quantum critical point.

TT 35.7 Tue 11:00 HSZ 204

Single crystal growth of the ferromagnetic heavy fermion compound $YbNi_4P_2$ — •Kristin Kliemt and Cornelius Krellner — Physikalisches Institut, Goethe University Frankfurt, 60438 Frankfurt am Main, Germany

In the heavy fermion metal $YbNi_4P_2$ a ferromagnetic (FM) transition at $T_C = 0.17$ K was observed recently [1]. This transition can be further suppressed by substituting As on the P site. Investigation of $YbNi_4(P_{1-x}As_x)_2$ showed the appearance of the first clear-cut example of a ferromagnetic quantum critical point in metals at $x \leq 0.08$ [2]. High quality single crystals are required to investigate this new compound in more detail.

Here, we report on the single crystal growth of $YbNi_4P_2$ in a Bridgman-type furnace. Because of the incongruent melting of $YbNi_4P_2$, the growth was done from a Ni-P self flux at about 1400°C. Subsequently, the flux was removed by centrifugation at 1000°C. The quality of the crystals was verified by resistivity and magnetic measurements from 300 to 2 K. In particular, we address the challenge, how to avoid the formation of impurity phases and flux inclusions by variation of crucible shapes and growth conditions like temperature, duration, velocity of cooling and flux composition. With this optimization we obtained single crystals suitable for several measurement techniques as e.g. ARPES, STM, NMR, ESR, and magnetization to unravel the nature of the ferromagnetism in $YbNi_4P_2$.

[1] C. Krellner et al., New J. Phys. 13, 103014 (2011)
[2] A. Steppke et al., Science 339, 933 (2013)

15 min. break.

TT 35.8 Tue 11:30 HSZ 204

Single crystal study of $SrCo_2P_2$: an unusual spin fluctuating system — •Christoph Bergmann, Christoph Geibel, Helge Rosner, and Deepa Kasinathan — Max-Planck-Institut für Chemische Physik fester Stoffe, Nöthnitzer Straße 40, 01187 Dresden Deutschland

Since the discovery of high temperature superconductivity in doped RFeAsO, transition metal pnictides have attracted considerable attention, especially those being close to a transition from a magnetic ordered to a non-magnetic ground state. $SrCo_2P_2$, a structural homologue of the AFe_2As_2 series of compounds, is such a system. Earlier investigation on polycrystals indicated a paramagnetic ground state, but a close proximity to magnetic ordering. Using a flux technique, we grew high quality single crystals with a residual resistivity ratio up to 140, and performed an in-depth study of the physical properties. Despite LDA calculation indicate a pronounced peak in the density of states at the Fermi level prone for electronic instability, we did not find any evidence for a phase transition. However we observed a quite unusual T dependence of the susceptibility with two distinct maxima, and Non-Fermi-liquid behavior in the resistivity at low T. Both features confirm $SrCo_2P_2$ to be a rather unusual spin fluctuating system close to a (quantum) critical point.

TT 35.9 Tue 11:45 HSZ 204

Competing order parameters in $NbFe_2$ — •Sven Friedemann[1], Max Hirschberger[1,2], William J Duncan[1], Andreas Neubauer[2], Thomas Bauer[3], Manuel Brando[3], Christian Pfleiderer[2], and F Malte Grosche[1] — [1]Cavendish Laboratory, University of Cambridge, Cambridge, UK — [2]Physik Department E21, TU München, Garching, Germany — [3]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

Quantum criticality in transition metal compounds imposes long-standing challenges: Near the border of magnetism at low temperature, T, prominent examples like the ferromagnets MnSi and $ZrZn_2$ obey unconventional power law-dependencies of the resistivity which cannot be understood within the standard magnetic fluctuation theory. Here, we present new results on $NbFe_2$ in which a $T^{3/2}$ dependence of the resistivity has also been observed [1]. $NbFe_2$ can be tuned by varying the composition, thus enabling detailed investigations not possible in pressure tuned systems. While slightly iron-rich samples are ferromagnetic at low $T < T_c$, T_c is suppressed to 0 on approaching stoichiometry and a new phase is observed above T_c. Using high-purity single crystals we conduct comprehensive studies of bulk magnetic, thermodynamic, and transport properties. These prove the presence of both ordered states. We show that our results are consistent with the competing order parameter theory of uniform and modulated magnetic states as proposed by Moriya and Usami [2]. We infer that the quantum critical behaviour in $NbFe_2$ is associated with the modulated magnetic order.

[1] Phys. Rev. Lett. **101**, 026401 (2008)
[2] Sol. State Comm. **23**, 935 (1977)

TT 35.10 Tue 12:00 HSZ 204

Microscopic study about the magnetic ground state of C14 systems: $Nb_{1-y}Fe_{2+y}$ and $Ta(Fe_{1-x}V_x)_2$ — •Daniela Rauch[1], Mathias Kraken[1], Jochen Litterst[1], Hubertus Luetkens[2], Manuel Brando[3], Michael Baenitz[3], William J Duncan[4], Andreas Neubauer[5], Christian Pfleiderer[5], Stefan Süllow[1], and F Malte Grosche[4] — [1]Institute of Condensed Matter Physics, TU Braunschweig, Braunschweig, Germany — [2]Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institute, Villigen, Switzerland — [3]Max-Planck Institute for Chemical Physics of Solids, Dresden, Germany — [4]Cavendish Laboratory, University of Cambridge, Cambridge, UK — [5]Physik Department E21, TU München, Garching, Germany

A large number of C14 Laves systems exhibits a complex magnetic phase diagram with ferromagnetic critical fluctuations. In this context, $Nb_{1-y}Fe_{2+y}$ and $Ta(Fe_{1-x}V_x)_2$ need to be discussed. $NbFe_2$ has been proposed to represent a very rare case of spin density wave order (SDW), which can be suppressed by slight changes to the stoichiometry to be ferromagnetic. Here, we present for the first time μSR of $Nb_{1-y}Fe_{2+y}$ and identify SDW and ferromagnetic phases on a microscopic scale and establish them as bulk magnetic phases. Moreover, we present a combined μSR study with the analysis of Mößbauer spectroscopy experiments on Fe-rich $Nb_{1-y}Fe_{2+y}$ and discuss the nature of the ground state magnetic phases. In addition, $Ta(Fe_{1-x}V_x)_2$ is of special interest because of ferromagnetic critical fluctuations, which evolved in the proximFor this reason, we report first Mößbauer experiments.

TT 35.11 Tue 12:15 HSZ 204

transport and torque magnetometry measurements on CeAuSb2 — •Lishan Zhao — University of St Andrews, St Andrews, Fife, UK

The tetragonal crystal CeAuSb2 has a layered structure and orders antiferromagnetically at T 6K. Under a c-axis magnetic field, the Neel temperature is gradually suppressed to zero at a possible field-tuned quantum critical point at about 6 T. Within this antiferromagnetic phase, between the QCP and about 2.8 T, there is an additional, novel phase[1]. We report transport measurements on purest-to-date single crystals of CeAuSb2, in fields of up to 15 T and from room temperature down to 100 mK. We also report torque magnetometry measurements. Unlike a recent report[2], we find single, sharp transitions into the novel phase. We discuss the nature of the novel phase.

[1] L. Balicas et al., Phys Rev B 72, 064422 (2005)
[2] K.-A. Lorenzer et al., Phys. Status Solidi B 250, 464 (2013)

TT 35.12 Tue 12:30 HSZ 204

Transport measurements in $Yb(Rh_{1-x}Co_x)_2Si_2$ with $x \leq 0.27$ — •Sandra Hamann[1], Stefan Lausberg[1], Christoph Klingner[1], Cornelius Krellner[2], Frank Steglich[1], Christoph Geibel[1], and Manuel Brando[1] — [1]Max Planck Institut for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany — [2]Institute of Physics, Goethe University Frankfurt, Max-von-Laue Str. 1, 60438 Frankfurt (Main), Germany

$YbRh_2Si_2$ is considered one of the standard materials for studying quantum criticality. It shows antiferromagnetic (AFM) order below $T_N = 0.07$ K and unconventional behavior at the magnetic-field-induced quantum critical point (QCP). Due to the low T_N and the tiny size of the ordered moments ($\approx 10^{-3}\mu_B$) the exact magnetic structure could not be determined, yet. However, because of the strong mag-

netic anisotropy the moments are expected to lie in the *ab*-plane of the tetragonal crystalline structure, the magnetic easy plane. Cobalt substitution was used as chemical pressure to increase T_N and the size of the ordered moments in $Yb(Rh_{1-x}Co_x)_2Si_2$. Previous studies with magnetic field $B \perp c$ pointed to a possible AFM groundstate for the whole series. Surprisingly, ferromagnetic order was found for $x = 0.27$ with moments along the *c*-axis. This motivated a re-investigation of the groundstate for $x \leq 0.27$. We present a comprehensive study of the resistivity in single crystals with $x \leq 0.27$ and $B \parallel c$. We discuss our results considering the competition between in-plane antiferromagnetism and out-of-plane ferromagnetism and the consequences this might have for the quantum critical behavior of $YbRh_2Si_2$.

TT 35.13 Tue 12:45 HSZ 204

Fermi liquid breakdown and superconductivity in YFe_2Ge_2 — Yang Zou[1], Zhuo Feng[1,2], •Peter Logg[1], Jiasheng Chen[1], Giulio Lampronti[3], and F. Malte Grosche[1] — [1]Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE — [2]Dept. of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ — [3]London Centre of Nanotechnology, University College London WC1H 0AH

The investigation of quantum critical phenomena associated with incipient antiferromagnetic or spin density wave order in transition metal compounds has been held back by the scarcity of candidate systems in this class of materials. The paramagnetic d-electron system YFe_2Ge_2 displays an unusually high Sommerfeld ratio of the specific heat capacity $C/T \simeq 100\,\mathrm{mJ/molK^2}$ at low temperature and can be tuned to the border of spin density wave order by partial substitution of Y with isoelectronic Lu [1], suggesting that YFe_2Ge_2 is located close to a spin density wave quantum critical point. Our ambient pressure, low temperature measurements reveal signatures of Fermi liquid breakdown such as an increasing C/T on cooling and a 3/2 power law temperature dependence of the electrical resistivity. Moreover, samples of YFe_2Ge_2 with high residual resistance ratios display full superconducting transitions below $T_c \simeq 1.8\,\mathrm{K}$ in the electrical resistivity and up to 80% Meissner volume fraction in bulk zero-field-cooled magnetisation measurements, or 20% in powdered samples [2].

[1] S. Ran et al., Phil. Mag. **91,** 4388 (2011).
[2] Y. Zou et al., arXiv:1311.0247 (2013).