TT 22: Correlated Electrons: Quantum-Critical Phenomena 2

Time: Wednesday 9:30–13:00 Location: HSZ 03

Invited Talk TT 22.1 Wed 9:30 HSZ 03

Thermal expansion and magnetostriction close to quantum criticality — •Markus Garst — Institut für Theoretische Physik, Universität zu Köln, Zülpicher Str. 77, 50937 Köln

Quantum phase transitions occur in materials at zero temperature upon tuning an external parameter, e.g., magnetic field to an instability of the ground state. A coupling of the quantum critical fluctuations to the lattice degrees of freedom can be exploited to probe quantum criticality at finite temperatures. We discuss the resulting anomalous signatures in thermal expansion, magnetostriction and the Grüneisen parameter, which provide a valuable tool not only to detect but also to classify a quantum phase transition. A smoking gun for the existence of such a transition is, e.g., the divergence of the Grüneisen parameter with an exponent characteristic for its universality class. We also explain that a negative thermal expansion naturally accompanies such transitions, and that its sign changes indicate the entropy distribution in the phase diagram. As examples, we discuss (a) quantum critical metamagnetism, a concept introduced for the bilayer ruthenate $Sr_3Ru_2O_7$, and (b) the critical properties of the spin-ladder compound $(C_5H_{12}N)_2CuBr_4$, that exhibits a diverging thermal expansion.

TT 22.2 Wed 10:00 HSZ 03

Low-temperature thermal expansion of $Nb_{1-y}Fe_{2+y}$ — •Stefan Lausberg[1], Manuel Brando[1], Rafik Ballou[2], F Malte Grosche[3], and Frank Steglich[1] — [1]Max-Planck-Institut für Chemische Physik fester Stoffe Nöthnitzer Str. 40, 01187 Dresden, Germany — [2]Laboratoire Louis Néel, CNRS, B.P. 166, 38042 Grenoble Cedex 9, France — [3]Cavendish Laboratory, Cambridge CB30HE, United Kingdom

The hexagonal C14 Laves phase system $Nb_{1-y}Fe_{2+y}$ exhibits a magnetically ordered ground state, the nature of which strongly depends on the concentration y. Stoichiometric $NbFe_2$ shows low-temperature ($T_N = 10$ K) spin-density-wave (SDW) order, while slight Fe-excess induces low-moment ferromagnetism (FM). A quantum critical point (QCP) is expected on the Nb-rich side at $y \sim -0.015$, where signatures of logarithmic Fermi-liquid breakdown have been reported [1]. The presence of a QCP can be thermodynamically tested by measuring the thermal expansion coefficient $\alpha(T)$: In metals close to a QCP, a divergence of the Grüneisen ratio $\Gamma = \alpha/c_p$ has been proposed, since α is more singular than c_p, while in metals with a Fermi-liquid ground state, α/T and c_p/T are constant. We report measurements of α for different single crystals with y close to the QCP. Surprisingly, we find an extremely large α coefficient, similar to that of heavy-fermion materials [2], and it increases with decreasing temperature. The behavior of the resulting Γ parameter will be discussed.

[1] M. Brando et al., PRL **101**, 026401 (2008).
[2] R. Küchler et al., Physica B **378-380**, 36 (2006).

TT 22.3 Wed 10:15 HSZ 03

Probing the quantum critical behavior of $CeCoIn_5$ via thermal expansion measurements — •Sebastian Zaum[1,2], Kai Grube[1], Roland Schäfer[1], Eric D. Bauer[3], Christoph Meingast[1], and Hilbert v. Löhneysen[1,2] — [1]Forschungszentrum Karlsruhe, Institut für Festkörperphysik, 76021 Karlsruhe, Germany — [2]Physikalisches Institut, Universität Karlsruhe, 76128 Karlsruhe, Germany — [3]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

The heavy-fermion compound $CeCoIn_5$ is an unconventional superconductor. Its tetragonal crystal structure leads to anisotropic superconducting properties with an upper critical field of $B_{c2} = 5\,\mathrm{T}$ and $11.8\,\mathrm{T}$ along the a- and c-axes, respectively. At its upper critical field $B_{c2} \parallel c$, $CeCoIn_5$ reveals a quantum critical point with pronounced deviations from Fermi-liquid behavior. We have measured the thermal expansion α_i ($i = a, c$) and magnetostriction λ_i longitudinal and transverse to the magnetic field. As expected, α_i/T changes its sign at B_{c2} and diverges with decreasing temperature. The effect of the quantum critical behavior on α_a, however, is qualitatively different from that on α_c. While α_c shows at $T = 0.3\,\mathrm{K}$ a crossover to a weaker divergence, α_a does not change its singular behavior down to the lowest measured temperature of 50 mK.

TT 22.4 Wed 10:30 HSZ 03

Divergence of the Magnetic Grüneisen Ratio at the Field-Induced Quantum Critical Point in $YbRh_2Si_2$ — Yoshi Tokiwa[1,2], Teodora Radu[1], •Philipp Gegenwart[2], Christoph Geibel[1], and Frank Steglich[1] — [1]Max-Planck Institute for Chemical Physics of Solids, D-01187 Dresden — [2]I. Physik. Institut, Georg-August Universität Göttingen, Friedrich-Hund Platz 1, 37077 Göttingen

We study quantum criticality in the heavy-fermion metal $YbRh_2Si_2$ by means of the low-temperature magnetization and specific heat[1]. The magnetic Grueneisen ratio $\Gamma_{\mathrm{mag}} = -(dM/dT)/C$ is derived, which is found to diverge in the approach of the field-induced quantum critical point. The data are compared with theoretical predictions for quantum criticality in heavy-fermion metals.

[1] T. Tokiwa et al., arXiv:0809.3705v2.

TT 22.5 Wed 10:45 HSZ 03

Thermoelectric power in the quantum critical regime of $YbRh_2Si_2$ and $CeNi_2Ge_2$ — •Stefanie Hartmann, Niels Oeschler, Cornelius Krellner, Nubia Caroca-Canales, Christoph Geibel, and Frank Steglich — MPI CPfS, Dresden, Germany

The heavy-fermion compounds $YbRh_2Si_2$ and $CeNi_2Ge_2$ are situated very close to a quantum critical point (QCP). $YbRh_2Si_2$ exhibits an antiferromagnetic ground state with $T_N = 70$ mK and a tiny critical field $B_c \approx 60$ mT. In $CeNi_2Ge_2$ a non-magnetic ground state is observed. While in $CeNi_2Ge_2$ a 3-dim. spin-density wave scenario is realized, the QCP in $YbRh_2Si_2$ is shown to be of anomalous nature with a critical break-down of the Kondo scale. We report on low-temperature thermopower $S(T)$ results in the quantum critical regimes of both compounds. S/T logarithmically diverges upon cooling down to 100 mK in the critical region of $YbRh_2Si_2$, reflecting the strongly diverging heavy quasi-particle mass upon approaching the QCP. However, a decrease and a sign change in S/T for $B < B_c$ point toward a "small"Fermi surface on the magnetic side. In the quantum critical regime of $CeNi_2Ge_2$, S/T remains comparably small and does not exhibit a divergence for $T \to 0$. In the field-induced Landau-Fermi-liquid regime, both compounds exhibit a constant S/T below T_{LFL} as expected for a renormalized metal-like state.

15 min. break

TT 22.6 Wed 11:15 HSZ 03

Tuning the magnetic behavior in $Yb(Rh_{1-x}Co_x)_2Si_2$ with Chemical Pressure — •Christoph Klingner, C. Krellner, C. Geibel, and F. Steglich — Max-Planck Institute for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany

In recent years $YbRh_2Si_2$ has been intensively investigated due to its proximity to an antiferromagnetic quantum critical point (QCP). As expected for Yb-Kondo lattice compounds the magnetic ordering of $YbRh_2Si_2$ (T_N=70mK) is stabilized by applying pressure. The complementary method of doping with Cobalt results in chemical pressure allowing therefore an investigation of the magnetic phase diagram and the physical behavior of the stabilized antiferromagnetic ordered state. A thorough understanding of the physical properties of this series, particularly for small amounts of Cobalt doping, are of high interest to understand the phenomena at the QCP in $YbRh_2Si_2$. In this contribution we report on the growth of a series of single crystals $Yb(Rh_{1-x}Co_x)_2Si_2$ with concentrations x from 0 to 1. The crystallographic parameters as well as low temperature properties studied by resistivity, specific heat and magnetization measurements will be presented and compared to already existing pressure data on $YbRh_2Si_2$. The qualitative agreement of the magnetic phase diagrams obtained from hydrostatic and chemical pressure experiments can be shown. With increasing x the change of the physical properties of the series $Yb(Rh_{1-x}Co_x)_2Si_2$ can be understood originating from the interplay of the Kondo- and RKKY- dominated exchange interaction.

TT 22.7 Wed 11:30 HSZ 03

Low-temperature magnetic phase diagram of the heavy-fermion compound $YbCo_2Si_2$ — •Luis Pedrero, Christoph Klingner, Manuel Brando, Christoph Geibel, and Frank Steglich — Max-Planck-Institut für Chemische Physik fester Stoffe

Nöthnitzer Str. 40, 01187 Dresden, Germany

We report on the first high-resolution DC magnetization $M(H,T)$ measurements on a single crystal of $YbCo_2Si_2$. M was measured down to 50 mK and fields up to 12 T with the field $H \perp c$ axis. The magnetic phase diagram of $YbCo_2Si_2$ was deduced from the isothermal curves along with susceptibility and heat-capacity measurements.
Two antiferromagnetic phase transitions have been detected at T_N = 1.65 K and $T_L = 0.9$ K. The signatures at T_N suggest that the phase transition is 2^{nd} order and it is suppressed by a field $\mu_0 H_N = 1.9$ T. At T_L latent heat has been observed in the heat capacity in zero field and hysteresis effects in the M *vs.* H confirm the 1^{st} order nature of the transition. The entropy below both transitions and the M value at H_N point to a local character of the Yb $4f$ quasi-hole, resulting in a very small Kondo temperature compared to the one in $YbRh_2Si_2$ [1]. However, the data at 50 mK reveals the presence of a kink in M *vs.* H at $\mu_0 H_N$ = 10.6 T, very similar to the one observed $YbRh_2Si_2$ at $\mu_0 H_N$ = 9.9 T, where a suppression of the Kondo fluctuations or a Lifshitz transition have been proposed [1,2]. The $T-H$ phase diagram as well as the nature of the high-field transition will be discussed.

[1] Y. Tokiwa et al. Phys. Rev. Lett. **94**, 226402 (2005).
[2] P. M. C. Rourke et al., submitted (2008).

TT 22.8 Wed 11:45 HSZ 03

Conduction Electron Spin Resonance (CESR) of the itinerant magnets $ZrZn_2$ and $NbFe_2$ — •Tobias Förster[1], Jörg Sichelschmidt[1], Manuel Brando[1], Noriaki Kimura[2], Rafik Ballou[3], and Frank Steglich[1] — [1]Max Planck Inst. f. Chem. Physik Fester Stoffe, Nöthnitzer Str. 40, 01187 Dresden,Germany — [2]Center f. Low Temp. Scien., Tohoku University, Sendai, Miyagi 980-8578, Japan — [3]Inst. Nèel, CNRS, B.P. 166, 38042 Grenoble Cedex 9, France

The two Laves phase compounds $ZrZn_2$ and $NbFe_2$ belong to the rather small group of low temperature itinerant magnets. $ZrZn_2$ has a cubic structure and shows a ferromagnetic (FM) order with a small ordered moment at T_C=27.5 K. When applying pressure the FM phase transition becomes first order and disappears around 16.5 kbar[1]. The properties of $ZrZn_2$ are well described by the concept of a marginal Fermi liquid[1]. In the light of these recent findings we reinvestigated the CESR on high quality single crystals of this compound.
$NbFe_2$ has a hexagonal structure and possesses a magnetically ordered ground state (T_N=10 K) which is believed to be of spin-density-wave (SDW) type. Signatures of a logarithmic Fermi-liquid breakdown [2] suggest the existence of a quantum critical point on the Nb-rich side of the phase diagram. In our contribution, we will present the first CESR measurements on a slightly Nb-rich single crystal with T_N=3.6 K, which shows an intriguing and unusual behavior.

[1] R. Smith et al., Nature **455**, 1220 (2008).
[2] M. Brando et al., Phys. Rev. Lett. **101**, 026401 (2008).

TT 22.9 Wed 12:00 HSZ 03

Nonequilibrium quantum criticality in open electronic systems — •So Takei[1,2], Aditi Mitra[3], William Witczak-Krempa[1], Yong Baek Kim[1], and Andrew J. Millis[4] — [1]University of Toronto, Toronto, Canada — [2]Max-Planck-Institute for Solid State Research, Stuttgart, Germany — [3]New York University, New York, U.S.A. — [4]Columbia University, New York, U.S.A.

A theory is presented of quantum criticality in open (coupled to reservoirs) itinerant electron magnets, with nonequilibrium drive provided by current flow across the system. Both departures from equilibrium at conventional (equilibrium) quantum critical points and the physics of phase transitions induced by the nonequilibrium drive are treated. Nonequilibrium-induced phase transitions are found to have the same leading critical behavior as conventional thermal phase transitions. The theory is also extended to the case of a coupled bilayer system of itinerant electron magnets where coupled critical dynamics between the two order parameters becomes possible.

TT 22.10 Wed 12:15 HSZ 03

Color Superfluidity and Trion Formation in Ultracold Fermionic Systems — •Akos Rapp — Institut für Theoretische Physik, Universität zu Köln, Zülpicher Str. 77 D-50937 Cologne Germany

We investigate the low temperature properties of the three component Hubbard model. This system might be realized by trapping 3 different hyperfine states of ultracold Li-6 atoms in optical lattices. Studies concerning the SU(3) symmetric attractive case based on a Gutzwiller variational method in $d = \infty$ suggest (see Phys. Rev. Lett. 98, 160405 (2007) and Phys. Rev. B 77, 144520 (2008)) that there is a continuous phase transition happening between a weak coupling color superfluid and a strong coupling trionic ground state. We construct and investigate the properties of the quantum field theory describing this quantum phase transition.

TT 22.11 Wed 12:30 HSZ 03

Infinite randomness fixed point of the superconductor-metal quantum phase transition — •Bernd Rosenow[1], Adrian Del Maestro[2], Markus Mueller[3], and Subir Sachdev[4] — [1]Max-Planck Institut für Festkörperforschung, D-70569 Stuttgart, Germany — [2]University of British Columbia , Vancouver, BC V6T1Z1, Canada — [3]University of Geneva, 1211 Geneva, Switzerland — [4]Harvard University, Cambridge, MA 02138, USA

We examine the influence of quenched disorder on the superconductor-metal transition, as described by a theory of overdamped Cooper pairs which repel each other. The self-consistent pairing eigenmodes of a quasi-one dimensional wire are determined numerically. Our results [1] support the recent proposal [2] that the transition is characterized by the same strong disorder fixed point describing the onset of ferromagnetism in the random quantum Ising chain in a transverse field.

[1] A. Del Maestro, B. Rosenow, M. Müller, and S. Sachdev, Phys. Rev. Lett. **101**, 035701 (2008).
[2] J. A. Hoyos, C. Kotabage, and T. Vojta, Phys. Rev. Lett. **99**, 230601 (2007).

TT 22.12 Wed 12:45 HSZ 03

Quantum phase transitions in systems of coupled spin dimers — •Sandro Wenzel[1], Wolfhard Janke[1], and Stefan Wessel[2] — [1]Institut für Theoretische Physik, Universität Leipzig, Postfach 100 920, 04109 Leipzig — [2]Institut für Theoretische Physik III, Universität Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart

We study quantum phase transitions in two-dimensional periodic arrangements of coupled spin-1/2 dimers, using a combination of quantum Monte Carlo simulations and effective field theories. Our numerical results on both ground-state properties and the finite-temperature scaling behavior in the quantum critical regime indicate, that depending on the spatial arrangement of the dimers, deviations occur to the scaling behavior of the three-dimensional Heisenberg universality class. We discuss the numerical evidence [1] for such unconventional quantum criticality, and possible relations to low-energy continuum theory beyond the conventional non-linear sigma model action.

[1] S. Wenzel, L. Bogacz, W. Janke, Phys. Rev. Lett. **101**, 127202 (2008).