TT 59: Correlated Electrons: Quantum-Critical Phenomena - Experiments

Time: Thursday 15:00–18:30 Location: H6

TT 59.1 Thu 15:00 H6

Quasi one-dimensional electronic structure of ferromagnetic heavy fermion $YbNi_4P_2$ — •Sven Friedemann[1], Swee K Goh[1], Michael Sutherland[1], F Malte Grosche[1], Cornelius Krellner[2], Christoph Geibel[3], Helge Rosner[3], Manuel Brando[3], and Frank Steglich[3] — [1]University of Cambridge, Cavendish Laboratory, CB3 0HE Cambridge, United Kingdom — [2]Physikalisches Institut, Goethe-UniversitätFrankfurt, 60438 Frankfurt am Main, Germany — [3]Max PlanckInstitute for Chemical Physics of Solids, 01187 Dresden, Germany

Quantum critical phenomena can be studied in great detail in lanthanide based heavy-fermion systems. Up to now, however, only materials with antiferromagnetic ground state were found. In the new heavy fermion material $YbNi_4P_2$ a clear ferromagnetic transition is observed at $T_C = 0.17$ K. $YbNi_4P_2$ has the prospect for studying ferromagnetic quantum criticality. Above the transition temperature strong evidence is found for the vicinity of $YbNi_4P_2$ to a quantum critical point: the specific heat diverges in a power-law form and the resistivity follows a linear temperature dependence. We present first Shubnikov-de Haas measurements in combination with electronic band structure calculations. The electronic structure is dominated by parallel disconnected sheets in accordance with the crystal structure featuring quasi-one-dimensional chains of Yb. The observed Shubnikov-de Haas oscillations are assigned to small quasi-two-dimensional portions of the Fermi surface. The experimentally observed mass enhancement of these orbits reflects the heavy-fermion character of $YbNi_4P_2$.

TT 59.2 Thu 15:15 H6

μSR investigations on the $4f$-derived ferromagnetic quantum quantum critical system $YbNi_4(P_{1-x}As_x)_2$ — •Rajib Sarkar[1], Johannes Spehling[1], Cornelius Krellner[2], Hubertus Luetkens[3], Chris Baines[3], Manuel Brando[4], Christoph Geibel[4], and Hans-Henning Klauss[1] — [1]IFP, TU Dresden, D-01069 Dresden, Germany — [2]Goethe University Frankfurt, D-60438 Frankfurt am Main, Germany — [3]PSI, CH-5232 Villigen PSI, Switzerland — [4]MPI-CPFS, D-01187 Dresden, Germany

Ferromagnetic quantum criticality (FMQC) is one central topic of research in strongly correlated electron systems. Despite adequate research so far there is no concrete evidence of FMQC. In this context, the recently discovered 4f-derived heavy fermion FM metal $YbNi_4P_2$ with T_c =170 mK, a Kondo temperature T_K=8 K and a very small ordered moment of $\approx 0.05\ \mu_B$, deserves particular interest [1]. With 8 % As substitution at the P site, T_c goes down to 28 mK and the Grüneisen ratio diverges as $\Gamma(T) \propto T^{-0.22}$, evidencing the presence of FMQC. For $YbNi_4P_2$, zero field μSR investigations prove static long range magnetic ordering [2] and the ordered moment is strongly suppressed with increasing As-substitution. For 8% As, μSR time spectra suggest that static ordering appears below 20 mK. Here, we present our recent μSR results for x $\leq$ 0.13 and discuss the dynamics of the quantum fluctutations at this ferromagnetic quantum critical point.

[1] New J. Phys. 13, 103014 (2011)
[2] Phys. Rev. B 85, 140406 (2012)

TT 59.3 Thu 15:30 H6

Ferromagnetic Quantum Critical Point in $YbNi_4(P_{1-x}As_x)_2$ — •Cornelius Krellner[1,2], Alexander Steppke[2], Robert Küchler[2], Stefan Lausberg[2], Edit Lengyel[2], Lucia Steinke[2], Robert Borth[2], Thomas Lühmann[2], Michael Nicklas[2], Sven Friedemann[3], Christoph Geibel[2], Frank Steglich[2], and Manuel Brando[2] — [1]Physikalisches Institut, Goethe-Universität Frankfurt, 60438 Frankfurt am Main, Germany — [2]Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany — [3]Cavendish Laboratory, University of Cambridge, United Kingdom

$YbNi_4P_2$ is a quasi-one-dimensional heavy-fermion system where recently a very low lying ferromagnetic (FM) transition at $T_C = 0.17$ K was observed [1]. Above this transition distinct deviations from the predictions of the Landau-Fermi-liquid theory were observed, indicating the presence of a nearby FM quantum critical point (QCP).

In this contribution, we present a thorough investigation of $YbNi_4(P_{1-x}As_x)_2$ single crystals where the ferromagnetism is further suppresed. We show that the FM phase transition line remains second order down to 30 mK for $x \leq 0.08$ with unexpected power-laws above T_C in all thermodynamic quantities. At $x = 0.08$, we found a power-law divergence of the Grüneisen ratio, demonstrating the existence of a FM QCP.

[1] C. Krellner *et al.*, New J. Phys. **13**, 103014 (2011).

TT 59.4 Thu 15:45 H6

Quantum criticality in partially frustrated $CePd_{1-x}Ni_xAl$ — •Veronika Fritsch[1], Sarah Woitschach[2], Oliver Stockert[2], Wolfram Kittler[1], and Hilbert v. Löhneysen[1,3] — [1]Physikalisches Institut, Karlsruher Institut für Technologie (KIT), 76131 Karlsruhe, Germany — [2]Max-Planck-Institut für chemische Physik fester Stoffe, Dresden, Germany — [3]Institut für Festkörperphysik, Karlsruher Institut für Technologie (KIT), 76021 Karlsruhe, Germany

In the antiferromagnetic (AF) heavy-fermion system CePdAl the magnetic Ce ions form a network of equilateral triangles in the (001) plane, similar to the kagomé lattice, with one third of the Ce moments not participating in the long-range order due to geometrical frustration. The Néel temperature $T_N = 2.7$ K is reduced upon replacing Pd by Ni in $CePd_{1-x}Ni_xAl$, with $T_N \to 0$ for $x \approx 0.14$. At this concentration the specific heat C exhibits a $C/T \propto -\log T$ dependence. This and the linear $T_N(x)$ dependence are indicative of two-dimensional (2D) critical AF fluctuations within the conventional description of quantum criticality after Hertz, Millis and Moriya, in marked contrast to the three-dimensional (3D) magnetic order found by neutron diffraction experiments in CePdAl. We discuss the role of frustration when approaching the quantum critical point in Ni-substituted CePdAl on the basis of measurements of the magnetization, specific heat, electrical resistivity, and neutron diffraction experiments.

TT 59.5 Thu 16:00 H6

Pressure- and Composition-Induced Structural Quantum Phase Transition in the Cubic Superconductor $(Sr,Ca)_3Ir_4Sn_{13}$ — •Swee K. Goh[1], Lina E. Klintberg[1], Patricia L. Alireza[1], Paul Saines[2], David Tompsett[1], Peter Logg[1], Jinhu Yang[3,4], Bin Chen[3,4], Kazuyoshi Yoshimura[4], and Malte Grosche[1] — [1]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom — [2]Department of Materials Science and Metallurgy, University of Cambridge, United Kingdom — [3]Department of Physics, Hangzhou Normal University, China — [4]Department of Chemistry, Kyoto University, Japan

The quasi-skutterudite superconductor $Sr_3Ir_4Sn_{13}$ has been reexamined recently. In addition to a superconducting transition at $T_c = 5$ K, pronounced anomalies can be seen in magnetic susceptibility and resistivity at $T^* = 147$ K. Using single crystal x-ray diffraction, we identify $T^* = 147$ K as the temperature where the system undergoes a structural transition from a simple cubic parent structure (I-phase) to a superlattice variant (I'-phase) with a lattice parameter twice that of the I-phase. Applying physical pressure or chemical pressure (via the isoelectronic substitution of Ca for Sr) leads to a rapid suppression of $T^* = 147$ K and an enhancement of T_c. Furthermore, a quasi-linear temperature dependence of resistivity is observed at the pressure where $T^* = 147$ K extrapolates to 0 K, reminiscent of quantum critical phenomena on the border of magnetism. We argue that the pressure phase diagram of $Sr_3Ir_4Sn_{13}$ features a superlattice quantum critical point.

TT 59.6 Thu 16:15 H6

Heat and charge transport study of quantum critical behavior in heavy fermion YbAgGe — •Jinkui Dong[1], Yoshi Tokiwa[1], Maik Schubert[1], Sergey L. Bud'ko[2], Paul C. Canfield[2], and Philipp Gegenwart[1] — [1]I. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany — [2]Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA

We have performed electrical resistivity and thermal conductivity measurements on the heavy fermion metal YbAgGe to investigate quantum critical behavior and the validity of Wiedemann-Franz law. A power law analysis of electrical resistivity $\rho(T)$, $\rho(T) = \rho_0 + AT^n$ showed that NFL behavior with $n < 2$ persists in fields up to 9 T. A broad maximum of $\rho(H)$ appeared in the vicinity of critical field $H_c \simeq 4.5$ T, where a field-induced quantum critical end point (QCEP) was expected. Far away from this critical region, the Lorenz ratio $L(T)/L_0$

converges to unity in the limit of $T \to 0$. However, near the QCEP, the extrapolation of $L(T)/L_0$ gives $L(T \to 0)/L_0 \simeq 0.91$. We associate this moderate violation of Wiedemann-Franz law at 4.5 T with the strong inelastic scattering of electrons from the quantum critical fluctuations.

15 min. break

Invited Talk TT 59.7 Thu 16:45 H6

Electron Spin Resonance (ESR) close to a Quantum Phase Transition: Probing $YbRh_2Si_2$ at mK Temperatures — •Marc Scheffler[1], Conrad Clauss[1], Mojtaba Javaheri[1], Martin Dressel[1], Jörg Sichelschmidt[2], Cornelius Krellner[2,3], Christoph Geibel[2], and Frank Steglich[2] — [1]1. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany — [2]Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany — [3]Physikalisches Institut, Goethe-Universität Frankfurt, Frankfurt/Main, Germany

The heavy-fermion material $YbRh_2Si_2$ is a model system for quantum criticality: the very weak antiferromagnetic order below 70 mK can be suppressed e.g. by a small magnetic field of 60 mT. This quantum phase transition results in unusual properties such as pronounced non-Fermi-liquid behavior. Previous electron spin resonance (ESR) studies on $YbRh_2Si_2$ revealed new insights concerning the spin dynamics of Kondo lattices, but were limited to temperatures above 500 mK and could not access the most interesting low-temperature regimes.

We recently developed a new measurement technique which we now use for ESR studies on $YbRh_2Si_2$ single crystals at temperatures down to 40 mK. With a set of ESR frequencies spanning 1.5-13 GHz and ESR fields as low as 30 mT, we address the temperature and field regimes close to the quantum critical point. Our results cover all three phases (antiferromagnet, non-Fermi liquid, field-induced Fermi liquid) and they open new opportunities to gain deeper insight into ESR of heavy-fermion systems and to investigate the quantum critical point.

TT 59.8 Thu 17:15 H6

Influence of charge carrier doping on the T^*-Scale in $YbRh_2Si_2$ — •M.-H. Schubert, Y. Tokiwa, H. S. Jeevan, E. Blumenröther, and P. Gegenwart — I. Physikalische Institut, Georg-August-Universtität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

$YbRh_2Si_2$ is a prototype heavy-fermion metal which displays a magnetic, field-induced antiferromagnetic (AF) quantum critical point (QCP). It has attracted much attention due to an additional low-energy scale $T^\star(B)$ merging at the QCP, whose origin is still under discussion. Here, we present our recent thermodynamic, magnetic and electrical transport measurements on different single crystalline samples of charge-carrier doped $Yb(Rh_{1-x}T_x)_2Si_2$ (T=Fe, Ni, Ru) at temperatures down to 15 mK and in magnetic fields up to 7 T. The partial substitution of Rh by either Fe or Ni introduces holes or electrons, respectively. The evolution of the single-ion Kondo scale is similar to isoelectronic Co substitution in accordance with the chemical pressure effect. However, while chemical pressure has little influence on $T^\star(B)$ in isoelectronic doped samples, we observe a drastic reduction or increase of $B^\star(T=0)$ by Fe- or Ni-doping, respectively. As the AF order is completely suppressed by Fe-doping, a heavy Fermi liquid ground state (without the $T^\star(B)$ anomaly) is observed. These results are compared to measurements on samples where Rh is partially substituted by Ru. Here the chemical pressure effect is minimized in order to investigate the pure charge doping effect.

Work supported by the DFG research unit 960 (Quantum phase transitions).

TT 59.9 Thu 17:30 H6

Competing Magnetic Anisotropies and Multicriticality: The Case of Co-doped $YbRh_2Si_2$ — •Eric C. Andrade[1], Manuel Brando[2], Christoph Geibel[2], and Matthias Vojta[1] — [1]TU Dresden — [2]MPI-CPfS

Motivated by the unusual evolution of magnetic phases in stoichiometric and Co-doped $YbRh_2Si_2$, we study Heisenberg models with competing single-ion and exchange anisotropies by large scale Monte-Carlo simulations. Upon also including the competition between ferromagnetic and antiferromagnetic order, we analyze the ingredients required to obtain the characteristic crossing point of susceptibilities observed experimentally in $Yb(Rh_{0.73}Co_{0.27})_2Si_2$. The models possess various multicritical points, which we speculate to be relevant for the behavior of Co-doped $YbRh_2Si_2$. We also make contact with experimental data on $YbNi_2P_4$.

TT 59.10 Thu 17:45 H6

Evolution of ferromagnetic order in $Yb(Rh_{1-x}Co_x)_2Si_2$ with $x \leq 0.27$ — •Sandra Hamann[1], Stefan Lausberg[1], Lucia Steinke[1], Christoph Klingner[2], Cornelius Krellner[3], Manuel Brando[1], Christoph Geibel[1], and Frank Steglich[1] — [1]Max Planck Institute for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany — [2]Max Planck Institute of Biochemistry, D-82152 Martinsried, Germany — [3]Institute of Physics, Goethe University Frankfurt, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany

Antiferromagnetic (AFM) order appears in $YbRh_2Si_2$ at $T_N = 70\,\text{mK}$ although strong ferromagnetic fluctuations are observed. The application of chemical pressure x in the series $Yb(Rh_{1-x}Co_x)_2Si_2$ stabilizes the AFM phase, i.e. T_N increases with increasing x. A second phase transition at $T_L < T_N$ emerges with increasing x and the strength of the ferromagnetic fluctuations raises up to a maximum for $x \approx 0.27$ [1]. Eventually, in pure $YbCo_2Si_2$ both phase transitions T_N and T_L are of AFM nature with $4f$ local moments aligned along the crystallographic ab-plane. However, the sample with $x = 0.27$ reveals only one phase transition at 1.30 K which is surprisingly ferromagnetic with moments parallel to the c-axis [2]. This motivates a deeper investigation of the magnetic properties in $Yb(Rh_{1-x}Co_x)_2Si_2$ with the magnetic field along the c-axis. Here, we present ac-susceptibilty measurements of single crystals with $x \leq 0.27$ down to a temperature of 25 mK.

[1] C. Klingner *et al.*, Phys. Rev. B. **83**, 144405 (2011)
[2] S. Lausberg *et al.*, arXiv:1210.1345

TT 59.11 Thu 18:00 H6

NMR as a local probe for ferromagnetic correlation and quantum criticality in 3d systems: YFe_2Al_{10} and $Ta(Fe_{1-x}V_x)_2$ — •P. Khuntia[1], M. Brando[1], A. Strydom[2], M. Aronson[3], G. Kreiner[1], F. Steglich[1], and M. Baenitz[1] — [1]Max Planck Institute for Chemical Physics of Solids, 01187, Dresden, Germany — [2]Physics Department, University of Johannesburg,South Africa — [3]Brookhaven National Laboratory, New York 11973, USA

Probing the q-averaged dynamic susceptibility at low energies, the spin lattice relaxation rate by T, $(1/T_1T)$ (SLR) is ideal for the investigation of FM and AFM spin fluctuations. At the verge of magnetic order, unusual scaling laws in T and H dependent SLR could be associated with quantum criticality. In YFe_2Al_{10}, fluctuation of Fe moments leads to enhanced χ and C/T values yielding large Wilson ratio accompanied by $^{27}(1/T_1T)\sim \chi$ reveal the dominant role of FM fluctuations in the spin excitation spectra [1].$Ta(Fe_{1-x}V_x)_2$ undergoes an itinerant AFM order, but for nominal V doping, the magnetic properties are reminiscent of itinerant FM at the verge of a FM instability. The enhanced $M(T \to 0)$ supported by $C/T\sim$ -ln$T$ behavior suggest the persistence of FM fluctuations.Additionally,the $^{51}(1/T_1T)\sim T^{-0.8}$ dependence in small fields indicates the co-existence of FM and AFM spin fluctuations.The Korringa product implies FM correlation between itinerant moments. Presented systems pose special interest since the bulk and microscopic data support low lying magnetic phase transitions and both are naturally located in the vicinity of FM QCP without any external tuning parameter.

[1] Phys. Rev. B (R), in press (2012)

TT 59.12 Thu 18:15 H6

High pressure transport studies of quantum critical behaviour close to ferromagnetism — •Yang Zou[1], Zhuo Feng[1,2], Peter Logg[1], Sven Friedemann[1], Hong En Tan[1], and F. Malte Grosche[1] — [1]Cavendish Laboratory, University of Cambridge, UK — [2]Department of Physics, University College London, UK

Metals close to a magnetic quantum critical point offer a comparatively clear and well-defined environment to investigate the breakdown of Landau's Fermi liquid theory. The low temperature band ferromagnet $ZrZn_2$ violates the predictions of Fermi liquid theory over a wide temperature range [1]. We present new measurements of the electrical resistivity and thermal conductivity as a function of applied magnetic field. These suggest that the temperature scale below which Fermi liquid behaviour is observed rises rapidly with field and reaches 6 K at $B = 9\,\text{T}$. A different kind of Fermi liquid breakdown is seen in the Kondo lattice ferromagnet $CeAgSb_2$ [e.g. 2]. The ferromagnetic transition temperature $T_C = 9.6\,\text{K}$ is sensitive to the application of both pressure and transverse magnetic fields. Therefore, tuning these parameters could be used to access a magnetic quantum phase transition. We present transport measurements under pressure and field tuning, as well as combined measurements of the specific heat and the magnetocaloric effect which provide a comprehensive transport and thermodynamic study of the system.

[1] Smith et al. Nature **455**, 7217 (2008)
[2] Araki et al. PRB **68**, 024408(2003)