ESF scientific programme on
Fermi-liquid instabilities in correlated metals (FERLIN)

International workshop on

Quantitative comparison of Fermi-liquid instabilities at magnetic-nonmagnetic transitions in terms of spin-fluctuation models and beyond

Il Ciocco, Castelvecchio Pascoli, Italy,

5 – 7 October 2000

European Science Foundation, 1 quai Lezay-Marnésia,
67080 Strasbourg Cedex, France

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Quantitative comparison of Fermi-liquid instabilities at magnetic-nonmagnetic transitions in terms of spin-fluctuation models and beyond

Il Ciocco, Castelvecchio Pascoli, Italy, 5 – 7 October 2000

Thursday 5 October

Morning Session

9.00 hrs **M. B. Maple:** Non-Fermi liquid temperature dependences of physical properties near magnetic quantum critical points

9.50 hrs **A. de Visser:** Magnetic quantum critical point and superconductivity in UPt_3 doped with Pd

10.40 hrs – *Coffee break* –

11.00 hrs **O. Stockert:** Critical fluctuations and magnetic order in $CeCu_{6-x}Au_x$ and $Cr_{1-x}V_x$ in the vicinity of the nonmagnetic-magnetic quantum phase transition

11.50 hrs **A. Schröder:** Unusual local magnetic fluctuations in the heavy fermion alloy $CeCu_{6-x}Au_x$ at the quantum critical point

13.00 hrs – *Lunch* –

Afternoon Session

15.00 hrs **P. Coleman:** Non-Fermi liquid behaviour in heavy fermion materials: is there a fundamentally new fixed point?

15.50 hrs **Q. Si:** Non-Fermi liquid behaviour and exotic (non-Hertz) quantum critical points in Kondo lattices

16.40 hrs *Coffee break*

17.00 hrs **M. Grilli:** Quantum critical point scenario for cuprates: successes and failures.

19.30 hrs – *Dinner* –

Friday 6 October

Morning Session

9.00 hrs **A. Loidl:** Non-Fermi liquid behaviour and spin-fluctuations in LiV_2O_4

9.50 hrs **P. Fazekas:** Pressure-induced non-Fermi-liquid state in the spin-orbital valence bond solid system $BaVS_3$

10.40 hrs – *Coffee break* –

11.00 hrs Short contributions / Poster session

Afternoon

Excursion to Lucca

20.00 hrs Meeting of the Steering Committee *(to be re-confirmed)*

Saturday 7 October

Morning Session

9.00 hrs **J. Flouquet:** Coexistence of superconductivity and magnetism in ferromagnet and antiferromagnet

9.50 hrs **D. Grempel:** Non-Fermi-liquid scaling in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$

10.40 hrs – *Coffee break* –

11.00 hrs **C. Pfleiderer:** Experimental studies of weakly magnetic transition metal compounds

11.50 hrs **G.G. Lonzarich**: Superconductivity on the border of itinerant-electron ferromagnetism

13.00 hrs – *Lunch* –

Afternoon Session

15.00 hrs **B. Keimer**: Spin excitations in cuprates and titanates

15.50 hrs **S. Hayden:** Quantitative comparisons between spin fluctuation spectra and the physical properties metals and superconductors

16.40 hrs – *Coffee break* –

17.00 hrs **N. Bernhoeft:** A critical view of spin dynamics data

19.30 hrs – *Conference dinner* –

Sunday 8 October

Morning Session

9.30 hrs First coach to Pisa airport/railway station *(to be re-confirmed)*

9.00 hrs General discussion

12.00 hrs – *Lunch* –

13.00 hrs Last coach to Pisa airport/railway station

Poster contributions

1.	D. Andreica et al.	ìSR studies of the nonmagnetic-magnetic transition in YbCu5-xAlx
2.	J. Boeuf et al.	Experimental investigation of the spin-density antiferromagnet Mn_3Si
3.	M. Chiao and S. R. Julian et al.	Fermi liquid instability at the metamagnetic transition in nearly ferromagnetic $Sr_3Ru_2O_7$
4.	J. Custers et al.	Low-temperature susceptibility and resistivity close to the quantum critical point of $YbRh_2Si_2$
5.	M. Galli et al.	Evolution of the ground state properties of $YbCu_{5-x}Au_x$
6.	P. Hinze et al.	Non-Fermi-Liquid behaviour and incipient superconductivity in the heavy-fermion compound $CeNi_2Ge_2$
7.	A. Huxley	UGe_2 A ferromagnetic spin triplet superconductor
8.	G. Knebel et al.	Electronic properties of $CeIn_3$ and $YbNi_2Ge_2$ at high pressure
9.	K. A. McEwen et al.	Scaling behaviour of the dynamical susceptibility in systems at magnetic-nonmagnetic transitions
10.	S. Mederle et al.	Unconventional metallic state in $YbRh_2Si_2$ - a high pressure study
11.	S. S. Saxena	
12.	G. Sparn et al.	Superconductivity and unconventional normal state in stoichiometric Ce/Yb (4f)-metals
13.	M. J. Steiner et al.	Anomalous low temperature resistivity exponent of $CeIn_3$ at the border of magnetic and superconducting order
14.	M. Uhlarz et al.	Effect of magnetic field on the temperature dependence of the resistivity in $ZrZn_2$

Abstracts of invited talks

(in order of workshop programme)

Non-Fermi liquid temperature dependences of physical properties near quantum critical points

M. B. Maple

Physikalisches Institut, Universität Karlsruhe, and
Department of Physics and Institute for Pure and Applied Physical Sciences,
University of California, San Diego

Experiments on chemically substituted U compounds reveal rich and complex temperature T-substituent composition x phase diagrams that consist of regions containing long range magnetic order, spin glass freezing, Kondo effect, non-Fermi liquid (NFL) behavior, and, in some cases, superconductivity. The NFL behavior is characterized by weak power law or logarithmic divergences in temperature of the physical properties at low temperature. In some situations, the NFL properties scale with U concentration and the Kondo temperature, suggesting that the NFL behavior is due to a single ion mechanism associated with an unconventional Kondo effect. In other cases, the NFL properties occur in the neighborhood of the substituent composition x or pressure where the magnetic ordering or spin glass freezing temperature vanishes (magnetic quantum critical point), indicating that the NFL behavior is associated with a cooperative phenomenon. In this talk, the T-x phase diagrams and NFL temperature dependences of the physical properties of several chemically substituted U systems are surveyed and compared to relevant theoretical models. Some recent experiments concerning the occurrence of superconductivity under pressure near magnetic quantum critical points are briefly described.

Magnetic quantum critical point and superconductivity in UPt_3 doped with Pd

A. de Visser[1], M. J. Graf[2], P. Estrela[1], A. Amato[3], C. Baines[3], D. Andreica[4], F.N. Gygax[4] and A. Schenck[4]

[1] Van der Waals-Zeeman Institute, University of Amsterdam,
1018 XE Amsterdam, The Netherlands
[2] *Department of Physics, Boston College, Chestnut Hill, MA 02467, USA*
[3] *Paul Scherrer Institute, CH-5232 Villigen, Switzerland*
[4] *Institute for Particle Physics, ETH Zürich, PSI, CH-5232 Villigen, Switzerland*

Transverse-field muon spin relaxation measurements have been carried out on the heavy-fermion superconductor UPt_3 doped with small amounts of Pd. We find that the critical Pd concentration for the emergence of the large-moment antiferromagnetic phase is ~0.6 at.%Pd. At the same Pd content, superconductivity is completely suppressed. The existence of a magnetic quantum critical point in the phase diagram, which coincides with the critical point for superconductivity, provides evidence for ferromagnetic spin-fluctuation mediated odd-parity superconductivity, which competes with antiferromagnetic order.

Critical fluctuations and magnetic order in $CeCu_{6-x}Au_x$ and $Cr_{1-x}V_x$ in the vicinity of the nonmagnetic-magnetic quantum phase transition

O. Stockert

H. H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, UK

Many metals close to an antiferromagnetic instability, including heavy-fermion systems and 3d transition metal systems, exhibit unusual behaviour in their low temperature physical properties because of their magnetic excitations. Inelastic neutron scattering studies on the heavy-fermion system $CeCu_{6-x}Au_x$ have revealed the presence of strongly anisotropic spin fluctuations in the vicinity of the magnetic instability, i.e. for Au concentrations $x = x_c = 0.1$, evolving into long-range magnetic order at higher x. Away from the critical concentration x_c the anisotropy of the fluctuations is less pronounced. The existence of these critical fluctuations with reduced dimensionality provides an explanation for the non-Fermi-liquid behavior observed in thermodynamic and transport properties of $CeCu_{6-x}Au_x$ with $x = 0.1$. We discuss the results in comparison to $Cr_{1-x}V_x$, a transition metal system at the borderline from itinerant antiferromagnetism to enhanced Pauli paramagnetism. In $Cr_{1-x}V_x$ antiferromagnetic order vanishes at a critical concentration of $x_c \approx 0.04$ and the spin fluctuations are isotropic and well described by a phenomenological model for the critical fluctuations in an itinerant antiferromagnet.

Unusual local magnetic fluctuations in the heavy fermion alloy $CeCu_{6-x}Au_x$ at the quantum critical point

A. Schröder

Physikalisches Institut, Universität Karlsruhe, Germany

An extensive set of neutron scattering data and uniform magnetisation measurements of the heavy fermion alloy $CeCu_{5.9}Au_{0.1}$ close to the quantum critical point, where the antiferromagnetic order vanishes, will be presented.

The magnetic fluctuations show an anomalous energy dependence close to the magnetic ordering vectors, which also extend over a wide region of the Brillouin zone, characterising this quantum critical point by the development of an unusual local dynamic. The same unusual exponent derived by the energy / temperature-scaling is confirmed by the successful field/ temperature-scaling of the uniform magnetisation in a magnetic field. These non Fermi liquid properties, clearly different from mean-field behaviour, hint at the emergence of magnetic moments with local character within the heavy fermion ground state.

Non-Fermi liquid behaviour in heavy fermion materials: is there a fundamentally new fixed point?

P. Coleman

Materials Theory Group, Rutgers, USA

We now have more than half a dozen heavy fermion systems of high purity, which display anomalous non Fermi liquid behaviour. I shall discuss the difficulties with incorporating these systems within a Millis Hertz description, and argue the case for seeking out a qualitatively new description of these phenomenon. I shall present some of our ongoing efforts to address the problem using a supersymmetric representation of spins.

Non-Fermi liquid behaviour and exotic (non-Hertz) quantum critical points in Kondo lattices

Q. Si

Rice University, United States

Recent neutron scattering experiments have raised new questions concerning the nature of the non-Fermi liquid state at a quantum critical point in heavy fermion metals. I will present the results of our own efforts at understanding this problem, based on an extended dynamical mean field analysis of the Kondo lattice models. Two types of QCPs are found. The first is an SDW transition, already known in the Doniach phase diagram. The second is a more exotic one where the local Kondo effect is also critical. The dynamical spin susceptibility at the first type of QCP is given by the Hertz theory, while that of the second type of QCP is very different. The condition under which each type of QCP arises will be specified, and comparison will be made with experiments. Finally, I will briefly discuss the broader implications of these results for other strongly correlated metals.

Quantum critical point scenario for cuprates: successes and failures

M. Grilli, C. Castellani and C. Di Castro

Universita di Roma "La Sapienza", Dipartimento di Fisica, Piazzale Aldo Moro 2 00185 Roma, Italy

Upon varying the doping level, the phase diagram of the high-temperature superconducting cuprates is commonly subdivided in three distinct regions where the systems display qualitative different behaviors. In the underdoped region a pseudogap opens below a temperature T* well above the superconducting critical temperature Tc suggesting a non-BCS superconducting transition. In the optimally doped region, where T* merges with Tc, the metallic properties diplay strong (and rather universal) deviations from the standard Fermi-liquid behavior. Finally, in the overdoped region the superconducting transition becomes BCS-like, while the normal phase smoothly acquires ordinary Fermi-liquid properties. These distinct regions have been connected with the three regions generically arising around a quantum critical point (QCP). The underdoped phase has been related to the (quasi)-ordered phase occurring below a critical line ending at zero temperature near optimal doping. The optimally doped region can be related to the quantum critical region above the QCP, while the overdoped region should correspond to the quantum disordered region. Although this framework is quite general and compatible with the generic properties of the cuprates, the actual type of ordering taking place in the underdoped cuprates is still a matter of active debate. In this regard the most relevant and recent proposals (including some exotic types of order) will be overviewed, with some special emphasis on the proposal put forward by the Rome group that the QCP is related to an incommensurate spatial order of the electronic charge leading to the formation of a stripe phase.

Non-Fermi liquid behaviour and spin fluctuations in LiV_2O_4

A. Loidl

Experimentalphysik V, Elektronische Korrelationen und Magnetismus
Institut für Physik, Universität Augsburg, D-86135 Augsburg

Amongst the transition metal oxides, LiV_2O_4 reveals the highest Sommerfeld coefficient at low temperatures reaching values close to 400 mJ/mole K^2. There is an ongoing dispute if the heavy-fermion behaviour is due to Kondo-compensation effects or due to magnetic frustration. On one hand Kondo scenarios have been developed by a number of groups, but on the other hand the vanadium spins form an ideal tetragonal lattice and certainly are frustrated against simple antiferromagnetic order. It is well established that LiV_2O_4 is very close to magnetic order and spin-glass phases evolves immediately on substituting small amounts of lithium by zinc or vanadium by titanium.

We present detailed susceptibility, heat capacity, NMR and neutron scattering results on pure, as well as on Zn and Ti doped samples which indeed demonstrate that LiV_2O_4 is close to a quantum critical point and that spin fluctuations play an important role. At low temperatures significant deviations from Fermi-liquid behaviour become apparent.

Pressure-induced non-Fermi-liquid state in the spin-orbital valence bond solid system $BaVS_3$

P. Fazekas[1], K. Penc[1], G. Mihály[2], Sz. Csonka[2], I. Kézsmárki[2], F. Zámborszky[2], M. Miljak[3], H. Berger[4], R. Gaál[4], and L. Forró[4]

[1] *Research Institute for Solid State Physics and Optics, Budapest, Hungary*
[2] *Budapest University of Technology and Economics, Budapest, Hungary*
[3] *Institute of Physics of the University, Zagreb, Croatia*
[4] *Institute of Physics, EPFL, Lausanne, Switzerland*

At ambient pressure, the strongly correlated $3d^1$ system $BaVS_3$ undergoes a phase transition from a bad metal to a non-magnetic Mott insulator at T_{MI}=69K [1]. T_{MI} decreases under pressure or in an external magnetic field. The insulating phase is fully suppressed at p_{cr}=20kbar [2]. $BaVS_3$ offers the opportunity to study the nature of the non-Fermi-liquid states which are adjacent to a spin-gapped Mott insulator.

The results of extensive susceptibility, resistivity and magnetoresistivity measurements on single crystal samples [1-3] are reported, and the nature of the metal-insulator transition, and of the exotic conducting and insulating states on either side of the phase boundary, are discussed. At p=1bar, the bad metal is characterized by a critically diverging resistivity and a susceptibility which is essentially that of uncompensated d-electron spins. At $p>p_{cr}$, the resistivity follows $\rho-\rho_0 \sim T^{1.25}$ for $1K<T<40K$. The behavior is somewhat similar to that of nearly antiferromagnetic systems, but it cannot be interpreted solely in terms of antiparallel spin correlations: the non-magnetic nature of the insulator requires the consideration of the orbital degrees of freedom. We find that (at least up to 15kbar) suppres-sing the insulating state is synonymous to suppressing the spin gap.

[1] G. Mihály et al.: Phys. Rev. B61, R7381 (2000).
[2] L. Forró et al.: Phys. Rev. Lett. 85, 1938 (2000).
[3] I. Kézsmárki et al.: submitted for publication.

Coexistence of superconductivity and magnetism in ferromagnet and antiferromagnet

J. Flouquet, A. Demuer, I. Sheikine, D. Braithwaite, A. Huxley, G. Knebel, and S. Raymond

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Focus will be given on two main cases $CePd_2Si_2$ and UGe_2 with respective dominant antiferromagnetic (AF) and ferromagnetic (F) interactions. For $CePd_2Si_2$, special attentions were made on the scattering through the magnetic quantum critical pressure (P_c) at low temperature, on the homogeneous nature of the magnetic and superconducting transition and on the upper critical field measurements. Comparisons are made with other heavy fermion systems: $CeIn_5$/$CeNi_2Ge_2$ and $CeCu_2Si_2$.

For UGe_2, the striking phenomena is the appearance of superconductivity in a magnetic phase which appears up to now as ferromagnetic. The link will be made on recent upper critical field measurements and the pressure and field dependence of a characteristic temperature T_x which may mark spin density wave or charge density wave. Comparisons are also made with the case of αUranium and metallic organic compounds.

The $CePd_2Si_2$ and UGe_2 works have been realized respectively with the group of D. Jaccard (Geneve) and G. Lonzarich (Cambridge).

Non-Fermi-Liquid Scaling in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$

D. R. Grempel[2,3], Y. Tabata[1], M. Ocio[2], T. Taniguchi and Y. Miyako[1]

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[3] *CEA/Grenoble, Service de Physique Statistique, Magnétisme et Supraconductivité, 38054 Grenoble Cedex, France*

We report the results of an experimental and theoretical study of the magnetic and transport properties of the non-Fermi-liquid compound $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$.

The type of anomaly exhibited by this system depends on the applied magnetic field.

Above 0.1 T, our results for the resistivity as well as the linear and non-linear susceptibilities can be quantitatively accounted for in terms of a recent dynamical mean-field theory (DMFT) of a Kondo alloy close to a spin-glass quantum critical point. In particular, the T and H-dependence of the physical properties can be cast in the form of universal scaling laws as predicted by the theory.

Below 0.1 T, additional diverging contributions are observed in c and C/T at low temperatures. These can be interpreted as coming from clusters of the Griffith type whose quantum fluctuations are suppressed under higher magnetic fields.

Experimental studies of weakly magnetic transition metal compounds

C. Pfleiderer

Physikalisches Institut, Universität Karlsruhe, D-76128 Karlsruhe, Germany

Experimental studies of the weakly magnetic d-electron systems MnSi, $ZrZn_2$ and Mn_3Si reviewed here, reveal unexpected deviations from Fermi liquid behaviour and the conventional assumptions underlying standard spin fluctuation theory. Properties of the weakly ferromagnetic compounds are inconsistent with Landau damping of spin fluctuations, expected for the high purity of the samples investigated, but are instead suggestive of diffusive spin dynamics. The spin-density wave antiferromagnet Mn_3Si exhibits exceptional stability at high magnetic field indicative of two vastly different energy scales and a novel mechanism that controls the onset of long range magnetic coherence. It is speculated that these properties are of similar origin and hint of a break-up of single electron excitations.

Work performed in collaboration with:
M. Uhlarz, J. Bouef, A. Faißt, H. v. Löhneysen, S. R. Julian, G. G. Lonzarich and S. M. Hayden

Superconductivity on the border of itinerant-electron ferromagnetism

G.G. Lonzarich

Cavendish Laboratory, Cambridge CB3OHE, UK

More and more examples are coming to light of exotic forms of superconductivity on the border of long range antiferromagnetic order. The corresponding phenomena in itinerant electron ferromagnetism, however, remains more illusive. We consider the reasons why this may be so and show how a number of obstacles to observing the phenomena are apparently avoided in the case of the band ferromagnet UGe_2.

S.S. Saxena, P. Agarwal, K.Ahilan, F.M. Grosche, R.K.W. Haselwimmer, M.J. Steiner, E. Pugh, I.R. Walker, S.R. Julian, P. Monthoux, G.G. Lonzarich, A. Huxley, L. Sheikin, D. Braithwaite & J. Flouquet, Nature 406 (2000) 587-592

Spin excitations in cuprates and titanates

B. Keimer

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In this talk, recent neutron scattering measurements of spin correlations in superconducting copper oxides and, for comparison, nonsuperconducting titanium oxides will be reviewed. The undoped parent compounds of the superconducting cuprates are antiferromagnetic insulators, and strong antiferromagnetic spin excitations persist deep into the superconducting state. Especially in the superconductors with the highest transition temperatures, these collective magnetic excitations are strongly coupled to charge carriers and play a major role in the mechanism of high temperature superconductivity. While doped $LaTiO_3$ also undergoes a transition from antiferromagnetic insulator to correlated metal, it does not become superconducting. Recent neutron scattering measurements indicate unusual spin excitations very different from those observed in the cuprates. Many characteristics of the magnetic spectra can be attributed to unquenched orbital degrees of freedom. In particular, experimental evidence points towards strong orbital quantum fluctuations even in the undoped, insulating parent compound.

Quantitative comparisons between spin fluctuation spectra and the physical properties metals and superconductors

S. Hayden*, G Aeppli, P Dai, H A Mook, T G Perring, R. Doubble and E. Fawcett

**H. H. Physics Laboratory, University of Bristol, Tyndall Ave, Bristol, BS8 1TL, UK.*

Spin fluctuations play an important part in determining the physical properties of materials close to a magnetic instability. We have made detailed measurements of the spin-fluctuation spectra in a the nearly-antiferromagnetic system $Cr_{1-x}V_x$ and the high temperature superconductors $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_5O_{6+x}$. I will show how the spin fluctuations evolve as a function of energy, wavevector and temperature in this system. Under certain approximations, the electronic specific heat can be calculated from the excitation spectrum. Specifically, when the spectrum consists of overdamped modes, Lonzarich et al have shown that the linear specific heat can be related to the appropriately-averaged spin-relaxation frequency. Scalapino et al have related the "resonant" excitation observed in $YBa_2Cu_5O_{6+x}$ to the specific heat. I will show how this approximation work in practice.

A critical view of spin dynamics data

N. Bernhoeft

CEA, Recherche Fondamentale sur la Matière Condensée, France

In recent years there has been a growing interest paid to the existence of phase transitions at zero temperature and the associated Quantum Critical Point (QCP). What, however, are consequences of the T = 0 K transition on physical properties at finite T? In particular we attempt to model the magnetisation density dynamics, as observed through inelastic neutron scattering experiments, in a wide series of materials commonly held to be located in the vicinity of a QCP. An outstandingly broad variety of spectral line shapes as a function of frequency have been reported. The apparent lack of a generic line shape characterising the fluctuation spectrum on the approach to a (magnetic) QCP is, at first sight, surprising; it is to the origin of this effect that we address ourselves.

Poster contributions

(in alphabetical order)

ìSR studies of the nonmagnetic-magnetic transition in $YbCu_{5-x}Al_x$

D. Andreica, A. Amato, F.N. Gygax, A. Schenck, G. Wiesinger, C. Reichl, E. Bauer

ETH-Zurich, PSI, TU-Wienna

Chemical pressure was applied to investigate the phase diagram of $YbCu_{5-x}Al_x$ (x=1, 1.5 and 2). The substitution of Cu by Al decreases the fluctuation rate of the Yb magnetic moments. Correlated fluctuations between the Yb magnetic moments were evidenced below around 50 K in both the $YbCu_{5.5}Al_{1.5}$ and $YbCu_5Al_2$ samples. The $YbCu_{5.5}Al_{1.5}$ sample is close to a quantum critical point, which is evidenced in the ìSR experiment by a continuous increase of the degree of correlated fluctuations of the Yb magnetic moments as T = 0 K is approached from above.

Experimental investigation of the spin-density antiferromagnet Mn_3Si

J. Boeuf, C. Pfleiderer, H. v. Löhneysen

Physikalisches Institut, Universität Karlsruhe, D-76128 Karlsruhe, Germany

The cubic Heusler alloy Mn_3Si enters below anantiferromagnetic spin-density-wave state $T_N \approx 23$ K. We report on measurements of the stability of long range magnetic order in Mn_3Si at high magnetic field which is unusually high compared to the energy scale $k_B T_N$ of magnetic ordering. Incoherent charge density fluctuations are considered as dominant mechanism to account for the low value of T_N.

Fermi liquid instability at the metamagnetic transition in nearly ferromagnetic $Sr_3Ru_2O_7$

May Chiao and S. R. Julian

Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

C. Pfleiderer

Physikalisches Institut, Universitat Karlsruhe, D-76128 Karlsruhe, Germany

S. Nakatsuji and Y. Maeno

Department of Physics, Kyoto University, Kyoto 606-8502, Japan

R. S. Perry, S. A. Grigera, A. J. Schofield and A. P. Mackenzie

School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham BI5 2TT, UK

We have studied transport and thermodynamic properties of the bilayer perovskite $Sr_3Ru_2O_7$. Below about 15 K, in an applied field oriented along the c-axis, a metamagnetic transition occurs at 7 tesla; in the ab-plane, a double transition occurs, at 5 and 5.5 tesla respectively. In the neighbourhood of this field-induced metamagnetic transition, we have found distinct non-Fermi liquid behaviour; the specific heat, c/T, diverges, and the resistivity is close to linear. This suggests the possible proximity to a ferromagnetic quantum critical point. The application of hydrostatic pressure, however, appears to drive the system away from magnetic order.

Low-temperature susceptibility and resistivity close to the quantum critical point of $YbRh_2Si_2$

J. Custers, P. Hinze, C. Langhammer, P. Gegenwart, O. Trovarelli, C. Geibel, F. Steglich

Max-Planck Institute for Chemical Physics of Solids, Dresden

$YbRh_2Si_2$ shows pronounced non-Fermi-liquid effects above a low-lying magnetic phase transition at T_N = 65 mK. The specific heat coefficient $\gamma = \Delta C/T$ and the electrical resistivity $\rho - \rho_0$ show a logarithmic and linear T-dependence respectively over a large T-range.

Slightly doping with only 5 at% isoelectronic Ge reduces T_N to $T_N < 10$ mK and allows to study the asymptotic low-T resistivity and susceptibility in the vicinity of the quantum critical point.

The resistivity shows a linear T-dependence from 10 mK up to 10 K while for the susceptibility a clear deviation from Curie-Weiss behaviour is observed: $\chi^{-1}(T) = \chi_0^{-1} + cT^{\eta}$ with $\eta < 1$. We compare these observations with those of pure $YbRh_2Si_2$ for $T > T_N$.

Evolution of the ground state properties of $YbCu_{5-x}Au_x$

M. Galli[1,2], S. Berger[1], L. Naber[1], H. Michor[1], G. Hilscher[1], E. Bauer[1] and F. Marabelli[2]

[1] *Institut für Experimentalphysik, Technische Universität Wien, A-1040 Wien, Austria*

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Cubic ternary $YbCu_4M$ compounds are known for a rich variety of ground state properties like ferro- or antiferromagnetism, temperature induced first order valence transitions as well as Fermi-liquid features. $YbCu_4Au$ orders antiferromagnetically below 0.6 K exhibiting a spiral-like magnetic structure. In this study we show that the cubic crystal structure is maintained by a Au/Cu substitution at least down to $YbCu_{4.8}Au_{0.2}$, while non-magnetic $YbCu_5$ crystallises in the hexagonal $CaCu_5$ structure. Such a substitution dramatically affects low temperature properties since long range magnetic order vanishes at a critical Cu concentration where non-Fermi-liquid properties are expected. The application of a magnetic field also suppresses magnetic order indicating a field driven NFL state in $YbCu_4Au$. In this contribution a number of bulk properties like temperature- field- and pressure dependent resistivity measurements, optical conductivity, specific heat, magnetic susceptibility as well as isothermal magnetisation studies are presented in order to trace the evolution of the ground state in this series.

Work supported by the ESF, project FERLIN and the Austrian FWF, P12899.

Non-Fermi-Liquid behaviour and incipient superconductivity in the heavy-fermion compound $CeNi_2Ge_2$

P. Hinze, P. Gegenwart, M. Lang, C. Geibel and F. Steglich

Max-Planck-Institute for Chemical Physics of Solids, D-01187 Dresden, Germany

$CeNi_2Ge_2$ is a clean stoichiometric heavy-fermion compound which shows Non-Fermi-liquid (NFL) behavior already at ambient pressure [1]. Recently the observation of incipient superconductivity (sc), i.e. a drop in $\rho(T)$ below $T < 0.1$ K in high-quality crystals ($\rho_0 \leq 1$ $\mu\Omega$cm) was reported[1,2].

Here we present a detailed investigation of the low-temperature resistivity $\rho(T,B)$ at $0.01\ K \leq T \leq 6\ K$ for various slightly off-stoichiometric $Ce_{1+x}Ni_{2+y}Ge_{2+z}$ polycrystals.

Particular attention is paid to the composition-dependence of the lattice constants, the residual resistivity ρ_0, and the occurrence of incipient sc. NFL behavior in the resistivity, i.e. $\rho(T) - \rho_0 \sim T^{\varepsilon}$, with $1.32 \leq \varepsilon \leq 1.5$ depending on the composition, is analyzed in terms of an antiferromagnetic quantum critical point. We examine the effect of impurity scattering for samples with ρ_0 varying between 0.1 and 10 $\mu\Omega$cm and compare it with recent theoretical predictions [3]. We shall present new results on the magnetic phase close to the quantum critical point in slightly Ge doped $CeCu_2Si_2$

[1]P. Gegenwart et al., Phys. Rev. Lett. 82, 1293 (1999).
[2]F.M. Grosche et al., cond-matt/9812133
[3]A. Rosch, Phys. Rev. Lett. 82, 4280 (1999)

UGe_2 A ferromagnetic spin triplet superconductor

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The identification of a spin triplet superfluid phase in ^{3}He naturally led to more general theoretical predictions that spin triplet superconductivity might occur near to a ferromagnetic instability in some metals. The recent discovery in Cambridge and Grenoble of superconductivity near to a ferromagnetic quantum critical point in UGe_2 now calls for these predictions to be re-examined experimentally. In this light it initially appears surprising that superconductivity in UGe_2 has only been detected in the ferromagnetic phase and not also at pressures above the critical pressure for the suppression of ferromagnetism. In this paper we provide evidence that the superconductivity is indeed a bulk property. We also observe the evolution with pressure of the magnetic order by neutron scattering and find that the ferromagnetic component of the order is still present at the pressures and temperatures where the superconductivity is found. In resistivity measurements to determine the pressure-temperature phase-diagram an additional transition within the ferromagnetic state is however identified. The characteristic temperature of this transition decreases with pressure and disappears at a pressure, P_x, close to the pressure at which the superconductivity is strongest. We speculate that this transition is due to a nesting instability of the majority spin Fermi-surface. Evidence is presented that the low-pressure phase below P_x can also be induced by application of a magnetic field at pressures just above P_x. An observed re-entrant behaviour of the superconductivity with field at such pressures is then qualitatively explained. Our work suggests that critical fluctuations related to the transition at P_x may be a key ingredient to the formation of the superconducting state. This affords an explanation as to why the superconductivity is found only in the ferromagnetic state, and not also in paramagnetic phase at higher pressure.

Electronic properties of $CeIn_3$ and $YbNi_2Ge_2$ at high pressure

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We have studied the electrical resistivity of $CeIn_3$ and $YbNi_2Ge_2$ single crystals under high hydrostatic pressure up to 40 kbar and magnetic fields up to 5 T. A full superconducting transition is found $CeIn_3$ in the range 22 - 28 kbar.

The temperature dependence of the upper critical field H_{c2} exceeds the Pauli limit but cannot be described by the weak coupling model, and possibly points to a strong interplay of the magnetism and the superconducting state. The temperature dependence of the normal state resistivity in this pressure range shows strong deviations from a Fermi-liquid behaviour, a quadratic temperature dependence is recovered at magnetic fields just above the upper critical field at low temperatures. In the paramagnetic compound $YbNi_2Ge_2$ the Fermi-liquid regime at low temperatures is suppressed with increasing pressure. The temperature dependence of the exponent n of the resistivity $\rho = \rho_0 + A T^n$ will be compared with the theoretical predictions of the spinfluctuation theory near the critical pressure.

Scaling behaviour of the dynamical susceptibility in systems at magnetic-nonmagnetic transitions

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Recent inelastic neutron scattering results from systems showing non-Fermi liquid behaviour at the boundary of magnetic-nonmagnetic transitions will be reviewed. New results from experiments at ISIS and ILL on Ce(Rh,Pd)Sb and on the stoichiometric compound U_2Pt_2In, will be presented. These systems exhibit the almost temperature independent scattering on the neutron energy loss side with an unusual E/T scaling, found earlier in $U(Cu,Pd)_5$. However, we find that the exponent characterising the scaling behaviour appears not to be universal, varying significantly between the systems studied.

Unconventional metallic state in $YbRh_2Si_2$ - a high pressure study

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The study of 3d- and 4f-electron compounds on the threshold of magnetism has brought to light a number of "strange" metals which appear to defy the conventional description of the metallic state in terms of well-defined fermionic and bosonic excitations. One of these compounds is $YbRh_2Si_2$ which is identified to be one of the few stoichiometric heavy fermion compounds close to a magnetic instability at ambient pressure. It reveals non-Fermi-liquid effects in both the electrical resistivity and the specific heat over more than a decade in temperature above a (presumed) antiferromagnetic phase-transition temperature at $T_{mh} \cong 70$ mK. We present results of a detailed study of the electrical resistivity and the specific heat under hydrostatic pressure and map out the magnetic phase diagram up to about 2.5 GPa. The results will be discussed in light of current theories of quantum critical behavior and in comparison to the isostructural compound $YbCo_2Ge_2$.

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The absence of elementary examples of superconductivity on the border of itinerant electron ferromagnetism has for many years cast doubt on the validity of conventional models of magnetically mediated superconductivity. On closer examination, however, very few systems have been studied under extreme conditions of purity, proximity to the ferromagnetic state, and very low temperatures required to definitively test the theory. Here we report the first observation of superconductivity on the border of ferromagnetism in a pure system, UGe_2, which is known to be qualitatively similar to the classic d-metal ferromagnets. The superconductivity that we observe below 1 K, in a limited pressure range on the border of ferromagnetism, would seem to arise from the same electrons that produce band magnetism. In this case, superconductivity is most naturally understood in terms of magnetic as opposed to lattice interactions and via a spin-triplet rather than the spin-singlet pairing normally associated with nearly antiferromagnetic metals.

Superconductivity and unconventional normal state in stoichiometric Ce/Yb (4f)-metals

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Deviations from the behavior predicted by Landau's Fermi-liquid theory (FLT) are observed in a growing number of metals. These so called "non-Fermi-liquid" (NFL) effects have very different physical origins. Among current theories to describe NFL systems the role of non-stoichiometric composition and disorder on the occurrence of NFL-behavior is controversially debated. Most importantly, to date these approaches fail on describing simultaneously the temperature dependence of different physical properties like e.g., the temperature dependent C/T-ratio in specific heat experiments and the anomalous exponent ($1 \leq \alpha \leq 1.5$) observed in electrical resistivity. To shed light on the role of disorder and the range of validity of the predicted temperature dependencies of the quantities in question, we performed measurements of the electrical resistivity and the specific heat under hydrostatic pressure on a series of pure and slightly doped samples of $CeCu_2Si_2$ and $CeNi_2Ge_2$. Our results indicate that the NFL phenomena in both compounds may have the same origin, i.e., the closeness to a magnetic instability ($T_N \rightarrow 0$ at a critical value of a characteristic parameter like e.g., chemical composition, pressure, magnetic field). Surprisingly, NFL phenomena exist in a large regime in pressure and temperature. This observation gains particular importance with respect to what kind of interaction promotes superconductivity (sc) in these compounds. While in the isostructural compound $CePd_2Si_2$ sc is found only within less than ± 0.5 GPa around p_c (which is interpreted as a hint towards magnetically mediated sc), in the above compounds sc is found in a large regime of pressure of more than 10 GPa. Finally, we compare these data to the NFL behavior found recently in two isostructural compounds based on Yb ($YbRh_2Si_2$, $YbCo_2Ge_2$).

Anomalous low temperature resistivity exponent of $CeIn_3$ at the border of magnetic and superconducting order

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The simple cubic intermetallic compound $CeIn_3$ is a prime candidate for unconventional, magnetically (spin fluctuation) mediated superconductivity. At ambient pressure, antiferromagnetic ordering sets in at the N\'eel temperature of $T_N = 10.2$ K. The compound is near a magnetic instability, thus a quantum phase transition between the antiferromagnetic and paramagnetic phases can be induced by the application of relatively low hydrostatic pressure of 27.5 kbar. In the vicinity of this critical pressure, a superconducting transition can be observed at temperatures below 200 mK. In recent measurements it has been demonstrated that the exponent of the temperature dependence of the resistivity in $CeIn_3$ locks into a value of slightly above 1.5 at low temperatures. The downturn of the exponent to a value of 1 in an intermediate temperature range between 100 mK and 3 K as predicted by Rosch (PRL 82 (1999) 420) has not been observed experimentally. Although the $T^{5/2}$ form of the resistivity is suggestive, a completely convincing picture of the non-Fermi liquid behaviour remains elusive.

Effect of magnetic field on the temperature dependence of the resistivity in $ZrZn_2$

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We present measurements of the field dependence of the temperature (T) dependent part of the electrical resistivity $\Delta\rho(T) \propto T^m$ in single-crystal samples of $ZrZn_2$. The variation of m with T and B is discussed with respect to magnetisation isotherms as measured for the same sample and the predictions of Ginzburg-Landau model of the magnetic equation of state, respectively.

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