

Are heavy-fermion metals Fermi liquids?

F. Steglich^{1,2}, P. Gegenwart¹, R. Helfrich¹, C. Langhammer¹, P. Hellmann¹, L. Donnevert¹, C. Geibel¹, M. Lang^{1,2}, G. Sparn^{1,2}, W. Assmus³, G.R. Stewart⁴, A. Ochiai⁵

¹ Institut für Festkörperphysik, SFB 252, TH Darmstadt, Hochschulstrasse 8, D-64289 Darmstadt, Germany

² Max-Planck-Institut für chemische Physik fester Stoffe, D-01187 Dresden, Germany

³ Physikalisches Institut, Universität Frankfurt, Robert-Mayer-Strasse 2-4, D-60325 Frankfurt/Main, Germany

⁴ Institut für Physik, Universität Augsburg, Universitätsstrasse 1, D-86159 Augsburg, Germany

⁵ Department of Material Science and Technology, Faculty of Engineering, Niigata University, Niigata 950-21, Japan

Abstract. We present the results of specific-heat and resistivity measurements as a function of temperature, magnetic field and hydrostatic pressure on the Kondo lattice CeNi_2Ge_2 , the heavy-fermion superconductors CeCu_2Si_2 and UBe_{13} as well as the low-carrier-density system Yb_4As_3 . “Non-Fermi-liquid” effects in the low-temperature normal-state properties of the three former systems are consistent with the existence of a “nearby” quantum critical point, presumably of antiferromagnetic type. Yb_4As_3 , though showing the outward appearance of a Landau-type heavy-fermion metal, behaves very differently, i.e. as an extreme two-fluid system.

1. Introduction

The common notion [1] of heavy-fermion (HF) metals, i.e. certain three-dimensional Ce-, Yb-, U- or Np-intermetallics, is that they behave as Kondo-lattices [2] just beyond a magnetic instability. Prototypical examples like CeRu_2Si_2 and CeCu_6 exhibit the properties of a heavy Landau Fermi liquid (HLFL) below a phenomenological crossover temperature $T_{coh} \ll T^*$, the lattice Kondo temperature, typically being of the order of 10 K [1]. Upon volume expansion as realized by suitable alloying, antiferromagnetic (afm) order can be induced in the two afore-mentioned systems. When approaching the “quantum critical point” (QCP), at which $T_N \rightarrow 0$ [3–6], i.e. at $x_c \simeq 0.08$ in $\text{Ce}_{1-x}\text{La}_x\text{Ru}_2\text{Si}_2$ [7] and at $x_c \simeq 0.1$ in $\text{CeCu}_{6-x}\text{Au}_x$ [8], strong deviations from HLFL behavior, so-called “non-Fermi-liquid” (NFL) effects, have been observed. In order to investigate the relationship between “NFL” and HLFL behavior, we focus in Sects. 2–4 on two Ce-based Kondo-lattice systems, CeCu_2Si_2 and CeNi_2Ge_2 . In Sect. 5 the canonical U-based HF-metal UBe_{13} [9] and its pertinent “NFL” properties [10] are addressed. Finally, in Sect. 6 we shall discuss the Yb-based compound Yb_4As_3 which has the outward appearance of a HLFL [11] although here, owing to its extremely low carrier concentration, a Kondo effect is most unlikely to be operative [12].

The paper is summarized in Sect. 7, including a short perspective.

2. “Non-Fermi-liquid” effects in heavy-fermion metals

Violation of Landau-Fermi-liquid behavior in f-ion systems has been the subject of vast recent research activities [13]. While the pioneering investigations were performed [14,15] on the moderately concentrated alloy system $\text{Y}_{1-x}\text{U}_x\text{Pd}_3$ ($x \simeq 0.2$), more dilute alloys such as $\text{Th}_{1-x}\text{U}_x\text{Ru}_2\text{Si}_2$ ($x \simeq 0.01$) [16] and $\text{La}_{1-x}\text{Ce}_x\text{Cu}_{2.2}\text{Si}_2$ ($x = 0.1$) [17,18] as well as an increasing number of disordered systems with intact f-ion sublattice, e.g. $\text{UCu}_{5-x}\text{Pd}_x$ [19,20], $\text{CePtSi}_{1-x}\text{Ge}_x$ and $\text{UCu}_{4+x}\text{Al}_{8-x}$ [21], have subsequently come into focus. It is fair to state that very different phenomenologies have been established in these different systems. No surprise, the theoretical scenarios developed to explain those observations span the whole range from quantum-impurity (multichannel Kondo) [22,23] and Kondo-disorder models [24,25] to the presence of a QCP, either of spin-glass [26,27] or of afm type [3–6]. Since disorder is likely to play a crucial role in most of the alloy systems mentioned above, we wish to focus in the remainder of this paper on *undoped* intermetallic compounds.

The HLFL state of prototypical Ce-based compounds like CeCu_6 ($T^* \simeq 4$ K) and CeRu_2Si_2 ($T^* \simeq 25$ K) is phenomenologically well understood: (i) Both the specific-heat coefficient γ and the Pauli-type spin susceptibility χ_s reveal effective quasiparticle masses as large as several hundred times the mass of the free electron. (ii) Though each of them being huge, their (Sommerfeld-Wilson) ratio $R \sim \chi_s/\gamma$ is of order unity only. (iii) An also huge term $\Delta\rho = \rho - \rho_0 = aT^2$ (ρ_0 : residual resistivity) exists whose coefficient scales roughly as $a \sim \gamma^2$ [28]. Given an effective two-band model, this is consistent with the action of “s-d”-type of scattering processes, in which light carriers are scattered off coherent heavy quasiparticles [29]. (iv) Short-range, “quantum” fluctuations of afm type have been demonstrated, via neutron-scattering experiments, to exist in the HLFL phase of both CeCu_6 [30,31] and CeRu_2Si_2 [31]. These are apparently essential for mediating the interactions

between carriers: In order to find an aT^2 contribution to the resistivity, i.e. a T -independent scattering cross section $\sigma^* \sim a$, these interactions have to be short lived and short ranged [5].

The occurrence of “NFL” phenomena upon approaching the QCP is commonly related to the growth (in space and time) of these afm correlations. The theoretical models, all dealing with a (widely oversimplifying) isotropic single-band system of itinerant fermions, arrive at the following conclusions [3,5,6]: At the QCP the specific-heat coefficient, though critically enhanced, should be finite, following $\gamma(T) = \gamma_0 - \alpha T^{1/2}$ when T is increased. Under the same circumstances, the resistivity coefficient a should diverge along with a progressive restriction of the validity of the T^2 dependence to a smaller T window. At the same time $\Delta\rho(T)$ should obey a $T^{3/2}$ law over a more extended temperature range. At elevated temperatures ($T \simeq T_0$, measuring the dispersion of the low-lying afm fluctuations), these asymptotic temperature laws should be replaced, within approximately one decade, by the following “crossover” laws [3,6]: $\gamma(T) \sim \ln(T_0/T)$ and $\Delta\rho(T) \sim T$.

In order to study the effect an extended and slowly fluctuating afm order parameter has on the low- T properties of an undoped HF metal, a few attempts have been reported, all of them starting out with a HF antiferromagnet being “tuned” through the QCP via application of hydrostatic pressure. For Ce_3Ni_7 with $T_N = 1.8$ K, $\gamma(T) \sim \ln(T_0/T)$ was observed in a surprisingly wide pressure range around the critical value $p_c = 0.3$ GPa ($T_N \rightarrow 0$) [32]. For CePd_2Si_2 ($T_N \simeq 10$ K), “crossover-type” behavior $\Delta\rho \sim T$ in a surprisingly extended temperature range at $p \gtrsim p_c \simeq 2.8$ GPa was found by one group [33], whereas another one reported $\Delta\rho \sim T^{3/2}$ below $T \simeq 1$ K in the same pressure regime [34]. Even more puzzling, the first group [33] discovered HF superconductivity below $T \simeq 0.4$ K for $p \gtrsim 2.2$ GPa, which was not seen by the second one [34]. The competition of HF superconductivity and some kind of presumably itinerant [35] afm order has been widely studied in CeCu_2Si_2 , a homologue to CePd_2Si_2 . Three types of groundstate behaviors could previously be established for CeCu_2Si_2 single crystals, i.e. before and after a particular heat treatment [36]: “S-type” crystals show a bulk HF superconducting transition at $T_c = 0.65$ K, whereas “A-type” crystals lacking bulk superconductivity undergo a broadened mean-field-type transition at $T_A = 0.7$ K – 0.8 K into a presumably afm ordered “phase A” [37], whose structure could not yet be unraveled via neutron diffractometry. In a single crystal of “AS type”, both groundstates are almost degenerate and can be replaced by one another, depending on temperature and/or magnetic field [38]. Yet another “phase B” that exists below 0.6 K and above 7 T was discovered with AS-type crystals [38].

These astonishing differences in the groundstate properties of CeCu_2Si_2 are most likely related to variations in site occupation within the single crystals. However, *no* significant differences in the lattice constants could be resolved through X-ray diffractometry. Using polycrystalline $\text{Ce}_{1+x}\text{Cu}_{2+y}\text{Si}_{2+z}$ samples with compositions deliberately chosen to be slightly off stoichiometry, Geibel et al. [39] recently succeeded in mapping those different groundstate behaviors to separate sectors of the narrow homogeneity range of the primary CeCu_2Si_2 phase within the chemical Ce-Cu-

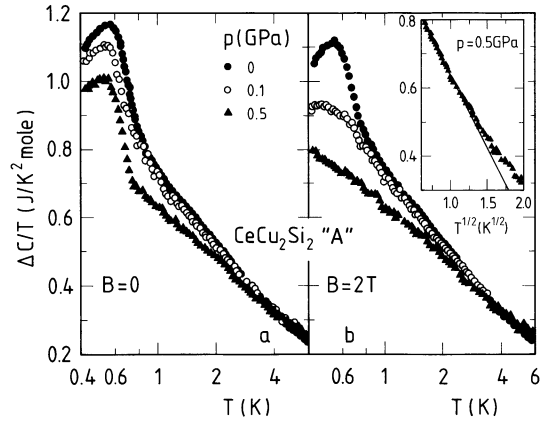


Fig. 1a,b. Ce increment to the specific heat, $\Delta C = C_{\text{CeCu}_2\text{Si}_2} - C_{\text{LaCu}_2\text{Si}_2}$, as $\Delta C/T$ vs T (on a logarithmic scale) for an A-type polycrystal at different pressures for $B = 0$ a and $B = 2$ T b. The inset shows the $p = 0.5$ GPa results for $T \leq 2$ K and $B = 2$ T as $\Delta C/T$ vs $T^{1/2}$

Si phase diagram. While Cu-rich samples are of type S, suggesting that HF superconductivity requires an intact Cu sublattice, A-type behavior is established in samples with slight Cu/Ce deficiency. Both, the S and A sectors are separated from each other by the AS sector containing the true stoichiometry point. The signatures of phase A are lost in transport and thermodynamic experiments inside the S sector, see subsequent section.

Figure 1 shows that “fine tuning” through the various sectors can be achieved by extremely small values of hydrostatic pressure. Using an A-type polycrystal, already $p = 0.1$ GPa, is sufficient to achieve AS behavior as inferred from the broad hump in Fig. 1b. For $p \geq 0.5$ GPa the sample is of type S. The specific heats of A- and AS-type polycrystalline CeCu_2Si_2 as well as of S-type single crystals (not shown) coincide for $T > 1.5$ K. In addition, the entropies (at $T = 2$ K) of the two former are almost identical. This illustrates the existence of a low-lying multicritical point: Very small changes either in the composition (mainly Cu/Si) or in the lattice spacings result in dramatic changes of the groundstate behavior. In fact, employing a bulk modulus $b = 125$ GPa [40], we estimate that for $p = 0.1$ GPa the relative change in the lattice parameters $|\Delta a|/a \simeq |\Delta c|/c$ is smaller than $3 \cdot 10^{-4}$, which is well below the resolution of X-ray diffractometry. Thus, it is not surprising that no differences between the various single crystals mentioned before can be resolved by this technique.

We now return to the possible existence of a QCP in the S sector of the homogeneity range: The normal (n)-state $B = 2$ T data, taken at $p = 0.5$ GPa may be described by $\gamma \sim \ln(T_0/T)$ for 3 K $< T < 6$ K. However, on the logarithmic T scale of Fig. 1 the T dependence becomes flatter at lower temperatures. For $T < 1.5$ K down to the lowest accessible temperature of 0.4 K, the predicted [3–6] law $\gamma(T) = \gamma_0 - \alpha T^{1/2}$ is verified, see inset. Though extension of these experiments to mK temperatures is most desirable (and is under current preparation), one may consider these data as suggestive of a QCP. This would imply that (i) phase A, in fact, represents some kind of itinerant afm order and (ii) the transition temperature T_A vanishes smoothly as a function of pressure as expected for a continuous phase transition.

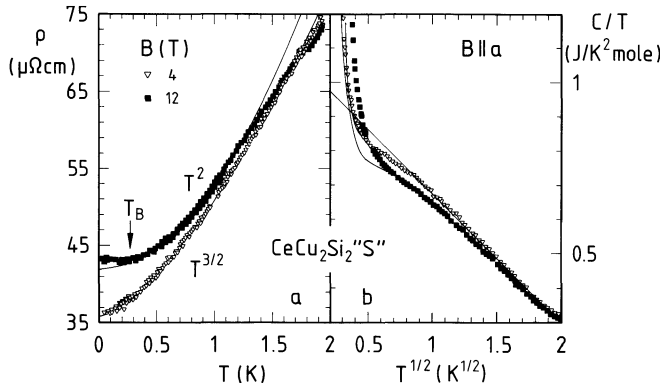


Fig. 2. Resistivity ρ vs T **a** and specific heat as C/T vs $T^{1/2}$ **b** at $B = 4$ and 12 T for an S-type CeCu_2Si_2 single crystal. Solid lines indicate $T^{3/2}$ and T^2 dependences in **a**, $T^{1/2}$ dependence as well as C/T data after subtraction of nuclear contributions due to the external B field in **b**. Arrow in **a** marks the onset of phase B, which is not visible in the C/T vs T data of **b**

In the following section the n-state ambient-pressure results on an S-type CeCu_2Si_2 single crystal will be addressed in order to investigate in more detail to which extent the predictions of the theoretical single-band models are met by the low- T properties of a realistic HF compound.

3. Phase diagrams for CeCu_2Si_2

Figure 2a and 2b display recent low-temperature resistivity and specific-heat results [41,42] on the same S-type CeCu_2Si_2 single crystal already studied in [37]. The n-state resistivity results at fields $B \leq 5$ T can be well described, between $T = 0.02$ K and $T \simeq 1.7$ K, by $\Delta\rho = \beta T^{3/2}$. For $B \lesssim 2$ T, a low- T superconducting transition occurs. No anomaly related to the A-phase transition can be resolved in this field range. However, for $B > 6$ T, $\Delta\rho = aT^2$ with $a \simeq 10 \mu\Omega\text{cmK}^{-2}$ is the best fit to the data below a field-dependent limiting temperature (cf. Fig. 3a). For $B > 8$ T up to the highest accessible field $B = 15.5$ T, a low- T transition is found into the high-field “phase B”, first discovered for an AS-type CeCu_2Si_2 single crystal [38]. This transition is rather broad and manifests itself in a gradual increase of $\rho(T)$ below $T = T_B$. Our results indicate that in an S-type sample, compared to one of type AS [38], phase B forms (i) at lower temperature and (ii) even in the absence of phase A.

A change from “NFL” ($\Delta\rho \sim T^{3/2}$) to HLFL ($\Delta\rho \sim T^2$) behavior around $B = 6$ T is also inferred from our results for the magnetoresistivity, $\Delta\rho(B) = \rho(B) - \rho(0)$. Making an isothermal field sweep we find $\Delta\rho(B)$ to change sign from an anomalous $\Delta\rho(B) < 0$ in the field range $B_{c2}(T = 0.02 \text{ K}) < B \leq 5$ T to $\Delta\rho(B) > 0$ (as characteristic for a Landau FL) at $B > 6$ T.

Our specific-heat results on the same crystal do *not* reveal the quantum critical behavior theoretically expected [3–6] on the basis of the $\Delta\rho(T, B)$ results. As shown in Fig. 2b, $\gamma(T) = C(T)/T$ can be approximately described by $\gamma_0 - \alpha T^{1/2}$ for $T > 0.5$ K only. The two fit parameters (taken at $B = 2$ T) slightly exceed those for the A-type polycrystal measured at $p = 0.5$ GPa (Fig. 1). When raising the

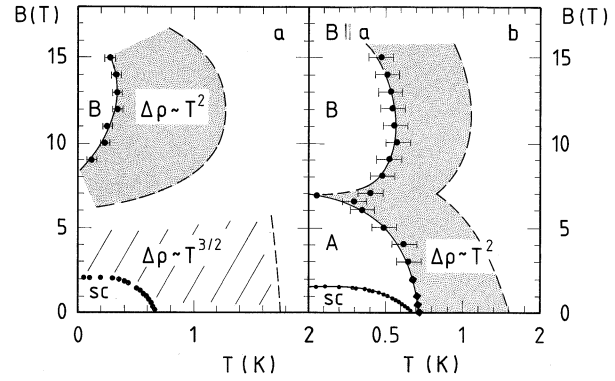


Fig. 3. B - T diagram, based upon resistivity results, for an S-type CeCu_2Si_2 single crystal **a** and an AS-type single crystal **b**. Dashed lines indicate temperature limits of the validity ranges for the $T^{3/2}$ and T^2 laws, respectively

field, both γ_0 and α are found to gradually decrease. Upon lowering the temperature to below $T \simeq 0.5$ K, $\gamma(T)$ flattens and appears to saturate as $T \rightarrow 0$. A detailed analysis of these data is, however, impeded by the steep upturn in $\gamma(T)$ below $T \simeq 0.25$ K. The latter cannot be explained by the Zeeman splitting of the nuclear Cu/Si spin states by the applied B field only. Taken together, the initial flattening and subsequent upturn in $\gamma(T)$ upon cooling to below 0.5 K are suggestive of a uniform “internal field”.

The $\gamma(T)$ results (Fig. 2b) do also not reflect the crossover between different behaviors inferred from the resistivity data when increasing the field from below to above 6 T. In addition, the B-phase transition (at $T_B \simeq 0.2$ K) is absent in $\gamma(T)$ measured at $B = 12$ T. This has been ascribed to a substantial reduction of the ordered Ce moment within phase B (presumed to be of SDW type), when compared to A- and AS-type samples [43].

A similar “discrepancy” between specific-heat and resistivity results has been noticed previously already at zero magnetic field, for both A-[44] and AS-[43] type CeCu_2Si_2 samples, showing $\gamma(T)$ of “NFL” kind (cf. Fig. 1), but $\Delta\rho = aT^2$ with a gigantic coefficient, $a \simeq 10 \mu\Omega\text{cmK}^{-2}$. The B - T diagram for an AS-type single crystal deduced from resistivity experiments is displayed in Fig. 3b.

To summarize, when carefully investigating the canonical HF compound CeCu_2Si_2 in the vicinity of its QCP, we obtain rather different “answers” from our resistivity experiments on the one hand and calorimetry on the other. In contrast to the theoretical assumption [3,5,6] of an isotropic single-band system of itinerant fermions, the complex quasiparticles in HF compounds give rise to highly anisotropic, multi-sheeted renormalized Fermi surfaces [29]. Our observations seem to support an effective two-band scenario not only in the HLFL phase [29], but also in the vicinity of the QCP: light carriers (probed by $\Delta\rho$) are scattered from heavy quasiparticles (probed by $\gamma(T)$). Further on, low-lying modes with small q may be relevant in addition to those with q values around the afm wave number.

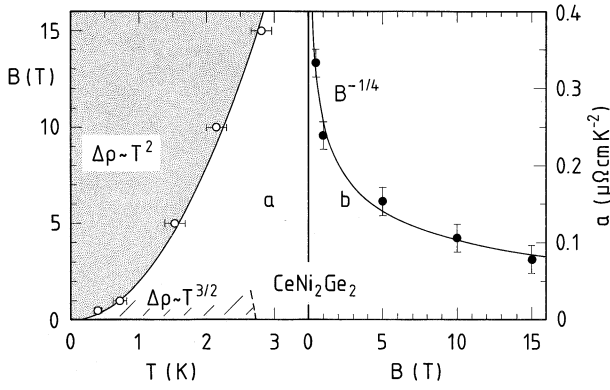


Fig. 4. **a** B - T diagram, based upon resistivity results, for a CeNi_2Ge_2 polycrystal. Solid line connecting circles and dashed line mark the limits of the T^2 and $T^{3/2}$ laws, respectively. **b** Coefficient a of the $\Delta\rho = aT^2$ fit to the low- T data as a function of the external field

4. Evidence for a quantum critical point “in the vicinity” of CeNi_2Ge_2

By scrutinizing the low- T properties of “simple”, i.e. neither afm ordering nor superconducting, homologues to CeCu_2Si_2 we found strong violation of HLFL behavior for CeNi_2Ge_2 [45]. “NFL” phenomena are observed, down to $T \simeq 0.4$ K, in the specific heat [45–48] as well as in the thermal expansion [49]. At lower temperatures, the $B = 0$ data for $C(T)/T$ [48] resemble the (finite-field) data for CeCu_2Si_2 , see Fig. 2b. For both single-crystal and polycrystalline samples with residual resistivities ρ_0 ranging between 1.5 and 2.5 $\mu\Omega\text{cm}$, i.e. resistivity ratios $\rho_{300\text{K}}/\rho_0$ ranging between 5 and 20, a $T^{3/2}$ power law was observed to describe well $\Delta\rho(T)$ over more than two decades in T ($0.02\text{ K} \leq T \leq 2.5\text{ K}$), if $B \leq 1\text{ T}$ [45]. At low B fields the isothermal magnetoresistance $\Delta\rho(B)$ was found to be negative, which was taken as evidence for a nearby QCP [45]. At sufficiently high fields $\Delta\rho(B)$ becomes positive as expected for a Landau FL. In fact, both specific-heat and resistivity results at $T \gtrsim 0.4\text{ K}$ indicate such a Landau FL phase to form at $B > 1\text{ T}$. In Fig. 4a we have plotted $T_\ell(B)$ values which define the limiting temperatures for the validity of the $\Delta\rho = a(B)T^2$ dependence at constant fields. $T_\ell(B)$ agrees satisfactorily with that temperature below which $\gamma(T)$ becomes almost constant at the same value of B [45]. A quadratic relationship, $B = AT_\ell^2$, describes these results reasonably well. Even for low fields, $B \leq 1\text{ T}$, where the $T^{3/2}$ law yields a very good fit to $\Delta\rho(T)$ in a wide T window, a narrow low-temperature range can be identified in which $\Delta\rho = a(B)T^2$ yields as good a fit to the data. As can be seen in Fig. 4b, the prefactor in this fit appears to diverge in proportion to $B^{-1/4}$ as $B \rightarrow 0$. This field dependence can be understood as follows: In the low-field range we find $a \sim T_\ell^{-1/2}$, in accord with $\Delta\rho \sim T^{3/2}$ for $T \geq T_\ell$. Owing to the empirical law $T_\ell(B) = A^{-1/2}B^{1/2}$ as read off Fig. 4a, one arrives at the observed $B^{-1/4}$ dependence of $a(B)$.

Two observations concerning this field-induced Landau-FL phase are worth mentioning: (i) Magnetic fields $B \gtrsim 1\text{ T}$ distinctly change the physical properties, i.e. by depressing “NFL” effects in both $C(T)$ [45–47] and $\Delta\rho(T)$. These fields are found to be smaller by more than one order of magnitude

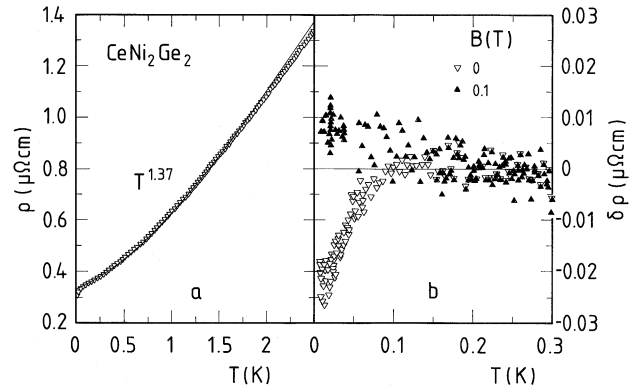


Fig. 5. **a** ρ vs T for a high-quality CeNi_2Ge_2 polycrystal obeying a $T^{1.37}$ power law (cf. solid line). **b** $\delta\rho = \rho - \rho_0 - \beta T^{1.37}$ vs T for the same sample as in **a** below $T = 0.3\text{ K}$ at $B = 0$ and 0.1 T , respectively

in proportion to the energy scale for the short-range, short-lived fluctuations that are believed to lead in CeNi_2Ge_2 to a $\chi(T)$ shoulder at $T = 28\text{ K}$ and to a “metamagnetic transition” at $B \simeq 42\text{ T}$ [50]. (ii) The prefactor in the low- T $\Delta\rho = a(B)T^2$ law is considerably smaller than estimated from the measured $\gamma(B)$ values [45–47], if the universal Kawasaki-Wood relation [28] is applied. For example: at $B = 8\text{ T}$, $a \simeq 0.12\ \mu\Omega\text{cmK}^{-2}$ is one order of magnitude smaller than that value of a expected from $\gamma \simeq 0.28\text{ J/K}^2\text{ mol}$ [45].

Apart from an external B field, hydrostatic pressure has been applied to CeNi_2Ge_2 in order to recover a Landau-FL phase [45–47]. A most surprising observation was made in recent specific-heat experiments: Out of the “moderately heavy” Landau FL ($\gamma \simeq 130\text{ mJ/K}^2\text{ mol}$) as established under application of $p = 1.7\text{ GPa}$, a second-order non-superconducting phase transition takes place at $T_1 = 0.9\text{ K}$. The fact that T_1 does not change in a field $B = 8\text{ T}$ is consistent with an antiferromagnetic phase transition, perhaps related to some Fermi-surface instability [45].

Preliminary resistivity measurements on CeNi_2Ge_2 single crystals under hydrostatic pressure by the Cambridge group [51] failed to confirm this transition of T_1 . Instead, a seeming superconducting transition was discovered at lower temperature, i.e. via a drop in $\rho(T)$ that occurs near $T = 0.25\text{ K}$ at $p = 1.55\text{ GPa}$ and near $T = 0.45\text{ K}$ at $p = 2.6\text{ GPa}$ [51].

In Fig. 5 we show our $\rho(T)$ results at ambient pressure for a polycrystalline sample of very high quality ($\rho_0 = 0.33\ \mu\Omega\text{cm}$, $\rho_{300\text{K}}/\rho_0 \simeq 200$). An attempt to fit a $T^{3/2}$ law to the low- T data proved to be unsuccessful, except for a limited temperature range, $0.1\text{ K} < T < 0.5\text{ K}$. Rather these results are well described, for $0.1\text{ K} \leq T \leq 1.6\text{ K}$, by $\Delta\rho \sim T^{1.37}$ (Fig. 5a). Note that for the isostructural compound CePd_2Si_2 studied near the critical pressure $p_c \simeq 2.8\text{ GPa}$ ($T_N \rightarrow 0$), a similar correspondence between the temperature dependence of the resistivity and its residual value was observed [52]: High-quality samples of CePd_2Si_2 exhibit a $\Delta\rho \sim T^{1.2}$ law over a wide T range, while samples with larger ρ_0 values show $\Delta\rho \sim T^{1.5}$, cf. [34]. In addition, only the high-quality samples undergo a low- T transition into a HF superconducting state [33,34,52]. As is seen in Fig. 5b, our high-quality CeNi_2Ge_2 sample, too, exhibits a resistivity

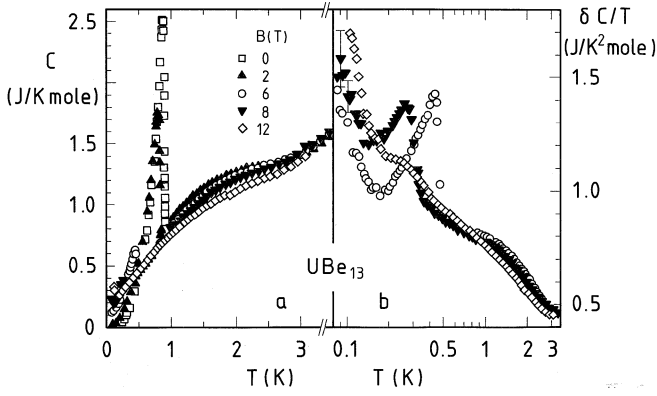


Fig. 6. **a** Specific heat C of a UBe_{13} single crystal as a function of temperature T below $T = 3.5$ K at differing magnetic fields. **b** $\delta C = C - C_{\text{nuclear}}$ as $\delta C/T$ vs T (on a logarithmic scale) for the same sample as in **a** at $B = 6, 8$ and 12 T, respectively

anomaly below $T = 0.1$ K which suggests an incipient superconducting transition, i.e. through a $\rho(T)$ drop of $\simeq 8\%$, accompanied by a shielded volume of less than 1% (not shown). A field as low as 0.1 T is apt to suppress this resistivity drop (Fig. 5b).

5. The “incoherent metal” UBe_{13}

The superconductor UBe_{13} [9] is one of the most prominent examples of HF compounds showing a “NFL”-type normal state. Two different types of UBe_{13} with markedly different superconducting and n-state properties have been identified [42]: “H-type” ($T_c = 0.85$ K – 0.9 K) and “L-type” ($T_c \simeq 0.75$ K). Most of the polycrystalline samples reported are of type H, while all L-type samples are single crystals. This led to the presumption [42] that the former may be poor while the latter may be rich in Be. Recently, the properties of an L-type single crystal have been thoroughly investigated [53]. Below, we concentrate on a UBe_{13} single crystal of type H ($T_c = 0.9$ K). Its specific heat is shown in Fig. 6 for the T range 0.08 K $\leq T \leq 3.5$ K and at magnetic fields $0 \leq B \leq 12$ T [42]. The n-state specific heat exhibits a broad shoulder around $T = 2$ K (Fig. 6a). In previous work a similar feature, sometimes even a distinct $C(T)$ peak [54], has been found which was moderately broadened by an external field. Entropy becomes redistributed both at higher [54,42] and lower temperatures. At fields $B > 6$ T this shift in entropy towards lower temperatures becomes much more pronounced (Fig. 6b). Note that fields in excess of 8 T are necessary to completely suppress HF superconductivity in this material. At the highest field $B = 12$ T, the specific-heat coefficient $\gamma(T) = \delta C(T)/T$ is roughly proportional to $-\ln T$ for $T > 0.3$ K, but gradually deviates to smaller values at lower temperature. Like in CeCu_2Si_2 , a more detailed analysis is prevented by the $\gamma(T)$ upturn below $T = 0.2$ K. Its origin is unclear, as $\delta C(T)$ already represents the specific-heat results after subtracting from the raw data the contributions due to the Zeeman splitting of nuclear spin states of ^9Be [42].

The specific-heat anomaly at $T \simeq 2$ K is commonly attributed [55] to some magnetic fluctuations. Simultaneous investigations of the thermal expansion show [56] that these

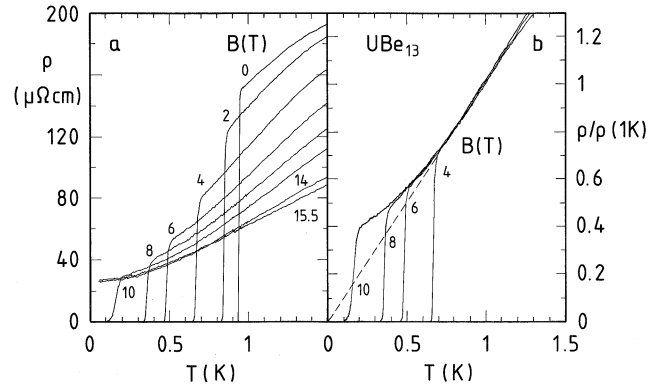


Fig. 7. **a** ρ vs T for the same sample as in Fig. 6 at differing magnetic fields. **b** Same data as in **a**, normalized to the respective ρ value at $T = 1$ K. Dashed straight line is an extrapolation to $T = 0$ of the data for $T \geq 0.8$ K

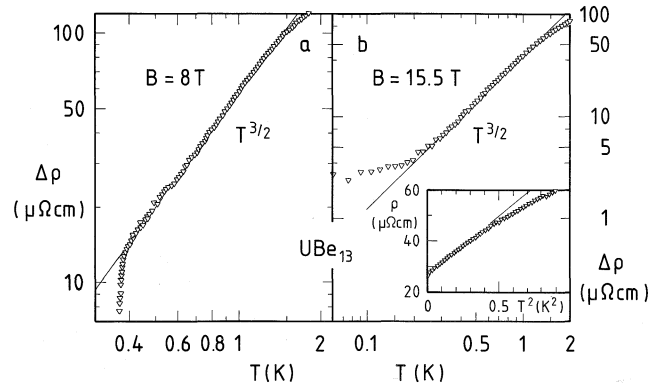


Fig. 8a,b. $\Delta\rho = \rho - \rho_0$ vs T (on logarithmic scales) for the same sample as in Fig. 6 at $B = 8$ T **a** and $B = 15.5$ T **b**, respectively. Inset shows low- T data of **b** as ρ vs T^2

“2 K fluctuations” are reminiscent of the local spin fluctuations in disordered Kondo systems. The “2 K fluctuations” manifest themselves also in a pronounced $\rho(T)$ maximum near $T = 2$ K [9], which can be efficiently suppressed by a magnetic field, see Fig. 7a. By an investigation of the same single crystal used for our specific-heat experiments we observe [41] an isothermal n-state magnetoresistivity $\Delta\rho(B)$ which is negative up to $B = 14$ T in a wide temperature regime, $T \geq 0.02$ K. The minimum value of the residual resistivity as obtained from a ρ vs T^2 plot (see below) for $B = 14$ T amounts to $\rho_0 \simeq 26$ $\mu\Omega\text{cm}$, about 10 $\mu\Omega\text{cm}$ higher [57] than for a previously studied polycrystalline UBe_{13} sample [58]. An *intrinsic* finite residual resistivity (at $B = 0$) was predicted for the “incoherent metal” UBe_{13} in the framework of the “two-channel Kondo-lattice” model [59].

In the following we wish to inspect more closely the temperature dependence of $\rho(T)$ as measured at constant fields. The first observation made is that the “2 K fluctuations” have a dominant effect only for $B < 4$ T. For, at fields 4 T $\leq B \leq 10$ T, we are able to scale the various $\rho(T)$ curves within $T_c(B) < T < 1.2$ K to a universal curve, i.e. by normalizing $\rho(T)$ by its respective value at $T = 1$ K (Fig. 7b): Above $T = 0.7$ K, a linear $\rho(T)$ dependence is found, that can be extrapolated to $\rho \simeq 0$ (as $T \rightarrow 0$), while ρ vs T becomes superlinear at lower temperatures.

As is demonstrated in Fig. 8a for the $B = 8$ T data, $\Delta\rho(T)$ can be well fitted between $T_c \simeq 0.4$ K and $T \simeq 1$ K by a $T^{3/2}$ law. The latter holds true even up to the highest field, $B = 15.5$ T (Fig. 8b). However, at $B = 14$ T as well as 15.5 T, the data for $T \leq 0.4$ K are better described by a T^2 dependence, see inset of Fig. 8b. At present, it cannot be decided whether this asymptotic T^2 dependence is restricted to such high fields, or whether it also exists at $B < 14$ T where it is masked by the superconducting transition. On the other hand, the isothermal magnetoresistance is *seen* to display a qualitative difference in these two field regimes: While $\Delta\rho(B)$ is negative for $B < 14$ T, it becomes positive at higher fields. In this respect UBe_{13} behaves phenomenologically similarly to its Ce-based counterparts which, however, show much lower ‘‘crossover’’ fields: $B_0 \simeq 6$ T (CeCu_2Si_2) and $B_0 \simeq 1$ T (CeNi_2Ge_2). Like for the latter compound, for UBe_{13} the coefficient of the asymptotic T^2 -dependence of $\Delta\rho(T)$ decreases with increasing B field, i.e. from $a = 52 \mu\Omega\text{cmK}^{-2}$ (14 T) to $a = 45 \mu\Omega\text{cmK}^{-2}$ (15.5 T).

6. Yb_4As_3 : A carrier-poor ‘‘heavy-fermion metal’’?

Yb_4As_3 , crystallizing in the cubic anti- Th_3P_4 structure (I43d), behaves as an ordinary metal at room temperature [11]. It belongs to the class of homogeneous intermediate-valence compounds, with the Yb valence being close to $\nu = 2.25$ [11]. This corresponds to an average ratio $\text{Yb}^{2+}:\text{Yb}^{3+} = 3 : 1$. Upon cooling to below $T_s = 293$ K, Yb_4As_3 undergoes a structural transition into the trigonal anti- Th_3P_4 structure (R3c) in which charge ordering of the smaller Yb^{3+} ions occurs along the $\langle 111 \rangle$ direction [11]. Unless a sample is cooled through T_s under a suitable uniaxial stress, all possible four trigonal domains with one short space diagonal are present. As inferred from Hall-effect measurements [11], the concentration of carriers (p holes) at low T becomes as small as 10^{-3} per formula unit. Surprisingly enough, $\Delta\rho(T)$ obeys a T^2 law with a gigantic coefficient $a \simeq 0.75 \mu\Omega\text{cmK}^{-2}$, suggesting HLFL behavior [11]. Using $\gamma = C/T \simeq 0.2 \text{ J/K}^2\text{mol}$ as taken at $T \gtrsim 0.5$ K (Fig. 9a), the Kadowaki-Wood scaling between a and γ^2 [28], which was observed for HF metals with large carrier concentration, seems to hold. In the following we will demonstrate, however, that transport properties on the one hand and specific heat on the other respond very differently to both alloying and application of a magnetic field. These experiments characterize Yb_4As_3 as an extreme two-fluid system.

Aoki et al. [60] have studied the effect of Sb doping on the transport properties for several $\text{Yb}_4(\text{As}_{1-x}\text{Sb}_x)_3$ samples. Already 12 at% Sb give rise to a dramatic reduction of the low- T resistivity, accompanied by a decrease of T_s , the temperature of the structural transition. This was interpreted by a pushing up of p states ($5p$ of Sb compared to $4p$ of As) resulting in an Sb-induced raise of the carrier concentration by which charge ordering becomes increasingly screened. Hall measurements support [60] this interpretation. Yb_4Sb_3 is a cubic intermediate-valence metal in the whole temperature range. On the other hand, doping of 30 at% P on As sites results in a p-type semiconductor [61]. In contrast to this overwhelming effect of doping on the carrier concen-

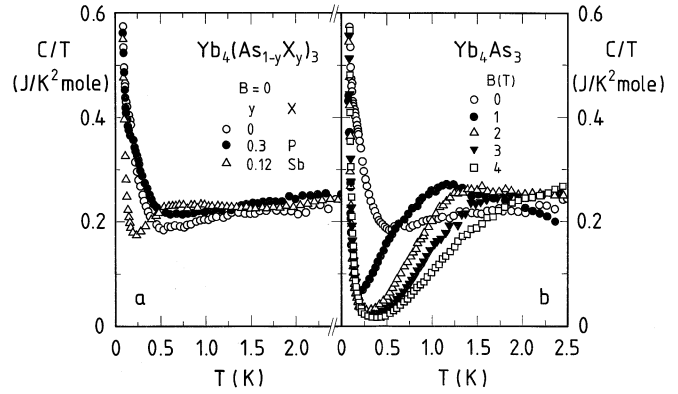


Fig. 9. Specific heat as C/T vs T for Yb_4As_3 , $\text{Yb}_4(\text{As}_{0.7}\text{P}_{0.3})_3$ and $\text{Yb}_4(\text{As}_{0.88}\text{Sb}_{0.12})_3$ at $B = 0$ a and for Yb_4As_3 at differing magnetic fields b

tration, the specific heat at $T \gtrsim 0.5$ K does hardly change (Fig. 9a). Similarly, the low- T susceptibility was found to be rather insensitive against doping [60,61].

Figure 9b illustrates that a magnetic field of only 1 T leads to a gross change of the specific heat: Ignoring the C/T upturn below $T \simeq 0.15$ K, we state a strong reduction of the γ value. The additional γ depression by fields $B > 1$ T is only moderate. Our data at intermediate temperatures for finite fields indicate the opening of a gap, E_g , in the low-energy excitation spectrum. E_g/k_B increases from 0.8 K at $B = 1$ T to 2.2 K at $B = 4$ T [42]. Compared to this pronounced depression of $\gamma(T)$ by a relatively low external field, the field dependence of the resistivity is rather weak: Both the residual value ρ_0 and the coefficient a of the T^2 term exhibit a (40–50)% increase in the highest accessible field of 15.5 T [41].

The experiments presented before strongly suggest that the spin degrees of freedom, dominating the specific heat, and the charge degrees of freedom are almost decoupled in Yb_4As_3 . As doping with P shows, γ remains unaffected upon further depletion of the charge carriers. Even higher γ values were observed for the *semiconducting* Sm_3X_4 compounds (X: Se, Te) [62,63].

Fulde et al. [12,64] have explained the charge-ordering process by the minimization of the Coulomb repulsion between Yb^{3+} ions through a band Jahn-Teller effect. As a result, $S = 1/2$ Heisenberg chains of Yb^{3+} ions form along $\langle 111 \rangle$. The corresponding magnon excitations could recently be demonstrated via neutron-scattering experiments by Kohgi et al. [65]. The linear magnon dispersion relation $\omega_m \sim q$ (as $q \rightarrow \pi/d$, d being the atomic separation within the Heisenberg chains) explains quite naturally the γT term dominating the specific-heat for temperatures sufficiently high so that the material behaves quasi-one-dimensionally. From the measured γ value of $0.2 \text{ J/K}^2\text{mol}$ (Fig. 9) an intra-chain exchange-coupling constant (or magnon band width) $J \simeq k_B \cdot 25$ K was estimated [12]. Further on, the field-induced gap observed in the spin-excitation spectrum as inferred from the data of Fig. 9b was obtained by taking into account a weak inter-chain coupling [64]. Future activities should address

- the possible existence of a three-dimensional afm transition at very low temperatures, the precursor of which

may manifest itself in the huge $C(T)/T$ upturn (Fig. 9), as well as

- the role of disorder within the $S = 1/2$ chains, presumably causing (i) the finite, though extremely low, carrier concentration [12], (ii) spin-glass type effects as seen in the specific heat below $T = 0.2$ K [42] and (iii) distinct deviations [65] from the expected dispersion relation at low q .

7. Summary and perspective

In this paper, the temperature, field and pressure dependences of the electrical resistivities and specific heats of some prototypical heavy-fermion metals have been presented. We have selected such undoped Ce-/U-compounds that display “non-Fermi-liquid” phenomena in their paramagnetic, normal-conducting states. Our observations for CeNi_2Ge_2 , CeCu_2Si_2 and UBe_{13} support in either case the existence of a “nearby” quantum critical point, probably of antiferromagnetic type. At the present state of our investigations, these compounds appear to behave as Fermi liquids of a generalized, i.e. non-Landau, type. Compared to the theoretical predictions for isotropic single-band systems of itinerant fermions [3–6], our experiments are more consistent with strongly anisotropic multi-band quasiparticle systems, containing both heavy and light fermions [29].

The following questions have yet to be answered by future research:

- Does the $T = 0$ transition, which is driven in Kondo lattices by a suitable control parameter such as hydrostatic pressure, indeed involve heavy-fermion *band* magnetism as assumed in [3–6], or is one rather dealing with antiferromagnetic order between (“Kondo-reduced”) *local* f-moments [1]? In the latter case, the $T = 0$ transition would be adequately described by a “Mott transition of the f electrons”, at which physical properties should be highly sensitive to disorder [66]. To shed more light on the effect disorder has on the “non-Fermi-liquid” phenomena in CeNi_2Ge_2 , we plan to study systematically the dependence of the exponent ϵ in the power law for the resistivity, $\rho = \rho_0 + \beta T^\epsilon$, on its residual value ρ_0 , cf. Fig. 4a.
- Given the existence of a quantum critical point in heavy-fermion metals, is this necessarily of the antiferromagnetic type? The possible occurrence of incipient superconductivity at ambient pressure and at very low temperatures in high-purity CeNi_2Ge_2 (Fig. 5b) raises speculations concerning a *superconducting* quantum critical point [67].

We conclude by recalling that there exist several heavy-fermion metals, like CeCu_6 and CeRu_2Si_2 , that *do* behave as heavy Landau Fermi liquids. However, not every compound with the outward appearance of a heavy Landau Fermi liquid does, in fact, show strongly renormalized carriers or “heavy fermions”. This was exemplified with the charge-ordering compound Yb_4As_3 .

We are grateful to E. Abrahams, G. Aeppli, P.W. Anderson, G. Baskaran, P. Coleman, D.L. Cox, C. di Castro, J. Flouquet, P. Fulde, D.I. Khomskii, F. Kromer, G. Kotliar, G.G. Lonzarich, R. Pittini, A.P. Ramirez, B. Schmidt, T. Suzuki, P. Thalmeier, K. Ueda and G. Zwicknagl for stimulating conversations, and C. Lang for her expert preparation of the manuscript. This work was supported by the BMBF grant No. 13 N 6608/1.

References

1. Grewe, N., Steglich, F.: In: Handbook on the Physics and Chemistry of Rare Earths, vol. 14, ed. by Gschneidner, K.A., Jr., & Eyring, L., Amsterdam: Elsevier 1991, p. 343
2. Doniach, S.: Physica **91B**, 2331 (1977)
3. Millis, A.J.: Phys. Rev. B **48**, 7183 (1993)
4. Continentino, M.A.: Phys. Rep. **239**, 179 (1994). Z. Phys. B **101**, 197 (1996)
5. Lonzarich, G.G.: College on Quantum Phases, ICTP Trieste 1994, unpublished
6. Moriya, T., Takimoto, T.: J. Phys. Soc. Jpn. **64**, 960 (1995)
7. Kambe, S., et al.: Physica B **223** & **224**, 135 (1996)
8. von Löhneysen, H.: Physica B **206** & **207**, 101 (1995)
9. Ott, H.R., et al.: Phys. Rev. Lett. **50**, 1595 (1983)
10. Cox, D.L.: Phys. Rev. Lett. **59**, 1240 (1987)
11. Ochiai, A., et al.: J. Phys. Soc. Jpn. **59**, 4129 (1990)
12. Fulde, P., et al.: Europhys. Lett. **31**, 323 (1995)
13. For a recent review, see: Maple, M.B., et al.: J. Phys.: Condens. Matter **8**, 9773 (1996)
14. Saeman, C., et al.: Phys. Rev. Lett. **67**, 2882 (1991)
15. Andraka, B., Tsvelik, A.M.: Phys. Rev. Lett. **67**, 2886 (1991)
16. Amitsuka, H., et al.: Physica B **206** & **207**, 461 (1995)
17. Andraka, B.: Phys. Rev. B **49**, 3589 (1994)
18. Buschinger, B., et al.: Phys. Rev. Lett., in press
19. Andraka, B., Stewart, G.R.: Phys. Rev. B **47**, 3208 (1993)
20. Aronson, M.C., et al.: Phys. Rev. Lett. **75**, 725 (1995)
21. Steglich, F., et al.: J. Low Temp. Phys. **95**, 3 (1994)
22. Cox, D.L.: Physica B **186-188**, 312 (1993)
23. Kim, T.S., Cox, D.L.: Phys. Rev. Lett. **75**, 1622 (1995)
24. Bernal, O.O., et al.: Phys. Rev. Lett. **75**, 2023 (1995)
25. Miranda, E., et al.: Physica B, in press
26. Sachdev, S., et al.: Phys. Rev. B **52**, 10286 (1995)
27. Sengupta, A.M., Georges, A.: Phys. Rev. B **52**, 10295 (1995)
28. Kadowaki, K., Wood, S.B.: Sol. State Commun. **58**, 507 (1986)
29. Zwicknagl, G.: Adv. Phys. **41**, 203 (1992)
30. Aeppli, G., et al.: Phys. Rev. Lett. **57**, 122 (1986)
31. Rossat-Mignod, J., et al.: J. Magn. Magn. Mat. **76** & **77**, 376 (1988)
32. Uemo, K., et al.: J. Phys.: Condens. Matter **8**, 9743 (1996)
33. Grosche, F.M., et al.: Physica B **223** & **224**, 50 (1996)
34. Link, P., et al.: Physica B **223** & **224**, 303 (1996)
35. Thalmeier, P.: Z. Phys. B **95**, 39 (1994)
36. Sun, W., et al.: Z. Phys. B **80**, 249 (1990)
37. Lang, M., et al.: Physica Scripta T **39**, 135 (1991)
38. Bruls, G., et al.: Phys. Rev. Lett. **72**, 1754 (1994)
39. Geibel, C., et al.: to be published
40. Spain, I.L., et al.: Physica B **139** & **140**, 449 (1986)
41. Gegenwart, P.: Dissertation, TH Darmstadt 1997, in preparation
42. Helfrich, R.: Dissertation, TH Darmstadt 1996, unpublished
43. Gegenwart, P., et al.: Physica B **230-232**, 572 (1997)
44. Steglich, F., et al.: In: Physical Phenomena at High Magnetic Fields II, ed. by Fisk, Z., Gor'kov, L., Meltzer, D., Schrieffer, R., Singapore, World Scientific 1996, p. 125
45. Steglich, F., et al.: J. Phys.: Condens. Matter **8**, 9909 (1996)
46. Hellmann, P., et al.: Czech. J. Phys. **46**, Suppl. 5, 2591 (1996)
47. Hellmann, P.: Dissertation, TH Darmstadt 1997, unpublished
48. Langhammer, C., Helfrich, R.: unpublished results
49. Kromer, F., et al.: to be published
50. Fukuhara, T., et al.: J. Phys. Soc. Jpn. **65**, 1559 (1996)
51. Grosche, F.M., et al.: Z. Phys. B, these proceedings
52. Julian, S.R., et al.: J. Phys.: Condens. Matter **8**, 9675 (1996)
53. Ramirez, A.P., et al.: to be published

54. Mayer, H.M., et al.: Phys. Rev. B **33**, 3168 (1986)
55. Knetsch, E.A.: Dissertation, University of Leiden 1993, unpublished
56. Deppe, M.: Diploma Thesis, TH Darmstadt 1997, unpublished
57. The uncertainty in the shape factor of the sample results in an uncertainty of the absolute resistivity by approximately 30%, cf. a previous report on the same sample by: Thomas, F., et al.: J. Low Temp. Phys. **102**, 117 (1996)
58. Rauchschalbe, U., et al.: Europhys. Lett. **1**, 71 (1986)
59. Cox, D.L., Jarrell, M.: J. Phys.: Condens. Matter **8**, 9825 (1996)
60. Aoki, H., et al.: Physica B **230–232**, 698 (1997)
61. Ochiai, A., et al.: Physica B **230–232**, 708 (1997)
62. Fraas, K., et al.: J. Magn. Magn. Mat. **108**, 220 (1992)
63. Ahlheim, U., et al.: J. Magn. Magn. Mat. **108**, 213 (1992)
64. Schmidt, B., et al.: Europhys. Lett. **35**, 109 (1996)
65. Kohgi, M., et al.: Physica B **230–232**, 638 (1997)
66. Anderson, P.W.: preprint (1995)
67. See, e.g.: Mackenzie, A.P., et al.: Phys. Rev. B **53**, 5848 (1996)