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# Are heavy-fermion metals Fermi liquids?

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**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 $Ce_{1-x}La_xRu_2Si_2$ [7] and at $x_c \simeq 0.1$ in $CeCu_{6-x}Au_x$ [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 $Y_{1-x}U_xPd_3$ ($x \simeq 0.2$), more dilute alloys such as $Th_{1-x}U_xRu_2Si_2$ ($x \simeq 0.01$) [16] and $La_{1-x}Ce_xCu_{2.2}Si_2$ ($x = 0.1$) [17,18] as well as an increasing number of disordered systems with intact f-ion sublattice, e.g. $UCu_{5-x}Pd_x$ [19,20], $CePtSi_{1-x}Ge_x$ and $UCu_{4+x}Al_{8-x}$ [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 $\gamma$ and the Pauli-type spin susceptibility $\chi_s$ 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 $\Delta\rho = \rho - \rho_0 = aT^2$ ($\rho_0$: 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 live 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]: $\gamma(T) \sim \ell n(T_0/T)$ 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, $\gamma(T) \sim \ell n(T_0/T)$ was observed in a surprisingly wide pressure range around the critical value $p_c$ = 0.3 GPa ($T_N \to 0$) [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 $Ce_{1+x}Cu_{2+y}Si_{2+z}$ 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-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.

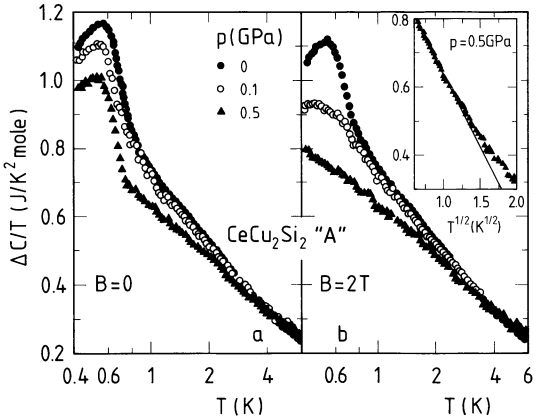


**Fig. 1a,b.** Ce increment to the specific heat, $\Delta C = C_{CeCu_2Si_2} - C_{LaCu_2Si_2}$, as $\Delta C/T$ *vs* $T$ (on a logarithmic scale) for an A-type polycrystal at different pressures for $B$ = 0 **a** and $B$ = 2 T **b**. The inset shows the $p$ = 0.5 GPa results for $T \leq$ 2 K and $B$ = 2 T as $\Delta C/T$ *vs* $T^{1/2}$

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 $\gamma \sim \ell n(T_0/T)$ 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.

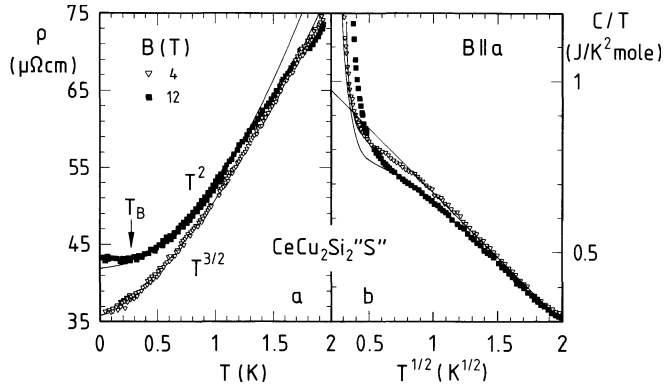


**Fig. 2.** Resistivity $\rho$ *vs* $T$ **a** and specific heat as $C/T$ *vs* $T^{1/2}$ **b** at $B = 4$ and 12 T for an S-type $CeCu_2Si_2$ single crystal. Solid lines indicate $T^{3/2}$ and $T^2$ dependences in **a**, $T^{1/2}$ dependence as well as $C/T$ data after subtraction of nuclear contributions 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**

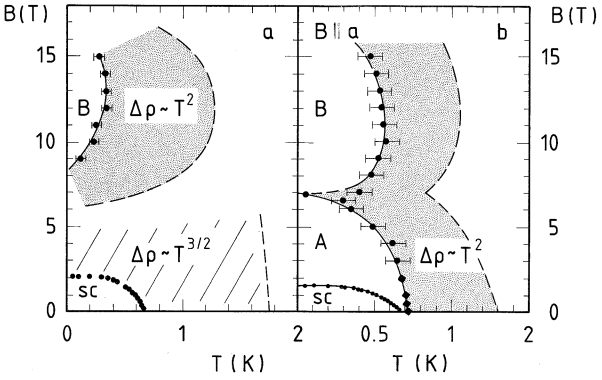


**Fig. 3.** $B$-$T$ diagram, based upon resistivity results, for an S-type $CeCu_2Si_2$ single crystal **a** and an AS-type single crystal **b**. Dashed lines indicate temperature limits of the validity ranges for the $T^{3/2}$ and $T^2$ laws, respectively

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 $B \leq 5\,\mathrm{T}$ can be well described, between $T = 0.02\,\mathrm{K}$ and $T \simeq 1.7\,\mathrm{K}$, by $\Delta\rho = \beta T^{3/2}$. For $B \lesssim 2\,\mathrm{T}$, a low-$T$ superconducting transition occurs. No anomaly related to the A-phase transition can be resolved in this field range. However, for $B > 6\,\mathrm{T}$, $\Delta\rho = aT^2$ with $a \simeq 10\,\mu\Omega\mathrm{cmK}^{-2}$ is the best fit to the data below a field-dependent limiting temperature (cf. Fig. 3a). For $B > 8\,\mathrm{T}$ up to the highest accessible field $B = 15.5\,\mathrm{T}$, 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 $B = 6\,\mathrm{T}$ 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 $B_{c2}(T = 0.02\,\mathrm{K}) < B \leq 5\,\mathrm{T}$ to $\Delta\rho(B) > 0$ (as characteristic for a Landau FL) at $B > 6\,\mathrm{T}$.

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 $T > 0.5\,\mathrm{K}$ only. The two fit parameters (taken at $B = 2\,\mathrm{T}$) slightly exceed those for the A-type polycrystal measured at $p = 0.5\,\mathrm{GPa}$ (Fig. 1). When raising the field, both $\gamma_0$ and $\alpha$ are found to gradually decrease. Upon lowering the temperature to below $T \simeq 0.5\,\mathrm{K}$, $\gamma(T)$ flattens and appears to saturate as $T \to 0$. A detailed analysis of these data is, however, impeded by the steep upturn in $\gamma(T)$ below $T \simeq 0.25\,\mathrm{K}$. 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 $T_B \simeq 0.2\,\mathrm{K}$) is absent in $\gamma(T)$ measured at $B = 12\,\mathrm{T}$. 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, $a \simeq 10\,\mu\Omega\mathrm{cmK}^{-2}$. 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.

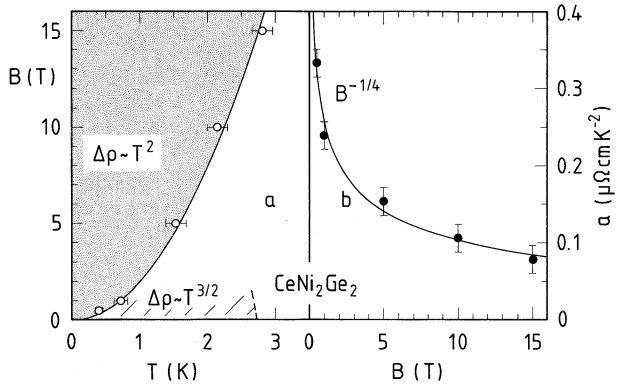


**Fig. 4. a** $B$-$T$ diagram, based upon resistivity results, for a $CeNi_2Ge_2$ polycrystal. Solid line connecting circles and dashed line mark the limits of the $T^2$ and $T^{3/2}$ laws, respectively. **b** Coefficient $a$ of the $\Delta\rho = aT^2$ fit to the low-$T$ data as a function of the external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

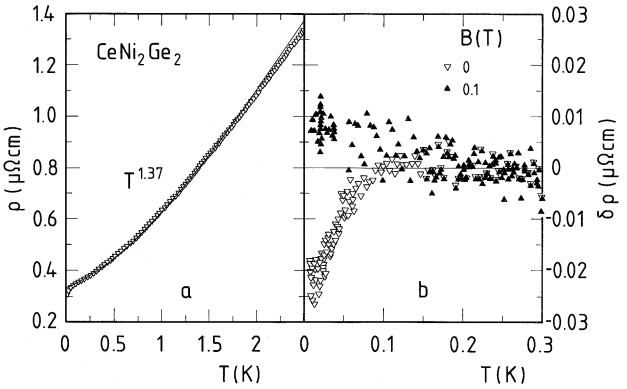


**Fig. 5. a** $\rho$ *vs* $T$ for a high-quality $CeNi_2Ge_2$ polycrystal obeying a $T^{1.37}$ power law (cf. solid line). **b** $\delta\rho = \rho - \rho_0 - \beta T^{1.37}$ *vs* $T$ for the same sample as in **a** below $T = 0.3$ K at $B = 0$ and 0.1 T, respectively

## 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 $\rho_0$ ranging between 1.5 and 2.5 $\mu\Omega$cm, i.e. resistivity ratios $\rho_{300K}/\rho_0$ 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 $T$ ($0.02\,\mathrm{K} \leq T \leq 2.5\,\mathrm{K}$), if $B \leq 1$ 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 $T \gtrsim 0.4$ K indicate such a Landau FL phase to form at $B > 1$ 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, $B \leq 1$ 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 $B \to 0$. 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 $B \gtrsim 1$ 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 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 $T = 28$ K and to a "metamagnetic transition" at $B \simeq 42$ 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 Kadowaki-Wood relation [28] is applied. For example: at $B = 8$ T, $a \simeq 0.12\,\mu\Omega\mathrm{cmK}^{-2}$ is one order of magnitude smaller than that value of $a$ expected from $\gamma \simeq 0.28\,\mathrm{J/K^2mol}$ [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 ($\gamma \simeq 130\,\mathrm{mJ/K^2mol}$) as established under application of $p = 1.7$ GPa, a second-order non-superconducting phase transition takes place at $T_1 = 0.9$ K. The fact that $T_1$ does not change in a field $B = 8$ 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 $T = 0.25$ K at $p = 1.55$ GPa and near $T = 0.45$ K at $p = 2.6$ GPa [51].

In Fig. 5 we show our $\rho(T)$ results *at ambient pressure* for a polycrystalline sample of very high quality ($\rho_0 = 0.33\,\mu\Omega$cm, $\rho_{300K}/\rho_0 \simeq 200$). An attempt to fit a $T^{3/2}$ law to the low-$T$ data proved to be unsuccessful, except for a limited temperature range, $0.1\,\mathrm{K} < T < 0.5\,\mathrm{K}$. Rather these results are well described, for $0.1\,\mathrm{K} \leq T \leq 1.6\,\mathrm{K}$, by $\Delta\rho \sim T^{1.37}$ (Fig. 5a). Note that for the isostructural compound $CePd_2Si_2$ studied near the critical pressure $p_c \simeq 2.8$ GPa ($T_N \to 0$), 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 $\rho_0$ 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

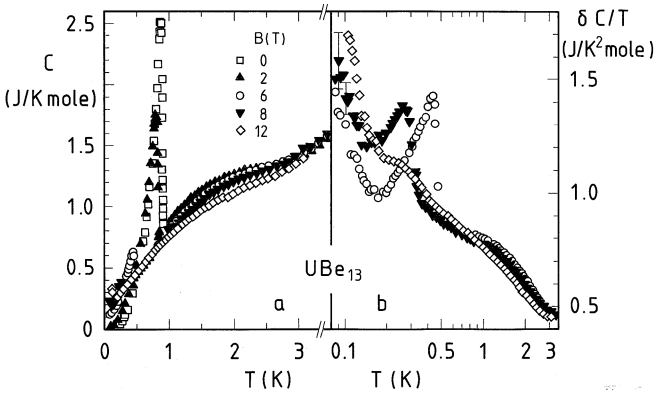


**Fig. 6. a** Specific heat $C$ of a $UBe_{13}$ single crystal as a function of temperature $T$ below $T = 3.5\,\mathrm{K}$ at differing magnetic fields. **b** $\delta C = C - C_{nuclear}$ as $\delta C/T$ *vs* $T$ (on a logarithmic scale) for the same sample as in **a** at $B = 6, 8$ and $12\,\mathrm{T}$,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

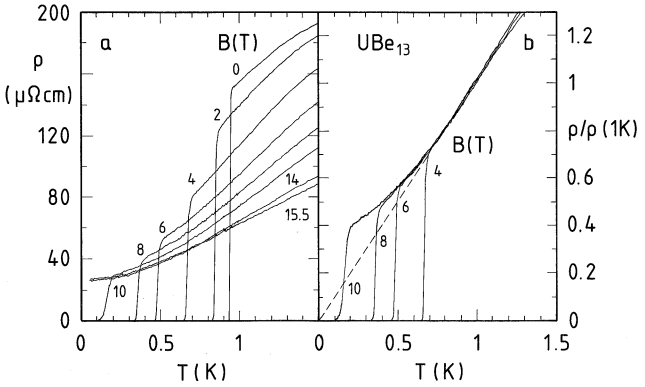


**Fig. 7. a** $\rho$ *vs* $T$ for the same sample as in Fig. 6 at differing magnetic fields. **b** Same data as in **a**, normalized to the respective $\rho$ value at $T = 1\,\mathrm{K}$. Dashed straight line is an extrapolation to $T = 0$ of the data for $T \geq 0.8\,\mathrm{K}$

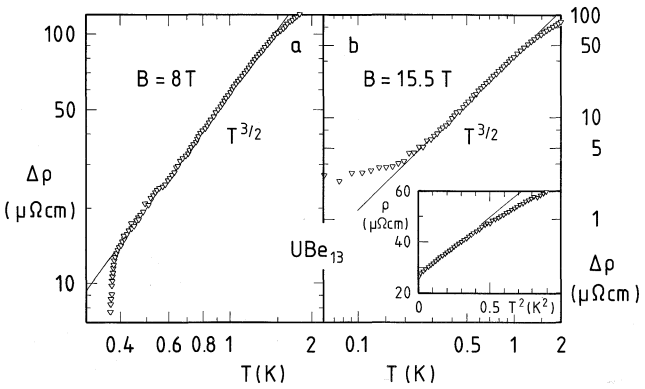


**Fig. 8a,b.** $\Delta\rho = \rho - \rho_0$ *vs* $T$ (on logarithmic scales) for the same sample as in Fig. 6 at $B = 8\,\mathrm{T}$ **a** and $B = 15.5\,\mathrm{T}$ **b**, respectively. Inset shows low-$T$ data of **b** as $\rho$ *vs* $T^2$

anomaly below $T = 0.1\,\mathrm{K}$ 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 $0.1\,\mathrm{T}$ 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" ($T_c = 0.85\,\mathrm{K} - 0.9\,\mathrm{K}$) and "L-type" ($T_c \simeq 0.75\,\mathrm{K}$). 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 ($T_c = 0.9\,\mathrm{K}$). Its specific heat is shown in Fig. 6 for the $T$ range $0.08\,\mathrm{K} \leq T \leq 3.5\,\mathrm{K}$ and at magnetic fields $0 \leq B \leq 12\,\mathrm{T}$ [42]. The n-state specific heat exhibits a broad shoulder around $T = 2\,\mathrm{K}$ (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 $B > 6\,\mathrm{T}$ this shift in entropy towards lower temperatures becomes much more pronounced (Fig. 6b). Note that fields in excess of $8\,\mathrm{T}$ are necessary to completely suppress HF superconductivity in this material. At the highest field $B = 12\,\mathrm{T}$, the specific-heat coefficient $\gamma(T) = \delta C(T)/T$ is roughly proportional to $-\ell nT$ for $T > 0.3\,\mathrm{K}$, 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 $T = 0.2\,\mathrm{K}$. 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 $T \simeq 2\,\mathrm{K}$ is commonly attributed [55] to some magnetic fluctuations. Simultaneous investigations of the thermal expansion show [56] that these "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 $T = 2\,\mathrm{K}$ [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 $B = 14\,\mathrm{T}$ in a wide temperature regime, $T \geq 0.02\,\mathrm{K}$. The minimum value of the residual resistivity as obtained from a $\rho$ *vs* $T^2$ plot (see below) for $B = 14\,\mathrm{T}$ amounts to $\rho_0 \simeq 26\,\mu\Omega\mathrm{cm}$, about $10\,\mu\Omega\mathrm{cm}$ 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 $B < 4\,\mathrm{T}$. For, at fields $4\,\mathrm{T} \leq B \leq 10\,\mathrm{T}$, we are able to scale the various $\rho(T)$ curves within $T_c(B) < T < 1.2\,\mathrm{K}$ to a universal curve, i.e. by normalizing $\rho(T)$ by its respective value at $T = 1\,\mathrm{K}$ (Fig. 7b): Above $T = 0.7\,\mathrm{K}$, a linear $\rho(T)$ dependence is found, that can be extrapolated to $\rho \simeq 0$ (as $T \to 0$), while $\rho$ *vs* $T$ becomes superlinear at lower temperatures.

As is demonstrated in Fig. 8a for the $B = 8\,\mathrm{T}$ data, $\Delta\rho(T)$ can be well fitted between $T_c \simeq 0.4\,\mathrm{K}$ and $T \simeq 1\,\mathrm{K}$ by a $T^{3/2}$ law. The latter holds true even up to the highest field, $B = 15.5\,\mathrm{T}$ (Fig. 8b). However, at $B = 14\,\mathrm{T}$ as well as 15.5 T, the data for $T \leq 0.4\,\mathrm{K}$ 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 $B < 14\,\mathrm{T}$ 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 $B < 14\,\mathrm{T}$, 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: $B_0 \simeq 6\,\mathrm{T}$ ($CeCu_2Si_2$) and $B_0 \simeq 1\,\mathrm{T}$ ($CeNi_2Ge_2$). 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 $a = 52\,\mu\Omega\mathrm{cmK}^{-2}$ (14 T) to $a = 45\,\mu\Omega\mathrm{cmK}^{-2}$ (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 ($I\bar{4}3d$), 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 $Yb^{2+}$:$Yb^{3+} = 3 : 1$. Upon cooling to below $T_s = 293\,\mathrm{K}$, $Yb_4As_3$ 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 $< 111 >$ 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 $a \simeq 0.75\,\mu\Omega\mathrm{cmK}^{-2}$, suggesting HLFL behavior [11]. Using $\gamma = C/T \simeq 0.2\,\mathrm{J/K^2mol}$ as taken at $T \gtrsim 0.5\,\mathrm{K}$ (Fig. 9a), the Kadowaki-Wood scaling between $a$ and $\gamma^2$ [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 $Yb_4(As_{1-x}Sb_x)_3$ 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 concentration, the specific heat at $T \gtrsim 0.5\,\mathrm{K}$ does hardly change (Fig. 9a). Similarly, the low-$T$ susceptibility was found to be rather insensitive against doping [60,61].

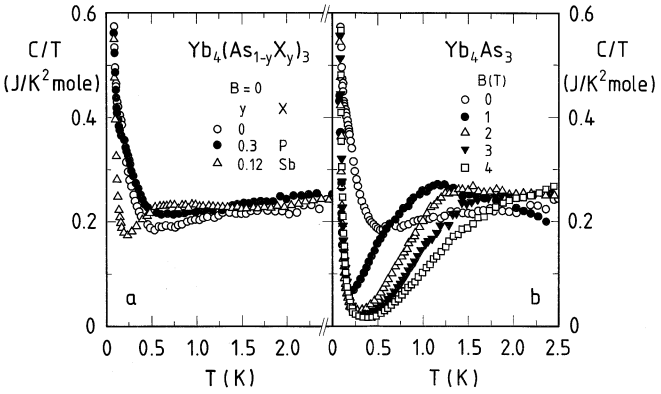


**Fig. 9.** Specific heat as $C/T$ *vs* $T$ for $Yb_4As_3$, $Yb_4(As_{0.7}P_{0.3})_3$ and $Yb_4(As_{0.88}Sb_{0.12})_3$ at $B = 0$ **a** and for $Yb_4As_3$ at differing magnetic fields **b**

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 $T \simeq 0.15\,\mathrm{K}$, we state a strong reduction of the $\gamma$ value. The additional $\gamma$ depression by fields $B > 1\,\mathrm{T}$ 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 $B = 1\,\mathrm{T}$ to 2.2 K at $B = 4\,\mathrm{T}$ [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 $\rho_0$ 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, $\gamma$ remains unaffected upon further depletion of the charge carriers. Even higher $\gamma$ 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 $< 111 >$. 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 $q \to \pi/d$, $d$ being the atomic separation within the Heisenberg chains) explains quite naturally the $\gamma T$ term dominating the specific-heat for temperatures sufficiently high so that the material behaves quasi-onedimensionally. From the measured $\gamma$ value of $0.2\,\mathrm{J/K^2mol}$ (Fig. 9) an intrachain exchange-coupling constant (or magnon band width) $\mathrm{J} \simeq k_B \cdot 25\,\mathrm{K}$ 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 $T = 0.2\,\mathrm{K}$ [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 $\epsilon$ in the power law for the resistivity, $\rho = \rho_0 + \beta T^{\epsilon}$, on its residual value $\rho_0$, 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 $Yb_4As_3$.

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