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MAGNETORESISTANCE OF Ce-BASED KONDO LATTICES: $CeCu_2Si_2$ AND $CeAl_3$

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The magnetoresistance $\Delta\rho(B)$ of $CeCu_2Si_2$ samples with different stoichiometry and of a $CeAl_3$ polycrystal has been measured at low temperatures and high magnetic fields A change of sign in $\Delta\rho$ marks the formation of a coherent low-temperature state, which can be destroyed by a magnetic field or by disorder in the lattice

Many properties of Kondo lattices displaying heavy-fermion behaviour [1] are very similar to those of dilute Kondo alloys like *Cu*Fe or *Cu*Cr [2], such as the susceptibility, the high-temperature resistivity and the electronic specific heat Hence, an important question concerning the investigation of Kondo-lattices is, whether these systems behave merely as concentrated Kondo-alloys, or if the periodic arrangement of the scattering centers introduces new features characteristic for the lattice Such a characteristic feature of the Kondo lattice not observed in dilute alloys is the low-temperature maximum in the electrical resistivity [3,4] It is usually ascribed to the onset of coherent scattering Besides this, Bredl et al [5], discovered a maximum in the specific heat coefficient γ near 0 4 K for both $CeCu_2Si_2$ and $CeAl_3$ This result was interpreted as an indication for a coherent narrow 4f-band (quasiparticle band) at the Fermi level, that is formed in the Kondo lattice at low temperatures [6]

The transition between incoherent and coherent scattering is also reflected in the temperature dependence of the magnetoresistivity $\Delta\rho = \rho(B) - \rho(0)$ In dilute systems, $\Delta\rho$ is negative at all temperatures [7] On the other hand, in $CeAl_3$ the negative $\Delta\rho$ that is observed above 1 K changes sign at very low temperatures [8,9] This change of sign was explained by the formation of a 4f-derived conduction band Similar behaviour of the magnetoresistance has later also been reported for $CeCu_2Si_2$ [10,11], but it was not clear, whether the observed change of sign in $\Delta\rho$ was an intrinsic effect, or was caused by non-transformed Ce^{3+} ions ("magnetic impurities") [10]

Therefore, we have performed a systematic investigation of the magnetoresistivity $\Delta\rho$ of a number of $CeCu_2Si_2$ polycrystals with varying Cu-content, ranging from $CeCu_{1\,8}Si_2$ to $CeCu_{2\,2}Si_2$ In agreement with [12] the properties of the samples depend strongly on their Cu-content the superconducting transition temperature varies smoothly from 250 mK ($CeCu_{1\,8}Si_2$) to 740 mK ($CeCu_{2\,2}Si_2$) The residual resistivity varies from $\rho_0 = 100$ μΩ cm in $CeCu_{1\,8}Si_2$ to 1 5 μΩ cm in an annealed sample of $CeCu_{2\,2}Si_2$, which is to our knowledge the smallest ρ_0-value ever measured in this compound A single crystal which was grown from a melt with composition $CeCu_{2\,2}Si_2$ was also studied ($T_c = 690$ mK, $\rho_0 = 10$ μΩ cm) For comparison, a $CeAl_3$ polycrystal was studied as well

The experiments were performed in a ^3He–^4He dilution refrigerator in magnetic fields up to 8 T The current through the sample was parallel to the field AC-resistances were measured continuously, while the field was swept Some samples were also studied up to fields of 35 T in a pulsed magnetic field at 1 5 and 4 2 K [14]

The results up to $B = 8$ T for four selected $CeCu_2Si_2$-samples are displayed in figs 1 and 2 At 4 2 K, $\Delta\rho(B) = \rho(B) - \rho(0)$ is negative for all samples, in agreement with previous observations [10,11] Typical values for $\Delta\rho/\rho(0)$ are 1–2% at $B = 8$ T The 4 2 K-results resemble those on

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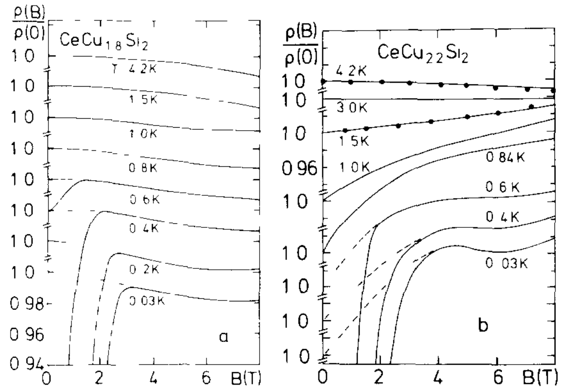

Fig 1 Resistivity in magnetic fields, $\rho(B)$, normalized to the zero-field value $\rho(0)$ for unannealed $CeCu_{1.8}Si_2$ (a) and $CeCu_{2.2}Si_2$ (b)-samples Dashed lines are extrapolations to $B=0$, assuming that $\rho(T, B=0)$ follows a T^2-law Dots in (b) are results of high-field experiments on the same sample (see fig 3) Absolute values of $\rho(B=0)$ are $\rho_{4.2K} = 140\ \mu\Omega\,cm$, $\rho_0 = 100\ \mu\Omega\,cm$ in (a) and $\rho_{4.2K} = 80\ \mu\Omega\,cm$, $\rho_0 = 20\ \mu\Omega\,cm$ in (b)

dilute Kondo systems [7] and, hence, represent the regime where the Ce-ions behave as independent, incoherent Kondo ions In the case of the unannealed $CeCu_{1.8}Si_2$-sample in fig 1a [15], this negative $\Delta\rho$ is found down to 30 mK, implying that no qualitative change in this incoherent scattering from the Kondo-ions in the Cu-deficit sample takes place

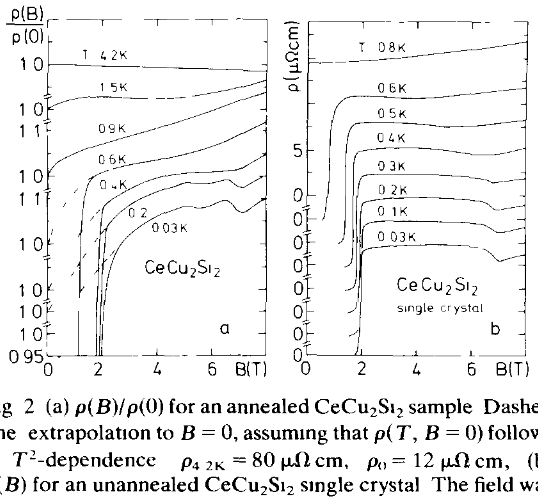

Fig 2 (a) $\rho(B)/\rho(0)$ for an annealed $CeCu_2Si_2$ sample Dashed line extrapolation to $B=0$, assuming that $\rho(T, B=0)$ follows a T^2-dependence $\rho_{4.2K} = 80\ \mu\Omega\,cm$, $\rho_0 = 12\ \mu\Omega\,cm$, (b) $\rho(B)$ for an unannealed $CeCu_2Si_2$ single crystal The field was applied perpendicular to the tetragonal c-axis

In all the other samples, the magnetoresistance changes sign and becomes positive between 4 2 and 1 K (figs 1b and 2) The temperature at which this happens increases with increasing T_c and decreasing ρ_0, tracking the dependence of the position of the $\rho(T)$-maximum at 10–25 K [3] Apart from additional anomalies in $\Delta\rho$ around 6–7 T, to which we will return later, the $\rho(B)$-dependence is especially strong at small fields, with a tendency to saturate at $B \approx 8$ T Typical values for $\Delta\rho$ are a few $\mu\Omega\,cm$ at $T \to 0$ and $B = 8$ T, corresponding to variations between a few % and 100%, depending on the residual resistivity The fact that this positive $\Delta\rho$ can be destroyed by a Cu-deficit leads one to conclude that it is, indeed, a phenomenon that requires the periodicity of the lattice We would, therefore, follow the explanation given in refs [8,9] for $CeAl_3$ that, at sufficiently low temperatures, a coherent 4f-band is formed which does then cause a usual metallic (positive) $\Delta\rho$

Fig 3 shows the high-field results on the Cu-excess sample of fig 1b, and on a $CeCu_{1.9}Si_2$-sample In agreement with the above results, $\Delta\rho$ of the Cu-deficit sample is negative at 1 5 and 4 2 K For $CeCu_{2.2}Si_2$ on the other hand, $\Delta\rho$ at 1 5 K is

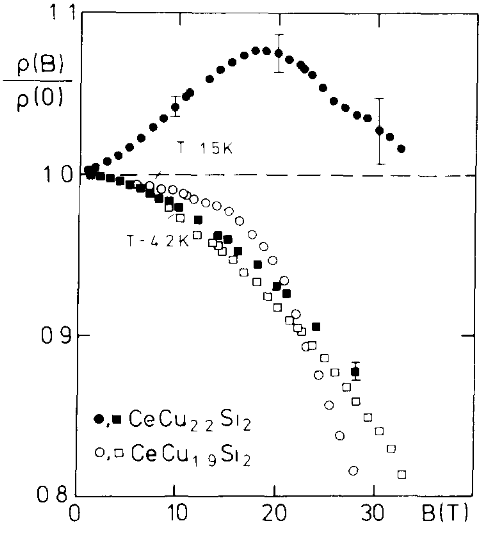

Fig 3 High-field results of $\rho(B)/\rho(0)$ for an unannealed $CeCu_{1.9}Si_2$ sample (open symbols) and for the $CeCu_{2.2}Si_2$ sample of fig 1b (full symbols)

positive, but passes through a maximum at $B = 20\,T$ Thus, it appears that the low-temperature coherent state evidenced by the positive $\Delta\rho$ can be affected by a high magnetic field Interestingly enough, the heavy-fermion compound UPt_3 shows a very similar behaviour [16,17], i e a change of sign in $\Delta\rho$ (near 14 K), and a maximum in the low-T magnetoresistivity near 20 T

We will now return to the additional anomaly in the $\rho(B)$-curves of high-quality $CeCu_2Si_2$ samples near 6–7 T it shows up as a shallow dip in the results for the $CeCu_{2\,2}Si_2$ polycrystal in fig 1b, as a sharp minimum in the results of the single crystal in fig 2b, and even as a double-structure in the case of the stoichiometric polycrystalline sample in fig 2a With increasing temperature, the feature broadens and shifts towards smaller magnetic fields, to become invisible at temperatures above 0 5 K Since this characteristic temperature is close to that of the maximum in the specific heat coefficient $\gamma(T) = C(T)/T$ (0 4 K [5]) and of the change of sign in the thermopower $S(T)$ [18], we propose to explain the novel anomalies in $\rho(B)$ by the same type of reasoning employed to explain the $\gamma(T)$ and $S(T)$ anomalies, namely by assuming a coherence-derived pseudo-gap in the heavy-fermion density of states (DOS) near E_F, on an energy-scale k_B 1 K [5,13] It is plausible to assume that, when the magnetic energy is comparable to the energy scale of the fine structure in the DOS, anomalies will show up in the resistivity on this magnetic field scale Thus, the observed minimum in $\Delta\rho(B)$ is proposed to be another signature of coherence effects in the Kondo lattice $CeCu_2Si_2$ This conclusion is further supported by the fact that the $\Delta\rho(B)$-minimum is most pronounced in high quality samples

Because of the similarities that are found in the specific heats and thermopowers of $CeAl_3$ and $CeCu_2Si_2$ [18], we have also studied a $CeAl_3$-sample Clearly, the results in fig 4 show no anomaly like the one in fig 2 In agreement with [8,9], $\Delta\rho$ is negative above 1 K We do, however, not observe a monotonously positive $\Delta\rho$ at low-temperatures, but rather a positive peak near 2 T Above $B \approx 3\,T$, $\Delta\rho$ is negative at all temperatures This is possibly related to the fact that we have measured the longitudinal magnetoresistance $I \parallel B$, while the results in ref [9] are obtained with $I \perp B$ At $T \geqq 1\,5\,K$, a distinct anisotropy between the two configurations is reported in ref [9]

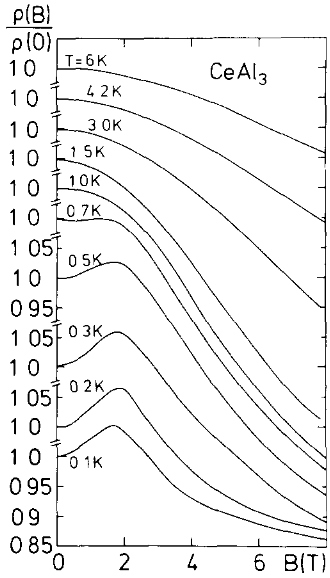

Fig 4 $\rho(B)/\rho(0)$ for a $CeAl_3$ polycrystal, (sample no 2 in ref [13]) $\rho_0 = 5\,\mu\Omega\,cm$

The peak in $\Delta\rho$ at 2 T has probably the same origin as the one found in $CeCu_2Si_2$ at 20 T, implying that the characteristic field scale in $CeAl_3$ is significantly smaller This may be the reason, why nothing equivalent to the "7 T-anomaly" in $CeCu_2Si_2$ is found in $CeAl_3$

To summarize, a change of sign of the magnetoresistance is observed in $CeAl_3$ and $CeCu_2Si_2$ In contrast to an earlier speculation [10], this feature is probably an intrinsic effect for *both* compounds and marks the formation of a coherent low-temperature state that can be destroyed by a sufficiently high magnetic field and by introducing disorder into the lattice It is, therefore, another typical property of the Kondo *lattice* An additional anomaly below 0 5 K in $\rho(B)$ of $CeCu_2Si_2$, which has no analogy in $CeAl_3$ may be considered another indication of a pseudo-gap structure in the heavy-fermion density of states that has been inferred from specific heat and thermopower data

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