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HALL EFFECT IN THE HEAVY FERMION SYSTEMS $CeCu_6$ AND UBe_{13}

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The Hall effect in both UBe_{13} and $CeCu_6$ becomes very large at low temperature showing, with the resistivity and specific heat, the transition into the heavy fermion state. The Hall constant of $CeCu_6$ changes sign, on cooling into the coherently scattering regime.

Heavy fermion systems [1,2] have a large density of states at the Fermi level, as indicated by their enormous low temperature specific heats. The origin of this narrow (of order 10 K) peak is a many-body Abrikosov–Suhl resonance, as occurs for Kondo impurities and/or the hybridization of a very narrow f level with a d band. Surprisingly, these systems can be superconducting, as well as magnetically ordered, or unordered. Previous studies of the Hall effect in the heavy fermion systems, $CeCu_2Si_2$, $CeAl_3$ and UB_{13} have shown a positive Hall constant, R_H, which increases to a very large value, without a sign change, with decreasing temperature. [2–6]. For $CePd_3$, which is not extremely heavy, R_H is large and positive above 10 K, but is negative below [6].

The purpose of this study is to see if the Hall effect of superconducting UBe_{13} [7] and normal $CeCu_6$ [8] shows behavior characteristic of the heavy fermion state and the transition into that state. $CeCu_6$ has similar electrical resistivity [9–12] to $CeAl_3$, the first known heavy fermion compound [13]. On cooling from room temperature, the resistivity of $CeCu_6$ rises, as in a Kondo impurity system, where all impurities scatter incoherently (fig. 1). However, below 10 K it drops rapidly to a low value, in contrast to the behavior of Kondo impurity systems. This observation has led to the suggestion that $CeAl_3$ and $CeCu_6$ are periodic Kondo lattices with all of the Ce ions scattering coherently at low temperature.

The temperature dependence of the Hall constant and the resistivity, ρ, have remarkably similar shape when drawn with a zero shift as in fig. 1. Our major new result is that the Hall constant, R_H, of $CeCu_6$ is slightly positive at room temperature, rises to a large positive peak and then changes sign going strongly negative as the scattering changes from incoherent to coherent and

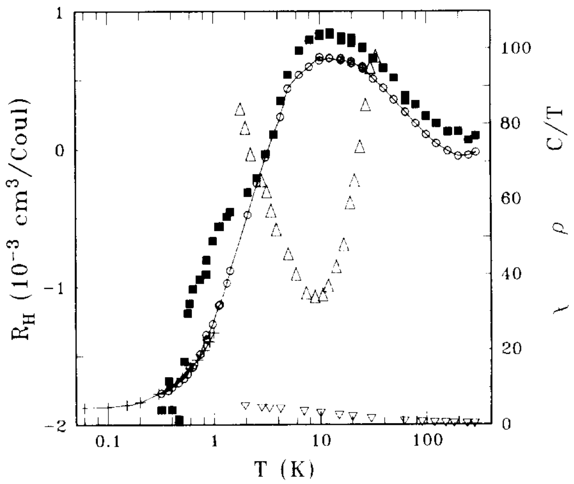

Fig. 1. Hall coefficient, ■; resistivity, -o-, (10^{-6} Ω cm); C/T, △, (10^{-2} J/mol K^2); susceptibility, ▽ (10^{-2} emu/mol); vs. temperature for $CeCu_6$. Resistivity, +, from ref. [11], divided by 1.6 to match our sample. C/T from ref. [8].

ρ approaches a constant small value. The linear temperature dependence of R_H below 1 K is shown in fig. 2 for a second similar sample. The Hall results on a $CeCu_6$ single crystal of ref. [14] show a small positive Hall constant at room temperature, which rises monotonically to a large value at the lowest temperature measured, about 4 K. This behavior is similar to ours above 20 K, but there is no peak and no sign change.

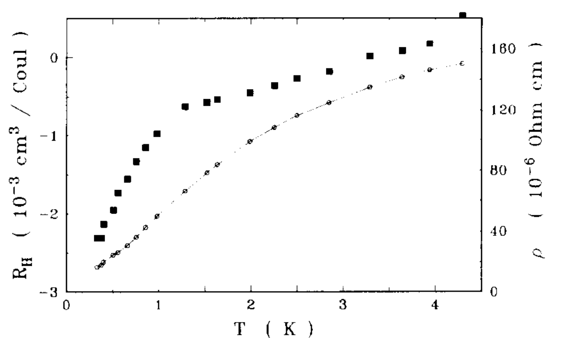

Fig. 2. Hall coefficient, ■, and resistivity, -o-, vs. temperature for a second $CeCu_6$ sample.

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The reason for this difference may be that our samples (and those of refs. [11] and 12]) have considerably lower resistivities at low temperature than those of ref. [9], and may therefore be closer to the 'coherent regime. For comparison, R_H of $CeAl_3$ increases positively to a large value at 2 K, where ρ is large, but was not measured in the very low temperature coherent regime [5].

The electronic (linear) contribution to the specific heat is normally determined from a plot of C/T vs. T^2. For $CeCu_6$, such a plot [8] is linear between about 10 K and 30 K with an intercept of about 250 mJ/mol K^2. As the temperature decreases below 8 K, C/T (from ref. [8], replotted in fig. 1) shows a sharp rise. According to ref. [11], C/T = 1530 mJ/mol K^2 between 0.1 and 0.5 K and is slighly higher at 1.0 K. The C/T results of ref. [15] are in general agreement with these. For comparison Cu has a C/T value of less than 1 mJ/mol K^2. These results indicate that $CeCu_6$ is already very heavy at 30 K in the region where ρ and R_H are increasing with decreasing T, showing increasing incoherent scattering. The transition from incoherent to coherent scatttering which occurs below 10 K, correlates with the strong increase in C/T.

UBe_{13} makes an interesting comparison with $CeCu_6$. The resistivity of UBe_{13} also rises as T decreases from room temperature. (fig. 2). It reaches a shoulder around 20 K, then below 4 K rises slightly to a small peak at 2 K. Below this peak, the decrease in ρ may indicate the onset of coherent scattering, as in $CeCu_6$. However, before a small ρ is reached, the sample becomes superconducting at 0.9 K [7]. The Hall constant is positive at room temperature T and increases with decreasing T. At 4 K, the rate of change increases sharply as the extreme heavy regime is entered. R_H peaks at about 1.5 K, below the resistivity peak, then decreases by about 20% before superconductivity sets in. One wonders if R_H would go strongly negative and ρ would tend smoothly to a low value, as in $CeCu_6$, had superconductivity not occurred first. Our Hall results are in agreement with the previous ones [4] at the temperatures reported (100, 4.2, 3, 1.9 K).

The specific heat of UBe_{13}, is nearly linear between 12 K and 7 K, with C/T about 150 mJ/mol K^2. [7]. However, between 4 and 0.9 K, C/T increases to 800 mJ/mol K^2. Like $CeCu_6$, UBe_{13} goes from moderately heavy to extremely heavy, where C is not linear with T. Both C/T and χ should be very large for $T < T_F$ if T_F is very small. However, C/T shows the onset of the heavy fermion regime more clearly than χ (figs. 1 and 3) because χT is already large at high temperature in the local moment regime.

In magnetic systems, the Hall resistivity [16] may be written as $\rho_h = R_o B + R_s 4\pi M$. Here R_o and R_s are the ordinary and spontaneous Hall coefficients. In paramagnetic systems, $R_H = R_o + R_s 4\pi\chi^*$ where $\chi^* = \chi/(1+4\pi\chi)$. If skew scattering dominates both ρ and R_s, then R_s is proportional to ρ. For side jump scattering, R_s is proportional to ρ^2. These relations are not obeyed for either system.

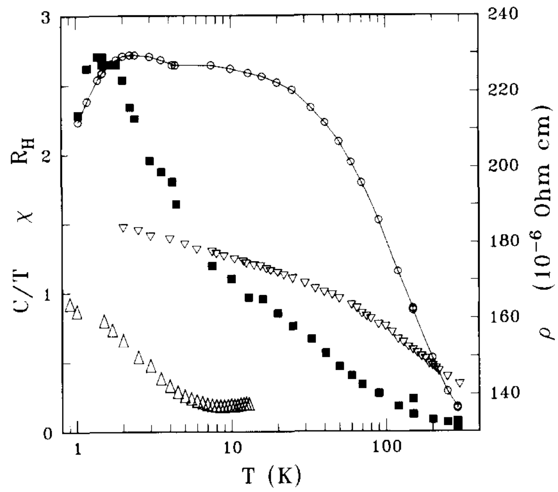

Fig. 3. Hall coefficient, ■, (10^{-2} cm^3/C); resistivity, -o-; C/T, △, (J/mol K^2); susceptibility, ▽ (10^{-2} emu/mol); vs. temperature for UBe_{13}. C/T and susceptibility from ref. [7].

The Hall effect for the Kondo lattice and mixed valence has been treated in the incoherent regime as a collection of indepenent resonant scatterers. [17]. The resonant levels at the Fermi energy causes skew scattering [18], resulting in a large anomalous Hall constant, R_s, which may change sign with temperature. This single impurity approach does not apply to the coherent regime.

It has been suggested [2,4,5] that a two band model with light and heavy bands could explain the large Hall effect in $CeAl_3$ and UBe_{13}. Sharp structure in the density of states, suggested to explain the strongly temperature dependent specific heat and thermopower in Kondo lattices [19] could also cause R_o to change rapidly with temperature.

Hall and resistivity measurements were made on two samples of each system, with essentially the same results. The preparation and properties of the UBe_{13} single crystals are described in ref. [7]. The $CeCu_6$ was cooled slowly from the melt in a Ta crucible. Our sample, a large grain polycrystalline disk, showed some anisotropy in the susceptibility. The χ data in fig. 1 is for the field in the plane of the disk, the direction with the largest χ. The Hall measurements were made with the field perpendicular to the disk.

In conclusion, the first Hall measurements on a heavy fermion system, $CeCu_6$, showing the transition to the coherently scattering regime, have been made. On cooling from the incoherently scattering high resistivity region to the low resistivity region, the Hall constant changes from strongly positive to strongly negative. In both systems studied, the behavior of ρ and R_H are correlated with the transition into the heavy fermion state, as determined by C/T.

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