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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$_2$Si$_2$, 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, $\rho$, 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 $\rho$ 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.
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 $\rho$ 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 slightly higher at 1.0 K. The $C/T$ results of
ref. [15] are in general agreement with these. For com-
parison 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 $\rho$ and $R_H$ are increasing
with decreasing $T$, showing increasing incoherent
scattering. The transition from incoherent to coherent
scattering 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 $\rho$ may indicate the
onset of coherent scattering, as in CeCu$_6$. However,
before a small $\rho$ is reached, the sample becomes super-
conducting 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 $\rho$ would tend
smoothly to a low value, as in CeCu$_6$, had superconduc-
tivity not occurred first. Our Hall results are in agree-
ment 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 $\chi$ 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 $\chi$ (figs. 1 and
3) because $\chi T$ is already large at high temperature in
the local moment regime.

In magnetic systems, the Hall resistivity [16] may be
written as $\rho_H = R_H B + R_A 4\pi M$. Here $R_A$ and $R_H$
are the ordinary and spontaneous Hall coefficients. In para-
magnetic systems, $R_H = R_0 + R_A 4\pi \chi^*$ where $\chi^*$
= $\chi/(1 + 4\pi \chi)$. If skew scattering dominates both $\rho$
and $R_A$, then $R_A$ is proportional to $\rho$. For side jump scatter-
ing, $R_A$ is proportional to $\rho^2$. These relations are not
obeyed for either system.

The Hall effect for the Kondo lattice and mixed
valence has been treated in the incoherent regime as a
collection of independent resonant scatterers. [17]. The
resonant levels at the Fermi energy causes skew scatter-
ing [18], resulting in a large anomalous Hall constant,$R_A$,
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 tem-
perature dependent specific heat and thermopower in
Kondo lattices [19] could also cause $R_A$ to change
rapidly with temperature.

Hall and resistivity measurements were made on two
samples of each system, with essentially the same res-
ults. 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 $\chi$ data in fig. 1 is
for the field in the plane of the disk, the direction with
the largest $\chi$. 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 $\rho$ and $R_H$
are correlated with the transition into the heavy fermion
state, as determined by $C/T$.  

![Fig. 3. Hall coefficient.](image)
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