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Hall effect measurements in the heavy-fermion system $CeCoIn_5$

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Abstract

Hall effect measurements have been conducted on high-quality single crystals of the heavy-fermion superconductor $CeCoIn_5$. The anomalous Hall contribution is negligible in the investigated temperature range from 0.05 to 5 K. The measured Hall resistivities ρ_{xy} show a noticeable change in slope between the low-field (initial Hall coefficient) and the high-field region. In the superconducting regime, $T<2.3$ K, Hall measurements are restricted to high magnetic fields $H>H_{c2}$, the upper critical field of superconductivity. The high-field Hall coefficient is almost constant for temperatures down to 250 mK. At $T\leqslant 250$ mK, an additional change in curvature of ρ_{xy} vs. H is observed.

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Keywords: Superconductivity; Heavy fermion compound; $CeCoIn_5$

In the Ce-based compounds $CeMIn_5$ ($M = Co, Rh, Ir$), the f electrons are subject to a competition of the RKKY interaction and the Kondo effect. Whereas the former one favors long-range magnetic order (typically antiferromagnetic), in the latter case the conduction electrons quench the magnetic moment of the localized f electrons giving rise to a heavy fermion (HF) state below the so-called coherence temperature T^*. This results in the well-known phase diagram by Doniach [1]. At the point where the two energy scales match, a quantum critical point (QCP) is expected. However, superconductivity often emerges in the vicinity of this critical point [2]. Therefore, these materials are ideally suited to study the mutual interplay of magnetic fluctuations and superconductivity.

The tetragonal crystal structure of $CeMIn_5$ can be thought of as a sequence of $CeIn_3$ and MIn_2 layers stacked along the *c*-axis. Even though the material cannot be regarded as truly two-dimensional (2D) this structural anisotropy certainly influences the magnetic and superconducting properties. As one likely consequence [3], the superconducting transition temperature of $CeCoIn_5$ is enhanced (with respect to the cubic parent compound $CeIn_3$) to $T_c = 2.3$ K [4], the highest value among the Ce-based HF systems known to date. Another consequence of the layered crystal structure may be anisotropic spin fluctuations near magnetic ordering as seen in NQR experiments [5,6]. Transport and specific heat experiments [7] also point at the existence of a field-induced QCP in $CeCoIn_5$ with the antiferromagnetic ground state superseded by superconductivity. Moreover, measurements of the de Haas–van Alphen (dHvA) effect in $CeCoIn_5$ revealed essentially two Fermi surfaces (FS) of quasi-2D character [8,9]. Accordingly, band structure calculations for $CeMIn_5$ ($M = Co, Ir$) mainly show a roughly cylindrically shaped FS of electron character and a complicated hole-like FS [8,10]. These investigations on $CeCoIn_5$ also reveal that the electron and hole FS volumes match and hence, this material is a (nearly) compensated metal.

Recently, Hall effect measurements have proven useful in studying HF materials close to a QCP [11]. Therefore, we investigated the Hall effect of high-quality single crystalline $CeCoIn_5$. Six contacts were spot-welded to samples of about $1 \times 1 \times 0.07\,mm^3$, the latter dimension

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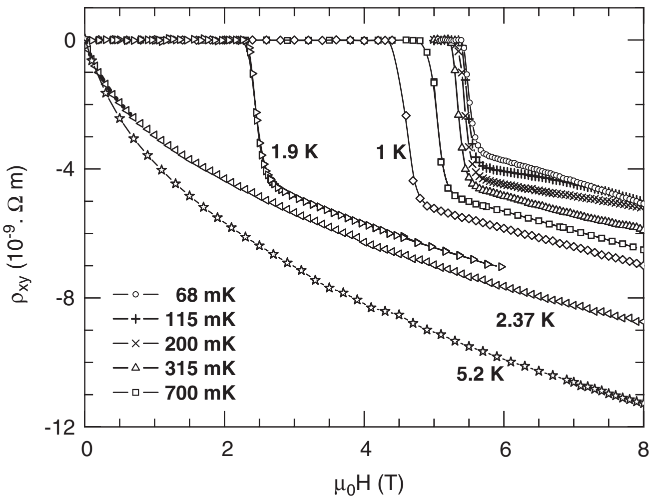

Fig. 1. Isothermally measured Hall resistivity of $CeCoIn_5$ for selected temperatures. Superconductivity at low temperatures and field-dependent Hall coefficients can be well recognized.

being parallel to the c-axis and to the applied magnetic field. Isothermal field sweeps were conducted at temperatures down to 0.05 K and the Hall voltage was obtained as the asymmetric contribution under field reversal. The symmetric contribution (much smaller than the asymmetric one for well-aligned contacts) was compared to the simultaneously measured transversal magnetoresistance as a consistency check. The results of Hall measurements at selected temperatures are shown in Fig. 1. Our Hall resistivity data ρ_{xy} can favorably be compared to those reported for temperatures down to 2 K [12] and 1 K [13].

The Hall coefficient $R_H = \rho_{xy}/\mu_0 H = R_0 + R_a$ is composed of the normal contribution R_0 (related to the FS topology) and the anomalous part usually ascribed to skew scattering. In an impurity model [14], $R_a \propto \rho\chi$ where ρ is the magnetic contribution to the electrical resistivity and χ is the magnetic susceptibility. In the coherent regime of HF metals, however, an impurity model is not applicable, rather it was argued [15] based upon an Anderson lattice model that $R_a \propto \chi$. Therefore, R_a usually assumes a positive maximum at around T^* and dominates R_H but drops rapidly at low temperatures. In $CeCoIn_5$, T^* is estimated to about 40 K (cf. also Refs. [4,12]). The facts that (i) such a maximum is not observed and (ii) the investigated temperature range of Fig. 1 is well below T^* substantiate a negligible contribution of R_a to R_H in our case [12,13]. This claim was reinforced [12] by comparing to results obtained from isostructural $LaCoIn_5$. Hence, R_0 mainly probes the FS of $CeCoIn_5$ at low temperatures. The above-mentioned properties of the FS of $CeCoIn_5$, however, complicate an analysis substantially. In case of multiple bands residing at the FS, the net R_H is determined by a mobility-weighted (and hence, carrier mass dependent) sum of the band contributions.

As seen from Fig. 1, $\rho_{xy}(H)$ shows a considerable change in slope at all temperatures. This holds even true for $T < T_c$ as any reasonable extrapolation of the high-field data would *not* intercept the origin of the ρ_{xy} vs. H plot without distinct change of R_H. Often, the initial Hall coefficient $R_H^0 = \lim_{H\to 0} R_H$ is analyzed. In our case, however, this is complicated (i) by the onset of superconductivity at a critical field $H_{c2}(T)$ and (ii) in a multi-band material R_H^0 also depends on the individual-band mobilities. The Hall coefficient in the high field limit, $R_H^\infty = \lim_{H\to\infty} R_H$, on the other hand, is difficult to obtain in our maximum field of 8 T: we estimate $\omega_c\tau \approx 3$ at 8 T (ω_c: cyclotron frequency, τ: average time between scattering). Nonetheless, if we take the values at maximum field we obtain a constant value of $R_H^{8\,T} \approx -6 \times 10^{-10}\,m^3/C$ for $T \geqslant 300$ mK. Only at 5.2 K, $R_H^{8\,T}$ is slightly increased most likely due to the fact that the high-field limit is not yet reached. We interpret this as a constant effective carrier concentration in the considered temperature range. The decrease in R_H^0 with falling temperature could then be thought of as a change of the individual-band mobilities. Considering the values of ρ_{xy} for $T < T_c$ and $H > H_{c2}$ one might even speculate this process to continue if it was not masked by superconductivity. Note that dHvA [8] shows a field-dependent effective carrier mass which may also contribute to the field dependence of R_H.

At $T \leqslant 250$ mK, we find marked deviations from the behavior at higher T, which we believe to be related to an onset of Fermi liquid behavior [7]. Here, further detailed research is in progress.

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