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Hall effect measurements in the heavy-fermion system CeCoIn₅

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Abstract

Hall effect measurements have been conducted on high-quality single crystals of the heavy-fermion superconductor CeCoIn₅. The anomalous Hall contribution is negligible in the investigated temperature range from 0.05 to 5 K. The measured Hall resistivities 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 > Hₐc, the upper critical field of superconductivity. The high-field Hall coefficient is almost constant for temperatures down to 250 mK. At T < 250 mK, an additional change in curvature of rᵧ vs. H is observed.

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In the Ce-based compounds CeMIn₅ (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 CeMIn₅ can be thought of as a sequence of CeIn₃ and MIn₂ 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 CeCoIn₅ is enhanced (with respect to the cubic parent compound CeIn₃) to Tc = 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 CeCoIn₅ with the antiferromagnetic ground state superseded by superconductivity. Moreover, measurements of the de Haas–van Alphen (dHvA) effect in CeCoIn₅ revealed essentially two Fermi surfaces (FS) of quasi-2D character [8,9]. Accordingly, band structure calculations for CeMIn₅ (M = Co, Ir) mainly show a roughly cylindrically shaped FS of electron character and a complicated hole-like FS [8,10]. These investigations on CeCoIn₅ 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 CeCoIn₅. Six contacts were spot-welded to samples of about 1 x 1 x 0.07 mm³, the latter dimension
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 $\rho_{xy}$ 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 $\rho$ is the magnetic contribution to the electrical resistivity and $\chi$ 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 $\rho_{xy}$ 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 $H_c(T)$ 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 ($\omega_c$: cyclotron frequency, $\tau$: average time between scattering). Nonetheless, if we take the values at maximum field we obtain a constant value of $R_H^\infty \approx -6 \times 10^{-10}$ m$^2$/C for $T \geq 300$ mK. Only at 5.2 K, $R_H^\infty$ 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 $\rho_{xy}$ for $T < T_c$ and $H > H_c$ 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 $T \leq 250$ 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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References