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Crossover from Landau Fermi liquid to non-Fermi liquid behavior: Indications from Hall measurements on CeCoIn$_5$

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Abstract

We conducted Hall effect measurements on the heavy-fermion superconductor CeCoIn$_5$ for temperatures 0.05–5 K and for pressures up to 1.2 GPa. A scaling of the magnetic field $H$ is introduced for the differential Hall coefficient, $R_{H}^{d} = \partial \rho_{xy}(T, H)/\partial H$ resulting in a single generic curve for $R_{H}^{d}(H)$ curves obtained at different $T$. We argue that the peak feature apparent in this generic curve corresponds to the crossover from non-Fermi liquid to Landau Fermi liquid behavior.

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The compound CeCoIn$_5$ is particularly suited to investigate the interplay of quantum criticality and unconventional superconductivity (SC) in which the pairing might be mediated by magnetic fluctuations. It exhibits the highest superconducting critical temperature, $T_c$, among the Ce-based ambient pressure superconductors [1], a magnetic field tuned quantum critical point (QCP) may exist [2] close to the upper critical field of SC, $H_{c2}$, and SC may hide an antiferromagnetic (AFM) order.

Hall effect measurements are a well established tool to shed light on the electronic properties of materials close to a QCP. Accordingly, such measurements have early been conducted for $T \geq 1$ K [3], even for applied pressures $p$ [4]. In our case, we want to concentrate on the low-$T$ region $0.05 \leq T \leq 5$ K and $p \leq 1.2$ GPa. At these $T$ well below the coherence temperature $T^* \approx 40$ K no anomalous Hall contribution is found. However, interpretation of Hall effect in CeCoIn$_5$ is complicated since SC inhibits a determination of the initial Hall coefficient and multiple bands at the Fermi level contribute to the Hall signal with a field dependent cyclotron mass [5].

For Hall measurements, isothermal field sweeps were conducted on single crystalline CeCoIn$_5$ samples with $H||c$. Measurements under pressure were carried out in a piston cylinder type pressure cell. The evolution of the Hall resistivity $\rho_{xy}$ (left) and its differential $R_{H}^{d} = \partial \rho_{xy}/\partial H$ (right) for increasing $p$ at $T = 120$ mK is shown in Fig. 1. A changing slope of $\rho_{xy}(H)$, as obvious from the $T = 120$ mK data, is observed for $0.1 \leq T \leq 0.3$ K at $p = 0$ and 0.3 GPa resulting in a minimum of $|R_{H}^{d}|$ (arrow). This feature is suppressed with increasing $p$ and can no longer be resolved at 1.2 GPa.

For further analysis, the $H$-values of the ambient pressure isothermal $R_{H}^{d}(T, H)$ vs. $H$ curves were scaled by $H_{\min}^{d}$. Here, $H_{\min}^{d}$ denotes the field value at which $|R_{H}^{d}|$ assumes its minimum for $70 \leq T \leq 200$ mK. As seen in...
and differential Hall coefficient $\rho_{xy}$. The arrow indicates the "peak feature" referred to in the text.

Fig. 2 ( ), all scaled $R_{\text{H}}^d$ curves collapse onto a single, generic curve. For $T$ below/above the given range, the $H$-values were scaled such that this generic curve is further completed towards larger/smaller values $H/H_{\text{min}}^d$. Here, $\rho_{\text{eff}} \propto 1/H_{\text{min}}^d$ can be viewed as effective mobility, averaged over all Fermi surfaces (FS) contributing.

(i) $p$ dependence: Applying pressure to CeCoIn$_5$ drives the system towards a heavy Landau Fermi liquid (LFL) state [6] by gradually suppressing the AFM SF [7]. This is likely related to the increase of $T_c$ with $p$ for small $p$, leading to maximum $T_c$ at $p^* \sim 1.3$ GPa. Our $R_{\text{H}}^d$ data at $p = 1.2$ GPa (+, Fig. 2), i.e. slightly below $p^*$, approach the base line, with minor deviations at $H/H_{\text{min}}^d \sim 0.7$. For intermediate $p = 0.8$ GPa, the $R_{\text{H}}^d$ values appear to be reduced for lower fields only. Note that for $H$ scaling at $p > 0$ the $H_{\text{min}}^d$ values obtained at $p = 0$ were used.

(ii) $R_{\text{H}}^d$ values: At low $H$ ($< 0.7H_{\text{min}}^d$) we obtain $-R_{\text{H}}^d \approx 6 \times 10^{-10}$ m$^3$/C with a slight $H$ dependence ($7 \times 10^{-10}$ m$^3$/C at $1.5H_{\text{min}}^d$). This value agrees remarkably well with the one reported [4] for the non-magnetic analogue LaCoIn$_5$ ($-5.5 \times 10^{-10}$ m$^3$/C). Generally, pressure drives Ce from a 4f$^1$ towards a non-magnetic 4f$^0$ configuration. Moreover, $R_{\text{H}}^d$ of the Ce- and the La-based compound agree well at $\mu_0H = 7$ T, i.e., in the LFL regime.

(iii) The $T$ dependence of $H_{\text{min}}^d$ as obtained from the scaling (Fig. 2) tracks the crossover [2] from non-Fermi liquid to LFL behavior (not shown).

The "peak feature" might be related to AFM SF or to the opening of an AFM gap at the FS if a spin density wave is formed. The latter may also cause a discontinuity in $R_{\text{H}}^d$ [8]. However, pressure suppresses the "peak feature" while changing the FS only little [5]. Note that Hall measurements (unlike thermodynamic ones) are sensitive to even weak fluctuations. Hence, the anisotropic AFM SF might be considered as a precursor of a gap opening.

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