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New hints on the origin of quantum criticality in CeCoIn$_5$: A Hall effect study

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Abstract

We report Hall Effect measurements under pressure in the normal state of CeCoIn$_5$, from 60 to 355 mK and for fields exceeding the superconducting upper critical field $H_{c2}$, with the field oriented parallel to [0 0 1]. At low pressures, the field dependence of the Hall coefficient exhibits a scaling consistent with the one reported in the normal state at higher temperatures, but at odds with the $\Delta H/T$ scaling expected near a field tuned quantum critical point. The breakdown of this scaling at higher pressures, concomitant with the suppression of spin fluctuations, suggests that it is a hallmark of the spin fluctuations.

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The tetragonal heavy fermion (HF) compounds CeMIn$_5$ ($M = $ Rh, Co, Ir) continue to provide an exciting opportunity for investigating quantum criticality and its interplay with unconventional superconductivity. The central issue is to understand how the Landau Fermi liquid (LFL) theory, describing the heavy quasiparticles, breaks down. This occurs near a quantum critical point (QCP), corresponding to a $T = 0$ phase transition between two different ground states. In this context, the question of whether the Fermi surface (FS) volume changes abruptly across the QCP has become a focus of attention in recent years [1]. The Hall effect is a particularly useful tool to address this issue. Investigations of Hall effect in YbRh$_2$Si$_2$ point to a crossover from a large to a small FS across the QCP [2]. It is important to extend such investigations to other systems.

CeCoIn$_5$ is an ambient pressure HF superconductor with a critical temperature $T_c = 2.3$ K [3]. Non-Fermi liquid (NFL) behavior is observed in the normal state for fields above the upper critical field ($H_{c2}$) corresponding to the suppression of the superconducting phase. Superconductivity (SC) occurs near a pressure tuned QCP in a variety of HF compounds, with a maximum of $T_c$ at the QCP [4]. In the unusual case of CeCoIn$_5$ [7], however, a magnetic field tuned QCP [8] is suggested. The corresponding critical field coincides with $H_{c2}$ in the $H$–$T$ phase diagram at ambient pressure [5–7,9]. The pressure evolution implies that this coincidence is accidental and that the origin of the QCP is not SC [10]. The presence of a superconducting Fulde–Ferrell–Larkin–Ovchinnikov [11,12] type of phase near $H_{c2}$ [13,14] introduces an additional complication. Recent investigations showed that this new phase is stabilized under pressure [15] whereas the QCP is suppressed [10], ruling out a direct connection between the two. On the other hand, CeCoIn$_5$ also exhibits NFL behavior at $H = 0$ for temperatures $T > T_c$ and an alternative picture is that the single-ion and lattice Kondo behaviors coexist at low $T$.

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[16,17]. It is not clear if the NFL behavior observed at $H = 0$ has the same origin as the one observed for $H \gg H_{c2}$, since the NFL exponents in the resistivity ($\rho$) are different. Here we report a scaling of the Hall effect at high fields similar to the previously reported scaling for $T > T_c$ [18]. This reveals a connection between the two NFL regimes.

The Hall effect is measured in single crystals of CeCoIn$_5$ using the lock-in technique with a low-$T$ transformer and a piston cylinder type pressure cell inside a dilution refrigerator. Fig. 1 shows the magnetic field dependence of the Hall coefficient, defined as $R_H = \rho_{xx}/H$, for $H > H_{c2}$ parallel to [001], and for $T \leq 0.35$ K, at pressures of 2.8 kbar (Fig. 1a; $H_{c2} = 5.15$ T) and 8 kbar (Fig. 1b; $H_{c2} = 4.9$ T). In both cases, $R_H$ exhibits a minimum at low $T$, which shifts to higher fields with increasing $T$, similar to the magnetoresistance (MR) [19]. In analogy with MR, the non-monotonic field dependence of $R_H$ can be understood as the result of two competing effects. The decrease in $R_H$ above $H_{c2}$ is likely due to the field suppression of the spin fluctuations, whereas the increase at higher fields is an effect of having two types of carriers, as inferred from FS studies [20]. Note also that the high field behavior is unchanged with pressure, consistent with the absence of change in the FS up to 12 kbar [21]. The presence of strong spin fluctuations near $H_{c2}$ was previously inferred from specific heat and $\rho$ [5].

Fig. 2 shows the $R_H(H)$ data at 2.8 kbar data scaled with respect to the minimum of $R_{Hm}$ at $H = H_{m}$. From the scaling we infer the value of $H_{m}(T)$ at temperatures for which $H_{m}$ is outside of the experimental field range. The vertical axis is scaled by a $T$-independent value of $R_{Hm} = 5.74(5.69) \times 10^{-10}$ m$^3$ C$^{-1}$ at 2.8 kbar for comparison. We recently reported an equivalent scaling for either $\rho_{xx}$ or $\rho_{xx}(= \partial \rho/\partial H)$ at ambient pressure ($p = 0$), and deduced a crossover from NFL to LFL from the Hall effect, which argues for a QCP value distinct from $H_{c2}$ [22]. The temperature dependence of $H_{m}(T)$ is shown in the inset of Fig. 2 together with power law fits. The $T = 0$ extrapolation of $H_{m}$ gives a value of $H_0 = 4.48 \pm 0.17$ T, strictly less than $H_{c2} = 5.15$ T at $p = 2.8$ kbar. The exponent $z = 0.67$ at $P = 2.8$ kbar is reduced compared to its $p = 0$ value (0.76) [22]. The decrease in $z$ with increasing pressure is consistent with a less divergent $\alpha$ coefficient of $\rho$ under pressure [10]. We identify $H_0$ as the QCP at 2.8 kbar. Since the data at 8 kbar do not scale in this fashion, we do not attempt to define the QCP at 8 kbar from Hall effect. The breakdown of scaling with increased pressure coincides with the suppression of the QCP [10], which suggests that the two are related. Note that our scaling form $R_H = R_{Hm}(H/H_0 + AT^\beta)$ is in clear contrast with the $\Delta H/T$ type of scaling (with $\Delta H = H - H_{QCP}$) expected near a field tuned QCP at $H_{QCP}$ [1]. A similar scaling of the form

$$R_H = R_H^{(0+\beta)}(H/(T_0 + T)^\beta)$$

was reported at $p = 0$ [18] in the limit of $\omega_c \tau \ll 1$ ($\omega_c$: cyclotron frequency, $\tau$: scattering rate) for $T > T_c$, with $T_0$ corresponding to the Kondo scale for the single-ion component of the two fluid analysis [16]. This suggests that the scaling of $R_H$ have a single origin in the entire $\omega_c \tau$ range and $(H_0 \approx H_{c2})$ reflects $(T_0 \approx T_c)$.

In summary, $R_H$ exhibits a scaling associated with the crossover from the NFL to LFL regimes at low $T$ in the normal state above $H_{c2}$. The conventional magnetotransport behavior for a multiple band system is recovered inside the Fermi liquid regime at high fields, with negligible pressure dependence. The breakdown of the scaling at higher pressures is likely associated with the suppression of spin fluctuations. The form of the scaling is similar to the one reported at higher $T$, suggesting a common origin.

Fig. 1. Hall coefficient vs magnetic field in single crystal CeCoIn$_5$ at the pressure of 2.8 kbar (a) and 8 kbar (b) in the field range 5–8 T, with $H||[001]$, in the temperature range 0.06–0.355 K as indicated.
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