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Journal
Physica B Condensed Matter, 403(5-9)

ISSN
0921-4526

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Publication Date
2008-04-01

DOI
10.1016/j.physb.2007.10.356

Available online at www.sciencedirect.com
ScienceDirect
Physica B 403 (2008) 1290–1292
PHYSICA B
www.elsevier.com/locate/physb

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.
Published by Elsevier B.V.

PACS: 75.30.−m; 75.30.Kz; 75.50.Ee; 77.80.−e; 77.84.Bw

Keywords: Hall Effect; Heavy fermion; Quantum critical

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 $YbRh_2Si_2$ 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 $T \geqslant T_c$ and an alternative picture is that the single-ion and lattice Kondo behaviors coexist at low T

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0921-4526/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.physb.2007.10.356

[16,17]. It is not clear if the NFL behavior observed at $H = 0$ has the same origin as the one observed for $H \geqslant H_{c2}$, since the NFL exponents in the resistivity (ρ) 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 $R_H = \rho_{xy}/H$, for $H > H_{c2}$ parallel to [0 0 1], and for $T \leqslant 0.35$ 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 ρ [5].

Fig. 2 shows the $R_H(H)$ data at 2.8 kbar data scaled with respect to the minimum of R_{H_m} 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 $R_{H_m} = 5.74(5.69) \times 10^{-10}\,m^3\,C^{-1}$ at 2.8(8) kbar for comparison. We recently reported an equivalent scaling for either R_H or $R_H^d (= \partial\rho/\partial H)$ 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

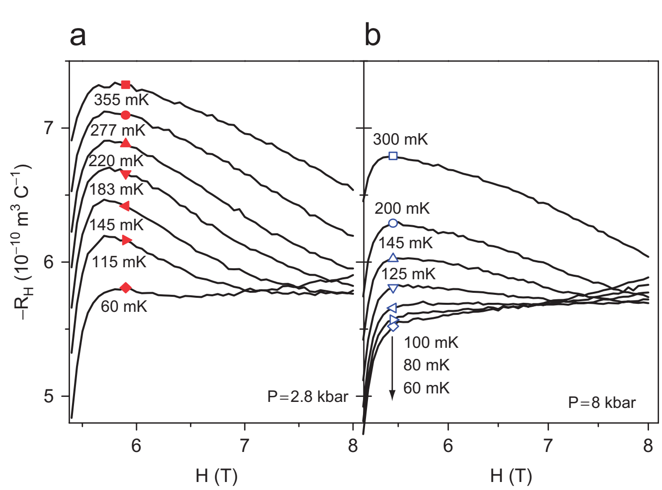

Fig. 1. Hall coefficient vs magnetic field in single crystal $CeCoIn_5$ at the pressure of 2.8 kbar (a) and 8 kbar (b) in the field range 5–8 T, with $H \| [0\,0\,1]$, in the temperature range 0.06–0.355 K as indicated.

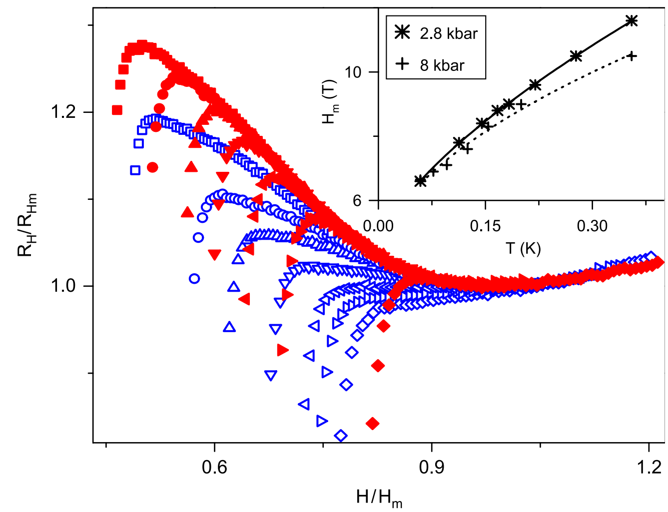

Fig. 2. Scaling of the Hall coefficient R_H/R_{H_m} vs. H/H_m at the pressure of 2.8 kbar (full symbols) and 8 kbar (open symbols). $[H_m, R_{H_m}]$ corresponds to the minimum of $R_H(H)$. Inset: temperature dependence of the scaling field H_m. Solid and dotted lines are power law fits for the data at 2.8 and 8 kbar.

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 $\alpha = 0.67$ at $P = 2.8$ kbar is reduced compared to its $p = 0$ value (0.76) [22]. The decrease in α with increasing pressure is consistent with a less divergent A coefficient of ρ 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 $R_H = R_{H_m} f(H/H_0 + AT^{\alpha})$ 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

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

was reported at $p = 0$ [18] in the limit of $\omega_c\tau \ll 1$ (ω_c: cyclotron frequency, τ^{-1}: 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 negligeable 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.

S.W. is partially supported by the EC through CoM*e*PhS 517039, and M.N. by the DFG through SFB 463. Z.F. is supported by the Alexander von Humboldt Foundation. H.L. and J.F.D. acknowledge support by the NSF through grants DMR 05 33560 and DMR 04 06140, respectively.

References

[1] P. Coleman, et al., J. Phys.: Condens. Matter 13 (2001) R723.
[2] S. Paschen, et al., Nature 432 (2004) 881.
[3] C. Petrovic, et al., J. Phys.: Condens. Matter 13 (2001) L337.
[4] N.D. Mathur, et al., Nature 394 (1998) 39.
[5] A.D. Bianchi, et al., Phys. Rev. Lett. 91 (2003) 257001.
[6] J. Paglione, et al., Phys. Rev. Lett. 91 (2003) 246405.
[7] F. Ronning, et al., Phys. Rev. B 71 (2005) 104528.
[8] P. Gegenwart, et al., Phys. Rev. Lett. 89 (2002) 056402.
[9] E.D. Bauer, et al., Phys. Rev. Lett. 94 (2005) 047001.
[10] F. Ronning, et al., Phys. Rev. B 73 (2006) 064519.
[11] P. Fulde, R.A. Ferrell, Phys. Rev. 135 (1964) A550.
[12] A.I. Larkin, Y.N. Ovchinnikov, Soviet Phys. JETP 20 (1965) 762.
[13] A.D. Bianchi, et al., Phys. Rev. Lett. 91 (2003) 187004.
[14] H. Radovan, et al., Nature 425 (2003) 51.
[15] C.F. Miclea, et al., Phys. Rev. Lett. 96 (2006) 117001.
[16] S. Nakatsuji, et al., Phys. Rev. Lett. 89 (2002) 106402.
[17] S. Nakatsuji, et al., Phys. Rev. Lett. 92 (2004) 016401.
[18] M.F. Hundley, et al., Phys. Rev. B 70 (2004) 035113.
[19] Y. Nakajima, et al., J. Phys. Soc. Japan 73 (2004) 5.
[20] H. Shishido, et al., J. Phys. Soc. Japan 71 (2002) 162.
[21] H. Shishido, et al., J. Phys.: Condens. Matter 15 (2003) L499.
[22] S. Singh, et al., Phys. Rev. Lett. 98 (2007) 057001.