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Field-induced quantum critical point in $CeCoIn_5$

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Abstract

The resistivity of $CeCoIn_5$ was measured down to 20 mK in magnetic fields of up to 16 T. With increasing field, we observe a suppression of the non-Fermi liquid behavior, $\rho \sim T$, and the development of a Fermi liquid state, with its characteristic $\rho = \rho_0 + AT^2$ dependence. The field dependence of the T^2 coefficient shows critical behavior with an exponent of ∼4/3. This is evidence for a new field-induced quantum critical point, occurring in this case at a critical field which coincides with the superconducting upper critical field H_{c2}.

Keywords: Quantum critical point; Non-Fermi liquid behavior; Heavy-fermion superconductor

The recent discovery of a new family of heavy-fermion superconductors with general formula $CeMIn_5$ (M = Co, Ir, Rh or their solid solutions) has generated much interest [1]. $CeCoIn_5$, with ambient pressure superconductivity below $T_c = 2.3$ K, is close to a point where the magnetic state becomes unstable as $T \to 0$ [2]. This proximity to a quantum critical point (QCP) is believed to be responsible for the unusual superconducting and normal state properties, but not much is known about the QCP itself.

Although long-range magnetic order is not present in $CeCoIn_5$ [3], the close proximity of this system to antiferromagnetic (AF) order [4] results in an abundance of spin fluctuations which lead to deviations from Fermi liquid (FL) behavior [1,5]. Since magnetic fluctuations play an essential role in quantum criticality, the response of this system to applied magnetic fields is of clear interest. In order to help elucidate the nature of the QCP, we have measured the low T, in-plane resistivity, ρ, of single-crystal samples of $CeCoIn_5$ in transverse fields, H, applied parallel to the c-axis.

In $CeCoIn_5$, notable magnetoresistance (MR) begins to appear below 30 K: the linear T dependence of $\rho(T)$ observed at $H = 0$ suffers a drastic change with increasing H, most pronounced at low T. The field dependence of ρ, obtained in constant temperature H-sweeps, is plotted in Fig. 1. The evolution of $\rho(H)$ with increasing temperature reveals the development of a *cross-over* in the sign of MR with increasing H and T. This cross-over is traceable to higher temperatures, and is a clear indication of a field-induced change in character of the spin fluctuations residing in this system [6]. The normal state, low-field MR (inset of Fig. 1) displays a notable range of *linear* field dependence, reproduced in negative field. This behavior, which is quite different from the usual H^2 dependence observed at such low fields in conventional metals, is not the H-linear MR

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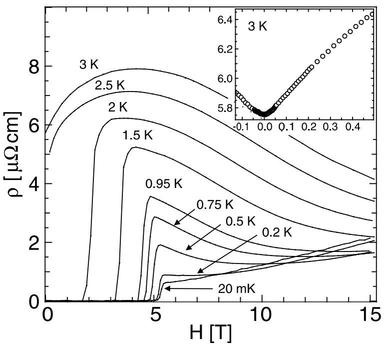

Fig. 1. Resistivity of $CeCoIn_5$ from constant-temperature field sweeps, shown as isotherms vs applied field. The inset displays a zoom of the anomalous linear magnetoresistance observed at low fields in the normal state (3 K).

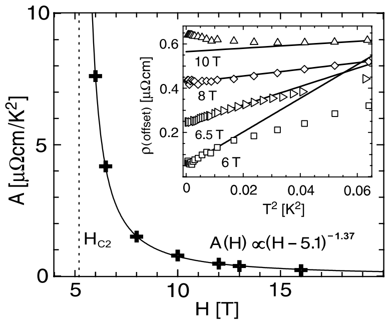

Fig. 2. Magnetic field dependence of the quadrati *c*-term coefficient A of $\rho(T)$. The solid line is a fit of the data points (+) to the displayed formula. The inset displays the low temperature resistivity of $CeCoIn_5$ plotted vs T^2 for several magnetic fields (data offset for clarity). The lines are linear fits to the data, showing the evolution of A (slope) with magnetic field.

often observed in the $\omega_c\tau \gg 1$ limit [6,7]. Rather, it may indicate the close proximity of $CeCoIn_5$ to a zero-field QCP [8].

An analysis of the $\rho(T)$ data obtained at high (constant) fields reveals the development of a clearly distinguishable range of $\rho \sim T^2$ behavior at low T. As shown by the linear fits of ρ vs T^2 in the inset of Fig. 2, the range of T^2 behavior is small at lower fields, appearing only below ~100 mK at 6 T. This range, which gradually becomes wider and more apparent with increasing field, [4] extending up to 2.5 K by $H = 16$ T, is identified with the recovery of a FL regime for $H \gtrsim 5$ T. Concomitantly, the slope of the fitted curves, i.e. the coefficient A in $\rho = \rho_0 + AT^2$, dramatically decreases with increasing field. The field dependence of A, or $A(H)$ (Fig. 2), displays *critical* behavior, best fitted by the function $A \propto (H - H^*)^{-\alpha}$ with parameters $H^* = 5.1 \pm 0.2$ T and $\alpha = 1.37 \pm 0.1$, indicative of a divergence in the strength of electron–electron interactions at the critical field H^*. This behavior, taken together with the development of a FL state above H^*, is commonly associated with quantum critical behavior, revealing the existence of a *field-induced* QCP in $CeCoIn_5$.

A number of other systems exhibit similar critical behavior in resistivity when approaching some critical field value associated with a QCP [9,10]. What is unique (and intriguing) about $CeCoIn_5$ is the fact that $H^* \approx H_{c2}(0) = 5.1$ T, which points to the existence of a QCP coincident with the superconducting transition at $T = 0$. However, because the H_{c2} transition in $CeCoIn_5$ is first-order below ~0.7 K [11], it is tempting to propose that the QCP is not associated with the superconducting state, but rather with a $T = 0$ transition of magnetic origin.

In conclusion, we have identified the anomalous low-temperature evolution of magnetoresistance in $CeCoIn_5$ with the development of a Fermi liquid regime away from a field-induced quantum critical point.

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[4] At low temperatures, a small upturn in $\rho(T)$ also starts to develop in fields above 8 T, but does not affect the T^2 analysis and is explained elsewhere [6].

References

[1] C. Petrovic et al., J. Phys. Condens. Matter 13 (2001) L337.
[2] M. Nicklas et al., J. Phys. Condens. Matter 13 (2001) L905;
H. Shishido et al., J. Phys. Soc. Jpn. 71 (2002) 162;
V.A. Sidorov et al., Phys. Rev. Lett. 89 (2002) 157004.
[3] W. Higemoto et al., J. Phys. Soc. Jpn. 71 (2002) 1023.
[4] Y. Kohori et al., Phys. Rev. B 64 (2001) 134526.
[5] S. Ikeda et al., J. Phys. Soc. Jpn. 70 (2001) 3187;
J.S. Kim et al., Phys. Rev. B 64 (2001) 134524;
R. Settai et al., J. Phys. Soc. Jpn. 71 (2002) 162.
[6] J. Paglione et al., Phys. Rev. Lett. 91 (2003) 246405.
[7] A.B. Pippard, Magnetoresistance in Metals, Cambridge University Press, Cambridge, 1989.
[8] A. Rosch, Phys. Rev. B 62 (2000) 4945.
[9] J. Flouquet et al., Physica B 319 (2002) 251;
P. Gegenwart et al., Phys. Rev. Lett. 89 (2002) 056402;
R.P. Dickey et al., Phys. Rev. B 56 (1997) 11169.
[10] F. Steglich, Trieste Workshop on Emergent Materials and Highly Correlated Electrons, Trieste, Italy, August 2002 (unpublished).
[11] A. Bianchi et al., Phys. Rev. Lett. 89 (2002) 137002;
T.P. Murphy et al., Phys. Rev. B 65 (2002) 100514(R);
K. Izawa et al., Phys. Rev. Lett. 87 (2001) 057002;
T. Tayama et al., Phys. Rev. B 65 (2002) 180504(R).