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 $\rho = \rho_0 + A T^2$ dependence. The field dependence of the $T^2$ coefficient shows critical behavior with an exponent of $\sim 4/3$. 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 $H_{c2}$.

Key words: 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, $\rho$, 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 $\rho$, obtained in constant temperature $H$-sweeps, is plotted in Fig.1. The evolution of $\rho(H)$ with increasing temperature reveals the development of a crossover in the sign of MR with increasing $H$ and $T$. This crossover 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 often observed in the $\omega_c \tau >> 1$ 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 $\rho$ vs. $T^2$ in the inset of Fig. 2, the
range of $T^2$ behavior is small at lower fields, appearing only below $\sim 100$ mK at 6 T. This range, which gradually becomes wider and more apparent with increasing field [9], 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.

Figure 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 [10,11]. 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 $\sim 0.7$ K [12], 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. This interpretation is reinforced by the fact that in antiferromagnetic Ge-doped YbRh$_2$Si$_2$, one also finds $A \propto (H - H^*)^{-\alpha}$ with $\alpha \sim 4/3$, but where $H^* = H(T_N \rightarrow 0)$ [11].

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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