Nonlinear paramagnetic magnetization in the mixed state of CeCoIn$_5$

H. Xiao$^{a,\ast}$, T. Hu$^a$, T. A. Sayles$^b$, M. B. Maple$^b$, C. C. Almasan$^a$

$^a$Department of Physics, Kent State University, Kent, OH, 44242
$^b$Department of Physics and Institute for Pure and Applied Physical Sciences, University of California at San Diego, La Jolla, CA, 92903

Abstract

Torque and magnetization measurements in magnetic fields $H$ up to 14 T were performed on CeCoIn$_5$ single crystals. The amplitude of the paramagnetic torque shows an $H^{2.3}$ dependence in the mixed state and an $H^2$ dependence in the normal state. In addition, the mixed-state magnetizations for both $H \parallel c$ and $H \parallel ab$ axes show anomalous behavior after the subtraction of the corresponding paramagnetic contributions as linear extrapolations of the normal-state magnetization. These experimental results point towards a nonlinear paramagnetic magnetization in the mixed state of CeCoIn$_5$, which is a result of the fact that both orbital and Pauli limiting effects dominate in the mixed state.

Key words: torque; magnetization; paramagnetism

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The recently discovered CeCoIn$_5$ heavy fermion material is an unconventional superconductor. A magnetic field destroys superconductivity by coupling to either the orbits (orbital limiting) or the spins of the electrons (Pauli limiting). The Pauli limiting effect dominates the low temperature and high field region of this system, as evidenced by the discovered Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state [1-2]. One expects an unusual mixed state in which diamagnetic and paramagnetic contributions could become anomalous since both orbital and Pauli limiting effects are equally important.

Torque and magnetization measurements were performed on CeCoIn$_5$ single crystals in a magnetic field $H$ up to 14 T, both in the normal and mixed states. The single crystal for which the data are presented here has a zero-field superconducting transition temperature $T_c(0)$ = 2.3 K.

Angular dependent torque was measured using a piezoresistive torque magnetometer. The sample was rotated in an applied magnetic field between $H \parallel c$ axis ($\theta = 0^\circ$) and $H \parallel a$ axis ($\theta = 90^\circ$). Torque gives the transverse magnetic moment $\vec{M}$ = $H \times \vec{H}$. Typical angular dependent torque data in the normal state are shown in Fig. 1(a). The data can be well fitted, as indicated by the solid line, with

$$\tau_n = \tau_{n,\text{max}} \sin 2\theta,$$

where $\tau_{n,\text{max}}$ is the amplitude of the normal-state torque. The inset to Fig. 1(a) shows that $\tau_{n,\text{max}} \propto H^2$. This magnetic field dependence of the torque is a result of the $H$ dependence of the normal-state paramagnetism of the heavy electrons: i.e., $T_n = (1/2)(\chi_c - \chi_a)H^2 \sin 2\theta$ [3].

The heavy electrons also contribute to the mixed-state paramagnetism. The mixed-state torque displays hysteresis, so it has both reversible and irreversible parts. The reversible torque is calculated as the average of the torque measured in increasing and decreasing angle. Shown in Fig. 1(b) is the angular dependent reversible torque measured in the mixed state, which is composed of paramagnetic and vortex contributions; i.e., $\tau_{\text{rev}}(\theta) = \tau_p + \tau_c$, where $\tau_c$ is described by Kogan’s model [4]. Hence,

$$\tau_{\text{rev}}(\theta) = \tau_{p,\text{max}} \sin 2\theta + \beta \frac{\gamma^2 - 1}{\gamma} \sin 2\theta \sin 2\chi \sin 2\theta \ln \left( \frac{\gamma H_{c2}^l}{H_c \theta} \right),$$

where $\tau_{p,\text{max}}$ represents the amplitude of the paramagnetic torque in the mixed state, $\beta \equiv \frac{\phi_0 H_c}{\lambda_{\parallel} \mu_0}$ [V is the volume of the sample, $\mu_0$ is the vacuum permeability, $\lambda_{\parallel}$ (787 nm, see Ref. [3]) is the penetration depth in the $ab$ plane, $\gamma = \sqrt{m_c/m_a}$, ($m_c$ and $m_a$ are the effective mass for $c$ and $a$ directions, respectively), $\chi = (\sin^2 \theta + \gamma^2 \cos^2 \theta)^{1/2}$, $\eta$ is a numerical parameter of the order of unity, and $H_{c2}^l$ is the upper critical field parallel to the $c$-axis [$H_{c2}^l(1.9 \text{ K}) = 2.35 \text{ T}$]. The solid line in Fig. 1(b) is the fit of the data with Eq. (2). The inset to Fig. 1(b) shows that $\tau_{p,\text{max}} \propto H^{2.3}$. The
fact that the paramagnetic contribution to the mixed-state torque is not proportional to $H^2$ implies that the mixed-state paramagnetism is not a simple extrapolation of the normal-state paramagnetic magnetization, i.e. not a linear function of $H$.

To get further evidence of this fact, we also performed $H$ dependent magnetization measurements on CeCoIn$_5$. The insets to Figs. 2(a) and 2(b) show the $H$ dependence of measured magnetization $M_{mes}$ for $H \parallel c$ and $H \parallel a$, respectively. The diamagnetic magnetization can be obtained by subtracting the paramagnetic contribution from $M_{mes}$ in the mixed state; i.e., $M_1 \equiv M_{mes} - \chi_{c,a}H$. Here we assume that the paramagnetic magnetization is just a simple extrapolation of the normal state magnetization. A plot of $M_1$ vs $H$ is shown in Figs. 2(a) and (b) for two $H$ directions. The obtained diamagnetic response is anomalous for both field orientations. The $M_1(H)$ curves show kinks, as indicated by the circles. A typical diamagnetic curve has no kinks in it. So, magnetization measurements provide further evidence that the assumption that the paramagnetic magnetization in the mixed state has the same linear field dependence as in the normal state is not correct and that there must be other contributions to the mixed-state magnetization. This conclusion is consistent with the theoretical calculations of Adachi et al. for superconductors in which both Pauli and orbital limiting effects are important.

In summary, both angular dependent torque and magnetization measurements were performed on CeCoIn$_5$ single crystals. The amplitude of the mixed-state torque has no longer an $H^2$ dependence, as in the normal state. The $H$ dependent diamagnetic magnetization curves are anomalous if we subtract the paramagnetic contribution in the mixed state as an extrapolation of the normal state. Both experiments indicate that the paramagnetism in the mixed state is no longer a linear function of $H$. The nonlinear paramagnetic magnetization is a result of the fact that both orbital and Pauli limiting effects dominate in this system.

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