Available online at www.sciencedirect.com
ScienceDirect
Physica B 403 (2008) 952–954
PHYSICA B
www.elsevier.com/locate/physb

Nonlinear paramagnetic magnetization in the mixed state of $CeCoIn_5$

H. Xiao[a,*], 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, USA
[b]Department of Physics and Institute for Pure and Applied Physical Sciences, University of California at San Diego, La Jolla, CA 92903, USA

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.
Published by Elsevier B.V.

PACS: 71.27.+a; 74.70.Tx; 75.30.Mb; 74.25.Ha

Keywords: Torque; Magnetization; Paramagnetism

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 $T_{c0} = 2.3$ 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 ($\theta = 0°$) and $H \parallel a$-axis ($\theta = 90°$). Torque gives the transverse magnetic moment since $\vec{\tau} = \vec{M} \times \vec{H}$. 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

$$\tau_n = \tau_n^{\max} \sin 2\theta, \tag{1}$$

where $\tau_n^{\max}$ is the amplitude of the normal-state torque. The inset to Fig. 1(a) shows that $\tau_n^{\max} \propto H^2$. 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., of $\tau_n = (1/2)(\chi_a - \chi_c)H^2 \sin 2\theta$ [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., $\tau_{\rm rev}(\theta) = \tau_{\rm p} + \tau_v$, where τ_v is described by Kogan's model [4]. Hence,

$$\tau_{\rm rev}(\theta) = \tau_{\rm p}^{\max} \sin 2\theta + \beta \frac{\gamma^2 - 1}{\gamma} \frac{\sin 2\theta}{\varepsilon(\theta)} \ln\left\{\frac{\gamma\eta H_{c2}^{\parallel c}}{H\varepsilon(\theta)}\right\}, \tag{2}$$

where $\tau_{\rm p}^{\max}$ represents the amplitude of the paramagnetic torque in the mixed state, $\beta \equiv \phi_0 HV/16\pi\mu_0\lambda_{ab}^2$ [V is the volume of the sample, μ_0 is the vacuum permeability,

*Corresponding author. Tel.: +1 330 672 2402; fax: +1 330 672 2959.
E-mail address: hxiao1@kent.edu (H. Xiao).

0921-4526/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.physb.2007.10.254

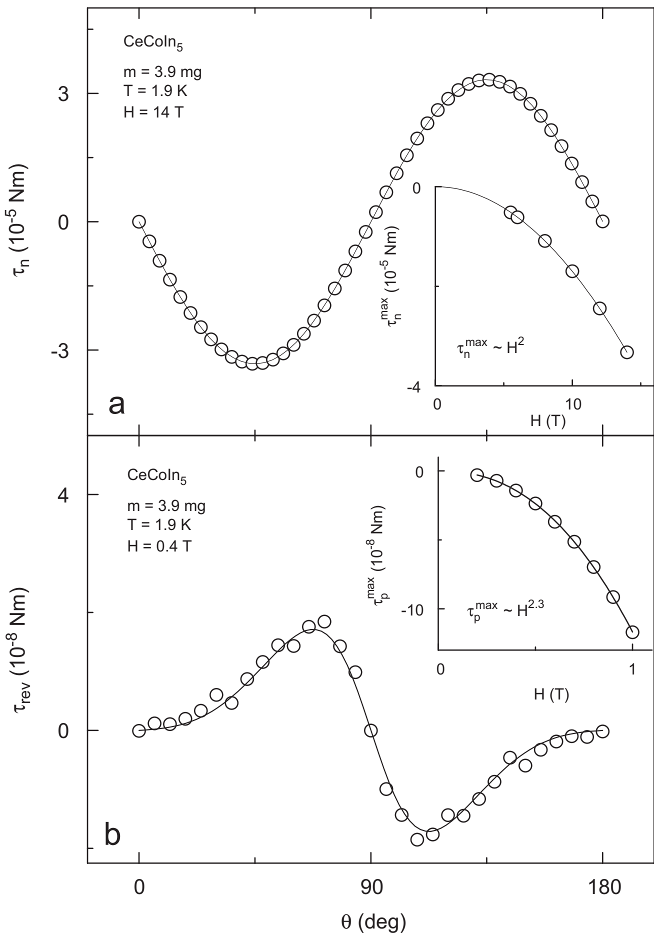

Fig. 1. Angular θ dependent (a) normal-state torque τ_n and (b) mixed-state reversible torque τ_{rev} measured at a temperature $T = 1.9\,\mathrm{K}$ and magnetic field H of 14 and 0.4 T, respectively. The solid lines are fits of the data with Eqs. (1) and (2), respectively. Insets: H dependence of the amplitude of the normal-state $\tau_n^{\max}$ and paramagnetic $\tau_{\mathrm{p}}^{\max}$ torques. The solid line is a fitting curves.

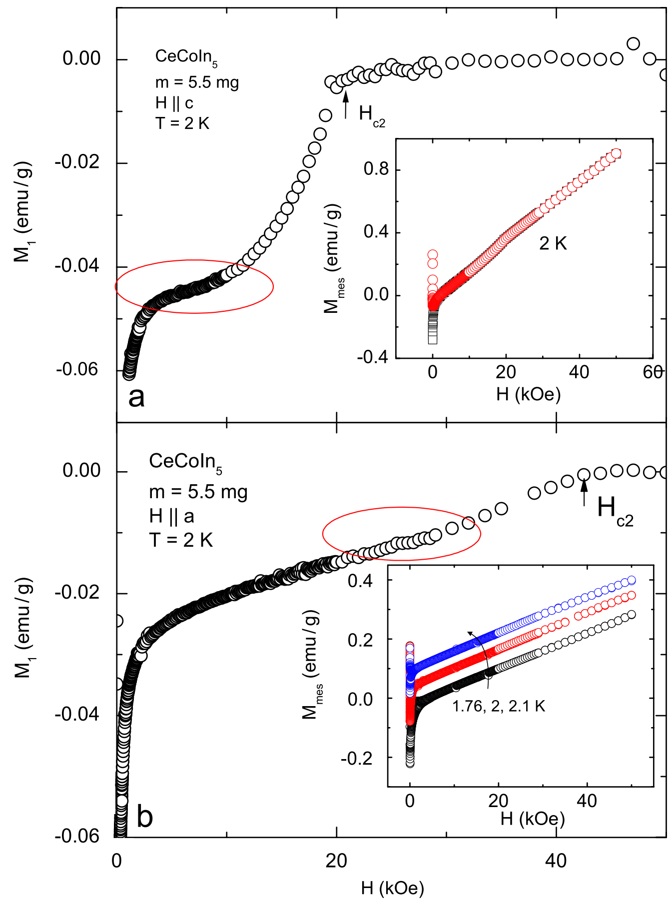

Fig. 2. Magnetic field H dependence of magnetization M_1 for (a) $H \parallel c$-axis and (b) $H \parallel a$-axis measured at 2 K. Insets: H dependence of the measured magnetization M_{mes} at $T = 2\,\mathrm{K}$ and $T = 1.76, 2, 2.1\,\mathrm{K}$, respectively. For clarity, the curves for 2, and 2.1 K are shifted by 0.05, and 0.1 emu/g, respectively.

λ_{ab} ($= 787\,\mathrm{nm}$, 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), $\varepsilon(\theta) = (\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}$, η is a numerical parameter of the order of unity, and $H_{c2}^{\parallel c}$ is the upper critical field parallel to the c-axis [$H_{c2}^{\parallel c}(1.9\,\mathrm{K}) = 2.35\,\mathrm{T}$]. The solid line in Fig. 1(b) is the fit of the data with Eq. (2). The inset to Fig. 1(b) shows that $\tau_{\mathrm{p}}^{\max} \propto H^{2.3}$. 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 $\mathrm{CeCoIn_5}$. The insets to Figs. 2(a) and (b) show the H dependence of measured magnetization M_{mes} for $H \parallel c$ and $H \parallel a$-axis, respectively. The diamagnetic magnetization can be obtained by subtracting the paramagnetic contribution from M_{mes} in the mixed state; i.e., $M_1 \equiv M_{\mathrm{mes}} - \chi_{c,a}H$. 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. [5] for superconductors in which both Pauli and orbital limiting effects are important.

In summary, both angular dependent torque and magnetization measurements were performed on $\mathrm{CeCoIn_5}$ 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.

This research was supported by the National Science Foundation under Grant no. DMR-0705959 at KSU and the US Department of Energy under Grant no. DE-FG02-04ER46105 at UCSD. H. X. and T. H. acknowledge support from I2CAM through NSF Grant no. DMR 0645461.

References

[1] C. Martin, et al., Phys. Rev. B 71 (2005) 020503R.
[2] A. Bianchi, et al., Phys. Rev. Lett. 91 (2003) 187004.
[3] H. Xiao, et al., Phys. Rev. B 73 (2006) 184511.
[4] V.G. Kogan, Phys. Rev. B 38 (1988) 7049.
[5] H. Adachi, et al., J. Phys. Soc. Japan 74 (2005) 2181.