Anisotropic low-field behavior and the observation of flux jumps in CeCoIn$_5$

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The magnetic behavior of the heavy fermion superconductor CeCoIn$_5$ has been investigated. The low-field magnetization data show flux jumps in the mixed state of the superconducting phase in a restricted range of temperature. These flux jumps begin to disappear below 1.7 K, and are completely absent at 1.5 K. The magnetization loops are asymmetric, suggesting that surface and geometrical factors dominate the pinning in this system. The lower critical field (H_{c1}), obtained from the magnetization data, shows a linear temperature dependence and is anisotropic. The calculated penetration depth (λ) is also anisotropic, which is consistent with the observation of an anisotropic superconducting gap in CeCoIn$_5$. The critical currents, determined from the high field isothermal magnetization loops, are comparatively low (around 4×10^3 A cm^{-2} at 1.6 K and 5 kOe).

Superconductivity in heavy fermion compounds is unconventional in nature. Over the last two decades, several Ce and U based heavy fermion superconductors have been discovered with superconducting transition temperatures (T_c) below 1 K. The magnetism and superconductivity are interrelated in these compounds, and it is argued that the superconducting state emerges out of the magnetic correlations rather than from any phonon mediated interactions.[1] Recently, a new class of heavy fermion compounds with the general formula CeMIn$_5$ (M = Co, Ir or Rh) has been discovered which shows anomalous superconducting properties. These compounds have a quasi-two-dimensional crystal structure consisting of CeIn$_3$ layers parallel to the ab plane. CeIrIn$_5$ is superconducting below 0.4 K and CeRhIn$_5$ shows superconductivity only under applied hydrostatic pressure. CeCoIn$_5$ is a superconductor at ambient pressure with a T_c = 2.3 K, which is relatively high compared to the T_c's of other heavy fermion superconductors. As a result, CeCoIn$_5$ provides us with a unique opportunity to investigate the nature of the superconductivity in this class of compounds. Magnetization measurements[2] indicate that the superconductivity in this layered compound is anisotropic in nature. The upper critical fields (H_{c2}) at 1.5 K have been reported to be around 80 and 30 kOe for magnetic fields applied parallel and perpendicular to the ab plane, respectively.[3] Recent heat capacity and thermal conductivity measurements indicate that the superconductivity in CeCoIn$_5$ is of non-BCS character with anisotropic gap formation at the Fermi surface.[4,5]

The values of the upper and lower critical fields are important parameters that help to characterize the nature of a superconductor. They enable us to estimate the microscopic superconducting length scales such as the penetration depth λ and the coherence length ξ. An exact determination of the critical fields, particularly H_{c1}, is often difficult due to demagnetization effects and the quality of the material available. However, it is possible to get convincing H_{c1} data by careful measurements and analysis on a high quality single crystal sample. In this paper we report on a detailed magnetic investigation of CeCoIn$_5$ single crystals. We have obtained the temperature dependence of H_{c1} for CeCoIn$_5$. The characteristic superconducting parameters λ and ξ were also cal-

culated from the critical field values. In addition, we have also investigated the critical current density of the material.

Single crystals of CeCoIn$_5$ were prepared by the indium flux technique. The crystals grew in the form of thin rectangular plates with an area of 2–3 mm^2 and a thickness of 0.2–0.3 mm. Concentrated hydrochloric acid was used to remove any residual indium from the surface of the crystals. X-ray Laue diffraction was performed to determine the crystallographic axes of the samples, and it was seen that the ab planes of the crystals coincide with the rectangular faces of the plates. An Oxford Instruments vibrating sample magnetometer (VSM) was used to measure the magnetization down to 1.5 K. The measurements were carried out on several crystals obtained from different batches. We have found no noticeable difference between the magnetization behavior of these crystals. The data presented here are the results of measurements on a rectangular crystal (1.24×0.75 ×0.09 mm^3), where the shortest dimension is along the c axis.

The low-field isothermal magnetization data of the compound CeCoIn$_5$ are shown in Fig. 1, with the field applied parallel to the a axis of the crystal. The data were collected at each temperature after zero-field cooling from 5 K. In order to minimize the effect of residual flux trapped in the superconducting coil of the VSM, the magnet was degaussed before each measurement by applying a damped oscillatory field cycle. The sample chamber in the VSM was flooded with helium exchange gas to ensure temperature stability during the measurements. The magnetization loops below the superconducting transition temperature of 2.3 K show a hysteresis typical of a type II superconductor.

In order to calculate the lower critical field (H_{c1}), it is essential to take into account the demagnetization effect of the sample, because, at low field, the field correction is comparable to the applied magnetic field. The demagnetization correction was performed using the relation $H_{eff} = H_{app} - 4\pi N_i M$, where H_{app} is the applied external field (in Oe), H_{eff} is the effective field (in Oe) on the sample after correction, N_i is the demagnetization factors for different directions ($i = a, b, c$), and M is the magnetization (emu/cm^3) of the sample. Assuming that the sample is ellipsoidal in shape, the
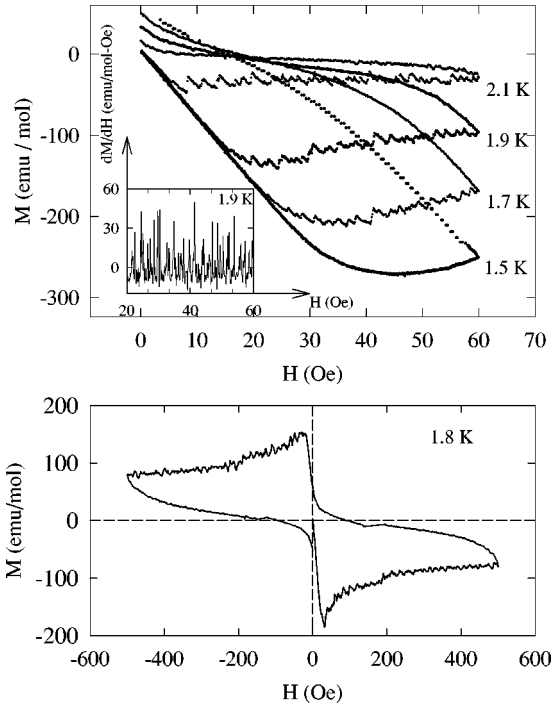
FIG. 1. The upper panel shows the low field (up to 50 Oe) magnetization (M) vs field (H) data at different temperatures with the applied magnetic field parallel to the a direction with a field sweep rate of 5 Oe/min. The inset shows the derivative of M with respect to H to depict the sharpness of flux jumps. The lower panel shows a four-quadrant M vs the H loop at 1.8 K in the same geometry as above up to $H = 500$ Oe with a field sweep rate of 50 Oe/min.

values of N_i, obtained from Ref. 6, are found to be 0.03, 0.05, and 0.92 for the a, b, and c directions, respectively.

The lower critical field of a superconductor is defined as the onset of the deviation from an ideal diamagnetic ($M/H = -1/4\pi$) behavior. For the calculation of the lower critical field, we have subtracted the ideal linear diamagnetic response $[M_{dia}(H) = -H/4\pi]$ from our magnetization data, to obtain the deviation $\delta M = M - M_{dia}$. This deviation δM varies as $(H - H_{c1})^2$ around H_{c1}.[7] Thus the value of H_{c1} can be obtained from the H intercept of a $(\delta M)^{1/2}$ versus H plot. We have also calculated the full penetration field H_p at different temperatures, by noting the magnetic field at which maximum diamagnetic signal is observed in the M versus H measurements. For the calculation of H_{c1} and H_p, we have used the demagnetization corrected field H_{eff}.

Figure 2 shows the variation of the lower critical field and the full penetration field with temperature for the field applied parallel to the a and c directions, respectively. The H_{c1} and H_p values fall almost linearly with temperature for both these directions. This linear behavior of H_{c1} is unusual in low-T_c superconductors. The H_{c1} values are anisotropic in magnitude with respect to the a and c directions. This is not unexpected given that CeCoIn$_5$ is a layered compound, and that it has shown anisotropies in its resistive and magnetic behavior.[2]

The M-H loops are found to be asymmetric (see Fig. 1) with respect to the $M = 0$ axis. This asymmetry is also seen
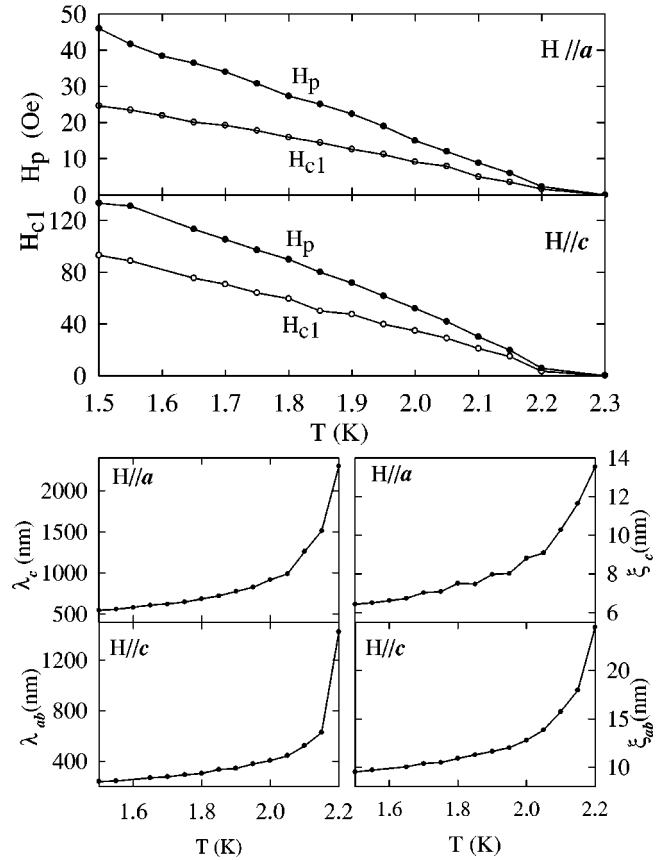

FIG. 2. The upper panels show the temperature dependence of the lower critical field (H_{c1}) and the full penetration field (H_p) for CeCoIn$_5$ with the applied field parallel to the a and c directions. The superconducting penetration depth (λ) and the correlation length (ξ) are plotted as functions of temperature in the lower panels.

in the magnetization data taken up to 500 Oe. This observation suggests that the magnetization behavior at low fields is dominated by surface and geometrical barriers rather than bulk pinning. We have scaled the low-field magnetization data by the full penetration field magnetization (M_p is the magnetization at H_p) and shown that at low fields ($H \leq 100$ Oe) the plots (not shown) of M/M_p versus H/H_p for different temperatures collapse onto each other. This confirms that temperature independent pinning mechanisms, such as surface and geometrical barrier effects, are present in this material.

In common with other magnetic superconductors (e.g., rare earth borocarbides, UPt$_3$), CeCoIn$_5$ has a field dependent positive contribution to the magnetization (M_{para}) superimposed on top of the diamagnetic response. As a result, the magnetization becomes positive well below the upper critical field. It is often difficult to discern the true nature of the hysteresis loop at high fields, where M_{para} is large. Nevertheless, we have estimated M_{para} from the magnetization data (at 2.4 K) just above the T_c of CeCoIn$_5$. We have then subtracted this M_{para} from the magnetization data obtained below T_c, assuming that the field dependence of M_{para} remains unchanged within the temperature range 1.6–2.4 K.[8] The resultant loops ($M - M_{para}$ versus H) are also asymmet-

ric with respect to the $M = 0$ line, indicating that surface and geometrical effects are important even in the high field state.

Another interesting observation in the low field measurements is the flux jumps in the magnetization data. The observed jumps are irregular and nonperiodic (see Fig. 1). The flux jumps are observed for measurements made in *increasing* field with the magnetic field applied along either the a or c axes. The jumps are completely absent (for $H \| a$ axis) or very weak (for $H \| c$) when the field is ramped *down*. The magnitude of these jumps is largest at 2.1 K, and then decreases slowly below 1.7 K. The flux jumps are completely absent at 1.5 K (see Fig. 1). The magnitude of the largest jump at 2.1 K is 0.16 emu/c.c. This corresponds to an entry of ~ 6000 flux quanta (Φ_0) into the sample. Flux jumps are observed in many type II superconductors.[9] During the field sweep, a small perturbation in the flux distribution in the critical state can give rise to a temperature fluctuation, which can in turn result in the movement of a flux bundle within the sample. A jump is then observed in the magnetization data. The gradual disappearance of these flux jumps below 1.7 K indicates that there is some difference in the nature of the flux distribution (due the variation of pinning mechanism or the thermal diffusibility) below 1.7 K. Note, however, that heat capacity and thermal conductivity data for CeCoIn$_5$ contain no unusual features below T_c.

In order to understand the nature of the flux jumps, we have measured the magnetization data with different field sweep rates (5 Oe/min to 10 kOe/min). In all cases, there is a large number of flux jumps that are small in magnitude. No avalanche-like large flux jumps (which can drive the system above T_c) were observed even at the highest sweep rate. The flux jumps were also observed in CeCoIn$_5$ crystals of different shape and size, and the qualitative features of the flux jumps were completely reproducible. It appears that the observed flux instabilities are due to local flux entry through the surface or geometrical barriers rather than any global instability. The asymmetry of the flux jumps with respect to the increasing and decreasing parts of the magnetization loop clearly indicate the existence of barriers at the surface (such as those of the Bean-Livingstone type) which prevent the smooth entry of flux lines into the sample, but are ineffective during flux expulsion.

Within the Ginzburg-Landau approximation, the characteristic superconducting length scales ξ and λ can be estimated from the knowledge of H_{c1} and H_{c2} using the following relations:

$$H_{c1} = \frac{\Phi_0 \ln \kappa}{4\pi\lambda^2}, \quad H_{c2} = \frac{\Phi_0}{2\pi\xi^2},$$

$$H_{c2}/H_{c1} = 2\kappa^2/\ln\kappa, \quad \kappa = \lambda/\xi. \quad (1)$$

The values of H_{c2} were obtained from the high-field M versus H data (not shown here) at different temperatures for fields applied parallel to the a and c axes. The field values where the irreversibility between the increasing and the decreasing branches disappears were taken as the upper critical field of the sample. Our values match well with the previously reported values of H_{c2} from magnetization data.[3] Us-
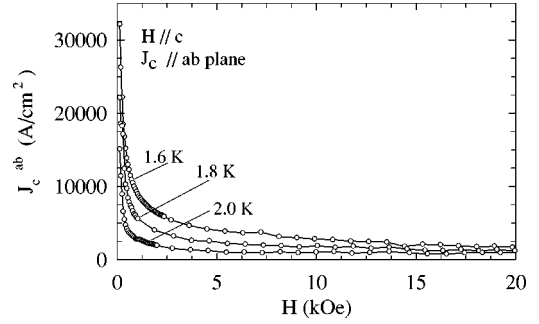

FIG. 3. Critical current density in the *ab* plane at different temperatures for CeCoIn$_5$ plotted against the applied magnetic field.

ing Eq. (1) we have obtained the values of κ ($= \lambda/\xi$). At 1.6 K, these are about 90 and 25 for the field applied parallel to the a and c axes respectively. Figure 2 shows the temperature dependence of λ and ξ for both directions ($H \| a$ and $H \| c$). Both parameters are anisotropic. The ratios λ_c/λ_{ab} and ξ_{ab}/ξ_c are ~ 2.3 and 1.5 in the temperature range 1.5–2.1 K, where the subscripts ab and c denote the ab plane and the c axis, respectively. Since the penetration depth is directly proportional to the square root of the effective mass (m^*), this implies that there is a large anisotropy in the effective mass within the material ($\Gamma = m_c^*/m_{ab}^* \sim 5.3$).[10] The anisotropy of λ is clearly consistent with the observation of nodes in the superconducting gap at particular points of the Fermi surface.[5] Anisotropies in H_{c1} and λ are also observed in other heavy fermion superconductors with anisotropic superconducting gap like UPt$_3$.[11] Our calculated values of λ from the magnetization measurements (for $H \| a$) are qualitatively similar and quantitatively close ($\lambda \sim 425$ nm in Ref. 12 as compared to our value of 540 nm at 1.5 K) to the values obtained recently from tunneling experiments.[12] The reasonably large value of λ (~ 500 nm) observed for CeCoIn$_5$ is typical of the heavy fermion superconductor [$\lambda \sim 1000$ nm for UPt$_3$ (Ref. 11)].

The critical current density, J_c, is not an intrinsic parameter of a superconductor. Furthermore, in systems such as CeCoIn$_5$, where surface effects are present, one should be careful when considering the critical currents within the material. Nevertheless, the use of a Bean-like critical state model can provide us with an indication of the strength of the pinning within the system. For a thin rectangular plate-like superconducting sample (sides t and ℓ, $\ell > t$) with an applied magnetic field perpendicular to the plane of the plate, J_c on the surface of the plate is given by[13]

$$J_c = 20(M\downarrow - M\uparrow)[t(1 - t/3\ell)]^{-1}, \quad (2)$$

where $M\downarrow$ and $M\uparrow$ are the magnetization (in gauss) for the decreasing and increasing fields respectively. This relation is valid only when we have isotropic critical currents perpendicular to the applied field. Since the superconducting properties of CeCoIn$_5$ appear to be isotropic in the ab plane, it is possible to apply Eq. (2) in order to calculate J_c^{ab} the critical current density in the ab plane. Figure 3 shows the variation of J_c^{ab} as a function of the applied field. The J_c values are derived from the high-field magnetization data measured

with the field parallel to the c direction. From Fig. 3 it is clear that J_c^{ab} drops smoothly with increasing magnetic field and temperature. No unusual variation in the behavior of J_c^{ab} with field or temperature was observed. The value of J_c^{ab} is about 4×10^3 A cm^{-2} at 1.6 K in an applied field of 5 kOe, which is a few orders of magnitude lower than some high-T_c materials.[13] However, a low value of J_c is not unusual when the bulk pinning is weak. For example, a critical current of similar magnitude ($\sim 10^3$ A/cm^2 at $T/T_c = 0.7$ with 5 kOe of applied field) has been observed in YNi$_2$B$_2$C crystals,[14] where the surface and geometrical effects are predominant over the bulk pinning.

CeCoIn$_5$ has a layered structure consisting of quasi-two dimensional CeIn$_3$ building blocks parallel to the a-b plane. The observed anisotropies in H_{c1}, λ and ξ, clearly support the idea that the CeIn$_3$ layers have an important influence on the superconducting properties of CeCoIn$_5$. The observation of flux jumps is interesting, however it is not clear at present why the flux jumps disappear below 1.7 K. Our measurement of the critical currents show no unusual change below 1.7 K.

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[1] N.D. Mathur, F.M. Grosche, S.R. Julian, I.R. Walker, D.M. Freye, R.K.W. Haselwimmer, and G.G. Lonzarich, Nature (London) **394**, 39 (1998).

[2] C. Petrovich, P.G. Pagliuso, M.F. Hundley, R. Movshovich, J.L. Sarrao, J.D. Thompson, Z. Fisk, and P. Monthoux, J. Phys.: Condens. Matter **13**, L337 (2001).

[3] T. Tayama, A. Harita, T. Sakakibara, Y. Haga, H. Shishido, R. Settai, and Y. Onuki, Phys. Rev. B **65**, 180504 (2002); T.P. Murphy, Donavan Hall, E.C. Palm, S.W. Tozer, C. Petrovic, Z. Fisk, R.G. Goodrich, P.G. Pagliuso, J.L. Sarrao, and J.D. Thompson, *ibid.* **65**, 100514 (2002).

[4] R. Movshovich, M. Jaime, J.D. Thompson, C. Petrovic, Z. Fisk, P.G. Pagliuso, and J.L. Sarrao, Phys. Rev. Lett. **86**, 5152 (2001).

[5] K. Izawa, H. Yamaguchi, Yuji Matsuda, H. Shishido, R. Settai, and Y. Onuki, Phys. Rev. Lett. **87**, 057002 (2001).

[6] J.A. Osborn, Phys. Rev. **67**, 351 (1945).

[7] V.V. Metlushko, G. Güntherodt, V.V. Moshchalkov, Y. Bruynseraede, and M.M. Lukina, Phys. Rev. B **47**, 8212 (1993).

[8] An extrapolation of the normal state (2.3 to 5 K) M vs H data for CeCoIn$_5$ collected in a field of 20 kOe down to 1.5 K indicates only a 2% increase in M_{para} between 2.4 and 1.6 K.

[9] M.E. McHenry, H.S. Lessure, M.P. Maley, J.Y. Coulter, I. Tanaka, and H. Kojima, Physica C **190**, 403 (1992), and references therein.

[10] This is an estimate, since the ratios λ_c/λ_{ab} and ξ_{ab}/ξ_c differ.

[11] Zuyu Zhao, F. Behroozi, S. Adenwalla, Y. Guan, J.B. Ketterson, Bimal K. Sarma, and D.G. Hinks, Phys. Rev. B **43**, 13 720 (1991); C. Broholm, G. Aeppli, R.N. Kleiman, D.R. Harshman, D.J. Bishop, E. Bucher, D.Ll. Williams, E.J. Ansaldo, and R.H. Heffner, Phys. Rev. Lett. **65**, 2062 (1990).

[12] S. Özcan, D.M. Broun, B. Morgan, R.K.W. Haselwimmer, J.L. Sarrao, Saied Kamal, C.P. Bidinosti, P.J. Turner, M. Raudsepp, and J.R. Waldram, cond-mat/0206069 (unpublished).

[13] E.M. Gyorgy, R.B. van Dover, K.A. Jackson, L.F. Schneemeyer, and J.V. Waszczak, Appl. Phys. Lett. **55**, 283 (1989).

[14] S.S. James, C.D. Dewhurst, R.A. Doyle, D. McK Paul, Y. Paltiel, E. Zeldov, and A.M. Cambell, Physica C **332**, 173 (2000).