

Upper critical magnetic field of the heavy-fermion superconductor  $\text{UPt}_3$ 

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The longitudinal and transverse upper critical magnetic fields  $H_{c2}^{\parallel}$  and  $H_{c2}^{\perp}$  as a function of temperature  $T$  of a single-crystal specimen of the heavy-fermion superconductor  $\text{UPt}_3$  were measured resistively with the current flowing along the hexagonal  $c$  axis. The slope of the linear part of the  $H_{c2}^{\parallel}(T)$  curve near the superconducting transition temperature  $T_c = 0.52$  K equals 63 kOe/K, from which a zero-temperature superconducting coherence length  $\xi_0 \sim 120$  Å can be inferred. An analysis using previously reported specific-heat data yields an effective mass  $\sim 200$  times the free-electron mass and a value of  $\xi_0 \sim 170$  Å. The electrical resistivity between  $T_c$  and 8 K varies as  $T^n$  with  $n = 1.6 \pm 0.1$ .

The heavy-fermion superconductors  $\text{CeCu}_2\text{Si}_2$  (Ref. 1) and  $\text{UBe}_{13}$  (Ref. 2) have attracted a great deal of attention because of their remarkable normal- and superconducting-state properties. Valence fluctuation or Kondo lattice types of anomalies<sup>3,4</sup> occur in the normal-state properties of both materials. The magnetic susceptibility, which displays local moment behavior at high temperature, approaches a constant value as  $T \rightarrow 0$  K, indicating that the ground state is nonmagnetic.<sup>5,6</sup> In particular, both compounds have enormous values of the electronic specific-heat coefficient  $\gamma$  of  $\sim 1$  J/g atom  $\text{K}^2$  from which effective masses  $\sim 200m_e$ , where  $m_e$  is the mass of a free electron, have been estimated.<sup>2,7</sup> The superconducting-state properties are characterized by low values of the superconducting transition temperature  $T_c \leq 1$  K,<sup>1,2</sup> as well as relatively large values of the upper critical magnetic field  $H_{c2}$  and its initial slope at  $T_c$ ,  $(-dH_{c2}/dT)_{T_c}$ .<sup>7,8</sup> Another compound  $\text{U}_6\text{Fe}$  has unusual properties<sup>9</sup> that may place it somewhere in a continuum between heavy-fermion and conventional superconductivity.

The compound  $\text{UPt}_3$  has recently been reported to exhibit bulk superconductivity with a  $T_c$  of 0.54 K.<sup>10</sup> There are certain similarities between the properties of  $\text{UPt}_3$  and those of the heavy-fermion superconductors  $\text{CeCu}_2\text{Si}_2$  and  $\text{UBe}_{13}$ , as well as some differences. One of these differences is in the temperature dependence of the electrical resistivity  $\rho$ . For  $\text{UPt}_3$ ,  $\rho$  increases monotonically with increasing temperature with substantial negative curvature,<sup>10</sup> while for both  $\text{CeCu}_2\text{Si}_2$  (Ref. 5) and  $\text{UBe}_{13}$ ,<sup>2</sup>  $\rho$  first increases, passes through a maximum at a few K, and then decreases with increasing temperature. A more significant difference may be the presence of spin fluctuations in  $\text{UPt}_3$ , the existence of which has been inferred from the temperature dependences of the magnetic susceptibility<sup>11,12</sup> and low-temperature specific heat.<sup>10,12</sup> Reports of a maximum in the magnetic susceptibility near 19 K (Ref. 12) and a temperature dependence of the electrical resistance near  $T_c$  that is close to  $T^2$  (Ref. 10) are consistent with this possibility. In addition, recent low-temperature specific-heat measurements in the normal state reveal a large electronic  $\gamma T$  term with  $\gamma = 450$  mJ/g atom  $\text{K}^2$  and a contribution that has been attributed to spin fluctuations<sup>13-15</sup> of the form  $T^3 \ln(T/T_{sf})$ ,

where  $T_{sf}$  is the spin fluctuation temperature.<sup>10</sup> In this paper we report resistive measurements of the longitudinal and transverse upper critical magnetic fields  $H_{c2}^{\parallel}$  and  $H_{c2}^{\perp}$  as a function of temperature of a single-crystal specimen of  $\text{UPt}_3$  with the current flowing in the direction of the hexagonal  $c$  axis.

The single-crystal specimen of  $\text{UPt}_3$  used in this investigation was prepared in a manner previously described.<sup>10</sup> A  $^3\text{He}$ - $^4\text{He}$  dilution refrigerator was employed to attain temperatures as low as 80 mK which were determined from a 100- $\Omega$  Speer carbon resistance thermometer that was calibrated against the magnetic susceptibility of cerium magnesium nitrate. The ac electrical resistance  $R$  was measured by means of a four-lead technique at 16 Hz on a needle-shaped  $\text{UPt}_3$  specimen with the current flowing along the hexagonal  $c$  axis. The current density was  $\sim 2$  A/cm<sup>2</sup>. A superconducting solenoid was used to produce magnetic fields as high as 20 kOe which were applied parallel or perpendicular to the current direction in separate experiments. The  $T_c$  in zero and applied magnetic fields was defined as the temperature at which  $R$  decreased to one-half of its value extrapolated from the normal state.

Shown in Fig. 1 are  $R$  vs  $T$  data in zero magnetic field below 8 K. The resistance is still changing with temperature all the way down to  $T_c$  and can be described by the expression  $R = R_0 + AT^n$  with  $R_0 = 0.16$  m $\Omega$ ,  $A = 0.25$  m $\Omega/\text{K}^n$ , and  $n = 1.6 \pm 0.1$  for  $0.54$  K  $\leq T \leq 8$  K. The resistance ratio  $RR \equiv R(296 \text{ K})/R(1 \text{ K}) \approx 150$  indicates that the  $\text{UPt}_3$  crystal is of high quality. Because of the somewhat irregular shape of the faceted  $\text{UPt}_3$  crystal, its geometrical factor could not be determined with high accuracy. However, within an error of about 40%, the electrical resistivity at 1 K is equal to 1.1  $\mu\Omega$  cm. Representative resistive superconducting transition data for longitudinal magnetic fields ranging from zero to 15 kOe are displayed in the inset of Fig. 1. The transition temperature was defined as the midpoint of the total change in the resistance. The width of the transitions defined from the 10% and 90% points increases from 22 mK for  $H = 0$  to 90 mK for  $H = 16$  kOe.

The longitudinal and transverse critical magnetic fields  $H_{c2}^{\parallel}$  and  $H_{c2}^{\perp}$  as a function of temperature are shown in Fig.

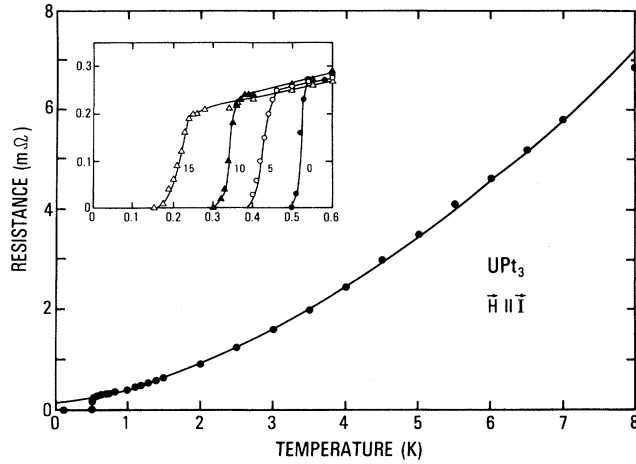


FIG. 1. Electrical resistance  $R$  vs temperature of  $\text{UPt}_3$  in zero applied magnetic field. The solid line represents a fit of the equation  $R = R_0 + AT^n$  with parameters  $R_0$ ,  $A$ , and  $n$  that are given in the text. Shown in the inset are resistive superconducting transition data in magnetic fields  $H$  of 0, 5, 10, and 15 kOe with  $H$  parallel to the current  $I$ .

2. Systematic errors in the temperature due to the magnetoresistance of the carbon thermometer<sup>16</sup> are estimated to be  $\leq 15$  mK for all fields. The reduction of the transverse upper critical magnetic field  $H_{c2}$  by the demagnetizing field is estimated to be  $\sim 0.1\%$ , assuming that the shape of the  $\text{UPt}_3$  sample can be approximated as a long circular cylinder for which the transverse demagnetizing factor is  $2\pi$  and using the basal-plane magnetic susceptibility data given in Ref. 12. Near  $T_c$ , both  $H_{c2}^{\parallel}$  and  $H_{c2}^{\perp}$  exhibit positive curvature as

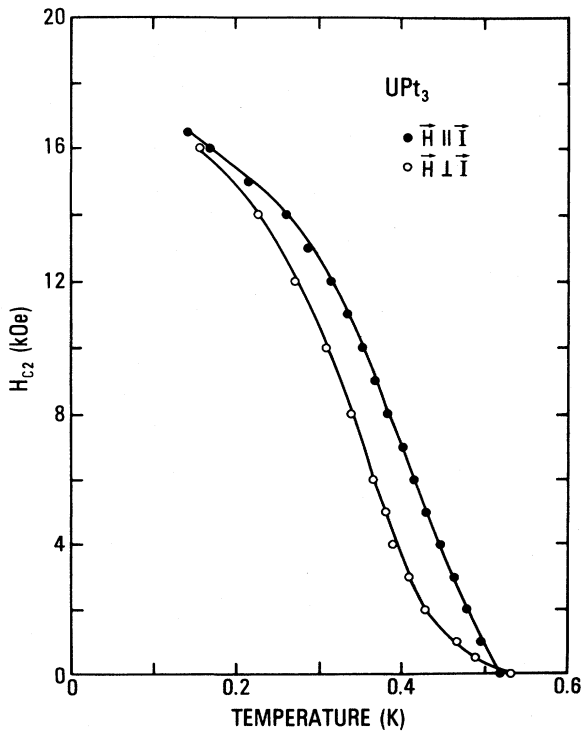


FIG. 2. Upper critical field vs temperature data for  $\text{UPt}_3$  with applied field  $H$  parallel or perpendicular to the current  $I$ .

a function of  $T$  which is considerably more pronounced for  $H_{c2}^{\perp}$ . Some of this curvature may be due to the field dependence of the transition width. Large anisotropy such as that displayed by  $H_{c2}(T)$  has also been observed in the dc magnetic susceptibility.<sup>12</sup>

Disregarding the positive curvature near  $T_c$ , the linear portion of the  $H_{c2}$  vs  $T$  curve has a slope  $(-dH_{c2}/dT)_{T_c} = 63$  kOe/K which can be used to estimate the superconducting coherence length at  $T=0$  K,  $\xi_0$ . First, the zero-temperature orbital critical magnetic field  $H_{c2}^*(0)$  can be determined from the weak-coupling formula<sup>17</sup>

$$H_{c2}^*(0) = 0.693 [(-dH_{c2}/dT)_{T_c}] T_c, \quad (1)$$

which gives  $H_{c2}^*(0) \sim 22.7$  kOe for  $T_c = 0.52$  K. This value can then be used to calculate  $\xi_0$  by means of the expression<sup>18</sup>

$$H_{c2}^*(0) = \frac{\Phi_0}{2\pi\xi_0^2}, \quad (2)$$

where  $\Phi_0 = ch/2e = 2.07 \times 10^{-7}$  Oe $\text{cm}^2$  is the flux quantum. The calculation gives  $\xi_0 = 120$  Å.

The paramagnetic limiting field at  $T=0$  K,  $H_{p0}$ , in the absence of spin-orbit scattering is given by the relation<sup>19,20</sup>

$$H_{p0}(0) = 18.4T_c(\text{kOe}), \quad (3)$$

which for  $T_c = 0.52$  K yields  $H_{p0} = 9.57$  kOe. Presumably, spin-orbit scattering is responsible for the fact that  $H_{c2}(0)$  exceeds  $H_{p0}$  by nearly a factor of 2.

The coherence length can also be obtained from the equation<sup>18</sup>

$$\xi_0 = 0.18 \frac{\hbar v_F}{k_B T_c}. \quad (4)$$

However, it is first necessary to estimate the Fermi velocity  $v_F$  of  $\text{UPt}_3$ , which can be done in the following way. Assuming a spherical Fermi surface, the Fermi wave vector  $k_F$  can be calculated from

$$k_F = \left( \frac{3\pi^2 Z}{\Omega} \right)^{1/3}, \quad (5)$$

where  $Z$  is the number of electrons per unit cell and  $\Omega$  the unit cell volume. As a rough approximation, we assume that the heavy electrons are contributed by trivalent U atoms so that  $Z = 6$  since there are two  $\text{UPt}_3$  formula units per unit cell. From the hexagonal lattice parameters  $a = 5.764$  Å and  $c = 4.899$  Å for the  $\text{UPt}_3$  specimen we investigated, we find  $\Omega = 1.41 \times 10^{-22}$   $\text{cm}^3$ . We then obtain  $k_F = 1.08 \times 10^8$   $\text{cm}^{-1}$  from Eq. (5). The effective mass  $m^*$  can be deduced from the relation

$$m^* = \frac{\hbar^2 k_F^2 \gamma}{\pi^2 (Z/\Omega) k_B^2}, \quad (6)$$

which gives  $m^* = 187m_e$ , where  $m_e$  is the free-electron mass. By means of the result

$$v_F = \hbar k_F / m^* \quad (7)$$

we find  $v_F = 6.67 \times 10^5$   $\text{cm s}^{-1}$ . Equation (4) then yields the value  $\xi_0 = 176$  Å, which is in reasonable agreement with the value inferred from  $H_{c2}$ , considering the approximations that we have made.

A different method for estimating  $k_F$  starting from the

measured initial slope of  $H_{c2}(T)$  given in Ref. 7 results in  $k_F = 9.5 \times 10^7 \text{ cm}^{-1}$ , 88% of the value found above. This indicates that our assumption of three heavy electrons per U atom used in our determination of  $k_F$  is reasonable.

The upper critical magnetic field measurements reported herein reveal that there is substantial anisotropy in  $H_{c2}(T)$  and positive curvature near  $T_c$  which is considerably more pronounced in  $H_{c2}^{\parallel}$  than in  $H_{c2}^{\perp}$ . Considerably less positive curvature in  $H_{c2}(T)$  near  $T_c$  has been observed for  $\text{CeCu}_2\text{Si}_2$ ,<sup>7</sup> and none at all for  $\text{UBe}_{13}$ .<sup>8</sup> The origin of the positive curvature in  $H_{c2}(T)$  near  $T_c$  in  $\text{UPt}_3$  is not present-

ly understood. Analysis of the  $H_{c2}$  vs  $T$  data yields an estimate for  $\xi_0$  of  $\sim 120 \text{ \AA}$ . Within the approximations that we have made, this value is consistent with an effective mass for  $\text{UPt}_3$  of  $\sim 200m_e$ .

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