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Upper critical magnetic field of the heavy-fermion superconductor 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 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 ~ 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 $CeCu_2Si_2$ (Ref. 1) and 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[3,4] 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.[5,6] In particular, both compounds have enormous values of the electronic specific-heat coefficient γ of ~ 1 J/g atom K^2 from which effective masses $\sim 200 m_e$, where m_e is the mass of a free electron, have been estimated.[2,7] The superconducting-state properties are characterized by low values of the superconducting transition temperature $T_c \lesssim 1$ K,[1,2] as well as relatively large values of the upper critical magnetic field H_{c2} and its initial slope at T_c, $(-dH_{c2}/dT)_{T_c}$.[7,8] Another compound U_6Fe has unusual properties[9] that may place it somewhere in a continuum between heavy-fermion and conventional superconductivity.

The compound UPt_3 has recently been reported to exhibit bulk superconductivity with a T_c of 0.54 K.[10] There are certain similarities between the properties of UPt_3 and those of the heavy-fermion superconductors $CeCu_3Si_2$ and UBe_{13}, as well as some differences. One of these differences is in the temperature dependence of the electrical resistivity ρ. For UPt_3, ρ increases monotonically with increasing temperature with substantial negative curvature,[10] while for both $CeCu_2Si_2$ (Ref. 5) and UBe_{13},[2] ρ 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 UPt_3, the existence of which has been inferred from the temperature dependences of the magnetic susceptibility[11,12] and low-temperature specific heat.[10,12] 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 γT term with $\gamma = 450$ mJ/g atom K^2 and a contribution that has been attributed to spin fluctuations[13-15] of the form $T^3 \ln(T/T_{sf})$, where T_{sf} is the spin fluctuation temperature.[10] 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 UPt_3 with the current flowing in the direction of the hexagonal c axis.

The single-crystal specimen of UPt_3 used in this investigation was prepared in a manner previously described.[10] A ^3He-^4He dilution refrigerator was employed to attain temperatures as low as 80 mK which were determined from a 100-Ω 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 UPt_3 specimen with the current flowing along the hexagonal c axis. The current density was ~ 2 A/cm^2. 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 $R_0 = 0.16$ mΩ, $A = 0.25$ mΩ/K^n, and $n = 1.6 \pm 0.1$ for $0.54 \text{ K} \leqslant T \leqslant 8$ K. The resistance ratio $RR \equiv R(296 \text{ K})/R(1 \text{ K}) \simeq 150$ indicates that the UPt_3 crystal is of high quality. Because of the somewhat irregular shape of the faceted 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.

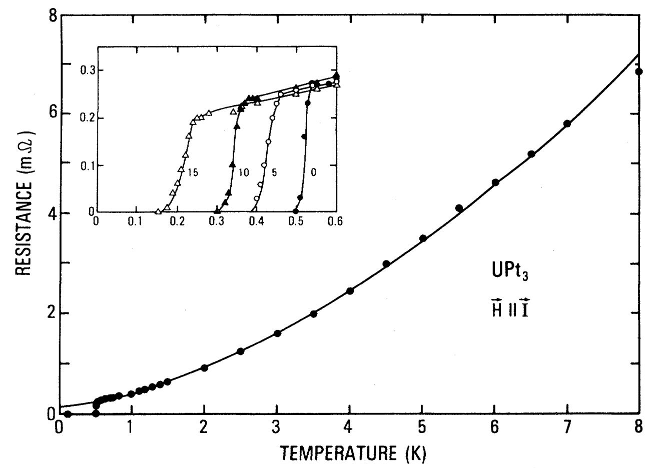

FIG. 1. Electrical resistance R vs temperature of UPt_3 in zero applied magnetic field. The solid line represents a fit of the equation $R=R_0+AT^n$ with parameters R_0, A, and n that are given in the text. Shown in the inset are resistive superconducting transition data in magnetic fields H of 0, 5, 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[16] are estimated to be ≤ 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 UPt_3 sample can be approximated as a long circular cylinder for which the transverse demagnetizing factor is 2π 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

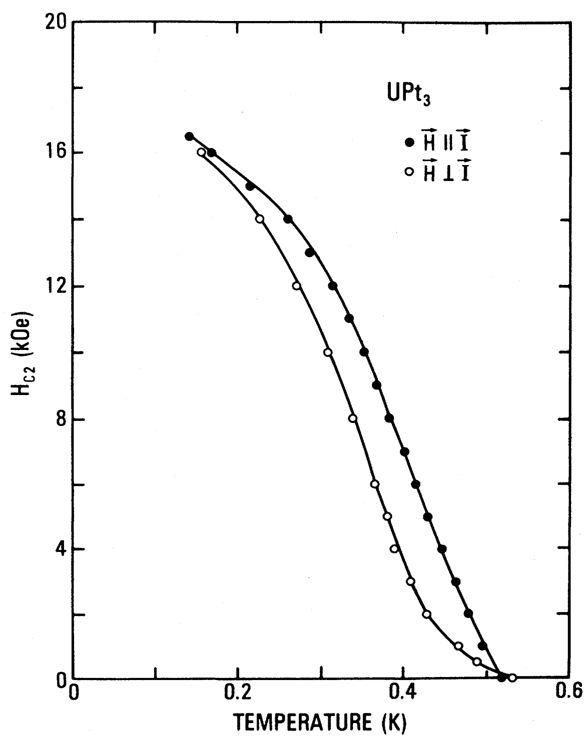

FIG. 2. Upper critical field vs temperature data for UPt_3 with applied field H parallel or perpendicular to the current I.

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.[12]

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, ξ_0. First, the zero-temperature orbital critical magnetic field $H_{c2}^{*}(0)$ can be determined from the weak-coupling formula[17]

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

which gives $H_{c2}^{*}(0)\sim 22.7$ kOe for $T_c=0.52$ K. This value can then be used to calculate ξ_0 by means of the expression[18]

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

where $\Phi_0=ch/2e=2.07\times10^{-7}$ Oe 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[19,20]

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

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[18]

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

However, it is first necessary to estimate the Fermi velocity v_F of 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

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

where Z is the number of electrons per unit cell and Ω 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 UPt_3 formula units per unit cell. From the hexagonal lattice parameters $a=5.764$ Å and $c=4.899$ Å for the UPt_3 specimen we investigated, we find $\Omega=1.41\times10^{-22}$ cm^3. We then obtain $k_F=1.08\times10^{8}$ cm^{-1} from Eq. (5). The effective mass m^* can be deduced from the relation

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

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

$$v_F=\hbar k_F/m^* \tag{7}$$

we find $v_F=6.67\times10^5$ 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 $k_F = 9.5 \times 10^7$ 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 $H_{c2}^{\perp}$ than in $H_{c2}^{\parallel}$. Considerably less positive curvature in $H_{c2}(T)$ near T_c has been observed for $CeCu_2Si_2$,[7] and none at all for UBe_{13}.[8] The origin of the positive curvature in $H_{c2}(T)$ near T_c in UPt_3 is not presently understood. Analysis of the H_{c2} vs T data yields an estimate for ξ_0 of ~ 120 Å. Within the approximations that we have made, this value is consistent with an effective mass for UPt_3 of $\sim 200 m_e$.

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