Anisotropy of the critical field in $CeCu_2Si_2$

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An anisotropy ($\sim 170\%$) of the derivative of the upper critical field at $T = T_c$ has been observed in the compound $CeCu_2Si_2$ during rotation of **H** in a plane near the basis plane. This anisotropy indicates that the superconducting gap may vanish along a line on the Fermi surface in this compound, in which a superconductivity arises in a heavy-fermion system at pressures $p \gtrsim 1$ kbar. The anisotropy disappears at $p > 9$ kbar.

1. Considerable interest has recently been attracted to superconducting systems with heavy fermions [$CeCu_2Si_2$ (Refs. 1–3), UBe_{13} (Ref. 4), and UPt_3 (Ref. 5)], in which the low-temperature electron state density is 10^2–10^3 times higher than in normal metals. This higher state density and also the superconductivity result from heavy fermions [$m^* \sim (10^2–10^3)m_0$]. Superconducting systems with heavy fermions are analogs of a sort of superfluid ^3He, and on this basis it has been suggested [6–10] that a nontrivial pairing may occur in these superconductors. Because of the strong spin-orbit interaction in heavy-fermion superconductors, the spins are "frozen" in the lattice, and they rotate along with the lattice under symmetry transformations. This circumstance has made it possible to carry out a symmetry analysis of superconducting states in $CeCu_2Si_2$, UBe_{13}, and UPt_3 (Refs. 6–8). This analysis predicts that the superconducting gap will vanish at certain points or along certain lines on the Fermi surface. The nature of this vanishing can be determined by studying the angular dependence of the upper critical field H_{c2} near T_c (Ref. 8). We have accordingly studied the anisotropy of the derivative $dH_{c2}/dT(T_c)$ in the tetragonal-symmetry heavy-fermion superconductor $CeCu_2Si_2$.

2. $CeCu_2Si_2$ single crystals of stoichiometric composition exhibit a superconductivity at pressures[2,3] $p \gtrsim 1$ kbar, so the stoichiometric single crystal used in the present experiments, a wafer with dimensions of $3\times1.5\times0.2$ mm, is mounted in a pressure chamber. The angle between the C_4 axis and the direction along the "bomb" channel is $\lesssim 8°$, and the direction of the current **i** (see the inset in Fig. 1) is not deliberately tied to a definite crystallographic direction in the basis plane. The rotation of the magnetic field **H** in the plane perpendicular to the "bomb" channel is achieved by means of two identical superconducting Helmholtz coils making an angle of 90° with respect to each other. The field **H** is rotated through an angle φ by passing currents $I\sin\varphi$ and $I\cos\varphi$ through these two coils. The temperature dependence of the resistance at fixed values of φ and **H** is measured by a four-contact method at a direct current $I = 0.1$–0.5 mA with an automatic apparatus using a ^3He-^4He dissolution refrigerator. The change in the resistance at the superconducting transition (Fig. 1), in the interval $(0.2–0.8)R_0$ (R_0 is the residual resistance), can be approximated by a linear dependence of R on T with a correlation coefficient no worse than 0.993. From the intersection of this dependence

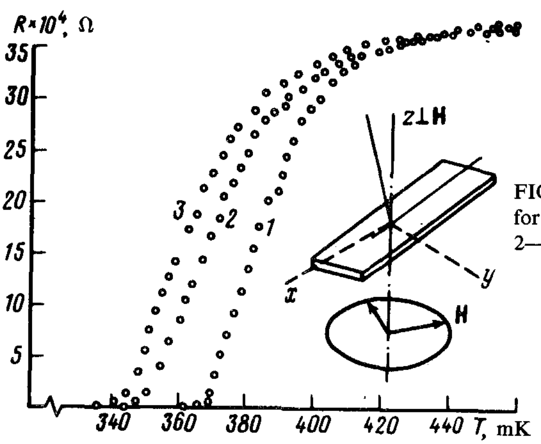

FIG. 1. Superconducting transitions in $CeCu_2Si_2$ for the angle $\varphi = 0$ in several fields: 1—$H = 0$; 2—2.14 kOe; 3—3.21 kOe.

with the level $0.5R_0$ we find the temperature of the superconducting transition, $T_c(H, \varphi)$. Special measurements of $T_c(H)$ carried out for various values of φ_0 at several fixed values of the field H and at several values of the current i showed that the critical temperature $T_c(H)$ does not depend on the current in the range $i = 0.1$–0.5 mA, and the T dependence of the critical field H_{c2} is linear in the region $H \lesssim 4$ kOe; in the limit $H \to 0$, this temperature dependence for the various angles φ_0 extrapolates to the same point $T_c(H = 0)$. The derivative of the upper critical field at $T = T_c$ is calculated from the known values of H, $T_c(H)$, and $T_c(H = 0)$: $dH_{c2}/dT = H/(T_c(H = 0) - T_c(H))$.

3. The angular dependence of dH_{c2}/dT found for a given $CeCu_2Si_2$ single crystal at two pressures is shown in Fig. 2. At $p = 9.6$ kbar there is no anisotropy within the experimental error ($\pm 7\%$). At a pressure of 5.7 kbar, the anisotropy of the upper critical field reaches 170–180% (Fig. 2). A characteristic feature of these curves of dH_{c2}/dT versus φ is that the onset of the anisotropy during rotation of the field **H** in a plane near the basis plane correlates with the pressure dependence of the anisotropy $dH_{c2}/dT(T_c)$ measured for two fixed directions, $\mathbf{H} \| C_4$ and $\mathbf{H} \perp C_4$, for a sample cut from the same bar (Fig. 3). In each case the anisotropy exists in the pressure interval 2–7 kbar and disappears at $p > 7$ kbar. In the pressure interval $p = 2$–7 kbar, we also

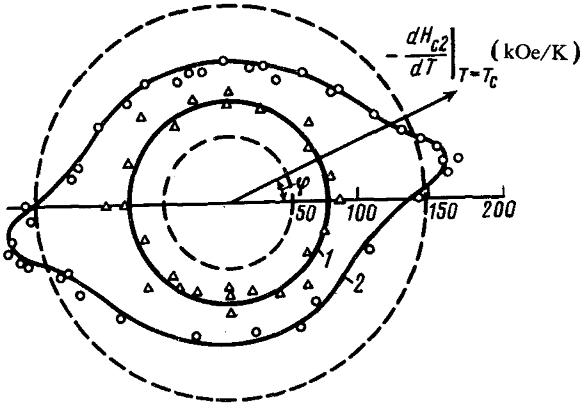

FIG. 2. Angular dependence of $dH_{c2}/dT(T_c)$ in $CeCu_2Si_2$ at two pressures: 1—$p = 9.6$ kbar; 2—5.7 kbar.

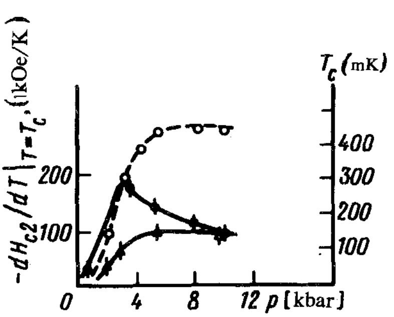

FIG. 3. Pressure dependence of $dH_{c2}/dT(T=T_c)$ for H$\|C_4$ (Δ) and H$\perp C_4$ (●) and of the temperature T_c (dashed line). These results were obtained from a sample cut from the same bar as the sample corresponding to Figs. 1 and 2.

observe an anisotropy of the fields[11] $H_{c2}(0)$ for H$\|C_4$ and H$\perp C_4$; for the $H_{c2}(T)$ curves, relatively large values of the derivative $dH_{c2}/dT(T_c)$ correspond to relatively small values of $H_{c2}(0)$. Over the entire pressure range, there is no anisotropy of the magnetoresistance, within 10%, in the basis plane at $T>T_c$.

4. The observed anisotropy of $dH_{c2}/dT(T_c)$ cannot be due to geometric factors (the shape of the sample, the relative orientation of **i** and **H**, etc.), since this anisotropy disappears with increasing pressure in the region in which the critical temperature T_c depends only very weakly on the pressure (Fig. 3). It is natural to suggest that the anisotropy of $dH_{c2}/dT(T_c)$ results from a passage of the vector **H** through directions along which the superconducting gap on the Fermi surface vanishes. The absence of a fourfold symmetry in the anisotropy of dH_{c2}/dT (Fig. 2) is evidence that the superconductivity classes corresponding to the one-dimensional representations of the D_4 group[7] do not occur for $CeCu_2Si_2$.

The observed anisotropy (Fig. 2) may be due to an intersection of the plane in which the vector **H** rotates with the line of zeros at the intersection of one of the vertical symmetry planes with the Fermi surface [the class $D_2(C_2)\times R$; Ref. 7]. If we allow some deviation from collinearity of the C_4 axis and the normal to the rotation plane of **H** (see the inset in Fig. 1), we conclude that the anisotropy $dH_{c2}/dT(T=T_c)$ (Fig. 2) may be caused by an intersection of the line of zeros running perpendicular to the C_4 axis [the $D_4(E)$ class[7]] with the **H** rotation plane or an intersection with the same plane of two (of the four possible) discrete points at which the gap vanishes in the basis plane.[7]

In summary, the results of the present study indicate that the gap in $CeCu_2Si_2$ probably vanishes along a line. The conclusion that the gap vanishes on a line is in agreement with the temperature dependence of the heat capacity of this compound,[12] $C(T)\sim T^2$, and the spin-lattice relaxation rate,[13] $1/T_1\sim T^3$, at $T<T_c$. For ordinary superconductors these functional dependences are exponential. For superconductors with a gap that vanishes at discrete points or along a line, we should observe the behavior $C(T)\sim T^3$, $1/T_1\sim T^5$ and $C(T)\sim T^2$, $1/T_1\sim T^3$, respectively. We do not rule out the possibility that the change in the anisotropy (Fig. 3) is an analog of a sort of the phase transitions that occur in superfluid ^{3}He under pressure and that the anisotropy $dH_{c2}/dT(T_c)$ itself exists only in a certain transition region between the " magnetic case" (p is small or even "$p<0$"), in which the Condon spin cancellation has not yet effectively come into play,[11] and a regime of a nonmagnetic superconducting Kondo lattice (p is large), in which the magnetic moments of the Ce^{3+} ions in the $CeCu_2Si_2$ are completely suppressed.

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