Anisotropy in the upper critical field and Hall effect of $CeCu_2Si_2$ in the coherent regime

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We have investigated the angular dependence of the upper critical field H_{c2} for the heavy-fermion superconductor $CeCu_2Si_2$ over the magnetic field interval $H \lesssim 3$ kOe and the hydrostatic pressure interval $p < 17$ kbar. We observed that an inclination of the magnetic field vector **H** by $\pm 5\%$ relative to the $CeCu_2Si_2$ basal plane led to a sharp decrease in the derivative $dH_{c2}/dT|_{T_c}$, and to the appearance of a region with positive curvature in the $H_{c2}(T)$ curves near T_c. To an accuracy of $\pm 55\%$, there was no anisotropy in $dH_{c2}/dT|_{T_c}$ as a function of rotation of the magnetic field within the basal plane. For temperatures $T < 2$ K we observed a maximum in the temperature dependence of the $CeCu_2Si_2$ Hall coefficient $R_H(T)$, which indicates the possibility of a transition at low temperatures to a regime in which electrons are coherently scattered by magnetic Ce^{3+} ions.

INTRODUCTION

In 1979, superconductivity was discovered by Steglich[1] in the compound $CeCu_2Si_2$; this compound possesses an unusually high density of states at the Fermi level at low temperatures, exceeding that of a normal metal by a factor of 10^2 to 10^3. The discovery of superconductivity in this system, which consists of quasiparticles with large effective mass $m^* \sim (10^2–10^3)m_0$—i.e., "heavy fermions"—stimulated a search for new superconductors of this type. At the present time, superconductivity in heavy-fermion (HF) systems has been observed in UBe_{13},[2] UPt_3 and URu_2Si_2.[4,5] Experimental and theoretical research in this area has progressed at such a rapid rate that it is now possible to speak of the birth of a new direction in the physics of superconductors. The interest in superconducting heavy-fermion systems stems from the fact that available experimental data[6] point to the possibility of "nontrivial" superconductivity in these materials, i.e., superconductivity which cannot be adequately described within the framework of the BCS theory. In HF systems, because of the strong spin-orbit interaction the electron spins are frozen into the lattice and "swivel" along with it when its symmetry changes; this makes it feasible to conduct a symmetry analysis of the possible superconducting states.[7] Such an analysis shows that in the case of singlet pairing the superconducting gap can reduce to zero both at isolated points and along the lines where the Fermi surface intersects the characteristic symmetry planes (see Fig. 6 below). In the case of pure "triplet" superconductivity the gap can reduce to zero only at the discrete points where the Fermi surface intersects the symmetry axes.

Thus, by comparing the results of this symmetry analysis with experimental data derived from investigating the anisotropy of superconducting HF systems, we can reach certain well-defined conclusions as to the character of the electron pairing which takes place in HF systems. Of special interest from this point of view are studies of the angular dependence of the upper critical field H_{c2} near the temperature T_c $(H = 0)$.[8] In Ref. 9, preliminary results were reported concerning an investigation of anisotropy in H_{c2} for tetragonal-symmetry single-crystal $CeCu_2Si_2$, in which the vector **H** was rotated in a fixed plane close to the basal plane.

In this paper we present a detailed study of the angular dependence of $H_{c2}(T)$ for various single crystal samples of $CeCu_2Si_2$ under conditions in which the vector **H** can have any specified orientation relative to the crystal. For the first time we have measured the temperature dependence of the Hall coefficient R_H in $CeCu_2Si_2$ for temperatures $T < 2$ K; at these temperatures, we expect to see the onset of coherent Kondo screening of the magnetic centers in the system of magnetic Ce^{3+} ions.

EXPERIMENTAL METHOD

A characteristic of investigations of critical-field anisotropy in HF systems at ultralow temperatures is the fact that the value of the derivative of the critical field near T_c for HF systems is extremely large; for example, in $CeCu_2Si_2$ $dH_{c2}/dT(T_c) \approx 200–300$ kOe/K.[10] Therefore, in order to determine possible changes in the slope of the dH_{c2}/dT curve at $T = T_c$, it is necessary to record shifts in the superconducting transition with errors in T_c less than 0.3 mK. In order to investigate the Hall EMF in $CeCu_2Si_2$ at ultralow temperatures, it is necessary to measure voltages ~ 100 nV to an accuracy of a few percent. This sort of measurement accuracy can be attained either by using a SQUID or with the help of mathematical signal processing on a computer as the experiment progresses. In the present paper the measurement was conducted using an automated setup built around a $^3He–^4He$ solution refrigerator from the SHE company (USA) and a computer. In order to transfer information between the computer and the external apparatus, a parallel interface was used, based on a series K-155 microprocessor.

Measurements of the specific resistivity ρ were conducted in the following fashion: with the help of a computer controlled by transistorized switches we alternately connected each of three channels to the input amplifier. After receiving and processing the information, the computer switched the current in the sample circuit and again recorded the reading on the voltmeter. For each direction of cur-

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rent the channel was queried ten times and the results were averaged. The computer calculated the half-difference of the signals, eliminating in this way the effects of thermo-EMFs and amplifier drift. In order to determine the temperature we used a "Speer" resistive thermometer, whose resistance was measured with a picowatt self-balancing potentiometer bridge. The thermometer was mounted on the high-pressure chamber holder opposite to the sample. Beyond the temperature T_c the superconducting transition is taken to be the temperature corresponding to half the residual sample resistance $\rho_{\rm rem}/2$. To measure the temperature dependences $\rho(T)$ the computer selected points lying in the interval 0.2–0.8 $\rho_{\rm rem}$, storing their values; after the superconducting transition had occurred, it approximated the function $\rho(T)$ in the interval by a direct least-squares method. The value T_c was defined as the point of intersection of the resulting curve with the horizontal line $\rho_{\rm rem}/2$. The reliability of this approximation is measured by the correlation coefficient, which was at least 0.99. The superconducting transition temperature T_c is reproduced to an accuracy which is essentially better than 0.1%.

We were able to change the magnitude and direction of the magnetic field **H** by using a system of superconducting coils: a vertical solenoid (with a 59 Oe/A constant), and four additional coils, forming a pair of mutually perpendicular Helmholtz systems, which were used to generate a horizontally directed magnetic field H. The four coils had constants of 107 Oe/A (see the inset of Fig. 3 below). By specifying the ratios of the currents I in the Helmholtz systems according to the law $I \sin\varphi$ and $I \cos\varphi$, we could create a magnetic field having arbitrary orientation (angle φ) in the horizontal plane. With the help of the vertical solenoid, the inclination of the vector **H** from the horizontal plane could be varied through an angle of θ up to $\pm 12°$ for $\mathbf{H} \leqslant 3$ kOe.

Because single crystals of $CeCu_2Si_2$, (i.e., the stoichiometric compound) are superconducting only when subjected to a pressure $P > 2$ kbar,[10] the single-crystal samples were mounted in a high pressure chamber in order to measure the anisotropy of their superconducting properties. The magnitude of the pressure was determined from the shift in T_c of a superconducting tin manometer. In order to investigate the temperature dependence of the Hall EMF, the magnetic field of the solenoid $H \leqslant 50$ kOe was fixed with the help of a superconducting switch. The full temperature interval is broken up into portions with $\Delta T \approx 30$ mK, within each of which the Hall resistance was averaged and stored. This interval was traversed twice for opposite directions of the magnetic field, after which for each interval T_j a value of the Hall resistance was determined

$$\rho_j^H = (\rho_j^{H^+} - \rho_j^{H^-})/2.$$

Thus, by using this setup we were able to carry out automatic measurements of the electrical characteristics of the sample for temperatures from 3 K down to 40 mK and for hydrostatic pressures up to 17 kbar, in a magnetic field whose orientation could be changed in the horizontal plane throughout the angular range 0°–360°, and inclined to a vertical plane at angles up to 12°. For these measurements, the accuracy in determining T_c amounted to 0.2 mK, while the accuracy in determining the electrical resistance amounted to $10^{-6}\ \Omega$.

Lamellar single crystals of $CeCu_2Si_2$, labelled No. 1 and No. 2, were grown in a slot between two polycrystalline ingots. In order to synthesize the polycrystalline $CeCu_2Si_2$ we used constituents of the following purities: Ce—99.85%, Cu—99.99%, Si—99.99%. The compound was prepared by direct alloying of stoichiometric amounts of the original components in a ceramic crucible made of aluminum oxide with a tungsten heater. The material mixtures were maintained in the alloyed state for a period of 30 minutes, and then were slowly cooled. The prepared crystals were subjected to a homogenizing annealing at a temperature of 800 °C over the course of 150 hours. In order to control composition and homogeneity an x-ray phase analysis was carried out, while for the single crystals we also performed an x-ray structural analysis. The potential and current contacts were welded on by the electric-spark method.

CRITICAL-FIELD CURVES OF H_{c2} FOR $CeCu_2Si_2$

We investigated first the features of the $H_{c2}(T)$ curves for single-crystal samples of $CeCu_2Si_2$. In the first series of experiments the sample was mounted in such a way that the C_4 axis was perpendicular to the "bomb" channel, while the vector **H** was rotated through an angle $(0 < \theta < 360°)$ in the plane C_2–C_4 (Figs. 1 and 2). For sample No. 1, which had dimensions $3 \times 1.5 \times 0.2$ mm^3, the critical field curves $H_{c2}(T)$ and the position of the crystallographic axes relative to the sample faces are shown in Fig. 1. Whereas for $H \| C_2$ the dependence of $H_{c2}(T)$ is linear up to $H \approx 3$ kOe (curve 1, Fig. 1a), inclining the vector **H** at an angle $\theta \sim 10°$ not only sharply decreases the slope of the linear portion of the function $H_{c2}(T)$, but also gives rise to the appearance of an appreciable nonlinear section of H_{c2} near $T_c(0)$ (Fig. 1a, curves 2,3). If we evaluate the derivative dH_{c2}/dT directly at the point $T_c(H=0)$, then $dH_{c2}/dT|_{T_c}(H\|C_2)$ exceeds $dH_{c2}/dT|_{T_c}(H\|C_4)$ by more than an order of magnitude. If, however, we determine the quantity $dH_{c2}/dt)$ for various values of θ from the slope of sufficiently extended linear portions of the functions $H_{c2}(T)$ (see Fig. 1), we find by this procedure a smaller anisotropy in dH_{c2}/dT. The angular dependence of the derivative dH_{c2}/dT determined by this latter method is shown in Fig. 1b for two values of pressure.

So as to elucidate whether or not the anisotropy in

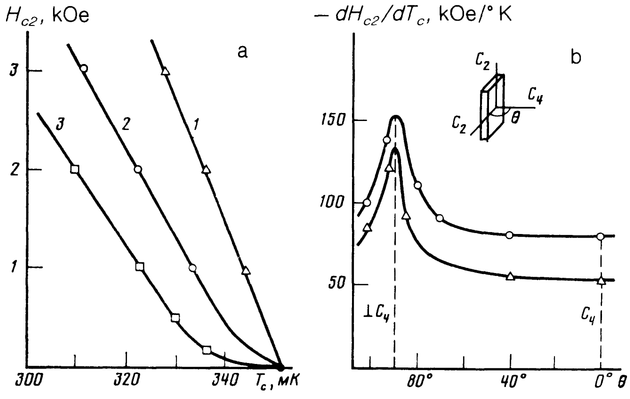

FIG. 1. (a) The dependence of $H_{c2}(T_c)$ in $CeCu_2Si_2$ sample No. 1 for various directions of magnetic field: 1—$\mathbf{H}\|C_2$, 2—**H** makes a 10° angle with C_2, 3—$\mathbf{H}\|C_4$. The filled circle is the value $T_c(0)$. (b) The angular dependence of the maximum slope dH_{c2}/dT in $CeCu_2Si_2$ sample No. 1 at $P = 5.7$ kbar (O) and $P = 17$ kbar (Δ).

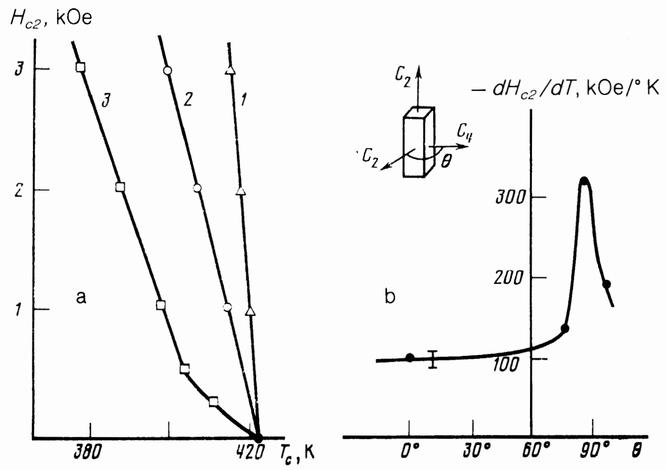

FIG. 2. (a) The $H_{c2}(T)$ curves in $CeCu_2Si_2$ sample No. 2 with the square cross section: 1—$\mathbf{H}\|C_2$, 2—**H** makes a 10° angle with C_2, 3—$\mathbf{H}\|C_4$, (b) The angular dependence of the maximum slope of dH_{c2}/dT at $P = 5.2$ kbar.

dH_{c2}/dT is connected with the sample shape (in sample No. 1 of $CeCu_2Si_2$ the basal plane coincided with the plane of the sample itself), sample No. 2 of $CeCu_2Si_2$ was prepared with dimensions of $0.4\times0.4\times3$ mm^3, oriented along the C_2 axis (Fig. 2). This sample was mounted along the channel of the "bomb" and investigated under a pressure of 5.2 kbar. In Fig. 2 we show the function $H_{c2}(T)$ for three directions of magnetic field as the vector **H** is rotated in the C_2–C_4 plane. For curve 1 ($\mathbf{H}\|C_2$), just as for the case of $CeCu_2Si_2$ sample No. 1, the characteristic dependence of H_{c2} on T is linear. Inclining the vector **H** from the C_2 axis in this case is accompanied by a considerable change in the function $H_{c2}(T)$ (see Figs. 1 and 2). The maximum slope dH_{c2}/dT sharply decreases (curve 2, **H** inclined from C_2 by 10°) and a nonlinear portion of the H_{c2} dependence on T appears near T_c (curve 3, $\mathbf{H}\|C_4$) In Fig. 2b we show the angular dependence of the slope of the straight-line portions of the $H_{c2}(T)$ curves near T_c as **H** rotated in the C_2–C_4 plane. As **H** passes through the basal plane, the magnitude of dH_{c2}/dT increases by more than a factor of 3 within the angular interval $\pm 5°$ (Fig. 2b).

Thus, the observed anisotropy cannot be related to sample geometry, since there exists no qualitative difference between the data obtained from $CeCu_2Si_2$ sample No. 1, which is in the form of a film, and $CeCu_2Si_2$ sample No. 2 with square cross section. Furthermore, in $CeCu_2Si_2$ sample No. 2 the observed anomalies appear even more marked. Errors in determining dH_{c2}/dT which arise from measuring the temperature with the "Speer" thermometer in the magnetic field, and also as a result of the weak dependence of its magnetoresistance on the field direction, were less than 10%.

With a goal of studying a possible anisotropy in the superconductive properties of $CeCu_2Si_2$ in the basal plane, we conducted a series of trials on sample No. 1, for which the perpendicular to the plane coincided with the C_4 axis (see the inset in Fig. 3). The sample was mounted in a high-pressure chamber in such a way that the angle between the C_4 axis and the direction along the "bomb" channel was less than 5–7°. The direction of the measurement current $i = 0.1$–0.5 mA was not tied to any specific crystallographic direction in the basal plane. It was found that if the magnetic

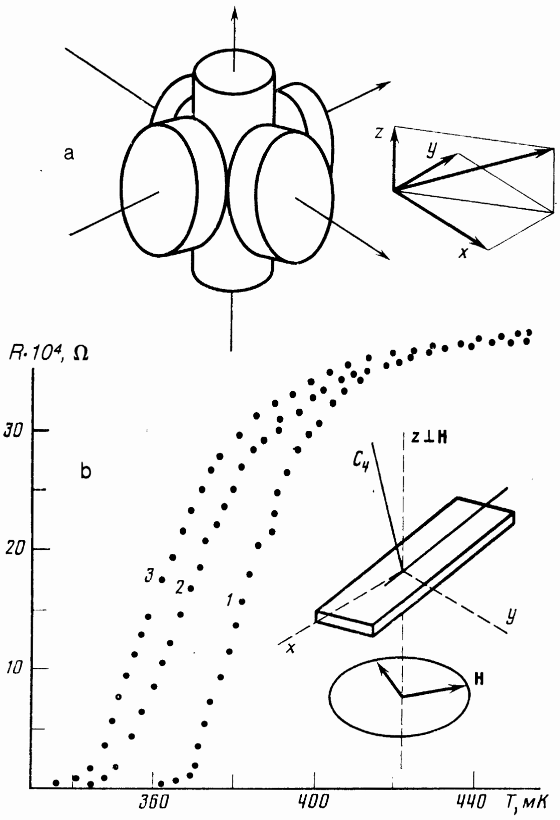

FIG. 3. (a) A schematic illustration of the system used to rotate the magnetic field in an arbitrary direction. On the plot (b) we illustrate typical superconducting transitions in $CeCu_2Si_2$ sample No. 1: 1—$H = 0$, 2—$H = 2.14$ kOe, 3—$H = 3.21$ kOe. The inset shows the experimental setup, with a rotation of the magnetic field in a plane close to the basal plane.

field vector was rotated in the xy plane (see Fig. 3). i.e., by using only the two pairs of Helmholtz coils, dH_{c2}/dT was found to have a two-fold symmetry axis (Figs. 4,5) at angles $\varphi = \varphi_{\max}$.

In order to clarify whether or not any anisotropy is observed when the sample's basal plane is inclined out of the xy plane, we carried out an experiment in which the vector **H** was inclined at an angle $\theta < 10°$ by using the vertical solenoid (Fig. 5). It turns out that the value of dH_{c2}/dT depends significantly on θ. The angle $\theta = \theta_{\max}$ at which dH_{c2}/dT attains its maximum equals zero for $\varphi = \varphi_{\max}$ (Fig. 5) and

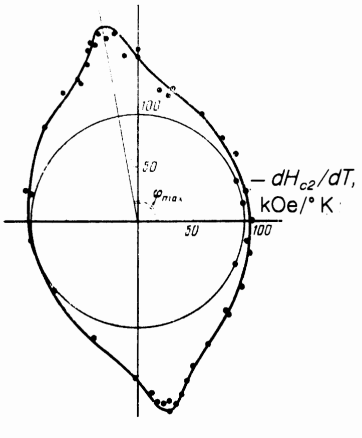

FIG. 4. The angular dependence of $dH_{c2}/dT|_{T_c}$ for $CeCu_2Si_2$ sample No. 1 as **H** is rotated in a plane close to the basal plane ($P = 5.7$ kbar).

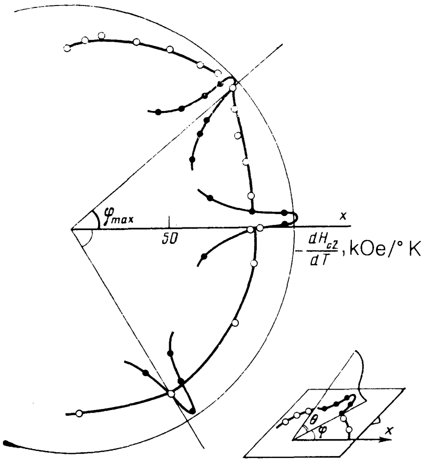

FIG. 5. The angular dependence of $dH_{c2}/dT|_{T_c}\{\varphi\}$ for $P = 8.7$ kbar (○) and when the plane of rotation of **H** is tilted by means of vertical solenoid (●).

$\theta_{max} \cong 5°$ for $\varphi = \varphi_{max} + \pi/2$ (Fig. 5). The value $dH_{c2}/dT|\theta_{max}$ itself is practically independent of φ, which to 5% accuracy indicates that dH_{c2}/dT is isotropic in the basal plane.

It should be noted that the anisotropy in the superconducting properties of $CeCu_2Si_2$ is not caused by anisotropy in the magnetoresistance $\rho(H)/\rho(0)$, which for the single crystals under study was less than the value 0.1% for $\mathbf{H} \leqslant 3$ kOe in any direction.[11]

ANISOTROPY OF THE UPPER CRITICAL FIELD IN $CeCu_2Si_2$

It is well known that in type I superconductors an anisotropic effective mass does not produce any appreciable anisotropy in the critical field. In type II superconductors the presence of significant anisotropy is as a rule connected with quasi-one-dimensional and quasi-two-dimensional subsystems. For classical three-dimensional superconducting systems the largest upper critical field anisotropy near T_c known to us is less than $\approx 20\%$.[12]

However, when it comes to superconductivity HF systems, at this time the following facts have been established: for UBe_{13} there is no anisotropy in the value 300 kOe/K of $-dH_{c2}/dT$ for $\mathbf{H}\|C_2$ and $\mathbf{H}\|C_4$,[13] while for UPt_3 [14] the curves $\mathbf{H}_{c2}(T)$ have a character similar to $CeCu_2Si_2$, the only difference being that in UPt_3 the function $H_{c2}(T)$ is linear for $\mathbf{H}\|C_6$ and has a portion with positive curvature near T_c when the magnetic field direction is in the basal plane. It must also be pointed out that in single-crystal $CeCu_2Si_2$ with excess copper the anisotropy in dH_{c2}/dT has a wholly different character from that of stoichiometric $CeCu_2Si_2$.[15,16] First of all, let us try to establish whether or not the anisotropy in dH_{c2}/dT for $CeCu_2Si_2$ is connected with the anisotropic character of the effective mass. We note that a direct measurement of cyclotron masses in HF systems is difficult, as a consequence of the small mean free paths $1 \sim 10$ Å of the heavy fermions. At the present time there are only indirect indications of the existence of an anisotropic m^* in $CeCu_2Si_2$. It has been established that in the region $T < T_k$ the specific resistivity, thermoelectric power and magnetic susceptibilty χ have a sharply anisotropic character; the value of χ along the C_4 axis is more than twice as large as its value along the C_2 axis.[17]

The theoretical calculations carried out by Fulde[18] for $CeCu_2Si_2$ when $T < T_K$, i.e., in the temperature range for which coherent Kondo spin screening takes place, confirm that the quasiparticle spectrum of $CeCu_2Si_2$ is significantly anisotropic: the effective mass can differ along various directions by 2–3 orders of magnitude. Nonetheless, from our view, the anisotropy in the superconducting properties of $CeCu_2Si_2$ (Figs. 1 and 2) cannot be satisfactorily explained within an effective mass model with isotropic BCS-type pairing,[19] since in this case it is difficult to obtain the unusually sharp angular dependence of dH_{c2}/dT near the basal plane.

It is also difficult to relate the unusual anisotropy in the properties of $CeCu_2Si_2$ in the superconducting state to the presence of surface superconductivity in $CeCu_2Si_2$, since the critical fields measured via the temperature dependences of the magnetic susceptibility and the resistive method are close to those measured in Ref. 20. Furthermore, the anomalies in $H_{c2}(T)\{\theta,\varphi\}$ for the sample with square cross section are found to be even more marked than those of the "planar" single-crystal $CeCu_2Si_2$.

Taken as a whole, all the properties of $CeCu_2Si_2$ in the superconducting state which have been studied up till now, including our observations of the anisotropy of $H_{c2}(T)$ in $CeCu_2Si_2$, can be explained by means of at least two theoretical models; at this time it is difficult to choose between them. They are a model of anisotropic s-pairing in Kondo lattices[21] and a model of p-pairing with nonzero electron orbital momentum.[6–8] Possible reasons for considering p-pairing in HF systems were discussed in the Introduction. The possibility of anisotropic s-pairing is connected with the low mobility of paired heavy fermions in HF systems, as a consequence of which the characteristic coherence scale

$$\xi \sim \{\Phi_0/(2\pi \cdot 0.693[-dH_{c2}/dT]|_{T_c}T_c)\}^{1/2}$$

(here Φ_0 is a flux quantum) amounts to some tens of angstroms in all. In this situation, the effective attraction between heavy fermions arises because of one-phonon processes and is sharply anisotropic. The most important conclusion of the theory of Ohkawa[21] is that it is possible for the superconducting gap to decrease to zero along a line, which can give rise to the sharp angular dependence of dH_{c2}/dT in $CeCu_2Si_2$. Along with this, we must note that in this theory there is as yet no indication as to the position of the line along which the superconducting gap reduces to zero relative to the crystallographic axes.

If, however, we assume that p-pairing of electrons occurs in the compound $CeCu_2Si_2$, then the angular dependence of dH_{c2}/dT on θ, φ must be investigated by including the symmetry analysis carried out in Refs. 7 and 22. The existence of a sharp anomaly in dH_{c2}/dT as the magnetic field vector passes through the basal plane and the circular symmetry $DH_{c2}/dT|_{T_c}[\varphi]$ (Fig. 6) in the basal plane point to the possibility of the superconducting gap reducing to zero along the curve where the Fermi surface intersects the basal plane. Such an angular dependence of the curves $H_{c2}(T)$ corresponds to the symmetry class $D_4(E)$ (see Figs. 6a, 6c). Comparison of the calculated angular dependence of $H_{c2}(\varphi)/H_{c2}(0)$[22] with the experimental data shows that if triplet pairing is also realized in $CeCu_2Si_2$, then the effective mass in the basal plane must be many times smaller than the effective mass for the direction along the C_4 axis. We note

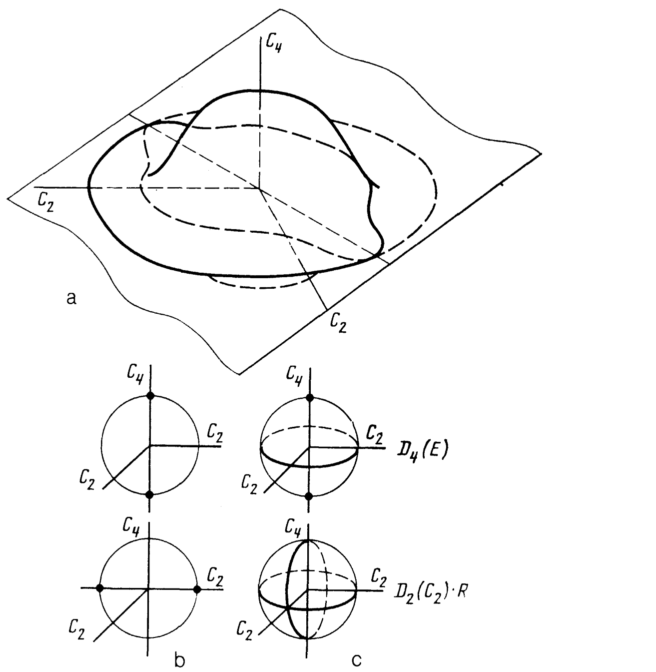

FIG. 6. (a) A three-dimensional diagram of dH_{c2}/dT in $CeCu_2Si_2$; (b) points at which the superconducting gap reduces to zero for $S = 1$ pairing (Ref. 7); (c) points where the superconducting gap vanishes for the classes $D_4(E)$ and $D_2(C_2)R$ (Ref. 7).

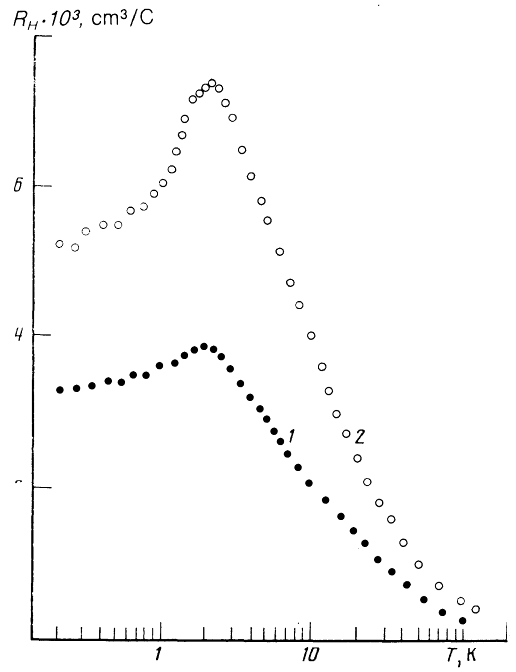

FIG. 7. Temperature dependence of the Hall coefficient R_H in $CeCu_2Si_2$ sample No. 1 (curve 1) and a superconducting polycrystalline sample of $CeCu_2Si_2$ (curve 2).

that Fulde's theory[18] gives the same inequality: $m^*_{c4} \gg m^*_{c2}$. In sum, the data on the anisotropy of H_{c2} argues in favor of the possibility of a vanishing superconducting gap for $CeCu_2Si_2$ along a curve on the Fermi surface. This conclusion agrees with the characteristic temperature dependence of the specific heat for $T < T_c : c_s \propto T^2$ (Ref. 23); the thermal conductivity: $\varkappa \propto T^2$ (Ref. 24); and the spin-lattice relaxation time; $1/T_1 \propto T^3$ (Ref. 25). For "triplet" superconductivity, Refs. 7 and 20 predict a fourfold symmetry axis as **H** is rotated in the basal plane (Fig. 6) and temperature dependences $1/T_1 \propto T^5$, $C_s \propto T^3$, which disagree with the available experimental data on $CeCu_2Si_2$.[23–25]

HALL EFFECT IN $CeCu_2Si_2$

The applicability of the theories of Ohkawa[21] and Volovik-Gor'kov[7,8] to real HF systems may be limited by the presence of impurities and defects, which lower the symmetry of the crystal environment. The accuracy of x-ray phase and structural analyses as a rule is at most 3%. In addition to this, it was recently established[26] for the example of $CeAl_3$ that even a relatively small disruption of the periodicity of the crystal lattice of a HF system can strongly influence the character of the temperature dependence of the Hall coefficient $R_H(T)$ for $T < T_k$ (T_k is the Kondo temperature). In connection with this, we have for the first time studied the behavior of $R_H(T)$ in the HF system $CeCu_2Si_2$ in the temperature range $0.1 < T < 3$ K in magnetic fields up to 60 kOe.

In Fig. 7 we present the temperature dependence of $R_H(T)$ for single-crystal $CeCu_2Si_2$ sample No. 1 ($p = 0$) along with a polycrystalline sample of $CeCu_2Si_2$. In the $CeCu_2Si_2$ sample No. 1, after a significant growth of $R_H(T)$ in the range $T < 150$ K (which was observed earlier; see Ref. 11), R_H goes through a maximum ($T_{max} \approx 1.8$ K), $R_{max} \approx 3.7 \times 10^{-3}$ cm^{-3}/C) and then decreases to a value of 3.2×10^{-3} cm^3/C) for $T \approx 0.3$ K. Qualitatively, the dependence of $R_H(T)$ in polycrystalline $CeCu_2Si_2$, which undergoes a percolation transition below T 2.5 K to the superconducting state, has the same form ($T_{max} \approx 2.2$ K, $R_{max} \approx 7 \times 10^{-3}$ cm^3/C).

The maximum in the curves of $R_H(T)$ for $CeCu_2Si_2$ cannot be related to a transition of the magnetic subsystem in $CeCu_2Si_2$ near $T = T_m \approx 2$ K to a "spin glass" state, since this transition takes place at magnetic fields $H > 1$ kOe[27] in this systems $Ce_xLa_{1-x}Cu_2Si_2$.

When combined with results obtained by studying the temperature dependences of the electronic thermal conductivity coefficient,[24] the electronic specific heat[28] and thermoelectric power[29] at ultralow temperatures, our data points to a reconstruction of the quasiparticle spectrum in $CeCu_2Si_2$ both above and below the transition temperature to the superconducting state. The reason for this transformation of the quasiparticle spectrum in $CeCu_2Si_2$ and other HF systems—$CeAl_3$ (Ref. 26), UBe_{13} (Ref. 30), $CeCu_6$ (Ref. 31)—are as yet unclear. One possible explanation for the anomalies in R_H for HF systems is based on the fact that for $T < T_{con} \approx T_K/10$, a smooth transition takes place from the incoherent to the coherent regime for electron scattering by Kondo centers.

The specifics of the Hall effect in $CeCu_2Si_2$ at ultralow temperatures include the fact that, as opposed to other HF systems, in $CeCu_2Si_2$ there is no sharp decrease of R_H below T_{max}. We should also note the similar $R_H(T)$ curves in nonsuperconducting stoichiometric single-crystal $CeCu_2Si_2$ and superconducting polycrystalline $CeCu_2Si_2$ (Fig. 7).

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