# Superconductivity of $CeCu_2Si_2$

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Single crystals of $CeCu_2Si_2$ are not superconductors at $T \geq 0.05$ K and at standard pressure, in contrast with polycrystalline samples, but they go superconducting when compressed. Their superconductivity has an anomalously large ratio $H_{C2}(0)/T_C(0) \simeq 38$ kOe/K and a derivative $H_{c2}/dT(T=T_c(0) \simeq 140$ kOe/K.

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1. So far, $CeCu_2Si_2$ is the only variable-valence compound for which a possible superconductivity is under discussion.[2] Steglich *et al.*[1] concluded from measurements of the temperature dependence of the resistivity $\rho(T)$, the magnetic susceptibility $\chi(T)$, and the specific heat $c(T)$ of polycrystalline $CeCu_2Si_2$ samples that this compound exhibits a superconductivity with $T_c \simeq 0.5$ K, which results from a hybridization of a $4f$ level and the $s$-$d$ conduction band.

In some recent studies[2,3] of polycrystalline $CeCu_2Si_2$ at $T \simeq 0.5$ K, a decrease in the resistivity was again observed, but the decrease did not go to zero. On this basis, Hull *et al.*[2] suggested that $CeCu_2Si_2$ does not exhibit a superconductivity, and that the anomalies observed in $\rho(T)$, $\chi(T)$, and $c(T)$ in Ref. 1 resulted from a superconductivity of inclusions of a second phase ($CeCu_2$ and $CeCu_6$) in the $CeCu_2Si_2$. Whether $CeCu_2Si_2$ exhibits a superconductivity thus remains an open question.

We have accordingly carried out the first study of the electrical properties of $CeCu_2Si_2$ single crystals, in addition to those of polycrystalline samples, over the temperature range 0.05-300 K, in magnetic fields up to 20 kOe, and at pressures $p$ up to 8 kbar.

2. For polycrystalline $CeCu_2Si_2$ samples, the temperature dependence of the resistivity $\rho$ (curve 1 in Fig. 1) corresponds to that observed in Refs. 1-3. Also in accordance with the other studies, the resistivity $\rho$ drops sharply (by a factor of several units) at $T \simeq 0.5$ K, but it does not drop to zero. The complete suppression of this effect by a magnetic field[3] $H \geqslant 20$ kOe indicates that the decrease in the resistivity results from the presence of a superconducting phase in the $CeCu_2Si_2$ samples.

The $\rho(T)$ dependence for $CeCu_2Si_2$ single crystals at standard pressure (curve 2 in Fig. 1) differs from the corresponding curve for the polycrystalline sample in that it does not have a minimum at $T \simeq 70$ K or a superconducting transition at $T \geqslant 0.05$ K. Furthermore, the first maximum, $T^{(1)}_{\max}$, on the $\rho(T)$ curve of the single crystal occurs several degrees to the left of that for the polycrystalline sample.

3. A study of the electrical conductivity of $CeCu_2Si_2$ single crystals under pressure revealed that at $p \gtrsim 0.9$ kbar there are clearly defined and sharp transitions to a superconducting state (curve 3 in Fig. 1). Extrapolation of the dependence $T_c(p)$ (Fig. 2) to

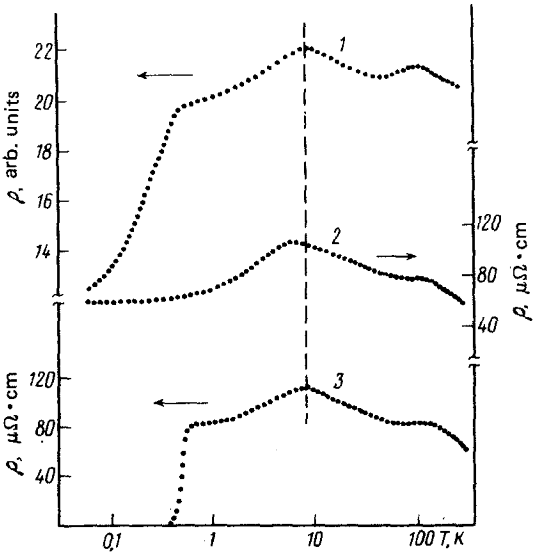

FIG. 1. Temperature dependence of the resistivity, $\rho(T)$. 1–Polycrystalline sample, at $p = 0$; 2, 3–single crystals, at 0 and 5.4 kbar, respectively.

$p = 0$ indicates that $CeCu_2Si_2$ single crystals apparently exhibit a superconductivity with $T_c \leqslant 0.05$ K at standard pressure.

At pressures $p \gtrsim 2.5$ kbar a new superconducting modification of $CeCu_2Si_2$ appears, with $T_c \simeq 0.5$ K. The temperature of the superconducting transition of this modification falls off slightly upon compression, at $\simeq 10^{-5}$ K/bar. The transition from $CeCu_2Si_2$-I (with $T_c \leqslant 0.05$ K, $p < p_t$) to the modification $CeCu_2Si_2$-II (with $T_c \simeq 0.5$ K, $p > p_t$) is probably a first-order phase transition, as is indicated by the hysteresis when the pressure is removed (the dashed curve in Fig. 2) and by the strong (more than twofold) increase in the width of the superconducting transition at $p = p_t$.

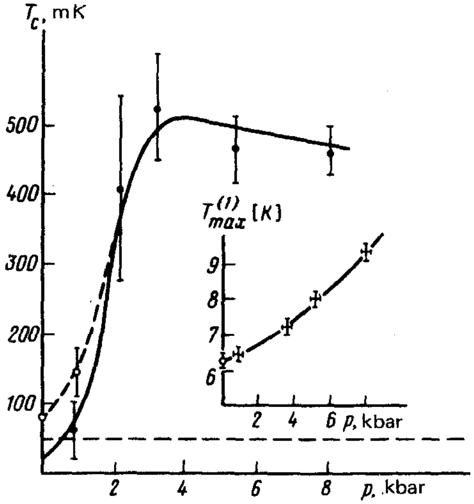

FIG. 2. Pressure dependence of the critical temperature $T_c$ and of the temperature $T_{\max}^{(1)}$ (the inset). The error in $T_c$ was determined from the temperatures corresponding to 0.9 $\rho_0$ and 0.1 $\rho_0$, where $\rho_0$ is the residual resistivity. ●–Recorded with increasing pressure; ○–with decreasing pressure.

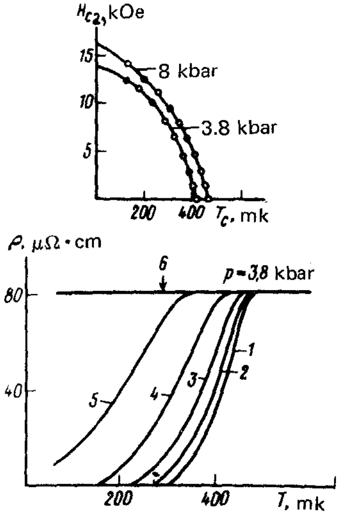

FIG. 3. Suppression of the superconductivity of the $CeCu_2Si_2$ single crystals by a magnetic field. 1–0; 2–1.5 kOe; 3–5 kOe; 4–9 kOe; 5–11.5 kOe; 6–20 kOe. The inset shows the dependence of the upper critical field $H_{c2}$ on the critical temperature $T_c$, determined from the midpoint of the transition.

On the other hand, the $p$ dependence of $T_c$ of the $CeCu_2Si_2$ single crystals can also be explained in the following way. In Kondo-lattice compounds such as[5] $CeCu_2Si_2$, the transition to the superconducting state can occur only at temperatures below a characteristic Kondo temperature $T_{Kondo}$, which corresponds to a complete Kondo screening of the magnetic cerium ions. It is also known[6] that $T_{Kondo}$ is a monotonically increasing function $f(T_{max}^{(1)})$ in concentrated Kondo systems.

From this point of view the absence of a transition at $p=0$ in $CeCu_2Si_2$ means that $T_{Kondo}$ is still very low–lower than 0.05 K, at the highest–and the unscreened magnetic moments suppress the superconductivity at $T \geqslant 0.05$ K. Under pressure (Fig. 2), $T_{max}^{(1)}$ and thus $T_{Kondo}$ increase, and the increase in $T_c$ in the interval $0 \leqslant p \lesssim 3$ kbar results from an increase $T_{Kondo} \approx T_c$. As soon as $T_{Kondo}$ comes to exceed a certain critical temperature, $T_{Kondo} > T_c^0 \simeq 0.5$ K, which corresponds to a superconducting transition in $CeCu_2Si_2$ with Kondo-suppressed cerium magnetic moments, a further increase in the pressure causes no further change in $T_c$ (Fig. 2).

Analysis of the $T_c(p)$ behavior (Fig. 2) leads to the conclusion that the superconducting transition with $T_c \simeq 0.5$ K which was observed by Steglich *et al.*[1] in polycrystalline $CeCu_2Si_2$ samples occurs because the polycrystalline samples contain–not $CeCu_2$ and $CeCu_6$, as suggested by Hull *et al.*[2] –but the superconducting modification $CeCu_2Si_2$-II, which results from local intercrystallite stresses $\Delta p \neq 0$. These stresses give the superconducting transition its percolation nature.

4. Figure 3 shows curves of the critical field $H_{c2}(T_c)$ measured in a longitudinal magnetic field. Interestingly, in the $CeCu_2Si_2$ single crystals under pressure there is a superconducting state with an anomalously large ratio $H_{c2}(0)/T_c(0)$: At $p=5.4$ kbar we have $H_{c2}(0)/T_c(0) \simeq 38$ kOe/K. In other words, $H_{c2}(0)$ is roughly twice the paramagnetic limit,[4] $\simeq 8.5$ kOe for $CeCu_2Si_2$.

Another distinguishing feature of the $H_{c2}(T_c)$ curves is the large derivative at the point $H=0$: $dH_{c2}/dT \simeq 140$ kOe/K ($p=5.4$ kbar). The analytic dependence of $H_{c2}$ on

$T_c$ at $T_c(0) - T_c(H) < 0.2$ K is described approximately by $H_{c2} = H_{c2}(0)\,[1 - (T_c(H)/T_c(0))^6]$.

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