Superconducting phase diagram of noncentrosymmetric heavy-fermion superconductor CeRhSi$_3$

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Abstract. We report the temperature dependence of the electrical resistivity $\rho(T)$ and resultant superconducting $B$-$T$ phase diagram of CeRhSi$_3$ for fields along the tetragonal $c$-axis. We have found a bend on the curve of upper-critical-field $B_{c2}(T)$ vs. temperature. The bend emerges at pressures above 2.4 GPa where the superconducting transition temperature is comparable to or higher than the Néel temperature under zero field. Associated with the emergence of the bend, the $\rho(T)$ curve at each field has an obvious change in the slope at a temperature under the magnetic fields.

1. Introduction

CeRhSi$_3$ is a noncentrosymmetric pressure-induced heavy-fermion superconductor discovered in 2005 [1]. It crystallizes in the BaNiSn$_3$-type tetragonal structure with the space group $I4mm$ (No. 107), which lacks an inversion center [2]. It exhibits antiferromagnetic ordering with an incommensurate wave vector below the Néel temperature $T_N = 1.6$ K at ambient pressure [2, 3]. As pressure $P$ is applied, $T_N$ initially increases and then turns to decrease above 0.75 GPa [1]. Superconductivity emerges above 0.2 GPa [4] and its transition temperature $T_c$ increases with increasing $P$ and becomes comparable to $T_N$ at about 2.4 GPa [1, 4]. The temperature dependence of the magnetic upper-critical-field $B_{c2}(T)$ is quite anisotropic. On the other hand, the shape of the $B_{c2}(T)$ curve for $B \parallel c$-axis did not seem to change systematically with $P$ [4]. The former observation has been qualitatively understood in terms of the absence or the strong reduction in the paramagnetic pair-breaking effect which is characteristic of the noncentrosymmetric (Rashba-type) crystal structure [4]. However, the latter observation has not been resolved.

To clarify the $P$-dependence of the $B$-$T$ phase diagram of CeRhSi$_3$, we have determined precisely the $B$-$T$ phase diagrams at several pressures via electrical resistivity measurements. From the precise measurements we have found that there are possibly two different

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superconducting phases which may be associated with anomalies found in the normal state resistivities.

2. Experiments
The single crystal of CeRhSi$_3$ was grown by using Czochralski pulling method in a tetra-arc furnace and was annealed at 900 °C under a vacuum of $2 \times 10^{-6}$ Torr for a week. The residual resistivity $\rho_0$ and its ratio (RRR) with current along the $c$-axis were 0.41 $\mu\Omega$ cm and 240, respectively. Hydrostatic pressures up to 2.85 GPa were produced by a clamped piston cylinder cell with 1 : 1 mixture of $n$- and $i$-propanol as pressure transmitting medium. The pressures at low temperature were determined by the resistance of manganin wire calibrated against the superconducting transition temperature of Sn. The resistivity measurements were performed using a dilution refrigerator equipped with a superconducting magnet at Tohoku University. The resistivity was measured by ac four-terminal method with $f = 15$ Hz and $j = 0.714$ A/cm$^2$. We have also performed dc measurements to confirm that both the results agree with each other.

3. Results and discussion

![Figure 1](image_url)

**Figure 1.** (a) Electrical resistivity of CeRhSi$_3$ as a function of temperature at several magnetic field strengths. The field is applied along the tetragonal $c$-axis and the pressure is 2.71 GPa. The onset, midpoint, and endpoint temperatures ($T^{\text{onset}}_c$, $T^{\text{mid}}_c$, and $T^{\text{end}}_c$, respectively) are indicated by arrows. The arrow denoted by $T^* (T^{**})$ indicates the temperature where the resistivity starts to deviate downwards (upwards) from the $T$ linear dependence. (To be precise, we define the peak of $\frac{d^2\rho}{dT^2}$ as $T^{**}$.) (b) Magnetic field dependence of the superconducting transition width $\Delta T \equiv T^{\text{onset}}_c - T^{\text{end}}_c$. The broken lines are the eye guides.
Figure 1(a) shows the $\rho(T)$-curves of CeRhSi$_3$ at several field strengths. The field is applied along the $c$-axis and the applied pressure is 2.71 GPa. As reported previously, we can see that the superconductivity persists at least up to 16 T even though $T_c$ at zero field is only about 1.1 K. Here, we define three characteristic temperatures of the superconductivity: the onset temperature at the beginning of the steep resistive drop ($T_{\text{onset}}$), and the temperatures for the resistivity reaching 50% and 0% of the value at $T_{\text{onset}}$ ($T_{\text{mid}}$ and $T_{\text{end}}$). In this study, we have found an interesting feature in the resistive drop at the superconducting transition.

Figure 1(b) displays the superconducting transition width $\Delta T \equiv T_{\text{onset}} - T_{\text{end}}$. As $B$ is applied, $\Delta T$ initially increases slightly and then steeply above about 12 T. We can see a wide and faint dip in the data from 8 T to 12 T. The dip structure is more pronounced at higher pressures. The sudden change in $\Delta T$ suggests that a superconducting property changes at this field.

A characteristic change at this field can be also noted on the upper-critical-field curve. Figure 2 shows the superconducting $B$-$T$ phase diagram compiled from the $B$-dependences of $T_{\text{onset}}$, $T_{\text{mid}}$, and $T_{\text{end}}$. There is an obvious bend on the $B_{c2}(T)$-curve at 12 T. This was not obviously seen in the previous study because the data points are more sparse [4]. The bend on the $B_{c2}(T)$-curve defined by $T_{\text{end}}$ is more pronounced than those on the other curves. The change in the slope of $B_{c2}(T)$-curve also suggests that there are two different superconducting states below and above 12 T.

The bend emerges from 2.4 GPa and the bend position moves towards higher magnetic fields and lower temperatures with increasing $P$. The $B_{c2}(T)$-curves below 2.4 GPa have a similar shape, while those above 2.4 GPa are not similar [4]. However, taking the behavior of the bend position into account, the change in the shape of the $B_{c2}(T)$-curve can be now understood systematically. It is noted in passing that 2.4 GPa is the pressure where $T_N = T_c$. 

Figure 2. $B$-$T$ phase diagram of CeRhSi$_3$ at 2.71 GPa. The field is applied along the tetragonal $c$-axis. Three upper-critical-field curves determined from $T_{\text{onset}}$, $T_{\text{mid}}$, and $T_{\text{end}}$ are displayed. We also plot $T^*$ and $T^{**}$ defined in Fig. 1(a).
We now show that the two superconducting states are probably associated with anomalies found in the resistivity of the normal state. As seen in Fig. 1(a), for fields above 1 T the \( \rho(T) \) curve deviates downwards from the \( T \)-linear dependence. Here, we define the temperature where the curve starts to deviate as \( T^* \). With increasing \( B \), \( T^* \) moves away from \( T_c \) and the deviation becomes more obvious. However, with further increase in \( B \), the \( T \)-linear dependence recovers and \( T^* \) becomes unclear especially at 12.5 T. Above this field, \( \rho(T) \) turns to deviate upwards making a kink-like anomaly at higher fields. For this anomaly we define another temperature \( T^{**} \). We plot \( T^* \) and \( T^{**} \) in Fig. 2. The field dependences of \( T^* \) and \( T^{**} \) are clearly different. This observation indicates that the origins of the two anomalies at \( T^* \) and \( T^{**} \) are different in nature. The field where the \( T^* \) and \( T^{**} \) curves meet approximately corresponds to that of the bend point of \( B_{c2}(T) \)-curve.

Finally we discuss the origin of the anomalies at \( T^{**} \) and \( T^* \). The bend appears at pressures above 2.4 GPa where \( T_N \) is less than \( T_c \). The anomaly at \( T^{**} \) is observed in the fields above the bend point. From these facts one may be tempted to attribute the anomaly to the antiferromagnetic transition. However, the behavior of the resistivity at \( T^* \) is quite different from those observed at pressures below 2.4 GPa, where the antiferromagnetic transition can be unambiguously identified and the resistivity at the antiferromagnetic transition drops obviously. The behavior of \( \rho(T) \) at \( T^* \) is also different that observed for the antiferromagnetic transition.

We think that these anomalies are not due to the antiferromagnetic transition, although we have no appropriate explanation for them at this stage. However, we would like to point out that the \( B \)-dependences of \( T^* \) and \( T^{**} \) are similar to the \( P \)-dependences of the pseudogap temperature \( T_{pg} \) and Fermi liquid temperature \( T_{FL} \), discussed in CeCoIn\(_5\) [6]. At ambient pressure, \( \rho(T) \) in CeCoIn\(_5\) deviates downwards from the \( T \)-linear dependence. With increasing \( P \), the \( \rho(T) \) turns to deviate upwards and at low temperatures has the \( T^2 \) dependence. The switching pressure from negative to positive curvature agrees with that for the minimum of \( \Delta T \) and with that for the maximum of \( T_c \). In ref. [6], the \( P \)-dependence of \( \rho(T) \)-behavior is interpreted as the evolution from the pseudogap nature to Fermi liquid one. Such evolution has been established for the hole-doping phase diagram of the cuprates. The \( B-T \) phase diagram of CeRhSi\(_3\) resembles the \( P-T \) one of CeCoIn\(_5\). This fact suggests that the same evolution may be realized in CeRhSi\(_3\) with \( B \) rather than with \( P \). In this respect, it is important to clarify the evolution of the normal state under the magnetic field, i.e., either from paramagnetic to antiferromagnetic or from pseudogap to Fermi liquid. This is also necessary to understand the novel superconducting properties in CeRhSi\(_3\) as well as in other heavy-fermion superconductors.

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