Anisotropy of the superconducting upper critical field and antiferromagnetism in pressure-induced superconductor CePt$_2$In$_7$

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Abstract. CePt$_2$In$_7$ is an antiferromagnet with $T_N = 5.4$ K, which shows pressure-induced superconductivity at transition temperature $T_c = 2.1$ K around a critical pressure $P_c = 3.2$ GPa. We have investigated an anisotropy of the superconducting upper critical field $H_{c2}$ in CePt$_2$In$_7$, which possesses two-dimensional tetragonal crystal structure and cylindrical Fermi surfaces elongated along $c$-axis. At 2.60 GPa, initial slope of $H_{c2}$ for $H \parallel [001]$ is smaller than that for $H \parallel [100]$, reflecting the two-dimensional Fermi surface of CePt$_2$In$_7$. However, Pauli paramagnetic suppression is strong for $H \parallel [100]$ compared with that for $H \parallel [001]$ in high magnetic field, and $H_{c2}(0)$ for $H \parallel [001]$ seems to be larger than that for $H \parallel [100]$ at 2.60 GPa in CePt$_2$In$_7$.

1. Introduction

A member of Ce$_m$M$_n$In$_{3m+2n}$ ($M$: transition metals) family CePt$_2$In$_7$ is an interesting compound in order to consider the relationship between antiferromagnetism and superconductivity and the role of two-dimensionality in superconductivity, because it exhibits pressure-induced superconductivity at transition temperature $T_{sc} = 2.1$ K around a critical pressure $P_c = 3.2 - 3.5$ GPa [1, 2]. CePt$_2$In$_7$ possesses two-dimensional tetragonal crystal structure and cylindrical Fermi surfaces elongated along $c$-axis [3]. In such compounds with two-dimensional crystal structure with long lattice parameter along $c$-axis, $H_{c2}$ is usually anisotropic, namely, $H_{c2}$ along the magnetic field $H \parallel c$-axis is smaller than that along $H \perp c$-axis due to orbital limiting and the anisotropy of the effective mass of the conduction electron.

Among the Ce$_m$M$_n$In$_{3m+2n}$ family CeCoIn$_5$ and CeIrIn$_5$ show such anisotropy in $H_{c2}$ with quasi-two dimensional Fermi surfaces [4, 5, 6, 7, 8]. On the other hand, pressure-induced superconductor CeRhIn$_5$ shows opposite behavior in spite of the similar topology of the Fermi surfaces except the volume of the Fermi surfaces. Namely, $H_{c2}(0) = 16.9$ T along $H \parallel [001]$ ($c$-axis) is larger than $H_{c2}(0) = 9.7$ T along $H \parallel [100]$ at $P_c = 2.45$ GPa [9]. In CeRhIn$_5$ antiferromagnetic state is induced by magnetic field just above $P_c$, where the antiferromagnetic state disappears by pressure at zero magnetic field. Pauli paramagnetic pair-breaking effect seems to be anisotropic in the field-induced antiferromagnetic state in CeRhIn$_5$, while isotropic in CeCoIn$_5$ [9]. We have investigated the anisotropy of $H_{c2}$ in CePt$_2$In$_7$, which shows similar pressure-induced superconductivity with CeRhIn$_5$. 

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Figure 1. Temperature dependence of the electrical resistivity under several pressure in CePt$_2$In$_7$ (a) below room temperature and (b) below 10 K.

2. Experimental

Single crystals of CePt$_2$In$_7$ were grown by In-self flux method according to temperature procedure similar to the literature [10]; 3N-Ce, 4N-Pt, and 5N-In were put in an alumina crucible with an atomic ratio, Ce : Pt : In = 1 : 3 : 30 and the crucible was sealed in a quartz ampoule under vacuum and heated up to 1050°C. After six hours, the furnace was cooled down to 800°C quickly and cooled down to 600°C with 0.5°C/hr and finally was switched off. The excess In-flux was removed by means of centrifuging. Typical and the largest size of the obtained single crystals were 0.5x0.5x0.05 mm$^3$ and 1x1x0.1 mm$^3$, respectively. Direction of the single crystal was determined by Laue and single crystal diffraction method. Electrical resistivity under pressure was measured by conventional ac four-contact method in Bridgman type pressure cell with Daphne 7373 oil as pressure transmitting medium. The sample was shapened to 0.18x0.045 mm$^2$ in cross-sectional area and 0.4 mm in length. The applied current was 0.1 mA, namely the current density was 12 mA/mm$^2$. Pressure was determined by the superconducting transition temperature of Pb. Anisotropy of $H_{c2}$ was measured in the same set-up of sample and pressure, namely, the pressure cell was rotated in order to change the direction of the magnetic field.

3. Experimental results and discussion

Figure 1 shows the electrical resistivity for the current along the [100] direction in CePt$_2$In$_7$ under several pressures from ambient pressure to 2.60 GPa. The residual resistivity ratio $RRR$ at ambient pressure is in the range from 100 to 750 depending on pieces of single crystals, indicating very high purity of the single crystals of CePt$_2$In$_7$. Specific heat measurement, which
Figure 2. (a) Pressure phase diagram and (b) pressure dependence of the $A$-value in the electrical resistivity $\rho = \rho_0 + AT^2$ in CePt$_2$In$_7$. Open marks in Fig. 2(a) are cited from Sidrov et al. [2].

is not shown here, also indicates no anomaly due to the impurity phase. The electrical resistivity shows two broad shoulders around 100 K and 20 K, like other cerium Kondo compounds. With increasing pressure the resistivity at room temperature increases but not so large compared with the result of Sidrov et al. [2]. The broad peak below 100 K slightly decreases and that below 20 K slightly increases with increasing pressure. A kink at the Néel temperature $T_N = 5.5$ K, as shown clearly in Fig. 1(b), first increases with increasing pressure but starts to decrease above 1.5 GPa.

Pressure dependence of $T_N$, onset and zero resistivity temperature of the superconducting transition at 2.60 GPa are summarized with the results of Sidrov et al., as shown in Fig. 2(a). Our result almost reproduces the result of Sidrov et al., but there are two differences. Comparing $T_N$ and $T_c$ at 2.60 GPa, $T_N$ is higher than that of Sidrov et al. by 1 K, and $\rho = 0$ is also attained at higher temperature. The $A$-value in the coefficient of $T^2$-term in the electrical resistivity increases with increasing pressure up to 2.60 GPa, as shown in Fig. 2(b), reflecting the approach to the quantum critical point around $P_c = 3.2$ GPa. Here we note that the $T^2$-dependence is limited in narrow temperature region.

Next, we show in Fig. 3 the electrical resistivity under several magnetic fields up to 7 T at 2.60 GPa, where the superconductivity appears in the antiferromagnetic state. Néel temperature is robust to the magnetic field for both field direction of [001] and [100], as shown in Fig. 3(a) and 3(c). Reflecting the superconductivity in the antiferromagnetic state, the transition is rather broad, $\Delta T_c = T_{c\text{onset}} - T_{\rho=0}$ is 0.35 K at zero field and becomes broader in magnetic field, as shown in Fig. 3 (b) and 3(d).

Figure 4 shows the temperature dependence of $H_{c2}$ and the magnetic field dependence of $T_N$ at 2.60 GPa in CePt$_2$In$_7$. The most interesting point is that $H_{c2}$ along $H \parallel [001]$ shows upward curvature, while that for [100] indicates the tendency of Pauli paramagnetic suppression with decreasing temperature. The initial slope of $H_{c2}^{\text{ onset}}$ ($H_{c2}^{\text{ onset}}$) is $-3.8$ T/K ($-12$ T/K) and $-5.3$ T/K ($-15$ T/K) for [001] and [100], respectively. These large values are characteristic to the heavy fermion superconductors. Here $T_c$ is suppressed rather quickly in the week magnetic
Figure 3. Temperature dependence of the electrical resistivity under several magnetic fields for $H \parallel [001]$ ((a) and (b)) and $H \parallel [100]$ ((c) and (d)) at 2.60 GPa in CePt$_2$In$_7$. Electrical resistivities under magnetic fields are shifted vertically for eyes.

Field below 1 T. Such behavior was also observed in the Sidorov’s result at 3.1 GPa [2]. The orbital limiting field $H_{\text{orb}} = -0.73(dH_{c2}/dT)T_c$ is estimated to be 3.9 T (12 T) and 5.8 T (20 T) for [001] and [100], respectively. The initial slope of $H_{c2}$ for $H \parallel [001]$ is smaller than that for $H \parallel [100]$. This is consistent to the anisotropy of the effective mass of the two-dimensional Fermi surface. However, the $H_{c2}(0)$ seems to be reversed, especially this tendency is remarkable in the onset of the superconducting transition (closed circles in Fig. 4), reflecting the stronger Pauli paramagnetic suppression for $H \parallel [100]$ direction. Note that the antiferromagnetic phase is also
slightly enhanced in magnetic field for $H \parallel [100]$ direction. Around the $P_c$ of 3.1 GPa, the initial slope is reported to be $-12.4$ T/K for $H \parallel [001]$ and the extrapolated $H_{c2}(0) \simeq 15$ T is lower than $H_p \simeq 19$ T, suggesting the Pauli paramagnetic suppression for $H \parallel [001]$ [2]. In order to clarify the difference of the Pauli paramagnetic suppression for $H \parallel [001]$ between present result and previous one, further study around $P_c$ is necessary.

4. Summary
We have investigated the anisotropy of the superconducting upper critical field $H_{c2}$ in CePt$_2$In$_7$. At 2.60 GPa, initial slope of $H_{c2}$ for $H \parallel [001]$ is smaller than that for $H \parallel [100]$, reflecting the two-dimensional Fermi surface of CePt$_2$In$_7$. However, the Pauli paramagnetic suppression is strong for $H \parallel [100]$ compared with that for $H \parallel [001]$ in high magnetic field, and $H_{c2}(0)$ for $H \parallel [001]$ seems to be larger than that for $H \parallel [100]$. Anisotropic behavior of the Pauli paramagnetic suppression in CePt$_2$In$_7$ seems to be similar to that of CeRhIn$_5$ rather than that of CeCoIn$_5$ [9]. Further investigation for the anisotropic behavior in $H_{c2}$ below and above $P_c$ is necessary to clarify the role of antiferromagnetism for superconductivity in CePt$_2$In$_7$.

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