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Physical Properties of Cd Doped CeIrIn$_5$ under Pressure

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We measured the electrical resistivity ρ of CeIr(In$_{1-x}$Cd$_x$)$_5$ under pressure for x = 0.05 and 0.10, which show the onset of superconductivity (SC) at $T_{\rm sc}^{\rm onset}$ ~ 0.9 K and antiferromagnetic transition at $T_{\rm N}$ ~ 3.4 K. For x = 0.05, $T_{\rm sc}^{\rm onset}$ increases by applying pressure up to 2.8 GPa and zero resistivity is observed at $T_{\rm sc}^{\rho=0}$ above 2.4 GPa. For x = 0.10, the pressure dependence of $T_{\rm N}$ shows peak at around 2 GPa and $T_{\rm N}$ seems to be 0 K toward 3 GPa, where SC phase appears. The maximum value of $T_{\rm sc}^{\rho=0}$ is independent on amount of doped Cd, showing 1.35 K. We analyzed the temperature dependence of the electrical resistivity ρ for x = 0.05 and 0.10 under pressure using the following equation, $\rho = \rho_0 + AT^n$. This analysis revealed that ρ shows the sublinear temperature dependence ($n < 1$) in the wide temperature region above $T_{\rm sc}^{\rho=0}$, and ρ_0 decreases abruptly in the pressure region where $T_{\rm sc}^{\rho=0}$ indicates a maximum.

1. Introduction

In the heavy-fermion (HF) compound, interesting physical phenomena are observed such as unconventional superconductivity (SC) or non-Fermi liquid (NFL) behavior in the vicinity of quantum critical point (QCP) where a magnetic phase transition temperature is suppressed to 0 K. These characteristic behaviors in f electron system are attributed to a competition between the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and the Kondo effect. The RKKY interaction enhances a long-range magnetic ordering. On the other hands, the Kondo effect quenches a magnetic moment of f electron. The RKKY interaction and the Kondo effect are expressed by the function of the strength of exchange interaction between f and conduction electrons, J_{cf}, which corresponds to the hybridization effect between them. The parameter of J_{cf} is tuned by external fields such as pressure, magnetic field, and chemical substitution. Thus, the pressure could be a powerful tool to study the electronic state of HF compounds in the vicinity of QCP. One of typical HF compounds CeTIn$_5$ (T = Co, Rh, Ir) that crystallizes in the tetragonal HoCoGa$_5$ type structure have provided knowledges of the relationship between unconventional SC and antiferromagnetic (AFM) transition in the vicinity of magnetic QCP. CeRhIn$_5$ with AFM transition temperature $T_{\rm N}$ = 3.8 K at ambient pressure shows the pressure induced SC phase dome centered at $P_{\rm c}$ ~ 2.1 GPa, where $T_{\rm N}$ becomes 0 K[1], which is typical feature in the vicinity of the magnetic QCP. CeCoIn$_5$ is a HF superconductor with SC transition temperature $T_{\rm sc}$ ~ 2.3 K[2]. Substituting In for Cd in CeCoIn$_5$, $T_{\rm sc}$ is suppressed and AFM order is induced[3]. The Cd doped CeCoIn$_5$ shows the similar phase diagram as CeRhIn$_5$. In the magnetic QCP regime, theoretical study revealed that electrical resistivity ρ shows the NFL behavior, $\rho \propto T^n$ (n = 1 ~ 1.5)[4], which is in good agreement with experimental results of CeCoIn$_5$[5].

CeIrIn$_5$ is a member of CeTIn$_5$ family and shows the SC at $T_{\rm sc}$ ~ 0.4 K[6]. With increasing pressure, $T_{\rm sc}$ increases and reaches a maximum value of 1 K at around 3 GPa[7, 8]. The mechanism of SC in CeIrIn$_5$ has not been clear yet. Interestingly, the pressure study in CeRh$_{1-x}$Ir$_x$In$_5$ reported that there are two SC phase [9]. The SC phase at lower and higher x are called SC1 and SC2, respectively[9]. The magnetic instability plays an important role in the SC1. On the other hand, the SC2 phase is far from the magnetic QCP, and non-magnetic fluctuation is considered to play an important role in the SC2[7]. Thus the origin of the SC of $\mathrm{CeIrIn_5}$ is expected to be the non-magnetic fluctuation. Nuclear quadrupole resonance (NQR) measurement of Cd doped $\mathrm{CeIrIn_5}$ suggests a valence instability contributes to the SC2[10]. On the other hands, nuclear magnetic resonance (NMR) and transport measurements suggest $\mathrm{CeIrIn_5}$ is in the vicinity of AFM QCP[11-15]. In order to clarify the relationship between SC and magnetic instability in $\mathrm{CeIrIn_5}$, we measured the electrical resistivity of Cd doped $\mathrm{CeIrIn_5}$ under pressure.

2. Experimental method

Single crystals of $\mathrm{CeIr(In_{1\text{-}x}Cd_x)_5}$ were grown by (In-Cd)-flux technique. Here, x is composition ratio of starting materials Ce : Ir : In : Cd = 1 : 1 : 20x : 20(1-x). The electrical resistivity was measured by four probe method from 0.7 to 300 K. We used Bridgman anvil cell (BAC) with Daphne oil 7373 as the pressure medium for electrical resistivity measurement under pressure. Pressure inside the pressure cell at low temperature was calibrated by the SC transition temperature of Pb.

3. Results and Discussions

3.1 Resistivity

3.1.1. x =0.05

Figure 1(a) shows the temperature dependence of ρ for x = 0.05 in the temperature range between 0 and 300 K. At ambient pressure, ρ shows a peak at T_ρ^{max} = 37 K. This peak is shifted to higher temperature by applying pressure, meaning that the hybridization effect between f electron and conduction electron becomes strong under pressure. At temperatures lower than T_ρ^{max}, ρ shows a hump just below T^* in the pressure range between 2.4 and 3.2 GPa, as shown in the inset of Fig. 1(a). T^* increases by applying pressure. As shown by the arrow in Fig. 1(b), a sudden drop in ρ is observed at $T_{\mathrm{sc}}^{\mathrm{onset}}$ ~ 0.9 K at ambient pressure, which corresponds to the onset of SC. In the previous specific heat measurement, any phase transition is not observed down to 0.2 K for x = 0.05[3]. This different experimental results between ρ and specific heat might be due not to the bulk SC but filamentary SC in $\mathrm{CeIrIn_5}$. With increasing pressure, $T_{\mathrm{sc}}^{\mathrm{onset}}$ increases and zero resistivity is observed at $T_{\mathrm{sc}}^{\rho=0}$ above 2.4 GPa. The difference between $T_{\mathrm{sc}}^{\mathrm{onset}}$ and $T_{\mathrm{sc}}^{\rho=0}$ shrinks by applying pressure.

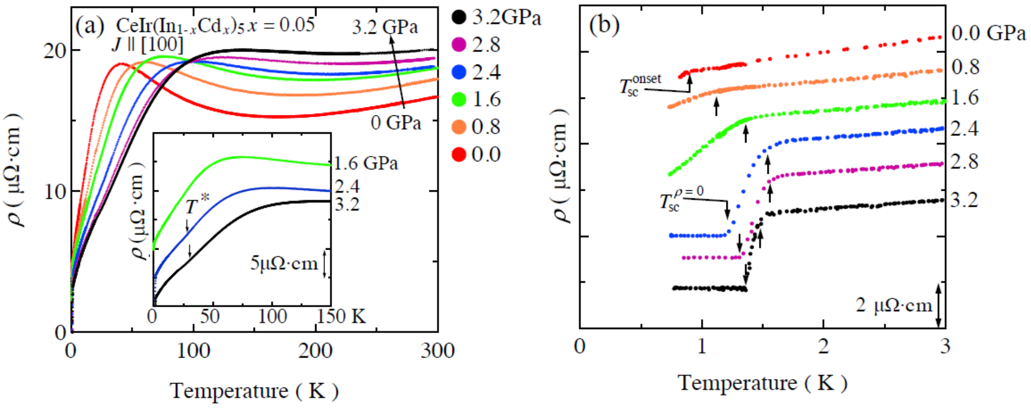

Fig. 1. Temperature dependence of electrical resistivity ρ for x = 0.05 at several pressures in the temperature range up to (a) 300 K, inset of (a) 150 K, and (b) 3 K, respectively. The data of ρ in inset of (a) and (b) is properly shifted for clarity.

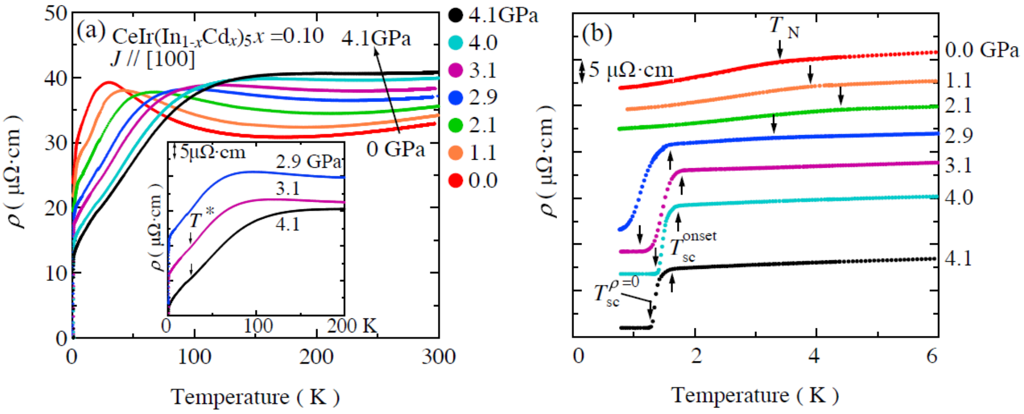

Fig. 2. Temperature dependence for ρ for $x = 0.10$ at several pressures in the temperature range up to (a) 300 K, inset of (a) 200 K, and (c) 6 K, respectively . The data of ρ in the inset of (a) and (b) is properly shifted for clarity.

3.1.2. *x* =0.10

We present the temperature dependence of ρ for $x = 0.10$ up to 300 K in Fig. 2(a). ρ shows peak at $T_\rho^{\max} = 28$ K at ambient pressure, which is smaller than that for $x = 0.05$, meaning the suppression of the hybridization effect. The peak at $T_\rho^{\max}$ is shifted to higher temperatures by applying pressure, and a hump of ρ is also observed above the 3.1 GPa, as shown by the arrow in the inset of Fig. 2(a), which are similar behavior for $x = 0.05$. At low temperature, ρ shows a kink at $T_\mathrm{N} = 3.4$ K, which is consistent with the previous specific heat study[3]. With increasing pressure, T_N reaches the maximum at 2.1 GPa and rapidly decreases above 2.1 GPa. At 2.9 GPa, SC emerges below T_N and zero resistivity is observed at 3.1 GPa with $T_\mathrm{sc}^{\rho=0} = 1.1$ K.

3.2. Phase diagram

From the experimental results of ρ under pressure, we constructed temperature (T)-pressure (P) phase diagram for $x = 0.05$ and 0.10, as shown in Figs. 3(a) and 3(b), respectively.

3.2.1. *x* =0.05

$T_\mathrm{sc}^\mathrm{onset}$ indicates the maximum value of 1.6 K at 2.8 GPa. On the other hands, $T_\mathrm{sc}^{\rho=0}$ indicates the maximum value of 1.35 K at 3.2 GPa, which is higher than that of $\mathrm{CeIrIn_5}$[8]. T^* appears above 2.4 GPa in the pressure region where zero resistivity emerges, and T^* increases by applying pressure. We analyzed the temperature dependence of ρ in low temperatures above $T_\mathrm{sc}^\mathrm{onset}$ at several pressures using the following equation, $\rho = \rho_0 + AT^n$, where ρ_0, A, and n are fitting parameters. ρ follows the equation up to about 20 K. Pressure dependences of power law exponent n (open circles on the left axis) and residual resistivity ρ_0 (closed circle on the right axis) are shown in Fig. 3(c). The data of n shows almost constant value of 0.9 up to 2 GPa. Above 2 GPa, n decreases and indicates a saturation of 0.6. ρ_0 shows the similar pressure dependence as n, that is, ρ_0 indicates a constant value up to 2 GPa and decreases above 2 GPa, which corresponds to the pressure where the zero resistivity is observed. Sublinear dependence of $\rho \propto T^n$ $(n < 1)$ could not be explained by magnetic fluctuation theory and valence one[4, 16]. The sublinear temperature behavior of ρ is also observed in $\mathrm{CeRhIn_5}$, and which is considered to be the electrical scattering by coexistence of spin and charge fluctuation[17]. However, the origin of sublinear temperature dependence in ρ is still an open question.

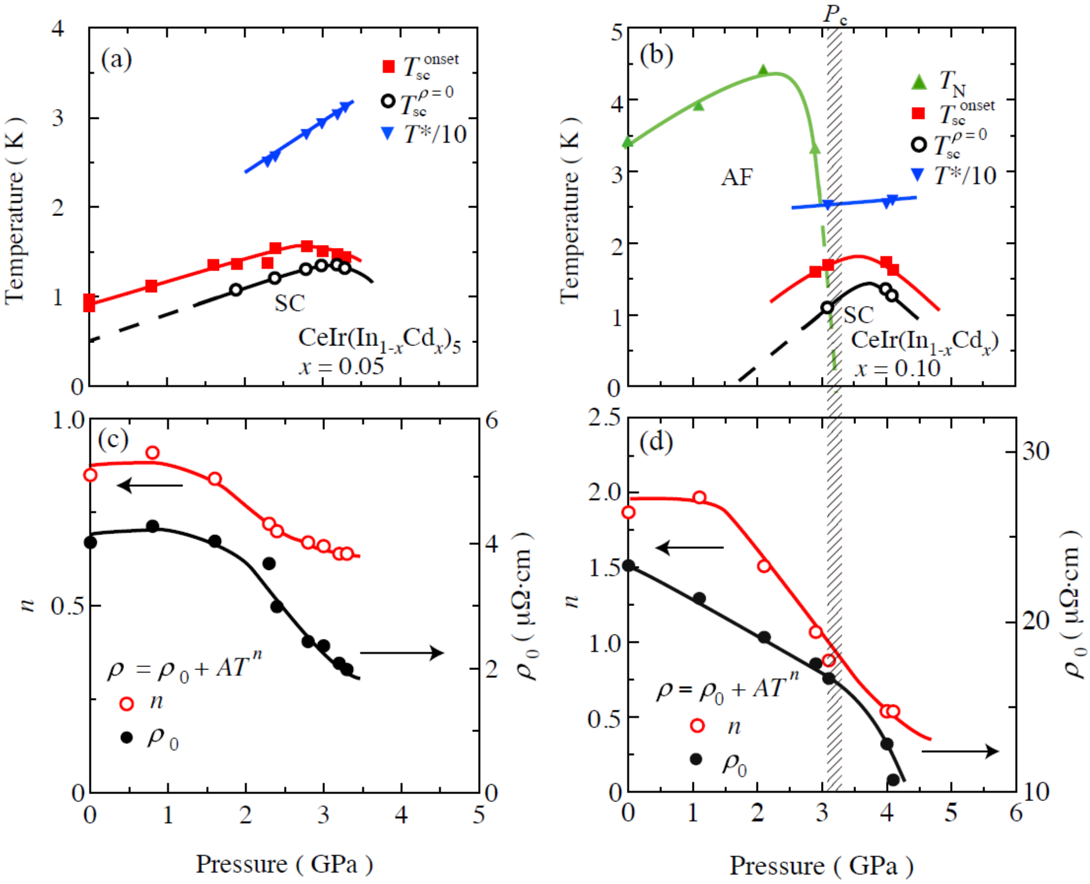

Fig. 3. Pressure dependence of T_{sc}^{onset} (closed square), $T_{sc}^{\rho=0}$ (open circle), T_N (closed triangle), and $T^*/10$ (closed inverted triangle) for (a) $x = 0.05$ and (b) $x = 0.10$, and fitting parameter n (on the left-hand scale, open circle) and ρ_0 (on the right-hand scale, closed circle) for (c) $x = 0.05$ and (d) $x = 0.10$. The shaded area in (b) and (d) indicates P_c.

3.2.2. *x* =0.10

In Fig. 3(b), T_N seems to become zero at P_c ~ 3.2 GPa, where SC phase emerges. The maximum value of $T_{sc}^{\rho=0}$ is 1.35 K at 4.0 GPa, which is the same value as that for $x = 0.05$. In non s-wave superconductor, SC is sensitive to a sample quality, and T_{sc} is easily suppressed by disorder, as observed in $CeRh_2Si_2$ under pressure or UPt_3[18, 19]. However, the maximum value of $T_{sc}^{\rho=0}$ is independent on amount of the doped Cd in CeIr(In$_{1-x}$Cd$_x$)$_5$. T^* for $x = 0.10$ also appears in the pressure region where zero resistivity appears as $x = 0.05$ and increases by applying pressure. Figure 3(d) displays the pressure dependence of fitting parameters n and ρ_0 for $x = 0.10$. ρ for $x = 0.10$ follows the power law up to T_N below 2.9 GPa, and ρ shows Fermi liquid behavior ($n = 2$) up to 1.0 GPa. Above 3.1 GPa, ρ also follows the power law up to about 20 K as $x = 0.05$. At pressures higher than 1.0 GPa, n decreases to about 1 at 3.0 GPa. Sublinear temperature dependence of ρ is observed above 3.1 GPa. Although ρ_0 for $x = 0.10$ is larger than that for $x = 0.05$, the pressure dependence of ρ_0 for $x = 0.10$ is similar to that for $x = 0.05$. ρ_0 monotonically decreases by applying pressure and shows a change of slope above 3.1 GPa, where $T_{sc}^{\rho=0}$ reaches the maximum. The decreases of ρ_0 at around P_c is different from the conventional pressure induced HF superconductor which shows the maximum of ρ_0 at P_c[17, 20].

4. Summary

We measured the electrical resistivity ρ of CeIr(In$_{1-x}$Cd$_x$)$_5$ for $x = 0.05$ and 0.10 under several pressures. AFM QCP probably exists at P_c ~ 3.2 GPa for $x = 0.10$. $T_{sc}^{\rho=0}$ reaches the maximum value of 1.35 K at 3.2 and 4.0 GPa for $x = 0.05$ and 0.10, respectively, which is higher than that of $CeIrIn_5$. The maximum of $T_{sc}^{\rho=0}$ in $CeIr(In_{1-x}Cd_x)_5$ is found to be independent of ρ_0 and x, meaning that the SC in $CeIrIn_5$ is insensitive to impurity. ρ shows a hump just below T * above 2.4 and 3.1 GPa for $x =$ 0.05 and 0.10, respectively. Although T* appears in the pressure region where SC phase emerges, the relationship between T* and SC, and the origin of T* are not clear yet. Our analysis of ρ at low temperatures revealed that ρ shows the sublinear temperature dependence and ρ_0 abruptly decreases in the pressure region where $T_{sc}^{\rho=0}$ becomes the maximum for both of $x = 0.05$ and 0.10. The impurity-insensitive behavior in SC and sublinear temperature dependence of ρ are not explained by the conventional magnetic QCP theory. Another fluctuations possibly contribute to the SC in $CeIr(In_{1-x}Cd_x)_5$. Experiments under high pressure and high magnetic field which suppresses the magnetic fluctuations are necessary in order to investigate the relationship between magnetic fluctuation and anomalous behaviors in $CeIr(In_{1-x}Cd_x)_5$. Specific heat measurement under pressures are also needed to discuss the bulk SC.

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