Effect of pressure on transport properties of CeIrIn$_5$

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Abstract. Electrical resistivity $\rho$ and thermoelectric power $S$ of a heavy-fermion superconductor CeIrIn$_5$ have been measured at temperatures from 2.0 K to 300 K under hydrostatic pressures up to 2.2 GPa. The thermoelectric power $S$ exhibits a large positive value up to 90 $\mu$V/K, which is characteristic of heavy-fermion systems. $S$ also shows a sharp maximum in its temperature dependence and its maximum temperature $T_S$;max increases with pressure, while its maximum value is constant independent of pressure. These experimental results strongly indicate that the Kondo temperature of CeIrIn$_5$ increases by applying the pressure.

1. Introduction

The interplay between magnetism and superconductivity (SC) remains an interesting topic in condensed matter physics. It has long been believed that these two long-range ordered states would be antagonistic because of their competitive nature, i.e., the exclusion of magnetic induction by Meissner effect and internal fields generated by magnetic orderings. According to investigations on heavy-fermion superconductors, however, antiferromagnetism (AFM) can coexist with SC, because the periodicity of AFM is usually much shorter than the SC coherence length, and hence the internal fields seen by itinerant electrons are canceled out. Actually, there is a growing list of heavy-fermion compounds the exhibiting coexistence of AFM and SC at ambient or high pressure [1, 2], however many questions remain to be resolved.

Members of the CeTIn$_5$ ($T =$ Rh, Ir and Co) family with a tetragonal HoCoGa$_5$-type crystal structure [3], are ideal for studying the correlation between AFM and SC, because its transition temperatures (Néel temperature $T_N$ and superconducting transition temperature $T_c$) can be controlled by the application of an external pressure and/or the chemical doping. At ambient pressure, CeIrIn$_5$ is a superconductor with $T_c = 0.4$ K and the electronic specific heat $\gamma = 700$ mJ/(K$^2$mol) [4]. As the pressure increases, $T_c$ passes through a maximum of 1.0 K around 2.5 GPa and then vanishes in the vicinity of 6 GPa [5]. Nuclear quadrupole resonance experiments [6] suggested that SC state has the line nodes of a superconducting energy gap, confirmed by the thermal conductivity measurements [7, 8].

Nowadays the measurements of $S$ have been carried out extensively to study the ground state of the strongly correlated electrons systems and gave an important information concerning to the electronic density of state near the Fermi level. No measurements of $S$, however, have been
performed on a heavy-fermion superconductor CeIrIn$_5$. In this paper, we report $S$ results of CeIrIn$_5$ for the first time.

2. Experimental

The single crystals of CeIrIn$_5$ were grown by the In-flux method of combining stoichiometric amounts of Ce and Ir with excess In. They were cut by spark erosion to a size of about $1 \times 1 \times 3$ mm$^3$. The measurements of electrical resistivity $\rho$ and thermoelectric power $S$ under pressure were carried out simultaneously by using the standard four-probe dc method and the differential method with a seesaw heating procedure, respectively. The thermoelectric power measurement technique of so-called “seesaw heating method” using two gradient heaters on both sides of the sample has been developed for the high sensitive and stable measurement under a strong magnetic field [9]. For the $S$ measurements under pressure, we employed the modified “seesaw heating method” with one gradient heater due to the limitation of the sample space [10]. Chromel-constantan thermocouples were used as the probes for thermoelectric power measurements because of the small temperature dependence of the pressure effects [11]. The junctions of the thermocouples were made by spot welding, and glued directly to the sample by using Ag paste. With this experimental setup, both electrical current $I$ and heat flow $Q$ were applied in the same direction of $a$-axis of the crystals. The crystals were cooled down to 2.0 K by using a conventional liquid-$^4$He pumping cryostat. A clamp-type NiCrAl/CuBe hybrid piston cylinder pressure cell with a pressure transmitting media of Daphne oil 7373 [12] was utilized for producing hydrostatic pressures up to 2.2 GPa at low temperature.

3. Results and Discussion

Figure 1 shows the temperature dependence of the $a$-axis electrical resistivity $\rho$ of CeIrIn$_5$ at the temperature range between 2.0 K and 300 K under pressure up to 1.5 GPa. The $\rho$ of LaIrIn$_5$ at ambient pressure [13] has been subtracted as the phonon backgrounds. One can recognize that $\rho$ exhibits the typical dense Kondo behavior: on cooling from room temperature at ambient pressure, the $\rho$ increases and shows a maximum of the coherence peak at $T_{\rho, \text{max}} = 42.2$ K, and then goes down into the coherent Kondo state. Inelastic neutron scattering measurements of CeIrIn$_5$ show the Kondo temperature $T_K$ is 56 K [14], which is comparable to $T_{\rho, \text{max}}$. One can also find that the coherence peak moves to higher temperatures up to 86.4 K for 1.5 GPa with increasing $P$.

In the Fermi liquid metals, $\rho$ varies as $\rho = \rho_0 + AT^n$ ($n = 2$) at low temperatures. In the case of CeIrIn$_5$, $n$ is estimated to be $\sim 1.0$ at ambient pressure, indicating the so-called non-Fermi liquid behavior. The $n$ value, shown in the inset of Fig. 1, increases linearly with pressure, exhibiting the gradual recovery of Fermi liquid behavior. It should be noted that the overall features in the $\rho$ results are in excellent agreement with the previous results [4, 15].

Figure 2 illustrated the temperature dependence of the $a$-axis thermoelectric power $S$ of CeIrIn$_5$. Compared with a simple metal, the $S$ value is found to be very large up to 90 $\mu$V/K, which is characteristic of heavy-fermion systems [16]. All the $S$ data presented in Fig. 2 have positive values and then there is a pronounced maximum in each pressure data. Cox and Grewe calculated the thermoelectric power of the Anderson lattice model by using the Average $T$-matrix Approximation [17]. They showed not only a development of a sharp peak near Fermi level in the electronic density of state but also a maximum in the temperature dependence of the thermoelectric power at $T = T_K/3$. We should remark that the temperature dependence of the $S$ results is qualitatively similar to their theory.

The maximum peak at $T_{S, \text{max}}$ moves to higher temperatures from 26 K (at 0 GPa) to 62 K (at 2.2 GPa) by applying the pressure, while its maximum value remains close to the ambient pressure value. The inset of Fig. 2 shows the thermoelectric power normalized to its maximum value, $S/S_{\text{max}}$, is plotted against the temperature normalized to its maximum peak.
Figure 1. The temperature dependence of the $a$-axis electrical resistivity of CeIrIn$_5$ after subtraction of the phonon backgrounds. The inset shows the pressure dependence of $n$ obtained from the low temperature electrical resistivity. See text for details.

Figure 2. The temperature dependence of the $a$-axis thermoelectric power of CeIrIn$_5$ as a function of $P$. The inset shows the pressure dependence of the normalized thermoelectric power vs the normalized temperature. See text for details.

temperature, $T/T_{S,\text{max}}$. One can clearly recognize its pressure-independent behavior below $T/T_{S,\text{max}} \sim 2.2$, which strongly illustrates that the thermoelectric power at temperature near $T_{S,\text{max}}$ is determined by the one energy parameter. Obtained values for $T_{\rho,\text{max}}$, $n$, $T_{S,\text{max}}$, and $T_{\rho,\text{max}}/T_{S,\text{max}}$ as a function of pressure are summarized in Table 1. In particular we stress that the ratio of $T_{\rho,\text{max}}/T_{S,\text{max}}$ are found to be a pressure-independent constant value around 1.6. These experimental findings strongly support that the increase of $T_{S,\text{max}}$ is due to that of $T_K$ by applying the pressure.

In the low temperature region below $T/T_{S,\text{max}} \sim 0.2$, there tends to have slight difference in the pressure dependence of $S/S_{\text{max}}$. We suppose that these difference might have the correlation with the quantum criticality of this system. To clarify this phenomena in detail, we need to perform the $S$ measurements at lower temperature as a function of pressure.

In summary, we measure electrical resistivity $\rho$ and thermoelectric power $S$ of a heavy-fermion superconductor CeIrIn$_5$ at temperatures from 2.0 K to 300 K under hydrostatic pressures up to 2.2 GPa. $S$ exhibits a large positive value up to 90 $\mu$V/K, which is characteristic of heavy-fermion systems. $S$ also shows a sharp maximum in its temperature dependence and then its maximum temperature $T_{S,\text{max}}$ increases with pressure, while its maximum value is constant independent of pressure. These experimental results indicate that the Kondo temperature of CeIrIn$_5$ increases by applying the pressure.

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Table 1. Values for $T_{\rho, \text{max}}$, $n$, $T_{S, \text{max}}$, and $T_{\rho, \text{max}}/T_{S, \text{max}}$.

| $P$ [GPa] | $T_{\rho, \text{max}}$ [K] | $n$ | $T_{S, \text{max}}$ [K] | $T_{\rho, \text{max}}/T_{S, \text{max}}$ |
|-----------|--------------------------|----|----------------------|---------------------------------|
| 0.0       | 42.2                     | 1.03 | 26.0                 | 1.62                            |
| 0.73      | 59.8                     | 1.09 | 38.3                 | 1.57                            |
| 1.5       | 86.4                     | 1.14 | 51.6                 | 1.67                            |
| 2.2       | —                        | —   | 61.6                 | —                               |

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