Hall effect in CeAl$_2$ under high pressure

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Abstract. We have measured the Hall effect of the single crystalline CeAl$_2$ under high pressure up to 3 GPa. An anomalous Hall effect was observed at high pressures. The Hall coefficient $R_H$ at 0.1 GPa is positive ($R_H \sim 1.7 \times 10^{-9}$ m$^3$/A·s). It decreases smoothly with increasing pressure below 2 GPa, but rapidly above 2 GPa. The sign of the Hall coefficient is found to change from positive to negative as pressure increases. These results suggest a pressure-induced crossover in the electronic state around 2.7 GPa.

1. Introduction

Some Ce-based intermetallic compounds are well known as the heavy fermions, and the anomalous properties are originated from the hybridization between $f$-electrons and conduction electrons [1, 2]. CeAl$_2$ with cubic C15 Laves-phase is one of the heavy fermion compounds, which has the electronic specific heat coefficient $\gamma = 135$ mJ/mol·K$^2$ and Kondo temperature $T_K = 6$ K [3]. At ambient pressure, antiferromagnetic ordering is observed below $T_N = 3.8$ K, which decreases with increasing pressure [4]. The experimental results under high pressure suggested that a quantum critical point (QCP) exists near 2.7 GPa [5, 6]. A non Fermi liquid behavior was observed around the QCP [6]. The magnetoresistance (MR) is negative at 4.2 K. The magnitude of MR is decreased by applying pressure, and the sign of MR changes from negative to positive around 2.6 GPa, which indicates a crossover from incoherent state to coherent one [7]. In general, the Hall effect of Ce compounds shows an anomalous Hall effect due to the skew scattering of the conduction electrons by magnetic moment of $f$-orbital [8]. It has been reported that the Hall effect is a good tool to investigate the QCP [9]. In this work, we measured the Hall resistivity at 4.2 K under high pressure up to 3 GPa in order to clarify the influence of the anomalous Hall effect around the QCP.
2. Experimental method

A single crystal CeAl$_2$ was grown by Czochralski pulling method. The Hall resistivity at 4.2 K was measured in the conventional six probe configuration. Hydrostatic pressure was generated by a WC piston and Ni-Cr-Mo hard alloy (MP35) cylinder up to 3 GPa [10]. Daphne-oil 7373 was used as the pressure transmitting medium. The pressure inside the cell was kept constant in whole temperature ranges by automatic controlling of the load. The measurements were carried out using superconducting magnet with field up to 9 T. The current direction was parallel to [1 0 0].

3. Results and Discussion

Figure 1 shows the magnetic field dependence of the Hall resistivity $\rho_H$ at 4.2 K under pressure up to 3 GPa. At 0.1 GPa, the $\rho_H$ increases with increasing magnetic field, and shows a broad peak around 7 T. The anomalous Hall effect is observed in the heavy fermion compounds [8], which is ascribed to skew scattering due to the asymmetry of the interaction between conduction electrons and $f$-electrons. According to skew scattering model, the $\rho_H$ is described as follows,

$$\rho_H(B) = R_0 B + \rho_H^a(M)$$

where $B$ is magnetic field, $R_0$ the normal Hall coefficient and $\rho_H^a(M)$ the anomalous Hall resistivity term, depending on magnetization $M$. The $\rho_H(B)$ of CeAl$_2$ changes largely as pressure increases. The broad peak is observed below 1 GPa, but not observed above 2.2 GPa in the magnetic field range up to 9 T. The initial slope of the $\rho_H(B)$ changes from positive to negative as pressure increases. At 2.7 GPa and 3 GPa, a shallow minimum is observed around 1 T and 2 T, respectively.
Figure 2 : Pressure dependence of the Hall coefficient at 4.2 K.

Figure 2 shows the pressure dependence of the Hall coefficient $R_H$ at 4.2 K. The $R_H$ was evaluated by the first-derivative of $\rho_H (B)$, $R_H = \partial \rho_H / \partial B$, below 1 T. At 0.1 GPa, the value of $R_H$ is $1.7 \times 10^{-9}$ m$^3$/A s, which is almost the same value at ambient pressure in the previous report [11]. The temperature dependence of the $R_H$ shows a broad peak around 4K at ambient pressure [12], indicating that the anomalous Hall effect is the largest around 4 K. Thus, at 0.1 GPa, the anomalous Hall effect is dominant in the $R_H$ of CeAl$_2$ at 4.2 K. The $R_H$ is decreased gradually by applying pressure, and shows a rapid decrease above 2 GPa. Above 2.7 GPa, the $R_H$ becomes a negative.

In this work, the pressure where the sign of the $R_H$ in CeAl$_2$ changes is nearly the same as that where the sign of the MR changes. The change of the sign of the $R_H$ indicates a crossover from 4f-localized state to itinerant one since that of the MR is due to a crossover from incoherent state to coherent one [3, 6]. On the other hand, since $\rho_H^a(M)$ is describe as $R_M$ at paramagnetic region, the Hall coefficient is written as follows,

$$R_H = R_0 + R_s \chi$$

(2)

, where $R_s$ is the anomalous Hall coefficient and $\chi$ is the susceptibility. The $R_s \chi$ decreases with increasing pressure since the anomalous Hall effect is dominant in the $R_H$, which might be due to the decrease of $\chi$ since the Curie paramagnetism changes to Pauli one by changing from 4f-localized state to itinerant one as pressure increases. Judging from these facts, it is suggested that the skew scattering due to the localized 4f-electrons decreases with increasing pressure, i.e., the anomalous $R_H$ term decreases as pressure increases, reflecting a delocalization of 4f-electrons.

In several substances such as CeRh$_2$Si$_2$ and Cr$_x$V$_{1-x}$ alloys, it has been reported that the large change of the $R_H$ is observed at critical pressure $P_C$ where magnetic ordering disappears [9, 13]. In the case of CeRh$_2$Si$_2$, the $R_H$ of CeRh$_2$Si$_2$ is continuously decreased by applying pressure, and changes the sign of the $R_H$ around $P_C \sim 1$ GPa [13]. In this pressure, it is suggested that the enhancement of many-body dynamical effect occurs according to the electrical resistivity measurement under high pressure [14]. Furthermore, the abrupt change of Fermi surface are observed around $P_C$ by a de Hass-Van Alphen experiment, which is due to a discontinuous change of the Fermi surface from 4f-localized
These results indicate the QCP exists around $P_c \sim 1$ GPa in CeRh$_2$Si$_2$, and the anomaly of the $R_H$ is observed at QCP. Thus, in CeAl$_2$, the change of sign of $R_H$ indicates that the QCP exists around 2.7 GPa, which is good agreement with the previous results of the electrical resistivity measurement under high pressure [5, 6]. It is implied that the abrupt change of the Fermi surface is observed around 2.7 GPa such as CeRh$_2$Si$_2$.

4. Summary

In this study, we have measured the Hall effect of CeAl$_2$ at 4.2 K under high pressure. At 0.1 GPa, the $R_H$ is a positive, and the anomalous Hall effect is dominant in the $R_H$ at 4.2 K. The anomalous Hall effect is found to decrease with increasing pressure, and the sign of $R_H$ changes at 2.7 GPa. From comparison with the result of MR under high pressure, it is suggested that the crossover from 4f-localized state to itinerant one exists around 2.7 GPa, which indicates that the QCP in CeAl$_2$ exists around 2.7 GPa.

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