Pressure-induced Suppression of the Antiferromagnetic Transition in YbNi$_3$Al$_9$ Single Crystal

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Abstract. We have measured the electrical resistivity $\rho(T)$ of heavy fermion antiferromagnet YbNi$_3$Al$_9$ under hydrostatic pressure up to 8 GPa. We found that the antiferromagnetic ordering temperature $T_N$ is suppressed with increasing pressure, whereas the localized character of the trivalent Yb state becomes stronger inferred from the reduction of the Kondo scattering. We will discuss the possible origin of the suppression of $T_N$ under pressure.

1. Introduction

In Ce- and Yb-based heavy fermion systems, tuning the ground state by pressure and/or magnetic field from a non-magnetic state to a magnetic state or vice versa has attracted attention because the anomalous behavior, such as unconventional superconductivity or non-Fermi liquid state, appears in the vicinity of quantum critical point (QCP). Due to the hole-electron analogy, it is known that the application of pressure in Yb-based compounds has an opposite effect compared to Ce-based compounds, i.e., applying pressure induces magnetically ordered state from nonmagnetic state. Once the system enters the magnetically ordered state away from the QCP, the magnetic order is stabilized and thus the magnetic transition temperature increases with increasing pressure. However, here we introduce the suppression of the antiferromagnetic (AF) ordered state by the application of pressure in heavy fermion compound YbNi$_3$Al$_9$.

Recently, Ohara et al. succeeded in growing YbNi$_3$Al$_9$ single crystal and reported low temperature physical properties [1]. YbNi$_3$Al$_9$ crystallizes in the ErNi$_3$Al$_9$ type crystal structure. There are three kinds of layers stacked along the $c$-axis: Yb$_2$Ni$_3$-layers, Al$_3$-layers and Ni$_3$-layers. Note that Yb ions are arranged in a two-dimensional honeycomb lattice in the Yb$_2$Ni$_3$-layers. The temperature dependence of electrical resistivity shows typical behavior of heavy fermion antiferromagnet with a Néel temperature of $T_N \sim 3.4$ K. Residual resistivity is less than $1\mu\Omega$ cm and RRR$\sim$30, indicating high quality of single crystal. In order to investigate the effect of pressure on Yb-based heavy fermion antiferromagnet, we have measured the electrical resistivity of high quality YbNi$_3$Al$_9$ single crystal up to 8 GPa.
2. Experimental

High pressure was generated by using two types of pressure cells; a hybrid piston cylinder cell (PCC) and cubic anvil cell (CAC) [2]. CAC is known to generate hydrostatic pressure owing to the multiple anvil geometry with a maximum pressure of \( \sim 8 \) GPa. The pressure at low temperature in PCC was determined by the pressure dependence of a superconducting transition temperature of Pb. The applied pressure in CAC is calibrated by the measurement of the resistivity changes of Bi and Te associated with their structural phase transitions at room temperature. Pressure transmitting medium for PCC and CAC was a glycerin and mixture of Fluorinert (FC70 and FC77), respectively. The electrical resistivity was measured by the four-terminal method with an excitation current of 500-1000 \( \mu \)A. The electrical current flows along the \( a \)-axis.

3. Result and Discussion

Figure 1 shows temperature dependence of electrical resistivity \( \rho(T) \) of YbNi\(_3\)Al\(_9\) at ambient pressure. \( \rho(T) \) exhibits the broad maximum centered at \( T_{\text{max}} \sim 40 \) K, which is related to incoherent Kondo-scattering processes on the ground state and the excited crystalline electronic field (CEF) level. According to specific heat measurement, the Schottky anomaly is observed with an energy splitting of \( \Delta \sim 40 \) K [3], consistent with the resistivity peak at \( T_{\text{max}} \). At lower temperatures, a clear kink at \( T_N \sim 3.2 \) K is associated with the antiferromagnetic transition of Yb moments. We define \( T_N \) as the minimum in the second derivative \( d^2\rho(T)/dT^2 \). The insets of Fig. 1(a) and (b) show \( \rho(T) \) at selected pressure and the pressure dependence of \( T_N \), respectively. Interestingly, \( T_N \) decreases with increasing pressure in the initial ratio of \(-0.23\) K/GPa. This observation is unexpected because the magnetic order of Yb compounds is stabilized with increasing pressure, as mentioned introduction. In order to confirm the suppression of \( T_N \) under pressure, we have performed resistivity measurement using CAC at higher pressure region.

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\begin{align*}
\text{Figure 1.} & \quad \text{Temperature dependence of the electrical resistivity for YbNi}_3\text{Al}_9 \text{ at ambient pressure. The electrical current flows along the } a-\text{axis. The inset (a) shows the temperature dependence of the electrical resistivity under pressure using PCC. The arrows indicate the AF transition temperature. The inset (b) shows the pressure dependence of } T_N \text{ for YbNi}_3\text{Al}_9. \text{ Dotted line is a guide to the eye.}
\end{align*}
\]
Figure 2 shows the temperature dependence of electrical resistivity up to 8 GPa. Applying pressure does not change the position of $T_{\text{max}}$ (see the inset of Fig. 2), however, the magnitude of the resistivity at $T_{\text{max}}$ significantly decreases with increasing pressure. Thus, the energy splitting of the CEF effect is almost pressure independent and the Kondo scattering is suppressed under pressure. This result indicates a strong localized character of Yb ions under pressure, namely the localized $f$ electrons are effectively decoupled from the conduction electrons. Next, we focus on the low temperature properties. Above 2 GPa, the resistivity anomaly at $T_N$ shifts to lower temperatures and no longer observable in the temperature range down to $\sim$2.4 K. This is consistent with the results obtained at lower pressure region using PCC.

Here we briefly discuss the possible origin of the unusual pressure dependence of $T_N$ in YbNi$_3$Al$_9$. Recently similar anomalous suppression of $T_N$ under pressure is also reported in some Yb-based compounds, such as Yb$_2$Pd$_2$Sn and YbAgGe [4, 5]. In these systems, it is suggested that $T_N$ is affected by a complex interplay of RKKY interaction, Kondo effect and the geometrical frustration. First, we consider the competition between Kondo and RKKY interaction. In Yb-based heavy fermion compounds, starting from the non-magnetic intermediate valence regime, the Kondo interaction is suppressed with increasing pressure and a long range magnetically ordered state appears. Thus, it is expected that the magnetic transition temperature increases with increasing pressure if the system is located close to a magnetic QCP. On the other hand, once the system enters the strongly localized regime, recent theoretical model predicts the enhancement of the Kondo interaction under sufficiently high pressures, resulting in the reduction of the magnetic interaction [6]. In practice, the Kondo scattering in YbNi$_3$Al$_9$ is monotonically suppressed with increasing pressure, although the valence state of Yb ions is close to trivalent state confirmed by X-ray absorption spectroscopy [7]. Hence, above theory is not applicable to the present system.

From the structural point of view, the Yb ions of YbNi$_3$Al$_9$ indeed lie on a honeycomb lattice with the potential for magnetic frustration. The magnetic frustration in a honeycomb lattice...
is only expected if both nearest and next-nearest neighbor interaction is antiferromagnetic, but the magnetization data of YbNi$_3$Al$_9$ suggest that Yb moments align ferromagnetically in the honey-comb layers while the each plane is coupled antiferromagnetically along the c-axis [1, 7]. Therefore, the scenario of the magnetic frustration is ruled out assuming that the aforementioned magnetic structure persists under pressure. At this stage, the origin of suppression $T_N$ is an open question. Further investigations, such as magnetic susceptibility and neutron diffraction measurements under pressure, are necessary to clarify this issue.

4. Summary
We present the effect of pressure on YbNi$_3$Al$_9$ single crystal under pressure. The pressure variation of the resistivity indicates the localized character of the trivalent Yb state under pressure. In contrast, we found the pressure-induced suppression of $T_N$ probably due to the complex interplay of the low energy interactions.

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