Pressure-induced transition from a canted antiferromagnetic state to a ferromagnetic state in YbRhSb

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Abstract. YbRhSb undergoes a transition at $T_{M1} = 2.7$ K into a canted antiferromagnetic state with a small spontaneous moment of $3 \times 10^{-3} \mu_B$/Yb. With increasing pressure $P$, $T_{M1}(P)$ has a deep minimum of 2.5 K at 1.7 GPa. We have studied the pressure effect on the magnetization, resistivity and specific heat of a single crystal. With increasing pressure, the Kondo temperature estimated from the magnetic entropy decreases rapidly with increasing pressure, but remains at a constant value above 1.5 GPa. For $P \geq 2$ GPa, the canted antiferromagnetic structure changes to a ferromagnetic one with a large moment 0.4 $\mu_B$/Yb lying in the orthorhombic $b-c$ plane. A metamagnetic behavior at $B \parallel a = 1.5$ T remains in the ferromagnetic state. It is ascribed to the competition between the single-ion crystalline electric field anisotropy with easy direction $\parallel a$ and the inter-site exchange interaction with easy $b-c$ plane.

1. Introduction

The magnetic phase diagram of cerium (Ce)- and ytterbium (Yb)- based heavy-fermion compounds has been believed to result from the competition between the Kondo interaction and the Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction. The former is favourable for a nonmagnetic ground state, while the latter leads to a long-range magnetically ordered state. By applying pressure $P$, the magnetic ordering temperature $T_M$ of a Ce compound is suppressed and its ground state moves to a nonmagnetic state through a quantum critical point (QCP) [1]. On the other hand, it is expected that pressure drives a nonmagnetic Yb system into a magnetically ordered state and its $T_M$ increases monotonically with pressure. In contrast to the expectation, the $T_M(P)$ of a heavy-fermion antiferromagnet YbRh$_2$Si$_2$ has a broad maximum around 5 GPa and vanishes at 8.5 GPa [2]. Above 9 GPa, $T_M$ increases abruptly, and a large moment state appears [3]. Furthermore, the ground state of YbNiSn with an orthorhombic $\varepsilon$-TiNiSi-type structure changes from a ferromagnetic (FM) state to a complex antiferromagnetic (AFM) state above 3 GPa [4]. These anomalous pressure-induced magnetic phase transitions cannot be attributed solely to the competition between the Kondo and RKKY interactions. For YbNiSn, it was attributed to another type of competition between the anisotropy of the magnetic exchange interaction with easy direction $\parallel c$ and the crystalline electric field (CEF) anisotropy with easy direction $\parallel a$ [4].
Recently, we have found that YbRhSb, being isostructural to YbNiSn, exhibits an anomalous $P - T$ phase diagram [5,6]. At ambient pressure, this compound undergoes a transition at $T_M = 2.7$ K into an unusual magnetic state, which is associated with a very small spontaneous moment of $2.3 \times 10^{-3} \mu_B$/Yb along all three principal directions [6]. A metamagnetic transition at 2.2 T in the isothermal magnetization process and the peaking of magnetic susceptibility at $T_M$ for $B \parallel b$ suggest that the weak ferromagnetism originates from a sort of canted antiferromagnetism [7]. Resistivity and ac magnetic susceptibility measurements under pressures revealed that another magnetic transition occurs at $T_{M2}$ above $T_{M1}$, and $T_{M1}(P)$ has a deep minimum of 2.5 K at $P_C = 1.7$ GPa [5,6]. Furthermore, dc magnetization measurements under pressures showed that a FM state with net moments lying along the $c$-axis is induced above 2 GPa. In order to determine the pressure dependence of the Kondo and RKKY interactions, specific heat and dc magnetization measurements of YbRhSb single-crystalline sample have been performed under pressures up to 3 GPa.

2. Experimental procedure

A single-crystalline sample of YbRhSb was grown by the Bridgeman method, as described previously [7]. Hydrostatic pressure was applied using an indenter-type pressure cell made of Cu-Be alloy [8] for $P < 2.5$ GPa. The dc magnetization was measured by using a commercial superconducting quantum interference device magnetometer (Quantum Design) in fields up to 5 T at temperatures from 2 K to 10 K. The electrical resistivity under pressures up to 3 GPa was measured by an ac four-terminal method using a piston-cylinder pressure cell. Daphne oil was used as a pressure medium in both pressure cells. The specific heat under pressure up to 3 GPa was measured by the ac method using a Bridgman anvil cell [9].

3. Results and discussions

The temperature dependence of the magnetic susceptibility $\chi = M/B$ along the $b$-axis under various pressures is shown in Fig. 1. With increasing pressure, the upturn of $\chi$ at $T_{M1}$ shifts to a higher temperature. Above 1.3 GPa, however, the upturn at $T_{M1}$ shifts to a lower temperature. A broad maximum which is the manifestation of an AF order appears at $T_{M2} = 3.5$ K. This maximum is consistent with the anomaly at $T_{M2}$ in the ac susceptibility [5]. With further increasing pressure, the upturn at $T_{M1}$ grows to a steep increase at $T_{M3}$ and shifts to a higher temperature, implying the enhancement of the FM component. To confirm the development of the FM state above 2 GPa, we have measured the dc magnetization under various constant pressures as a function of magnetic field. As shown in the inset of Figure 1, the magnetization curve for $B \parallel b$ at 2.49 GPa exhibits a definite ferromagnetic behavior with the remanent moment of $0.4 \mu_B$/Yb.

Pressure induced magnetic transition above 1.3 GPa also manifests itself in the specific heat $C(T)$ as shown in Fig. 2. As pressure is increased up to 1.5 GPa, one peak splits in two peaks. The small hysteresis appearing at $T_{M1}$ suggests a first-order transition. Above 2 GPa, the jump of the specific heat at $T_{M3}$ becomes larger. This finding implies that the RKKY interaction overcomes the Kondo interaction. In fact, the magnetic entropy $S_m$ at $T_M$ almost doubles from $S_m(T_{M1}) = 0.26 R n 2$ at $P = 0$ to $S_m(T_{M3}) = 0.45 R n 2$ at 2.95 GPa.

Figure 3 shows the temperature dependence of the electrical resistivity $\rho$ along the $a$-axis of YbRhSb under various pressures up to 2.7 GPa. The temperatures at the kink and sharp drop agree, respectively, with the ordering temperatures determined from the results of Figs. 1 and 2. The broad maximum at $T_{\text{max}} = 30$ K for $P = 0$ is attributed to the Kondo effect. With increasing pressure, the $T_{\text{max}}$ shifts to low temperature. This observation suggests that the Kondo temperature $T_K$ decreases with pressure. In order to make clear the pressure dependence of $T_K$, we evaluate the $T_K$ using the specific heat data of Fig. 2. If we neglect the contribution from short-range magnetic correlations, we can estimate $T_K$ using the relation
The inset shows isothermal magnetization curves $M(B)$ for $B \parallel b$ at 2 K under various constant pressures.

$S_m(T_M) = S_K(T_M/T_K)$, which is relevant for a Kondo impurity with a spin $s = 1/2$, where $S_K(T_M/T_K)$ is the Kondo entropy at $T_M$ [10]. Thus obtained $T_K$, which are plotted as a function of pressure in Fig. 4(a), decreases steeply up to 1.5 GPa above which pressure $T_K(P)$ remains at a constant value. This behavior of $T_K$ corresponds with that for $T_{\text{max}}$ derived from $\rho(T)$, as shown in the same figure.

The pressure dependence of the magnetic ordering temperatures determined from $C(T)$, $M_b(T)$ and $\rho(T)$ is plotted in Fig. 4(b). In the previous paper, we took the temperature at the upturn of $\chi$ as $T_{M1}$ and $T_{M3}$[6]. However, the evaluated temperatures were somewhat higher than the present values because of the field dependence of the magnetization. For a FM order, the temperature at the negative peak of $d\chi/dT$ gives the ordering temperature, which in fact agrees with the temperature at the midpoint of the jump of $C(T)$ in Fig. 2. It is noteworthy that $T_{M3}(P)$ increases sharply above 2 GPa, whereas $T_K(P)$ is almost constant. This fact suggests that the increment of $T_{M3}$ is not due to the suppression of Kondo interaction, but the enhancement of RKKY interaction.

We now focus on the pressure dependence of magnetic structure of YbRhSb. The magnetization and recent Sb NMR measurements at ambient pressure [11] suggested that the magnetic moments are lying along the $b$-axis below $T_{M1}$. Above 2 GPa, a FM state is induced with a spontaneous moment of 0.3 $\mu_B$/Yb orienting the $c$-axis [6], and above 2.5 GPa, the FM moments are lying in the $b-c$ plane. However, a metamagnetic behavior for $B \parallel a$ = 1.5 T remains in the FM state [6]. The similar metamagnetic behavior along the $a$-axis has been observed in the isostructural compound YbNiSn. The ground state has a collinear FM structure with moments parallel to the $c$-axis [12]. This unusual situation arises from the competition between the strong anisotropic exchange interaction with the easy direction along the $c$-axis and the CEF anisotropy with the easy $a$-axis. The CEF anisotropy of YbRhSb with easy $a$-axis hardly changes under pressures up to 2.5 GPa because the $a$-axis remains the easy direction in magnetic susceptibility in the paramagnetic state up to 2.5 GPa (not shown) [13]. Furthermore, the $T_K$ Kondo temperature also hardly changes above 1.5 GPa. Therefore, the complicated pressure-induced magnetic phase of YbRhSb is attributed to the enhancement of inter-site exchange interaction with easy $b-c$ plane. In order to determine the detailed magnetic structures, neutron diffraction and NMR measurements under pressures are highly desired.
Figure 3. Temperature dependence of electrical resistivity along the a-axis of YbRhSb. Data sets for each value of P are shifted upward consecutively by 60 $\mu$Ωcm for clarity.

Figure 4. (a) Pressure dependence of the Kondo temperature $T_K$ and the maximum temperature of the electrical resistivity, $T_{max}$ for YbRhSb. (b) $P$ − $T$ phase diagram of YbRhSb.

In summary, dc magnetization measurements of YbRhSb under pressures showed that a ferromagnetic state with net moments lying in the $b$ − $c$ plane is induced by applying pressure above 2.5 GPa. The Kondo temperature estimated from the magnetic entropy decreases rapidly with increasing pressure up to 1.5 GPa. A metamagnetic behavior for $B \parallel a = 1.5$ T remains in the ferromagnetic state. It is ascribed to the competition between the single-ion crystalline electric field anisotropy with easy direction $\parallel a$ and the inter-site exchange interaction with easy $b$ − $c$ plane.

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