Pressure-induced ferromagnetic order in the weak ferromagnet YbRhSb

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Abstract. YbRhSb has a small spontaneous moment of 0.003 µB/Yb below TM₁ = 2.7 K at ambient pressure. We have studied the pressure effect on the weak ferromagnetism by the measurements of dc magnetization for a single crystal up to 2.5 GPa. With increasing P, TM₁(P) increases to a maximum value of 3.3 K. For 0.9 < P < 1.5 GPa, another magnetic transition occurs at TM₂ above TM₁, and TM₁(P) has a deep minimum of 2.5 K at PC = 1.7 GPa. For P > 2 GPa, a spontaneous moment of 0.3µB/Yb appears along the orthorhombic c-axis. In the ferromagnetic state above 2 GPa, magnetization curves for B || a and B || b exhibit sharp metamagnetic transitions at around 1.5 T. The complexity of the magnetic behaviors may be ascribed to the competition between single-ion crystal field anisotropy with easy direction || a and inter-site exchange interaction with easy direction || c.

1. Introduction
It has been long believed that the ground state of cerium (Ce)- and ytterbium (Yb)- based heavy-fermion compounds is determined by 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. Applying pressure P on Ce compounds suppresses the magnetic ordering temperature TM and its ground state moves to a nonmagnetic state through a quantum critical point [1]. On the other hand, it is expected that application of pressure drives a nonmagnetic Yb system into a magnetically ordered state and its TM increases monotonically. In contrast to this expectation, the TM of YbRh₂Si₂ has a broad maximum around 5 GPa and increases abruptly above 9 GPa [2]. Furthermore, the ground state of YbNiSn with an orthorhombic ε-TiNiSi-type structure changes from a ferromagnetic state to a complex antiferromagnetic state above 3 GPa [3]. 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 competition between the anisotropy of the magnetic exchange interaction with easy direction || c and the crystalline electric field (CEF) anisotropy with easy direction || a [3].

Recently, we have found that an isostructural compound YbRhSb has an anomalous P − T phase diagram [4]. At ambient pressure, this compound undergoes a transition at TM = 2.7 K into an unusual magnetic state, which is associated with a very small spontaneous moment of
$2 \sim 3 \times 10^{-3} \mu_B/Yb$ along three principal directions [5]. A metamagnetic transition at 2.2 T in the magnetization curve and the peaking of magnetic susceptibility at $T_M$ for $B \parallel b > 1.75$ T suggest that the weak ferromagnetism originates from canted antiferromagnetism [5]. A resistivity measurement under pressure revealed that $T_M(P)$ has a pronounced minimum at $P_C = 1.7$ GPa [4]. In order to investigate the pressure-induced transition above $P_C$, magnetization measurements of YbRhSb single-crystalline sample have been performed under pressures up to 2.5 GPa.

2. Experimental procedures

A single-crystalline sample of YbRhSb was grown by the Bridgeman method, as described previously [4,5]. 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. Hydrostatic pressure was applied using a piston-cylinder pressure cell made of NiCrAl alloy [6] for $P < 1.6$ GPa and an indenter-type pressure cell made of Cu-Be alloy [7] for $P < 2.5$ GPa. In both pressure cells, Daphne oil was used as a pressure medium.

![Figure 1](image1.png)  
**Figure 1.** $P$–$T$ phase diagram of YbRhSb.

![Figure 2](image2.png)  
**Figure 2.** Temperature dependence of the magnetic susceptibility of YbRhSb along the $a$-axis under pressures.

3. Results and discussions

In Fig. 1, we present the $P$–$T$ phase diagram of YbRhSb constructed from the present data of dc magnetization $M$ and the previous data of the resistivity and ac magnetic susceptibility [8]. In the previous paper, we took the peak temperature of ac magnetic susceptibility as the ordering temperatures both $T_{M1}$ for $P > 1$ GPa and $T_{M3}$ for $P > 1.7$ GPa. However, the dc magnetization measurements in this paper showed that the magnetically ordered state is a ferromagnetic state. For the ferromagnetic order, the temperature at the upturn of dc and ac
susceptibility rather than the peak temperature gives the ordering temperature. It should be noted that another transition occurs at $T_{M2}$ above $T_{M1}$, and $T_{M1}$ has a pronounced minimum (2.6 K) at 1.7 GPa. Above this pressure, the transition temperature is denoted by $T_{M3}$, which increases sharply with pressure.

The temperature dependence of the magnetic susceptibility $\chi = M/B$ along the $a$-axis under various constant pressures is shown in Fig. 2. 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 and a broad maximum appears at $T_{M2}$=3.5 K. This finding is consistent with the anomaly at $T_{M2}$ observed in the ac susceptibility [4]. The upturn at $T_{M1}$ grows to a steep increase at $T_{M3}$ and shifts to a higher temperature, implying enhancement of the ferromagnetic component. To confirm the development of the ferromagnetic state above 2 GPa, we have measured the dc magnetization under various constant pressures as a function of magnetic field.

Figure 3 shows the magnetization curves at 2 K under pressures up to 2.5 GPa. With increasing pressure, the magnitude of $M(B \parallel a)$ doubles and the weak metamagnetic-like anomaly at $B_{M}=3.2$ T observed for $P=0$ becomes sharper and shifts to 1.5 T for $P=2.5$ GPa. However, the magnetization curve for $B \parallel c$ above 1.75 GPa exhibits a definite ferromagnetic behavior with the remanent moment of 0.3 $\mu_B$/Yb. The magnetic anisotropy of YbRhSb with a ferromagnetic component above 2 GPa resembles that for the isostructural compound YbNiSn at ambient pressure, which orders ferromagnetically below $T_C=5.6$ K [9,10]. In YbNiSn, $M(B \parallel c)$ exhibits a remanent moment of 0.6 $\mu_B$/Yb, while $M(B \parallel a)$ shows metamagnetic transitions at $1 \sim 2$ T and reaches 1.4 $\mu_B$/Yb at 8 T, but that for $B \parallel b$ increases linearly without showing a metamagnetic transition [9].
Now, we discuss the pressure dependence of magnetic structure of YbRhSb. The magnetization measurements at ambient pressure suggested that the magnetic moments are lying along the $b$-axis below $T_{M1}$, which is confirmed by the recent Sb NMR measurements \[11\]. Above 2 GPa, the magnetic structure of YbRhSb is expected to be similar to that of YbNiSn because of the close resemblance in the anisotropy in the magnetization curves. In the early stage of the study of YbNiSn, a canted antiferromagnetic structure with Yb$^{3+}$ moments lying in the $ac$-plane was proposed because the CEF anisotropy shows easy $a$-axis magnetization \[9\]. Later, a collinear ferromagnetic structure with moments parallel to the $c$-axis was revealed by a neutron diffraction study \[10\]. 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 GPa because the easy direction in magnetic susceptibility in the paramagnetic state remains $a$-axis up to 2 GPa (not shown) \[12\]. Therefore, application of pressure has induced the reorientation of the easy axis in the ordered state from the $b$-axis to the $c$-axis. Furthermore, the small remanent moment along the $a$-axis remains above 2 GPa, which manifests itself in the hysteresis of $\chi$ along the $a$-axis below $T_{M3}$ in Fig. 2. However, such a hysteretic behavior in the hard directions was not reported for YbNiSn. The magnetic structure of YbRhSb above 2 GPa may be more complicated than the collinear ferromagnetic structure of YbNiSn. In order to examine the detailed magnetic structures, neutron diffraction experiments under pressure are highly desired.

In summary, dc magnetization measurements of YbRhSb under pressures showed that a ferromagnetic state with net moments lying along the $c$-axis is induced by applying pressure above 2 GPa. The magnetization curves for $B \parallel a$ and $B \parallel b$ exhibit sharp metamagnetic transition at around 1.5 T. However, the magnetization along the $a$-axis still possess the small remanent moments. These unusual magnetic behaviors should arise from the competition between the strong anisotropic exchange interaction and CEF anisotropy. This competition rather than the conventional competition between Kondo and RKKY interactions may play the dominant role in the magnetism of certain Yb-based heavy fermion compounds.

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