Frustrated antiferromagnet YbAgGe under magnetic fields and pressures

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Abstract. We present a detailed study of the field ($B$)- temperature ($T$) phase diagram under pressures ($P$) up to 2.7 GPa for the heavy-fermion antiferromagnet YbAgGe that crystallizes in the hexagonal ZrNiAl-type structure with a quasi-kagome lattice of Yb ions. This compound undergoes two magnetic transitions at $T_{M1} = 0.8$ K and $T_{M2} = 0.65$ K in zero field at ambient pressure. In the ground state, $M(B)$ shows a metamagnetic transition at $B_M = 4.6$ T for the easy magnetization direction $B \parallel a$. This transition field decreases to 3.3 T as $P$ is increased to 2.2 GPa. At 2.7 GPa, $\rho(B)$ exhibits successive transitions at 5.0, 6.0, 7.5, and 9.0 T. On the other hand, for the hard direction $B \parallel c$, $T_M$ increases with applied field in the $P$ range above 0.5 GPa. This increase of $T_M(B)$ is opposite to the decrease of $T_M(B)$ for a conventional antiferromagnetic phase. These findings suggest that the application of pressure releases in part the magnetic frustration in YbAgGe.

1. Introduction

Ytterbium (Yb)-based compounds exhibit interesting physical phenomena such as quantum critical behavior and suppression of a long-ranged magnetic order due to geometrical frustration. According to the Doniach model[1], the ground state of Yb-based compounds is determined by the competition between the Kondo effect and the Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction, both of which are governed by the exchange interaction between the 4$f$ electron and conduction electrons. In the vicinity of a quantum critical point (QCP), it is expected that application of pressure drives the magnetic ordering temperature $T_M$ to increase monotonically. In the system YbRh$_2$Si$_2$, $T_M$ increases continuously with increasing pressure for $P < 3$ GPa, like it is expected for a Yb-based system driven away from a quantum critical point[2]. Whereas for higher pressures, $T_M$ passes through a broad maximum at 4-5 GPa and vanishes at $P = 9$ GPa, then $T_M$ strongly increases with pressure[2]. The anomalous pressure dependence of $T_M$ for $P > 3$ GPa cannot be understood by the Doniach phase diagram.

It has been proposed that the coexistence of geometrical frustration and instability of magnetic moments near the magnetic-nonmagnetic transition gives rise to a complicated magnetic phase diagram including a partially ordered state[3, 4]. Indeed, anomalous magnetic properties originating from geometrical frustration have been found in a triangular-lattice
antiferromagnet such as CsCuCl₃[5] and a quasi-kagome lattice antiferromagnet such as YbPtIn[6, 7, 8]. The field ($B$)- temperature ($T$) phase diagram of CsCuCl₃ with horizontal boundaries are consistent with those calculated for a frustrated XY-model of a triangular-lattice antiferromagnet with $s = 1/2$[5]. In YbPtIn with the hexagonal ZrNiAl-type structure, three Yb ions lie on a kagome-like triangular lattice in the $c$ plane of this structure[6]. This compound undergoes two transitions at $T_{N1} = 3.4$ K and $T_{N2} = 1.4$ K. Below $T_{N2}$, multistep metamagnetic transitions occur for $B \perp c$, which may be attributed to a complex magnetic structure originating from the frustrated magnetic interactions[7].

The heavy-fermion antiferromagnet YbAgGe, being isostructural to YbPtIn, undergoes two magnetic transitions at $T_{M1} = 0.8$ K (second order) and $T_{M2} = 0.65$ K (first order)[9, 11]. The magnetic frustration in YbAgGe manifests itself in the $q$-independence of the characteristic spin fluctuating energy in the basal plane of the hexagonal structure[10]. An tail in the specific-heat $C(T)$ extending above $T_{M1}$ is consistent with the magnetic frustration[11]. Recently, an anomalous $T$-$P$ phase diagram under pressures of YbAgGe has been constructed from $C(T)$ and the resistivity $\rho(T)$ measurements[12, 13]. For $0.5 < P < P^* = 1.6$ GPa, $T_{M}(P)$ remains constant, while above $P^*$ the $T_{M}(P)$ increases linearly as $P$ is increased to 3.2 GPa[13]. The magnetic entropy at $T_{M}$ rises for $P > P^*$, whereas the Kondo temperature $T_{K}$ does not change, contrary to the behavior expected from the Doniach phase diagram. These findings suggest that the sudden rise of $T_{M}(P)$ for $P > P^*$ is not due to the lowering of $T_{K}$ but the release of the magnetic frustration. In order to examine the suppression of spin fluctuation with applying fields and the enhancement of the magnetic moment above $P^*$, we have measured $\rho$ and magnetization $M$ under magnetic fields up to 9.5 T in the pressure range up to 2.8 GPa.

2. Experimental procedures
Single-crystalline samples of YbAgGe were grown by the Bridgman method, which was described previously[11]. A Faraday method using a high-resolution capacitive magnetometer[14] was used for the magnetization measurements in the ranges $0.3 \leq T \leq 1.5$ K and $0 \leq B \leq 9.5$ T. The measurement of $\rho$ was performed by an ac four-terminal method in the ranges $0.3 \leq T \leq 1.8$ K and $0 \leq B \leq 9.5$ T. Hydrostatic pressures for the $M$ ($P \leq 2.2$ GPa) and $\rho$ ($P \leq 2.7$ GPa) measurements were applied using hybrid piston-cylinder pressure cells made of NiCrAl and Cu-Be alloy. In both pressure cells, Daphne oil was used as a pressure medium.

3. Results and discussion
The magnetization curves $M_a(B)$ and $M_c(B)$ for $B \parallel a$ and $B \parallel c$, respectively, at 0.3 K under constant pressures up to 2.2 GPa are shown in Fig. 1(a). With increasing pressure, the whole curves of $M_a(B)$ increase and the weak metamagnetic-like anomaly at $B_{M} = 4.6$ T for $P = 0$ shifts to 3.3 T for $P = 2.2$ GPa. However, the $M_c(B)$ hardly changes with pressure. In Fig. 2, the value of $M_a/B$ at 1.0 T is plotted as a function of $P$. The sharp rise above $P^* = 1.6$ GPa suggests the magnetic frustration is released at $P > P^*$. This is consistent with the increase of the magnetic entropy at $T_{M}$ for $P > P^*$[13]. Figure 1(b) shows $dM_a(B)/dB$ at 0.3 K under constant pressures up to 2.2 GPa. Three anomalies are observed at $B_{M1} = 1.1$ T, $B_{M2} = 2.6$ T, $B_{M3} = 4.6$ T for $P = 0$. With increasing pressure, $B_{M1}$ and $B_{M2}$ disappear, $B_{M3}$ shifts to 3.3 T for 2.2 GPa. Above 1.5 GPa, other anomalies appear at $B_{M4}$ and $B_{M5}$. These anomalies of $M_a(B)$ could be the manifestation of the lift of the degenerated ground state. It means that the ground state of YbAgGe is sensitive to not only the applied pressure but also the applied magnetic field.

In Fig. 3, all data sets of transition temperatures and magnetic fields are plotted in $B$-$T$ phase diagrams for $B \parallel a$. At $P = 0$, our data of $B_M(T)$ are in good agreement with those reported by Niklowitz et al.[15], which are plotted in Fig. 3. With increasing pressure, the area of phase I expands, whereas the phases II and III disappear. Another phase IV appears in the
Figure 1. (a) Magnetic field dependence of $M_a(B)$ and $M_c(B)$ and (b) $dM_a(B)/dB$ of YbAgGe at 0.3 K up to 2.2 GPa.

The high-field region and a boundary exists near 8 T. At $P > P^*$, the expansion of the phase I may be related to the release of the frustration. For the isostructured YbPtIn, the $B$-$T$ phase diagrams for $B \perp c$ was studied under pressure[7]. At 0.95 GPa, a phase appears below 7 K at 0.1 T[7]. This phase was interpreted as an antiferromagnetically ordered phase, where the magnetic frustrations are lifted in part by the applied pressure. By analogy, there may be a low-field boundary in YbAgGe.

In Fig. 4, all data of $T_M$ and $B_M$ are plotted in $B$-$T$ phase diagrams of YbAgGe for $B \parallel c$ under constant pressures. Our data of $T_{M1}$ at low fields are smaller than that reported by Bud'ko et al.[16], but the dependence of $T_{M2}$ on $B$ is in good agreement. The most significant in the phase diagrams for $P \geq 0.5$ GPa is the appearance of the phase V above 8.5 T, which boundary increases with increasing field. This behavior is opposite to the decrease of $T_M$ for a conventional antiferromagnetic phase.

In summary, magnetization and resistivity measurements of YbAgGe single crystals under pressures and magnetic fields showed that the magnetic moment for $B \parallel a$ is increased by applying pressure above 1.6 GPa. With increasing pressure, magnetic phases IV and V appear. The $T_M$ of phase V increases with increasing field $B \parallel c$. This behavior is opposite to the decrease of $T_M$ for a conventional antiferromagnetic phase. These unusual magnetic behaviors should arise from the partial release of the magnetic frustration in the quasi-kagome lattice of Yb ions under pressure.

Figure 2. Pressure dependence of $M_a/B$ at 0.3 K, 1.0 T. The dotted line is a guide to the eye.
Figure 3. Field \((B \parallel a)\)-temperature phase diagram of YbAgGe under pressures. Solid lines are guides to the eye. Symbols: filled square from \(M(T)\) and \(M(B)\), filled triangles from \(\rho(T, B)\). The open triangles represent the data from \(\rho(T, B)\) reported in ref.[15].

Figure 4. Field \((B \parallel c)\)-temperature phase diagram of YbAgGe under pressures. Solid lines are guides to the eye. Symbols: filled square from \(M(T)\) and \(M(B)\), filled triangles from \(\rho(T, B)\). The open circles represent the data from \(\rho(T, B)\) and \(C(T, B)\) reported in ref.[16].

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