Metamagnetic Transition in Heavy Fermion Compounds YbT$_2$Zn$_{20}$ ( T : Co, Rh, Ir )

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Abstract. We measured the magnetization in high magnetic fields up to 500kOe, together with the magnetic susceptibility, ac-susceptibility and magnetoresistance for heavy fermion compounds YbT$_2$Zn$_{20}$ ( T : Co, Rh, Ir ). The metamagnetic behaviour or an abrupt nonlinear increase of magnetization was observed at the magnetic field $H_m$ at temperatures lower than a characteristic temperature $T_{max}$ below which the magnetic susceptibility becomes almost constant: $T_{max}$ = 7.4K and $H_m$ = 97kOe in YbIr$_2$Zn$_{20}$, $T_{max}$ = 5.3K and $H_m$ = 64kOe in YbRh$_2$Zn$_{20}$, and $T_{max}$ = 0.32K and $H_m$ = 6kOe in YbCo$_2$Zn$_{20}$. From the present data and the data in several Ce and U heavy fermion compounds, a simple relation between $T_{max}$ and $H_m$ was obtained: $H_m$(kOe) = 15$T_{max}$(K).

1. Introduction

Most of Ce and U compounds order antiferromagnetically. Some compounds such as CeCu$_6$, CeRu$_2$Si$_2$ and UPt$_3$ exhibit no long-range magnetic ordering[1]. The magnetic susceptibility of these compounds shows a maximum at a characteristic temperature $T_{X_{max}}$. Below $T_{X_{max}}$, the susceptibility becomes almost temperature-independent, and an $f$-electron nature is changed into a new electronic state, called the heavy fermion state. Here, $T_{X_{max}}$ approximately corresponds to the Kondo temperature $T_K$. One of the characteristic properties in the heavy fermion compounds is the metamagnetic behaviour or an abrupt nonlinear increase of magnetization at the magnetic field $H_m$ at temperatures lower than $T_{X_{max}}$. The metamagnetic behaviour appears at $H_m = 77$kOe in CeRu$_2$Si$_2$ and $H_m = 200$kOe in UPt$_3$, for example[2],[3].

Very recently, we found the metamagnetic behaviour at $H_m = 97$kOe for $H // (100)$ in a new heavy fermion compound YbIr$_2$Zn$_{20}$ with the cubic cage-structure[4]. Here we report the metamagnetic behaviour in YbIr$_2$Zn$_{20}$ and the similar compounds YbRh$_2$Zn$_{20}$ and YbCo$_2$Zn$_{20}$ by measuring the magnetization, magnetic susceptibility, ac-susceptibility and magnetoresistance, and propose a relation between $T_{X_{max}}$ and $H_m$ in the heavy fermion compounds.
Figure 1. (a) Single crystal ingot, (b) temperature dependence of the magnetic susceptibility, (c) magnetization and (d) transverse magnetoresistance in YbIr$_2$Zn$_{20}$.

2. Experimental results

Single crystal ingots, grown by the the Zn-flux method, are pyramidal in shape, as shown in Figures 1(a) and 3(a) for YbIr$_2$Zn$_{20}$ and YbCo$_2$Zn$_{20}$, respectively, where flat planes correspond to the \{111\} planes, reflecting the diamond structure of Yb atoms. Yb and T atoms are surrounded by Zn atoms, forming a cubic cage-structure.

Figure 1(b) shows the temperature dependence of the magnetic susceptibility for $H // \langle 100 \rangle$. The susceptibility follows the Curie-Weiss law of $\chi = C/(T + \theta_P) + \chi_0$ : the Curie term with an effective magnetic moment $\mu_{\text{eff}} = 4.54\mu_B/Yb$, close to $\mu_{\text{eff}} = 4.57\mu_B/Yb$ of Yb$^{3+}$, a paramagnetic Curie temperature $\theta_P = -27K$ and $\chi_0 = -1.05 \times 10^{-3} \text{emu/mol}$. The susceptibility possesses a broad peak at $T_{\chi_{\text{max}}} = 7.4K$, which is characteristic in the heavy fermion compounds. The present result is the same as the previous one[5].

The high-field magnetization for $H // \langle 100 \rangle$ is shown in Figure 1(c), revealing a metamagnetic behaviour at $H_m = 97kOe$. The corresponding magnetoresistance is also shown in Figure 1(d). A change of the magnetoresistance was observed at $H_m = 97kOe$, as shown by an arrow, together with small change at $H'_m = 60kOe$ and $H''_m = 120kOe$. The metamagnetic transition field is slightly anisotropic : $H_m = 120kOe$ for $H // \langle 110 \rangle$.

The similar measurements were carried out for YbRh$_2$Zn$_{20}$, as shown in Figure 2. The magnetic susceptibility has a maximum at $T_{\chi_{\text{max}}} = 5.3K$, as shown in Figure 2(b). The metamagnetic behaviour was observed at $H_m = 64kOe$ in the magnetization, as shown in Figure 2(b) and another anomaly was furthermore observed at $H_m' = 84kOe$ in the magnetoresistance, as shown in Figure 2(c).

In YbCo$_2$Zn$_{20}$, the metamagnetic behaviour was observed at a very small magnetic field $H_m = 6kOe$ at temperatures lower than 0.3K. The susceptibility increases with decreasing temperature down to 1.8K, following the Curie-Weiss law, as shown in Figure 3(b). We therefore measured the ac-susceptibility below 1K, and obtained a peak at $T_{\chi_{\text{max}}} = 0.32K$, as shown in inset of Figure 3(b). The magnetization at 1.3K didn’t reveal the metamagnetic behaviour, as shown in Figure 3(c). The metamagnetic behaviour at $H_m = 6kOe$ is reflected in the ac-susceptibility at 60mK, as shown in inset of Figure 3(c), and in the magnetoresistance at 100mK, as shown.
in Figure 3(d). YbCo$_2$Zn$_{20}$ is therefore located in the vicinity of the quantum critical point. In fact, the electronic specific heat coefficient $\gamma$ is very large, 8000mJ/K$^2$-mol[5].

From the present results of the metamagnetic behaviour, together with those of Ce and U compounds, we constructed the relation between $T_{\chi_{max}}$ and $H_m$, as shown in Figure 4. A solid line in Figure 4 indicates a simple relation of $H_m$(kOe) = 15$T_{\chi_{max}}$(K).

Figure 2. (a) Temperature dependence of the magnetic susceptibility, (b) magnetization and (c) transverse magnetoresistance in YbRh$_2$Zn$_{20}$.

Figure 3. (a) Single crystal ingot, (b) temperature dependence of the magnetic susceptibility, (c) magnetization and (d) transverse magnetoresistance in YbCo$_2$Zn$_{20}$. 
3. Conclusion
A simple relation between the characteristic temperature $T_{\chi_{\text{max}}}$ and the metamagnetic field $H_m$ was obtained experimentally for heavy fermion compounds YbT$_2$Zn$_{20}$ ($T$: Ir, Rh, and Co): $H_m = 15 T_{\chi_{\text{max}}}$ (K). In YbCo$_2$Zn$_{20}$, an electronic state with a very small Kondo temperature $T_{\chi_{\text{max}}} = 0.32$K is realized, which corresponds to a very large $\gamma$ value of $8000 \text{mJ/K}^2 \cdot \text{mol}$. This might be mainly due to a long distance between Yb atoms, 6Å, together with the cage structure.

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