Metamagnetic Behavior in Heavy Fermion Compounds UCo$_2$Zn$_{20}$ and UIr$_2$Zn$_{20}$

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Abstract. The metamagnetic behavior, which is typical in heavy fermion compounds, is observed in UCo$_2$Zn$_{20}$ and UIr$_2$Zn$_{20}$ at $H_m = 80$ and 20 kOe, respectively. Reflecting the metamagnetic behavior, the magnetoresistance is suppressed in magnetic fields larger than $H_m$, and the corresponding $A$-value of a Fermi liquid relation in the electrical resistivity indicates a peak at around $H_m$. Pressure suppresses this behavior in UIr$_2$Zn$_{20}$.

1. Introduction

UT$_2$Zn$_{20}$ (T : Co, Ir) crystallizes in the cubic structure with a large lattice constant $a \simeq 14$ Å and the U-U distance $d \simeq 6$Å. UCo$_2$Zn$_{20}$ was reported to be a non-magnetic heavy fermion compound[1]. The magnetic susceptibility follows a Curie-Weiss law at high temperatures and possesses a maximum at $T_{\chi_{\text{max}}} = 7$ K. The corresponding specific heat coefficient $C/T$ also possesses a broad maximum at 5 K. On the other hand, UIr$_2$Zn$_{20}$ was a ferromagnet with a Curie temperature $T_C = 2.1$ K[1]. Both compounds, however, possess large electronic specific heat coefficients $\gamma = 230$ and 450 mJ/(K$^2$·mol), respectively. Another experimental results were reported very recently, claiming that UCo$_2$Zn$_{20}$ and UIr$_2$Zn$_{20}$ are non-magnetic heavy fermion compounds with $T_{\chi_{\text{max}}} = 8.2$ and 4.5 K, and the electronic specific heat coefficient $\gamma = 350$ and 400 mJ/(K$^2$·mol), respectively[2].

Recently, a non-linear increase of magnetization, namely a metamagnetic behavior was observed at the magnetic field $H_m$ in the similar non-magnetic heavy fermion compounds YbT$_2$Zn$_{20}$ (T : Co, Rh, and Ir)[3]. A simple relation between $T_{\chi_{\text{max}}}$ and $H_m$ in Ce-, U-, and Yb-based heavy fermion compounds including YbT$_2$Zn$_{20}$ was obtained as $15T_{\chi_{\text{max}}}$(K) $= H_m$(kOe), namely $k_B T_{\chi_{\text{max}}} = \mu_B H_m$. Here, $T_{\chi_{\text{max}}}$ roughly corresponds to the Kondo temperature, and the corresponding metamagnetic behavior is observed below $T_{\chi_{\text{max}}}$. The almost localized $f$-electron nature at high temperatures is changed into a heavy fermion state at temperatures lower than $T_{\chi_{\text{max}}}$. The heavy fermion state can be, however, changed into the almost localized $f$-electron nature at magnetic fields larger than $H_m$.  

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Figure 1. (a) Electrical resistivity of UCo$_2$Zn$_{20}$ and UIr$_2$Zn$_{20}$, (b) specific heat in the form of $C/T$(inset:$C/T$ vs $T^2$), (c) magnetic susceptibility and the corresponding inverse susceptibility, (d) high-field magnetization and (inset:single crystal ingots), (d) transverse magnetoresistance, and (e) magnetic field dependence of the $\Delta$ value in UCo$_2$Zn$_{20}$.

In the present study, we grew single crystals of UCo$_2$Zn$_{20}$ and UIr$_2$Zn$_{20}$, and measured the electrical resistivity, specific heat, magnetic susceptibility and magnetization to investigate the metamagnetic behavior.

2. Experimental results and analyses

2.1. UCo$_2$Zn$_{20}$

First, we show in Fig. 1(a) the temperature dependence of the electrical resistivity $\rho$ in UCo$_2$Zn$_{20}$, together with that in UIr$_2$Zn$_{20}$. The resistivity increases slightly with decreasing temperature, has a broad maximum around 100 K, and decreases steeply at lower temperatures. The resistivity follows a Fermi liquid relation of $\rho = \rho_0 + AT^2$ below 3 K, as shown by a thin solid line in inset
Figure 2. (a) Specific heat in the form of $C/T$ (inset: $C/T$ under 0, 20, and 50 kOe), (b) magnetic susceptibility and the corresponding inverse susceptibility, (c) high-field magnetization (inset: single crystal ingots), (d) magnetization, (e) transverse magnetoresistance at several temperatures, and (e) field dependence of the $A$ value under pressures in UIr$_2$Zn$_{20}$.

of Fig. 1(a). The $A$ value is 0.49 $\mu\Omega \cdot \text{cm/K}^2$, which corresponds to $\gamma \approx 220 \text{ mJ/(K}^2\cdot\text{mol})$ from a Kadowaki-Woods relation $A/\gamma^2 = 1.0 \times 10^{-5} \mu\Omega \cdot \text{cmK}^{-2}/(\text{mJK}^{-2}\cdot\text{mol}^{-1})^{-2}$[4]. We note that $A = 1.3 \mu\Omega \cdot \text{cm/K}^2$ and $\gamma = 360 \text{ mJ/(K}^2\cdot\text{mol})$ are obtained for UIr$_2$Zn$_{20}$. The low-temperature specific heat coefficient $C/T$ possesses a broad peak at 6 K, as shown Fig. 1(b), and the $\gamma$ value is 300 mJ/(K$^2$-mol), which are approximately consistent with the previous results[1, 2], together with $\gamma = 220 \text{ mJ/(K}^2\cdot\text{mol})$ estimated from the $A$ value, mentioned above. The magnetic susceptibility $\chi$ increases with decreasing temperature, and possesses a peak at $T_{\chi_{\text{max}}} = 8.5$ K. No anisotropy is observed below and above $T_{\chi_{\text{max}}}$ for $H//\langle 100 \rangle; \langle 110 \rangle; \text{and} \langle 111 \rangle$. The present peak is therefore not due to a magnetic ordering, but is based on a characteristic heavy fermion behavior, as mentioned in Introduction. The effective magnetic moment and the paramagnetic Curie temperature are obtained as $\mu_{\text{eff}} = 3.44 \mu_B/\text{U}$ and $\theta_P = -63$ K, respectively. The present
magnetic moment is close to 3.58 $\mu_B/U$ of $5f^2$ and 3.62 $\mu_B/U$ of $5f^3$ configuration.

A metamagnetic behavior, which is characteristic in heavy fermion compounds, is clearly observed at $H_m \approx 80$ kOe for $H//\langle 100 \rangle, \langle 110 \rangle, \langle 111 \rangle$, as shown in Fig. 1(d). The magnetic moment at 500 kOe is small, 1.1 $\mu_B/U$. This means that the $5f$ electrons are not fully localized even at high magnetic fields and still contribute to the conduction electrons. The present metamagnetic behavior is also reflected in the transverse magnetoresistance, as shown in Fig. 1(e). We also obtained the $A$ value from the temperature dependence of the resistivity under constant magnetic fields. The magnetic field dependence of the $A$ value is shown in Fig. 1(f), revealing a broad maximum at around $H_m$.

2.2. UIr$_2$Zn$_{20}$

A broad maximum in $C/T$ is observed at 3.5 K in UIr$_2$Zn$_{20}$, as shown in Fig. 2(a), and the $\gamma$ value is roughly estimated as 450 mJ/(K$^2 \cdot $mol), which is also consistent with the previous results[2] and $\gamma = 370$ mJ/(K$^2 \cdot $mol) estimated from the $A$ value. The present $\gamma$ value is reduced by 400 mJ/(K$^2 \cdot $mol) at 50 kOe, as shown in Fig. 2(a). Note that $C/T$ at 20 kOe, which is a metamagnetic field, shown below, increases with decreasing temperature. No anisotropy of the magnetic susceptibility is also observed for $H//\langle 100 \rangle, \langle 110 \rangle$, and $\langle 111 \rangle$, as shown in Fig. 2(b). The $\mu_{\text{eff}}$ and $\theta_F$ are 3.55 $\mu_B/U$ and -85.8 K, respectively. $T_{\chi_{\text{max}}}$ is obtained at 5.3 K.

The metamagnetic behavior is observed at $H_m = 20$ kOe, as shown in Figs. 2(c) and 2(d). An increase of transverse magnetoresistance below 4.0 K is suppressed above $H_m$, as shown in Fig. 2(c). It is noted that 4.0 K is below $T_{\chi_{\text{max}}} = 5.2$ K. The $A$ value indicates a sharp peak at $H_m = 20$ kOe. This peak is, however, reduced with increasing pressure, and most likely diminishes at high pressures of 4 GPa. It is also noted that the $A$ value at $H = 0$ kOe is approximately unchanged with respect to pressure. This behavior is in contrast with that in YbIr$_2$Zn$_{20}$, where the peak structure is shifted to lower magnetic fields with increasing pressure, and finally $H_m$ becomes zero at a critical pressure $P_c = 5.2$ GPa, reaching quantum critical point. The $A$ value is increased from $A = 0.29 \mu \Omega \cdot$cm/K$^2$ at ambient pressure to $A = 380 \mu \Omega \cdot$cm/K$^2$ at $P_c[5]$.

3. Conclusion

We observed a metamagnetic behavior at $H_m = 80$ kOe for $T_{\chi_{\text{max}}} = 8.5$ K in UCo$_2$Zn$_{20}$ and at $H_m = 20$ kOe for $T_{\chi_{\text{max}}} = 5.2$ K in UIr$_2$Zn$_{20}$. The present metamagnetic behavior is typical in heavy fermion Ce, Yb, and U compounds, and a simple relation of $15 T_{\chi_{\text{max}}} (K) = H_m (kOe)$ is roughly applied to UCo$_2$Zn$_{20}$. UIr$_2$Zn$_{20}$ is found to deviate from the relation. This is needed to study in more detail.

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