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| メタデータ | 言語: en<br>出版者: IOP Publishing<br>公開日: 2018-03-13<br>キーワード (Ja):<br>キーワード (En):<br>作成者: 川村, 幸裕, 大金, 優太, 西岡, 孝, 加藤, 治一, 松村,<br>政博, 松林, 和幸, 上床, 美也<br>メールアドレス:<br>所属: |
| URL   | <a href="http://hdl.handle.net/10258/00009588">http://hdl.handle.net/10258/00009588</a>  |

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To cite this article: Yukihiro Kawamura *et al* 2011 *J. Phys.: Conf. Ser.* **273** 012038

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# Magnetic and transport properties of $\text{CeT}_2\text{Al}_{10}$ ( $T = \text{Fe, Ru, Os}$ ) under pressure

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**Abstract.** The results of electrical resistivity  $\rho$  measurements for  $\text{CeT}_2\text{Al}_{10}$  ( $T = \text{Fe, Ru, Os}$ ) under pressure are reported. The abrupt increase was observed at  $T_0 \sim 27$  K for  $\text{CeRu}_2\text{Al}_{10}$  and 29 K for  $\text{CeOs}_2\text{Al}_{10}$  at ambient pressure. By applying pressure,  $T_0$  for  $\text{CeRu}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$  suddenly disappeared at 4 GPa and 2 GPa, respectively. Although the ground state of  $\text{CeRu}_2\text{Al}_{10}$  is metal at ambient pressure,  $\rho$  at low temperatures increased and the ground state became semiconductor at 2 GPa. The increase in  $\rho$  suppressed above 3 GPa and the ground state became metal above 5 GPa. Magnetic contribution to  $\text{CeRu}_2\text{Al}_{10}$  above 4 GPa shows maximum, which seems to be attributed to Kondo coherence. These systematical change in  $\rho(T)$  was also observed in  $\text{CeFe}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$ . From the pressure dependence of the temperature of the maximum, we suggest that  $\text{CeFe}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$  is corresponding to 3.2 GPa and 1.3 GPa of  $\text{CeRu}_2\text{Al}_{10}$ .

## 1. Introduction

Heavy fermion compounds  $\text{CeT}_2\text{Al}_{10}$  ( $T = \text{Fe, Ru, Os}$ ) crystallizes in the  $\text{YbFe}_2\text{Al}_{10}$ -type crystal structure (orthorhombic, space group  $Cmcm$ ) [1, 2]. These compounds are characteristic of their new phase transition, which occurred at  $T_0 \sim 27$  K on  $\text{CeRu}_2\text{Al}_{10}$  [3] and 29 K on  $\text{CeOs}_2\text{Al}_{10}$  [4], and for Kondo semiconducting behavior on  $\text{CeFe}_2\text{Al}_{10}$  [5]. At first the new phase transition is reported to be attributed to antiferromagnetic order [3]. However,  $^{27}\text{Al}$ -NQR study for  $\text{CeRu}_2\text{Al}_{10}$  denies it because the splitting of line spectrum below  $T_0$  is different from antiferromagnetic order [6]. Besides, 27 K is too high to order antiferromagnet in this small concentration of magnetic system, where the nearest-neighbor of Ce exceeds  $5\text{\AA}$ . This is why this new phase transition is attracted much attention. Recently,  $\mu^+\text{SR}$  and neutron diffraction experiments revealed that this transition is due to long-range magnetic ordering of the Ce sublattice with a reduced moment of  $0.34 \mu_B$  [7]. However, the origin of very high  $T_0$  and low value of the ordered moments has not clarified yet. In addition, the relation between Kondo semiconducting behavior and this phase transition is not clarified. The scaling behavior against pressure among isostructural  $\text{CeT}_2\text{Al}_{10}$  ( $T = \text{Ru, Os and Fe}$ ) may be one of the key aspects to reveal these issues.

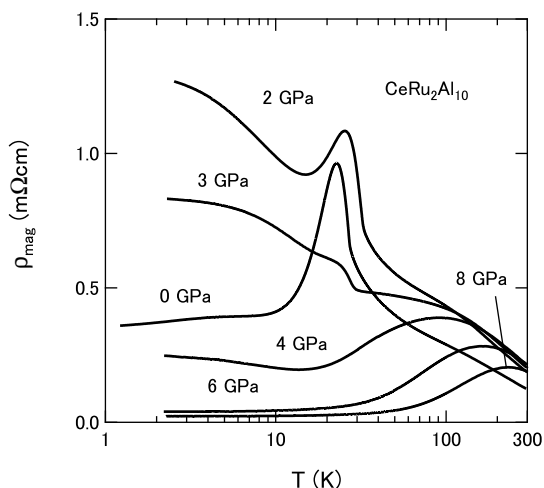
The purpose of this study is to clarify the relationship between each  $\text{CeT}_2\text{Al}_{10}$ . In our previous study, we reported overall behavior of  $\rho(T)$  for  $\text{CeT}_2\text{Al}_{10}$  under pressure. In this paper, we report

$\rho(T)$  for  $\text{CeT}_2\text{Al}_{10}$  in detail. In addition, we discuss pressure dependence of each characteristic temperature.

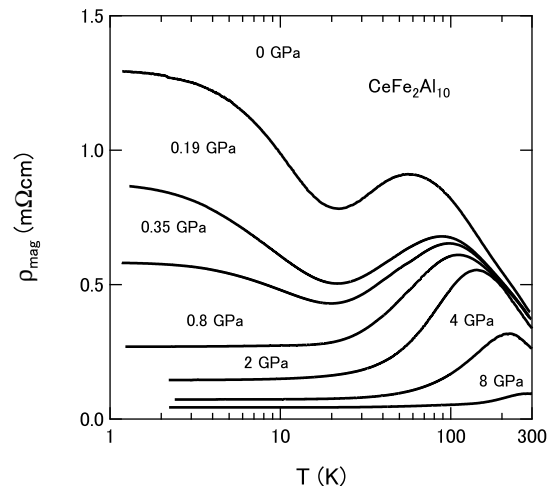
## 2. Experimental

Single crystals of  $\text{CeT}_2\text{Al}_{10}$  ( $T = \text{Fe, Ru, Os}$ ) were grown by using Al self-flux method. The starting composition of  $\text{CeT}_2\text{Al}_{10}$  was placed in an  $\text{Al}_2\text{O}_3$  crucible, sealed in a quartz ampule in vacuum and heated to  $1000^\circ\text{C}$  and then cooled to  $720^\circ\text{C}$  at a rate of  $5^\circ\text{C/h}$  and the Al flux was removed by centrifugation. The remaining flux was removed by sinking 5 mol/L NaOH solution for 24 hours. The resulting single crystals were confirmed as single phase by powder X-ray diffraction. The electrical resistivity under 2 GPa was measured by the ac 4 terminal method with the frequency of 40 Hz and effective current is 3 mA. The pressure was applied by using piston cylinder type pressure cell with Daphne 7373 oil as a pressure transmitting oil. The pressure was calibrated by the temperature of the superconductivity on In. The electrical resistivity above 2 GPa was measured by the conventional dc 4 terminal method with effective current of 3 mA. The pressure was applied by cubic anvil cell with the mixture of Fluorinert FC70:FC77=1:1 as a pressure transmitting oil.

## 3. Results and Discussion



**Figure 1.** Temperature dependence of the magnetic contribution to the electrical resistivity  $\rho_{\text{mag}}$  (see text in detail) for  $\text{CeRu}_2\text{Al}_{10}$  under pressure.

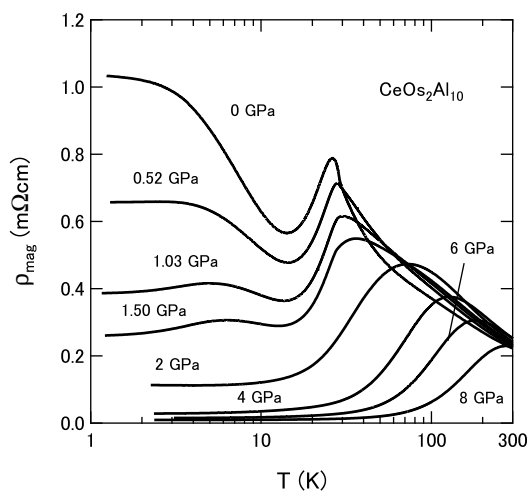


**Figure 2.**  $\rho_{\text{mag}}$  vs  $T$  for  $\text{CeFe}_2\text{Al}_{10}$  under pressure.

Fig. 1 shows temperature dependence of the magnetic contribution to the electrical resistivity  $\rho_{\text{mag}}$  for  $\text{CeRu}_2\text{Al}_{10}$  under pressure. We have evaluated the  $\rho_{\text{mag}}$  from the experiment by subtracting the phonon contribution  $\rho_{\text{ph}}$  of the appropriate La compound. At ambient pressure,  $\rho(T)$  increases with decreasing temperature from room temperature to 27 K. At 27 K,  $\rho(T)$  increases abruptly reflecting the appearance of the new phase transition. It exhibits a maximum at 23 K and then shows decreasing gap-like below 23 K. At 2 GPa,  $T_0$  increases to 33 K. The value of  $\rho$  at low temperatures increases. This increase in  $\rho$  at low temperatures indicates ground state of this compound becomes semiconductor from metal. At 3 GPa,  $T_0$  decreases to 29 K. With decreasing  $T_0$ ,  $\rho(T)$  at low temperatures suppresses. The broad peak, which seems to be attributed to high density Kondo effect, is observed over 4 GPa, where the novel phase transition

disappears. The temperature of this maximum denotes  $T_{\max}$ . The  $T_{\max}$  increases monotonically with pressure.

Fig. 2 shows the temperature dependence of  $\rho_{\text{mag}}$  for  $\text{CeFe}_2\text{Al}_{10}$ . At ambient pressure,  $\rho_{\text{mag}}$  exhibits a maximum at  $T_{\max} \sim 70$  K and shows increasing at low temperatures. The former seems to be attributed to dense Kondo effect and the latter seems to be attributed to Kondo semiconducting gap. This behavior is similar to  $\rho_{\text{mag}}$  for  $\text{CeRu}_2\text{Al}_{10}$  at 4 GPa. However, the rate of the increase in  $\rho_{\text{mag}}$  for  $\text{CeFe}_2\text{Al}_{10}$  is higher than that for  $\text{CeRu}_2\text{Al}_{10}$ . On the other hand,  $\rho_{\text{mag}}$  for  $\text{CeFe}_2\text{Al}_{10}$  does not show phase transition, which one can see that for  $\text{CeRu}_2\text{Al}_{10}$  at 3 GPa. Thus,  $\rho_{\text{mag}}$  for  $\text{CeFe}_2\text{Al}_{10}$  is considered to be attributed to that for  $\text{CeRu}_2\text{Al}_{10}$  at the pressure between 3 GPa and 4 GPa. Increasing at low temperatures suppresses and  $T_{\max}$  increases with pressure. Although semiconducting behavior at 0 GPa suddenly suppresses at 2 GPa in our previous study, we confirmed that semiconducting behavior gradually suppresses with pressure in this study.

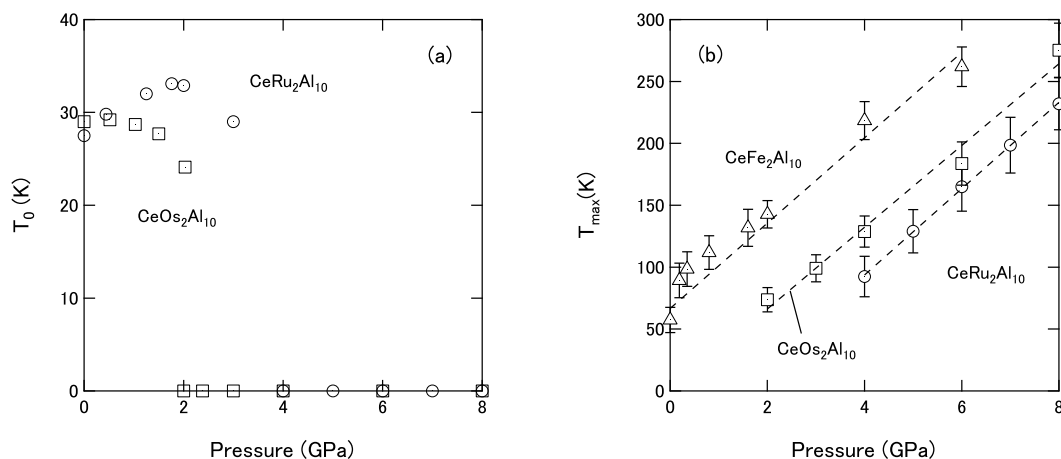


**Figure 3.**  $\rho_{\text{mag}}$  vs  $T$  for  $\text{CeOs}_2\text{Al}_{10}$  under pressure.

Fig. 3 shows the temperature dependence of  $\rho_{\text{mag}}$  for  $\text{CeOs}_2\text{Al}_{10}$ . At ambient pressure,  $\rho(T)$  in  $\text{CeOs}_2\text{Al}_{10}$  increases abruptly at  $T_0 \sim 29$  K and exhibit a peak at 26 K followed by a minimum and increasing with decreasing temperature. The behavior of  $\rho_{\text{mag}}$  for  $\text{CeOs}_2\text{Al}_{10}$  is similar to that for  $\text{CeRu}_2\text{Al}_{10}$  at 2 GPa, although the value of a peak after  $T_0$  is smaller than that for  $\text{CeRu}_2\text{Al}_{10}$ . At 0.52 GPa, the abrupt increase in  $\rho_{\text{mag}}$  below  $T_0$  is suppressed. At 1.03 GPa, the kink appears instead of the abrupt increase. This kink decreases with increasing pressure. On the other hand, the increase at low temperature is gradually suppressed as the pressure increases. The ground state become metal above 2 GPa. Above 3 GPa,  $T_{\max}$  gradually increases with pressure.

Fig. 4(a) shows the pressure dependence for  $T_0$ .  $T_0$  for  $\text{CeRu}_2\text{Al}_{10}$  increases slightly with pressure at first and exhibit a maximum at around 2 GPa. At 4 GPa,  $T_0$  disappears suddenly like first order transition. On the other hand,  $T_0$  for  $\text{CeOs}_2\text{Al}_{10}$  decreases slightly with pressure and suddenly disappears at 2 GPa. Fig. 4(b) shows the pressure dependence for  $T_{\max}$ .  $T_{\max}$  increases monotonically with pressure in each sample. The dotted line indicates least square fitting to the each data.  $T_{\max}$  obtained from the data of pressure measurements using piston cylinder cell is considered to be higher than actual value, because the pressure is calibrated at low temperatures and expected to be higher at high temperatures. Thus, we used the data of ambient pressure measurements and of pressure measurements using cubic anvil cell as fitting

data. The  $dT_{\max}/dP$  is similar to each other. The pressure of the extrapolation to the x axis for  $\text{CeFe}_2\text{Al}_{10}$ ,  $\text{CeRu}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$  is -1.9 GPa, 1.3 GPa and 0 GPa, respectively. This result suggests that  $\text{CeFe}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$  is corresponding to 3.2 GPa and 1.3 GPa of  $\text{CeRu}_2\text{Al}_{10}$ . Since the lattice constant of  $\text{CeFe}_2\text{Al}_{10}$  is smaller than that of  $\text{CeRu}_2\text{Al}_{10}$ , this result is consistent with chemical pressure. However the lattice constant of  $\text{CeRu}_2\text{Al}_{10}$  is almost same as but is smaller than that of  $\text{CeOs}_2\text{Al}_{10}$ . Although it contradicts to present results, the reason is not clarified.



**Figure 4.** (a)  $T_0$  vs  $P$  for  $\text{CeRu}_2\text{Al}_{10}$  (open circle) and for  $\text{CeOs}_2\text{Al}_{10}$  (open square). The data pointed at 0 K indicates that there is not any phase transition above 2 K. (b)  $T_{\max}$  vs  $P$  for  $\text{CeFe}_2\text{Al}_{10}$  (open triangle),  $\text{CeRu}_2\text{Al}_{10}$  (open circle) and  $\text{CeOs}_2\text{Al}_{10}$  (open square). The dotted line indicates least square fitting to the each data (see text in detail).

#### 4. Summary

$\rho(T)$  for  $\text{CeRu}_2\text{Al}_{10}$  increases abruptly at  $T_0$  and exhibit a maximum at 23 K and then decreases with temperature. By applying pressure,  $T_0$  slightly increases and  $\rho(T)$  at low temperatures enhances. This behavior is similar to  $\rho(T)$  for  $\text{CeOs}_2\text{Al}_{10}$  at ambient pressure. At 4 GPa, Kondo semiconducting like behavior is observed, which is similar to  $\rho(T)$  for  $\text{CeFe}_2\text{Al}_{10}$  at ambient pressure. The broad peak, which is seems to be attributed to high density Kondo effect, is observed over 4 GPa. The temperature of this broad peak increases monotonically with pressure, which is also observed in  $\rho(T)$  for  $\text{CeOs}_2\text{Al}_{10}$  and  $\text{CeFe}_2\text{Al}_{10}$ . From these behaviors, we suggests that  $\text{CeFe}_2\text{Al}_{10}$  and  $\text{CeOs}_2\text{Al}_{10}$  is corresponding to 3.2 GPa and 1.3 GPa of  $\text{CeRu}_2\text{Al}_{10}$ .

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