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Electrical resistivity and effect of pressure on the thermal expansion of a single crystal of YbCu$_2$Si$_2$

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Electrical resistivity $\rho(T)$ and thermal expansion $\Delta l/l$ were measured for the intermediate valence compound (IVC) YbCu$_2$Si$_2$ and its counterpart LuCu$_2$Si$_2$ between 4.2 K and 300 K. It was found that the thermal expansion coefficient $\alpha(T)$ has a negative minimum around 31 K ($= T_{\text{m}}$) at atmospheric pressure and $T_{\text{m}}$ decreases with increasing pressure at the rate $\partial T_{\text{m}}/\partial P = -0.45$ K/kbar.

1. Introduction

Ytterbium (Yb) intermetallic compounds show a wide variety of interesting physical properties such as heavy fermion behavior, intermediate valence, etc. [1]. Yb compounds are considered to be hole analogues to heavy fermion Ce compounds, because the valence of Yb$^{3+}$ has a hole relative to the fully occupied 4f shell Yb$^{2+}$. YbCu$_2$Si$_2$ crystallizes in the tetragonal body-centered ThCr$_2$Si$_2$-type structure [2] and is characterized as an intermediate valence compound reflecting the strong hybridization between the 4f localized electrons and the conduction band electrons [3]. YbCu$_2$Si$_2$ is shown to be a nonmagnetic compound down to 0.05 K [4] with a large $\gamma$-value of 210 mJ/mol K$^2$ [5]. It is well known that the hybridization is very sensitive to external forces such as pressure, temperature and magnetic field. It is worthwhile to investigate the physical properties of YbCu$_2$Si$_2$ at high pressure because considerable change in the electronic structure is expected.

In this paper, we report the measurement of the electrical resistivity $\rho(T)$ and thermal expansion $\Delta l/l(T)$ of a single crystal of YbCu$_2$Si$_2$ up to 20 kbar in order to study the effect of pressure on the electronic state of Yb compounds.

2. Experimental

Details of the sample preparation and characterization were reported previously [5]. The electrical resistivity was measured by the standard four-probe method in the temperature range from 4.2 to 300 K at atmospheric pressure. The thermal expansion was measured by means of the standard strain gauge method (Kyowa Dengyo, KFL02-C1-11, gauge factor 2.03) in the temperature range from 4.2 to 300 K under high pressure up to 20 kbar. The sample was placed in a Cu–Be cylinder vessel (8 mm plain diameter) and loaded by a 20 ton hydraulic press using a W-C piston. A 1:1 mixture of Fluorinert, FC70 and FC77, was used as a pressure transmitting medium. The pressure inside the cylinder was kept constant throughout the experiment by controlling the oil pressure of the hydraulic press. Temperature was measured with a calibrated Cu(Fe)-Chromel thermocouple. Details of the high-pressure apparatus were reported previously [6].

3. Results and discussion

3.1. Electrical resistivity $\rho$ of single crystals of YbCu$_2$Si$_2$ and LuCu$_2$Si$_2$

Figure 1 shows the temperature dependence of the electrical resistivity $\rho(T)$ of YbCu$_2$Si$_2$ and LuCu$_2$Si$_2$ in the current along the $a$-axis. Here $\rho(T)$ of YbCu$_2$Si$_2$ increases with increasing temperature up to around
100 K and becomes nearly constant above 150 K. No maximum is observed in \( \rho(T) \). This result is in good agreement with recent studies by Müller et al. [7]. The \( \rho(T) \) of LuCu\(_2\)Si\(_2\) was measured to estimate the phonon contribution in the \( \rho(T) \) of YbCu\(_2\)Si\(_2\), because the 4f shell of nonmagnetic Lu has 14 electrons. The \( \rho(T) \) of LuCu\(_2\)Si\(_2\) shows a smooth variation against temperature, which is the same as that of normal metal. The magnetic contribution to \( \rho(T) \), \( \rho_{\text{mag}}(T) \), is defined as \( \rho_{\text{mag}}(T) = \rho(\text{YbCu}_2\text{Si}_2) - \rho(\text{LuCu}_2\text{Si}_2) \). This \( \rho_{\text{mag}}(T) \) exhibits a broad maximum at \( T = 112 \) K and \( \ln T \) dependence above 200 K, which is characteristic behavior due to Kondo scattering of conduction electrons as observed in many Ce compounds [8]. There is no \( T^2 \)-dependence in the \( \rho_{\text{mag}}(T) \) at low temperature. This suggests that YbCu\(_2\)Si\(_2\) does not behave as a Fermi liquid in the temperature range of the present work (\( T > 4.2 \) K).

### 3.2. Effect of pressure on the thermal expansion coefficients of YbCu\(_2\)Si\(_2\)

The thermal expansion of YbCu\(_2\)Si\(_2\) is shown in fig. 2 as a function of temperature at various pressures. Linear thermal expansion \( \Delta l/l(T) \) at atmospheric pressure is found to decrease with increasing temperature up to around 50 K and then begins to increase above 70 K after showing a minimum at 60 K (= \( T_{\text{min}} \)). This anomalous temperature dependence of \( \Delta l/l(T) \) may originate from instability in the valence of Yb at low temperature such as IVC YbCuAl [3,9]. The minimum value of \( \Delta l/l(T) \) at \( T_{\text{min}} \) decreases with increasing pressure.

In order to obtain the linear thermal expansion coefficient, \( \alpha(T) = (1/l)(\Delta l/l)(dT) \), the \( \Delta l/l(T) \) curve was differentiated by temperature. The thermal ex-

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**Fig. 1.** Temperature dependence of the electrical resistivity of YbCu\(_2\)Si\(_2\) and LuCu\(_2\)Si\(_2\) single crystals. \( \rho_{\text{mag}} \) is also shown as a function of temperature.

**Fig. 2.** Temperature dependence of the linear thermal expansion \( \Delta l/l \) in YbCu\(_2\)Si\(_2\) single crystal at various pressures.

**Fig. 3.** Thermal expansion coefficients of YbCu\(_2\)Si\(_2\) defined as \( \alpha = (1/l)(\Delta l/l)(dT) \).
approximately linear fashion at a rate $\frac{\partial T_{\text{min}}}{\partial P} = -0.45 \text{ K/kbar}$. $T_{\text{min}}$ may be related to the Kondo temperature $T_K$ [11]. By assuming that $T_{\text{min}}$ is approximately proportional to $T_K$, the value of the pressure derivative of $T_K$ is estimated to be $(1/T_K)\frac{\partial T_K}{\partial P} = (1/T_{\text{min}})\frac{\partial T_{\text{min}}}{\partial P} = -1.45 \times 10^{-2} \text{ kbar}^{-1}$. The absolute value of $(1/T_K)(\frac{\partial T_K}{\partial P})$ is of the same order magnitude as that of the intermediate valence compound CePd$_3$ [12]. The negative pressure derivative of $T_{\text{min}}$ or $T_K$ of YbCu$_2$Si$_2$, which is in sharp contrast with the case of Ce compounds, may be one of the distinctive characteristics of Yb compounds.

The pressure dependence of $\Delta l/l$ along the $a$-axis of YbCu$_2$Si$_2$ is shown in fig. 5 up to 10 kbar at room temperature. The $a$-axis decreases linearly with increasing pressure. The linear compressibility along the $a$-axis is $\kappa_a = 4.18 \times 10^{-4} \text{ kbar}^{-1}$, which is the same order of magnitude as those of Ce compounds [12]. The Grüneisen parameter $\Gamma_a$ for the $a$-axis may be defined as $\Gamma_a = -\frac{\partial \ln(T_{\text{min}})}{\partial \ln V} = \frac{1}{\kappa_a} \frac{\partial T_{\text{min}}}{\partial P}$ [13]. $\Gamma_a$ is estimated as $-35$, which is the same as that of YbCuAl, $\Gamma = -35$ [3], and comparable to $\Gamma_a = -29$ estimated [5] from the low temperature $T^2$-coefficient of resistivity of YbCu$_2$Si$_2$.

4. Conclusions

Thermal expansion coefficient $\alpha(T)$ of YbCu$_2$Si$_2$ has a negative minimum around 31 K ($= T_{\text{min}}$) at atmospheric pressure and $T_{\text{min}}$ decreases with increasing pressure with the rate $\frac{\partial T_{\text{min}}}{\partial P} = -0.45 \text{ K/kbar}$. The Grüneisen parameter $\Gamma_a$ is estimated to be $-35$. The negative pressure dependence of $T_K$ and the Grüneisen parameter $\Gamma_a$ of YbCu$_2$Si$_2$ may be some of the distinctive characteristics of Yb compounds.

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References