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Electrical resistance of amorphous and crystalline $CeCu_6$ under high pressure

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Abstract

The electrical resistance of crystalline and amorphous $CeCu_6$ have been measured as a function of temperature at various pressures. Application of pressure induces the coherent state in the crystalline $CeCu_6$ (c-$CeCu_6$) at low temperature, while the amorphous $CeCu_6$ (a-$CeCu_6$) is still in the incoherent state at 20 kbar. The Kondo effect in a-$CeCu_6$ is found to be strongly enhanced by applying pressure and the values of $|JN(0)|$ increase with increasing pressure to three times larger than that at ambient pressure. This is in sharp contrast with that of c-$CeCu_6$. The origins of the difference between c-$CeCu_6$ and a-$CeCu_6$ is briefly discussed.

1. Introduction

The intermetallic compound $CeCu_6$ is a typical heavy fermion substance with a large specific heat coefficient, $\gamma = 1.5$ J/mol K^2 without any magnetic order [1]. The electrical resistivity $\rho(T)$ of $CeCu_6$ shows a logarithmic temperature dependence over a wide range of temperature but decreases suddenly below 15 K because of the periodicity of the cerium ion in the Kondo lattice and then a T^2-dependent electrical resistivity is observed below 1 K which means that the system enters the coherent state [2]. This kind of behavior of $\rho(T)$ is always observed in other HF substances such as $CeAl_3$ [3] or $CeInCu_2$ [4]. It was reported for $CeInCu_2$ that the residual resistivity ρ_0 is very large and the coefficient of the T^2 term, A, is extremely small compared with other HF substances [5], which is due to disorder of the lattice site between the Ce and In atoms in the Heusler type structure [6]. Anomalous results are also reported for the thermal expansion coefficient of $CeInCu_2$ [7]. The facts indicate that the site of atomic disorder is one of the important factors dominating the physical properties of HF compounds.

Recently, amorphous $CeCu_6$ (a-$CeCu_6$) was characterized as a HF compound with large γ-value of 1.3 J/mol K^2 [8], which is almost the same as that of crystalline $CeCu_6$ (c-$CeCu_6$). But the $\rho(T)$ curve of a-$CeCu_6$ is very different from that of c-$CeCu_6$, in which $\rho(T)$ increases gradually with decreasing temperature below 250 K and markedly below 25 K, which is due to the Kondo effect. In other words, the $\rho(T)$ curve of a-$CeCu_6$ does not show any peaks and any coherence at low temperature. Thus, the lattice disorder suppresses the coherence and the Kondo effect. It was reported that the range of T^2-dependence becomes broader as the pressure increases [9], *i.e.* the temperature range showing coherence is expanded at high pressure. This indicates that the pressure induces the coherent state.

In the present work, we made an attempt to measure the temperature dependence of electrical resistivity $\rho(T)$ of a-$CeCu_6$ at high pressure in order to examine the interplay between the pressure-induced coherent state and the atomic disorder and to further clarify the similarities and differences between c-$CeCu_6$ and a-$CeCu_6$.

2. Experimental procedure

The sample of a-$CeCu_6$ was prepared by the sputter-deposition method. The details of the preparation and the characterization of the sample have been described elsewhere [8]. The crystalline $CeCu_6$ was the same as that used previously [10]. The electrical resistance was measured by usual four-probe method, in which the electrical leads were attached to the sample by silver paste or indium soldering.

Hydrostatic pressure up to 2 GPa was generated using a Cu–Be piston-cylinder device and a 1:1 mixture of Fluorinert FC 70 and 77 as a pressure transmitting

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medium. The pressure was changed only at room temperature to minimize internal strain in the specimen and the load was controlled to within ±1% throughout the measurements. The details of the present high pressure apparatus have been reported previously [11].

3. Results and discussion

3.1. Effect of pressure on the electrical resistivity of c-$CeCu_6$

Here we show the temperature dependent electrical resistivity $\rho(T)$ of single crystalline $CeCu_6$ (c-$CeCu_6$) in the current direction along the *b*-axis, $J \| b$. Figure 1 illustrates the $\rho(T)$ curves at various pressures up to 30 kbar together with that of single crystalline $LaCu_6$. At ambient pressure $\rho(T)$ shows a typical heavy fermion behavior; a clear maximum in the $\rho(T)$ curve is observed at 15 K($=T_{max}$), a shallow minimum near 200 K and a logarithmic temperature dependence is seen in the range $50\,K<T<300\,K$ as shown later. As pressure increases, T_{max} increases from 15 K at ambient pressure to about 90 K at 30 kbar and the peak seems to become less prominent, which agrees qualitatively with the previous results [12,13]. $\rho(T)$ of $LaCu_6$ increases smoothly with increasing temperature like normal metals. Figure 2 shows T_{max} of c-$CeCu_6$ as a function of pressure. The average value of the pressure coefficient of T_{max} is 3.0 K/kbar between 10 and 30 kbar. Since T_{max} is proportional to the Kondo temperature T_K [14], the present results in Fig. 2 indicate that T_K increases with pressure.

To estimate the magnetic contribution to the electrical resistivity, $\rho_m(T)$, we use the following relation:

$$\rho_m(T)=\rho(CeCu_6)-\rho(LaCu_6) \qquad (1)$$

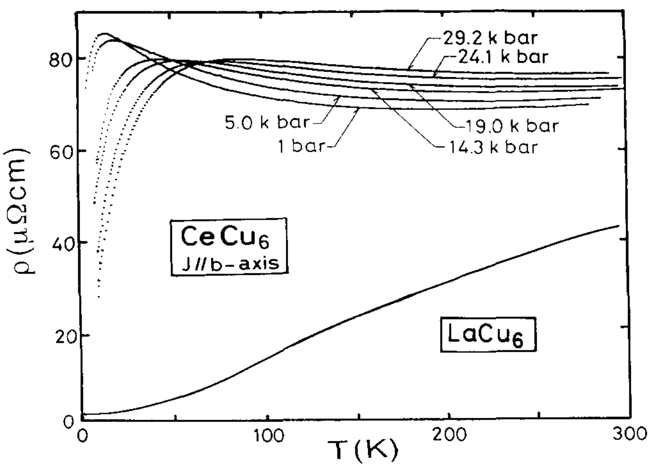

Fig. 1. Temperature dependent electrical resistivity $\rho(T)$ of c-$CeCu_6$ in the current direction along the *b*-axis at various pressures up to 30 kbar. The $\rho(T)$ curve of $LaCu_6$ is also shown for comparison.

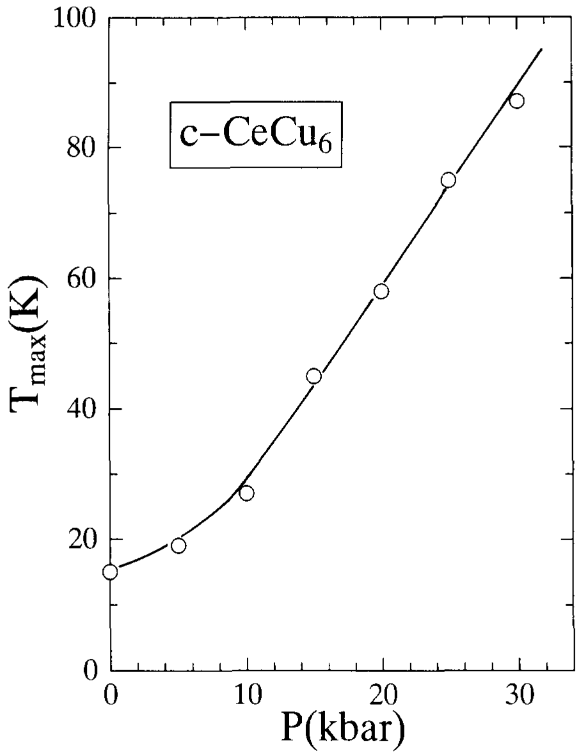

Fig. 2. Pressure dependence of the temperature showing the maximum in the $\rho(T)$ curves, T_{max} for c-$CeCu_6$.

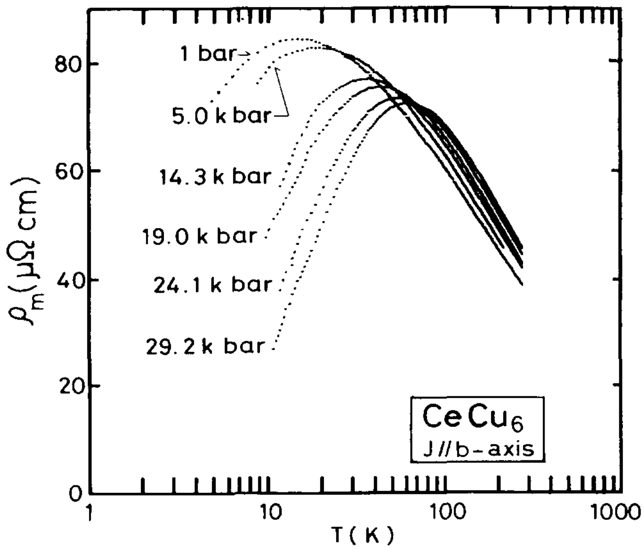

Fig. 3. The magnetic contribution to the electrical resistivity of c-$CeCu_6$, $\rho_m(T)$, on a logarithmic scale of T at various pressures.

assuming that $\rho(LaCu_6)$ is the contribution from the phonon because La has no magnetic 4f electron. Figure 3 shows $\rho_m(T)$ as a function of T on a logarithmic scale at various pressures. A linear relationship is found in Fig. 3 between ρ_m and $\log T$ at all pressures in the present work. The slope in the ρ_m versus $\log T$ plot increases with increasing pressure. The slope is discussed later.

3.2. Effect of pressure on the electrical resistivity of a-$CeCu_6$

Figure 4 shows the temperature dependent electrical resistance $R(T)/R(200\ \mathrm{K}) = r(T)$ at various pressures, where $R(T)$ and $R(200\ \mathrm{K})$ are the resistance at T and 200 K, respectively. At 3 kbar, r increases gradually with decreasing temperature and increases remarkably below 25 K, which is almost the same behavior as that at ambient pressure [8]. However, the increasing rate of $r(T)$ with decreasing temperature becomes larger by applying pressure.

The $\rho(T)$ shows approximately linear dependence against temperature between 30 K and 100 K. The values of $\mathrm{d}r/\mathrm{d}T$ are estimated from Fig. 4 as $-1.9\times10^{-5}\ \mathrm{K}^{-1}$ at 3 kbar and $-10.6\times10^{-5}\ \mathrm{K}^{-1}$ at 20 kbar, respectively. It was pointed out that the ρ of a-$CeCu_6$ is dominated by lattice defects and random atomic configuration [15], which is an origin for masking the Kondo and coherence effect. The large change in $\mathrm{d}r/\mathrm{d}T$ implies that the randomness of the atomic configuration is strongly affected by an application of pressure.

Further, the small increase in the magnitude of ρ below 25 K at ambient pressure, which is due to the Kondo effect, is enhanced largely by pressure. In order to clarify this fact, we plotted the values of r for a-$CeCu_6$ as a function of $\log T$ in Fig. 5 at various pressures. A linear relationship between r and $\log T$, which identifies the Kondo scattering, is clearly seen even at high pressure. The slope in the r versus $\log T$ plot increases drastically with increasing pressure. Here we define the value of m as $m = -\mathrm{d}r/\mathrm{d}(\log T)$. The normalized values of m/m_0 are plotted as a function of pressure in Fig. 6, where m and m_0 are the values of m at high and ambient pressure, respectively. m/m_0 increases with increasing pressure for both a-$CeCu_6$ and c-$CeCu_6$ but a large difference is found in the pressure derivative of m/m_0 between a-$CeCu_6$ and c-$CeCu_6$.

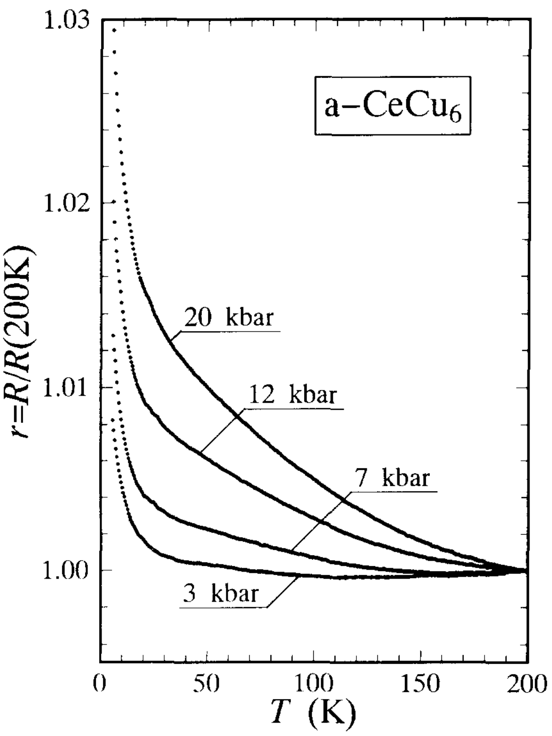

Fig. 4. The normalized resistance $r = R(T)/R(200\ \mathrm{K})$ of a-$CeCu_6$ as a function of temperature at various pressures, where $R(200\ \mathrm{K})$ is the resistance at $T = 200$ K.

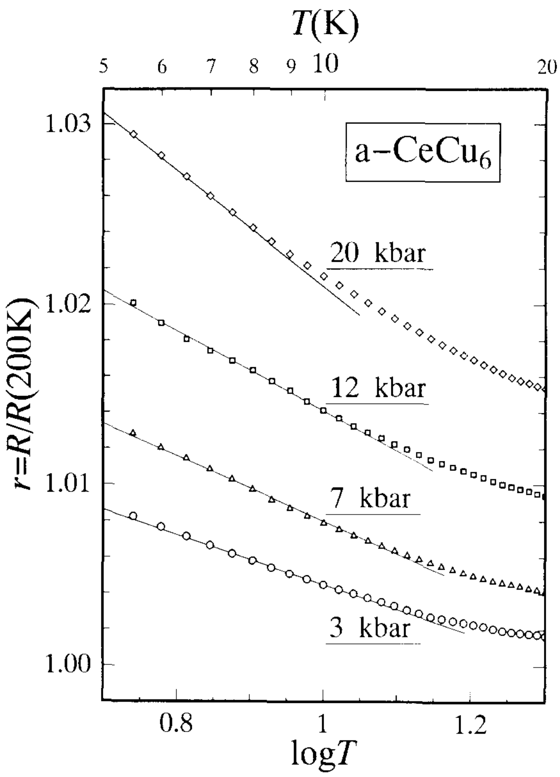

Fig. 5. The temperature dependence of r below 20 K on a logarithmic scale of T at various pressures. The straight line shows the linear part in the r versus $\log T$ plot.

The values of $\mathrm{d}(m/m_0)/\mathrm{d}P$ are estimated to be $0.004\ \mathrm{kbar}^{-1}$ and $0.1\ \mathrm{kbar}^{-1}$ for c-$CeCu_6$ and a-$CeCu_6$, respectively. The value of a-$CeCu_6$ is about 25 times larger than that of c-$CeCu_6$, which indicates that the Kondo effect in a-$CeCu_6$ is enhanced strongly by pressure. It is shown that the value of m is related to $JN(0)$ as follows [16]:

$$m = -\frac{\partial \rho_m}{\partial \log T} \propto -|JN(0)|^3 \tag{2}$$

where J is the s–f exchange interaction and $N(0)$ the density of state at the Fermi level.

If we approximate $\mathrm{d}\rho_m/\mathrm{d}(\log T)$ for a-$CeCu_6$, the large increase in the value of $|JN(0)|$ in a-$CeCu_6$ indicates a huge increase in the magnitude of J because $N(0)$ is expected to decrease at high pressure. Since the Kondo and the coherence effects are suppressed by the randomness of the atomic arrangement, the above

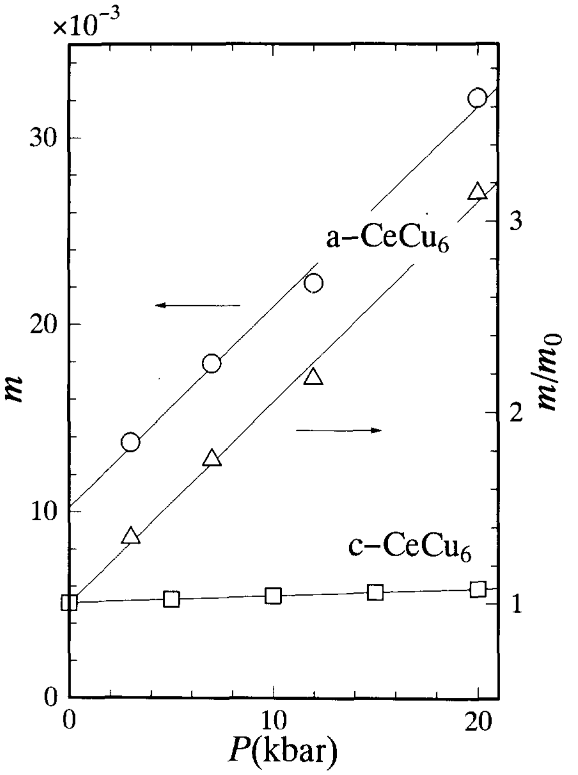

Fig. 6. The values of the slope, $m = -dr/d(\log T)$, for a-$CeCu_6$ as a function of pressure. The pressure dependence of normalized values m/m_0, are plotted for a- and c-$CeCu_6$.

result suggests that the application of pressure on a-$CeCu_6$ suppresses the scattering of conduction electrons by the randomness or the disorder in the Kondo lattice of a-$CeCu_6$ to give a large value of $JN(0)$. Recently, we measured the electrical resistivity of single crystalline $CeInCu_2$ [4,5], which is a typical heavy fermion compound and includes atomic disorder between Ce and In sites. The residual resistivity ρ_0 is larger than that of c-$CeCu_6$ by about an order of magnitude, but by application of pressure, it decreases more rapidly than c-$CeCu_6$, in which ρ_0 is almost independent of pressure [17]. This indicates that the pressure suppresses the scattering of electrons due to atomic disorder or the random arrangement of the 4f magnetic moment. This consideration of the randomness in the Kondo lattice is consistent with the present result.

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