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Effect of pressure on the magnetoresistance of $CeInCu_2$

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Abstract

The electrical resistance of the heavy fermion compound $CeInCu_2$ has been measured at high magnetic field and hydrostatic pressure. It is found that the high pressure induces positive magnetoresistance, which is characteristic of the Kondo coherent state, associated with the enhancement of the Kondo temperature. The result is discussed briefly on the basis of the theoretical model presented by Kawakami and Okiji.

1. Introduction

Recently, high pressure studies on heavy fermion (HF) systems have been performed to clarify the effect of external force on the characteristic electronic configuration of HF systems [1]. The application of pressure to Ce- or U-based HF materials is well known to enhance the Kondo temperature T_K [2,3], which is one of the most important energy scales in the HF system and roughly estimated from the resistivity maximum temperature T_{max}. The T_K is considered to be the temperature at which the system changes from an ensemble of non-interacting Kondo impurities at high temperatures ($T > T_K$) to a Kondo coherence regime at low temperatures ($T < T_K$). At low temperatures well below T_K, a characteristic behavior of the Fermi liquid is expected to appear, *e.g.* in magnetoresistance, specific heat, Hall coefficient, *etc.* Since the HF system has a low T_K of the order of several degrees Kelvin and is expected to show a pressure-induced crossover to the high T_K intermediate valence (IV) state [2,3], the coherent state is stabilized over a wide range of temperature by applying pressure.

$CeInCu_2$ is a cubic Heusler-type HF compound with a large value for the specific heat coefficient $\gamma \sim 1.2$ J/mol K^2 at 1 K [4,5]. The various physical properties of $CeInCu_2$ are isotropic reflecting cubic symmetry [6]. It was reported for $CeInCu_2$ that a change in the sign of the magnetoresistance (MR) from negative to positive, which implies entrance to the coherent Fermi liquid region, was not observed down to 0.6 K [4]. This is in contrast to results for other HF compounds which are mentioned below.

In this paper, the electrical resistivity of $CeInCu_2$ is reported down to 0.4 K and up to 9 T at ambient pressure, and down to 2 K and up to 5 T at high pressure up to 2 GPa, in order to examine how the crossover in the electronic configuration of HF systems is induced by external forces, low temperatures, high pressures and high magnetic fields. The results are compared with those reported previously and discussed briefly on the basis of the theory presented by Kawakami and Okiji [7].

2. Experimental procedure

Single crystalline $CeInCu_2$ and $LaInCu_2$ were prepared by the Czochralski pulling method [4]. Electrical resistance was measured up to 9 T at ambient pressure and up to 5 T at high pressure by using a standard four-probe method and superconducting solenoid. Hydrostatic pressure up to 2 GPa was generated using a Cu–Be piston-cylinder device and a 1:1 mixture of

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kerosene and transformer oil as a pressure transmitting medium. The pressure was changed only at room temperature to minimize internal strain in the specimen and the load was controlled to within $\pm 1\%$ throughout the measurement. The details of the present high pressure apparatus have been reported previously [8].

3. Results and discussion

The temperature dependence of the electrical resistivity $\rho(T)$ at various pressures up to 2 GPa is shown in Fig. 1. The values of ρ at high pressure were corrected by taking the change of geometrical factor l/S of the specimen into account, using thermal expansion [6] and compressibility data [9]. At ambient pressure, ρ increases gradually with decreasing temperature, reaches a maximum at 27 K and then decreases by further cooling. This behavior is typically observed in HF systems. The T_{max} increases exponentially with increasing pressure and reaches 120 K at 2 GPa. Since T_{max} is proportional to the Kondo temperature T_K [10], the result is explained by the fact that the application of pressure enhances T_K and induces a crossover from the well-localized 4f state to the IV state. The initial pressure coefficient of T_K is estimated to be $(\partial \ln T_K/\partial P)_{P=0} \approx 0.7$/GPa.

A large effect of pressure not only on the T_{max} but also on the magnitude of $\rho(T)$ at low temperature should also be noticed. Figure 2 indicates the pressure dependence of the value of the residual resistivity ρ_0

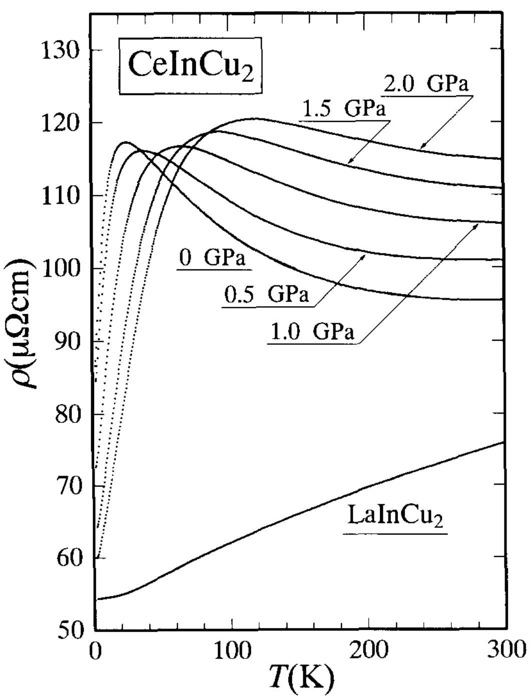

Fig. 1. The electrical resistivity ρ of $CeInCu_2$ under high pressure as a function of temperature.

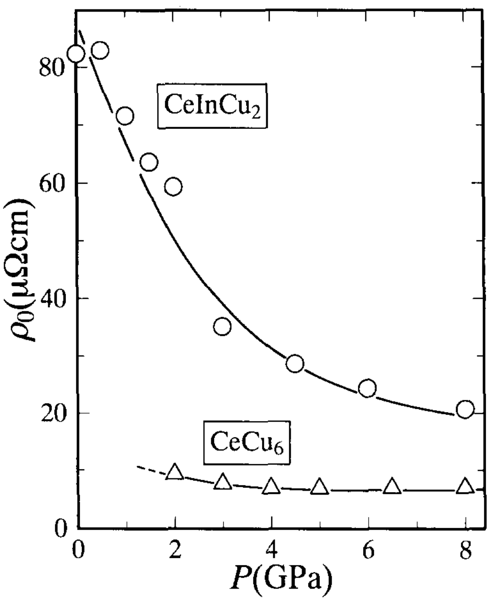

Fig. 2. Pressure dependence of the value of residual resistivity ρ_0 for $CeInCu_2$ and $CeCu_6$. The data above 2 GPa have been reported previously in ref. 2 for $CeInCu_2$ and ref. 11 for $CeCu_6$.

for $CeInCu_2$ and $CeCu_6$ [11]. The data between 2 and 8 GPa have been reported previously [2]. The ρ_0 of $CeInCu_2$ is about six times greater than that of $CeCu_6$, which is interpreted to be mainly due to the lattice disorder between Ce- and In-sites [12]. Alternatively the 4f-electrons are arranged irregularly in $CeInCu_2$. The application of pressure largely decreases ρ_0 of $CeInCu_2$, but it has little influence on ρ_0 of $CeCu_6$. By applying pressure, 4f-electrons are delocalized and the scattering by disordered moment is reduced in $CeInCu_2$. Since the 4f disordered moment gives rise to a large ρ in the temperature range where a well-known T^2-dependent resistivity is observed, the coefficient A of the T^2 term is consequently reduced. In fact, the value of A of $CeInCu_2$ at ambient pressure, $\sim 0.8\ \mu\Omega$-cm/K^2, is two orders of magnitude smaller than that of $CeCu_6$ [13] or $CeAl_3$ [14], of which γ-values are comparable to that of $CeInCu_2$. In a dense Kondo system, the larger the γ, the larger A is observed, in an approximately linear relationship between γ and $\sqrt{A}$, for a variety of materials [15]. Thus, $CeInCu_2$ would ideally have A value as great as $CeCu_6$ or $CeAl_3$. Taking account of these facts, the magnitude of A of $CeInCu_2$ is almost suppressed by the existence of the disorder in magnetic moment or the disorder in the Kondo lattice.

The field dependence of MR $\Delta\rho/\rho = [\rho(H) - \rho(0)]/\rho(0)$ at ambient pressure for $CeInCu_2$ and also for $LaInCu_2$ as a reference is illustrated at various temperatures in Fig. 3. $LaInCu_2$ shows a positive MR as expected for ordinary non-magnetic materials, while $CeInCu_2$ shows a negative MR, which is expected in a local magnetic moment system but is very small in

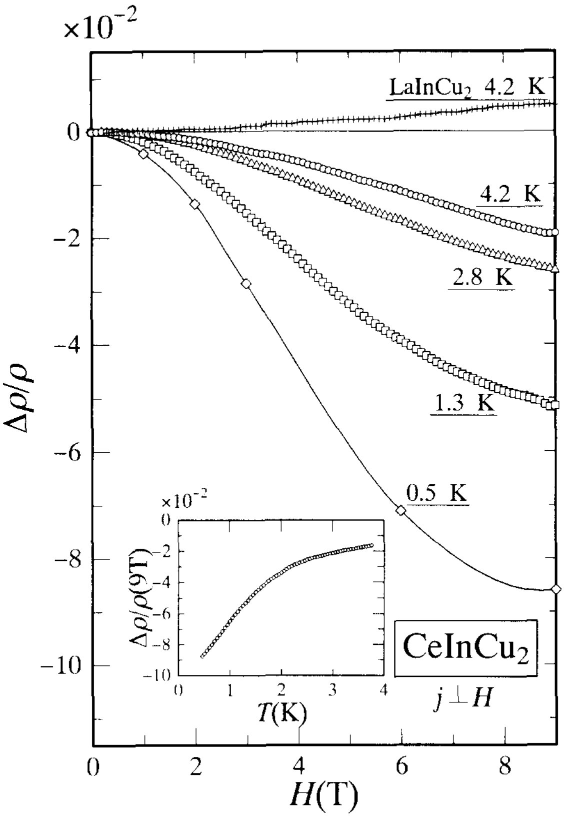

Fig. 3. The magnetoresistance $\Delta\rho/\rho$ versus magnetic field $H(T)$ up to 9T at various temperatures. The inset shows the temperature dependence of the magnitude of ρ at 9 T.

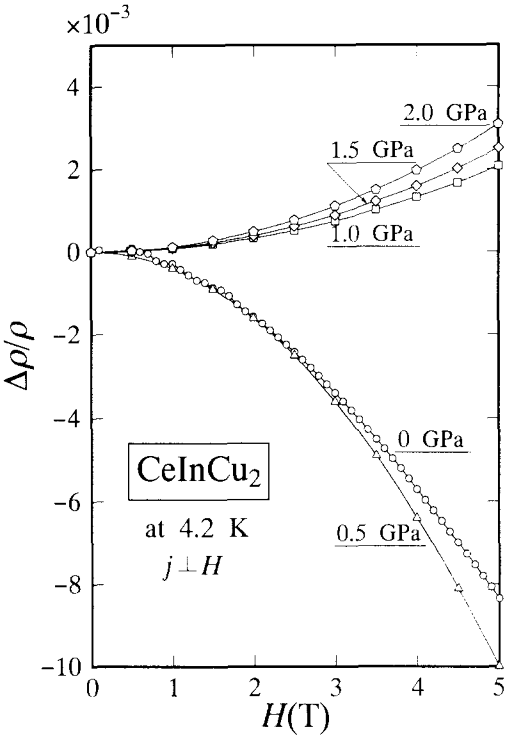

Fig. 4. The $\Delta\rho/\rho$ at 4.2 K as a function of H at various pressures.

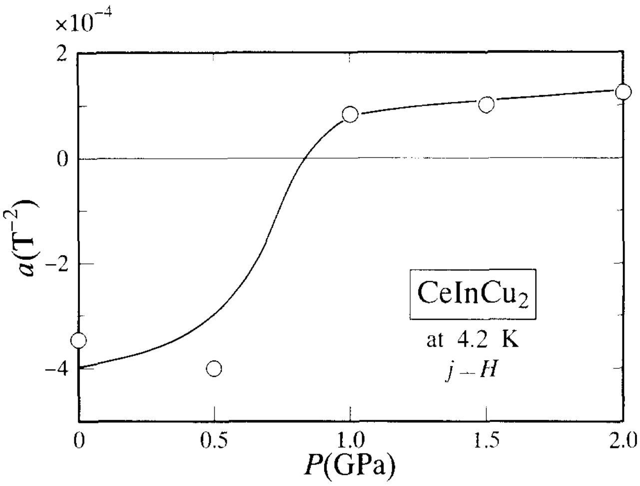

Fig. 5. The coefficient a in the relation $\Delta\rho/\rho = aH^2$, as a function of pressure.

magnitude compared with other Ce-based HF compounds such as $CeCu_6$ [13]. The negative MR increases in magnitude with decreasing temperature, as shown in the inset. The result is in sharp contrast to the fact that the sign of the MR in $CeCu_6$ [13], $CeAl_3$ [16] and $CeCu_2Si_2$ [17] changes from negative to positive below around 1 K. The coherent state may be broken by the existence of 4f-site disorder in $CeInCu_2$.

Next we show the data at high pressures. The field dependence of the MR at 4.2 K is plotted at various pressures up to 2 GPa in Fig. 4. The $\Delta\rho/\rho$ under pressures below 1 GPa is negative, but the sign changes between 0.5 and 1.0 GPa. Above 1 GPa, the $\Delta\rho/\rho$ increases with increasing H, *i.e.* a positive MR is observed, but the effect of pressure on the $\Delta\rho/\rho$ is relatively small. The MR shows a H^2-dependence in the present field range. The coefficient a of the H^2 term in the relation $\Delta\rho/\rho = aH^2$ is illustrated as a function of pressure in Fig. 5. The change in the sign of MR is clearly seen near 1 GPa. As mentioned previously, the origin of the change in the sign of MR is due to the crossover from a localized f-electron state to an itinerant or coherent one. Therefore, the present result implies that the crossover, which lies below 0.4 K at ambient pressure, is induced at 4.2 K by a pressure of $\sim$1 GPa.

The temperature dependence of MR was calculated for a Ce-based heavy fermion system by Kawakami and Okiji [7] as a function of T/T_K using the periodic Anderson model. According to their result, the positive MR appears at low temperature $T/T_K < 0.2$ due to the gap structure of the Kondo resonance a little above the Fermi level. Their calculation succeeded in explaining qualitatively, many characteristic properties for the MR of $CeAl_3$ and $CeCu_6$. At ambient pressure, the coherent state is induced only by temperature. On the other hand, it is also induced by high pressure because T_K increases largely by an application of pressure to give a small value of T/T_K. Since the T_K of $CeInCu_2$ at 1 GPa, as mentioned above, is several times larger than that at ambient pressure, the reduction in T/T_K at $T=4.2$ K by applying pressure of 1 GPa may be sufficient to induce a positive MR (coherent state).

4. Conclusion

For $CeInCu_2$, the crossover from the heavy fermion state to the itinerant 4f state is induced by applying a pressure of 2 GPa, associated with a large enhancement in the Kondo temperature. Although the magnetoresistance persists in negative sign down to 0.4 K at ambient pressure, reflecting the break in the coherent state because of the disorder in the Kondo lattice, the application of pressure induces positive magnetoresistance. This result is qualitatively explained as the enhancement of T_K by applying pressure.

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