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Magnetoresistivity of $CePb_2$ heavy fermion compound

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Abstract. The dependence of magnetoresistivity on the temperature and the magnetic field for the antiferromagnetic $CePb_2$ heavy fermion compound has been investigated. In the paramagnetic temperature region above the Néel temperature $T_N = 3.6$ K, the magnetoresistivity exhibits a negative magnetic field dependence due to the Kondo effect. From Schlottmann's scaling for the Kondo impurity model, the characteristic Kondo field and the Kondo temperature T_K were found to be about 5.1 T and 0.8 K, respectively. The value of T_K is relatively in accord with the value evaluated from the paramagnetic Curie temperature and also the relation between T_K/T_N and a specific heat jump associated with the magnetic ordering. In the antiferromagnetic temperature region, the magnetoresistivity at 2 K shows a broad peak around 6 T, suggesting that the antiferromagnetic spin configuration is changed under applied magnetic field.

1. Introduction

A large amount of attention has been focused on both Ce and U heavy fermion compounds [1, 2]. In particular, the investigation of electrical properties is one of the important subjects in the field of highly correlated electron systems. The magnetic contribution to the electrical resistivity increases logarithmically with decreasing temperature, being characteristic of the Kondo system. Furthermore, the contribution to the magnetoresistivity changes its sign around the temperature $T = T_K/2\pi$ [3–5], where T_K is the Kondo temperature. Above the temperature $T = T_K/2\pi$, the negative magnetoresistivity exhibits a quadratic behaviour against the magnetic field [6], and the characteristic Kondo field is estimated from Schlottmann's scaling for the Kondo impurity model [6–8]. Therefore, the Kondo temperature can be deduced from the electrical properties.

Since the Kondo effect affects other physical properties, one can obtain information on the Kondo temperature from not only the magnetoresistivity but also other experiments. For example, the measurements of the paramagnetic Curie temperature and the electrical specific heat coefficient are useful for this purpose. It is very important to know the Kondo temperature in heavy fermion compounds, because their various physical properties are dominated by only one energy scale, that is, the Kondo temperature. The Kondo temperature characterizes the degree of the hybridization of 4f electrons with conduction electrons and also embodies the width of the Kondo resonant peak appearing near the Fermi energy.

The $CePb_2$ compound has been reported to have a tetragonal $MoSi_2$-type structure and to be a heavy fermion compound showing an antiferromagnetic ordering below 3.6 K [9, 10]. In the present work, the temperature dependence of magnetoresistivity of the $CePb_2$ compound has been investigated in the temperature region from 2 K to 300 K and magnetic fields up to 9 T. By using the present data, the characteristic Kondo field, the magnetic moment on the

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Kondo ion and the Kondo temperature have been deduced from Schlottmann's scaling for the Kondo impurity model. In addition, the antiferromagnetic state in the applied magnetic fields is discussed as well.

2. Experiment

The starting materials were 99.9% pure Ce, La and 99.999% pure Pb for $CePb_2$ and the $LaPb_2$ reference sample. The alloying was performed by arc-melting in an argon gas atmosphere purified with a Ti getter. The ingots were turned over and remelted four times to homogenize. The temperature dependence of the electrical resistivity was measured by a conventional DC four-probe method in the temperature region from 2 to 300 K. Magnetoresistivity measurements were carried out by the same method in magnetic fields up to 9 T. The current direction was perpendicular to the applied magnetic field. The temperature dependence of the magnetic susceptibility and the magnetization at 2 K were measured with a SQUID magnetometer and by an extraction-type magnetometer, respectively. The specific heat measurement was made by a relaxation method in magnetic fields up to 5 T.

3. Results and discussion

The temperature dependence of the magnetic contribution to the electrical resistivity ρ_{mag} of the $CePb_2$ compound in the magnetic fields of 1, 5 and 9 T is shown in figure 1. The abscissa is given by logarithmic temperature. The value of ρ_{mag} is defined as the difference between the total resistivity and the phonon term of the $LaPb_2$ reference compound. The electrical resistivity of the $CePb_2$ compound in 0 T is zero below 7 K, which comes from the superconducting transition temperature of pure Pb. This behaviour is not an intrinsic property of the $CePb_2$ compound. Similar behaviour has often been observed in other RE (RE = rare earth element)–Pb system compounds [11, 12]. Furthermore, it has been pointed out that the Ce–Pb system compounds are rapidly attacked by high humidity, resulting in lead and hydroxide of Ce [13]. In the present study, however, no existence of pure Pb was confirmed by x-ray diffraction. Moreover, the temperature dependence of the specific heat shows no anomaly around 7 K (see figure 3). By applying magnetic field above the critical field of Pb, the intrinsic electrical properties of $CePb_2$ compound would be observed. As seen from figure 1, ρ_{mag} increases logarithmically with decreasing temperature and shows a broad maximum around 22 K due to the coherency of the Kondo lattice in analogy with many heavy fermion compounds. Moreover, a large decrease is observed due to the antiferromagnetic ordering below 3.6 K with decreasing temperature.

Figure 2 shows the temperature dependence of the magnetic susceptibility measured in 1 and 5 T for $CePb_2$, and figure 3 the specific heat in 0, 1 and 5 T. A magnetic order–order transition has been reported from the results of the magnetic and specific heat measurements by the previous study [10]. However, in the present study, no other peak associated with the magnetic transition is observed as shown in figures 2 and 3, nevertheless the Néel temperature T_N coincides with the published previous data. The magnetic properties of $CePb_2$, therefore, seem to have a sensitive sample dependence. Although T_N is not affected by the magnetic field up to 1 T, it is lowered to about 3.0 K in a magnetic field of 5 T.

Figure 4 shows the normalized magnetoresistivity $\rho(B)/\rho(0)$ of the $CePb_2$ compound in the magnetic field up to 9 T at various temperatures in the paramagnetic temperature region. Here, $\rho(B)$ and $\rho(0)$ are resistivities in the applied magnetic field and zero field, respectively. The magnetoresistivity exhibits a quadratic behaviour against the magnetic

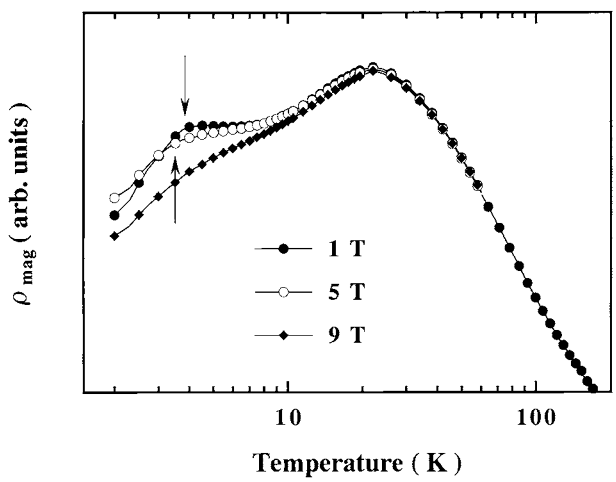

Figure 1. Temperature dependence of the magnetic contribution to the electrical resistivity ρ_{mag} of the $CePb_2$ compound in magnetic fields of 1, 5 and 9 T.

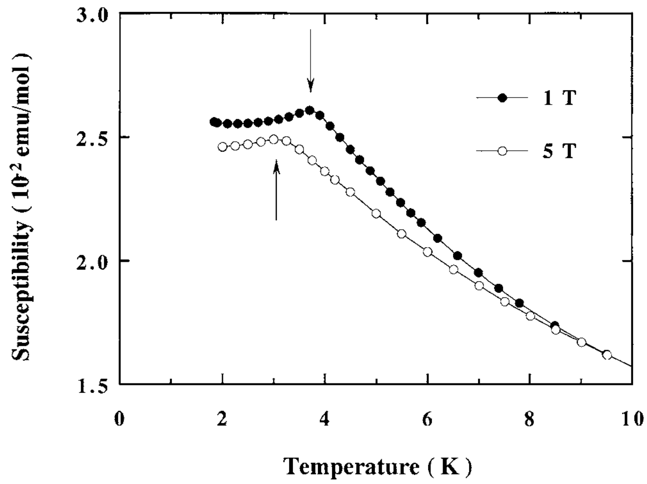

Figure 2. Temperature dependence of the magnetic susceptibility of the $CePb_2$ compound measured in the magnetic fields of 1 and 5 T.

field $B(T)$. The negative contribution to the magnetoresistivity decreases with increasing temperature. Schlottmann gave an exact solution of the Bethe *ansatz* equations for the single-ion Kondo impurity model in external magnetic fields [6]. From the results of the solutions, the negative contribution to the magnetoresistivity is scaled by the characteristic Kondo field. That is to say, this behaviour implies that the physical properties of the Kondo impurities are dominated by only one energy scale, the Kondo temperature. The normalized magnetoresistivity $\rho(B)/\rho(0)$ versus $B(T)/B^*(T)$ of the $CePb_2$ compound is given in figure 5, where $B^*(T)$ is the characteristic Kondo field at various temperatures. The solid line represents Schlottmann's scaling curve, and the inset shows the temperature dependence of the characteristic Kondo field estimated on the basis of the scaling. The temperature dependence

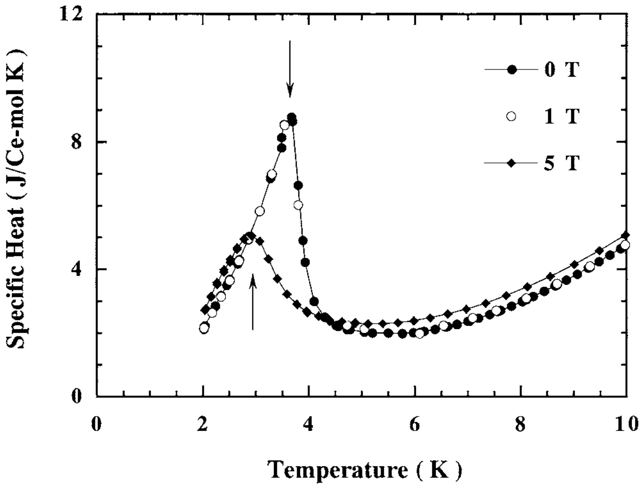

Figure 3. Temperature dependence of the specific heat of the $CePb_2$ compound in the magnetic fields of 0, 1 and 5 T.

of the characteristic Kondo field $B^*(T)$ is given by

$$B^*(T) = B^*(0) + k_B T/g\mu \qquad (1)$$

where the zero-temperature characteristic Kondo field $B^*(0)$ is related to the Kondo temperature as

$$T_K = B^*(0)g\mu/k_B \qquad (2)$$

where g, μ and k_B are the Landé factor, the magnetic moment of the Kondo ion and the Boltzmann constant, respectively. From figure 5 and these expressions, the characteristic Kondo field $B^*(0)$, the magnetic moment of the Kondo ion and the Kondo temperature of the $CePb_2$ compound are found to be 5.1 T, $0.12\mu_B$ and 0.8 K, respectively. The Kondo temperature of several kinds of heavy fermion compound has been estimated in the same way [14–16], in accordance with that evaluated from other physical properties [5, 17]. From the calculation based on the $S = 1/2$ Kondo Hamiltonian [18], the Kondo temperature is estimated as $|\theta_p|/2$, where θ_p is the paramagnetic Curie temperature obtained from the temperature dependence of the magnetic susceptibility. The paramagnetic Curie temperature of the $CePb_2$ compound is about −2 K. Therefore, the Kondo temperature obtained from the magnetoresistivity is comparable to that from the paramagnetic Curie temperature.

In a single impurity Kondo system, the electrical specific heat coefficient γ is related to the Kondo temperature T_K as $\gamma \propto 1/T_K$. This relation suits well the nonmagnetic heavy fermion compounds such as $CeAl_3$, $CeCu_6$ [20] of which the electrical specific heat coefficient reaches a large value, about 1.5 J $mol^{-1}K^{-2}$. In the case of heavy fermion compounds having a magnetic ordering, however, the electrical specific heat coefficient is much smaller than the value estimated from the relation $\gamma \propto 1/T_K$ [21, 22]. The specific heat profile and the specific heat jump ΔC_{mag} at the magnetic ordering temperature were explained by using a theory for Kondo systems with an $S = 1/2$ resonant level extended to the Kondo lattices using a mean-field approach [21, 23]. Within the framework of the theoretical calculations for the specific heat, ΔC_{mag} at the magnetic ordering temperature T_N is given by

$$\Delta C_{mag} = \frac{6k_B}{\psi'''(\frac{1}{2}+\zeta)}\left[\psi'(\tfrac{1}{2}+\zeta) + \zeta\psi''(\tfrac{1}{2}+\zeta)\right]^2 \qquad (3)$$

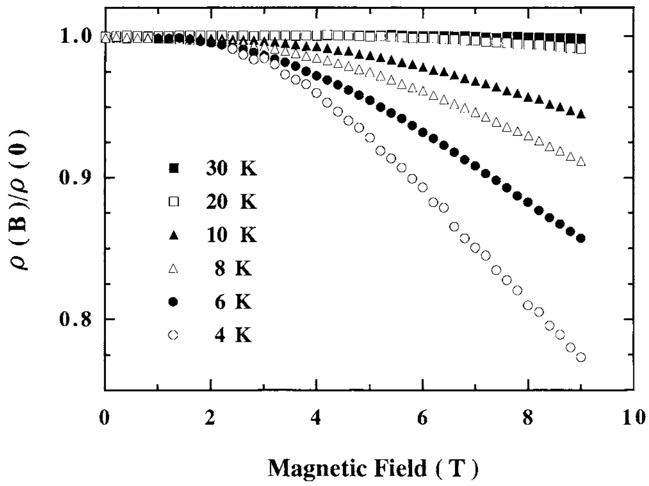

Figure 4. Normalized magnetoresistivity $\rho(B)/\rho(0)$ of the $CePb_2$ compound in magnetic field up to 9 T at various temperatures in the paramagnetic temperature region.

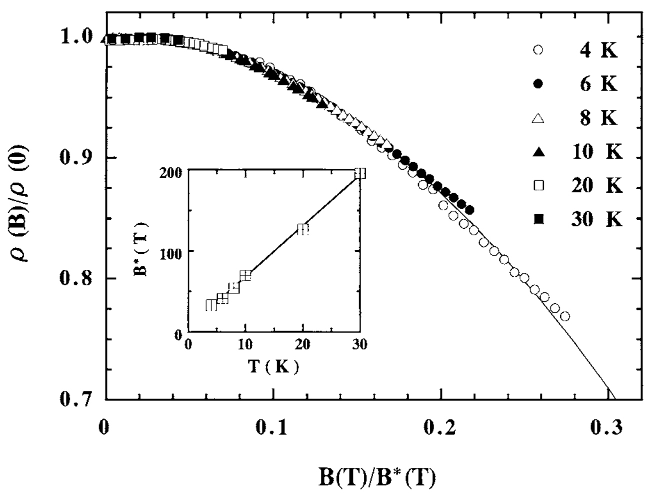

Figure 5. Normalized magnetoresistivity $\rho(B)/\rho(0)$ versus $B(T)/B^*(T)$ for the $CePb_2$ compound. The solid line represents Schlottmann's scaling curve. The inset shows the temperature dependence of the characteristic Kondo field $B^*(T)$.

where $\zeta = (T_K/T_N)/2\pi$ and ψ', ψ'' and ψ''' are the first, second and third derivatives of the digamma function. The value of ΔC_{mag} is numerically calculated as a function of T_K/T_N from the above equation. ΔC_{mag} decreases continuously with increasing T_K/T_N from the value $\frac{3}{2}k_B N = 12.48$ J mol^{-1} K^{-1} for a purely magnetic system ($T_K = 0$), where k_B and N are the Boltzmann and the Avogadro constants, respectively. The dependence of ΔC_{mag} on T_K/T_N is in agreement for several kinds of heavy fermion compound having a magnetic ordering [21, 24]. As shown in figure 3, the Néel temperature T_N and ΔC_{mag} of $CePb_2$ compound are about 3.6 K and 7.5 J mol^{-1} K^{-1}, respectively. Consequently, the Kondo temperature of the $CePb_2$ compound deduced from the magnetoresistivity is in accord with that obtained from the relation between T_K/T_N and ΔC_{mag}.

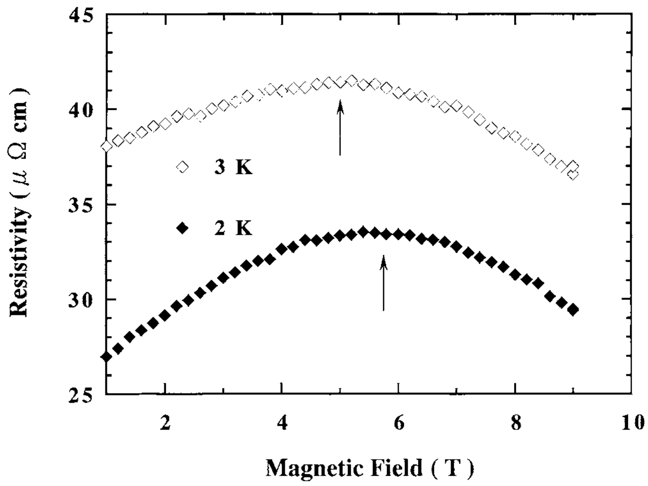

Figure 6. Magnetoresistivity in magnetic fields up to 9 T for the $CePb_2$ compound at 2 and 3 K in the antiferromagnetic temperature region.

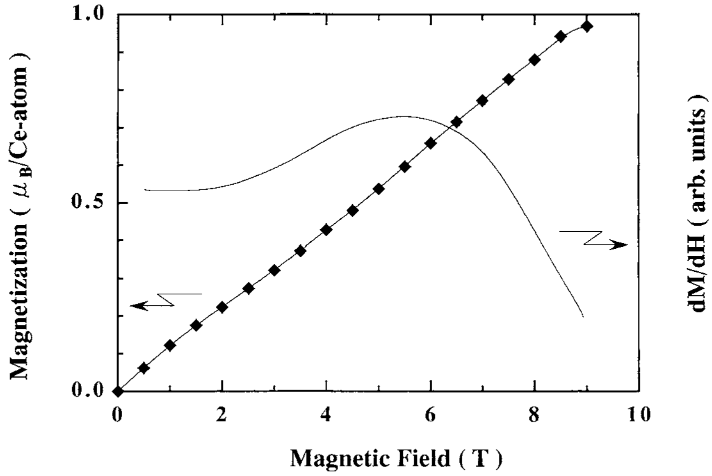

Figure 7. The magnetization curve at 2 K and its field differential $\mathrm{d}M/\mathrm{d}H$ for the $CePb_2$ compound.

Figure 6 shows the magnetoresistivity at 2 and 3 K in the magnetic field range up to 9 T. The $CePb_2$ compound is antiferromagnetic at these temperatures. A broad peak is observed in the magnetoresistivity around 6 and 5 T at 2 and 3 K, respectively. This magnetoresistivity behaviour differs from that in the paramagnetic state as shown in figure 4, which shows a monotonic negative magnetoresistivity. According to a single-impurity scattering calculation by Zlatić [3], the contribution to the magnetoresistivity is positive at $T = 0$ K and changes to negative at temperature $T = T_K/2\pi$. A maximum observed in the magnetoresistivity of $CeAl_3$ [4] and $CeCu_6$ [5, 17] has been explained quantitatively by the calculated result. However, in the case of the $CePb_2$ compound, $T = T_K/2\pi$ becomes of the order of 100 mK by using the Kondo temperature obtained in the present study. Therefore, the broad peaks observed at 2 and 3 K are thought to be caused by another effect.

The magnetization curve at 2 K for $CePb_2$ compound and its field differential $\mathrm{d}M/\mathrm{d}H$ are plotted in figure 7, and a broad peak in $\mathrm{d}M/\mathrm{d}H$ around 6 T is observed. Such behaviour is similar to that of the $CePb_3$ heavy fermion compound [25]. From the sound velocity investigation [26] and the magnetoresistivity study of a single crystal [27], it has been pointed out that the spin configuration in the antiferromagnetic state of the $CePb_3$ compound is changed under applied magnetic field. The magnetoresistivity has the highest value when the spin aligns perpendicular to the applied magnetic field, and decreases gradually as the spin alignment becomes the same direction as the applied magnetic field, resulting in a broad peak in the magnetoresistivity. Therefore, the broad peak of the magnetoresistivity in the antiferromagnetic temperature region for the $CePb_2$ compound can be attributed to the change of the spin configuration from the antiferromagnetic to the perpendicular, and finally to the ferromagnetic state to the magnetic field direction.

4. Conclusion

Magnetoresistivity measurements have been carried out for the $CePb_2$ heavy fermion compound in the temperature region from 2 K to 300 K and in magnetic fields up to 9 T. The temperature dependence of the magnetic contribution to the electrical resistivity for the $CePb_2$ compound exhibits a typical Kondo behaviour, that is, a logarithmic temperature dependence and a negative contribution to the magnetoresistivity. From the negative magnetoresistivity in the paramagnetic temperature region, the Kondo temperature T_K was evaluated to be about 0.8 K from Schlottmann's scaling for the Kondo impurity model. Moreover, the Kondo temperature is in accord with that deduced from the paramagnetic Curie temperature and also the relation between T_K/T_N and the specific heat jump ΔC_{mag} associated with the magnetic ordering.

A broad peak of the magnetoresistivity observed in the antiferromagnetic temperature region would be due to the change of the spin configuration from the antiferromagnetic to the perpendicular, and finally to the ferromagnetic state to the magnetic field direction.

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