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Effect of pressure on transport properties of mixed-valence compound $YbAl_3$

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Abstract

The pressure effects on the electrical resistivity and the Hall effect have been measured for $YbAl_3$ and $LuAl_3$. $LuAl_3$ is a normal metal and has negative pressure coefficient of resistivity -5×10^{-3} $kbar^{-1}$ at room temperature, which is explained by a phonon stiffening effect. In the mixed-valence compound $YbAl_3$, the magnetic contribution to the resistivity is increased by pressure. The Grüneisen parameter of the Kondo temperature $\Omega_K = -\partial \ln T_K / \partial \ln V$ is estimated -7 for $YbAl_3$ from the coefficient of the quadratic temperature dependence of the resistivity at low temperatures. The decrease of T_K with pressure indicates that the density of conduction electron states at the Fermi energy and/or the exchange of 4f and conduction electrons are suppressed by pressure in $YbAl_3$. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Transport property; Pressure effect; Kondo temperature; $YbAl_3$; $LuAl_3$

1. Introduction

For understanding physical properties of Ce- and Yb-based mixed-valence and heavy fermion compounds, pressure is a powerful tool because it strongly affects the Kondo temperature T_K. Under high pressure, the valence of rare-earth ions generally increases, leading to the pressure-induced demagnetization and magnetization of Ce ion and Yb ion, respectively. There have been a lot of high pressure studies for valence instability in the Ce-intermetallic compounds [1]. However relatively few studies of Yb-compounds have been carried out, because of difficulties of the single crystal growth. Furthermore, only a few Yb-based compounds have been known as mixed-valence and heavy fermion compounds, because in most Yb-compounds, ytterbium exhibits a non-magnetic divalent state Yb^{2+} ($4f^{14}$).

Recently, we have grown a high quality single crystal of $YbAl_3$ with a residual resistivity ratio of about 50. $YbAl_3$ has the simple cubic Cu_3Au-type structure and well known as a mixed-valence compound. Although a large number of studies have been made on $YbAl_3$ at ambient pressure [2], little is known about pressure effect on the electronic properties. In this paper we report the pressure effect on the electrical resistivity and the Hall effect for $YbAl_3$. We also report electronic properties of the non-magnetic material $LuAl_3$ for comparison. At ambient pressure, the electronic-specific heat coefficient of $YbAl_3$ is 45 mJ mol^{-1} K^{-2} [3]. The magnetic susceptibility shows maximum near 120 K and follows a Curie–Weiss law for $T>250$ K with a Curie–Weiss temperature of -225 K and an effective moment of 4.2 μ_B [4], the value quite close to that for free Yb^{3+}. Since these physical properties are very similar to those of the Kondo compound $CeSn_3$, $YbAl_3$ is suitable to study as a counterpart of $CeSn_3$ with respect to 4f-electron and 4f-hole symmetry. Both of $YbAl_3$ and $CeSn_3$ are high-T_K compounds and do not order magnetically.

2. Experimental

Single crystals of $YbAl_3$ and $LuAl_3$ were grown from metallic fluxes [5] using the high purity Yb (3N), Lu(3N) and Al(6N). The starting materials, 7at%Yb in 93at%Al for $YbAl_3$ and 4at%Lu in 96at%Al for $LuAl_3$, were placed in an alumina crucible and sealed into a quartz ampoule under high vacuum. The ampoule was heated to 800°C and cooled down slowly to 600°C for 2–4 days. An excess of Al surrounding the grown crystals was eaten away by NaOH solution, which does not attack the crystals. The crystal shapes were cube with each edge ~1 mm and plate

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typically 3×3×0.3 mm^3. The crystal structures and lattice constants of these crystals examined by X-ray powder diffraction agree with the reported data, Cu_3Au-type cubic structure, $a=4.202$ and 4.189 Å for $YbAl_3$ and $LuAl_3$, respectively [3,6].

Measurements of the electrical resistivity and the Hall effect were made in a clamp-type piston (WC) and cylinder (Cu–Be) pressure cell with an oil (Daphne 7373) as pressure transmitting fluid. Pressure dependence of the resistivity up to 17 kbar was measured by an usual DC-probe method at room temperature, and the temperature dependence was obtained at a fixed pressure over the temperature range 1.8–300 K. The Hall effect measurements were carried out at 1.3 K using a superconducting magnet with a magnetic field up to 9 T. The de Haas–van Alphen effect under high pressure was also measured for $LuAl_3$.

3. Results and discussion

Fig. 1 shows the pressure dependence of the electrical resistivity for $YbAl_3$ and $LuAl_3$ at room temperature. With increasing hydrostatic pressure, the resistivity of $LuAl_3$ decreases linearly, whereas the resistivity of $YbAl_3$ gradually increases except for the low pressure region ($P<3$ kbar). The pressure coefficient of resistivity $\partial \ln \rho / \partial P$ are -5×10^{-3} $kbar^{-1}$ for $LuAl_3$ and $+1\times10^{-3}$ $kbar^{-1}$ for $YbAl_3$ at high pressure region. The negative pressure coefficient of resistivity for $LuAl_3$ can be explained by a phonon stiffening effect, as described below. The volume dependence of electrical resistivity for isotropic normal metals such as $LuAl_3$, is generally written as [7]

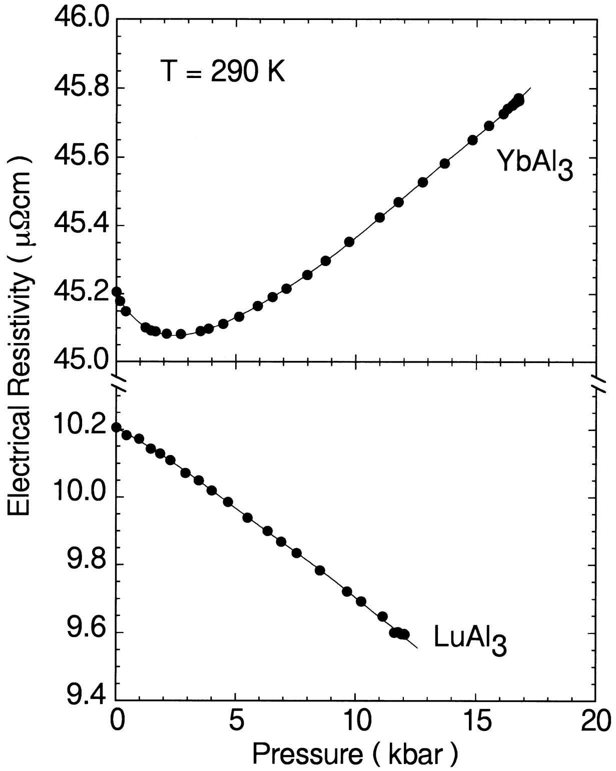

Fig. 1. Pressure dependence of the electrical resistivities at room temperature for $YbAl_3$ and $LuAl_3$.

$$\frac{\partial \ln \rho}{\partial \ln V} = \frac{\partial \ln A_F}{\partial \ln V} - \frac{\partial \ln \theta}{\partial \ln V}\left(1 + \frac{\partial \ln \rho}{\partial \ln T}\right) \qquad (1)$$

where V is the volume, θ the Debye temperature, and A_F a coefficient that includes all the pressure-dependent quantities coming from the geometry of the Fermi surface. In the high temperature region with phonon scattering, $\rho \propto T$, Eq. (1) is reduced to

$$\frac{1}{\rho}\frac{\partial \rho}{\partial P} = \frac{1}{A_F}\frac{\partial A_F}{\partial P} - 2\gamma\kappa \qquad (2)$$

using the Grüneisen constant $\gamma = -\partial \ln \theta / \partial \ln V$ and compressibility $\kappa = -\partial \ln V / \partial P$. From the de Haas–van Alphen (dHvA) effect measurements under high pressure for $LuAl_3$, the pressure coefficients of Fermi surface volume were obtained that $+0.9\times10^{-3}$ and 1.0×10^{-3} $kbar^{-1}$ for the largest (21% of the first Brillouin zone) and the second-largest (7.4%) spherical Fermi surfaces of $LuAl_3$, respectively [8]. Since these pressure coefficients are the same order of magnitude, these expands of Fermi surfaces could be explained by expanding of the reciprocal space with compression of the real space, assuming the compressibility $\kappa \sim 1\times10^{-3}$ $kbar^{-1}$. Using this compressibility value and the usual Grüneisen constant $\gamma = 2$–3 for normal metal, the phonon stiffening term $-2\gamma\kappa$ is calculated to be of -4–6×10^{-3} $kbar^{-1}$, in good agreement with the observed pressure coefficient -5×10^{-3} $kbar^{-1}$ for $LuAl_3$. These results indicate that the phonon stiffening effect is the main contribution to the decrease of the resistivity with pressure for $LuAl_3$. In $YbAl_3$, the electrical resistivity ρ is described as $\rho = \rho_0 + \rho_{ph}(T) + \rho_{mag}(T)$, where ρ_0 is the residual resistivity, $\rho_{ph}(T)$ the phonon term and $\rho_{mag}(T)$ represents the 4f magnetic contribution. Since the decrease of phonon term is also the case for $YbAl_3$ and contribution of ρ_0 is negligibly small at room temperature, the positive pressure coefficient of $YbAl_3$ may be ascribed to the increase of 4f magnetic contribution.

The Kondo temperature is proportional to $\exp\{-1/D(E_F)\ J_{cf}\}$, where $D(E_F)$ is the density of conduction electron states at the Fermi energy and J_{cf} is the magnetic exchange coupling strength between 4f local moment and conduction electrons [1]. Thus obtaining the changes in T_K is a good estimate of the shift of the 4f magnetic contribution for electronic properties. Pressure effect on T_K can be obtained from a pressure dependence of a coefficient A of the quadratic temperature dependence of the electrical resistivity at low temperature region, because the coefficient A is inversely proportional to T_K^2 [1]. Fig. 2 shows the temperature dependence of the resistivity ρ at several pressures up to 15 kbar for $YbAl_3$. For comparison,

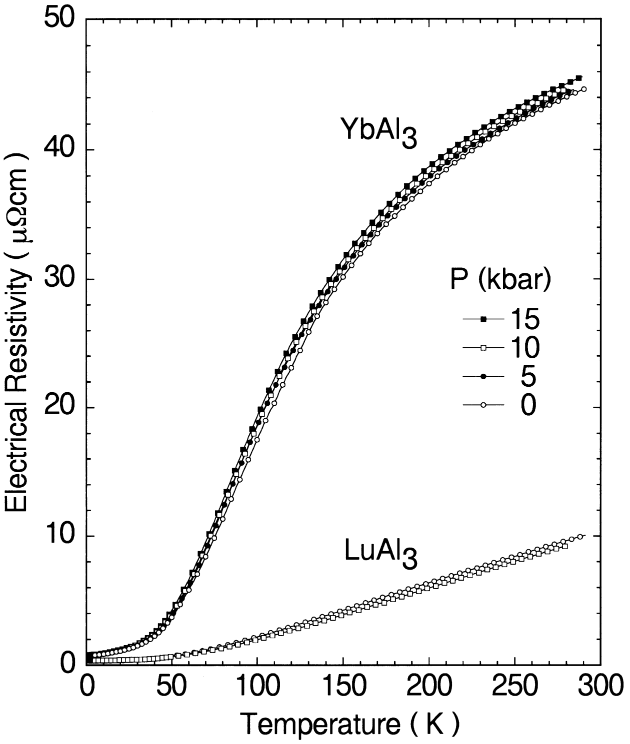

Fig. 2. Temperature dependence of the electrical resistivities for $YbAl_3$ at ambient pressure (0), 5, 10 and 15 kbar. The resistivities of $LuAl_3$ at ambient pressure and 10 kbar are also illustrated.

the results of $LuAl_3$ at ambient pressure and 10 kbar were also illustrated. The resistivity of $LuAl_3$ shows normal metallic behaviors and represents the phonon contribution $\rho_{ph}(T)$ to resistivity of $YbAl_3$. As can be seen, the magnetic contribution $\rho_{mag}(T)$ in $YbAl_3$ is very large as compared to the $\rho_{ph}(T)$. In order to obtain the low temperature variation of the magnetic resistivity $\rho_{mag}(T)$ of $YbAl_3$, we subtract the resistivity of $LuAl_3$ as the phonon term from the resistivity of $YbAl_3$. In low temperature region, the phonon contribution to the total resistivity of $YbAl_3$ can be considered pressure independent. In Fig. 3, the residual and magnetic part to the total resistivity are plotted as a function of T^2 up to 14 K for $YbAl_3$. In all pressure, the T^2-dependence is clearly observed as shown by straight line in Fig. 3. In Fig. 4a,b, we show the pressure change of the residual resistivity ρ_0 and the coefficient A for $YbAl_3$. With increasing pressure, both of ρ_0 and A increase, in contrast to the Ce-compounds [1]. To clear the pressure effect on the Kondo temperature T_K, we also plot $A^{-1/2}$ versus pressure in Fig. 4c. With increasing pressure the $A^{-1/2}$ decreases indicating that the Kondo temperature decreases with pressure in $YbAl_3$. The decrease of T_K under pressure indicates that the density of state $D(E_F)$ and/or the Kondo coupling J_{cf} are suppressed by pressure in $YbAl_3$. We have estimated the Grüneisen parameter of Kondo temperature $\Omega_K = -\partial \ln T_K / \partial \ln V=$

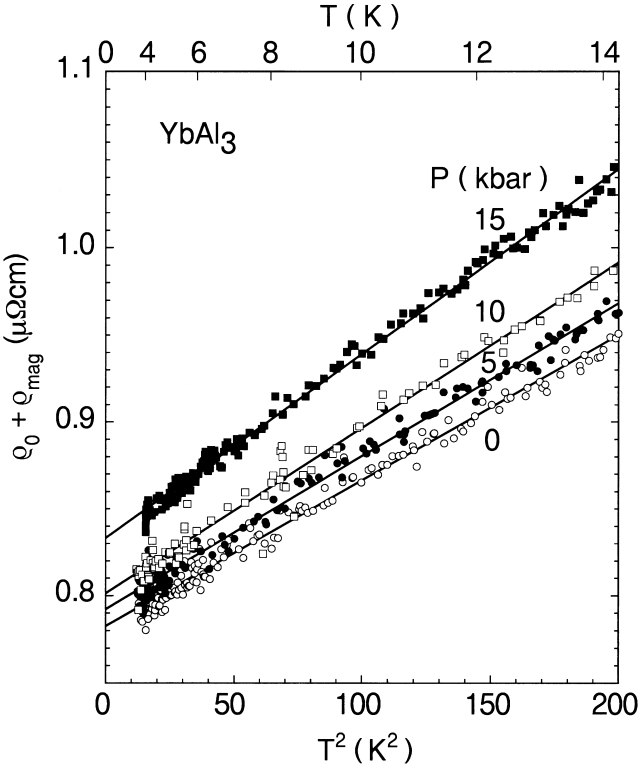

Fig. 3. Low temperature variation of $\rho_0 + \rho_{mag}(T)$ as a function of T^2 for $YbAl_3$ at ambient pressure (0), 5, 10 and 15 kbar.

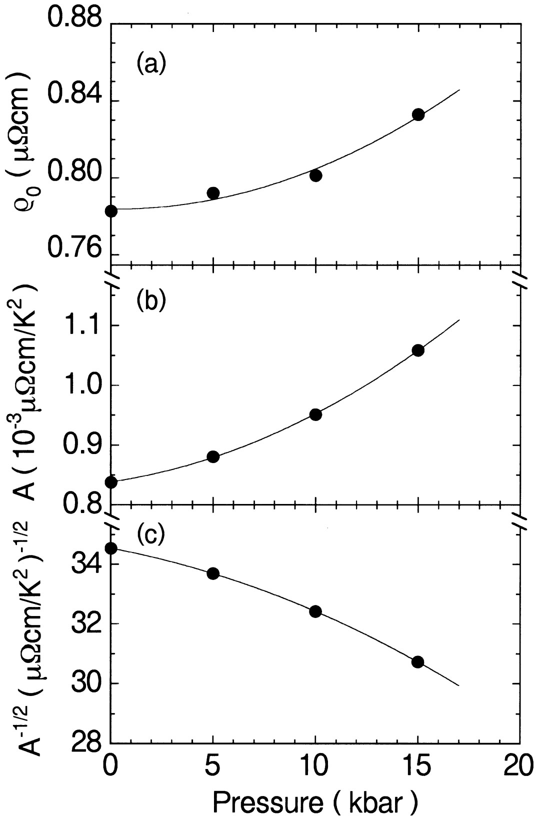

Fig. 4. Pressure dependence of (a) the residual resistivity ρ_0, (b) the coefficient of the quadratic temperature dependence of the electrical resistivity A and (c) the $A^{-1/2}$ of $YbAl_3$.

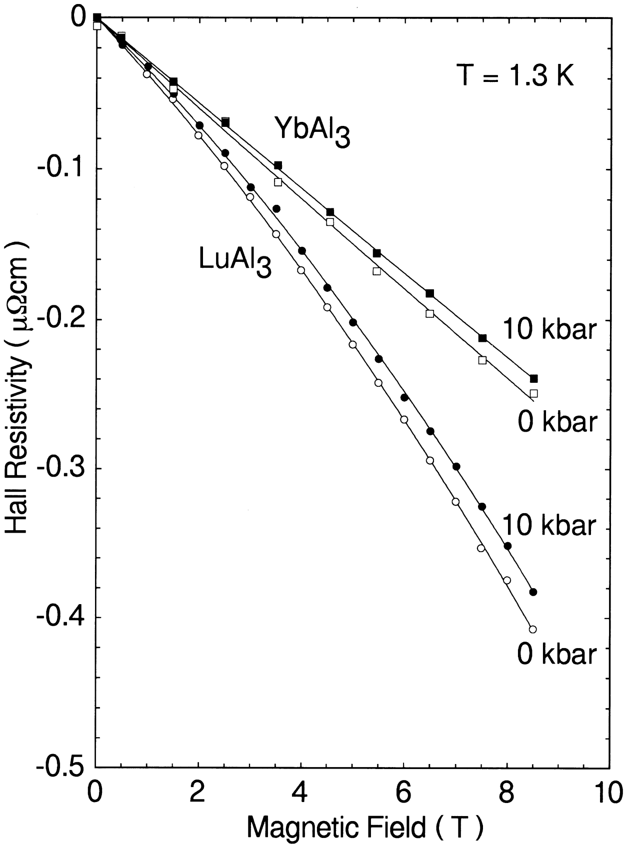

Fig. 5. Magnetic field dependence of the Hall resistivities for $YbAl_3$ and $LuAl_3$ at ambient pressure (0) and 10 kbar.

$\kappa^{-1}\partial \ln A^{-1/2}/\partial P = -7$, using $\kappa = 1\times10^{-3}$ kbar^{-1} and $\partial \ln A^{-1/2}/\partial P = -7\times10^{-3}$ kbar^{-1}. Note that the Kondo Grüneisen parameter for $CeSn_3$ is +7 [1], which is the same magnitude but opposite sign for that of $YbAl_3$. These magnitudes of Ω_K are smaller than these of typical heavy fermion compounds such as $CeAl_3$ ($\Omega_K = +383$, $T_K = 2.9$ K), $CeRu_2Si_2$ (+177, 11.3 K), $YbCu_2Si_2$ (−48, 226 K) [1,9].

Fig. 5 shows the Hall resistivity of $YbAl_3$ and $LuAl_3$ at ambient pressure and 10 kbar as a function of the magnetic field up to 9 T at 1.3 K. For each compounds, the Hall coefficient R_H are negative and the absolute value of R_H decreases by 7% with applying pressure from 1 bar to 10 kbar. Between $YbAl_3$ and $LuAl_3$, there are no large difference of pressure effect on the Hall coefficient R_H at 1.3 K. It indicates that the anomalous Hall effect in $YbAl_3$ is weak at low temperature. However, such a large decrease of $|R_H|$ could not be explained by a simple lattice compression with compressibility $\kappa = 1\times10^{-3}$ kbar^{-1}. More detailed studies are required for further understanding of the pressure effects on Hall effects of these materials.

In summary, we have found that the Kondo temperature T_K of $YbAl_3$ is decreased by pressure. We have estimated Kondo Grüneisen parameter $\Omega_K = -7$. This Ω_K is same magnitude but opposite sign to that for $CeSn_3$. The decrease of T_K with pressure indicates that the density of conduction electron states at the Fermi energy $D(E_F)$ and/or the magnetic exchange coupling strength between 4f local moment and conduction electrons J_{cf} are suppressed by pressure in $YbAl_3$.

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