

## Pressure dependence of the electrical resistivity of YbCu<sub>4</sub>Ag

E. Bauer, R. Hauser, E. Gratz, and K. Payer

*Institut für Experimentalphysik, Technische Universität Wien, A-1040 Wien, Austria*

G. Oomi and T. Kagayama

*Department of Physics, Kumamoto University, Kumamoto 860, Japan*

(Received 17 March 1993; revised manuscript received 29 July 1993)

Pressure-dependent measurements of the electrical resistivity,  $\rho(T, p)$ , of YbCu<sub>4</sub>Ag show a noticeable decrease of the resistivity maximum and a strong increase of the coefficient  $A$  in the  $T^2$  term of  $\rho(T)$  when the pressure rises. This indicates that the Kondo temperature  $T_K$  of this compound decreases with increasing pressure, stabilizing the  $4f^{13}$  configuration of the Yb ion. In the scope of the compressible Kondo model, a value for the coupling constant times the electronic density of states at the Fermi energy has been deduced.

### I. INTRODUCTION

The substitution of Cu by Ag in YbCu<sub>5</sub> (CaCu<sub>5</sub> structure) leads to the ordered ternary compound YbCu<sub>4</sub>Ag exhibiting the MgCu<sub>4</sub>Sn type of structure.<sup>1,2</sup> This compound shows those characteristic features which are known for typical Kondo lattices.

In particular, the temperature-dependent electrical resistivity  $\rho(T)$  shows a smooth maximum around 80 K followed by a decrease towards lower temperatures. Below about 30 K, the behavior of  $\rho(T)$  can be described by  $\rho = \rho_0 + AT^2$ , where  $\rho_0$  is the residual resistivity and the coefficient  $A$  is a measure for the electronic density of states at the Fermi level. The overall resistivity behavior may be understood as a crossover from incoherent Kondo scattering processes of conduction electrons on the Yb ions at high temperatures to coherent scattering at Kondo sites distributed periodically throughout the lattice taking place at low temperatures.

Other interesting features of this compound are its thermodynamic properties. The temperature-dependent magnetic part of the specific heat and the magnetic susceptibility are described successfully using results of the Bethe-ansatz solution of the  $j=7/2$  Coqblin-Schrieffer model<sup>3</sup> and assuming a characteristic temperature  $T_0$  of about 150 K.<sup>1,4</sup> Considering the large- $N$  approximation,<sup>5</sup> this temperature is found to be about 100 K.<sup>6</sup> Both the large value of the characteristic temperature and the noticeable agreement of the magnetic susceptibility and the specific heat with the predictions of the theoretical models prove that for this compound and in general for most of the Yb systems, the coupling of the conduction electrons with the  $4f$  moments is much larger than the intersite Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and crystal field terms.

Inelastic neutron scattering experiments performed on this compound did not reveal clear transitions associated with crystal field levels.<sup>7</sup> However, very recently Polatsek and Bonville<sup>6</sup> reanalyzed the results obtained by Severing *et al.*<sup>7</sup> in terms of the Anderson impurity

model using a simple approximation scheme<sup>8</sup> for the solution of the noncrossing approximation. Based on this model, the magnetic spectral response of YbCu<sub>4</sub>Ag could be accounted for by a characteristic temperature  $T_0 = 60$  K and the following crystal field level scheme:  $\Gamma_7$ ,  $\Gamma_8$ , and  $\Gamma_6$  at energies 0, 45, and 80 K. However, the  $\Gamma_7$  doublet as ground state seems not to coincide with field-dependent magnetization measurements  $M(H)$  at low temperatures.<sup>4,9</sup> These measurements exhibit a positive curvature above about 10 T. Theoretically, such a behavior is possible only for the case,  $N > 3$ ,<sup>10</sup> with  $N$  being the degeneracy of the ground state. Additionally, the maximum in the magnetic susceptibility around 31 K (Ref. 1) is only consistent with the model of Rajan<sup>3</sup> for  $N > 3$ . Similar features such as the positive curvature in isothermal magnetisation measurements or the maximum in the susceptibility data have been found also for the compound YbCuAl, where exact results of the  $j = 7/2$  Coqblin-Schrieffer model, appropriate for an Yb<sup>3+</sup> ion without crystal field splitting, are applicable.<sup>11</sup>

Measurements of the temperature-dependent photoemission spectra of YbCu<sub>4</sub>Ag confirmed the existence of the Kondo or Abrikosov-Suhl resonance below the Fermi energy, which is strongly depressed when the temperature rises.<sup>12</sup> The temperature dependence of the integrated intensity of the Kondo peak allows one to assume both the mentioned crystal field level scheme with a Kondo temperature of about 65 K as well as no crystal field splitting but a Kondo temperature of about 150 K.

The aim of this paper is to study the pressure-dependent evolution of the Kondo lattice state in YbCu<sub>4</sub>Ag. As is well known, hydrostatic pressure mainly influences the parameter  $JN(E_F)$  [ $J$ ,  $s$ - $f$  coupling constant;  $N(E_F)$ , electronic density of states at the Fermi energy] which determines both characteristic energies of Kondo lattices, namely, the Kondo temperature  $T_K$  and the temperature of the RKKY interaction,  $T_{\text{RKKY}}$ . Since these characteristic energies depend on  $JN(E_F)$  in different analytical ways, the application of hydrostatic pressure may influence the balance of these energies, and pos-

sibly alter the ground state of the compound under investigation.

## II. EXPERIMENTAL DETAILS

Polycrystalline  $\text{YbCu}_4\text{Ag}$  samples were prepared from stoichiometric amounts of elements using high frequency melting under protective argon atmosphere. Subsequently, a heat treatment at  $T=700^\circ\text{C}$  during 14 days in an argon atmosphere was applied. The phase purity of the samples was proved from x-ray diffraction measurements. The electrical resistivity of bare shaped samples was measured using a four-probe dc method in the temperature range 1.5 K up to room temperature. Two different methods to generate high pressure were applied: In a range up to 20 kbar a liquid pressure cell with a 4:1 methanol-ethanol mixture as pressure transmitter, was used. Beyond 20 kbar, the Bridgman technique with  $\text{Al}_2\text{O}_3$  anvils and pyrophyllit gaskets was applied. Steatit served as pressure transmitting medium. The absolute value of the pressure was determined from the superconducting transition of lead.<sup>13</sup> The pressure-dependent variation of the lattice constants was obtained from Guinier x-ray photographs. There, hydrostatic pressure was generated by a Bridgman anvil made of tungsten carbide. The powdered sample together with NaCl was placed in a 0.3 mm hole at the center of a beryllium disk of 0.5 mm in thickness, which was used as gasket. Again the 4:1 alcohol mixture was used as a pressure transmitting medium. The pressure in this cell was evaluated considering Decker's equation of state of NaCl.<sup>14</sup>

## III. RESULTS AND DISCUSSION

Figure 1 shows the influence of hydrostatic pressure on the temperature-dependent electrical resistivity  $\rho(T)$  of

$\text{YbCu}_4\text{Ag}$ . Reinforced pressure causes at moderately low temperatures a pronounced maximum to appear, which additionally is shifted downwards (inset, Fig. 1). Simultaneously, the initial slope of  $\rho(T)$  increases. This behavior is in contrast to the reported dependence of all cerium- and uranium-based compounds but resembles the behavior of the yet investigated Yb-compounds.<sup>15-18</sup> In particular, the  $\rho(T, p)$  dependence up to about 18 kbar of  $\text{YbCu}_4\text{Ag}$ , studied by Thompson *et al.*,<sup>17</sup> is recovered. Above about 100 K, the resistivity behavior of  $\text{YbCu}_4\text{Ag}$  can be successfully accounted for considering the single-impurity Kondo effect. To show this behavior in more detail, we consider the most dominant scattering mechanisms contributing to the electrical resistivity:

$$\rho(T) = \rho_0 + \rho_{\text{ph}}(T) + \rho_{\text{mag}}(T) = a + b \cdot T - c \cdot \ln(T) . \quad (1)$$

$\rho_0$  originates from scattering of conduction electrons on lattice imperfections, and  $\rho_{\text{ph}}(T)$  describes the resistivity contribution due to the interaction of conduction electrons with thermally excited phonons, whereas  $\rho_{\text{mag}}(T)$  is inferred from spin-dependent scattering processes. At elevated temperatures, the different contributions to  $\rho(T)$  follow simple analytical temperature dependences [cf. Eq. 1)]. A least squares fit according to this equation reveals satisfactory agreement (solid lines in Fig. 1) which proves the importance of the Kondo interaction in this compound. For clarity, the results are indicated for  $p=1$  bar and  $p=60$  kbar only.

The obtained parameters  $a$ ,  $b$ , and  $c$  as a function of pressure show a large increase of  $\rho_0$  with rising pressure, no essential change of the electron-phonon contribution but also a weak increase of  $c$  which is proportional to the Kondo interaction strength. The latter quantity consists of contributions due to the electronic density of states  $N(E_F)$  and of the  $s$ - $f$  coupling constant  $J$ .<sup>19</sup>

However, below about 100 K, Eq. (1) does not further account for the observed behavior. This can be caused

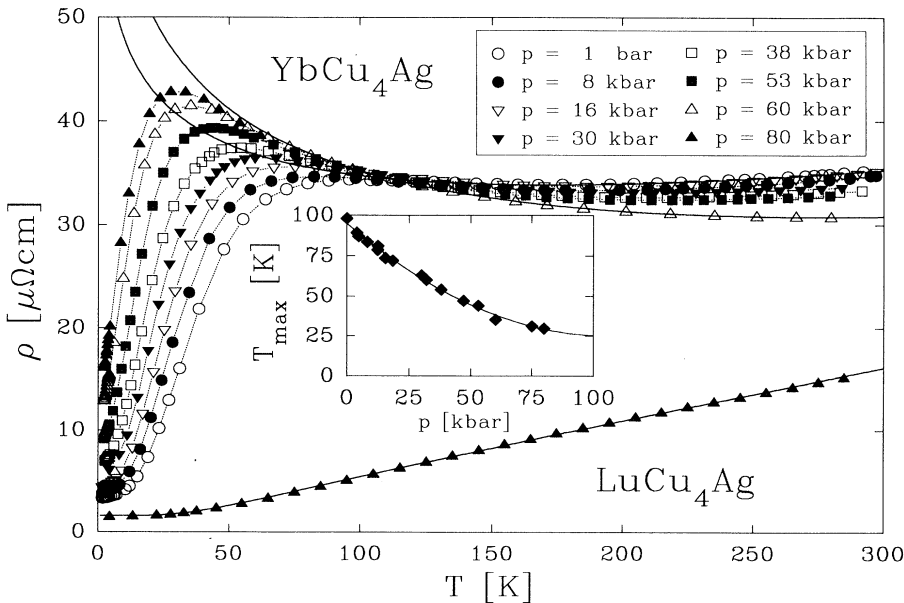


FIG. 1. Temperature-dependent electrical resistivity  $\rho(T)$  of  $\text{YbCu}_4\text{Ag}$  at various pressures. The  $\rho(T)$  behavior of  $\text{LuCu}_4\text{Ag}$  is also included in this figure. The solid lines are least squares fits explained in detail in the text. The inset shows the pressure dependence of  $T_{\text{max}}$ .

from various mechanisms such as the formation of the Kondo lattice state, RKKY interaction, or crystal field splitting. Since both latter mechanisms are thought to be weak, at least at ambient pressure,<sup>1,4</sup> the Kondo lattice property may become important. Kondo lattices are characterized by a Fermi liquid behavior for temperatures small compared to the respective Kondo temperature. This Fermi liquid state gives rise to a  $T^2$  behavior of the electrical resistivity, where the prefactor  $A$  is related to the density of states at the Fermi level by  $A \propto [N(E_F)]^2$ .<sup>20</sup> The application of hydrostatic pressure to YbCu<sub>4</sub>Ag reveals a strong increase of the coefficient  $A$  from about 8 nΩ cm/K<sup>2</sup> at ambient pressure to 277 nΩ cm/K<sup>2</sup> at 80 kbar (Fig. 2). The absolute value of  $A$ , however, though it is strongly enhanced by pressure, is considerably smaller than that obtained at ambient pressure for cerium-based heavy fermion compounds such as CeCu<sub>6</sub> ( $A=110 \mu\Omega \text{ cm/K}^2$ ),<sup>21</sup> CeAl<sub>3</sub> ( $A=35 \mu\Omega \text{ cm/K}^2$ ),<sup>22</sup> or CeCu<sub>2</sub>Si<sub>2</sub> ( $A=10.7 \mu\Omega \text{ cm/K}^2$ ),<sup>23</sup> but matches for example the value of CePd<sub>3</sub>.<sup>24,25</sup>

Various models have been developed to explain the distinct features in the temperature-dependent resistivity of Kondo lattices. Most of them are based on the periodic Anderson model with large Coulomb interaction. These models (see, e.g., Refs. 26–29) account fairly well for the experimental findings such as the low-temperature  $T^2$  behavior, the resistivity maximum at higher temperatures, and the logarithmic dependence above it. However, these models neither include intersite interactions nor crystal field splitting. More realistic starting conditions have been chosen by Fischer.<sup>30</sup> His resistivity calculation of the Anderson lattice is based on a single  $f$ -electron spin which is coupled to all other spins and to the conduction electrons. Multiple intersite scattering is neglected. The Kondo resistivity of independent spins is modified in this case by the spin dynamics. This leads at high temperatures only to a small modification of the Kondo effect,

but at low temperatures to a  $T^2$  law in the resistivity which scales with the Kondo temperature  $T_K$ . Deviations from this  $T^2$  law are expected at temperatures of the order of  $0.2T_K$ . On the other hand, Schilling<sup>31</sup> has argued that the maximum in  $\rho$  vs  $T$  of Kondo lattices arises from the competition between Kondo and RKKY interactions. Several studies<sup>32–34</sup> on the pressure dependence of Kondo lattices seem to confirm this assumption. However, even RKKY interactions are responsible for producing the resistivity maximum and the coherent state at low temperatures, they do not alter substantially the pressure response of  $T_{\text{max}}$ ,  $A$ , and the Sommerfeld constant  $\gamma$ .<sup>35</sup> To leading order it appears therefore that the pressure response of the resistivity of Kondo lattices is primarily determined by the Kondo effect. This is possibly understood from a small energy scale  $k_B T^*$  which is strongly influenced by volume changes.<sup>17,35</sup> The small energy scale is supposed to emerge from the competition of intrasite and intersite interactions. In the limit of large Kondo temperatures,  $T^*$  can be expressed as<sup>17,36</sup>

$$T^* \approx T_K(1 - T_{\text{RKKY}}/T_K), \quad (2)$$

with  $T_{\text{RKKY}}$  being the intrasite scale while  $T_K$  is the ordinary Kondo temperature. Here it should be noted that the temperatures  $T_0$  and  $T_K$  are related via the Wilson number  $W_j = T_K/T_0$ .<sup>10</sup> The Wilson number, which increases with an increasing total angular momentum  $j$ , connects the high-temperature perturbative regime ( $T_K$ ) with the low-temperature strong coupling regime ( $T_0$ ).

For  $T_K > T_{\text{RKKY}}$  the pressure response of  $T^*$  is mainly that of  $T_K$  which can be associated with the change of the resistivity maximum  $T_{\text{max}}$ . On the other hand, if  $T_{\text{RKKY}} > T_K$ , Eq. (2) is no longer valid since intrasite interactions dominate and the system orders magnetically. The observed dependences for YbCu<sub>4</sub>Ag, as the increase of  $A$  or the decrease of  $T_{\text{max}}$ , imply that  $\partial T^*/\partial p < 0$ , indicating that  $T_{\text{RKKY}}/T_K$  approaches 1

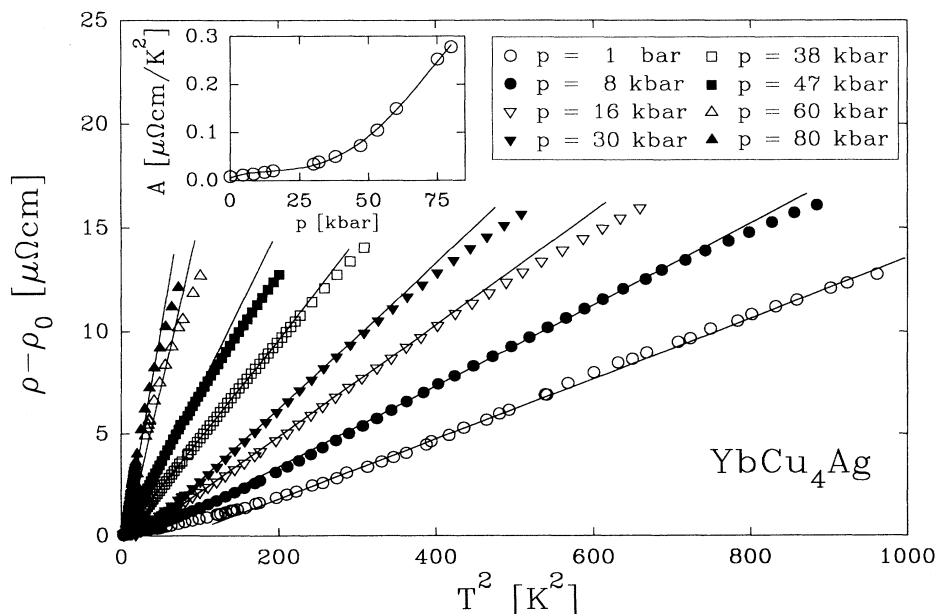


FIG. 2.  $\rho(T) - \rho_0$  vs  $T^2$  of YbCu<sub>4</sub>Ag. The solid lines indicate the  $T^2$  dependence. The inset shows the pressure dependence of the coefficient  $A$  of YbCu<sub>4</sub>Ag.

with increasing pressure, causing a magnetic instability to occur. It is therefore supposed that beyond our covered pressure range  $\text{YbCu}_4\text{Ag}$  orders magnetically. Experimentally, such an onset of magnetic order due to high pressure in Yb compounds was found for  $\text{YbCuAl}$  by Mignot and Wittig at roughly 100 kbar.<sup>16</sup> Some experimental evidence for a change of the magnetic state of the Yb ion in  $\text{YbCu}_4\text{Ag}$  can be found from a plot of the pressure-dependent resistivity according to  $\rho/\rho(T_{\text{max}})$  vs  $T/T_{\text{max}}$  (Fig. 3). While for smaller values of applied pressure a scaling behavior is found, in agreement to the results of Thompson *et al.*,<sup>17</sup> the enhancement of pressure causes deviations of it. This behavior seems to announce the growing importance of the RKKY interaction, which may become comparable to the rapidly decreasing Kondo interaction as the pressure is strengthened. Simultaneously, crystal field effects will have much more impact on the temperature-dependent resistivity, causing the observed breakdown of scaling. A scaling behavior of the resistivity in a limited pressure range has been obtained in different compounds such as  $\text{CeCu}_6$ ,<sup>37,38</sup>  $\text{URu}_2\text{Si}_2$ ,<sup>34</sup> or  $\text{YbCu}_2\text{Si}_2$  and  $\text{YbRh}_2\text{Si}_2$ ,<sup>17</sup> which has been explained by the fact that the ground state degeneracy stays almost unchanged.

The magnetic contribution to the electrical resistivity in the whole temperature range,  $\rho_{\text{mag}}(T)$ , of  $\text{YbCu}_4\text{Ag}$  can be obtained by a comparison with the data of an isostructural nonmagnetic compound.  $\text{LuCu}_4\text{Ag}$  is thought to account for the contribution owing to electron-phonon interactions and to the interaction of the conduction electrons with static imperfections properly.  $\rho(T)$  of the latter compound is also included in Fig. 1 and is well described by the Bloch-Grüneisen formula<sup>39</sup> which yields a constant proportional to the temperature-independent electron-phonon interaction strength  $R=0.050 \mu\Omega \text{ cm/K}$  and the Debye temperature  $\Theta_D = 215 \text{ K}$ . The theoretical temperature dependence according to both parameters is added to Fig. 1 as a solid line.

The difference of the resistivity data is displayed in Fig. 4 using a logarithmic temperature scale. At ambient pressure and for temperatures above about 100 K,  $\rho_{\text{mag}}(T)$  shows a negative logarithmic behavior, indicating clearly Kondo scattering processes. Under applied pressure the absolute resistivity values at the highest investigated temperatures decrease while the slope of the logarithmic  $\rho(T)$  contribution slightly increases; in the low-temperature range,  $\rho_{\text{mag}}$  increases. This trend of  $\rho_{\text{mag}}(T)$ , at least in the high-temperature range, can be understood in terms of a model of Cornut and Coqblin.<sup>19</sup> Within this model, the magnetic contribution to the electrical resistivity  $\rho_{\text{mag}}(T)$  consists of a sum of the spin disorder resistivity and the Kondo  $(-\ln T)$  term. While the former contribution depends on  $J^2 N(E_F)$ , the latter is a function of  $|J^3 [N(E_F)]^2|$ . Cornut-Coqblin theory predicts a logarithmic dependence of  $\rho_{\text{mag}}(T)$  for temperatures much larger or smaller than the temperature of a certain crystal field level and for the fully occupied multiplet of a cerium or ytterbium ion. From this model it follows that the pressure-induced slight enhancement of the logarithmic slope in  $\rho_{\text{mag}}(T)$  is a consequence of an increasing value of the product  $|J^3 [N(E_F)]^2|$ . However, much of the observed effect most likely arises from the fact that the maximum in  $\rho(T)$  is shifted towards lower temperatures while the coefficient of the  $T^2$  term increases. The observed pressure-induced reduction of the absolute resistivity values at elevated temperatures follows directly from the contribution of the spin disorder resistivity if  $J^2 N(E_F)$  decreases. On the contrary, the increase of  $\rho_{\text{mag}}(T)$  at high temperatures, found for cerium compounds in an extended range of increasing pressure,<sup>42</sup> indicates that  $J^2 N(E_F)$  rises.

The treatment given in the following, which helps to analyze the pressure dependence of the electrical resistivity, has been successfully applied to various Ce compounds such as  $\text{CePd}_3$ ,<sup>25</sup>  $\text{Ce}(\text{In}_{0.8}\text{Sn}_{0.2})_3$ ,<sup>40</sup>  $\text{CeInCu}_2$ ,<sup>41</sup> or  $\text{CeCu}_6$ ,<sup>42</sup> and is now used to check the properties of

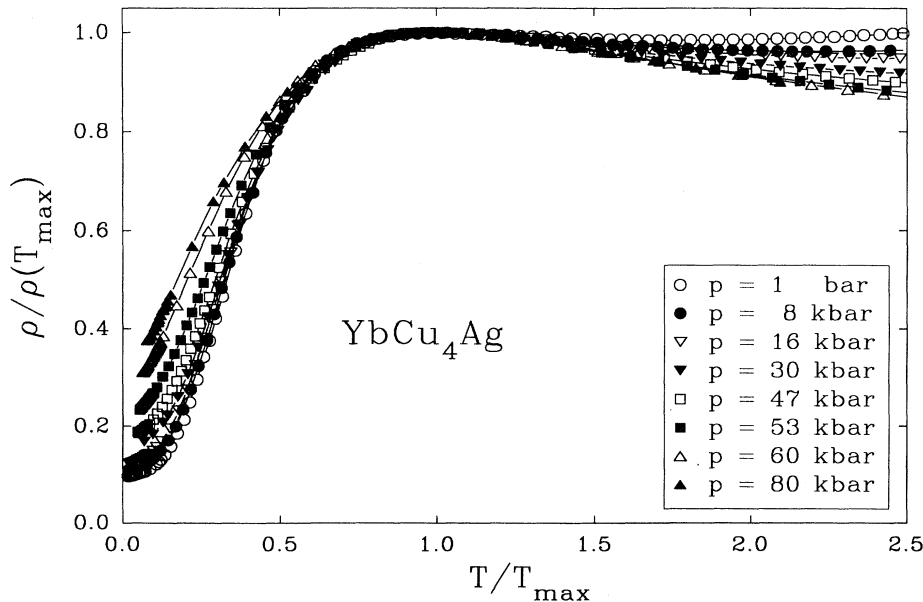


FIG. 3. Resistivity  $\rho$  normalized to its maximum value  $\rho(T_{\text{max}})$  as a function of the reduced temperature  $T/T_{\text{max}}$  of  $\text{YbCu}_4\text{Ag}$  at various pressures.

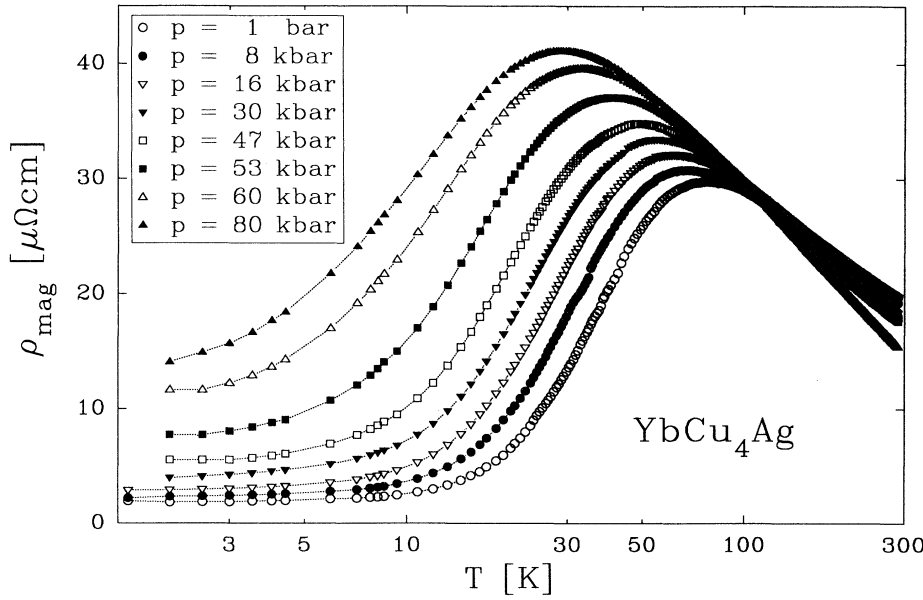


FIG. 4. Temperature-dependent magnetic contribution to the electrical resistivity  $\rho_{\text{mag}}$  of YbCu<sub>4</sub>Ag at various pressures plotted in a semilogarithmic representation.

YbCu<sub>4</sub>Ag as well. This procedure is partly based on results of the periodic version of the Anderson Hamilton operator in its integer valent limit. It has been shown<sup>27–30</sup> that the characteristic temperature of the system, the Kondo temperature  $T_K$ , depends on the coefficient  $A$  by  $A \propto T_K^{-2}$  and the maximum temperature  $T_{\text{max}}$  is related to  $T_K$  via  $T_{\text{max}} \propto 1/\sqrt{A}$ . The latter expression can easily be verified by plotting  $1/\sqrt{A}$  as a function of the maximum temperature  $T_{\text{max}}$  (Fig. 5). The increase of  $A$  in the low-temperature range corresponds to a decrease of  $T_K$  caused by the hydrostatic pressure.

Since the temperature of the maximum in electrical resistivity is related to  $T_K$ , it is directly connected to the parameter  $JN(E_F)$ ,

$$T_{\text{max}} \propto T_K \propto \exp\left(-\frac{1}{|JN(E_F)|}\right). \quad (3)$$

The decrease of the maximum in  $\rho(T)$  with increasing pressure therefore points to a decrease of the product  $JN(E_F)$ . Since an increase of the density of states is ex-

pected from the variation of the coefficient  $A$  when the pressure rises, we have to anticipate that the coupling constant  $J$  decreases rapidly enough to overcome the increase of  $N(E_F)$ . Also recent pressure-dependent studies of the specific heat on YbCu<sub>4.5</sub> (Ref. 43) indicated that  $\gamma$  and therefore  $N(E_F)$  increases with pressure, confirming the deduced low-temperature behavior of YbCu<sub>4</sub>Ag. An estimation of the parameter  $JN(E_F)$  may be found in the scope of the compressible Kondo model,<sup>44</sup>

$$|JN(E_F)| = |JN(E_F)|_0 \exp\left(-q \frac{V - V_0}{V_0}\right), \quad (4)$$

where  $|JN(E_F)|_0$  is the value of  $|JN(E_F)|$  at ambient pressure.  $V$  and  $V_0$  are the volumes at pressure  $p$  and at ambient pressure, respectively.  $q$  is a dimensionless parameter and may be termed as a Grüneisen parameter of  $|JN(E_F)|$ , i.e.,

$$q = -\left.\frac{\partial \ln |JN(E_F)|}{\partial \ln V}\right|_{V=V_0}. \quad (5)$$

For the Yb compound investigated, it is evident that  $q$  is negative, opposite in sign to Ce compounds. For various Kondo systems the absolute value of  $q$  has been found to range between 6 and 8.<sup>42</sup> Now, the Grüneisen parameter for the Kondo temperature  $T_K$  follows from Eqs. (3) and (5):

$$-\left.\frac{\partial \ln T_K}{\partial \ln V}\right|_{V=V_0} = \left|\frac{q}{|J \cdot N(E_F)|}\right|_0. \quad (6)$$

Considering the relation between  $A$  and  $T_{\text{max}}$ , i.e.,  $T_{\text{max}} \propto 1/\sqrt{A}$ , Eqs. (3) and (4) yield the expression

$$\ln \left[\frac{T_{\text{max}}(p)}{T_{\text{max}}(0)}\right] = -\frac{1}{2} \ln \left[\frac{A(p)}{A(0)}\right] = -\frac{q}{|JN(E_F)|_0} \frac{V_0 - V}{V_0}. \quad (7)$$

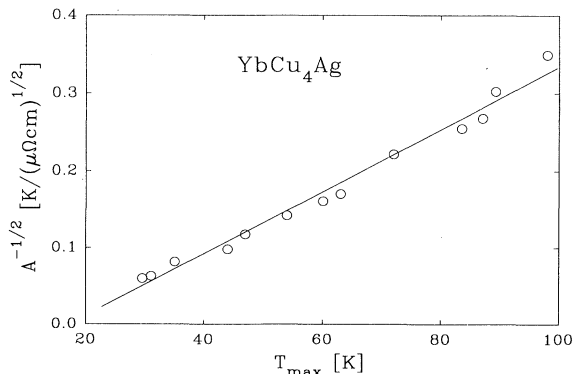


FIG. 5.  $1/\sqrt{A}$  vs  $T_{\text{max}}$  of YbCu<sub>4</sub>Ag. The solid line shows a least squares fit according a linear dependence.

The evaluation of the parameter  $|JN(E_F)|$  requires the knowledge of  $(V_0 - V)/V_0$ . We have, therefore, performed pressure-dependent x-ray diffraction measurements to determine the volume change of YbCu<sub>4</sub>Ag. Figure 6 shows the relative change of the volume of the unit cell  $V/V_0$  of YbCu<sub>4</sub>Ag as a function of pressure at room temperature.  $V/V_0$  decreases smoothly with increasing pressure. No anomaly up to 140 kbar is found, indicating that YbCu<sub>4</sub>Ag does not exhibit a pressure-induced valence transition at room temperature. The volume change of YbCu<sub>4</sub>Ag can be accounted for considering the first-order Murnaghan's equation of state,<sup>45</sup>

$$\frac{V_0 - V}{V_0} = 1 - \left( \frac{B_0}{B_0^*} p + 1 \right)^{-\frac{1}{B_0^*}}, \quad (8)$$

where  $B_0$  is the bulk modulus and  $B_0^*$  its pressure derivative. The results of a least squares fit give  $B_0 = 1080$  kbar and  $B_0^* = 3.3$ . To trace the dependence predicted by Eq. (7), the experimental results are plotted as  $\ln[T_{\max}(p)/T_{\max}(0)]$  versus  $(V_0 - V)/V_0$  and  $(-1/2)\ln[A(p)/A(0)]$  versus  $(V_0 - V)/V_0$  in Fig. (7). This figure indicates an almost linear dependence of both  $\ln[T_{\max}(p)/T_{\max}(0)]$  and  $(-1/2)\ln[A(p)/A(0)]$  on the volume change due to applied pressure. The slope of both curves yields  $-18.6$  kbar<sup>-1</sup> and  $-27.8$  kbar<sup>-1</sup> for  $q/|JN(E_F)|_0$ , as deduced from the variation of the maximum temperature  $T_{\max}$  and the dependence of the coefficient  $A$ , respectively. It is supposed that the former value is more accurate since the absolute value of the coefficient  $A$  depends directly on the geometrical cross section of the sample, which can be wrong due to microcracks or pores.

The parameter  $|JN(E_F)|_0$ , as follows from Fig. (7) using  $q = -6$ , is determined to be 0.32. This value has to be compared with  $|JN(E_F)|_0$  of 0.091 and 0.081 for CeCu<sub>6</sub> and CeInCu<sub>2</sub>, respectively, evaluated from a similar analysis.<sup>42</sup> Both latter compounds are known for Kondo temperatures of the order of 10 K, while that of YbCu<sub>4</sub>Ag is an order of magnitude larger.

#### IV. CONCLUDING REMARKS

Measurements of the electrical resistivity and the lattice constant of YbCu<sub>4</sub>Ag at various values of applied

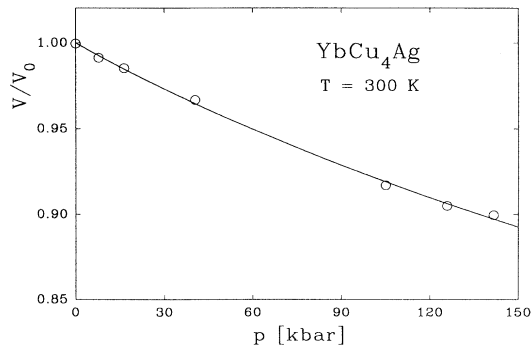


FIG. 6. Relative change of the volume  $V/V_0$  of YbCu<sub>4</sub>Ag as a function of pressure.

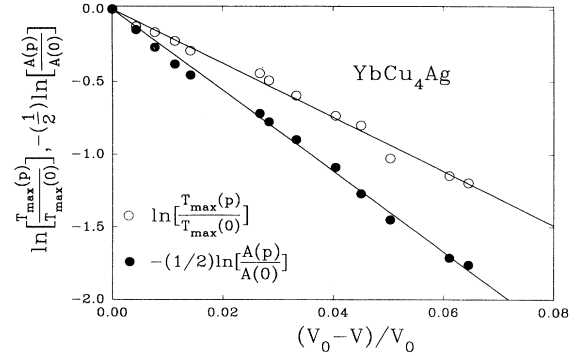


FIG. 7.  $\ln[T_{\max}(p)/T_{\max}(0)]$  and  $(-1/2)\ln[A(p)/A(0)]$  versus pressure of YbCu<sub>4</sub>Ag.

pressure evidence the sensitivity of the main parameters to a change of the volume of the system. This of course is a general feature of Kondo systems and heavy fermions and may be explained by the balance of the principal interaction mechanisms at low temperature. The observed behavior of YbCu<sub>4</sub>Ag, which is found to be opposite to related Ce systems, can be understood qualitatively regarding particular features in the electronic density of states near the Fermi energy. In the scope of the Anderson impurity model, and in the large  $U$  limit ( $U$  is the Coulomb interaction between  $f$  electrons) the following relation was obtained:<sup>46</sup>

$$n_f/(1 - n_f) = N_f \Delta / T_K, \quad (9)$$

where  $\Delta$  is the hybridization parameter between  $4f^{14}(ds)^2$  and  $4f^{13}(ds)^3$  electronic states,  $n_f$  is the number of holes, and  $N_f$  represents the degeneracy of the  $f$  electrons. It was demonstrated that the number of  $f$  holes in Yb compounds increases if the pressure is raised.<sup>47</sup> Hence the valency increases accordingly, while the Yb  $4f$  moment is strengthened. This is related to the fact that the atomic radius of the  $4f^{13}$  state is smaller than that of the  $4f^{14}$  state. Consequently, Eq. (9) indicates that  $N_f \Delta / T_K$  should increase with increasing pressure. Pressure, however, influences both the hybridization parameter  $N_f \Delta$  as well as the Kondo temperature  $T_K$ . The latter quantity behaves as  $T_K = D \exp(-\pi|\epsilon_f|/N_f \Delta)$ , where  $D$  is an effective bandwidth and  $\epsilon_f$  is the binding energy of bare  $f$  holes. Since the Kondo temperature changes exponentially,  $T_K$  varies more rapidly than the hybridization parameter. We, therefore, expect that the Kondo temperature decreases for YbCu<sub>4</sub>Ag as the number of  $f$  holes increases. Simultaneously, the width  $\Gamma$  of the Abrikosov-Suhl resonance (ASR) below the Fermi energy decreases with decreasing Kondo temperature, i.e.,  $\Gamma = \pi T_K / N_f$ .<sup>5</sup> A decrease of  $T_K$ , however, can be obtained also from a change of the hybridization with pressure, which does not necessarily require a change in the  $f$  hole count. It has been shown that the formation of quasiparticle bands and the splitting of the ASR do not modify significantly the resistivity.<sup>30</sup> This is due to the fact that the elec-

tric current is carried only by conduction electrons which contribute only very little to this resonance in the the quasiparticle band. For this reason, the splitting of the ASR seems to be of minor importance in case of transport properties of Kondo lattices. The noticeable pressure dependence of the coefficient  $A$  for this ytterbium compound follows then from the  $f$  hole density of states  $\rho_f(0)$  by<sup>5</sup>  $\rho_f(0) = 1/(\pi\Gamma) \sin^2(\pi n_f/N_f)|_{T=0}$ . Due to the decreasing width of the ASR with increasing pressure,  $\rho_f(0)$  increases too, hence explaining the growing value of  $A$ . This fits to the low-temperature resistivity calculations of the Anderson lattice, giving a  $T^2$  behavior which

scales by the Kondo temperature.<sup>30</sup> The pressure inferred decrease of  $T_K$  thus causes the rapidly rising value of  $A$ .

#### ACKNOWLEDGEMENTS

This work has been supported by the "Austrian Science Foundation" under Project No. P7608-PHY. We are grateful to Professor Oh and Dr. Cho (University of Seoul) for helpful discussions. One of us (E.B.) is indebted to the "Österreichische Forschungsgemeinschaft" for financial support.

- <sup>1</sup> C. Rossel, K.N. Yang, M.B. Maple, Z. Fisk, E. Zirngiebl, and J.D. Thompson, *Phys. Rev. B* **35**, 1914 (1987).
- <sup>2</sup> D.T. Adroja, S.K. Malik, B.D. Padalia, and R. Vijayaraghavan, *J. Phys. C* **20**, L307 (1987).
- <sup>3</sup> V.T. Rajan, *Phys. Rev. Lett.* **51**, 308 (1983).
- <sup>4</sup> M.J. Besnus, P. Haen, N. Hamdaoui, A. Herr, and A. Meyer, *Physica B* **163**, 571 (1990).
- <sup>5</sup> N.E. Bickers, D.L. Cox, and J.W. Wilkins, *Phys. Rev. Lett.* **54**, 230 (1987).
- <sup>6</sup> G. Polatsek and P. Bonville, *Z. Phys. B* **88**, 189 (1992).
- <sup>7</sup> A. Severing, A.P. Murani, J.D. Thomson, Z. Fisk, and C.K. Loong, *Phys. Rev. B* **41**, 1739 (1990).
- <sup>8</sup> G. Zwicknagl, V. Zevin, and P. Fulde, *Z. Phys. B* **79**, 229 (1990).
- <sup>9</sup> K. Yoshimura, T. Nitta, M. Mekato, T. Shimizu, T. Sakakibara, T. Goto, and G. Kido, *Phys. Rev. Lett.* **60**, 851 (1988).
- <sup>10</sup> A.C. Hewson and J.W. Rasul, *J. Phys. C* **16**, 6799 (1983).
- <sup>11</sup> A.C. Hewson, D.M. Newns, J.W. Rasul, and N. Read, *J. Magn. Magn. Mater.* **47-48**, 354 (1985).
- <sup>12</sup> P. Waibel, M. Grioni, D. Malterre, B. Dardel, Y. Baer, and M.J. Besnus, *Z. Phys. B* **91**, 341 (1993).
- <sup>13</sup> A. Eiling and J. Schilling, *J. Phys. F* **11**, 623 (1981).
- <sup>14</sup> D.L. Decker, *J. Appl. Phys.* **42**, 3239 (1971).
- <sup>15</sup> D. Jaccard, F. Haenssler, and J. Sierro, *Helv. Phys. Acta* **53**, 590 (1980).
- <sup>16</sup> J.M. Mignot and J. Wittig, in *Physics and Solids under High Pressure*, edited by J.S. Schilling and R.N. Shelton (North-Holland, Amsterdam, 1981), p. 311.
- <sup>17</sup> J.D. Thompson, H.A. Borges, Z. Fisk, S. Horn, R.D. Parks, and G.L. Wells, in *Theoretical and Experimental Aspect of Valence Fluctuations and Heavy Fermions*, edited L.C. Gupta and S.K. Malik (Plenum, New York, 1987), p. 151.
- <sup>18</sup> T. Matsumoto, T. Shimizu, Y. Yamada, and K. Yoshimura, *J. Magn. Magn. Mater.* **104-107**, 647 (1992).
- <sup>19</sup> D. Cornut and B. Coqblin, *Phys. Rev. B* **5**, 4541 (1972).
- <sup>20</sup> W.G. Barber, *Proc. R. Soc. London* **258**, 383 (1937).
- <sup>21</sup> H.R. Ott, H. Rudigier, Z. Fisk, J.O. Willis, and G.R. Stewart, *Solid State Commun.* **53**, 235 (1985).
- <sup>22</sup> K. Andres, J.E. Graebner, and H.R. Ott, *Phys. Rev. Lett.* **35**, 1779 (1975).
- <sup>23</sup> F. Steglich, C.D. Bredl, W. Lieke, U. Rauchschwalbe, and G. Sparn, *Physica B* **126**, 82 (1984).
- <sup>24</sup> J.M. Lawrence, J.D. Thompson, and Y.Y. Chen, *Phys. Rev. Lett.* **54**, 2537 (1985).
- <sup>25</sup> G. Oomi, Y. Onuki, and T. Komatsubara, *Physica B* **163**, 405 (1990).
- <sup>26</sup> N. Grewe and T. Pruschke, *Z. Phys. B* **60**, 311 (1985).
- <sup>27</sup> A. Yoshimori and H. Kasai, *J. Magn. Magn. Mater.* **31-34**, 475 (1983).
- <sup>28</sup> P. Coleman, *J. Magn. Magn. Mater.* **63-64**, 245 (1987).
- <sup>29</sup> D.L. Cox and N. Grewe, *Z. Phys. B* **71**, 321 (1988).
- <sup>30</sup> K.H. Fischer, *Z. Phys. B* **74**, 475 (1989).
- <sup>31</sup> J. Schilling, *Phys. Rev. B* **33**, 1667 (1986).
- <sup>32</sup> J.D. Thompson, R.D. Parks, and H.A. Borges, *J. Magn. Magn. Mater.* **54-57**, 377 (1986).
- <sup>33</sup> J.D. Thompson, Z. Fisk, and H.R. Ott, *J. Magn. Magn. Mater.* **54-57**, 393 (1986).
- <sup>34</sup> M.W. McElfresh, J.D. Thompson, J.O. Willis, M.B. Maple, T. Kohara, and M.S. Torikachvili, *Phys. Rev. B* **35**, 43 (1987).
- <sup>35</sup> J.D. Thompson, Z. Fisk, and G.G. Lonzarich, *Physica B* **161**, 317 (1989).
- <sup>36</sup> C.J. Pethick and D. Pines, in *Recent Progress in Many Body Theory*, edited by A. J. Kallio, E. Pajanne, and R. F. Bishop (Plenum, New York, 1988), Vol. 1, p. 17.
- <sup>37</sup> J.D. Thompson, *J. Magn. Magn. Mater.* **63-64**, 358 (1987).
- <sup>38</sup> S. Yomo, L. Gao, R.L. Meng, P.H. Hor, C.W. Chu, and J. Susaki, *J. Magn. Magn. Mater.* **76-77**, 257 (1988).
- <sup>39</sup> G. Grimvall, *The Electron-Phonon Interaction in Metals* (North-Holland, Amsterdam, 1981).
- <sup>40</sup> G. Oomi, T. Numata, and J. Sakurai, *Physica B* **149**, 73 (1988).
- <sup>41</sup> T. Kagayama, G. Oomi, H. Takahashi, N. Mori, Y. Onuki, and T. Komatsubara, *Phys. Rev. B* **44**, 7690 (1991).
- <sup>42</sup> T. Kagayama and G. Oomi, in *Proceedings of the Hiroshima Workshop on Transport and Thermal Properties of f-electron Systems*, edited by G. Oomi, H. Fujii, and T. Fujita (Plenum, New York, 1993).
- <sup>43</sup> A. Amato, R.A. Fisher, N.E. Phillips, D. Jaccard, and E. Walker, *Physica B* **165-166**, 389 (1990).
- <sup>44</sup> M. Lavagna, C. Lacroix, and M. Cyrot, *J. Phys. F* **13**, 1007 (1983).
- <sup>45</sup> F.D. Murnaghan, *Finite Deformation of an Elastic Solid* (Dover, New York, 1951), p. 68.
- <sup>46</sup> O. Gunnarsson and K. Schönhammer, *Phys. Rev. B* **28**, 4315 (1983).
- <sup>47</sup> D. Wohlleben, in *Moment Formation in Solids*, edited by W.J.L. Buyers (Plenum, New York, 1984), p. 171.