Low-temperature resistivity and magnetoresistivity of cerium compounds

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The low-temperature resistivity and magnetoresistivity of cerium compounds are computed with a model describing both the crystalline field and Kondo effects, thus extending to low temperatures a previous calculation [Phys. Rev. B 5, 4541 (1972)]. The theoretical results can account for the resistivity data of cerium compounds, either those which order magnetically (such as $CeAl_2$ or CeB_6) or those which become nonmagnetic (such as $CeAl_3$ or $CeCu_2Si_2$) at low temperatures.

I. INTRODUCTION

Cerium compounds have been extensively studied in the last few years. It is well known that we can distinguish between intermediate valence compounds and Kondo compounds which have an almost integer valence but which present a Kondo behavior due to the proximity of the $4f$ level to the Fermi level.[1]

The transport properties of cerium Kondo compounds have been previously studied within a model which describes both the Kondo effect and the crystalline field of the $(2j+1)$ degenerate $4f^1$ configuration. This model essentially yields a resistivity which behaves as $\ln T$ at low and high temperatures compared to the overall crystalline-field splitting and goes through a broad maximum at a temperature of order Δ. The theoretical model has successfully accounted for the resistivity of $CeAl_2$ and $CeAl_3$ compounds at sufficiently high temperatures, i.e., roughly above 10 K.

However, such a one-impurity model breaks down completely at low temperatures, because, in fact, cerium Kondo compounds either order magnetically like $CeAl_2$ or become nonmagnetic like $CeAl_3$. This difference of behavior is due to the relative strength of the one-impurity Kondo coupling and of the indirect interaction between different cerium atoms.[2] More precisely, let us call T_k^0 the Kondo temperature corresponding to the one-impurity case or to the extremely dilute case and T_N^0 the ordering temperature as if there were no Kondo effect on each cerium atom. Thus, we obtain at low temperatures either a magnetic ordering if $T_N^0 \gg T_k^0$ or a nonmagnetic Kondo-type state if $T_N^0 \ll T_k^0$.

Several cerium Kondo compounds, $CeAl_2$, CeB_6 (Ref. 3), CeS (Ref. 4), CeTe (Ref. 5) show a magnetic ordering at low temperature. $CeAl_2$ (Ref. 6) and CeB_6 (Ref. 3) compounds present a modulated magnetic ordering, respectively, below 3.85 and 2.8 K. The low-temperature resistivity decreases rapidly with increasing applied field around the Néel temperature and the magnetoresistivity disappears at about 15 K. When temperature increases above the Néel temperature, there is, at zero magnetic field, a resistivity decrease which subsists in CeB_6 up to at least 85 kOe (Ref. 7) and disappears in $CeAl_2$ at high fields giving rise to a continuous increase at 50 kOe (Ref. 8).

On the contrary, $CeAl_3$ (Ref. 9) and $CeCu_2Si_2$ (Ref. 10) compounds become nonmagnetic at very low temperatures and even $CeCu_2Si_2$ becomes superconducting.[11] The resistivity of $CeCu_2Si_2$ behaves as $\ln T$ at high temperatures and goes through a maximum at 100 K corresponding roughly to the crystalline-field overall splitting.[12] When temperature is still decreasing, the resistivity goes through a second broad maximum at roughly 20 K and then decreases continuously down to 1.5 K, as shown in the inset of Fig. 6; the low-temperature maximum does not seem to originate from crystalline-field effects.[12] The resistivity of $CeAl_3$ is continuously decreasing with decreasing temperature down to the lowest measured temperature.[13]

The purpose of the present paper is to extend at low temperatures the previous calculation of the resistivity of cerium Kondo compounds, in the framework of the effective Hamiltonian appropriate for describing the $4f^1$ configuration. Firstly, we study the case of cerium compounds which order magnetically at low temperatures and we compute also the magnetoresistivity of such compounds. Then we present a phenomenological model which describes the case of cerium compounds which become nonmagnetic at low temperatures.

II. THEORETICAL MODEL

We present here the theoretical model used to describe the resistivity and the magnetoresistivity of cerium Kondo compounds which order magnetically at low temperatures. The same model with some minor changes will be used to describe phenomenologically cerium Kondo compounds which become nonmagnetic at low temperatures. A brief account of this work has previously been reported elsewhere.[14]

The resistivity is described in the formalism of Ref. 1. We discuss the case of a cubic crystalline field for cerium, giving rise to a Γ_7 doublet and a Γ_8 quartet. The presence of an applied magnetic field and magnetic ordering splits

the states of Γ_7 and Γ_8. The application of an external magnetic field and the onset of a magnetic ordering split the two states of Γ_7 by δ_0, two states of Γ_8 by δ_1, and the two other ones by δ_2 (with $\delta_2 > \delta_1$).

In the following, we will always call 1 the new ground-state of energy E_1, and denote by $i=2,3,\ldots,6$ the five new excited states of increasing energy E_i. We will also call Δ the energy splitting of Γ_7 and Γ_8 without a magnetic field and $\Delta_{ij}=E_i-E_j$ the new energy splittings. If Γ_7 is the ground state without magnetic field, the splittings Δ_{i1} are equal to 0, δ_0, $\Delta+(\delta_0-\delta_2)/2$, $\Delta+(\delta_0-\delta_1)/2$, $\Delta+(\delta_0+\delta_1)/2$, and $\Delta+(\delta_0+\delta_2)/2$, for, respectively, $i=1,2,\ldots,6$. If Γ_8 is the ground state without magnetic field, the splittings Δ_{i1} are equal to 0, $(\delta_2-\delta_1)/2$, $(\delta_2+\delta_1)/2$, δ_2, $\Delta+(\delta_2-\delta_0)/2$, and $\Delta+(\delta_0+\delta_2)/2$, for, respectively, $i=1,2,\ldots,6$.

There are two contributions to the δ_i splittings: The first one $\delta_i^{(1)}$ is due to the applied magnetic field and is given by

$$\delta_i^{(1)}=2g_J\mu_B\langle J_z\rangle_i H=\alpha_i H \ , \tag{1}$$

where g_J is the Landé factor of the $4f^1$ multiplet and $\langle J_z\rangle_i$ is the average value of J_z within each eigenfunction of the considered ith doublet.

For cerium, the α_i are given (in K) by

$$\alpha_0=0.095, \quad \alpha_1=0.058, \quad \alpha_2=0.21 \tag{2}$$

with H expressed in kOe.

The second contribution $\delta_i^{(2)}$ is due to the magnetic ordering. We treat it here within the molecular-field approximation in the case of a ferromagnetic ordering; this choice, which, indeed, simplifies the calculations, is, in fact, not crucial for the derivation of the resistivity.

In the ordered regime, the statistical thermal average value $\langle\langle J_z\rangle_i\rangle$ within the ith doublet is, indeed, no longer zero for $H=0$. We use here a straightforward adaptation of the classical molecular-field approximation: first, we compute one chosen $\langle\langle J_z\rangle_i\rangle$ value for one doublet (i.e., Γ_7 for a Γ_7 ground state and the $i=1$ doublet for a Γ_8 ground state) by the classical molecular-field law:

$$\langle\langle J_z\rangle_i\rangle=J\mathscr{L}\left[\frac{\delta_i}{kT}\right]=J\mathscr{L}\left[\frac{\alpha_i H}{kT}+\frac{3T_N}{T}\frac{\langle\langle J_z\rangle_i\rangle}{J}\right] . \tag{3}$$

In (3), T_N is the ordering temperature and $\mathscr{L}(x)=\coth x-1/x$ is the Langevin function.

The mean value $\langle\langle J_z\rangle_i\rangle$ within the chosen doublet is determined self-consistently by Eq. (3) by taking T_N equal to the experimental value and $S=\frac{1}{2}$; the results are almost independent of the S value. Then the magnetic ordering contributions $\delta_i^{(2)}$ are taken to be proportional to the α_i between each other, i.e., $\delta_j^{(2)}=(\alpha_j/\alpha_i)\delta_i^{(2)}$.

Finally, we get the three values of $\delta_i=\delta_i^{(1)}+\delta_i^{(2)}$, the six values of E_i, and the different values of Δ_{ij} in the presence of both a magnetic field and magnetic ordering.

For the $4f^1$ configuration of cerium, the occupation numbers $\langle n_i\rangle$ of the six levels are given by

$$\langle n_i\rangle=\frac{e^{\Delta\beta_{i1}}}{1+\sum\limits_{j(\neq 1)} e^{\beta\Delta_{j1}}} \tag{4}$$

with $\beta=1/kT$.

We use the expression of the resistivity derived in Ref. 1 for the effective-exchange Hamiltonian describing the resonant scattering of cerium. We take here the exchange integrals $J_{MM'}$ and the normal scattering potential constants v_{MM} of Ref. 1 respectively equal to J and v. We use for the resistivity the expression written in the so-called "$f_k=\frac{1}{2}$ approximation" [Eqs. (117)–(120) of Ref. 1], since we have checked that it yields results very close to the exact results. Indeed, a calculation which does not use this simplifying approximation would be easy to perform.

Thus, the resistivity ρ, up to third order in J, in the presence of an applied magnetic field and in both the paramagnetic and magnetically ordered regions is given by

$$\rho=\frac{3m^2\pi v_0 c}{e^2\hbar^3 k_F^2(2j+1)}\left[(\sigma^{(2)})^{-1}+\frac{\sigma^{(3)}}{(\sigma^{(2)})^2}\right] , \tag{5}$$

where m, k_F, v_0, and c are, respectively, the mass of the conduction electrons, their wave number at the Fermi energy, the sample volume, and the cerium concentration; for cerium, $(2j+1)=6$.

The second-order term $\sigma^{(2)}$ is given [see Eqs. (119) of Ref. 1] by

$$(\sigma^{(2)})^{-1}=6v^2+\sum_{i=1}^{6} J^2\langle n_i\rangle(1-\langle n_i\rangle)+\sum_{\substack{i,j=1\\(i\neq j)}}^{6}\frac{2J^2\langle n_j\rangle}{1+e^{\beta\Delta_{ij}}} . \tag{6}$$

The third-order term $\sigma^{(3)}$ is given [see Eq. (120) of Ref. 1] by

$$\frac{\sigma^{(3)}}{(\sigma^{(2)})^2}=2n(E_F)J^3\sum_{\substack{i,j=1\\(i\neq j)}}^{6}\left[\langle n_i\rangle(1-\langle n_i\rangle+\langle n_j\rangle)\Gamma^1(\Delta_{ji},0)+\frac{2\langle n_j\rangle}{1+e^{\beta\Delta_{ij}}}\sum_{l=1}^{6}\Gamma^1(\Delta_{li},0)\right] , \tag{7}$$

where $\Gamma^1(\Delta,0)$, defined in Ref. 1, is given by

$$\Gamma^1(\Delta,0)=\frac{1}{n(E_F)}\int_{-\infty}^{+\infty}\left[-\frac{\partial f_k}{\partial\epsilon_k}\right]g(\epsilon_k+\Delta)d\epsilon_k \tag{8}$$

with

$$f_k=\frac{1}{1+e^{\beta(\epsilon_k-E_F)}} , \tag{9}$$

$$g(\epsilon)=\sum_q\frac{f(\epsilon_q)}{\epsilon_q-\epsilon} . \tag{10}$$

$n(E_F)$ and E_F are, respectively, the density of states at the Fermi energy for one spin direction and the Fermi energy for the conduction band. The sum in (10) is performed over all the energies ϵ_q of the conduction band.

According to Ref. 15, $\Gamma^1(\Delta,0)$ is given by

$$\Gamma^1(\Delta,0)=\ln\frac{2\pi T}{D}+\mathrm{Re}\psi\left[i\frac{\Delta}{2\pi T}\right]-1 -\frac{\Delta}{2\pi T}\mathrm{Im}\psi'\left[\frac{i\Delta}{2\pi T}\right], \quad (11)$$

where D is a cutoff, and $\psi(z)$ and $\psi'(z)$ are, respectively, the digamma and trigamma functions.

Thus, the equations from (1) to (11) allow us to determine the magnetic resistivity ρ in the ferromagnetic or paramagnetic region and with or without an applied magnetic field. We will now present the results in several different cases.

III. RESISTIVITY AND MAGNETORESISTIVITY OF CERIUM COMPOUNDS WHICH ORDER MAGNETICALLY AT LOW TEMPERATURES: CASE OF A GROUND-STATE DOUBLET

The first studied case corresponds to cerium compounds which order magnetically at low temperatures and have a ground-state doublet Γ_7 in the crystalline-field scheme. The typical example for this case is $CeAl_2$.

Figure 1 shows the theoretical plot of the relative magnetic resistivity for a set of parameters already used for $CeAl_2$: $J=-0.089$ eV, $n(E_F)=2.2$ states/eV atom, $2j+1=6$, and $\Delta=100$ K. In addition to these parameters, we choose T_N as equal to the experimental value of $T_N=3.85$ K for $CeAl_2$. The theoretical plot reproduces, in the paramagnetic domain, the previously described resistivity curve, i.e., low- and high-temperature $\ln T$ behaviors separated by a broad maximum around Δ. But at T_N there is a rapid drop of the resistivity, as expected in the domain of magnetic ordering. The theoretical plot agrees quite well with the experimental curve of $CeAl_2$, as shown in Fig. 1.

Figures 1 and 2 describe also the magnetic resistivity under applied field. When the magnetic field increases, the resistivity decreases, yielding thus a negative magnetoresistivity, and the resistivity curve becomes smoother. For the Δ value of 100 K used in Ref. 1 for $CeAl_2$, there is still a minimum for $H=50$ kG and there is a continuous increase of the resistivity for $H=100$ kG, as shown in Fig. 1.

We show in Fig. 2 only the low-temperature domain where the magnetoresistivity is different from zero. The parameters are the same as those used in Fig. 1, except that we take here $\Delta=65$ K. For that value of Δ, the resistivity minimum disappears at a field a little larger than 30 kG and for $H=100$ kG the resistivity curve is very smooth. The theoretical curves shown in Fig. 2 agree quite well with the low-temperature experimental curves of $CeAl_2$,[8] as shown in the inset.

Thus, we consider that the magnetic ordering extends the previous resistivity calculation[1] to low temperatures and both resistivity and magnetoresistivity are in very good agreement with experimental data on $CeAl_2$. A similar agreement can be easily found with the experimen-

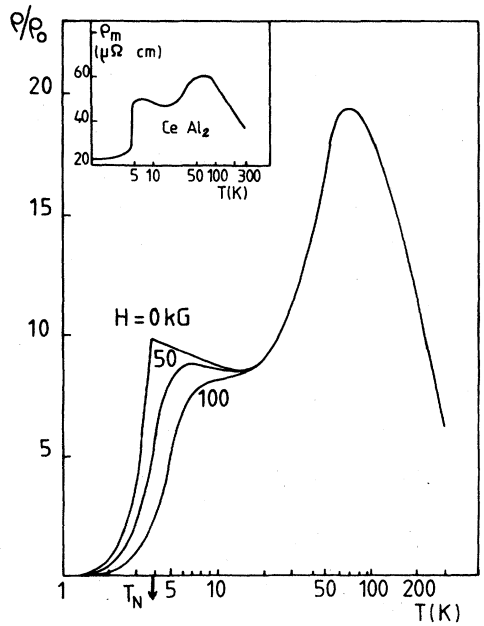

FIG. 1. Theoretical plot vs temperature (in logarithmic scale) of the relative magnetic resistivity with a Γ_7 ground state, $T_N=3.85$ K, $\Delta=100$ K, $n(E_F)=2.2$ states/eV atom, $J=-0.089$ eV, for $H=0$, 50, and 100 kG. The experimental magnetic resistivity of $CeAl_2$ is plotted in the inset.

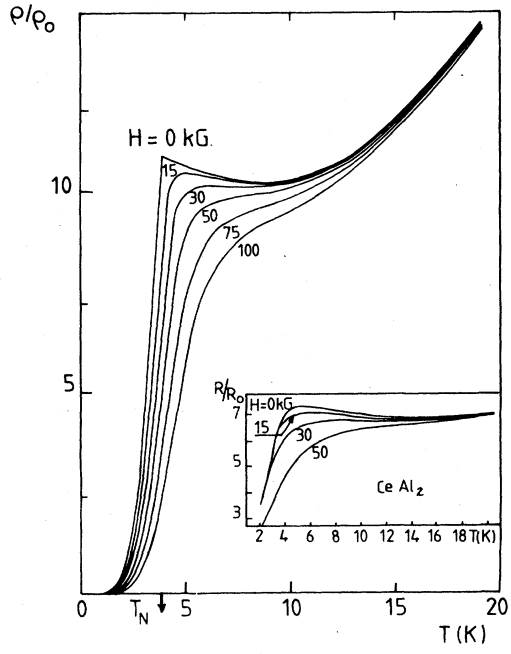

FIG. 2. Theoretical plot vs temperature of the relative magnetic resistivity with a Γ_7 ground state, $T_N=3.85$ K, $\Delta=65$ K, $n(E_F)=2.2$ states/eV atom, $J=-0.089$ eV, for $H=0$, 15, 30, 50, 75, and 100 kG. The experimental resistivity of $CeAl_2$, as deduced from Ref. 8, is plotted in the inset.

tal resistivity curve of CeS (Ref. 4) which orders at around 8 K and has a crystalline-field splitting a little larger than $CeAl_2$.

IV. RESISTIVITY AND MAGNETORESISTIVITY OF CERIUM COMPOUNDS WHICH ORDER MAGNETICALLY AT LOW TEMPERATURES: CASE OF A GROUND-STATE QUARTET

We study now the case of cerium compounds which order magnetically at low temperatures but have a ground-state quartet Γ_8 in the crystalline-field scheme. The case of a Γ_8 ground state, which has been less studied theoretically, also seems to be relatively rare from an experimental point of view. We think that CeB_6 has a Γ_8 ground state, but this is not unambiguously proved.[3,16]

We show in Figs. 3—5 three typical plots of the relative magnetic resistivity for a Γ_8 ground state. The curves have been computed for $J=-0.27$ eV, $n(E_F)=0.65$ states/eV atom, $T_N=2.8$ K, and three different Δ values: $\Delta=5$, 100, and 500 K (Figs. 3, 4, and 5, respectively). The most striking point of these curves is that the effect of the crystalline field is much less pronounced here than for a Γ_7 ground state; this difference results from the different ratios (equal to 3:35 for a Γ_7 ground state and to 15:35 for a Γ_8 one) of the low- and high-teperature resistivity $\ln T$ slopes. The difference between Figs. 1 and 4 both obtained with $\Delta=100$ K is particularly striking. As a consequence, the result is that the curves are not so different when Δ increases from 5 to 500 K for a Γ_8 ground state.

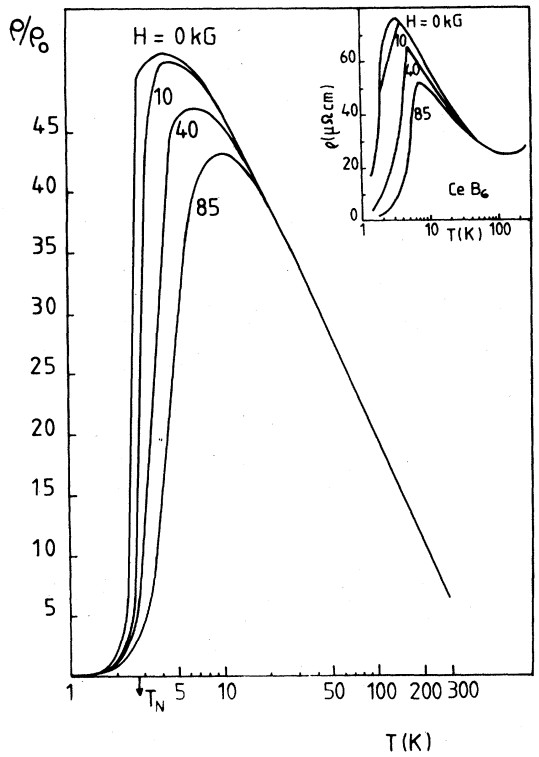

FIG. 3. Theoretical plot vs temperature (in logarithmic scale) of the relative magnetic resistivity with a Γ_8 ground state, $T_N=2.8$ K, $\Delta=5$ K, $n(E_F)=0.65$ states/eV atom, $J=-0.27$ eV, for $H=0$, 10, 40, and 85 kG. The experimental resistivity of CeB_6, as deduced from Ref. 7, is plotted in the inset.

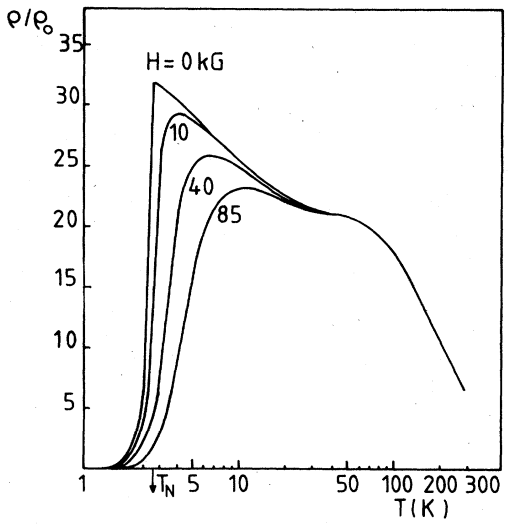

FIG. 4. Theoretical plot vs temperature (in logarithmic scale) of the relative magnetic resistivity with a Γ_8 ground state and with the same parameters as for Fig. 3, except $\Delta=100$ K.

The resistivity of CeB_6 is peculiar,[7] because it increases very rapidly up to approximately 3 K, with a change of slope at around 2 K; then the experimental resistivity, including both magnetic and phonon contributions, decreases rapidly with a $\ln T$ behavior up to roughly 100 K. Above that temperature, the total resistivity increases as due to phonons and the magnetic contribution is certainly still decreasing, as shown when the resistivity of LaB_6 is substrated from that of CeB_6. According to the analysis of magnetic and neutron diffraction measurements, it is thought that CeB_6 has a Γ_8 ground state with probably a large crystalline-field splittings.[3,16]

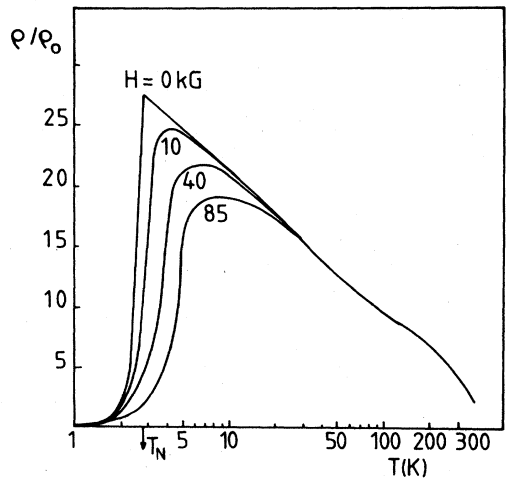

FIG. 5. Theoretical plot vs temperature (in logarithmic scale) of the relative magnetic resistivity with a Γ_8 ground state and with the same parameters as for Fig. 3, except $\Delta=500$ K.

When we compare the experimental resistivity curves[7] of CeB_6 shown in the inset of Fig. 3 to the different theoretical curves, we are more likely to think that the resistivity curves support much more the possibility of a Γ_8 ground state than of a Γ_7 one. Moreover, the experimental curves are very similar to those obtained in Fig. 3 for $\Delta=5$ K, but they are, in fact, also close to those shown in Fig. 5 for $\Delta=500$ K, since the effect of crystalline field is not very well marked for a Γ_8 ground state.

Thus, the resistivity curves of CeB_6 can be interpreted on the basis of the present model with a Γ_8 ground state, but we cannot really decide on a precise value for the crystalline-field splitting. Finally, we also note that the effect of the crystalline field is really small for a Γ_8 ground state and this fact, which was not clearly pointed out in the previous paper,[1] will be interesting for the interpretation of further experiments.

Note added in proof. It was recently established[20] by Raman and neutron spectroscopy that CeB_6 has a Γ_8 ground state with a crystalline field splitting of 530 K. Thus, the theoretical resistivity curves of CeB_6 correspond to those of Fig. 5, which agree quite well with the experimental curves shown in the inset of Fig. 3.

V. RESISTIVITY OF CERIUM COMPOUNDS WHICH BECOME NONMAGNETIC AT LOW TEMPERATURES

The last studied case corresponds to cerium compounds which become nonmagnetic at low temperatures, as, for example, $CeAl_3$ (Ref. 9) or $CeCu_2Si_2$ (Ref. 10). This situation happens when the Kondo effect on each cerium atom is more important than the magnetic interaction between different cerium atoms, as discussed in the Introduction. The calculation of the resistivity for cerium Kondo compounds is certainly very difficult to perform, especially if one tries to include a full description of the "dense Kondo" problem at all temperatures. In particular, Yoshimori and Kasai[17] have computed the temperature dependence of the resistivity by computing the Green's function for a periodic Anderson model but with neglecting intersite contributions to the self-energy. They have found a resistivity going through a maximum at a temperature of the order of the Kondo temperature T_k (Ref. 17) and behaving as T^2 at very low temperatures below T_k, according to the well-known results of the Kondo effect.[18] However, this theoretical maximum of the resistivity cannot account for the resistivity of $CeAl_3$ where the observed maximum is certainly due to crystal-field effects; on the contrary, the lowest temperature maximum observed in the resistivity of $CeCu_2Si_2$ can be accounted for by the model of Yoshimori and Kasai.[17]

Thus, we would like to describe the influence of the Kondo effect on the low-temperature resistivity by a *phenomenological* model, where the many-body Kondo effect is simply viewed as a splitting of levels. More precisely, the low-temperature effects are described here by an effective field within a single impurity model and, indeed, we cannot treat the coherent scattering effects which occur at low temperatures. However, the advantage of our approach is to well describe the different experimental situations, as we will see later on. This type of semiphenomenological approach had already been used by Newns and Hewson[19] to describe the specific heat and the magnetic susceptibility of intermediate valence systems within an independent resonant model.

We discuss here the case of a Γ_7 ground state and a Γ_8 excited state. The central assumption of our model is to choose a splitting δ_0 of the two Γ_7 states, which depends on the ratio T/T_k, T_k being the characteristic or phenomenological Kondo temperature; the four Γ_8 states are also chosen to remain all together at a distance Δ from the ground state.

There is no theoretically derived form of δ_0 and we have plotted the curves of Fig. 6 with the following chosen phenomenological form:

$$\delta_0 = D\left[\frac{\pi}{2} - \arctan\left[\frac{T}{T_k}\right]\right] \tag{12}$$

for several values of T_k from 0.01 to 10 K and with $D=5$ K and $\Delta=100$ K.

The precise analytical form (12) for δ_0 is not very important, since we have obtained similar physical results with other forms, such as, in particular, a form in $\arctan\ln(T/T_k)$ instead of $\arctan(T/T_k)$. This point can be considered as a justification *a posteriori,* since there is no direct theoretical justification of the form (12).

The high-temperature behavior is identical to that obtained for $\delta_0=0$ and there is a marked difference for temperatures below the maximum temperature corresponding roughly to Δ. For a large T_k value, the resistivity is continuously decreasing with decreasing temperature. On the contrary, for a small T_k value, there is a minimum of the resistivity corresponding roughly to $\Delta/5$. Then, the resis-

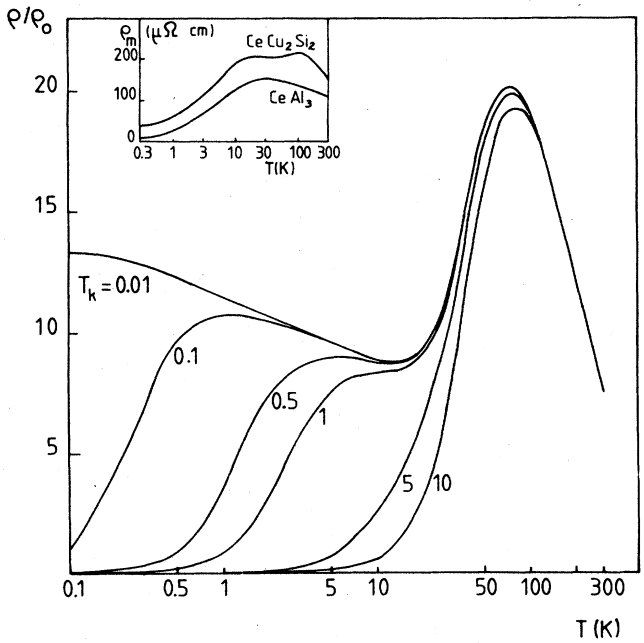

FIG. 6. Theoretical plot vs temperature (in logarithmic scale) of the relative magnetic resistivity with a Γ_7 ground state, $\Delta=100$ K, $n(E_F)=2.2$ states/eV atom, $J=-0.089$ eV, and δ_0 given by (12) with $D=5$ K and T_k varying from 0.01 to 10 K. The experimental resistivity of $CeAl_3$ and $CeCu_2Si_2$, as deduced, respectively, from Refs. 13 and 12, is plotted in the inset.

tivity increases firstly as $\ln T$, and goes through a maximum at a temperature of order $10T_k$, before decreasing rapidly with decreasing temperature. In the temperature scale shown in Fig. 6, we see several different behaviors for the magnetic resistivity: Either a continuous and rapid decrease, or a continuous decrease with a marked bump, or a clear maximum following the minimum, or finally a resistivity increase essentially as $\ln T$. Thus, such a phenomenological model is able to give the resistivity of cerium compounds which tends to zero at very low temperatures, in contrast to the situation of dilute Kondo alloys where the magnetic resistivity reaches a finite value at very low temperatures.

Thus, we apply the present model of a cubic crystalline-field effect to cerium compounds, even if they are not cubic, as, for example, $CeAl_3$, since there is no indication for the position of the different excited levels in noncubic cerium compounds. The theoretical curves shown in Fig. 6 can, therefore, explain the different experimental behaviors found in cerium compounds which become nonmagnetic at low temperatures. For example, the theoretical curve corresponding to $T_k = 5$ K can account for the experimental resistivity of $CeAl_3$.[13] On the contrary, a theoretical curve with a smaller T_k value, let us say $T_k = 0.5$ K, can yield a fairly good explanation of the experimental resistivity of $CeCu_2Si_2$,[12] which has two maxima, one clearly due to the crystalline-field effect and the other one probably connected to the Kondo effect. Our model, although qualitative, can give an explanation of the low-temperature maximum found in the resistivity of $CeCu_2Si_2$, which was unexplained until now.

The magnetoresistivity of such cerium compounds is negative, as expected for Kondo systems; however, at very low temperatures, when the resistivity is decreasing rapidly with decreasing temperature, such cerium compounds become nonmagnetic and their magnetoresistivity no longer corresponds to that of Kondo systems. Thus, this point can give a qualitative interpretation of the change from negative to positive which occurs at 0.5 K in the magnetoresistivity of $CeAl_3$.[13] It would be nice to perform similar measurements in $CeCu_2Si_2$, in order to see if there is also a change of magnetoresistivity sign at even lower temperatures. Finally, we can also note that our phenomenological model provides a very rough estimation of the Kondo temperature, which is of order 5 K in $CeAl_3$ and smaller in $CeCu_2Si_2$. The last case is even more complicated, since $CeCu_2Si_2$ becomes superconducting at very low temperatures.[11]

VI. CONCLUSION

Thus, the theoretical results presented here extend to very low temperatures the previously derived calculation of the resistivity given in Ref. 1. We have discussed the two cases found in cerium compounds, either the case of a magnetic ordering or that of nonmagnetic Kondo-type state observed at very low temperatures. We have also computed the magnetoresistivity and found good agreement with experimental data. Indeed, it would be interesting to perform resistivity measurements at very high fields in such cerium compounds.

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