

Competition between the Kondo effect and exchange interactions in the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds

D. Gignoux

Laboratoire Louis Néel, Centre National de la Recherche Scientifique, 166X, 38042 Grenoble Cédex, France

J. C. Gomez-Sal

Departamento de Optica y Estructura de la Materia, Facultad de Ciencias, Santander, Spain

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Magnetic and resistivity measurements performed on the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds show that this system is one of the best examples of a ferromagnetic dense Kondo system in which Ruderman-Kittel-Kasuya-Yosida exchange interactions compete with the Kondo effect. The variations of the Curie temperature T_C and of the Kondo temperature T_K as a function of the Ni content are in qualitative agreement with those calculated as a function of the product $|\Gamma n(E_F)|$ in the Kondo lattice model, where $\Gamma (< 0)$ is the coupling constant between the $4f$ shell and the conduction band. The increase of $|\Gamma n(E_F)|$ as a function of the Ni content is suggested to be mainly due to the decrease of the separation between the f level and the Fermi level.

I. INTRODUCTION

CePt as well as CeNi crystallizes in the same CrB-type orthorhombic structure¹ (space group $Cmcm$). In CePt the Fermi level is sufficiently high above the $4f$ level so that Ce is magnetic. This compound orders ferromagnetically² at 5.8 K, and magnetization, resistivity, and heat-capacity measurements seem to indicate a Kondo effect in this compound.³ In contrast, for CeNi the Fermi level is very close to the $4f$ level. Lattice-parameter analyses and thermal-expansion studies have shown that CeNi is an intermediate-valence compound in which the Ce valence state varies with temperature.⁴ This compound behaves as an enhanced Pauli paramagnet in which the magnetic susceptibility along the \vec{c} axis passes through a maximum at around 140 K. The spin-density map deduced from polarized neutron scattering⁵ has shown that the induced magnetization originates from Ce $4f$ electrons alone; the Ni $3d$ band being filled up. The magnetic susceptibility, as well as resistivity and heat-capacity measurements, is characteristic of an almost magnetic Fermi liquid in which spin fluctuations are present.⁴ However, unlike the

other cerium intermediate-valence compounds which are generally cubic, large anisotropic effects due to the local surroundings are observed in CeNi because of its orthorhombic symmetry. Thus in the intermetallic alloys $\text{CeNi}_x\text{Pt}_{1-x}$ we can expect to observe the sequence: magnetic ordering \rightarrow trivalent spin-fluctuation behavior (Kondo effect) \rightarrow intermediate-valence state.

In this paper we present bulk magnetic properties and resistivity measurements performed on polycrystalline samples of $\text{CeNi}_x\text{Pt}_{1-x}$ alloys. In order to determine the magnetic contribution to the resistivity of these compounds, we have also performed resistivity measurements on the isomorphous $\text{LaNi}_x\text{Pt}_{1-x}$ alloys.

II. EXPERIMENTAL

The samples were prepared by melting together the starting materials under argon atmosphere in a cold crucible induction furnace. The starting materials were 99.9% pure cerium and 99.99% pure nickel and platinum. Magnetic measurements were performed at the Service des Mesures d'Aimantation du Laboratoire Louis Néel between 1.5 and 300 K and in fields up to 77 kOe produced by a superconducting coil. The resistivities were measured between 1.5 and 300 K by an alternating-current four-probe method.

III. LATTICE-PARAMETER ANALYSIS

All the x-ray patterns performed on the $\text{CeNi}_x\text{Pt}_{1-x}$ and $\text{LaNi}_x\text{Pt}_{1-x}$ compounds are characteristic of the

TABLE I. Comparison between the lattice parameters of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds.

x	a (Å)	b (Å)	c (Å)	V (Å ³)
0	3.918	10.908	4.527	193.47
0.1	3.905	10.889	4.522	192.30
0.2	3.890	10.877	4.515	191.04
0.3	3.885	10.869	4.508	190.35
0.4	3.881	10.865	4.491	189.37
0.5	3.860	10.860	4.487	188.09
0.6	3.851	10.855	4.465	186.63
0.7	3.840	10.835	4.445	184.94
0.8	3.830	10.790	4.430	183.07
0.85	3.825	10.697	4.417	180.73
0.9	3.789	10.668	4.404	178.00
1	3.754	10.575	4.376	173.68

TABLE II. Comparison between the lattice parameters of the $\text{LaNi}_x\text{Pt}_{1-x}$ compounds.

x	a (Å)	b (Å)	c (Å)	V (Å ³)
0	4.000	11.020	4.538	199.97
0.2	3.980	11.015	4.528	198.52
0.5	3.941	10.993	4.492	194.62
0.7	3.917	10.926	4.473	191.43
1	3.895	10.836	4.399	185.66

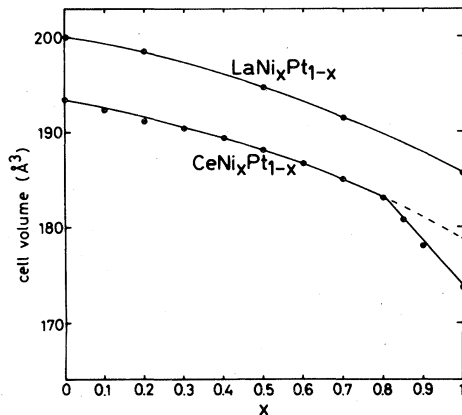


FIG. 1. Cell volume of the $\text{LaNi}_x\text{Pt}_{1-x}$ and $\text{CeNi}_x\text{Pt}_{1-x}$ compounds as function of the Ni concentration x .

CrB-type structure. The lattice parameters of the orthorhombic cell were determined by the Debye-Scherrer technique with Cr $K\alpha$ radiation. These parameters are reported in Tables I and II and the cell volume is plotted in Fig. 1 as a function of the Ni content x . For $x \leq 0.8$ the variations of the cell parameters of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds as a function of the Ni content x follow the same regular variation as observed for the $\text{LaNi}_x\text{Pt}_{1-x}$ compounds. For $x > 0.8$, the a and b parameters, as well as the volume, decrease faster. This may be an indication of an intermediate-valence state of cerium in these compounds.

IV. MAGNETIC MEASUREMENTS

The field dependence of the magnetization measured at 1.5 K on the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds for $0 \leq x \leq 0.9$ are shown in Fig. 2. All the compounds are ferromagnetically ordered at this temperature. The Curie temperatures were determined from the thermal dependence of the initial susceptibility and from the Arrott plot (M^2 versus

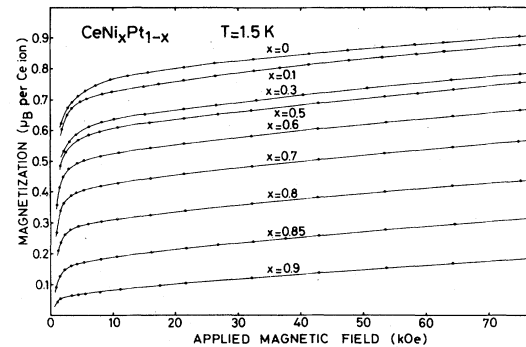


FIG. 2. Magnetization as a function of the applied magnetic field at 1.5 K for the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds.

H/M) near the Curie temperature. These Curie temperatures T_C are reported in Table III and plotted as a function of x in Fig. 8. When Pt is replaced by Ni, the Curie temperature (which is 5.8 K in CePt) first increases, passes through a maximum at 8.6 K for $x=0.5$, and then decreases for larger values of x . In $\text{CeNi}_{0.9}\text{Pt}_{0.1}$ the Curie temperature is 4.0 K. In addition, at 1.5 K in a given field the magnetization decreases regularly when x increases (Fig. 2). The estimated spontaneous magnetization and the magnetization in a 77 kOe applied field are reported in Table III.

Above 50 K, the susceptibility of all the samples follows a Curie-Weiss behavior. As an example, the thermal dependence of the reciprocal susceptibility of the compounds with $x=0, 0.5, 0.7, 0.85$, and 0.9 are drawn in Fig. 3. The Curie constants deduced from the slopes of the linear variation of the reciprocal susceptibility lead to effective moments very close to that of the free Ce^{3+} ion, which is $2.54\mu_B$. While all the compounds order ferromagnetically at low temperature, the paramagnetic Curie temperatures are negative. These Curie temperature values are reported on Table III. Moreover, the absolute values of these Curie temperature Θ_p increase strongly

TABLE III. Characteristic values of the magnetic properties of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds: Curie temperature T_C , paramagnetic Curie temperature Θ_p , magnetization M_0 extrapolated in zero internal field at 1.5 K, and magnetization M in a 77 kOe applied field at 1.5 K.

x	T_C (K)	Θ_p (K)	M_0 at 1.5 K (μ_B per Ce ion)	M in 77 kOe at 1.5 K (μ_B per Ce ion)
0	5.8	-20	0.715	0.908
0.1	7.0	-22	0.675	0.880
0.3	8.0	-24	0.580	0.785
0.5	8.6	-25	0.550	0.758
0.6	8.5	-25	0.470	0.670
0.7	8.5	-30	0.390	0.568
0.8	8.2	-49	0.275	0.439
0.85	6.2	-64	0.145	0.315
0.9	4.0	-98	0.047	0.185
0.95		-122	0	Pauli paramagnet
1		-198	0	Pauli paramagnet

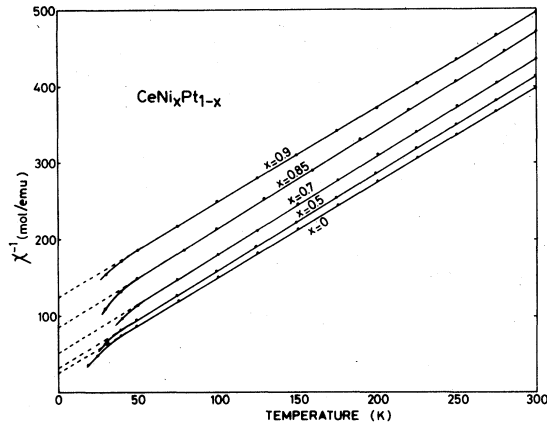


FIG. 3. Thermal dependence of the reciprocal susceptibility of some $\text{CeNi}_x\text{Pt}_{1-x}$ compounds with $x=0, 0.5, 0.7, 0.85,$ and 0.9 .

with the Ni content; in $\text{CeNi}_{0.9}\text{Pt}_{0.1}$, Θ_p reaches -98 K.

The $\text{CeNi}_{0.95}\text{Pt}_{0.05}$ compound behaves as an enhanced Pauli paramagnetic. As for many valence-fluctuation materials, the magnetic susceptibility exhibits a broad maximum (around 75 K) and shows a Curie-Weiss-like behavior at higher temperatures (above ~ 200 K). The deduced paramagnetic Curie temperature is -122 K. At 1.5 K the susceptibility reaches 3.95×10^{-3} emu/mol.

V. RESISTIVITY MEASUREMENTS

Resistivity measurements were performed on eight samples of $\text{LaNi}_x\text{Pt}_{1-x}$ and $\text{CeNi}_x\text{Pt}_{1-x}$ with $x=0, 0.1, 0.5,$ and 0.7 . Figures 4 and 5 show the total resistivity ρ_t versus T for these samples. The data on the La-based compounds were taken in order to estimate the phonon contribution to the resistivities of the Ce-based samples. For all the Ce compounds a discontinuity of slope of ρ_t versus T is observed at T_C . The magnetic resistivities ρ_m (Fig. 6) of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds were obtained by subtracting the phonon contribution ρ_p deduced from the resistivities of the $\text{LaNi}_x\text{Pt}_{1-x}$ compounds and the estimated residual resistivity ρ_r . Because of the small values of the ordering temperatures there is an uncertainty on ρ_r , and hence the zero of ρ_m is not well defined. For $x=0, 0.1,$ and 0.5 , ρ_m exhibits a plateau just above the

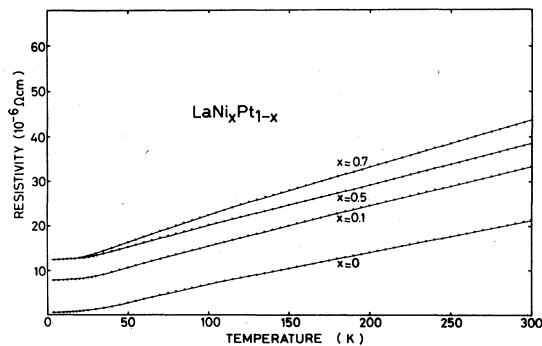


FIG. 4. Thermal dependence of the resistivity ρ_t of the $\text{LaNi}_x\text{Pt}_{1-x}$ compounds with $x=0, 0.1, 0.5,$ and 0.7 .

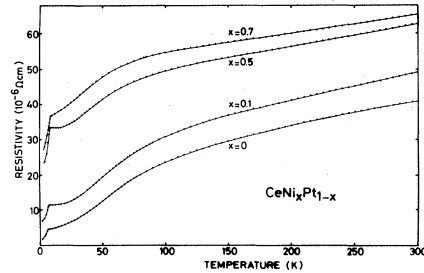


FIG. 5. Thermal dependence of the resistivity ρ_t of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds with $x=0, 0.1, 0.5,$ and 0.7 .

Curie temperature. Especially in $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ where a decrease of ρ_m is observed when temperature increases from 9 to 15 K. For all the Ce-based compounds at higher temperatures, ρ_m increases and passes through a broad maximum and then decreases. The temperature of this maximum decreases when the Ni amount increases.

VI. ANALYSIS AND DISCUSSION

The main characteristics of the properties observed in the ferromagnetic $\text{CeNi}_x\text{Pt}_{1-x}$ compounds are the following: (i) near room temperature the magnetic contribution to the resistivity decreases as the temperature is increased; (ii) the value of the spontaneous magnetization at low temperatures is small and decreases as the Ni content increases; (iii) paramagnetic Curie temperatures are negative and decrease when the Ni amount increases. Since the Ni and Pt contributions to the magnetism are negligible, these properties indicate the existence of a Kondo effect which is due to the cerium. This effect arises from an antiferromagnetic coupling between the spin of the conduction electrons and that of the 4f electrons, which leads to the formation of a nonmagnetic singlet ground state at low temperatures. Competing with this effect is the positive exchange interactions between Ce ions. For the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds with $0 \leq x \leq 0.9$, the ferromagnetic exchange dominates, leading to a magnetically ordered ground state. In order to justify this interpretation of a ferromagnetic dense Kondo system, we will compare, in detail, the experimental data with the expectations based on this model.

The estimated values of the magnetization M_0 extrapo-

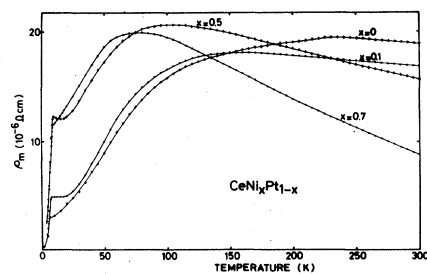


FIG. 6. Thermal dependence of the magnetic resistivity ρ_m of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds with $x=0, 0.1, 0.5,$ and 0.7 .

lated in zero internal field at 1.5 K for the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds are reported in Table III. Although they are not determined with good accuracy ($\Delta M_0/M_0 \approx 0.03$), these values per Ce ion are much smaller than the free Ce^{3+} -ion value ($g_J\mu_B J = 2.14\mu_B$) and decrease regularly as the Ni content increases. This reduction results partly from the fact that the measurements were performed on polycrystalline samples with a strong uniaxial magneto-crystalline anisotropy due to crystalline electric field (CEF) effects. Assuming a collinear magnetic structure in which the Ce magnetic moments are, as in PrPt (Ref. 6) and PrNi (Ref. 7), parallel to one of the three main symmetry axes \vec{a} , \vec{b} , or \vec{c} , the measured value of M_0 is one-half the value of the Ce magnetic moment in the case of a random distribution of the crystallites. In fact, the Ce moment deduced in this way is not very accurate because small texture effects are observed when measuring the same polycrystalline sample under different orientations. Keeping in mind these restrictions, we estimate that the value of the magnetic moment in the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds is about twice the values of the magnetization M_0 extrapolated in zero internal field.

In all the compounds there is still a strong difference between the Ce moment deduced from M_0 and the free Ce^{3+} ion value. Moreover, this difference increases strongly when x increases from 0 to 0.9. For example, the Ce moment is near $1.43\mu_B$, $1.10\mu_B$, and $0.09\mu_B$ in the compounds with $x=0$, 0.5, and 0.9, respectively. This reduction could be due to CEF effects and/or to a Kondo effect. These CEF effects are very difficult to determine quantitatively because in such compounds with very low symmetry the CEF Hamiltonian depends on five parameters. The only way to discuss more quantitatively the CEF effects in compounds with very low symmetry is to use the point-charge model to make estimates. With a $3+$ charge on cerium and no charges on platinum and nickel, the CEF in $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ splits the $J = \frac{5}{2}$ multiplet into three doublets, the eigenvalues and eigenstates of which are reported in Table IV. The corresponding overall splitting is $\Delta = 183$ K. The easy magnetization axis would be \vec{a} and the magnetic moment in the estimated molecular field (325 kOe) would be $1.98\mu_B$ per Ce ion, a value which is smaller than the free Ce^{3+} ion one, but much larger than the observed one ($\approx 1.10\mu_B$). The calculation performed for the other compounds shows that these values are not very different from one compounds to the other. Although quite unrealistic, this model suggest that CEF effects, especially the moment reduction, might be quite similar in CePt and $\text{CeNi}_{0.9}\text{Pt}_{0.1}$; the moment reduction by CEF is perhaps somewhat smaller in the

latter compound since the molecular field is much higher than that in CePt. Thus we believe it is very unlikely that all the reduction of the Ce moment, and especially its large increase as the Ni content increases, can be attributed to crystal-field effects. The analysis of the magnetization of the different compounds favors a Kondo effect.

The existence of paramagnetic Curie temperatures Θ_p , which are strongly negative, and the absolute values which increase with Ni content are also experimental evidence of a Kondo effect in these compounds. Indeed, in a ferromagnetic material without CEF effects Θ_p is very close to T_C , while with CEF effects present Θ_p can deviate from T_C to some degree. For example, in orthorhombic compounds second-order terms in the CEF Hamiltonian lead to paramagnetic Curie temperatures which are different when the susceptibility is measured along the \vec{a} , \vec{b} , or \vec{c} directions of a single crystal.⁸ However, we can show that with a polycrystalline sample these effects compensate one another and Θ_p must be very close to T_C . Finally, fourth-order terms can also lead to slight deviations between Θ_p and T_C . But these deviations are expected to be smaller than those observed in the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds and they should not increase with the Ni content because, as we will see below, the maximum of ρ_m seems to indicate a slight decrease of the CEF splitting as the Ni content increases. We can then attribute the main difference between Θ_p and T_C to the Kondo effect. In the absence of theoretical calculations for the high-temperature susceptibility of a dense Kondo system, we use the relation obtained for a single-impurity problem:⁹ $\chi(T) = C/(T + 2T_K)$. Then, neglecting exchange interactions and CEF effects, it is possible to estimate the Kondo temperatures T_K . These values are plotted as a function of x in Fig. 8. Although it is not possible to define a Kondo temperature T_K for the Pauli paramagnets $\text{CeNi}_{0.95}\text{Pt}_{0.05}$ and CeNi, which behave as intermediate-valence compounds, we have reported the value of $\Theta_p/2$ (equal to T_K in the other compounds). Such a temperature corresponds to what is called a spin-fluctuation temperature T_{SF} in this type of compound ($T_{\text{SF}} \approx \Theta_p$).¹⁰ These values of $\Theta_p/2$ extend the variation of T_K of the ferromagnetic compounds. The values of T_K , as well as the values of the spontaneous magnetization at 1.5 K, show that the Kondo effect increases with the Ni content.

The strong increase of the magnetic resistivity of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds above their Curie temperature results from crystal-field effects. On the other hand, the occurrence of the maximum at high temperature and, especially, the decrease of ρ_m at higher temperature originate from the Kondo effect on cerium. As shown in Fig. 7,

TABLE IV. $\text{CeNi}_{0.5}\text{Pt}_{0.5}$: splitting of the $J = \frac{5}{2}$ multiplet into three doublets by the CEF calculated in the point-charge model. For the calculation we have assumed a $3+$ charge on cerium and no charge on platinum and nickel.

energies (K)		Eigenstates	
102	$-0.120 \pm \frac{5}{2} \rangle$	$-0.793 \pm \frac{1}{2} \rangle$	$+ 0.597 \mp \frac{3}{2} \rangle$
-20	$0.966 \pm \frac{5}{2} \rangle$	$-0.231 \pm \frac{1}{2} \rangle$	$-0.115 \mp \frac{3}{2} \rangle$
-81	$0.228 \pm \frac{5}{2} \rangle$	$+ 0.563 \pm \frac{1}{2} \rangle$	$+ 0.794 \mp \frac{3}{2} \rangle$

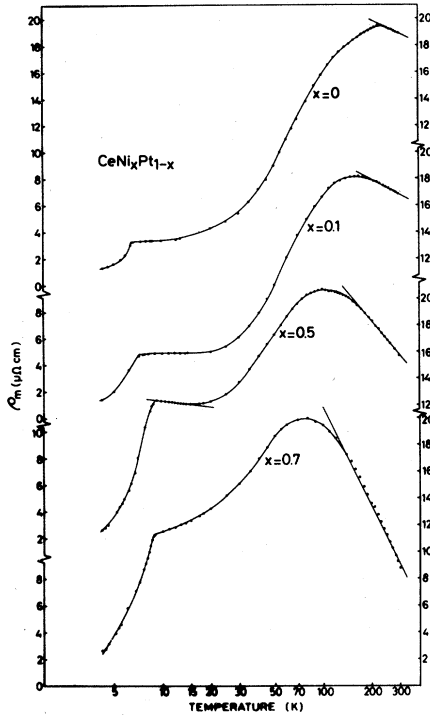


FIG. 7. Magnetic resistivity ρ_m versus $\ln(T)$ for the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds with $x=0, 0.1, 0.5,$ and 0.7 .

the $\ln T$ dependence of these decreases of ρ_m is consistent with the calculations of Cornut and Coqblin¹¹ for cerium-diluted alloys in the presence of crystal fields. The decrease of ρ_m (also in $\ln T$) observed just above the Curie temperature in $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ has the same origin. This behavior is very similar to that observed in CeAl_2 ,¹² which is one of the best examples of a Kondo system. When $T \ll \Delta$ or $T \gg \Delta$, where Δ is the overall crystal-field splitting, the expression of the magnetic resistivity ρ_m is

$$\rho_m = A\Gamma^2 \frac{\lambda_n^2 - 1}{\lambda_n(2J + 1)} + 2A\Gamma^3 n(E_F) \frac{\lambda_n^2 - 1}{2J + 1} \ln \left[\frac{kT}{D_n} \right],$$

where Γ (<0) is the coupling constant between the $4f$ shell and the conduction band, $n(E_F)$ is the density of states at the Fermi level, λ_n is the number of occupied states (two for a doublet ground state at low temperatures and six for the high-temperature range), and D_n is an effective energy cutoff. In the intermediate region where $T \approx \Delta$, the spin disorder, which is the temperature-independent term in the above expression of ρ_m , increases with temperature because of the increase of λ_n . This leads to a variation of the magnetic resistivity ρ_m similar to that observed in $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ above T_C .

In $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ the ratio of the logarithmic slope is $\delta_{\text{HT}}/\delta_{\text{LT}} = 11.6 \pm 1.0$, where δ_{HT} and δ_{LT} are, respectively, the high- and low-temperature slopes. The value of this ratio is very close to

$$\frac{(2J + 1)^2 - 1}{\lambda_0^2 - 1} = 11.7,$$

where $\lambda_0 = 2$ corresponds to the degeneracy of the ground state. Then the decrease of ρ_m just above T_C originates from the Kondo effect on the ground-state doublet, which is well below the other excited states, whereas the decrease at high temperatures is due to the Kondo effect on the whole multiplet. This is in agreement with the point-charge model which predicts a ground-state doublet well below the first excited state.

According to Cornut and Coqblin,¹¹ the high-temperature maximum of ρ_m takes place at a temperature slightly smaller than the overall CEF splitting Δ . In $\text{CeNi}_{0.5}\text{Pt}_{0.5}$ the calculated value of Δ (182 K) is in rather good agreement with the temperature of the maximum of ρ_m (≈ 100 K). These values are close to those determined in CeMg_3 where Δ was deduced from inelastic neutron scattering measurements.¹³ When the Ni content x increases from 0 to 0.7 the maximum of ρ_m decreases approximately from 230 to 80 K. This could arise from a decrease of Δ but more probably from the increase of the Kondo effect when the Ni content increases.

From the slope of the resistivity ρ_m versus $\ln(T)$ at high temperature, we have determined the values of $A\Gamma^3 n(E_F)$ for the different compounds. Assuming that ρ_m at T_C is around $A\Gamma^2/4$ (as expected for a doublet), we have deduced the values of $|\Gamma n(E_F)|$ which are approximately 0.012, 0.012, 0.014, and 0.022 for $x=0, 0.1, 0.5,$ and 0.7 , respectively. Note that $|\Gamma n(E_F)|$ increases with the Ni content.

The decrease of ρ_m just above T_C is observed only in $\text{CeNi}_{0.5}\text{Pt}_{0.5}$. In the other compounds this is not the case either because the Kondo effect is not sufficiently strong (CePt) or because the ground-state doublet is not sufficiently far below the other excited states.

Magnetic and resistivity measurements show that the $\text{CeNi}_x\text{Pt}_{1-x}$ system ($x \leq 0.9$) is thus one of the best examples of a ferromagnetic dense Kondo system. The first example of such behavior was the Ce-Si system and especially the $\text{CeSi}_{1.8}$ and $\text{CeSi}_{1.7}$ compounds which were discovered recently.¹⁴

As described above, the variations of T_C and T_K as a function of the Ni content x are shown in Fig. 8. While T_C increases first, passes through a maximum, and then decreases rapidly for $x > 0.7$, T_K always increases with x , first weakly and then more and more rapidly. These variations provide evidence of the competition between the Ruderman-Kittel-Kasuya-Yosida-type (RKKY) exchange interactions which favor magnetic ordering, and the Kondo-type interactions which act in the opposite direction because they favor a (nonmagnetic) singlet ground state. In the model of the Kondo lattice worked out by several authors,¹⁵⁻¹⁸ both interactions increase when the product $|\Gamma n(E_F)|$ increases. However, when this product becomes higher than a critical value, the Kondo effect becomes dominant and the system is not magnetic. The variations of T_C and T_K as a function of $|\Gamma n(E_F)|$ then predicted in the model are shown in Fig. 9. These last variations are very similar to those observed in the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds when the Ni content increases. With this system we then have one of the best experimental evidences of the competition between magnetic ordering and the Kondo effect as a function of $|\Gamma n(E_F)|$.

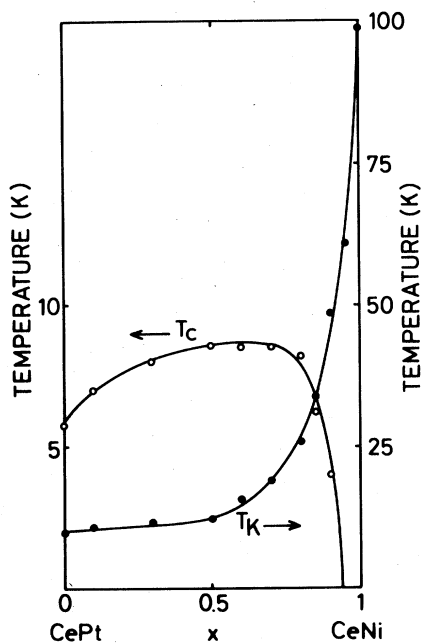


FIG. 8. Curie temperature T_C and Kondo temperature T_K of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds as a function of the Ni content x . For the $\text{CeNi}_{0.95}\text{Pt}_{0.05}$ and CeNi compounds, which are Pauli paramagnetic and intermediate-valence compounds, it is not possible to define a Kondo temperature. However, we have reported the values of $\Theta_p/2$ which well extend the variation of T_K of the ferromagnetic compounds.

The observed properties of the $\text{CeNi}_x\text{Pt}_{1-x}$ compounds show that the product $|\Gamma n(E_F)|$ increases with the Ni content. This can be understood as due to the evolution of the electronic structure by assuming that

$$\Gamma = \frac{2|V|^2}{E_0 - E_F},$$

where V is the intra-atomic Coulomb correlation between f and conduction electrons, E_0 is the $4f$ level, and E_F is the Fermi level. The main contribution to the increase of $|\Gamma n(E_F)|$ as a function of the Ni content must arise from the decrease of $|E_0 - E_F|$. Indeed, whereas in Pt metal the Fermi level lies above the Fermi level of Ce metal, in Ni metal it lies below. In CePt there is an electron transfer from the Pt $5d$ band towards the Ce $5d$ band. The Fermi level (E_F) is sufficiently high above the $4f$ level (E_0) so that $|\Gamma n(E_F)|$ is small and the exchange interactions overcome the Kondo effect which remains weak. In CeNi , on the contrary, there is an electron transfer from the Ce $5d$ band towards the Ni $3d$ band,

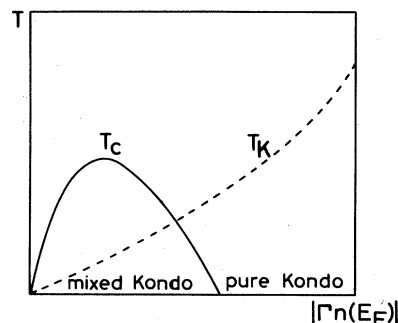


FIG. 9. Schematic variations of the ordering temperature and of the Kondo temperature as a function of the product $|\Gamma n(E_F)|$ after Lavagna (Ref. 18).

and the Fermi level E_F is sufficiently close to the $4f$ level E_0 so that Ce is in an intermediate-valence state. By substituting progressively Pt by Ni in CePt , the Fermi level draws nearer the $4f$ level, leading to an increase of the product $|\Gamma n(E_F)|$. The increase of the product could also be due to an increase of $n(E_F)$ and $|V|$. Such an assumption is supported by the fact that the width of the $3d$ band is much smaller than that of the $5d$.

From the cell parameter analysis of the $\text{CeNi}_{0.85}\text{Pt}_{0.15}$ and $\text{CeNi}_{0.9}\text{Pt}_{0.1}$ compounds, it seems that in these compounds there is a coexistence of magnetism and intermediate valence. The possibility of ferromagnetism in intermediate-valence systems was recently investigated in the $s-f$ model by Matlak and Nolting.¹⁹ They find as the main condition for ferromagnetism that the average $4f$ occupation number n_f should exceed a critical value $n_f^{(c)}$. In our compounds, where n_f is almost equal to one, such a condition must be satisfied.

In conclusion, we have found the following: (i) that the $\text{CeNi}_x\text{Pt}_{1-x}$ system with $x \leq 0.9$ is one of the best examples of a dense ferromagnetic Kondo system in which RKKY exchange interactions compete with the Kondo effect; (ii) thanks to a large variation of the product $|\Gamma n(E_F)|$ as a function of the Ni content we have experimental evidence for the variations of T_C and T_K as a function of $|\Gamma n(E_F)|$, which is responsible simultaneously for the exchange interactions and the Kondo effect. These experimental variations agree with those obtained in the model of the Kondo lattice.

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