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Antiferromagnetic Kondo lattice behaviour of $YbNiAl_2$ alloy

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ABSTRACT

We report measurements on the thermal and electronic transport properties for the $YbNiAl_2$ compound. At low temperatures, the electrical resistivity exhibits a logarithmic increase below a local minimum at 23 K, followed by a sharp decrease into the coherent/magnetically ordered state below 4.8 K. From the magnetic contribution to the specific heat (c_{mag}), a Kondo temperature $T_K = 5$ K and an entropy value of 0.8Rln2 at the transition are estimated. The extrapolation of c_{mag}/T vs T plot to lower temperatures gives an estimate of the electronic coefficient $\gamma_0 = 300$ mJ/mol K^2, which classifies this compound as a moderate heavy-fermion system. The magnetoresistance shows a single impurity Kondo scaling, with a single-ion characteristic temperature $T^* = -1.2$ K. This negative sign implies the presence of strong ferromagnetic correlations, as suggested from the previously reported magnetization data. The results indicate that the $YbNiAl_2$ alloy is an antiferromagnetic Kondo lattice system with a similar energy scales of the Kondo and RKKY interactions.

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1. Introduction

Ce, Yb and U compounds display a variety of ground states as intermediate valence, heavy-fermion behaviour and Kondo effect [1–3]. Among them, a special attention have been paid to the study of magnetically ordered Kondo lattices, which is a current topic of great interest because the observed phenomenology near to the quantum critical point [4]. The nature of the ground state in Kondo lattice materials depends on the competition between the Kondo effect and the Ruderman–Kittel–Kasuya–Yosida (RKKY) interactions [5,6]. When RKKY interaction dominates, the system orders magnetically, for comparable strength of these two interactions, the system shows Kondo-type behaviour but still orders magnetically. In this intermediate situation an enhanced density of electronic states at the Fermi energy is possible and a magnetically heavy-fermion state could be observed. Finally, when the Kondo-type interaction dominates, the ground state is nonmagnetic. It is worth noticing that most of the studies on Kondo lattice systems have been devoted to Ce and U compounds, whereas only few examples in Yb compounds has been reported. In this sense, YbNiAl was characterized as a heavy-fermion ($\gamma = 350$ mJ/mol K^2) with antiferromagnetic order at $T_N = 2.9$ K and a characteristic Kondo behaviour below 100 K, and down to 3 K. In YbPtAl a local minimum was observed at $T = 35$ K, followed by a maximum at 10 K, and a step decrease below $T_N = 5.8$ K indicating the onset of antiferromagnetism [7,8]. In YbPtIn, YbRhSn and YbNiGa a typical logarithmic increase with the decrease of the temperature was also observed [9]. In the other hand, other antiferromagnetic Kondo lattice compounds also display additional interesting features as quenched superconductivity by the Kondo effect in $Yb_2Fe_3Si_5$[10] and antiferromagnetic fluctuations in $YbNiB_4$[11]. The magnetic properties of $YbNiAl_2$ alloy, crystallizing in orthorhombic $MgCuAl_2$-type of structure were reported very recently [12]. An antiferromagnetic behaviour below $T_N =$ 4.8 K, and a field-induced ferromagnetic order above 9.3 kOe were observed. In view of this, we present in this work a more detailed study of this alloy with the thermal and electronic transport properties. The measurements were performed in a Quantum Design PPMS in the temperature range 0.35–300 K and magnetic fields up to 90 kOe.

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2. Results and discussion

In Fig. 1, the temperature dependence of the specific heat of $YbNiAl_2$ is presented. Above the magnetic transition, for $T > 15$ K, the data was analyzed considering the electronic, phononic and crystal field contributions, the last one with three doublets according to the splitting of the Yb^{3+} ion in orthorhombic symmetry. The result of the fitting procedure yields $\gamma = 33$ mJ/mol K^2, $\theta_D = 364$ K, $\Delta_1 = 101$ K, $\Delta_2 = 205$ K and $\Delta_3 = 227$ K, and the result is depicted by a solid line in Fig. 1. In the inset of this figure, details of the field dependence of the specific heat at low temperatures around the magnetic transition are shown. At zero magnetic field, a local maximum at 4.1 K, associated to the magnetic transition, is observed.

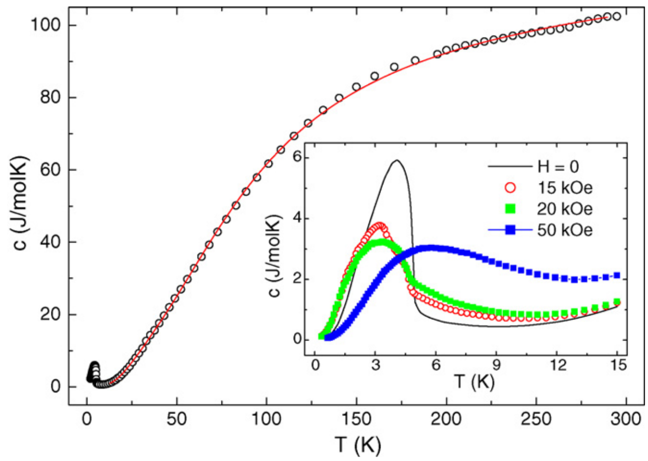

Fig. 1. Temperature dependence of the specific heat of the $YbNiAl_2$ intermetallic. The solid line is the result of the fitting considering the electronic, phononic, and crystal field contributions. In the inset, details of the magnetic field dependence of the specific heat around the magnetic transition are presented.

This peak shifts to lower temperatures (3.3 K) when the magnetic field increases up to 15 kOe, and to higher temperatures (5.8 K) with it's further increase, as presented for 50 kOe, which is consistent with an antiferromagnetic behaviour and a field-induced ferromagnetic order, as observed from the DC-magnetic susceptibility measurements [12].

The magnetic contribution to the specific heat (c_{mag}) can be obtained by substraction of the electron–phonon contribution, using the values of $\gamma = 33$ mJ/mol K^2 and $\theta_D = 364$ K extracted from the fitting of the high temperature data, as presented in Fig. 2. Using the $S = 1/2$ resonant level model which relates the jump Δc_{mag} with the T_N/T_K ratio, and the value of the jump at the magnetic transition of 5.4 J/mol K, a Kondo temperature $T_K = 5$ K can be estimated [13]. The magnetic entropy (S_{mag}) at several magnetic fields can also be calculated, using the expression $S_{mag} = \int (c_{mag}/T)dT$, and the result is presented in Fig. 2. It reaches a value of 0.8Rln2 at the magnetic transition, as expected from the magnetic ground state doublet with a reduced value from Rln2 due to the Kondo effect, which is in agreement with the estimated value of T_K [13]. Another visible feature is that with the increase of the magnetic field, the magnetic entropy smears out, which is consistent with the ferromagnetic order. The analysis of the c_{mag}/T vs T dependence at low temperatures gives an estimate of the electronic

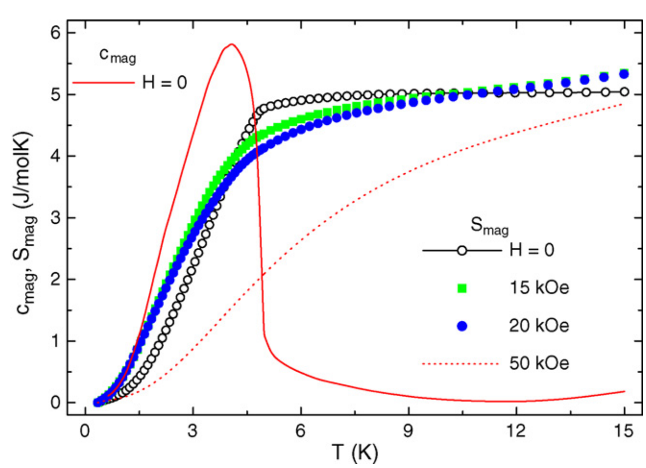

Fig. 2. Magnetic contribution to the specific heat and field dependence of the magnetic entropy. At zero field, the magnetic entropy reaches a value near to Rln2 characteristic of a doublet ground state.

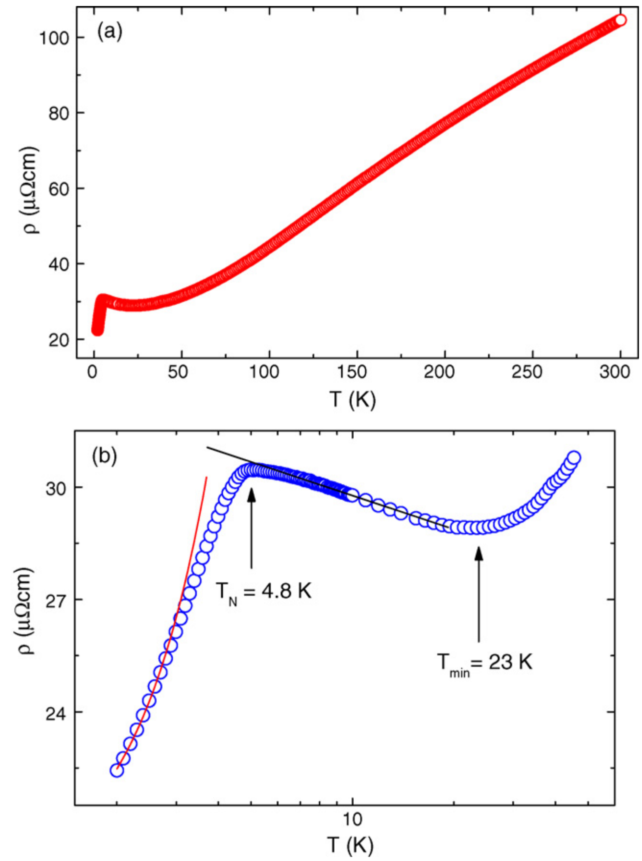

Fig. 3. (a) Temperature dependence of the electrical resistivity. (b) Details of low temperature region with a local minimum around 25 K and a logarithmic dependence characteristic of the Kondo effect down to 5 K. The solid line below T_N is a fit with a $\rho_0 + A\,T^2$ dependence.

coefficient $\gamma_0 = 300$ mJ/mol K^2, thus indicating, a moderate heavy-fermion behaviour of the $YbNiAl_2$ compound.

Measurements of the electrical resistivity also give useful information about the magnetic and Kondo interactions. In Fig. 3a, the temperature dependence of the electrical resistivity is shown. At high temperatures, well above the magnetic transition, a typical metallic behaviour is observed. However, a deviation from this behaviour is clearly seen below 40 K. Fig. 3b displays details of the low temperature region. A local minimum at 23 K and a maximum near to the magnetic transition at $T_N = 4.8$ K, are observed. At low temperatures below the transition the data is well described considering the $\rho_0 + A\ T^2$ dependence with $\rho_0 = 19\ \mu\Omega$ cm and $A = 0.81\ \mu\Omega$ cm K^{-2}. The first term can be ascribed to the residual resistivity, due to impurities and lattice faults (in a magnetic or nearly magnetic metal this term includes a spin fluctuation contribution) and the second term is related to electron–electron and/or electron–magnon scattering [14].

In Fig. 4, the temperature dependence of the electrical resistivity at different magnetic fields is presented. In the high temperature region for $T > 20$ K, above the magnetic transition, the electrical resistivity rises with the increase of the magnetic field, which is consistent with a metallic behaviour [15]. However, the opposite behaviour is observed for lower temperatures where the scattering of electrons with the spin waves is relevant with the appearance of magnetic correlations. In addition, the Kondo scattering mechanism may also play an important role [16], as follows from inspection of Fig. 3b. In order to analyze the magnetic field dependence of $\rho(T)$ below the magnetic transition, a fitting of the data with the $\rho_0 + A(H)\,T^2$ dependence was carried out, and the results are presented in the inset of Fig. 4. This last result indicates that

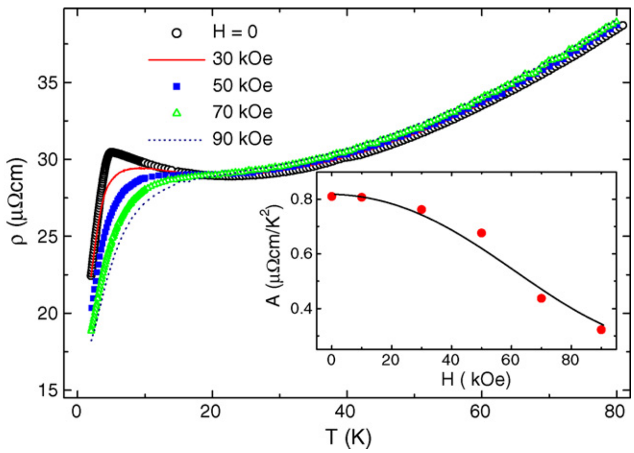

Fig. 4. Temperature dependence of the electrical resistivity for several magnetic fields. In the inset, details of the behaviour of the A coefficient of the low temperature electrical resistivity as function of the magnetic field are depicted.

the electron-magnon scattering is being quenched by the magnetic field, and the main contribution would be associated to the scattering with electrons, impurities and defects in the crystal lattice. However, it is worth commenting that this decrease in the resistivity at low temperatures is found in the ferromagnetic state of the $YbNiAl_2$ alloy, which is observed for magnetic fields higher than 10 kOe [12]. Therefore, at magnetic fields below 10 kOe and for $T < T_N$, the resistivity will behave as expected for an antiferromagnetic system, where the magnetic field softens the elementary excitations, differently from the ferromagnetic case where they are quenched by the field. In order to clarify this point, magnetoresistance $(MR) = [\rho(H,T) - \rho(0,T)]/\rho(0,T) = \Delta\rho/\rho(0)$ curves at different temperatures are presented in Fig. 5. For temperatures lower than 5 K, below the magnetic transition, a positive MR appears at low magnetic fields. This feature is clearly observed at 2 K, as shown in the inset of Fig. 5a, where the arrows indicate the presence of metamagnetic transitions and the onset of the field-induced ferromagnetic state. For temperatures above the magnetic transition (5–15 K), MR is always negative (see Fig. 5b) and it decreases from 24 % at 5 K to 3 % for 15 K, probably as result of decrease of the magnetic correlations. These magnetic correlations are of the ferromagnetic type, as suggested by the analysis of the magnetic susceptibility data [12], giving a negative MR.

The negative values of MR for temperatures in the range between 5 and 15 K, near to the magnetic transition, could not only be due to the magnetic correlations between *4f* moments, but also to the suppression of the Kondo scattering upon increasing the field [16]. This behaviour of MR above the ordering temperature suggests a description in terms of a single-ion Kondo model. In fact, Fig. 6 shows that the normalized MR $\Delta\rho/\rho(0)$ can be scaled when plotted as a function of $(T+T^*)/H$, where T^* is a measure of the Kondo temperature. This scaling law analysis is derived from the Bethe-anzatz studies [17], and has been proven to describe quantitatively MR results of some Kondo lattice systems [1]. In our case, the results for the $YbNiAl_2$ sample are in good agreement with this scaling behaviour with a value of $T^* = -1.2$ K. This negative value of the characteristic temperature T^* was also observed in the MR studies of other Yb material: YbPtSn [18], and it is attributed to the presence of ferromagnetic correlations. Indeed, the results of DC-magnetic susceptibility of the $YbNiAl_2$ alloy were consistent with such kind of correlations [12].

As suggested by the results of Fig. 4, for temperatures above 20 K, a positive MR of the metallic contribution consistent with the Kohler's rule is expected to play the main role [15]. The Kohler's rule state that for a given metal, the change of electrical resistivity

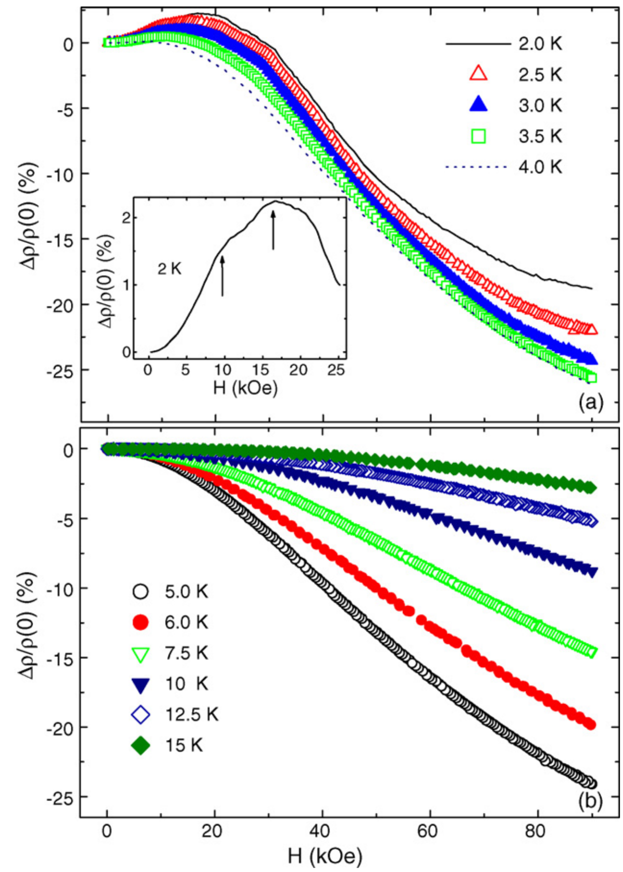

Fig. 5. Magnetoresistance of the $YbNiAl_2$ alloy at different temperatures: (a) 2 K ≤ T ≤ 4 K. The inset, details the low field region of the 2 K curve with two metamagnetic transitions, as indicated by the arrows; (b) 5 K ≤ T ≤ 15 K, where the tendency to positive values with the increase of the temperature is observed.

$\Delta\rho$, in a field H, can be represented in the form $\Delta\rho/\rho(0) = F(H)/\rho(0)$, where ρ (0) is the resistivity at zero field and F is a function depending only on the geometrical configuration and on the metal. In Fig. 7 the Kohler's plot of $\Delta\rho$ vs H/ρ (0) at several temperatures is shown. At high magnetic fields, a crossover from negative values at 20 K to positive ones for 40 K and 50 K, is observed.

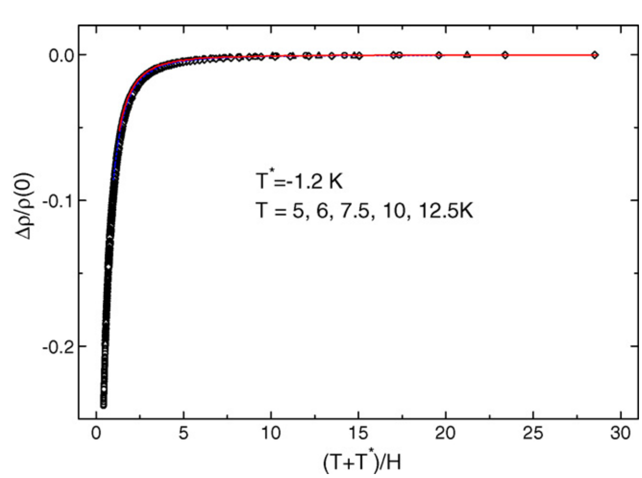

Fig. 6. Magnetoresistance $\Delta\rho/\rho(0)$ as function of $(T+T^*)$/H at different temperatures and with $T^* = -1.2$ K. The negative sign of the characteristic temperature T^* implies the presence of ferromagnetic correlations.

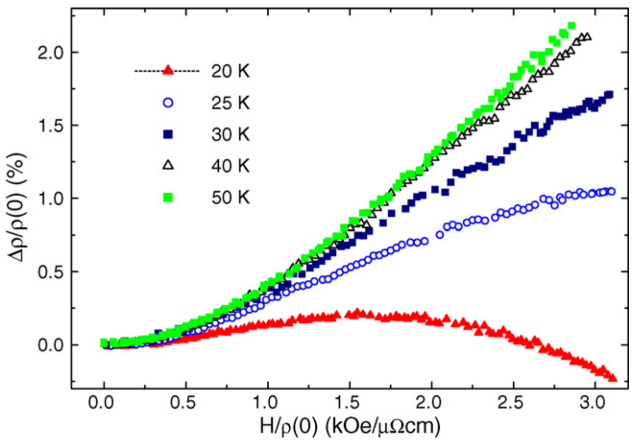

Fig. 7. Kohler's plot in the temperature range above 15 K. A tendency to a metallic behaviour with the increase of the temperature is observed.

3. Conclusions

Summarizing, the measurements of the field and temperature dependence of the specific heat and electrical resistivity of the $YbNiAl_2$ alloy show the typical behaviour of an antiferromagnetic Kondo lattice system with similar Kondo and RKKY energy scales $T_K \approx T_N$ and a moderate heavy-fermion feature. From the field dependence of the electrical resistivity, the antiferromagnetic and a field-induced ferromagnetic order were evidenced, which is in agreement with the results of the DC-magnetic susceptibility [12]. The logarithmic dependence in $\rho\ (T)$ with the existence of a local minimum indicates the presence of Kondo interactions. In addition, the scaling behaviour of the magnetoresistance with a negative characteristic temperature $T^* = -1.2$ K suggests the presence of ferromagnetic correlations, and indicates the underlying physics associated to a single impurity behaviour. Further studies on the electronic transport properties under pressure are underway to better understand the magnetic behaviour of this material.

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