Magnetic and magnetoresistive behavior of the ferromagnetic heavy fermion YbNi$_2$

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Abstract

We present a study on the magnetic susceptibility $\chi(T)$ and electrical resistance, as a function of temperature and magnetic field $R(T,H)$, of the ferromagnetic heavy fermion YbNi$_2$. The X-ray diffraction analysis shows that the synthesized polycrystalline samples crystallizes in the cubic Laves phase structure C15, with a spatial group $Fd\overline{3}m$. The magnetic measurements indicate a ferromagnetic behavior with transition temperature at 9 K. The electrical resistance is metallic-like at high temperatures and no signature of Kondo effect was observed. In the ferromagnetic state, the electrical resistance can be justified by electron-magnon scattering considering the existence of an energy gap in the magnonic spectrum. The energy gap was determined for various applied magnetic fields. Magnetoresistance as a function of applied magnetic field, subtracted from the $R(T,H)$ curves at several temperatures, is negative from 2 K until about 40 K for all applied magnetic fields. The negative magnetoresistance originates from the suppression of magnetic disorder by the magnetic field.
INTRODUCTION

The Yb and Ce-based alloys and compounds have been a subject of interest due to its physical properties like heavy fermion behavior, mixed valence state and Kondo lattice behavior [1–5]. These properties are associated to the hybridization between conduction-electron band and \( f \)-electron band. The interaction is mediated via the polarization of the conduction electrons, which is known as RKKY (Ruderman-Kittel-Kasuya-Yosida) interaction [6, 7]. In the last years the study of quantum criticality in heavy fermion (HF) systems have constituted a subject of interest in the condensed matter physics, due to the phenomena related to magnetic critical points at low temperatures, where quantum fluctuations compete with classical thermal fluctuations [8, 9]. Examples of such phenomena are unconventional superconductivity and non-Fermi liquid (NFL) behavior. Usually, the search for the existence of a quantum critical point (QCP) is through the modification of the system using a non-thermal parameter, such as pressure, magnetic field or chemical doping.

The ferromagnetic (FM) order in HF systems is rare compared with the antiferromagnetic (AFM) order or superconductivity. In the Laves phases the RNi\(_2\) alloys, where R is a rare-earth element, the magnetic properties are associated to the rare-earth element. It was proposed that in these alloys the \( d \)-shell of Ni atoms is full, \( 3d^{10} \) configuration [10, 11], consequently Ni does not carry a magnetic moment and does not contribute to the magnetic properties. The exchange interactions responsible of magnetism must take place between the \( 4f \) electron magnetic moments of the rare-earth element mediated by the conduction electrons.

In particular, the YbNi\(_2\) alloy has been classified as a heavy fermion because the Sommerfeld coefficient determined at low temperatures is \( \gamma = 573 \) mJ/mol K [12]. At low temperatures YbNi\(_2\) is ferromagnetic below a transition temperature \( T_C = 10.5 \) K [12]. Calculations of the electronic density of states show that the electrons of the conduction band are hybridized with the Yb \( 4f \)-electrons, this hybridization confirms the heavy fermion character of YbNi\(_2\) [13]. However, there is a lack of studies on the electronic transport properties. The present work studies the magnetic field effects on the electrical resistance of the YbNi\(_2\) alloy. We found that in the ferromagnetic state the temperature dependence of the electrical resistance is produced by the scattering of the conduction electrons by magnons. Furthermore, an energy gap in the magnonic spectrum was inferred.
EXPERIMENTAL DETAILS

Polycrystalline samples of YbNi$_2$, were synthesized weighting stoichiometry quantities of high purity Yb (99.9% Sigma-Aldrich) and Ni (99.99% Sigma-Aldrich) powders. An excess of Yb 10% wt was added to compensate the Yb loss because its low melting point. The powders were mixed and pelletized into a plastic bag with Ar atmosphere. Afterward, the pellet was melted in high-purity Ar atmosphere in an arc furnace. The produced button was turned and remelted several times in order to obtain an homogeneous sample. The structural characterization was performed with the X-ray powder method using a Bruker diffractometer model D8 Advanced, with a Cu-K$_\alpha$ radiation. The diffraction patterns were collected at room temperature and over a 2$\theta$ range of 20 – 120$^\circ$ with a step size 0.02$^\circ$. The Rietveld refinement of the X-ray pattern was performed using the MAUD software [14].

DC-magnetization measurements were made in a SQUID based magnetometer (Quantum Design, MPMS-5) in the temperature range of 2-300 K with an applied magnetic field of 200 Oe. Electrical resistance, as a function of temperature and magnetic field, was measured through the conventional AC four-probe method. For this purpose the sample was connected using Cu wires glued with Ag paint. The measurements were performed in a Physical Property Measurement System (PPMS, Quantum Design) at temperatures ranging from 2 K to 300 K and magnetic fields ranging from 0 up to 90 kOe. The magnetic field was applied perpendicular to the electrical current applied to the sample.

RESULTS AND DISCUSSION

Figure 1 shows the powder X-ray diffraction pattern of YbNi$_2$. The analysis of these data indicates that the crystalline structure of the sample corresponds to YbNi$_2$ (JCPDS No 03-065-5017), however a faint trace of Yb$_2$O$_3$ (JCPDS No 00-041-1106) are observed. This oxide is indicated by an asterisk in the diffraction pattern. The X-ray diffraction pattern was Rietveld-fitted using a space group $Fd\bar{3}m$ (No 227), considering the presence of Yb$_2$O$_3$. The value obtained for the lattice parameter $a = 7.0965(3)$ Å is in agreement with the values reported previously [12] [15] [16].

Figure 2 shows the temperature dependence of the magnetic susceptibility, $\chi(T)$, and the inverse magnetic susceptibility, $\chi^{-1}(T)$, measured in a magnetic field of 200 Oe. The
FIG. 1. X-ray diffraction pattern and Rietveld fitting of YbNi$_2$. The $R$-factors of refinement are: $R_{wp} = 5.2$, $R_b = 3.9$, $R_{exp} = 4.1$ and $\sigma^2 = 1.2$. The vertical red bars indicate the Bragg reflections of YbNi$_2$. The continuous line at the bottom is the difference between the experimental data and the fit.

FIG. 2. Magnetic susceptibility $\chi = M/H$ (circles) and $\chi^{-1}$ (triangles), as a function of temperature measured under 200 Oe. The continuous line is a linear fit of $\chi^{-1}(T)$ data from 150 K to room temperature. The inset shows the determination of $T_C$ like the minimum in $d\chi/dT$.

magnetic susceptibility between 2 K and 300 K shows a fast increase at low temperatures, which characterize the ferromagnetic behavior. The inset in this figure shows the $\chi(T)$ and $d\chi/dT$ curves at low temperatures, here the ferromagnetic behavior is clearly noted and the minimum in $d\chi/dT$ is defined as the ferromagnetic transition temperature $T_C = 9$ K. This
value is lower than $T_C = 10.5$ K earlier reported [12, 17]. In spite of the tiny amount of Yb$_2$O$_3$ in our sample, its influence on the magnetic properties of YbNi$_2$ was not considered, since it has an antiferromagnetic transition temperature at 2.1 K [18].

To analyze the paramagnetic state, $\chi^{-1}(T)$ is plotted in Fig. 2 (right scale). The continuous line is a linear fit of the data from 150 K to 300 K. The linear behavior can be described by the Curie-Weiss law, $\chi(T) = C/(T - \theta_{CW})$, where $C$ is the Curie constant and $\theta_{CW}$ is the Curie-Weiss temperature. The effective magnetic moment, $\mu_{eff}$, can be determined from $C$. In the present case, the values of these parameters obtained from the fitting were: $\theta_{CW} = 7.86$ K and $C = 2.71$ emu K/mol Oe which gives $\mu_{eff} = 4.65 \mu_B$. This effective magnetic moment is near to the theoretical value, $\mu_{eff} = g_J[J(J+1)]^{1/2} = 4.53 \mu_B$, reported for the Yb$^{3+}$ ion [19].

Rojas et al. [12] calculated the magnetic entropy of YbNi$_2$ based on specific heat measurements. The entropy saturates around 130 K, which is congruent with a full population of the crystalline electric field (CEF) effects. As observed in Fig. 2, there is a deviation of $\chi^{-1}(T)$ from the linear behavior, this deviation could be related to the CEF effect on the magnetization below 150 K.

The electrical resistance of YbNi$_2$ as a function of temperature in zero magnetic field is shown in the inset of Fig. 3. The curve displays a metallic-like behavior and shows a sharp

FIG. 3. Electrical resistance as a function of temperature and applied magnetic field, measured between 2 K and 100 K. The inset shows the electrical resistance, without applied magnetic field, at temperatures between 2 K and 300 K.
decrease about the ferromagnetic transition at low temperatures. However, for temperatures between \( T_C \) and 15 K the electrical resistance shows a \( T^2 \) dependence indicative of a Fermi liquid behavior. The onset of the sharp resistance decrease is about \( T_{on} = 8 \) K, this value is near to the \( \theta_{CW} \) determined from the magnetic measurements. It is noteworthy the absence of a logarithmic increase of \( R(T) \), signature of a Kondo effect, this behavior suggest that the Kondo effect is weak and that the RKKY interaction dominates. The Kondo temperature has been reported as \( T_K = 27 \) K, determined from the jump of the specific heat at the ferromagnetic transition [12]. Taking the approximation \( |\theta_{CW}| = 2T_K \) [20, 21] we obtain \( T_K = 3.93 \) K. This \( T_K \) value is lower than reported, but congruent to the Kondo signature fault in \( R(T) \).

The residual resistance ratio (RRR) is defined by the relation \( RRR = R(300 \) K)/\( R(2 \) K), this ratio provides qualitative information about the electron scattering by structural defects. For YbNi\(_2\) was obtained \( RRR = 2.7 \), which indicates that our samples have defects, probably included Yb vacancies because of the low melting point of Yb. The RRR value is similar to the already observed values in other RNi\(_2\) alloys [22, 23].

The main panel of Fig. 3 shows the \( R(T) \) curves measured under different applied magnetic fields. Above 40 K the curves are similar to the one measured at zero magnetic field. The changes occur at low temperature, the electrical resistance decreases as the magnetic field increases. At first sight, the application of a magnetic field smooth out the magnetic transition and moves up in temperature as the magnetic field is increased; this behavior is characteristic of a ferromagnetic ordering. The reduction of \( R(T) \) with magnetic field suggest a negative magnetoresistance (MR), as expected for a ferromagnetically ordered system. Qualitatively, it is observed that the MR magnitude increases as the temperature increases from 2 K, it reaches a maximum and goes to zero as the temperature increases. A negative MR indicates that the magnetic fluctuations decreases as the magnetic field increases [24].

To analyze the electrical resistance of YbNi\(_2\) below the ferromagnetic transition temperature we assume that the main scattering process is electron-magnon. With this assumption, we use the Andersen and Smith model [25]. According to this model, the magnetic resistance \( (R_{mag}) \) can be describe by:

\[
R_{mag} = AT\Delta e^{(\Delta/T)} \left[ 1 + 2\frac{T}{\Delta} + \frac{1}{2} e^{(-\Delta/T)} + \cdots \right],
\]

(1)
where $\Delta$ is an energy gap in the magnonic density of states and $A$ is a constant dependent on the material \[25\]. In the case of $\Delta = 0$ we deal with an isotropic ferromagnet and then $R_{mag} \propto T^2$. However, fitting the experimental data to a $T^2$ dependence the results were not acceptable. Taking in account Eq. \[1\] just with the first term, and considering the residual resistance the data fit is good. Then the electrical resistance is given by:

$$R(T) = R_0 + AT\Delta e^{(-\Delta/T)} ,$$  \hspace{1cm} (2)

where $R_0$ is the residual resistance. We fit the $R(T, H)$ curves at temperatures between 2 K and approximately 7.5 K. The phonon contribution is considered negligible because the Curie temperature $T_C = 9$ K is small compared to the Debye temperature reported, $\theta_D = 272$ K \[12\]. Since the $R(T, H)$ curves below $T_C$ can be fitted with Eq. \[2\] we conclude that the same scattering mechanism persists for the applied fields, i.e., the electrical resistance is produced by the electron-magnon scattering. Figure \[4\] shows the temperature dependence of the electrical resistance in YbNi$_2$ at different magnetic fields in a temperature range between 2 K and 16 K. In this figure the continuous lines are the best fit obtained with Eq. \[2\] Table \[1\] presents the parameters obtained from the fitting.

FIG. 4. Electrical resistance of YbNi$_2$ as a function of temperature at different magnetic fields indicated in the plot. The continuous lines are data fit using Eq. \(2\).

It is well known that the magnonic energy gap is modified in the presence of an external magnetic field as a consequence of the Zeeman effect. The magnonic energy gap as a function of a magnetic field is given by $\Delta = \Delta_0 + gJ\mu_B\mu_0 H$ \[26\], where $\Delta_0$ is the magnonic energy
TABLE I. Parameters obtained from fits using Eq. 2. \( R_0 \) is the residual resistance, \( A \) is a constant related to material and \( \Delta \) is the magnonic energy gap.

| \( H(\text{kOe}) \) | \( R_0(\text{m\Omega}) \) | \( A(\text{m\Omega/K meV}) \) | \( \Delta \) (meV) |
|-----------------|-----------------|-----------------|-----------------|
| 0               | 0.2817(5)       | 0.0089(1)       | 0.31(1)         |
| 10              | 0.2690(2)       | 0.0080(7)       | 0.21(2)         |
| 30              | 0.2730(6)       | 0.0035(1)       | 0.39(3)         |
| 60              | 0.2701(6)       | 0.0021(1)       | 0.51(4)         |
| 90              | 0.2691(6)       | 0.0014(1)       | 0.62(8)         |

FIG. 5. Magnonic energy gap \( \Delta \) as a function of the applied magnetic field. \( \Delta \) was obtained from the fits of \( R(T,H) \) curves of YbNi\(_2\). The continuous line is a linear fit of data.

gap at zero field, \( g_J = 1.14 \) is the Landé factor of Yb\(^{3+}\) ion and \( g_J\mu_B = 0.065 \text{ meVT}^{-1} \). The \( g_J\mu_B \) value is the factor that determines the change of \( \Delta \) as a function of the magnetic field. Figure 5 shows the magnonic energy gap as a function of the applied magnetic field, as expected, \( \Delta \) increases as the magnetic field is increased. The best linear fit of \( \Delta(H) \) gives that \( \Delta(H) = 0.24(4) + 0.0043(6)H \), the slope must be equivalent to \( g_J\mu_B \), but its value is 0.043 meVT\(^{-1} \) lower than the calculated for the Yb\(^{3+}\) ion. In addition, it was noted that the parameter \( A \) depends on magnetic field.

Finally, the magnetoresistance as a function of applied magnetic field at several temperatures was extracted from the \( R(T,H) \) curves (Fig. 3). The magnetoresistance was defined as
FIG. 6. Magnetoresistance $MR$ of YbNi$_2$ as a function of applied magnetic field at various temperatures. The data were extracted from curves of Fig. 3. The lines are a guide for the eye.

$MR = [R(H) - R(0)]/R(0)$, where $R(0)$ is the electrical resistance measured without applied magnetic field and $R(H)$ is the electrical resistance measured with an applied magnetic field $H$. Figure 6 shows the plot of $MR(H)$ at 2, 5, 10, 15, 20 and 50 K. The maximum $MR$ observed in YbNi$_2$ is about -20% at 5 K and 10 K (near $T_C$) under 90 kOe. At temperatures below 50 K, the $MR$ is negative above and below $T_C$ for all applied magnetic fields. At fixed magnetic field the $MR$ magnitude increases with temperature until about $T_C$, for temperatures above $T_C$ it diminishes. This behavior has been observed in other ferromagnetic Yb-based HF such as YbPtGe [27] and YbPdSi [28]. A negative MR for $T < T_C$ can be associated with a reduction of the spin-disorder suppressed by the magnetic field. For $T > T_C$, a negative MR could be associated with the existence of ferromagnetic short-range correlations or spin fluctuations that preceded the onset of long-range magnetic order. Further experiments on YbNi$_2$, under magnetic field and/or pressure, must be performed to get more insight in their physical properties.

CONCLUSIONS

We have synthesized polycrystalline samples of YbNi$_2$, the structure type and cell parameter were determined using X-ray diffraction analysis. Magnetic measurement as a function of temperature shows a ferromagnetic transition at 9 K. The effective magnetic moment determined from the magnetic measurements suggest a localized magnetism associated to
Yb\(^{3+}\) ions. Electrical resistance as a function of temperature shows metallic-like behavior at high temperatures. From this measurement, we infer that the RKKY is the dominant interaction regard to Kondo effect. Below the ferromagnetic transition temperature, the electrical resistance results from the electron-magnon scattering, even in the presence of an external magnetic field. In addition, the electrical resistance analysis indicates the presence of an energy gap in the magnonic spectrum indicating that the ferromagnetic state is anisotropic. The increment of the energy gap can be associated to the Zeeman effect.

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