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Magnetic and Transport Properties of PrNi Single Crystal

S. Maťaš, Marián Mihalik, M. Zentková

Institute of Experimental Physics, Slovak Academy of Sciences
Watsonova 47, 040 01 Košice, Slovak Republic

and Matúš Mihalik

Charles University, Faculty of Mathematics and Physics
Department of Electronic Structures
Ke Karlovu 5, 121 16 Prague 2, Czech Republic

Frequency dependence of $\chi''(T)$, different position of a maximum in $\chi''(T)$ for different crystal orientations, hysteretic behavior between magnetization measurements in zero-field cooling and field coolding regime are attributed to strong magneto-crystalline anisotropy of PrNi ferromagnetic single crystal with $T_{\mathrm{C}} = 20.5$ K, which is driven by crystal field effect. Applied pressure shifts T_{C} to higher temperatures ($\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p = 1$ K/GPa). Susceptibility follows the Curie–Weiss law except for b-axis, which is hard magnetic axis. An anisotropic behavior was seen in resistivity measurements with the largest difference between b-axis and c-axis. Resistivity below T_{C} can be described by power law with $\rho \sim T^{2.24}$ and is field dependent with a positive magnetoresistance.

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1. Introduction

In spite of the nonmagnetic singlet ground state PrNi undergoes a ferromagnetic transition at $T_{\mathrm{C}} = 20.5$ K [1]. The compound crystallizes in the orthorhombic CrB-type structure (space group $Cmcm$) with unit cell dimensions: $a = 0.38307(9)$, $b = 1.0543(2)$, $c = 0.4369(1)$ nm [2]. The system is highly anisotropic with b-axis as the hard magnetic axis and c-axis as the easy axis [1]. Magnetic ordering in this compound could be described by the concept of induced magnetism which anticipates ordering only if the exchange interaction exceeds the critical value when compared to the energy scale of the crystal field (CF) interaction [3]. In this case the transition to ordered state is accompanied by a strong softening of excitations [4, 5]. The magnetic ordering is due to the exchange coupling between the Pr ions, Ni is nonmagnetic in this compound. The goal of our paper is a more detailed study of bulk magnetic properties of the PrNi single crystal including AC susceptibility, and magnetization measurements in zero-field cooling (ZFC) and field cooling (FC) regimes, investigation of pressure effect on T_{C}, and study of electrical transport properties.

2. Experimental

The PrNi single crystal was grown in a tri-arc furnace by the Czochralski method under an argon atmosphere. The energy dispersive X-ray spectroscopy (EDS) confirmed the chemical composition of the single crystal. The orthorhombic CrB-type structure was confirmed by X-ray diffraction. The single crystal was oriented with help of 4 circle X-ray diffractometer and then cut along the main crystal directions. Magnetization, AC susceptibility, resistance and magneto-resistance measurements were performed on MPMS and PPMS equipments (Quantum Design) operating in the temperature range from 1.8 K to 400 K and in magnetic fields up to 5 T and 9 T, respectively. The effect of pressure on ferromagnetic transition in PrNi single crystal was studied by a transformer method in the piston cylinder type of CuBe pressure cell. The temperature in the range from 3.5 K to 300 K was varied by two-stage close-cycle helium refrigerator.

3. Results and discussion

The transition to magnetically ordered state is accompanied by a steep increase in the in-phase AC susceptibility $\chi'(T)$ with a maximum at about $T = 20$ K (see Fig. 1). The Curie temperature $T_{\mathrm{C}} = 20.5$ K, corresponding to the results published in [1, 4], is defined as a minimum on $\mathrm{d}\chi'(T)/\mathrm{d}T$. The shape of $\chi'(T)$ curve depends on the crystal axis.

Figure 1 shows the out-phase susceptibility $\chi''(T)$ which is frequency and crystal orientation dependent. The frequency dependent peak in $\chi''(T)$ below T_{C} has maximal height and appears at the highest temperature for $f = 111$ Hz. Temperature of the maximum T_{m} depends on the crystal orientation $T_{\mathrm{m}}(a\text{-axis}) = 17$ K and $T_{\mathrm{m}}(b\text{-axis}) = 6$ K.

Magnetization measurements revealed hysteretic behavior between ZFC an FC regime as it is seen from Fig. 2a, where magnetization is recalculated on DC susceptibility $\chi(T)$. The hysteretic behavior is less pronounced for c-axis, which is magnetic easy axis. Frequency dependent lambda anomaly in $\chi''(T)$ and hysteretic behavior between ZFC and FC regime can point to spin-glass-like behavior in PrNi, but in our opinion this behavior can be fully attributed to magneto-crystalline anisotropy. An increase in T_{C} was observed from both $\chi'(T)$ and $\chi''(T)$ measurements under applied pressure and is demonstrated in Fig. 2b. The applied hydrostatic pressure shifts T_{C} nearly linearly to higher temperatures, $\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p = 1$ K/GPa, due to an increase in exchange interactions between Pr ions. The increase can be attributed to simple compression of the lattice or/and is connected with CF changes induced by pressure.

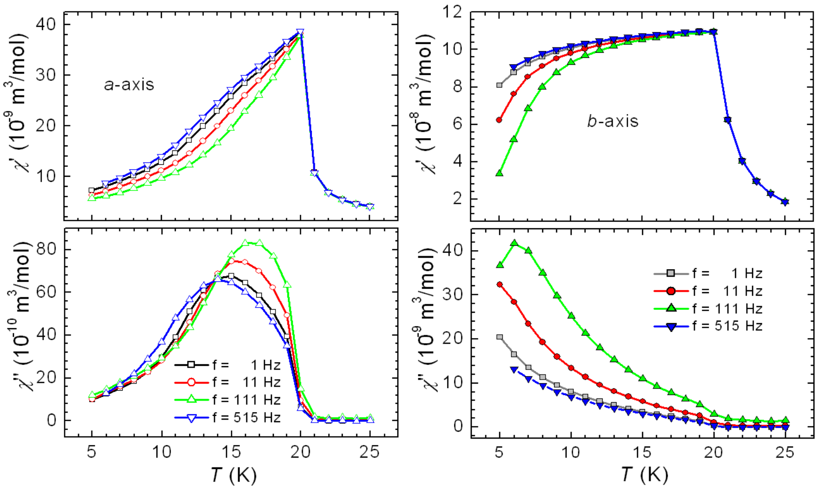

Fig. 1. AC susceptibility measured along a- and b-axes.

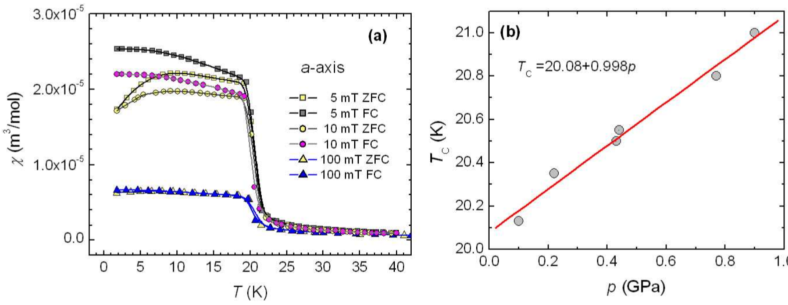

Fig. 2. Irreversibility of magnetization measured in ZFC and FC regime (a); effect of pressure on the Curie temperature T_C: $\mathrm{d}T_C/\mathrm{d}p = 1$ K/GPa, common orientation (b).

Magnetization measurements confirmed a huge anisotropy of the compound observed in [1] (Fig. 3a). There is no hysteresis loop for c-axis: remanent magnetization and coercive force are equal to zero, and there is very small remanent magnetization and coercive force for remaining axes. Huge anisotropy was observed in $1/\chi(T)$ susceptibility measurements (Fig. 3b). The Curie–Weiss law is fulfilled for the c- and a-axes and in contrary to [1] is not valid for b-axis.

A weak anisotropic behavior was observed in resistivity measurements, too. The main difference is between resistivity measured along b- and c-axes (Fig. 4a); there is no difference between a- and c-axes above and small difference below 100 K. The resistivity above T_C can be described by the Bloch–Grüneisen formula with the Debye temperature $\Theta_D = 140 \pm 6$ K for all main axes (Fig. 4a). The $\rho(T)$ dependence below T_C can be very well fit by the power-law $\rho = \rho_0 + AT^{2.24}$, whereas simple relation $\rho \sim T^2$ is expected for fully isotropic ferromagnetic

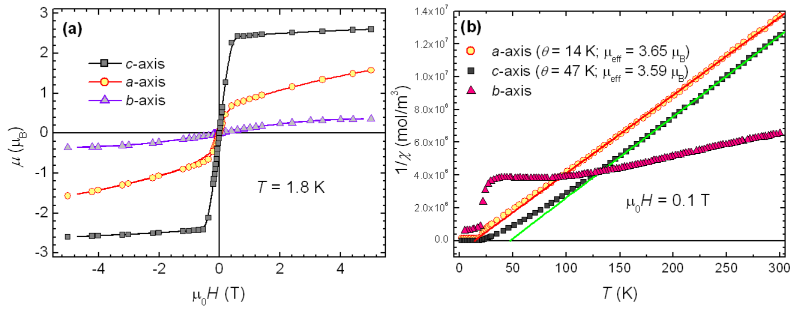

Fig. 3. Demonstration of magneto-crystalline anisotropy in field dependence of magnetization (a) and susceptibility plotted in $1/\chi(T)$ representation (b).

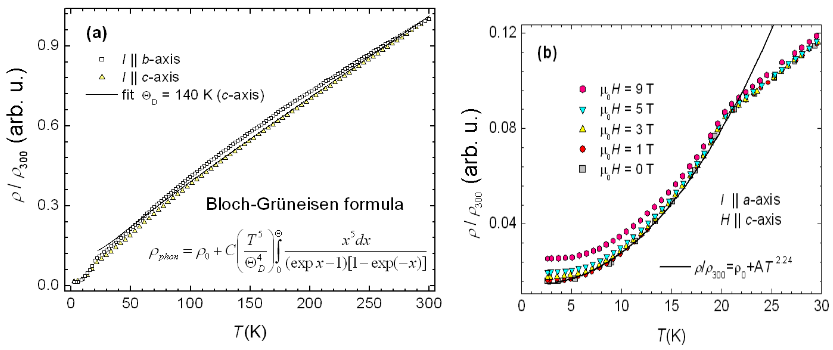

Fig. 4. Anisotropy in resistance (a) effect of magnetic field on resistance (b).

system with no anisotropy gap in magnon dispersion relation. Resistivity is field dependent (all axes) below T_C with the positive magneto-resistance MR $= 100(\rho_{9\mathrm{T}} - \rho_{0\mathrm{T}})/\rho_{0\mathrm{T}} = 58\%$ for 9 T at 3 K (Fig. 4b).

Acknowledgments

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