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# Magnetic Properties of $Ho_5Ni_2In_4$

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X-ray diffraction and magnetic measurements of $Ho_5Ni_2In_4$ are reported. This compound crystallizes in the orthorhombic $Lu_5Ni_2In_4$-type structure. Magnetic data indicate ferromagnetic properties below $T_c = 30$ K.

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## 1. Introduction

Intermetallic rare earths (R)–nickel–indides have attracted broad interest in recent years [1]. These compounds form different 19 crystal structures [2]. Only for RNiIn magnetic measurements were performed indicating that this compound is ferromagnet [3]. The $R_5Ni_2In_4$ compounds with a large concentration of the rare-earth element exist for R = Dy–Tm and Lu, Y [4, 5] and crystallize in an orthorhombic crystal structure of the $Lu_5Ni_2In_4$-type [6].

This work reports the results of the X-ray diffraction and magnetic measurements of $Ho_5Ni_2In_4$.

## 2. Experimental

Polycrystalline sample $Ho_5Ni_2In_4$ was prepared by arc melting of high-purity raw metals (Ho: 3N, Ni: 4N and In: 5N) in a titanium gettered argon atmosphere. The sample was then annealed in evacuated vycor capsules at 600 ℃ for 1 week.

X-ray powder diffraction pattern was collected at room temperature using Cu $K_\alpha$ radiation (Philips X'PERT PRO diffractometer). The diffraction data were analyzed using the Rietveld-type program Fullprof [7]. DC magnetic susceptibility measurements were carried out in the temperature range between 2 K and 300 K in magnetic fields up to 50 kOe using a MPMS SQUID magnetometer. Additional AC magnetic susceptibility measurements were performed in low magnetic field. Both in-phase, $\chi'$ and out-of-phase, $\chi''$, component of the $\chi_{ac} = \chi' - \chi''$ are measured at the frequency 100 Hz in magnetic field $H = 3$ Oe.

## 3. Results

The X-ray diffraction pattern of $Ho_5Ni_2In_4$ is shown in Fig. 1. The analysis confirmed the orthorhombic crystal structure of the $Lu_5Ni_2In_4$-type (space group *Pbam*). In this structure the Ho atoms occupy three different sublattices: Ho1 2a site: $0, 0, 0$; Ho2 and Ho3 4g site: $x, y, 0$ with different values of the $x$ and $y$ parameters, Ni atoms occupy 4h site: $x, y, 1/2$ and In atoms form two sublattices In1 and In2 both at 4h site: $x, y, 1/2$ but with different values of $x$ and $y$ parameters. The determined crystal structure parameters are collected in Table. These parameters agree well with the published data [1, 4, 5]. The additional peaks of the small intensities connected with HoNiIn and $Ho_2Ni_{2-x}In$ phases are observed.

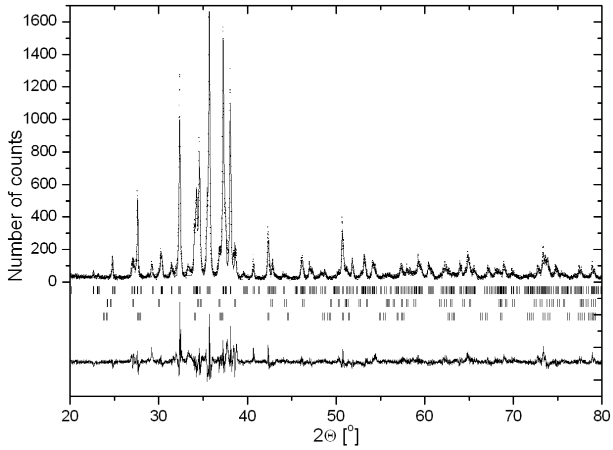


Fig. 1. X-ray powder diffraction pattern of $Ho_5Ni_2In_4$ compound together with the Rietveld fit and the difference plot. Vertical ticks indicate the positions of Bragg reflections. First row corresponds to $HoNi_2In_4$, second to HoNiIn, and third to $Ho_2Ni_{2-x}In$.

The results of the magnetic measurements are presented in Figs. 2 and 3. The Curie–Weiss law is fulfilled with the positive value of the paramagnetic Curie temperature equal to 12.6(3) K which indicates that the ferromagnetic interactions are dominant and the effective magnetic moment equal to 10.85(5) $\mu_B$ which is slightly

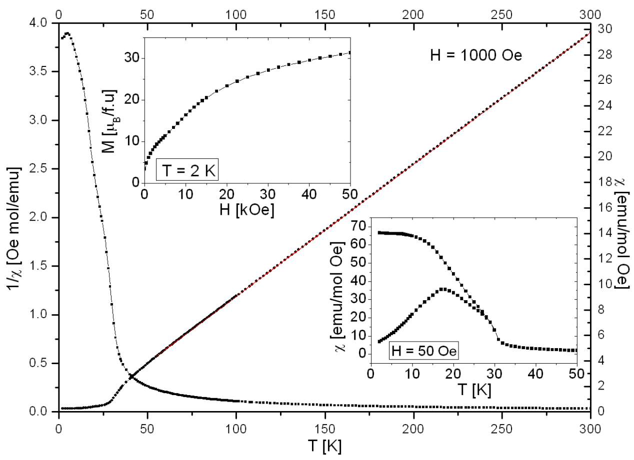


Fig. 2. Temperature dependence of magnetic susceptibility of $Ho_5Ni_2In$. The solid line represents the Curie–Weiss law fit. The insets show the magnetization versus external magnetic field at 2 K (top) and temperature dependences of the ZFC and FC curves (lower).

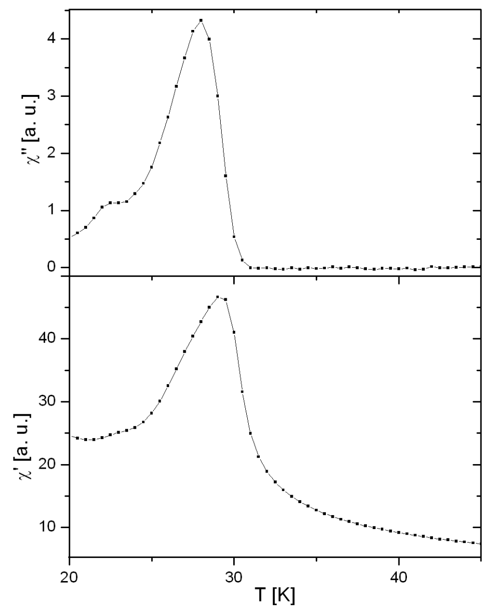


Fig. 3. Temperature dependence of the real $\chi'$ and imaginary $\chi''$ part of the AC magnetic susceptibility near the Curie temperature.

larger than the free $Ho^{3+}$ ion value (10.61 $\mu_B$). Below 30 K an increase in the magnetization is observed. In this temperature an anomaly in the temperature dependence of the real $\chi'$ and imaginary $\chi''$ part of the ac susceptibility and difference between zero field cooling (ZFC) and FC curves are also detected (see Fig. 3).

The magnetization curve at 2 K is not saturated (see inset in Fig. 2). At $T = 2$ K and the magnetic field $H = 50$ kOe the value of the magnetic moment is equal to 31.6 $\mu_B$ per chemical formula which gives the Ho magnetic moment equal to 6.3 $\mu_B$ on Ho atom, i.e. significantly smaller than the free $Ho^{3+}$ ion value (10 $\mu_B$). This result suggests the non-collinear magnetic structure with the ferromagnetic component or the ferrimagnetic structure.

TABLE

Crystal structure parameters of $Ho_5Ni_2In_4$ determined from the X-ray data at room temperature.

| Atom | Wyckoff position | Occupancy [%] | $x$ | $y$ | $z$ |
|---|---|---|---|---|---|
| Ho1 | 2a | 100 | 0 | 0 | 0 |
| Ho2 | 4g | 100 | 0.2208(2) | 0.2464(4) | 0 |
| Ho3 | 4g | 100 | 0.4140(2) | 0.1216(4) | 0 |
| Ni | 4h | 100 | 0.3014(5) | 0.0163(11) | 0.5 |
| In1 | 4h | 100 | 0.5690(2) | 0.2135(4) | 0.5 |
| In2 | 4h | 100 | 0.8476(2) | 0.0761(4) | 0.5 |

$a$ = 17.7710(12) Å, $b$ = 7.8825(5) Å, $c$ = 3.5709(3) Å; $R_{\text{Bragg}} = 11.7\%$, $R_F = 10.2\%$ for phase $Ho_5Ni_2In_4$.

## 4. Discussion and conclusions

The results presented in this work confirm that the $Ho_5Ni_2In_4$ compound crystallizes in the orthorhombic $Lu_5Ni_2In_4$-type crystal structure. In this structure the holmium atoms occupy three different sublattices with different atomic surroundings. Magnetic data indicate ferromagnetic ordering below $T_c = 30$ K. A large difference between the values of the Ho magnetic moment in the paramagnetic state, in which it is equal to the free $Ho^{3+}$ ion value, and in the ordered state, in which it is significantly smaller, is observed. This result together with the magnetic field dependence of the magnetization suggests complex magnetic structure in the ordered state. In order to explain it, neutron diffraction experiments are planned.

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