Magnetic phase transitions in the rare earth intermetallic compounds

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The aim of this work is not to give a complete review of magnetic properties of different types of rare earth compounds. The work will focus on some examples chosen to illustrate the large variety of magnetic properties encountered among rare earth intermetallics. Their main features will be stressed by comparing the results of magnetic and neutron diffraction measurements.

Properties typical for antiferromagnetic compounds are observed for HoRhSi. This compound crystallizes in the orthorhombic TiNiSi-type structure. The temperature dependence of magnetization at low magnetic fields shows an anomaly at 8.8 K. The magnetic reflections in the neutron pattern collected at 1.5 K are indexed with the propagation vector **k**= (½, 0, ½). The analysis of the magnetic peak intensities indicates a collinear magnetic structure. The thermal variations of the intensities of magnetic peaks show that they disappear at 8.5 K, which corresponds to the Néel temperature. The results of magnetometric and neutron diffraction measurements indicate, in conformity, that the magnetic order is stable in the temperature range between 1.5 K and the Néel temperature.

Different situation is observed in large number of rare earth intermetallic compounds, in which a change in the magnetic structure while increasing temperature is observed. Such dependence is observed in ErRhGe. The magnetic peaks in the neutron diffraction pattern collected at 1.5 K can be indexed with the wave vector **k**= (0, ½, 0), which indicates a collinear antiferromagnetic structure (the magnetic unit cell doubled along the *b*-axis with respect to the crystallographic one). While increasing temperature the positions of the magnetic peaks change about 5 K. The magnetic peaks above 5 K are indexed with the propagation vector **k**= (0, k_y, 0), where $k_y \neq ½$. The magnetic structure in the temperature region between 5 K and T_N (equal 9.7 K) is a sine-wave modulated one. This phase transition from an incommensurate structure about the Néel temperature to a commensurate one at low temperatures is called the "lock-in" transition. The temperature dependence of magnetization gives the anomaly at T_N= 9.7 K and a further phase transition at about 4 K.

The $TbCo_2Si_2$ compounds can serve as an another interesting example. The temperature dependence of DC susceptibility gives only one anomaly typical for the para-antiferromagnetic transition at 45 K. Neutron diffraction data indicate the phase transition from a commensurate antiferromagnetic structure, described by the propagation vector **k**= (0, 0, 1), to a sine-wave modulated structure, described by the propagation vector **k**= (0, 0, 1-k_z) with $k_z \approx 0.045$, in the temperature range between 43.5 K and T_N= 45 K. This transition, from the commensurate to the incommensurate magnetic structure, is observed only in the temperature dependence of $d\chi'/dT$.

Temperature dependence of magnetic susceptibility $\chi(T)$ of TbPtGa shows the maximum at the Néel temperature of 27 K. Below the Néel temperature a very small anomaly in the $\chi(T)$ dependence at T_t = 18 K is observed. The neutron diffraction measurements indicate the collinear antiferromagnetic structure described by the propagation vector **k**= (0, ½, 0). With increasing temperature changes in the positions and intensities of the magnetic peaks are observed at T_t. Below T_t only a collinear magnetic structure was found, while above T_t two magnetic phases: collinear and modulated with **k**= (0, ky, 0) with $k_y \neq ½$ coexist.

At low magnetic fields the thermal dependence of magnetization of $TbPtGe_2$ shows a maximum at 11.4 K, two further anomalies at 2.45 K and 7 K and a very small anomaly at 24.2 K. Neutron diffraction data indicate magnetic ordering stable up to 24.2 K. $TbPtGe_2$ compounds crystallize in the orthorhombic $YIrGe_2$-type structure in which the Tb atoms occupy two nonequivalent positions 4i and 4h. Analysis of magnetic peak intensities indicates that below the Néel temperature the Tb magnetic moments at 4(i) sites order and form a collinear antiferromagnetic structure. At 11.4 K the Tb magnetic moments at 4h sites order while at 7 K a change of magnetic structure in the 4(h) sublattice is observed.

Thermal dependence of the AC magnetic susceptibility of $TbPd_2Ge$ gives three anomalies: at 10 K, 14.5 K and 19 K. In contradiction to these results the neutron diffraction data give the evidence only for two phase transitions: at 19 K – the Néel temperature and at 10 K – the transition from a collinear commensurate antiferromagnetic structure to a sine-wave modulated incommensurate one. Comparison of the data from magnetic and neutron diffraction measurements suggest that the maximum in $\chi'(T)$ and $\chi''(T)$ which occurs at 14.5 K is probably connected with the reorganization of the domain structure.

The data collected for $TbCu_2Ge_2$ give the opportunity to compare the results obtained by different methods and on samples of different types (polycrystalline, single crystal). The magnetic and neutron diffraction data for a polycrystalline sample indicate the collinear antiferromagnetic structure described by the wave vector $\mathbf{k} = (½, 0, ½)$ with the Tb magnetic moment parallel to the [110] direction. The new DC susceptibility measurements as well as the resonant and nonresonant magnetic X-ray scattering carried out for a single crystal clearly show two phase transitions: at $T_N = 12.3$ K and $T_t = 9.6$ K. At T_t the reorientation of the Tb magnetic moments from the [110] direction below T_t to the [010] direction for temperatures $T_t < T < T_N$ [1] is observed.

Summary. The results presented in this work clearly show that it is possible to obtain a complete information on magnetic properties of rare earth intermetallic compounds from investigations carried out by means of complementary methods: temperature dependence of magnetization, magnetic susceptibility and neutron diffraction. From such measurements it is possible to determine all the phases in magnetically ordered state. The data presented here should worn also not to draw conclusions on the properties of an investigated compound from measurements carried out using only one method.

[1] C. Song, D. Johnson, D. Wermeille, A. I. Goldman, S. L. Bud'ko, I. R. Fisher, P. C. Canfield, 2001; *Phys. Rev. B;* 64; 224414.

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