# MAGNETIC PROPERTIES
# OF THE RCoSn (R = Tb–Er)
# AND RRhGe (R = Ce,Nd) COMPOUNDS*

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Magnetic properties of orthorhombic RCoSn (R = Tb–Er) and RRhGe (R = Ce,Nd) (of the TiNiSi-type of crystal structure), were studied by magnetometric and neutron diffraction methods. All RTX compounds order antiferromagnetically at low temperatures. The magnetic structure of TbCoSn and HoCoSn is sine-wave-modulated with the wave vectors $k_1 = (0, 0.25, 0.11)$ and $k_2 = (0, 0.333, 0)$, respectively. The magnetic structures of CeRhGe and NdRhGe compounds are collinear (C mode). Magnetic moments of 1.4(2) and 2.0(2) $\mu_B$ localized respectively on Ce and Nd ions, are aligned along the $a$-axis.

PACS numbers: 75.25.+z

## 1. Introduction

Equiatomic ternary lanthanide–transition metal silicides, germanides and stannides exhibiting the crystal structure of TiNiSi-type were found to have interesting magnetic properties at low temperatures [1]. We have therefore undertaken a study of magnetic and structural properties of some of the RCoSn (R = Tb,Dy,Ho,Er) and RNiGe (R = Ce,Nd) compounds at low temperatures.

## 2. Experimental

RCoSn and RNiGe compounds were obtained by arc melting of stoichiometric amounts of high purity constituting elements. The samples were subsequently annealed in vacuum for 100 hours at 800°C. The examination of X-ray patterns

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confirmed a single phase nature of the samples. Their lattice parameters were determined and found to be in fair agreement with those reported before [2, 3].

Magnetometric measurements were performed in the temperatures from 2 to 300 K in magnetic fields up to 50 kOe using a vibrating sample magnetometer.

Neutron diffraction patterns were run at 4.2 and 293 K using the DN500 powder diffractometer at Świerk reactor EWA, with the wavelength of 1.326 Å.

## 3. Results

X-ray and neutron diffraction measurement at 293 K confirmed that all samples exhibited the orthorhombic crystal structure of TiNiSi-type (space group *Pnma*). At low temperatures the magnetic susceptibility shows maxima characteristic for the transition to antiferromagnetic state at: 20.5 K for TbCoSn, 10 K for DyCoSn, 7.8 K for HoCoSn, 10 K for CeRhGe and 14 K for NdRhGe. Above the Néel temperature the reciprocal susceptibility of all samples obeys the Curie–Weiss law. The determined values of paramagnetic moments which were found to be close to the free ion values and the paramagnetic Curie temperatures are listed in Table I.

TABLE I

Magnetic data for RCoSn and RRhGe compounds: $T_N$ — the Néel temperature, $\theta_p$ — the paramagnetic Curie temperature, $\mu_{eff}$ — the value of the effective magnetic moment in paramagnetic states. $\mu$ — the value of magnetic moment determined: $M$ — from magnetization (at $T = 4.2$ K and $H = 50$ kOe), $ND$ — from neutron diffraction data (at $T = 4.2$ K).

| Compound | $T_N$ [K] | $\theta_p$ [K] | $\mu_{eff}$ [$\mu_B$/R$^{3+}$] | | $\mu$ [$\mu_B$/R$^{3+}$] | | | |
|----------|-----------|----------------|------|--------|------|------|--------|------------|
| | | | exp. | theor. | $M$ | $ND$ | theor. | $H_C$ [kOe] |
| TbCoSn | 20.5 | 15 | 9.81 | 9.72 | 5.5 | 8.3 | 9.0 | 2.9 |
| DyCoSn | 10.0 | 9 | 10.49 | 10.67 | 5.6 | – | 10.0 | 2.6 |
| HoCoSn | 7.8 | 6.5 | 10.44 | 10.61 | 6.0 | 8.6 | 10.0 | 3.5 |
| ErCoSn | – | 0 | 9.55 | 9.58 | 7.1 | – | 9.0 | – |
| CeRhGe | 10 | −19 | 2.25 | 2.54 | 0.75 | 1.4 | 2.14 | 25.0 |
| NdRhGe | 14 | −10 | 3.73 | 3.62 | 0.17 | 2.0 | 3.27 | – |

The magnetization curves measured at 4.2 K indicate the metamagnetic phase transition with critical fields listed in Table I. The magnetization curve of ErCoSn is typical for paramagnetic materials. For CeRhGe the magnetization is a linear function of the magnetic field. At $H = 50$ kOe the magnitudes of magnetic moments of R$^{3+}$ ions are smaller than the free ion values. Neutron diffractograms of TbCoSn and HoCoSn recorded at 4.2 K show a large number of additional reflections of a magnetic origin (see Fig. 1). The magnetic peaks were indexed on magnetic unit cells characterized by propagation vectors: $k = (0, 0.25, 0.11)$ in TbCoSn and $k = (0, 0.333, 0)$ in HoCoSn. The best agreement between the calculated and observed intensities was obtained for a sine-wave-modulated structure.
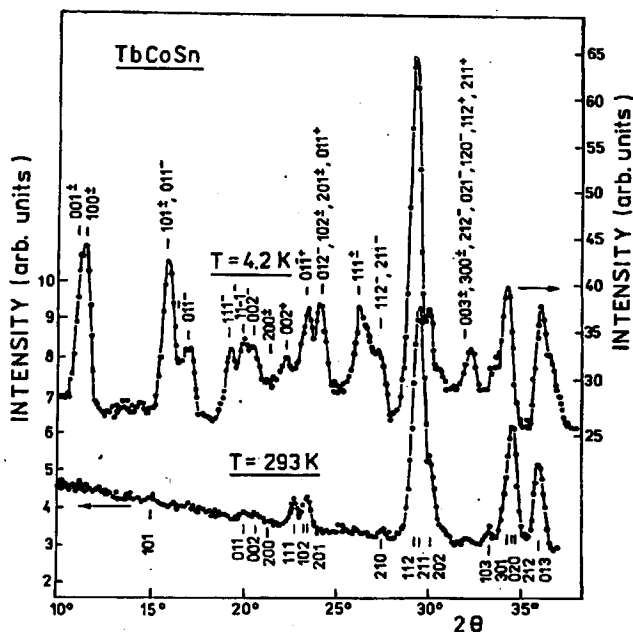
Fig. 1.  Neutron diffraction patterns of TbCoSn taken at 4.2 K and 293 K.

The magnetic moments of $S_1(x, 1/4, z)$ and $S_2(\bar{x}, 3/4, \bar{z})$ form the one modulation, whereas $S_3(1/2-x, 3/4, 1/2+z)$ and $S_4(1/2+x, 1/4, 1/2-z)$ the second one. The direction of the magnetic moments is described by the Euler angles $\theta$ (angle with the $c$-axis) and $\varphi$ (with $a$-axis). The values of angles and the magnetic moments are given in Table II.

TABLE II

Parameters of the magnetic structure of TbCoSn and HoCoSn.

| Compound | $\theta$ | $\phi_1$ | $\phi_2$ | $\mu$ [$\mu_B$] |
|----------|----------|----------|----------|-----------------|
| TbCoSn   | 70.10    | 30.60    | 97.60    | 8.3             |
| HoCoSn   | 113.30   | 47.8     | 132.2    | 8.6             |

$\theta$ — angle with the $c$-axis; $\phi_1$ and $\phi_2$ — angles with $a$-axis.

The projection of the magnetic structures on the $b$–$c$ plane of both compounds is presented in Fig. 2.

In the case of CeRhGe and NdRhGe a magnetic unit cell has the same dimensions as the crystal one. The magnetic structure is collinear with the following orientation of magnetic moments along $a$-axis: $S_1 + S_2 - S_3 - S_4$. The magnitudes
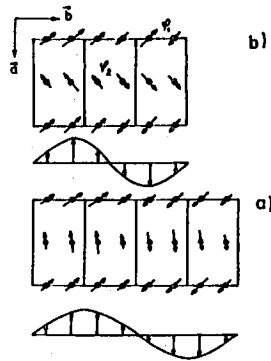
Fig. 2.   The projection of the magnetic structure of (a) TbCoSn and (b) HoCoSn.

of magnetic moments at 4.2 K localized on Ce and Nd ions were determined to be 1.4(2) and 2.0(2) $\mu_B$, respectively.

## 4. Discussion

The magnetic ordering in rare earth intermetallic compounds may be explained as due to the competition between exchange interactions of the RKKY-type and the magnetocrystalline anisotropy caused by the influence of the crystalline electric field on $4f$-electrons. The RKKY-type exchange interactions favour a long-range oscillatory antiferromagnetic ordering while the magneto-crystalline anisotropy favours a uniaxial magnetic ordering.

The observed sine-wave-modulated ordering, as well as the fact that the Néel and paramagnetic Curie temperatures of RCoSn compounds obey the de Gennes function, suggest that their magnetic properties may be explained in terms of the RKKY model of indirect interactions via conduction electrons.

The determined magnitudes of ordered magnetic moments at 4.2 K localized on $Tb^{3+}$ and $Ho^{3+}$ ions are close to the respective free ion values, indicating a small influence of the crystal electric field. Different properties observed in RRhGe compounds suggest a strong influence of crystal electric field.

## Acknowledgments

## References

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