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PHYSICA B

Magnetic anisotropy and exchange interaction in $(\text{Er}, \text{Y})_2\text{Co}_7\text{B}_3$ compounds

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Abstract

The Er–Co exchange interaction, J_{ErCo} , and the magnetic anisotropy in $\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ compounds with $x = 1.4, 1.5, 1.7, 1.9$ and 2.0 have been investigated by measuring the free-powder magnetization at 4.2 K . Magnetic transitions are found in the Y-rich compounds. A model description is presented to explain the rotation processes in the Er- and Co-sublattice moments, taking into account the Er- and Co-sublattice anisotropy energy, J_{ErCo} and the Zeeman energy. The experimental results have been fitted to this model. The experimentally observed easy- and hard-magnetization curves obtained on magnetically aligned samples can be well reproduced by using the values for J_{ErCo} and for the magnetic-anisotropy constants derived by analyzing the free-powder magnetization. For $\text{Er}_2\text{Co}_7\text{B}_3$, a value for $-J_{\text{ErCo}}/k$ has been derived of about 10.5 K . This value is compared with $-J_{\text{ErCo}}/k$ values in other Er–Co compounds.

1. Introduction

The exchange interaction between the $4f$ and $3d$ electrons and the role played by the $5d$ electrons have been studied in the past few years in many classes of rare-earth $3d$ -transition-metal intermetallic compounds by measuring the free-powder high-field magnetization [1]. In the present work, we have focused our attention on the R–T exchange interaction and the magnetic anisotropy in $\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ compounds.

$\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ alloys with $x = 1.4, 1.5, 1.7, 1.9$ and 2.0 were prepared by arc melting, followed by annealing at 1050°C for 4 weeks. From X-ray diffraction measurements it was found that the main phase has the $\text{Ce}_2\text{Co}_7\text{B}_3$ -type of structure, some secondary phases being present in negligible amounts. The magnetization curves were measured in the High Field Installation at the University of Amsterdam.

2. Experimental results and discussions

Fig. 1 shows the magnetization curves of the $\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ compounds. The circles correspond to the results obtained in stepwise changing fields and the dots represent results obtained in pulses in which the field changes continuously. The occurrence of magnetic transitions is clearly seen in all four curves. For ferrimagnetic compounds, when the field is low, the R- and T-sublattice moments are antiparallel, $M = |M_{\text{R}} - M_{\text{T}}|$, but when the field is high enough, the R- and T-sublattice moments will become parallel, $M = |M_{\text{R}} + M_{\text{T}}|$. Therefore, from the values of M at low and high fields one can determine the T-sublattice moment by assuming the R-ion moment to be constant. The results are collected in Table 1, where the M_{T} values for $\text{Er}_{0.3}\text{Y}_{1.7}\text{Co}_7\text{B}_3$ and $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$ are marked with star, because these values were derived from M^{H} (magnetization at infinitely high field), M_{T} and M_{R} having already rotated discontinuously at very low fields ($B < 1.3\text{ T}$). For these compounds, the values of M before the first step

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Fig. 1. Free-powder magnetization curves at 4.2 K for $\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ compounds.

Table 1

Magnetic moments of the R and T sublattices and critical fields of the magnetic transitions in $\text{Er}_{2-x}\text{Y}_x\text{Co}_7\text{B}_3$ compounds

	M_R ($\mu_B/\text{f.u.}$)	M_T ($\mu_B/\text{f.u.}$)	$B_{cr,1}$ (T)	$B_{cr,2}$ (T)
$\text{Y}_2\text{Co}_7\text{B}_3$	—	3.3	—	—
$\text{Er}_{0.1}\text{Y}_{1.9}\text{Co}_7\text{B}_3$	0.9	3.3	9.5	22.0
$\text{Er}_{0.3}\text{Y}_{1.7}\text{Co}_7\text{B}_3$	2.7	3.2*	9.5	21.5
$\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$	4.5	3.3*	12.0	21.0
$\text{Er}_{0.6}\text{Y}_{1.4}\text{Co}_7\text{B}_3$	5.4	3.1	15.5	20.7

(1.3 T < B < 10 T) do not correspond to $|M_R - M_T|$. All compounds show two jumps except $\text{Er}_{0.3}\text{Y}_{1.7}\text{Co}_7\text{B}_3$ and $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$ in which three jumps occur. The magnetization behaviour in the compositional range from $x = 1.7$ to $x = 1.5$ seems more complex.

One can see from Fig. 1 that if M_R is larger than M_T , hysteresis exists before and after the transition around

12 T. For compounds with M_R smaller than M_T , no hysteresis is found. In the magnetic transition at about 20 T, none of the four compounds shows hysteresis. As all compounds have same structure, the difference in hysteretic behaviour seems difficult to explain with domain theory. Possibly, the hysteresis is related to the nature of the magnetic anisotropy in these compounds. This problem will be discussed in a separate paper.

In order to analyse the magnetization curves shown in Fig. 1, we will investigate the behaviour expected for a single crystal which can rotate freely in the external fields by taking into account the anisotropies of the R and the T sublattices [3, 4]. By using the notations in Ref. [3], the free energy of the system can be expressed as

$$\begin{aligned}
 E = & K_1^R \sin^2 \theta_R + K_2^R \sin^4 \theta_R + K_3^R \sin^6 \theta_R \\
 & + K_1^T \sin^2 \theta_T + K_2^T \sin^4 \theta_T + K_3^T \sin^6 \theta_T \\
 & + n_{RT} M_R M_T \cos(\theta_R - \theta_T) - \mathbf{B} \cdot \mathbf{M},
 \end{aligned} \quad (1)$$

Fig. 2. Comparison of calculated and measured magnetization curves of $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$ for a free-powder sample and for magnetically aligned samples measured at 4.2 K. The solid lines represent the calculated results.

Table 2

Calculated magnetization parameters of $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$, K_i^R and K_i^{Co} are expressed in 10^{-20} J/f.u., n_{RCo} in 10^{23} T f.u./Am² and M_R and M_{Co} in μ_B /f.u.

	$\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$
K_1^R/K_1^{Co}	$0.031 \pm 0.005/0.028 \pm 0.004$
K_2^R/K_2^{Co}	$-0.030 \pm 0.012/-0.025 \pm 0.004$
K_3^R/K_3^{Co}	$0.057 \pm 0.029/0.032 \pm 0.003$
n_{RCo}	5.47 ± 0.11
M_R	4.48 ± 0.07
M_{Co}	3.12 ± 0.08

where

$$M = (M_R^2 + M_T^2 + 2M_R M_T \cos(\theta_R - \theta_T))^{1/2}. \quad (2)$$

If only nearest-neighbour interactions are considered and if the R–T exchange interaction is assumed to be isotropic, n_{RT} can be expressed as

$$n_{\text{RT}} = \left(1 - \frac{1}{g_R}\right) \frac{Z_{\text{RT}}}{N_T \mu_B^2} J_{\text{RT}}, \quad (3)$$

where Z_{RT} is the number of the nearest T-atom neighbours of an R atom and, being equal to about 14 for

$\text{Er}_2\text{Co}_7\text{B}_3$, and N_T is the number of transition-metal atoms per formula unit [2].

From Eqs. (1) and (2) one can derive the field dependence of the magnetization by minimizing the free energy E . Finally, by fitting the magnetization curves of Fig. 1 one can obtain the anisotropy constants of the R and T sublattices, as well as the molecular-field coefficient n_{RT} by continuously varying the fitting parameters, K_i^R , K_i^T , n_{RT} , M_R and M_T . As an example, the best-fit parameters of the sample $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$ are collected in Table 2. Fig. 2 shows the calculated magnetization curves in $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$. To check our calculations, we calculated the easy- and hard-magnetization curves by using the set of parameters given in Table 2 and compared them with the experimental results (Fig. 2) obtained on magnetically aligned powder samples. The anisotropy constants for the R sublattice given in Table 2 depend strongly on the composition of the compounds and, because there are several inequivalent rare-earth sites in this structure, one cannot expect a simple dependence of the anisotropy constants with the rare-earth composition. We have limited the calculations to the compound with $x = 0.5$ because only for this composition we were able to prepare a well-aligned sample, so that this is the only compound for which the results of the free-powder analysis can be compared with the results on aligned

Fig. 3. Dependence of the Er-Co exchange energy on the Co concentration.

material. Because some of the powder particles may consist of more than one grain and because of the presence of some impurity phase, one cannot expect the fitting quality to be extremely good. It can be seen that the jumps correspond to discontinuous rotations of the angles θ_R and θ_{Co} .

If we assume the n_{RCo} value of $\text{Er}_{0.5}\text{Y}_{1.5}\text{Co}_7\text{B}_3$ to be about the same as for the pure $\text{Er}_2\text{Co}_7\text{B}_3$ compound, which is reasonable because there is no reason to expect that n_{RT} will change appreciably upon Y substitution, we find $-J_{\text{ErCo}}/k$ for $\text{Er}_2\text{Co}_7\text{B}_3$ to be about 10.5 K. Fig. 3 shows the Er-Co exchange energy as found for various types of Er-Co compounds plotted as a function of the Co concentration. The value found for $\text{Er}_2\text{Co}_7\text{B}_3$ seems to be in agreement with general trend that the magnetic coupling energy $-J_{\text{ErCo}}/k$ decreases with increasing Co content. A similar tendency has been found for Fe-based compounds [1].

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