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EXPERIMENTAL STUDY OF SPIN-ORBIT INTERACTION IN INTERMETALLIC COMPOUNDS OF THE Er-In SYSTEM

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Normal, R_0, and anomalous, R_S, components of the Hall coefficient are determined from the results of experimental investigations of temperature dependences of the Hall coefficient, magnetic susceptibility, and specific electrical resistance for intermetallic Er_2In, ErIn, and Er_3In_5 compounds. Effective parameters of spin-orbital interaction λ_{SO} of intermetallic compounds are calculated from anomalous components R_S of the Hall coefficient and specific electrical resistance. The results calculated for the band parameters and effective parameters of spin-orbital interaction λ_{SO} for Er–In system intermetallides coincide by orders of magnitude with the results obtained in [4, 7, 8] from the optical spectra of pure rare-earth metals.

Keywords: Hall coefficient, specific electrical resistance, magnetic susceptibility, effective spin-orbital interaction parameter.

An integrated study of electric, magnetic, and galvanomagnetic properties of intermetallic compounds can be used to estimate the effective spin-orbital interaction parameter for the Er–In system. According to our knowledge, there are no other works in this direction in Russia and abroad except [1, 2] devoted to theoretical determination of the spin-orbital interaction parameter and results of investigations of the optical spectra.

Theoretical calculations of the spin-orbital interaction are rather complicated. It is well known (for example, see [3]) that the magnetic Hamiltonian of rare-earth ions is written as follows:

$$H = H_{\text{coul. free}} + H_{SO} + H_{\text{cryst. field}} + H_{\text{earthmet}}. \quad (1)$$

From here the spin-orbital Hamiltonian has the form

$$H_{SO} = \lambda\, \mathbf{L}\cdot\mathbf{S}, \quad (2)$$

where λ is the effective spin-orbital interaction parameter.

In this work, an attempt is undertaken for the first time to estimate the effective spin-orbital interaction parameter from experimental values of the specific electrical resistance, paramagnetic susceptibility, and the Hall coefficient. Exactly this fact provides originality of our approach in comparison with other authors, for example, Krupicka [4].

In the present work, electrical resistances ρ of the intermetallic Er–In system were experimentally investigated in a wide temperature interval. At 77–1000 K, they were measured using the conventional four-probe method, and at 800–2000 K, they were measured by the contactless method of rotating magnetic field.

Figure 1 shows the experimental temperature dependence of the specific electrical resistance ρ(T) of Er–In system compounds. An analysis of the ρ(T) dependence demonstrates that clearly pronounced bends are observed for 80Er – 20In and Er_2In samples at temperatures of 200 and 180 K that correspond to ferromagnet-paramagnet phase transitions; for other samples, this dependence is close to linear one both for the solid and liquid states. The specific electrical resistance at the melting point increases abruptly due to an essential increase in the entropy caused by the destruction of the long-range order in the arrangement of atoms in the crystal and the increased coordination number of the nearest atoms.

Figure 2 shows the experimental dependences of the Hall coefficient R_H for intermetallic Er_2In, ErIn, and Er_3In_5 compounds at temperatures in the range 300–1000 K. To measure R_H, the method of alternating current and variable magnetic field of different frequencies was used [5].

Figure 3 shows the temperature dependences of the magnetic susceptibility χ for the intermetallic Er–In systems at temperatures in the range 300–1000 K [6]. From Figs. 2 and 3 it can be seen that with increasing temperature, the Hall coefficient R_H and the magnetic susceptibility χ monotonically decrease.

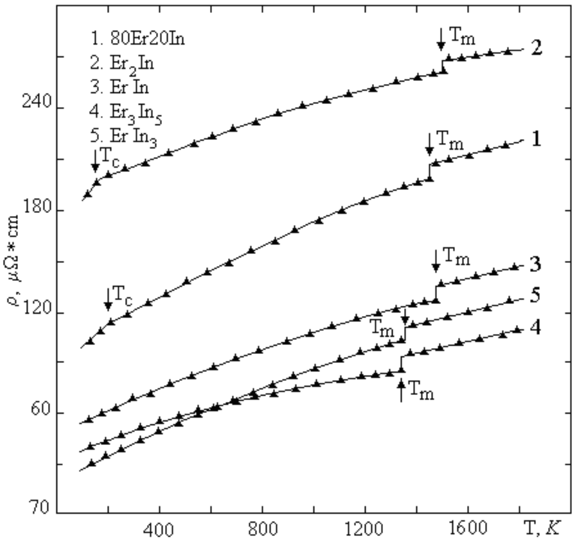

Fig. 1. Temperature dependences of the specific electrical resistance ρ(T) for the intermetallic Er–In system in the solid and liquid states. Here curve 1 is for 80Er–20In, curve 2 is for Er_2In, curve 3 is for ErIn, curve 4 is for Er_3In_5, and curve 5 is for $ErIn_3$.

This demonstrates that 4f-electrons, localized in sites of the Er sublattice, play the dominant role in the formation of magnetic properties of the examined compounds.

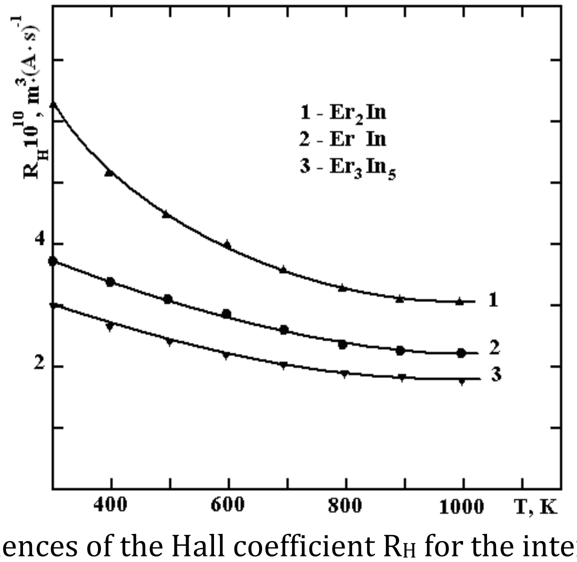

Fig. 2. Temperature dependences of the Hall coefficient R_H for the intermetallic Er–In compounds. Here curve 1 is for Er_2In, curve 2 is for ErIn, and curve 3 is for Er_3In_5.

Because of a number of circumstances indicated in [1], calculations of the effective spin-orbital interaction parameter are rather difficult. It is well known (for example, see [2]) that the anomalous Hall effect in rare-earth metals (REM) is a consequence of the spin-orbital interaction. In the paramagnetic region, the Hall coefficient R_H can be written in the form

$$R_{\mathrm{H}} = \frac{\rho_{\mathrm{H}}}{B} = R_0 + \frac{2e^2}{\mu_0 \mu_{\mathrm{B}} \hbar g} \rho^2 \lambda_{\mathrm{SO}} \chi = R_0 + R_S \chi \,, \quad (3)$$

where $\mu_B = 0.927\cdot10^{-23}$ J/T is the Bohr magneton, $\mu_0 = 4\pi\cdot10^{-7}$ G/m is the magnetic constant, $\hbar = 1.054\cdot10^{-34}$ J·s is the Planck constant, e = $1.6\cdot10^{-19}$ C is the electron charge, g is the Lande factor, ρ is the specific resistance, and λ_{SO} is the effective spin-orbital interaction parameter.

Then the effective spin-orbital interaction parameter λ_{SO} is

$$\lambda_{SO} = \frac{R_S \mu_0 \mu_B \hbar g}{2e^2\rho^2}. \quad (4)$$

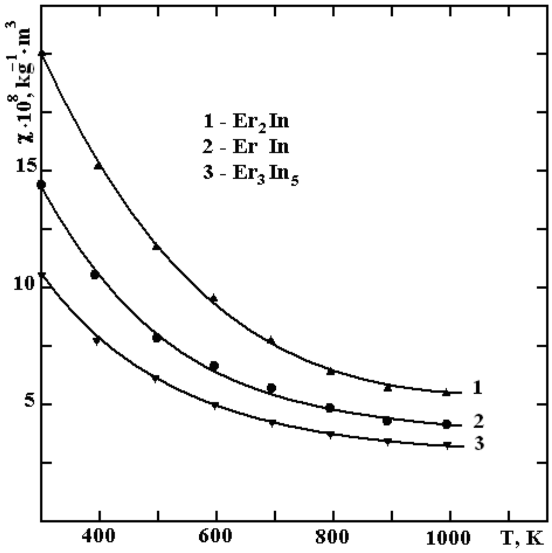

Fig. 3. Temperature dependences of the magnetic susceptibility χ of the intermetallic Er–In compounds [2]. Here curve 1 is for Er_2In, curve 2 is for ErIn, and curve 3 is for Er_3In_5.

An analysis of the experimental data demonstrates a correlation between the Hall coefficient R_H and the magnetic susceptibility χ for the intermetallic Er_2In, ErIn, and Er_3In_5 compounds shown in Fig. 4. As can be seen from the figure, the dependence of R_H on χ is linear for the samples. Extrapolating R_H to zero (OY axis), the normal, R_0, and anomalous, R_S, components of the Hall coefficients can be determined.

The effective spin-orbital interaction parameter λ_{SO} of electrons was calculated for the examined samples from the obtained anomalous component of the Hall coefficient R_S and the specific electrical resistance ρ.

The calculated results are given in Table 1.

TABLE 1. Normal and Anomalous Components of the Hall Coefficient and Effective Spin-Orbital interaction parameter

Compounds	$R_0\cdot10^{10}$, $m^3\cdot C^{-1}$	$R_S\cdot10^7$, $m^3\cdot C^{-1}$	$\lambda_{SO}\cdot10^{-13}$, erg
Er_2In	1.95	2.48	0.27
ErIn	1.8	1.72	2.28
Er_3In_5	1.4	1.77	4.17

As demonstrated our calculations, the results on the band parameters and effective spin-orbital interaction parameters λ_{SO} for the intermetallic Er–In systems coincide by the order of magnitude with the results obtained in [4, 7, 8] from the optical spectra of pure REM. The coincidence of χ and R_H signs demonstrates that the physical reason for the anomalous Hall effect is the spin-orbital interaction.

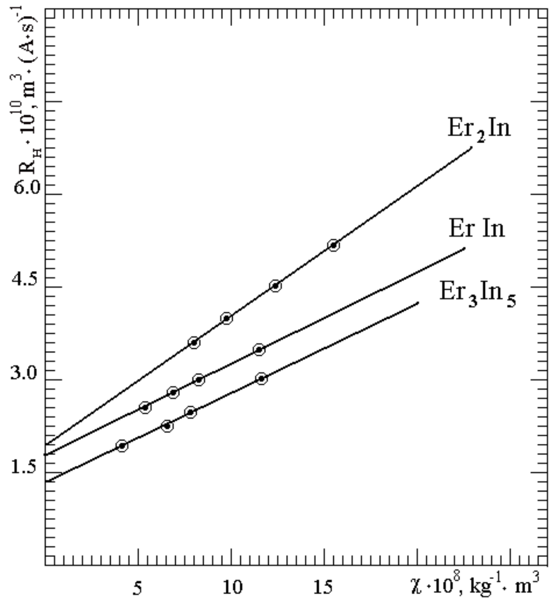

Fig. 4. Dependence of R_H on χ for the intermetallic Er–In compounds.

CONCLUSIONS

- The normal, R_0, and anomalous, R_S, components of the Hall coefficient were determined from experimental investigations of temperature dependences of the Hall coefficient, magnetic susceptibility, and specific electrical resistance of the intermetallic Er_2In, ErIn, and Er_3In_5 compounds.
- However, the coefficient of the anomalous Hall effect decreases with increasing indium concentration, whereas the effective spin-orbital interaction parameter λ_{SO} increases. This can be explained for the Kondo model [9]. It is assumed that magnetic electrons are localized, their magnetizing action on the conduction electrons can be neglected, and that exactly non-magnetized conduction electrons are carriers of the anomalous Hall effect. Therefore, the Kondo model is applicable to REM, since 4f-electrons do not participate in the formation of current.
- The effective spin-orbital interaction parameters λ_{SO} of the examined intermetallic compounds were calculated from the anomalous components R_S of the Hall coefficient and the specific electrical resistance.

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