

# Itinerent metamagnetism and the features of the magnetic structures of $(\text{Er}_{1-x}\text{Y}_x)\text{Co}_2$ compounds

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Magnetization, electrical resistance, thermal expansion and neutron diffraction analyses are used to show that  $d$ -band splitting of cobalt vanishes and the Er subsystem becomes disordered due to a phase transition of the first kind in  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds as the yttrium concentration increases to  $x = 0.4$ . It is found that for  $x \sim 0.45$  application of a moderate external magnetic field  $\mu_0 H \geq 0.4$  T stimulates growth in the magnetization of the partially-disordered Er subsystem accompanied by irreversible  $d$ -band splitting and an increase in the magnetic moment of cobalt from 0.3 to  $0.9 \mu_B$ . The minima in the temperature dependences of the electrical resistance observed in  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds ( $0.2 < x \leq 0.6$ ) at temperatures above the magnetic ordering temperature are related to spin density fluctuations in the cobalt subsystem.

The rare-earth intermetallic compounds  $\text{RCo}_2$  with an  $\text{MgCu}_2$  crystalline structure represent a type of magnet in which two interacting subsystems with different magnetic properties may coexist.<sup>1,2</sup> Indirect exchange RKKY interaction between the localized  $4f$ -electrons is largely responsible for the magnetic ordering in the R ion subsystem. The state of the subsystem of collectivized  $3d$ -electrons of Co hybridized with the  $5d$  ( $4d$  in the case of yttrium) electrons of the R ions will depend on the magnitude of the effective field  $H_{\text{eff}}$  acting on the subsystem which is determined by  $f$ - $d$ -exchange. Specifically the  $\text{YCo}_2$  compound is an exchange-enhanced Pauli paramagnet,<sup>3</sup> while the  $\text{RCo}_2$  compounds, in which the R ion has an intrinsic magnetic moment, are dual-sublattice ferro- or anti-ferromagnets with a magnetic moment on the cobalt atom  $\mu_{\text{Co}}$  of up to  $1.0 \mu_B$  (Ref. 4). Here  $\mu_{\text{Co}}$  has a metamagnetic dependence on  $H_{\text{eff}}$ , i.e., a weak growth of  $\mu_{\text{Co}}$  is first observed with increasing  $H_{\text{eff}}$ , while a sharp jump in  $\mu_{\text{Co}}$  occurs due to a phase transition of the first kind when the critical value  $H_{\text{eff}}^{\text{cr}}$  is attained.<sup>5</sup> This behavior of  $\mu_{\text{Co}}$  is due to the specific features of the electronic energy spectrum in the  $\text{RCo}_2$  compounds.<sup>6</sup> The itinerent metamagnetism of the cobalt subsystem is manifested specifically in the case where an external magnetic field in the  $\text{RCo}_2$  compounds ( $\text{R} = \text{Ho}, \text{Er}$ ) is applied at temperatures exceeding the ferromagnetic ordering temperature  $T_c$ <sup>4,7,8</sup> and in quasi-binary compounds with nonmagnetic R-ions<sup>9,10</sup>

$\text{Y}(\text{Co}_{1-x}\text{Al}_x)_2$  and  $\text{Lu}(\text{Co}_{1-x}\text{Al}_x)_2$ .

In addition to the external magnetic field it is also possible to alter  $H_{\text{eff}}$  by diluting the R subsystem with yttrium or lutetium.<sup>1,2</sup> At a specific diluent concentration  $H_{\text{eff}}$  drops below  $H_{\text{eff}}^{\text{cr}}$ , which causes the  $d$ -band splitting to vanish and results in a sharp drop in the magnetic moment of Co.<sup>1,2</sup> It is therefore possible to affect the  $d$ -band state by varying  $H_{\text{eff}}$  either by application of an external magnetic field or by altering the temperature or concentration of the magnetoactive R-ions.

Since the dilution of the R-subsystem will not only alter the state of the  $d$ -band but will also change the nature of the magnetic order in the R-subsystem itself, both subsystems must be included in the analysis, particularly near critical concentration.

The present paper describes an investigation of the behavior of the  $d$ - and R-subsystems by altering the yttrium

concentration and the temperature and by applying an external magnetic field for the case of  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds using magnetization, electrical resistance, thermal expansion and neutron diffraction measurements.

## EXPERIMENTAL TECHNIQUE

The  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  specimens were fabricated and their electrical resistance and magnetization were measured by techniques in Ref. 8. The temperature dependence of the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  crystalline lattice was investigated in a 5–80 K temperature range by means of a flow-type helium cryostat-attachment to an x-ray diffractometer. The magnetic field  $\mu_0 H = 0.4$  T was produced by a system of permanent magnets.

The neutron diffraction measurements were carried out on one horizontal channel in the IVV-2M reactor. The neutron wavelength was  $2.42 \cdot 10^{-1}$  nm. Cylindrical specimens fabricated from powder were used in the field measurements. A magnetic field with an induction of up to 0.95 T was generated by an electromagnet with superconducting windings. The nuclear scattering amplitudes of neutrons by Er, Y, and Co atoms as well as the form-factors for Er and Co were taken from Refs. 11, 12.

## EXPERIMENTAL RESULTS

**Electrical resistance.** As we see from Fig. 1 the temperature dependence of the electrical resistivity  $\rho(T)$  of the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds in the paramagnetic region ( $T > 35$  K) is independent of the concentration of erbium ions. This behavior of  $\rho$  was also observed for other  $\text{R}_{1-x}\text{Y}_x\text{Co}_2$  compounds<sup>13,14</sup> and is explained by assuming that the  $s$ - $d$ -scattering mechanism played a determinant role. In our specimens the behavior of  $\rho(T)$  varies with  $\text{Er}^{3+}$  ion concentration at low temperatures only. Replacing erbium with yttrium to  $x = 0.2$  will initially serve only to reduce the ferromagnetic ordering temperature where, as in the initial  $\text{ErCo}_2$  compound, a sudden change in  $\rho$  accompanying the magnetic phase transition of the first kind is observed. A further increase in yttrium concentration will produce a qualitative change in  $\rho(T)$ . First, as we see from Fig. 1, for  $x > 0.4$  no sharp drop in  $\rho$  is observed on the  $\rho(T)$  curves measured in zero magnetic field (curves 1). This sug-

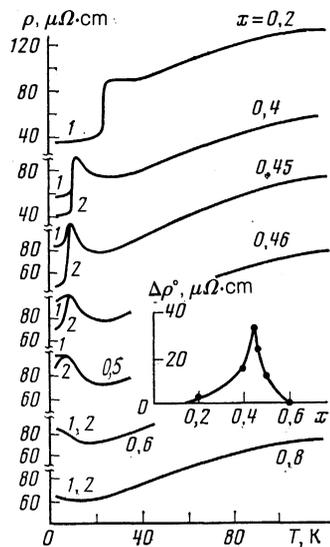


FIG. 1. Temperature dependence of the electrical resistivity for  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds of various chemical composition. Trace 1 was measured in zero field, trace 2 was measured after field action  $\mu_0 H > 0.4$  T at  $T = 1.8$  K. The insert shows the concentration relation of the difference  $\Delta\rho^\circ$  in the electrical resistivities in the initial state and after field action at  $T = 1.8$  K.

gests a conversion from a magnetic phase transition of the first kind to a magnetic phase transition of the second kind and is confirmed by Ref. 15. Second, an electrical resistance minimum is observed in compounds containing yttrium in concentrations exceeding  $x = 0.2$  above the magnetic ordering temperature  $T_c$ ; a substantial increase in the electrical resistance is also observed when  $T$  drops to  $T_c$ . Third, for  $x > 0.4$  the behavior of  $\rho(T)$  below  $T_c$  will depend on the previous treatment of the specimens. Thus if a magnetic field  $\geq 0.4$  T is applied to specimens with  $0.4 < x < 0.8$  at  $T = 1.8$  K, the specimens remain in a metastable stimulated state after removal of the field; in this state they have a substantially lower electrical resistance ( $|\Delta\rho/\rho|$  reduces to 40%). Only upon heating to  $T \sim T_c$  will curves 2 in Fig. 1 corresponding to the metastable state converge to curves 1.

As seen from Fig. 2a,b, which show the field dependence of the magnetization and electrical resistance for the

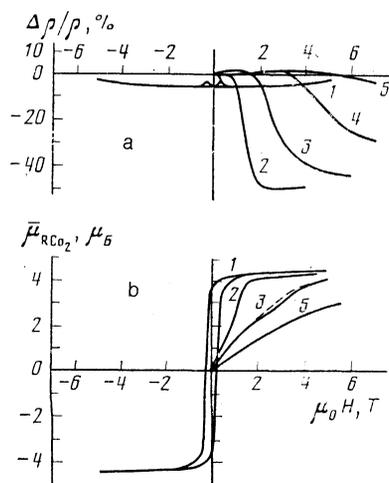


FIG. 2. Field dependences of the longitudinal magnetoresistance (a) and magnetization (b) for the compound  $\text{Er}_{0.8}\text{Y}_{0.2}\text{Co}_2$  at various temperatures: 1—4.2; 2—22; 3—26; 4—28; 5—30 K (the dashed curve represents magnetization with diminishing field).

$\text{Er}_{0.8}\text{Y}_{0.2}\text{Co}_2$  compound at  $T < T_c \approx 24$  K, the behavior of  $\mu_{\text{RCO}_2}(H)$  is typical of ferro- or ferrimagnets. Judging by the magnetization curve and accounting for the fact that the magnetocrystalline anisotropy and exchange interaction energies are comparable, the magnetic hysteresis at  $T = 4.2$  K may be due to the intrinsic coercivity of the domain boundaries.<sup>16</sup> The electrical resistance of the specimen under field action at 4.2 K, as indicated by Fig. 2a, varies from 0 to 5% due to the changing number of and volume of the domain boundaries and the paraprocess. For  $T > T_c$  the magnetization curves, as is the case in other  $\text{RCO}_2$  compounds,<sup>4,7</sup> have metamagnetic anomalies associated with the irregular rise in the magnetic moment of the cobalt subsystem due to  $d$ -band splitting at the critical effective field  $H_{\text{eff}}$ . The metamagnetic nature of the magnetization process at  $T > T_c$  becomes more clearly manifested in electrical resistance analyses. Figure 2a clearly indicates that a rise in  $H$  to  $H_{\text{cr}}$  at  $T = 20, 26$  K will initially cause an insignificant change in  $\rho$  even though the magnetization of the compound, which is determined by the erbium subsystem in these fields, reaches approximately one-half of the maximum value. However a sharp drop in the electrical resistance of the specimen amounting to nearly a factor of two is observed for  $H \sim H_{\text{cr}}$  when there is a jump in the magnetization associated with  $d$ -band splitting and the establishment of ferrimagnetic order. This behavior of  $\rho$  confirms a previous conclusion<sup>8</sup> that the kinetic properties of the test compounds are substantially dependent on the state of the  $d$ -band.

An increase in the yttrium concentration to  $x > 0.4$  causes a qualitative change not only in the temperature but also the field dependences of  $\rho$ . Figure 3a,b displays  $\bar{\mu}_{\text{RCO}_2}(H)$  and  $\Delta\rho(H)/\rho$  for the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound as an example. No metamagnetic anomalies are observed in this compound for  $T > T_c \approx 8$  K on either the magnetization curves or on the longitudinal magnetoresistance curves. Moreover at  $T = 1.8$  K, in spite of the qualitative similarity of the  $\bar{\mu}_{\text{RCO}_2}(H)$  relations for  $x = 0.2$  and  $x = 0.45$ , a fundamental change in the behavior of the electrical resistance is observed. Applying a magnetic field to the specimen cooled at  $H = 0$  to  $T = 1.8$  K initially causes an insignificant rise and then at  $\mu_0 H \approx 0.4$  T a sharp drop in the electrical resistance ( $|\Delta\rho/\rho| \sim 40\%$ ), which accompanies growth in the

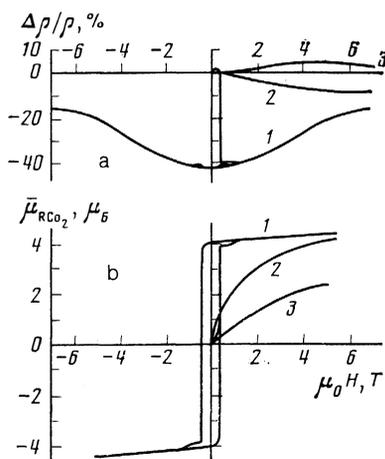


FIG. 3. Field dependence of the longitudinal magnetoresistance (a) and magnetization (b) for the compound  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  at various temperatures: 1—1.8; 2—12; 3—20 K.

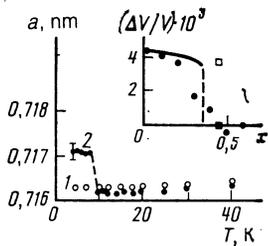


FIG. 4. Temperature dependences of the crystalline lattice parameter of the compound  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  measured in zero field (○) and at  $\mu_0 H = 0.4$  T (●). The insert shows the concentration relation of the magnetovolumetric anomaly in the compound  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  based on Ref. 15; □ and ■ represent the values of  $\Delta V/V$  obtained in the present study for  $\mu_0 H = 0.4$  and 0 T, respectively.

magnetization of the specimen. Further variation of the field is accompanied by a change  $\Delta\rho/\rho$  following the galvanomagnetic hysteresis loop, although this will not return the specimen to its initial electrical resistance state even after the magnetic field is removed. The specimen can be returned to its initial state only after heating to  $T \sim T_c$  (see Fig. 1) and subsequent cooling in zero field.

**Thermal expansion.** As indicated by Fig. 4 the temperature dependence of the lattice parameter of the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound measured in zero external magnetic field does not reveal any anomalies in the 5–40 K temperature range, which is consistent with the data from Ref. 15. However for  $\mu_0 H = 0.4$  T, which suffices (see Fig. 3) to drive the specimen to a state with a low  $\rho$ , the  $a(T)$  relation shows a substantial deviation from a Debye relation at  $T < 10$  K. The change in the unit cell volume  $\Delta V/V \sim 3.8 \cdot 10^{-3}$  in this case. Qualitative differences in the behavior of the electrical resistance and thermal expansion of the specimens, both under magnetic field action and when the yttrium concentration near  $x = 0.45$  is altered, indicate a change in the magnetic state of the compounds as the concentration of the magnetoactive ions  $\text{Er}^{3+}$  decreases, which is confirmed by neutron diffraction analyses of the magnetic structure.

**Neutron diffraction analysis.** Neutron diffraction patterns of powder specimens of  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds with various concentrations of  $\text{Er}^{3+}$  ions were recorded at room temperature and at  $T = 4.2$  K. Nuclear scattering patterns characteristic of the  $\text{MgCu}_2$  structure were observed at  $T = 300$  K. Our neutron diffraction pattern obtained for the  $\text{ErCo}_2$  compound at 4.2 K was in good agreement with Ref. 17. Hence Fig. 5 provides only those sections of the neutron diffraction patterns near the (111) reflex that demonstrate changes in the magnetic structure of the compounds under dilution by yttrium. As is seen from Fig. 5, the magnetic contribution to coherent neutron scattering at 4.2 K associated with the existence of long-range ferrimagnetic order in the compounds vanishes as early as  $x = 0.6$ . Intensity maxima due to the diffuse scattering of neutrons in regions of short-range magnetic order are observed in the concentration range near  $x = 0.45$  in addition to peaks caused by coherent magnetic and nuclear scattering. An increase in the yttrium concentration to  $x = 0.6$  will cause the diffuse scattering to vanish. Consequently according to the neutron diffraction data at  $x = 0.6$  both short-range and long-range magnetic order are absent in the test compounds. Figure 6

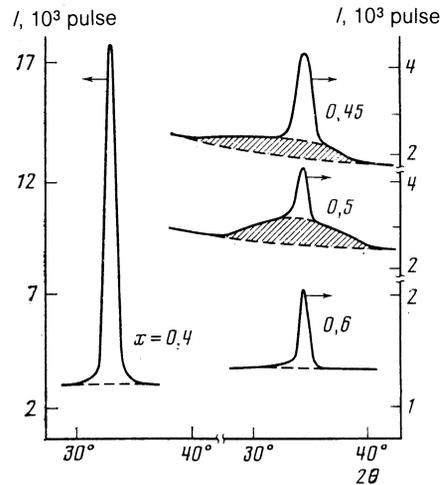


FIG. 5. Neutron diffraction pattern sections near the (111) reflexes measured at 4.2 K for powder specimens of  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds of various chemical composition (the shaded area represents the intensity due to diffuse neutron scattering).

shows concentration relations of the mean magnetic moments at 4.2 K at the cobalt atom ( $\bar{\mu}_{\text{Co}}$ ) and the R ion ( $\bar{\mu}_{\text{R}}$ ) calculated from neutron diffraction patterns of powder samples with various concentrations of yttrium. The derived values of  $\bar{\mu}_{\text{Co}}$  and  $\bar{\mu}_{\text{R}}$  differ insignificantly from the corresponding values as  $T \rightarrow 0$  K since the magnetizations of the erbium and cobalt subsystems are weakly dependent on temperature near the measurement temperature of 4.2 K (see the insert to Fig. 6). As indicated by Fig. 6 an increase in  $x$  to  $x > 0.4$  will cause a sharp drop in  $\bar{\mu}_{\text{Co}}$  and  $\bar{\mu}_{\text{R}}$  where  $\bar{\mu}_{\text{Co}}$  vanishes at an yttrium concentration ( $x \sim 0.5$ ) below  $\mu_{\text{R}}$  ( $x \sim 0.6$ ).

## DISCUSSION OF RESULTS

Replacement of the  $\text{Er}^{3+}$  ions by  $\text{Y}^{3+}$  ions in the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds will cause molecular field fluctuations in the erbium subsystem

$$\langle \mathbf{h}_i \rangle = (1-x) \sum_j I_{ij}^{\text{RKKY}} (2k_{\text{F}} \mathbf{R}_{ij}) \boldsymbol{\mu}_j(\text{Er}) \quad (1)$$

where summation is carried out solely over the erbium-occupied sites and  $\boldsymbol{\mu}_j$  is the magnetic moment of Er at site  $j$ . The

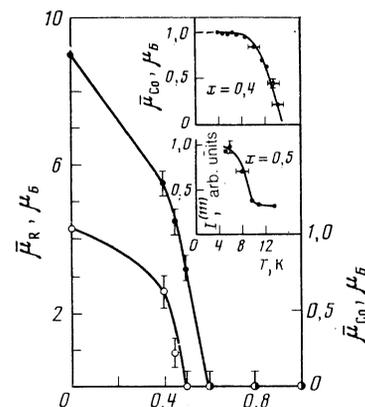


FIG. 6. The concentration relations of the average magnetic moments on the cobalt atom ( $\bar{\mu}_{\text{Co}}$ ) and the R ion ( $\bar{\mu}_{\text{R}}$ ) based on neutron diffraction data. The insert shows the temperature dependences of  $\bar{\mu}_{\text{Co}}$  for  $x = 0.4$  and the reflex intensities  $I^{(111)}$  for  $x = 0.5$ .

primary properties of such a molecular field  $\mathbf{h}$  include the average

$$|\langle \mathbf{h}_i \rangle| = (1-x) \left| \sum_j I_{ij}^{\text{RKKY}} (2k_F \mathbf{R}_{ij}) \mu_j(\text{Er}) \right| \quad (2a)$$

and the dispersion

$$D_h = \langle \mathbf{h}_i^2 - \langle \mathbf{h}_i \rangle^2 \rangle = (1-x) x \sum_j [I_{ij}^{\text{RKKY}} (2k_F \mathbf{R}_{ij})]^2 \mu_j^2(\text{Er}) \quad (2b)$$

( $\langle \dots \rangle$  represents averaging over the distribution of the erbium atoms. Summation is carried out over all sites). Dilution of the erbium subsystem to a certain critical level  $x_{\text{cr}}$  gives rise to a situation where the dispersion exceeds the molecular field average  $D_h^{1/2} > |\langle \mathbf{h} \rangle|$ , which causes a breakdown in long-range magnetic order. It is possible to obtain an estimate of the critical concentration from the expression

$$(1 - x_{\text{cr}}) = (\gamma + 1)^{-1} \gamma, \quad (3a)$$

where

$$\gamma = \left| \sum_j I_{ij}^{\text{RKKY}} (2k_F \mathbf{R}_{ij}) \mu_j(\text{Er}) \right|^{-2} \times \sum_j [I_{ij}^{\text{RKKY}} (2k_F \mathbf{R}_{ij})]^2 \mu_j^2(\text{Er}). \quad (3b)$$

Estimates yield  $\gamma \gg 1$ , since the contributions of the different coordination shells are compensated in the summing process in the denominator of (3b) due to oscillations of the integral  $I^{\text{RKKY}}$ . It follows that the breakdown of the long-range magnetic order is initiated even at low yttrium concentrations. Long-range magnetic order cannot exist here in the concentration range  $x_{\text{cr}} < x < x_t$  ( $x_t$  is the threshold for the onset of flow) in the entire system with an average, even nonsaturated, order parameter  $\langle \mu_j \rangle$  since its fluctuations are always (when  $x > x_{\text{cr}}$ ) greater than the averages. This suggests that a continuous concentration transition from ideal order at  $x = 0$  to a completely disordered state ( $\mu_j = 0$ ) is impossible. Consequently the magnetic order may be altered by dilution in the test compounds due to a phase transition of the first kind. Itinerent metamagnetism of the cobalt subsystem provides additional stimulus for an irregular transition.

"Microscopic" phase transitions of the first kind are observed in clusters that arise due to concentration fluctuations in the transition from  $x = 1$  to lower yttrium concentrations; the dimensions of these fluctuations are substantial compared to the Debye radius of the  $d$ -electrons in the  $3d$ -band, while the corresponding quantity  $H_{\text{eff}}$  produced by the erbium subsystem exceeds the critical value  $H_{\text{eff}}^{\text{cr}}$ .

Yttrium dilution of the erbium subsystem to  $x = 0.4$ , as indicated by the experimental results, serves to reduce the effective field  $H_{\text{eff}}$  acting on the cobalt subsystem. A further increase in the yttrium concentration will cause a breakdown in the long-range magnetic order in the erbium subsystem and will generate regions of short-range order. An estimate of the dimensions of these regions at the half-width of the diffusion maximum<sup>18</sup> yields a value of approximately 30 Å for  $x = 0.45$ . The coexistence of short- and long-range magnetic order at  $x = 0.45$  indicates that the disordering of the erbium subsystem from dilution in fact occurs via a phase transition of the first kind. The disappearance of long-range magnetic order near the critical concentration  $x = 0.45$  is accompanied by the vanishing of  $d$ -band splitting and a sharp drop in  $\mu_{\text{Co}}$ . This fact combined with neutron diffraction data is confirmed by the qualitative variation in

the behavior of the electrical resistance of the compounds (see Figs. 1–3) as well as the vanishing of anomalies in the temperature dependence of the unit cell bulk associated with  $d$ -band splitting.<sup>15</sup>

The effective field  $H_{\text{eff}}$  acting on the cobalt subsystem in  $\text{RCO}_2$  compounds can be described by the following expression:

$$H_{\text{eff}} = \lambda_{\text{Er-Co}} (1-x) \langle \mu_{\text{Er}}(\mathbf{H}) \rangle + \mathbf{H}, \quad (4)$$

where  $\lambda_{\text{Er-Co}} < 0$  is the molecular field constant characterizing the exchange interaction between the erbium and cobalt subsystems and  $\langle \mu_{\text{Er}} \rangle$  is the average magnetic moment of the erbium. One might expect that the application of the external magnetic field would, in accordance with (4), reduce  $|H_{\text{eff}}|$  and, consequently, the magnitude of  $3d$ -band splitting as well as the average magnetic moment of the Co ions. However such an assumption does not account for possible changes in  $\langle \mu_{\text{Er}} \rangle$  in the field and contradicts experimental results.

In fact, as indicated by electrical resistance measurements, the application of a moderate external field  $\mu_0 H \geq 0.4$  T will produce an irreversible drop in  $\rho$  by a factor of approximately two at  $T = 1.8$  K in the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound (Fig. 3b). In this case the  $\rho(T)$  relation after removal of the field becomes qualitatively similar to the  $\rho(T)$  relation for a specimen with a lower yttrium concentration such as  $x = 0.2$  in which  $\bar{\mu}_{\text{Co}} \sim 1.0 \mu_B$  (Fig. 1). Consequently we can assume that  $d$ -band splitting occurs in the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound at  $\mu_0 H \geq 0.4$  T. This assumption is confirmed by anomalies appearing in the temperature dependence of the lattice parameter  $a(T)$  (Fig. 4) measured in this same compound when  $\mu_0 H = 0.4$  T. The volumetric change  $\Delta V/V$  in the specimen with  $x = 0.45$  in the presence of the field is consistent with the data from Ref. 15 (see the insert in Fig. 4) obtained for  $x < 0.4$  in zero field.

The field dependence of the (111) reflex intensity  $I^{(111)}$  on a neutron diffraction pattern recorded from a specimen with  $x = 0.45$  at 4.2 K was measured to perform a direct test for  $d$ -band splitting in a magnetic field  $\mu_0 H \geq 0.4$  T and to verify associated changes in the magnetic structure of (Er,Y)Co<sub>2</sub> compounds. Unlike the initial ErCo<sub>2</sub> compound for which, as anticipated,  $I^{(111)}$  remains virtually independent of  $\mu_0 H$  in the range 0–1.0 T, an irreversible  $I^{(111)}(H)$  relation was detected in the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound. It is clear from Fig. 7 that an insignificant growth of  $I^{(111)}$  initial occurs with increasing  $H$ , then for  $\mu_0 H > 0.4$  T a sharper rise in intensity appears which saturates at  $I_{\text{sat}}^{(111)}$  in a field of  $\sim 0.8$  T. After the field is removed the reflex intensity re-

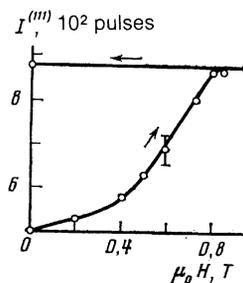


FIG. 7. Field dependence of the peak (111) reflex intensity measured in a powder specimen of the compound  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  at 4.2 K.

mains equal to  $I_{\text{sat}}^{(111)}$ . Since  $I^{(111)}$  is dependent on the average magnetic moments of both the erbium and the cobalt,

$$I^{(111)} = K(2^{1/2}\bar{\mu}_R + 2\bar{\mu}_{\text{Co}})^2,$$

where  $K$  is a constant, we carried out calculations of  $\bar{\mu}_R$  and  $\bar{\mu}_{\text{Co}}$  based on two reflexes in a range of angles  $2\theta = 30^\circ - 60^\circ$  from neutron diffraction patterns recorded at 4.2 K in zero magnetic field, and after application and subsequent removal of an external magnetic field of  $\mu_0 H = 0.95$  T. These values in the first case were  $\bar{\mu}_R = 4.12 \pm 0.08\mu_B$ ,  $\bar{\mu}_{\text{Co}} = 0.3 \pm 0.1\mu_B$ ; in the second case they were  $\bar{\mu}_R = 4.43 \pm 0.08\mu_B$ ,  $\bar{\mu}_{\text{Co}} = 0.9 \pm 0.1\mu_B$ .

Therefore electrical resistance, thermal expansion and neutron diffraction analyses suggest that application of a field of  $\mu_0 H > 0.4$  T increase the average magnetic moments of erbium and cobalt in the  $\text{Er}_{0.55}\text{Y}_{0.45}\text{Co}_2$  compound. Since the magnetic structure of this compound is partially disordered according to neutron diffraction analysis, application of an external magnetic field evidently has an ordering effect on the magnetic moments of erbium and causes  $\mu_{\text{Er}}$  to grow. Consistent with (4) a significant rise in the effective field  $H_{\text{eff}}$  acting on the cobalt system occurs in this case and produces  $d$ -band splitting. Using the data from Ref. 19 for the molecular field constant  $\lambda_{\text{Er-Co}}$  and the values of  $\bar{\mu}_R$  and  $\bar{\mu}_{\text{Co}}$  provided above for  $x = 0.45$  we find that after application of an external field of  $\mu_0 H \sim 0.95$  T the value of  $\mu_0 H_{\text{eff}}$  grows from 66 to 72 T. It is obvious that the fields used in our experiment [the second term in (4)] make a substantially smaller contribution to the change in  $H_{\text{eff}}$  compared to the contribution from changes in the magnetization of the erbium subsystem [the first term in (4)].

We note that the irreversibility of the behavior of the electrical resistance as well as the magnetization of the erbium and cobalt subsystems with field application and removal and the metastable state in the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds with  $x$  near  $x = 0.45$  may be associated with hysteresis in the  $\mu_{\text{Co}}(H_{\text{eff}})$  relation near  $H_{\text{eff}}^{\text{cr}}$  accompanying the phase transition of the first kind in the  $d$ -electron system. According to Ref. 20 the magnitude of such hysteresis may reach  $\sim 25$  T. The rather high magnetocrystalline anisotropy of  $(\text{Er}_{1-x}\text{Y}_x)\text{Co}_2$  compounds may also facilitate field-induced stabilization of the state so that the magnetic moments of the  $\text{Er}^{3+}$  ions orient along the [111]

crystallographic axes. We note that the very existence of irreversible changes in the electrical resistivity characterized by a value  $\Delta\rho^0$  (see the insert in Fig. 1) evidently suggest a metamagnetic transition in the  $d$ -band. Specifically the itinerant metamagnetism becomes manifested in relatively moderate magnetic fields of  $\mu_0 H \geq 0.4$  T in a concentration range of  $0.2 < x < 0.6$ .

As noted above clearly-expressed minima for  $T > T_c$  are observed on the  $\rho(T)$  relations (Fig. 1) for  $0.2 < x < 0.8$ . Such minima can be attributed to a variety of causes<sup>21</sup>; specifically, the minimum has been attributed to the Kondo effect in light rare-earth-metal alloys where the  $s$ - $f$ -exchange integral is negative. It has a low probability for  $\text{Er}^{3+}$  ions due to the positive sign of the  $s$ - $f$ -exchange integral.<sup>22</sup> Since two magnetic subsystems coexist in our test compounds and each makes its own contribution to the kinetic effects, in order to differentiate these contributions we measured the  $\rho(T)$  relations for  $\text{Er}_{1-x}\text{Y}_x\text{Ni}_2$  isostructural compounds. In the  $\text{RNi}_2$  compounds nickel has no magnetic moment due to the extraordinarily low density of  $d$ -states on the Fermi level.<sup>23</sup> Consequently the magnetic contribution to the total electrical resistance of the  $\text{RNi}_2$  compounds is due primarily to scattering by the localized magnetic moments of erbium. As clearly indicated by Fig. 8 a  $\rho(T)$  relation typical of metallic ferromagnets is observed for  $\text{ErNi}_2$  with an anomaly at  $T_c = 8.2$  K corresponding to a phase transition of the second kind from the paramagnetic state to the ferromagnetic state. The lower value of  $T_c$  in  $\text{ErNi}_2$  compared to the  $\text{ErCo}_2$  compound arise because there is no contribution from the  $f$ - $d$ -exchange attraction to the system energy.<sup>1</sup> Replacement of erbium by yttrium in the  $\text{ErNi}_2$  compound causes a linear drop in  $T_c$  to  $x = 0.5$  (see insert in Fig. 8). No minima are observed in the  $\rho(T)$  relations for  $x < 0.5$  above  $T_c$ , unlike the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds. A further dilution of the erbium subsystem to  $x = 0.6$  is the only measure that will cause an increase in electrical resistance with diminishing temperature below 4.2 K, evidently due to the increasing contribution to scattering by irregularities in the magnetic structure as the threshold for the onset of flow is approached:  $x_i = 0.65 - 0.7$ .

Differences in the behavior of the electrical resistance of  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  and  $\text{Er}_{1-x}\text{Y}_x\text{Ni}_2$  compounds for  $T > T_c$  indicate that the minimum on the  $\rho(T)$  relations and the substantial growth in  $\rho$  (to  $20\mu\Omega\cdot\text{cm}$ ) as  $T$  drops to  $T_c$  in the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds with an yttrium concentration of  $0.2 < x < 0.6$  are due to the cobalt subsystem. The source of additional conduction electron scattering as the temperature decreases to  $T \sim T_c$  in the  $\text{Er}_{1-x}\text{Y}_x\text{Co}_2$  compounds evidently includes fluctuations in its spin density that are in turn caused by the onset of short-term order and effective field fluctuations in the Er subsystem due to the statistically-irregular erbium atom distribution throughout the lattice. "Microscopic" phase transitions accompanied by changes in the local density of states of the cobalt and spin density fluctuations occur, as in the case of changes in concentration, in the regions of short-range magnetic order (clusters) when the critical local effective field level is reached with diminishing  $T$ .

The substantial increase in electrical resistance as  $T_c$  is approached is likely due to the increasing number and volume of such clusters.<sup>24</sup> The establishment of long-range

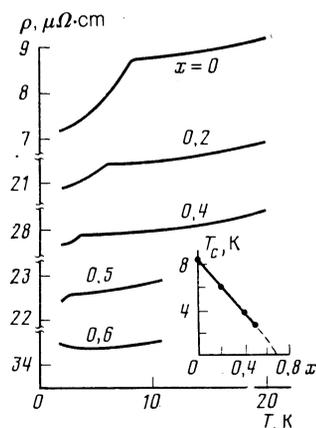


FIG. 8. The temperature dependences of the electrical resistivity of  $\text{Er}_{1-x}\text{Y}_x\text{Ni}_2$  compounds of various chemical composition. The insert shows the concentration dependence of the Curie temperature  $T_c$ .

magnetic order in the system at  $T = T_c$  is accompanied by a sharp drop in  $\rho$  (Fig. 1,  $x = 0.4$ ). However as noted above the long-range magnetic order, even at low temperatures ( $\leq 4$  K), is not set up uniformly through the volume of the specimens in the concentration range  $0.4 < x < 0.5$ , but rather coexists with regions of short-range magnetic order. The role of spin fluctuations in the cobalt subsystem when  $T > T_c$  is evidently substantially lower in compounds with a higher yttrium concentration ( $0.6 < x \leq 0.8$ ) for which  $H_{\text{eff}} \ll H_{\text{eff}}^{\text{cr}}$ , while the role of the electrical resistance with diminishing  $T$  can be attributed, by analogy to Ref. 25, to the onset of a stochastic magnetic structure of the spin glass type.

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