Magnetic states of a (110) plate of $Er_3Fe_5O_{12}$ in the temperature range 4.2–300 K. Coincidence of the spin-reorientation and compensation temperatures

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A visual investigation is made of the domain structure in a (110) plate of $Er_3Fe_5O_{12}$ in the temperature range 4.2–300 K, and of the absorption spectrum of the Er^{3+} ion in each magnetic phase. The application of such a complex microspectral method enabled us to detect experimentally phase transitions due to reorientation of the magnetic moments, to determine their nature, fully to understand the character of the changes of the magnetic structure of $Er_3Fe_5O_{12}$ over the whole temperature range investigated, and also to separate clearly the features due to the phenomena of spin reorientation and of compensation of the magnetic moments. A theoretical analysis carried out for a (110) plate of a cubic ferrimagnet, with allowance for induced anisotropy, showed that all the experimentally observed magnetic phases are thermodynamic-equilibrium phases, and that the phase transitions reflect the temperature variations of the magnetic parameters of the erbium iron garnet. It is observed that in $Er_3Fe_5O_{12}$ a complex situation occurs when the phenomenon of spin reorientation stimulates the appearance of a compensation point. This effect is associated with the proximity of the spin-reorientation and compensation temperatures in the case of $Er_3Fe_5O_{12}$ and with the anisotropy of the magnetic moment of the Er^{3+} ion.

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In recent years, much attention has been paid to the investigation of phase transitions (PT) of the spin-reorientation (SR) type, resulting from a change of direction of the magnetic moments with respect to the crystallographic axes on variation of the temperature. In multiaxial magnetic materials (for example, in cubic ferrites with the garnet structure), the SR process is considerably complicated by the presence of a domain structure (DS) and the complicated reconstruction of it. Rare-earth ferrites with the garnet structure are rewarding model materials because of the fact that for these compounds, over the low-temperature range, there is wide variation of the values of the magnetic moment, of the magnetic anisotropy energy, of the magnetostriction, etc. This leads to the appearance of a large variety of magnetic states of the system and to various PT between them. In the present paper, we investigate and identify the magnetic states and the phase transitions in a (110) plate of erbium iron garnet ($Er_3Fe_5O_{12}$) in the temperature range 4.2–300 K.

At room temperature, the axis of easy magnetization (AEM) of $Er_3Fe_5O_{12}$ is ⟨111⟩; at $T = 4.2$ K, ⟨100⟩ (see, for example. Ref. 1). The question of the character and localization of the spin-reorientation phase transition (SRPT) has been investigated in a number of papers (the most complete bibliography is collected in Ref. 2), but so far it is debatable; and according to the data of different authors, the temperature range of the SR varies within the limits 74–135 K. Furthermore, there is information about the phenomenon of compensation of magnetic moments in the same range: $T_{comp} \sim 84$ K.[3] The proximity of T_{SR} and T_{comp} commands attention and in our opinion deserves more careful study.

In this paper, a detailed investigation is made of the DS of $Er_3Fe_5O_{12}$ and of the optical absorption spectrum of the Er^{3+} ion for each domain, over the temperature range 4.2–300 K (such a complex investigation was validated earlier as a microspectral method of investigation of magnetic states[1]). This method enabled us to separate clearly the features due to the phenomena of spin reorientation and of compensation of the magnetic moments and to determine the temperature interval and nature of the complicated PT. With $Er_3Fe_5O_{12}$ as an example, it is shown that superposition of SR and compensation effects can occur. In particular, in $Er_3Fe_5O_{12}$ a situation occurs in which SR stimulates compensation of the magnetic moments of the sublattices. This effect is associated with the proximity of T_{SR} and T_{comp} for $Er_3Fe_5O_{12}$ and with the anisotropy of the magnetic moment of the Er^{3+} ion.

The specimen studied was a monocrystalline plate of thickness 60 μm, with developed plane (110). Mechanically polished plates were annealed in an oxygen atmosphere for 30 h at $T = 1300$ °C to remove working-induced strains and to decrease the uniaxial growth anisotropy; they were then subjected to chemical polishing in orthophosphoric acid. The large value of the Faraday effect (FE) and the good optical transparency of such a plate permitted visual observation of its DS and investigation of the optical absorption spectrum on apparatus like that of Ref. 1. The light source was a xenon lamp DKSIP-120. For investigation over the temperature range 4.2–300 K, the specimen was freely mounted on a mandrel in a special continuous-flow cryostat.[4] Fixation of it along the contour by means of several lugs of fine soft wire eliminated mechanical strains of the material of the specimen and insured effective ventilation of the developed surface of the plate by a jet of gas with a prescribed temperature. The accuracy of maintenance and variation of the specimen temperature was no worse than 0.1 K.

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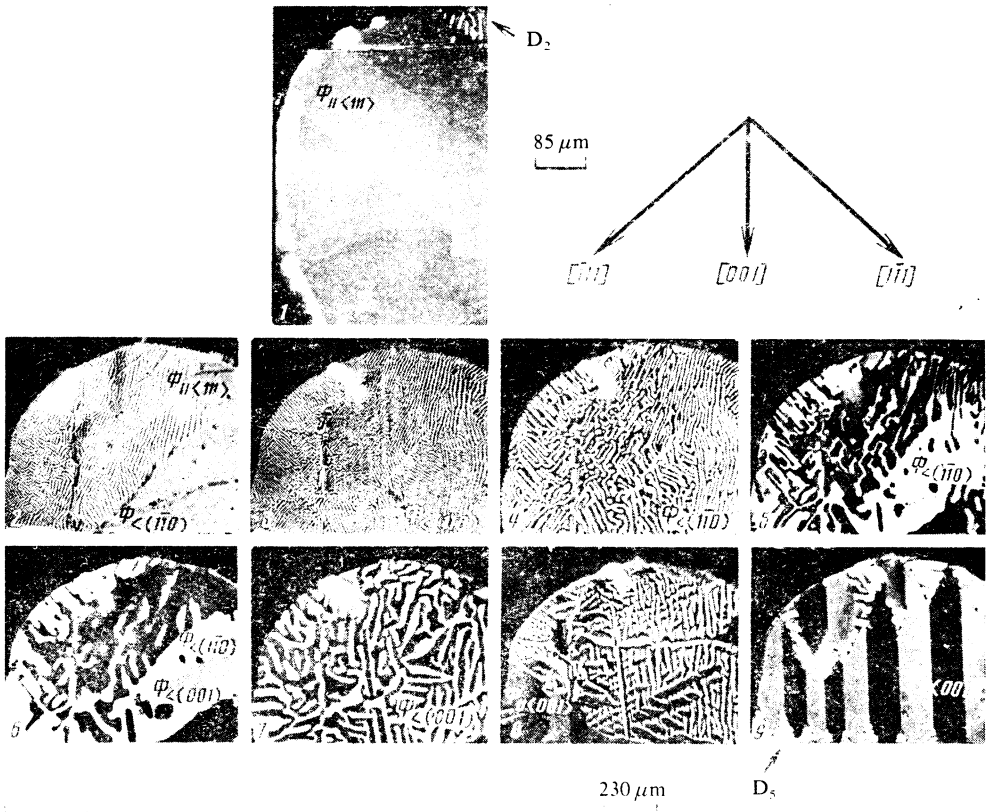

FIG. 1. Domain structure of $Er_3Fe_5O_{12}$ at various temperatures: 1) D1, T_{room}–200 K; 2) D1 + D2, 200–150 K; 3) D2, 150–96 K; 4) D2, 92 K; 5) D2, 91–89 K; 6) D2 + D5, 88.8–88 K; 7) D5, 87.4 K; 8) D5 + D6, 83 K; 9) D6, 4.2 K.

1. EXPERIMENTAL RESULTS

The experimental results obtained in the research are given in Figs. 1 and 2. Figure 1 shows the most characteristic DS obtained in a (110) plate of $Er_3Fe_5O_{12}$ over the temperature range 4.2–300 K. The absorption spectra of the Er^{3+} ion in the region of the transition ${}^4I_{15/2} \rightarrow {}^4S_{3/2}$, for specific magnetic states at corresponding temperatures, are shown in Fig. 2.

At room temperature, the DS of a (110) plate of $Er_3Fe_5O_{12}$ (Fig. 1,1) is completely analogous to that known earlier for a stress-free $Y_3Fe_5O_{12}$ specimen.[5] One observes a typical biaxial DS (D1), characteristic of the case when the magnetization lies along an AEM of the type ⟨111⟩ in the plane (110) (the phase $\Phi_{\parallel\langle 111\rangle}$ [1)]), which persists to $T \sim 200$ K. The absorption spectrum of the phase $\Phi_{\parallel\langle 111\rangle}$ could not be photographed in the temperature range 300–200 K because of the strong temperature dependence of the intensity of the absorption bands, which falls practically to zero at $T > 160$ K for the chosen thickness of the plate.

At $T = 4.2$ K, the DS (D6) consists of alternating bands of domains with clear boundaries, parallel to the axis ⟨001⟩ in the plane (110) (phase of the type $\Phi_{\parallel\langle 001\rangle}$) (Fig. 1,9). The linear polarization of the bands 3, 5, 7 in the absorption spectrum of the phases $\Phi_{\parallel\langle 001\rangle}$, connected with the directions ⟨001⟩ in the plane of the plate (Fig. 2), and the peculiarities of the behavior of the DS in a magnetic field enabled us to conclude that the total magnetic moment of $Er_3Fe_5O_{12}$ at $T = 4.2$ K, which determines the formation of the DS, is paralled to the AEM ⟨001⟩.[1]

Figure 1,1 and 1,9 show DS that are typical of the case when the magnetic moment **M** of the specimen lies in the plane of the plate, and that can be observed only if the light beam is inclined to the perpendicular to the specimen surface. At places of mechanical defects and stresses, as a rule, at the edge of the specimen (Figs. 1,1 and 1,9) DS (D2 and D5 respectively) are observed by the FE and therefore consist of domains in which the magnetization departs from the plane of the plate and is anti-parallel in neighboring domains.[1] It is possible that the formation of such DS is stimulated by the tendency toward closure of the magnetic flux at the ends of the plate.[6] According to experimental data (Figs. 1,1 and 1,9), however, such closure is not mandatory. A parallel investigation of the DS D2 at room temperature (Fig. 1,1) by a magneto-optic method and by means of a powder suspension showed that the powder figures, indicating the exits of the closure-domain boundaries at the plate surface, pass through the middle of the Faraday figures. Similar structures were observed earlier in $Y_3Fe_5O_{12}$ and were interpreted as DS with closure domains at the specimen surface.[7]

On lowering of the temperature, within the interval $150 < T < 200$ K the DS D1 changes in stages to D2 (phases $\Phi_{\angle(1\bar{1}0)}$). The spectrum of $\Phi_{\parallel\langle 111\rangle}$ could be photographed at $T = 160$ K, when the remains of this phase coexist with the $\Phi_{\angle(1\bar{1}0)}$ (Fig. 1,2). In the absorption spectrum corresponding to the magnetic phases $\Phi_{\parallel\langle 111\rangle}$, the bands 2′, 4, 6′ are linearly polarized, and they have maximum intensity just at orientation of the electric vector of the light wave $\mathbf{E} \perp \langle 111\rangle$ in the domain (Fig. 2).

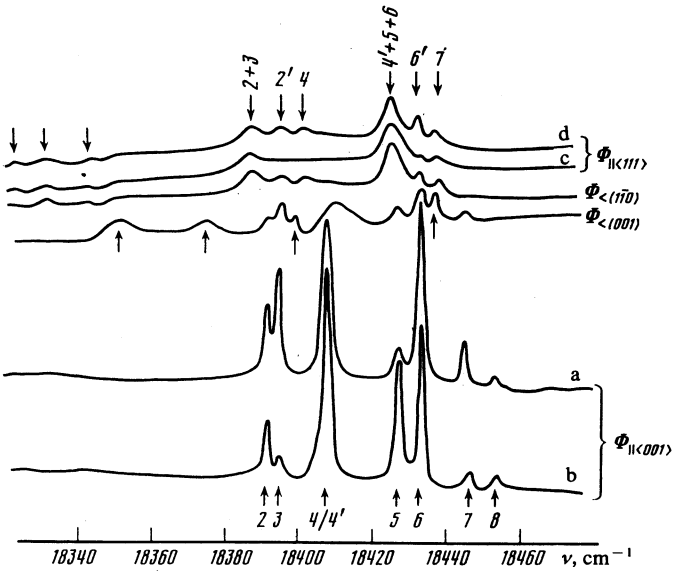

FIG. 2. Absorption spectra of the Er^{3+} ion in the region of the transition ${}^4I_{15/2} \rightarrow {}^4S_{3/2}$ for specific magnetic states, corresponding to a fixed temperature: $\Phi_{\parallel\langle 111\rangle}$, $T = 160$ K. (c, E||[111]; d, E⊥[111]); $\Phi_{\angle\langle 1\bar{1}0\rangle}$, $T = 110$ K (spectrum unpolarized); $\Phi_{\angle\langle 001\rangle}$, $T = 86$ K (spectrum unpolarized); $\Phi_{\parallel\langle 001\rangle}$, $T = 4.2$ K (a—E||[001]; b—E⊥[001]). On the spectra of the low-temperature phases $\Phi_{\parallel\langle 111\rangle}$, $\Phi_{\angle\langle 1\bar{1}0\rangle}$, and $\Phi_{\angle\langle 001\rangle}$ the unnumbered arrows show the absorption bands due to population of excited states of the Er^{3+} ion, which disappear at low temperatures.

For $T \leqslant 150$ K, the DS D2 fills the whole volume of the crystal (Fig. 1,3). This DS is observed in the FE geometry, i.e. the magnetic moment departs from the plane (110). The absorption spectrum of the phase $\Phi_{\angle\langle 1\bar{1}0\rangle}$ has the same structure as the spectrum of the $\Phi_{\parallel\langle 111\rangle}$ but is not polarized (Fig. 2).

Lowering of the temperature within the interval 96–88 K leads to the result that the domains enlarge appreciably, as is characteristic of the approach to T_{comp} (Fig. 1, 4–6). The structure of the spectrum remains unchanged over the interval $89 < T < 160$ K. Lowering of the temperature causes only a slight shift of the bands in the short-wave region.

The maximum domain size, characteristic of the region of magnetic compensation, is retained in the interval $\Delta T = 88.8$–88 K (Fig. 1,6). In this same temperature range, pulsations of the light of each domain abruptly appear without change of the contour of the main DS (the domain boundaries do not shift). In Fig. 1, 6 this shows up in the appearance of optical contrast within the limits of a single domain (for example, part of the lighter domain (the phase $\Phi_{\angle\langle 1\bar{1}0\rangle}$) looks like the darker, (the phase $\Phi_{\angle\langle 001\rangle}$). With lowering of the temperature, the volume of the new phase $\Phi_{\angle\langle 001\rangle}$ increases, and for $T < 88$ K the domains completely change color. Thus Fig. 1, 6 shows the magnetic state of a specimen in which there exist four magnetic phases. The color characteristic of a domain in this case is very sensitive to a change of temperature and indicates that a domain belongs to a strictly determined magnetic phase. Change of color of a domain means change of the angle of Faraday rotation of the corresponding magnetic phase, i.e. change of orientation of its magnetic moment.

At $T = 87.4$ K, there again coexist two magnetic phases of the type $\Phi_{\angle\langle 001\rangle}$, forming DS D5, and the DS begins to grow smaller (Fig. 1, 7). For $T \leqslant 88$ K ($T < T_{SR} = T_{comp}$), the structure of the spectrum changes fundamentally. The spectrum corresponding to the magnetic phase $\Phi_{\angle\langle 001\rangle}$ coincides in structure with the spectrum of the phase $\Phi_{\parallel\langle 001\rangle}$ but is unpolarized (Fig. 2). In the temperature interval $88 < T < 88.8$ K, pulsations of the light of the domains correspond to synchronous pulsations of the spectrum. There is no possibility of photographing the spectrum in this range. Visual observations enable us to conclude that in this range, the spectrum is the sum of spectra corresponding to coexistent magnetic phases of the types $\Phi_{\angle\langle 1\bar{1}0\rangle}$ and $\Phi_{\angle\langle 001\rangle}$ (Fig. 1, 6).

Practically simultaneously with the beginning of the growing smaller of the DS, there appears abruptly a nucleus of a new DS (D6) (phase $\Phi_{\parallel\langle 001\rangle}$) (Fig. 1,8), in which contrast between the domains is observed only if the beam of incident light is inclined to the perpendicular to the plane of the specimen; this indicates that the magnetic moment of the crystal lies in the plane. With futher lowering of the temperature, the nucleus of this phase grows, filling practically the whole crystal at $T = 4.2$ K (Fig. 1, 9).

Thus the experimentally observed features of the behavior of the DS and absorption spectrum in separate domains enable us to draw completely definite conclusions about the magnetic states of a (110) plate of $Er_3Fe_5O_{12}$ and about the nature of the PT between them in the temperature range 4.2–300 K. Here two facts are used that were established earlier[1,8] about the peculiarities of the absorption spectrum in the neighborhood of the transition ${}^4I_{15/2} \rightarrow {}^4S_{3/2}$ for the various magnetic phases of $Er_3Fe_5O_{12}$ that are produced by a weak external magnetic field: the splitting of the energy levels of the Er^{3+} ion is anisotropic and depends on the orientation of the magnetic moment of the crystal; the linear dichroism of the polarized bands fully reflects the direction of the magnetic moment in the crystal.

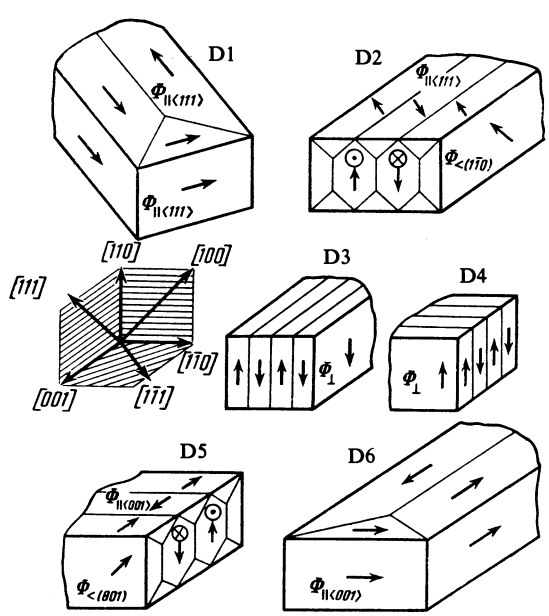

FIG. 3. Models of nonuniform states in a (110) plate of $Er_3Fe_5O_{12}$.

1. At high temperatures ($T > 200$ K), and $Er_3Fe_5O_{12}$ plate with developed plane (110) is divided into stripe domains, whose magnetic moments are parallel to the plane of the specimen but are opposite in neighboring domains (Fig. 1,1). The structure of the spectrum of a single domain (phase $\Phi_{\parallel\langle 111\rangle}$) corresponds to a magnetic structure with the magnetic moment parallel to axis $\langle 111\rangle$ (Fig. 2). Here the linear polarization of bands 2′, 4, 6′ is due to orientation of the electric vector **E** of the incident light along an AEM of the type $\langle 111\rangle$.

2. In the temperature range $150 < T < 200$ K, there occurs by stages a PT to an irregular stripe DS, in the main domains of which the magnetic moment departs from the plane of the specimen (phase $\Phi_{\angle(1\bar{1}0)}$) (Fig. 1,2). The transition to the magnetic phase $\Phi_{\angle(1\bar{1}0)}$ is not connected with a change of structure of the spectrum, but the bands become unpolarized (Fig. 2). This means that the magnetic moment reorients to a direction close to that $\langle 111\rangle$ axis that lies at an angle to the plane of the plate.

3. In the interval $\Delta T = 88.8$–88 K, there is observed a feature of the DS that is characteristic of T_{comp} (Fig. 1,6).

4. The region ΔT is accompanied by the phenomenon of SR, in which the magnetic moment, by a PT of first order, changes its orientation, remaining at an angle to the plane; i.e., $T_{comp} = T_{SR}$. Here there occurs a fundamental change of the structure of the absorption spectrum. To the phases $\Phi_{\angle(001)}$, which form an irregular stripe DS below $T_{SR} = T_{comp}$, corresponds an unpolarized spectrum (Fig. 2) whose structure is equivalent to the spectrum of phase $\Phi_{\parallel\langle 001\rangle}$. Consequently the magnetic moment reorients to directions close to axes $\langle 001\rangle$ that lie at an angle to the plane of the plate.

5. In the temperature range $4.2 < T < 87$ K, there is completed in stages a transition to a uniaxial stripe DS, in whose domains the magnetic moments are parallel to the plane of the specimen but are opposite in neighboring domains; i.e., **M** lies in the plane of the plate. The structure of the spectrum of a single domain (phase $\Phi_{\parallel\langle 001\rangle}$) and the polarization of its band correspond to a magnetic phase with orientation of the AEM along axis $\langle 001\rangle$ (Fig. 2).

Thus in the range 4.2–300 K, is a (110) plate of $Er_3Fe_5O_{12}$, one observes experimentaly three PT of first order, due to reorientation of the magnetic moment in domains and accompanied by a corresponding change of DS (two of these, in the temperature interval 88.8–87 K, undergo no temperature hysteresis).

2. MODELS OF SRPT IN A (110) PLATE OF A CUBIC FERRIMAGNET WITH INDUCED ANISOTROPY. DISCUSSION OF EXPERIMENTAL RESULTS

The experimentally observed behavior of the DS in $Er_3Fe_5O_{12}$ in the temperature range 4.2–300 K has been successfully interpreted within a framework of a model of nonuniform magnetic phases, occurring in a (110) plate of a cubic ferrimagnet with induced anisotropy. Before we construct models of nonuniform magnetic phases, we shall consider uniform magnetic states and PT between them.

Uniform magnetic phases

To find the uniform magnetic states, we assume the presence of induced anisotropy in a (110) plate of $Er_3Fe_5O_{12}$. This assumption is justified by many reports of the presence

To find the uniform magnetic states, we assume the presence of induced anisotropy in a (110) plate of $Er_3Fe_5O_{12}$. This assumption is justified by many reports of the presence of such anisotropy ($\sim 10^3$ erg/cm^3) in ferrites with the garnet structure, obtained by the method of spontaneous crystallization from the melt, and of retention of it during annealing of the specimens.[9] Also known are indications of the important role of induced anisotropy in the formation of DS in (110) plates of rare-earth iron garnets.[7] In the general case, this anisotropy has orthorhombic symmetry. For the plate studied, its value is not known. Since for the purpose of the present work the presence of induced anisotropy in the plane of the plate has no fundamental importance, we restrict ourselves to consideration of the simplest case, when the axis of induced anisotropy is perpendicular to the plane of the plate.

$$E = K_u \sin^2\theta + K_1/4(\cos^4\theta(\sin^4\varphi + \sin^2 2\varphi) + \sin^4\theta + \sin^2 2\theta - 3/2\sin^2 2\theta \sin^2\varphi), \quad (1)$$

where $K_u < 0$ is the constant of perpendicular anisotropy; K_1 is the first constant of cubic anisotropy; $\beta = K_u/K_1$; $K_2 \approx 0$ in the temperature range 70–300 K (Ref. 9) θ and φ are the polar and azimuthal angles of the magnetic moment in the system of coordinates shown in Fig. 3 (polar axis $z \| [110]$, φ measured from the axis $x \| [001]$).

In the first octant of the coordinate system, the results look as follows:

1. Phase $\Phi_{\parallel\langle 111\rangle}$; $\theta = 0$, $\varphi = \arcsin(2/3)^{1/2}$ ($\mathbf{M} \| [1\bar{1}1]$); $K_1 < 0$, $\beta \leqslant 2/3$.

2. Phase $\Phi_{\angle(1\bar{1}0)}$; $\theta = \arcsin(2/3(1+\beta))^{1/2}$, $\varphi = 0$ (**M** in plane $(1\bar{1}0)$): $K_1 < 0$, $-2/5 \leqslant \beta \leqslant 1/2$.

3. Phase $\Phi_\perp$; $\theta = \pi/2$ ($\mathbf{M} \parallel [110]$): $K_1 < 0$, $\beta \geqslant 1/2$; $K_1 > 0$, $\beta \leqslant -1$.

4. Phase $\Phi_{\angle(001)}$; $\theta = \arcsin(1/2(1-\beta))^{1/2}$; $\varphi = \pi/2$ (**M** in plane (001)): $K_1 > 0$, $-1 \leqslant \beta \leqslant 1$.

5. Phase $\Phi_{\parallel\langle 110\rangle}$; $\theta = 0$, $\varphi = \pi/2$ ($\mathbf{M} \parallel [1\bar{1}0]$): $K_1 > 0$, $\beta > 1$.

6. Phase $\Phi_{\parallel\langle 001\rangle}$; $\theta = 0$, $\varphi = 0$ ($\mathbf{M} \parallel [001]$): $K_1 > 0$, $\beta > -1$.

The lines of PT are determined by the following conditions:

$\Phi_{\parallel\langle 111\rangle} \rightleftarrows \Phi_{\angle(1\bar{1}0)}$: $K_1 < 0, \beta = 0$ (transition of first order):

$\Phi_{\angle(1\bar{1}0)} \rightleftarrows \Phi_\perp$: $K_1 < 0, \beta = \frac{1}{2}$ (transition of second order);

$\Phi_\perp \rightleftarrows \Phi_{\angle(001)}$: $K_1 > 0, \beta > -1$ (transition of second order);

$\Phi_{\angle(001)} \rightleftarrows \Phi_{\parallel\langle 001\rangle}$: $K_1 > 0, \beta = 0$ (transition of first order).

We note that the states $\Phi_{\parallel\langle 111\rangle}$, $\Phi_{\angle(1\bar{1}0)}$, and $\Phi_{\angle(001)}$ are fourfold degenerate, while the states $\Phi_\perp$, $\Phi_{\parallel\langle 001\rangle}$, and $\Phi_{\parallel\langle 110\rangle}$ are doubly degenerate in the angles θ and φ.

Nonuniform magnetic phases

In finite specimens, for example plates, because of the demagnetizing effect of the surface, phases with a nonuniform distribution of magnetization often prove energetically

favorable. Far from second-order PT points and in the presence of degeneracy of the uniform states with respect to angles, it may be expected that the nonuniform states will have the character of a DS. In order to calculate the energies of the DS, which are possible in the temperature range 4.2–300 K, we shall draw on a model representation. In the construction of DS models with closure domains and in the calculation of their energies, the standard assumptions of the Landau-Lifshitz theory[10] are made.

At room temperature for $Er_3Fe_5O_{12}$,

$K_1 = -6\cdot10^3$ erg/cm^3 (Ref. 9), $4\pi M_s = 1241$ G (Ref. 11),

$|K_u| \ll |K_1|$,

i.e., $|K_u| \ll |K_1| \ll 2\pi M_s^2$. The values of the magnetostriction constants are $\lambda_{111} = -4.9\cdot10^{-6}$, $\lambda_{100} = 2\cdot10^{-6}$ (Ref. 9). Because of the absence of data for $Er_3Fe_5O_{12}$, we shall use the values of the elastic constants for $Y_3Fe_5O_{12}$: $c_{11} = 26.9\cdot10^{11}$, $c_{12} = 10.77\cdot10^{11}$, $c_{44} = 7.64\cdot10^{11}$ dyn/cm^2 (Ref. 12). According to common notions, for such materials the energetically most favorable DS is one with closure of the magnetic flux within the specimen. In specimens in which, besides an AEM perpendicular (or inclined) to the surface of the plate, there is an AEM parallel to the surface, closure of the magnetic flux is produced by closure domains.[10,13] Such a DS follows from experimental magneto-optic and powder investigations (Sec. 1).

Starting from what has been set forth, and taking into account the results of Sec. 1, one can assert that in a (110) plate at room temperature, there is competition between the two types of DS (D1 and D2) schematically represented in Fig. 3. In the first structure, the volume of the closure domains is minimal (Fig. 3 shows the simplest methods of flux closure at the edge of the plate, when an edge is parallel to an AEM). In the second structure (in the presence of perpendicular anisotropy), the density of anisotropy energy in the main domains is minimal.

We shall estimate the value of the perpendicular-anisotropy constant for which a PT occurs between these nonuniform phases; for this purpose, we shall compare the equilibrium values of their energies.

We shall suppose that the energy density of unit volume of D1 is approximately equal to the energy density of the regions magnetized in the plane of the plate:

$$E_1 \approx K_1/3. \tag{2}$$

The equilibrium values of the energy density E_2 of unit volume and of the period P_2 and D2 (when $\beta < 1/2$) are respectively

$$E_2 = 2(\sigma K_u/3h)^{1/2}(1+\beta)^{-1/4}(1+\beta/2)^{1/2} + K_1/3(1+\beta)^2; \tag{3}$$

and

$$P_2 = 2(3\sigma h/\bar{K}_u)^{1/2}(1+\beta)^{1/4}(1+\beta/2)^{-1/2}, \tag{4}$$

where

$$\sigma = 2/\sqrt{3}(A|K_1|)^{1/2}((1+4\beta)(\arcsin(2/3(1+\beta))^{1/2} - \pi/4) + (2(1+\beta)(1-2\beta))^{1/2})$$

is the surface energy density of a 180-degree Bloch domain wall,

$$\bar{K}_u = -K_u + 4c_{44}\lambda_{111}^2(1+\beta/4) - {}^3/_2(c_{44}\lambda_{111}^2 - {}^1/_2(c_{11}-c_{12})\lambda_{100}^2)\beta^2; \tag{5}$$

and h is the thickness of the plate.

From (2) and (3), one can find that in a plate of thickness ≈ 40 μm, D2 becomes energetically more favorable when $|K_u| > 10^2$ erg/cm^3. This is a really significant anisotropy in an iron garnet.

In the temperature range $300 > T > 150$ K, K_1 increases in modulus, reaching the value $K_1 \sim -2\cdot10^4$ erg/cm^3 at 150 K. The value of $4\pi M_s$ remains approximately constant.[11] The value and the temperature dependence of K_u are unknown. But we note that the contribution to the value of the induced anisotropy resulting from the presence of internal stresses ($\sim\lambda_{111}\sigma$) increases significantly with lowering of temperature, in consequence of the increase of the magnetostriction constants[9] and of the value of the elastic stresses. Starting from these considerations and taking into account that with lowering of the temperature D2 occupies the whole volume of the crystal (Fig. 1,3), one may assume an increase of $|K_u|$. Thus the PT D1→D2 is to be expected.

In the temperature interval $T_{SR} = T_{comp} < T < 100$ K, K_1 decreases sharply in modulus; this leads (when $\beta = 1/2$) to disappearance of the AEM parallel to the surface. Furthermore, the value of the magnetic moment decreases sharply.[9,11] Thus in the vicinity of $T_{SR} = T_{comp}$, $|K_u| \gg K_1$, $2\pi M_s^2$; i.e., the conditions for realization of a structure with closure domains are lacking. Then an "open" DS must form (D3 to the right of T_{SR}, D4 to the left of T_{SR}). Unfortunately, experimental detection of the difference between D2 and D3 (D4) has not been possible because of the impossibility of using the powder method at low temperatures.

In the temperature interval $4.2 < T < T_{SR} = T_{comp}$, the value of the constant K_1, after a change of sign, increases sharply; this leads (when $\beta > -1$) to occurrence of an AEM parallel to the surface. Simultaneously, the value of the magnetic moment increases.[11] Conditions for realization of structures with closure domains (D5, D6) (Fig. 3) again occur. The position of the PT point between them is determined by the relation between the constants K_u and K_1. We compare the equilibrium values of their energies:

$$E_5 = (2^{1/2}\sigma\bar{K}_u/h)^{1/2}(1-\beta)^{-1/4}(1-\beta/2)^{1/2} + K_u/2(1-\beta/2), \tag{6}$$

$$P_5 = 4(\sigma h/2^{1/2}\bar{K}_u)^{1/2}(1-\beta)^{1/4}(1-\beta/2)^{-1/2}, \tag{7}$$

$$E_6 \approx 0, \tag{8}$$

where

$$\sigma = 2(AK_1)^{1/2}((1-\beta^2)^{1/2} + \beta(\pi/2 - 2\arcsin({}^1/_2(1-\beta))^{1/2}))$$

is the surface energy density of a 180-degree domain boundary, P_5 is the period of D5, and

$$\bar{K}_u = -K_u + {}^9/_4(c_{11}-c_{12})\lambda_{100}^2 + {}^9/_8(\lambda_{111}^2 c_{44} - {}^1/_2(c_{11}-c_{12})\lambda_{100}^2)\beta^2.$$

By analyzing (6) and (8), one easily establishes that for every prescribed value of K_u, there is a critical value K_{1cr} of

K_1, such that when $K_1 > K_{1cr}$, the structure D6 is energetically more favorable. On lowering of the temperature to 4.2 K, K_1 reaches the value $6 \cdot 10^6$ erg/cm^3 (Ref. 14). This fact explains the experimentally observed transition D5→D6 at low temperatures.

The phase transitions D1⇄D2 and D5⇄D6 are PT of first order, since the transition points lie inside the region of intersection of the regions of stability of the nonuniform phases; this is also observed experimentally (we considered the region of stability of a DS with closure domains to be the region of intersection of the regions of stability of the uniform phases of which it consists).

Thus the assumed thermodynamic models of nonuniform magnetic states and of the PT between them satisfactorily describe the experimental results. This proves the correctness of the assumptions made and the fact that the observed DS are in thermodynamic equilibrium. Especially to be emphasized is the necessity for assuming the presence of induced anisotropy in order to explain the whole set of experimental results. The present investigation shows that in the study of the magnetic states of iron garnets, allowance must be made for the actually present induced anisotropy. Its influence substantially increases in those cases in which the constants of natural magnetocrystalline anisotropy nearly vanish, for example in the neighborhood of a SRPT.

At present there is no quantitiative theory of the contribution of the Er^{3+} ion to the magnetic anisotropy energy and to the saturation magnetization of $Er_3Fe_5O_{12}$. This fact is in considerable measure attributable to the absence of unambiguous data on the complicated character of the splitting of the ground multiplet $^4I_{15/2}$ of the Er^{3+} ion in a crystal in crystalline and exchange fields that are comparable in value. Therefore at present it seems to us to be possible to give only a qualitative explanation of the experimentally observed coincidence of T_{SR} and T_{comp}.

Because of the low symmetry of the crystalline field and the anisotropic character of the Er^{3+}-Fe^{3+} exchange interaction, it may be expected that the spontaneous magnetization of the erbium sublattice in erbium iron garnet will be anisotropic. The anisotropy of the magnetic moment and the change of sign of K_1 with lowering of temperature, under the influence of an increase of the Er^{3+}-Fe^{3+} exchange interaction, can be explained qualitatively within the framework of molecular-field theory with allowance for the anisotropy of the exchange interaction.[15]

Anisotropy of the spontaneous magnetization of the erbium sublattice in $Er_3Fe_5O_{12}$ has been observed experimentally[16]: at $T = 4.2$ K, the mean magnetic moment of the Er^{3+} ions per $3Er_2O_3 \cdot 5Fe_2O_3$ molecule is 29.7 μ_B for $\mathbf{M} \| \langle 111 \rangle$ and 33.8 μ_B for $\mathbf{M} \| \langle 100 \rangle$; this amounts to $\Delta M_{Er} = M_{Er\langle 100 \rangle} - M_{Er\langle 111 \rangle} = 81.7$ G.

Thus at T_{SR} the magnetic moment of the erbium sublattice varies by the amount

$$\Delta M_{Er}(T_{SR}) = M_{Er\langle 100 \rangle}(T_{SR}) - M_{Er\langle 111 \rangle}(T_{SR}).$$

At the same time, the total moment $M_{Fe}(T)$ of the iron sublattices is independent of direction because of the fact that Fe^{3+}-Fe^{3+} exchange interaction is isotropic and large in comparison with the Er^{3+}-Fe^{3+} interaction and therefore does not feel the influence of the Er^{3+} ion. Therefore under the condition

$$M_{Er\langle 111 \rangle}(T_{SR}) < M_{Fe}(T_{SR}) < M_{Er\langle 100 \rangle}(T_{SR}),$$

the phenomenon of spin reorientation will be connected with compensation of the magnetic moment of the sublattices. This phenomenon apparently occurs in the case of $Er_3Fe_5O_{12}$.

[1)]The notation for the phases (Φ) contaims an indication of the orientation of the magnetic moment **M** in the plane of the plate (‖), at an angle to it (∠), or perpendicular to it (⊥), and also notes parallelism of **M** to axes of a certain type ⟨ ⟩ or to a plane ( ) in the coordinate system of Fig. 3.

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