Linear magnetostriction and antiferromagnetic domain structure in dysprosium orthoferrite

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Linear magnetostriction in dysprosium orthoferrite at temperatures below the Morin point is investigated experimentally and theoretically. The linear-magnetostriction coefficient of the material is determined. The phenomenon is shown to be closely related to the character of the antiferromagnetic domain structure in the sample. The physical mechanisms capable of controlling the antiferromagnetic domains and of producing a homogeneous antiferromagnetic state are considered.

1. Linear magnetostriction, i.e., the appearance of magnetostriction strains linear in the external magnetic field, is an effect common to both ferro- and antiferromagnets belonging to 66 magnetic classes.[1] Linear magnetostriction was first observed by Borovik-Romanov and co-workers in CoF_2 single crystals.[2] This phenomenon was investigated in considerable detail in hematite,[3,4] and in the latter references it is pointed out, in particular, that a connection exists between the linear magnetostriction and the antiferromagnetic (AFM) domain structure.

Interesting opportunities for the study of linear magnetostriction are provided by a large class of weak ferromagnets with distorted perovskite structure, the most popular representatives of which are the rare-earth orthoferrites $RFeO_3$ and orthochromites $RCrO_3$. These compounds are subject to a great variety of spin-reorientation (SR) transitions, both spontaneous and induced by an electric field,[5] creating favorable conditions for the investigation of the distinguishing features of magnetoelastic properties.

Our purpose here is a study of the linear magnetostriction that accompanies an induced phase transition from an AFM state into a weakly ferromagnetic (WFM) state in dysprosium orthoferrite.

An external magnetic field **H** applied parallel to the c axis ($\mathbf{H}_c$) leads to a transition from an AFM phase Γ_1 to a WFM phase Γ_4 via an intermediate canted phase Γ_{14}, and it is the presence of the latter which ensures the possibility of observing the linear magnetostriction due to rotation of the antiferromagnetism vector.

2. If the antiferromagnetism vector **G** is rotated in the ab plane, the magnetoelastic energy can be represented in the form (Ref.5)[1)]

$$\Phi_{\rm me}=(L_a\varepsilon_{aa}+L_b\varepsilon_{bb}+L_c\varepsilon_{cc})G_x^2+\mu_3\varepsilon_{ab}G_xG_y, \tag{1}$$

where L_a, L_b, L_c, and μ_3 are the magnetoelastic constants. The equilibrium values of the elastic strains ε_{ik} are obtained by minimizing the elastic and magnetoelastic energies:

$$\varepsilon_{ii}=\varepsilon_{ii}^{(0)}\sin^2\varphi\quad (i=a,b,c),\qquad \varepsilon_{ab}=\varepsilon_{ab}^{(0)}\sin 2\varphi, \tag{2}$$

where $\varepsilon_{ii}^{(0)}$ and $\varepsilon_{ab}^{(0)}$ are the maximum values of the corresponding strains, and φ is the angle between the vector **G** and the a axis in the ab plane. Relations (2) reveal the fundamental difference between the quadratic strain ε_{ii} and the shear ε_{ab} that leads to monoclinic distortions of the crystal lattice. If the ε_{ii} are even functions of φ, ε_{ab} is an odd function of the angle φ. This means that in the SR transition Γ_1–Γ_4 induced by an external magnetic field $\mathbf{H}_c$ the ε_{ii} are even functions of the field and ε_{ab} is odd:

$$\varepsilon_{ab}=p_{123}H_c+\ldots, \tag{3}$$

where P_{123} is the linear-magnetostriction constant, which determines in fact the corresponding piezomagnetic effect.

The fundamentally different character of the angular dependences (2) of the quadratic and shear strains in an *SO* transition indicates also that they are differently affected by the domain structure of the sample in the *SR*-transition region. If we denote by ρ_+ and ρ_- the relative fractions of the domains for which $G_y>0$(G_y^+ domain) and $G_y<0$(G_y^- domain), with $\rho^+\rho- =1$, we have for the total shear strain in the single crystal

$$\varepsilon_{ab}=\varepsilon_{ab}^{(0)}(\rho_+-\rho_-)|\sin 2\varphi|, \tag{4}$$

whereas ε_{ii} does not "feel" the domain structure. Thus, the shear strain in the SR transition region serves as an integral characteristic of the domain structure.

3. The fact that the two types of AFM domain (G_y^+ and G_y^-) are not equivalent in energy and that the AFM domain structure in $DyFeO_3$ can be controlled in principle by external action, is due to the presence, in the free energy, of an invariant of the type

$$\Delta\Phi=-a\mu_BH_xH_yH_zG_y-b\mu_B\sigma_{xy}H_zG_y\equiv-\mu_BH_s, \tag{5}$$

where σ_{xy} is the elastic stress tensor and H_s is the internal staggered field H_s induced by the external magnetic field and by the elastic stresses. The field H_s is the cause of nonequivalence of the domains G_y^+ and G_y^-, while $2\Delta\Phi$ is equal to the pressure exerted by the field H_s on the AFM domain wall. The first term in the right-hand side of (5) is due to the invariant[5,9] $\frac{1}{2}\chi_\perp$ $[\mathbf{H}^2-(\mathbf{H}\cdot\mathbf{G})]$ of the thermodynamic potential of $DyFeO_3$.[2)] Putting

$$G_x\approx m_zH_z/K_{ab}\equiv(p_{123}/\varepsilon_{ab}^{(0)})H_z,$$

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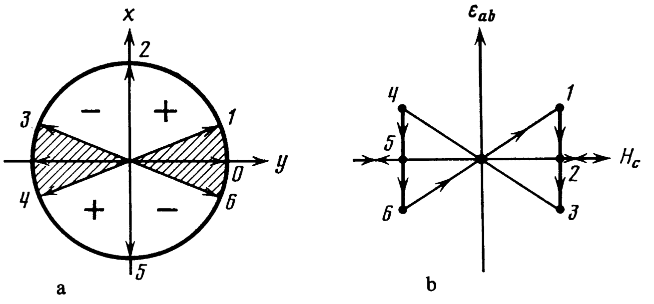

FIG. 1. Schematic representations of a) reorientation of the antiferromagnetism vector **G** in the crystal *ab* plane; b) field dependence of the linear magnetostriction ε_{ab}.

where m_z is the WMF moment along the *c* axis and K_{ab} is the anisotropy constant in the *ab* plane, we obtain an expression similar to (5), where $a=\chi_\perp P_{123}/\varepsilon_{ab}^{(0)}\mu_B$. At $T=6$K, $H_z=H_{cr}\approx 4$kOe, and $H_x=H_y\approx 0.1H_z$ we get $H_s=2$Oe. This value of H_s results also from a stress $\sigma_{xy}\approx 10$ bar.

4. We consider now the basic features of the field dependences of the monoclinic strains ε_{ab} for a Γ_1-Γ_{14}-Γ_4 transition in a field $\mathbf{H}_c$, assuming that the preference given to a definite type of AFM domain is due to the direction of the external field **H**, inasmuch as when the latter is reserved the nonuniform field H_s reverses sign, so that the G_y^- domains become preferred to Gy^+, and vice versa.

To have $H_s\neq 0$ we need either some disorientation of the external magnetic field relative to the *c* axis, or else the presence of internal shear stresses σ_{xy} [see (5)]. In addition, we assume the coercivity of the AFM domain to be large enough so that the magnetization reversal (the rearrangement of the magnetic structure) takes place via rotation of the antiferromagnetism vector in the external field H_s, and not by displacement of the AFM domain walls. This is indicated by the character of the observed field dependences of the magnetostriction and by theoretical estimates.

Figure 1a shows that possible orientations of the antiferromagnetism vector in the *ab* plane of dysprosium orthoferrite for a complete cycle of field variation from $H_c>H_{cr}$ to $H_c<-H_{cr}$ and in the opposite direction. Figure 2b shows the possible plot of ε_{ab} (H_c) if the sign of this quantity is chosen to coincide with the sign of the product G_xG_y. The form of the ε_{ab} field dependence in accordance with the scheme 0⟶1⟶2⟶3⟶4⟶5⟶6⟶0 corresponds to the initial state of a sample with a very high density of AFM domains, which are "inconvenient" for the positive direction of the external field. In this case the vector **G** rotates initially smoothly to a certain critical angle φ_{cr} (the section 0⟶1), and then at $H_c=H_{cr}$ it jumps into position 2 (the Γ_4 phase) and the AFM domain structure vanishes.

It is clear that now even a decrease of the magnetic field stength will be accompanied by a jump of the vector **G** into position 3 with a sign of G_y that is convenient for this direction of **H**, followed by smooth rotation on the section 3⟶4 with reversal of the sign of the G_x component when the field is switched over. Further motion of the vector **G** along the section 4⟶5⟶6 is similar to the rotation in accord with the 1⟶2⟶3 scheme. The characteristic dependence of the sign of the monoclinic deformation on the orientation of the antiferromagnetism vector ($\propto G_xG_y$) leads to singularities of the field dependence of ε_{ab} following the full magnetic-field switching cycle, as can be seen from Fig. 1b. If the sample had an AFM domain structure in the initial state that was convenient for the "future" magnetic-field direction, the vector would rotate in accordance with a scheme such as 0⟶3⟶2⟶3⟶4⟶5⟶6⟶0 in the same field-switching cycle. Clearly, if preference were given to some type of AFM domain that is not connected in any way with the external-field direction, the motion of the vector **G** and hence the field dependence of ε_{ab} would follow the scheme 0⟶1⟶2⟶1⟶0⟶6⟶5⟶6⟶0 in the same remagnetization cycle without formation of a characteristic "butterfly" on the ε_{ab} (H_c) curve.

5. To investigate monoclinic distortions in the *ab* plane for the SR transition $\Gamma_1\to\Gamma_4$ in an external field $\mathbf{H}\|c$ we measured the magnetostriction strain λ_{ab} along the diagonal in the *ab* plane, a strain determined by the contribution of the quadratic magnetostriction along the axes *a* and *b* and of the shear strain:

$$\lambda_{ab}={}^1/_2(\varepsilon_{aa}+\varepsilon_{bb})+\varepsilon_{ab}={}^1/_2(\varepsilon_{aa}^{(0)}+\varepsilon_{bb}^{(0)})\sin^2\varphi+\varepsilon_{ab}^{(0)}\sin 2\varphi. \quad (6)$$

Figure 2a shows the experimental field dependence of $\lambda_{ab}(H_c)(T=6{,}1\text{K})$ in a complete external-magnetic-field switching cycle. Figure 2b shows[3] for comparison a typical field dependence of the quadratic magnetostriction ε_{aa}. In accordance with the theoretical assumptions, the λ_{ab} (H_c) dependence has a complicated character that indicates su-

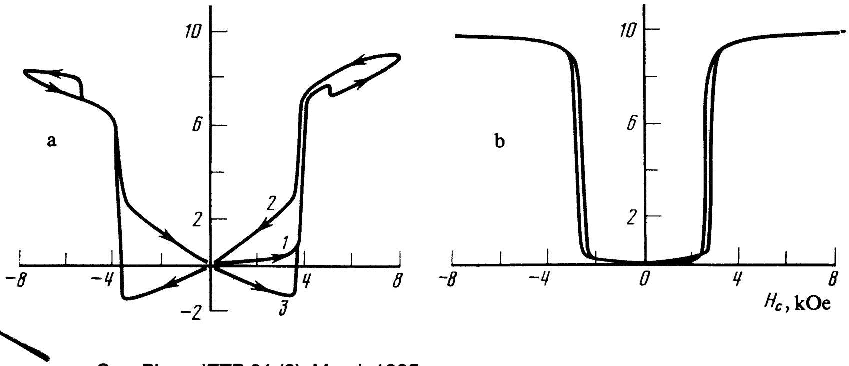

FIG. 2. Field dependences of a) the magnetostriction λ_{ab} in $DyFeO_3$ at $T=6.1$ K; b) the quadratic magnetostriction ε_{aa} in $DyFeO_3$ at $T=5.25$K.

perposition of a quadratic and shear strains with basically different field dependences. It follows from Fig. 2 that the critical field of the $\Gamma_{14} \rightarrow \Gamma_4$ transition is 3.7 kOe, in good agreement with the data of Ref. 5.

Taking into account the angular dependence of the quadratic magnetostriction ($\propto \sin^2\varphi$) we can calculate from the data of Fig. 2 the critical angle: $\varphi_{cr} \approx 21°$, which agrees well with the data obtained in Refs. 10 and 11 by measuring the linear magnetooptic effect in $DyFeO_3$. Knowing φ_{cr} and the shear strain corresponding to this angle ($2 \cdot 10^{-6}$), we obtain the maximum possible value of ε_{ab}, viz., $|\varepsilon_{ab}^{(0)}| \approx 3.10^{-6}$. In addition, from the slope of the $\lambda_{ab}(H_c)$ plot at $H_c = 0$ we obtain the linear magnetostriction constant $P_{123} \approx 6 \cdot 10^{-10}$ Oe^{-1}, which is somewhat larger than the corresponding constants in hematite.[3,4] We call attention to the appreciable difference between the dependence of the linear magnetostriction on H during the initial stage of the measurement (curve 1 of Fig. 2) and in the succeeding stages (curves 2 and 3); this is due to the fact that during the initial phase there exists in the sample an AFM domain structure, i.e., $\rho^+ \approx \rho^-$, which yields practically zero linear magnetostriction, whereas during the succedding stages, as stated above, a uniform restructuring takes place $(\rho^+ - \rho^-| \approx 1)$.

Uniform magnetization reversal presupposes that the maximum pressure on the AFM domain wall did not exceed in our experiments the coercivity of the domain-wall displacement.

6. We have thus measured the linear magnetostriction constant of the tensor of the magnetoelastic coefficients in $DyFeO_3$. We have demonstrated the close connection between linear magnetostriction and the AFM domain structure. We have shown that the combination of elastic stresses described by the off-diagonal components of the strain tensor, in conjunction with an external magnetic field, permits control of the AFM domain structure and can produce a homogeneous AFM state in orthoferrites.

[1)]Linear magnetostriction in $YFeO_3$ and $YCrO_3$ was investigated[7,8] when the antiferromagnetism vector was reoriented in the *ac* plane.
[2)]At low temperatures account must be taken of the $f\chi_\perp$ anistropy due to its renormalization by the Dy–Fe interaction,[5,9]
[3)]Figure 2 shows experimental curves obtained with an automatic *x-y* plotter. The experimental-setup sensitivity was $0.5 \cdot 10^{-7}$. The absolute value of the magnetostriction was determined to within 10%.

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