SOVIET PHYSICS JETP VOLUME 29, NUMBER 4 OCTOBER, 1969

MAGNETOELASTIC PROPERTIES OF HEMATITE

R. Z. LEVITIN, A. S. PAKHOMOV, and V. A. SHCHUROV

Moscow State University

Submitted November 25, 1968

Zh. Eksp. Teor. Fiz. 56, 1242-1251 (April, 1969)

The longitudinal and transverse magnetostriction of an hematite single crystal are measured along various crystallographic directions at temperatures between 100 and 300° K in magnetic fields up to 150 kOe. The magnetostriction constants of hematite are determined on the basis of these data and the magnetoelastic interaction constants of the substance are evaluated by thermodynamics. The contribution of magnetoelastic energy to the anisotropy energy of hematite is calculated and it is shown that in the antiferromagnetic region, at temperatures about 20—30° below the Morin temperature, magnetoelastic interaction does not exert a significant effect on the magnetic properties of hematite. By comparing the experimental data with calculations of dipole-dipole energy in hematite it is shown that magnetoelastic interaction in this substance is due to the deformation-dependent dipole-dipole interaction.

HEMATITE (α-Fe_2O_3) has a rhombohedral crystal structure and the arrangement of the atoms in it is described by the space group D_{3d}^6. Below the Neel temperature ($T_N \sim 950°K$) and down to the Morin temperature ($T_M \sim 260°K$), hematite is an antiferromagnet with weak ferromagnetism. In this temperature region, the vector of spontaneous magnetization m_s is directed along the twofold axis (x axis), and the antiferromagnetism vector l is practically parallel to the line of intersection of the symmetry plane with the basal plane of the crystal (y axis). Below the Morin point, there is no weak ferromagnetism; the antiferromagnetism vector in this temperature region is parallel to the trigonal axis of the crystal (z axis)[1-6].

The weak ferromagnetism of hematite was first explained by Dzyaloshinskiĭ, who has shown that it is due to deviation, by a small angle, of the magnetic moments of the sublattices of the antiferromagnet from strict antiparallelism[7]. Subsequently many investigations were devoted to the features of the magnetic properties of hematite on the basis of Dzyaloshinskiĭ's theory[8-12].

A number of investigations were devoted to the study of the magnetoelastic properties of hematite: for example, measurements were made on the even[13-15] and linear[14-16] magnetostriction, of the influence of the elastic stresses on the magnetization[17], of the Morin point[18-20], and of magnetic resonance in hematite[21-22]. However, the available information on the magnetoelastic properties of hematite is not complete. In particular, the constants of the magnetoelastic interaction of hematite were not determined and the influence of this interaction on the magnetic properties of this substance have not been estimated.

In this connection, we have undertaken an investigation of the magnetostriction of hematite, aimed at determining the constants of the magnetoelastic interaction of this substance on the basis of the corresponding thermodynamic theory and at estimating the influence of this interaction on the processes of magnetization in hematite.

EXPERIMENTAL PROCEDURE AND SAMPLES

The constants of magnetoelastic interaction were determined by measuring the magnetostriction of single-crystal hematite along different crystallographic directions. We investigated both the longitudinal magnetostriction (field parallel to the measurement direction) and the transverse magnetostriction (field perpendicular to the measurement direction). The samples (in the form of rods with approximate dimensions $10 \times 2 \times 2$ mm) were cut from synthetic hematite crystals grown from the solution in the melt at the Crystallography Institute of the USSR Academy of Sciences. Samples were prepared and oriented along the axes x, y, and z, and also along directions lying in the xy plane (at 45° to the x axis), in the xz plane (40° to the z axis) and the yz plane (52° to the z axis). The magnetostriction was measured in pulsed magnetic fields in the temperature interval 100—300°K (i.e., both above and below the Morin point), using a setup described earlier[14,23]. The longitudinal magnetostriction was measured in fields of intensity up to 150 kOe, and the transverse magnetostriction up to 100 kOe.

EXPERIMENTAL RESULTS

Figure 1 shows isotherms of the longitudinal and transverse magnetostrictions along different directions above and below the Morin point. Our measurements have shown that in each of these temperature regions the character of the isotherms varies little with changing temperature, so that the figure shows only one isotherm each for temperatures above and below the Morin point.

As seen from the figure, the magnetostriction at $T > T_M$ reaches saturation in weak fields, and with further increase of the field it changes insignificantly. Below the Morin point, in the antiferromagnetic state, the saturation sets in stronger fields and a comparison with the data of the magnetic measurements shows that the magnetostriction saturation field coincides with the

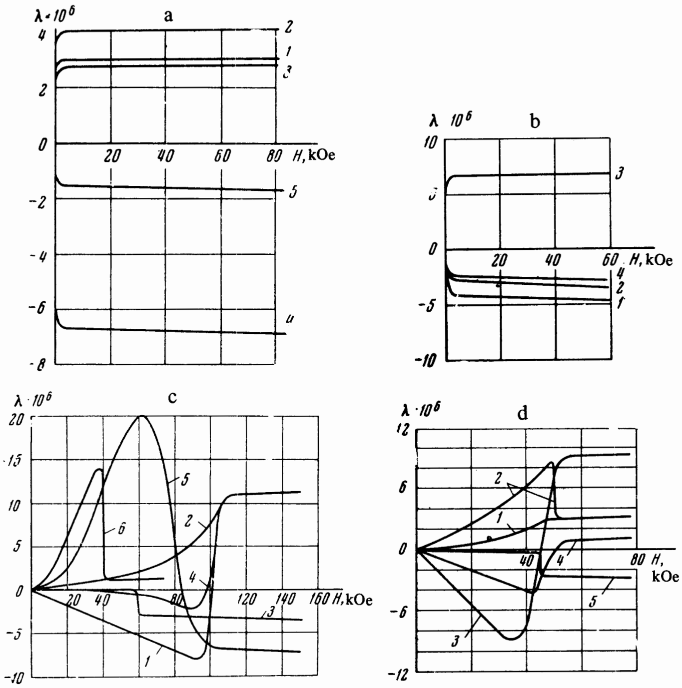

FIG. 1. Longitudinal and transverse magnetostrictions of hemitate. a—Longitudinal magnetostriction, $T = 295°K > T_M$. Curve 1—along x a axis, 2—along y axis, 3—in xy plane, at an angle 45° to the x axis, 4—in yz plane at 52° to the z axis; 5—in xz plane at 40° to the z axis. b—Transverse magnetostriction, $T = 295°K > T_M$. Curve 1—along the x axis, $\mathbf{H} \parallel y$; 2—along the y axis, $\mathbf{H} \parallel x$; 3—in the yx plane at 52° to the z axis, $\mathbf{H} \parallel x$; 4—in xz plane at 40° to the z axis, $\mathbf{H} \parallel y$. c—Longitudinal magnetostriction, $T = 185°K < T_M$. Curve 1—along x axis, 2—along y axis, 3—along z axis, 4—in xy plane at 45° to the x axis, 5—in yz plane at 52° to the z axis, 6—in xz plane at 40° to the z axis, T = 245°K, d—Transverse magnetostriction, $T = 230°K < T_M$. Curve 1—along x axis, $\mathbf{H} \parallel y$; 2—along y axis, $\mathbf{H} \parallel x$; 3—in yz plane at 52° to the z axis, $\mathbf{H} \parallel x$; 4—in xz plane at 40° to the z axis, $\mathbf{H} \parallel y$; 5—along z axis, field in basal plane.

field of the transition from the antiferromagnetic to the weakly-ferromagnetic state H_c (for details see[14]). We also call attention to the fact that the magnetostriction at $T < T_M$, as a function of the direction of the measurement and of the direction of the field, either varies with the field (when $H \leq H_c$) monotonically (longitudinal magnetostriction along the y axis, transverse magnetostriction along the x axis, longitudinal and transverse magnetostriction along the z axis, etc.), or else passes through a maximum or a minimum (transverse magnetostriction along the y axis, longitudinal magnetostriction along the x axis, etc.). The magnetostriction of hematite is connected with the change of the magnitude and direction of the vectors $\mathbf{l}$ and $\mathbf{m}$ in the field. As shown earlier[14], the magnetostriction of hematite, due to the change of the magnitude and direction of $\mathbf{m}$ in the field, is small. We likewise disregard the change of the absolute value of the antiferromagnetism vector $\mathbf{l}$ in the field (i.e., the change of the sublattice magnetization with the field), since our measurements were made much below the Neel point.

Thus, we assume that the magnetostriction of hematite is due to the change of the direction of the antiferromagnetism vector in the magnetic field.

To interpret the obtained results it is necessary to know how the magnetic structure of the hematite changes when a field is applied. Up to now, processes of magnetization of the hematite have been insufficiently investigated. However, it can be regarded as established, both theoretically[7] and experimentally[6], that above the Morin point (in the weakly ferromagnetic state), the field rotates the vector $\mathbf{l}$ in the basal plane, and upon saturation the vector $\mathbf{l}$ is perpendicular to the field. Below the Morin point (in the antiferromagnetic state), a sufficiently strong field (regardless of its direction) leads to rotation (jumpwise or more gradually, depending on the direction of the field) of the vector $\mathbf{l}$ from the z axis of the crystal to the basal plane (i.e., to a transition from the antiferromagnetic to the weakly-ferromagnetic state), and in this case the vector $\mathbf{l}$ is perpendicular to the field when $H \geq H_c$.

Much fewer studies have been made of the processes of magnetization of hematite in the antiferromagnetic region, in fields smaller than the field of transition from the antiferromagnetic to the weakly-ferromagnetic state. Recent theoretical and experimental investigations[4,8-12] have shown that upon magnetization of the antiferromagnetic modification of hematite in a field parallel to the trigonal axis of the crystal (z axis), the transition from the antiferromagnetic to the weakly-ferromagnetic state occurs jumpwise. If the field is applied in the basal plane of the crystal, then, with increasing field, the antiferromagnetism vector $\mathbf{l}$ first rotates smoothly from the z axis in the plane perpendicular to the field, and with further increase of the field goes jumpwise to the basal plane. The critical angle between the vector $\mathbf{l}$ and the z axis, at which this jump takes place, depends strongly on the temperature, and is close to $\pi/2$ at temperatures 20—30° lower than the Morin point. It must be noted that the picture described here, of the behavior of $\mathbf{l}$ in magnetization in the basal plane, was obtained with allowance for only the interactions that are isotropic in this plane, although at the present time it is not clear whether such an assumption is valid.

MAGNETOELASTIC INTERACTION CONSTANTS OF HEMATITE

Starting from the expression given in[24,25] for the thermodynamic potential Φ of the hematite, and assuming in it that the external stresses σ_{ij} are equal to zero, we can obtain from the conditions

$$\partial\Phi / \partial u_{ij} = 0 \tag{1}$$

the following expressions for the strains u_{ij} of the single crystal of hematite in terms of the direction cosines γ_i of the antiferromagnetism vector $\mathbf{l}$:

$$\begin{aligned} u_{xx} &= (K+M)\gamma_x^2 + (K-M)\gamma_y^2 + L\gamma_z^2 + 2N\gamma_y\gamma_z, \\ u_{yy} &= (K-M)\gamma_x^2 + (K+M)\gamma_y^2 + L\gamma_z^2 - 2N\gamma_y\gamma_z, \\ u_{zz} &= R(\gamma_x^2+\gamma_y^2) + Q\gamma_z^2, \quad u_{xy} = 2(M\gamma_x\gamma_y + N\gamma_x\gamma_z), \\ u_{xz} &= 2(U\gamma_x\gamma_y + V\gamma_x\gamma_z), \quad u_{yz} = U(\gamma_x^2-\gamma_y^2) + 2V\gamma_y\gamma_z. \end{aligned} \tag{2}$$

Substituting these expressions in the well known formula for the magnetostriction elongation in an arbitrary direction in the crystal, defined by the cosines α_i, we obtain

$$\lambda = \left(\frac{\Delta l}{l}\right)_{\gamma_i\alpha_i} = \sum_{(i,j)} u_{ij}(\gamma_i\gamma_j)\alpha_i\alpha_j = (\alpha_x^2+\alpha_y^2)(K-L)(1-\gamma_z^2)$$

$$+(\alpha_x^2-\alpha_y^2)[M(\gamma_x^2-\gamma_y^2)+2N\gamma_y\gamma_z]+\alpha_z^2(R-Q)(1-\gamma_z^2)$$
$$+4\alpha_x\alpha_y(M\gamma_x\gamma_y+N\gamma_x\gamma_z)+4\alpha_x\alpha_z(U\gamma_x\gamma_y+V\gamma_x\gamma_z)$$
$$+2\alpha_y\alpha_z[U(\gamma_x^2-\gamma_y^2)+2V\gamma_y\gamma_z]. \tag{3}$$

The magnetostriction constants contained in (3) are expressed in the following manner in terms of the constants of the magnetoelastic interaction δ_i and the elastic modulus c_i[24]:

$$K-L=-\frac{c_3(\delta_1+\delta_2)+2c_4\delta_3}{2[c_3(c_1+c_2)-2c_4^2]},\quad N=\frac{c_6\delta_4-2c_5\delta_5}{4[c_5(c_1-c_2)-2c_6^2]}$$
$$R-Q=\frac{c_4(\delta_1+\delta_2)+(c_1+c_3)\delta_3}{[c_3(c_1+c_2)-2c_4^2]},\quad V=\frac{4c_6\delta_5-(c_1-c_2)\delta_4}{8[c_5(c_1-c_2)-2c_6^2]}, \tag{4}$$
$$M=\frac{c_6\delta_6-c_5(\delta_1-\delta_2)}{2[c_5(c_1-c_2)-2c_6^2]},\quad U=\frac{2c_6(\delta_1-\delta_2)-(c_1-c_2)\delta_6}{4[c_5(c_1-c_2)-2c_6^2]}$$

From formula (3), recognizing that upon saturation the antiferromagnetism vector l lies in the basal plane of the crystal and is perpendicular to the field, we can express the saturation magnetostriction in the weakly ferromagnetic region λ_{wf}^S and in the antiferromagnetic region λ_{af}^S in terms of the angle φ between the x axis and the projection of the field **H** on the basal plane:

$$\lambda_{wf}^s=-M\{(\alpha_x^2-\alpha_y^2)(\cos 2\varphi-{}^2/_3)+2\alpha_x\alpha_y\sin 2\varphi\}$$
$$-2U\{\alpha_x\alpha_z\sin 2\varphi+\alpha_y\alpha_z(\cos 2\varphi-{}^2/_3)\}, \tag{5}$$
$$\lambda_{af}^s=(\alpha_x^2+\alpha_y^2)(K-L)+(R-Q)\alpha_z^2-M[(\alpha_x^2-\alpha_y^2)\cos 2\varphi$$
$$+2\alpha_x\alpha_y\sin 2\varphi]-2U[\alpha_x\alpha_z\sin 2\varphi+\alpha_y\alpha_z\cos 2\varphi]. \tag{6}$$

In formula (5) for the saturation magnetostriction in a weakly-ferromagnetic state we took into account the spontaneous striction: in the derivation of the equation it was assumed that in the demagnetized state the volumes of the domains with direction of the weakly ferromagnetic moment along the three twofold axes in the basal plane are the same. In real samples, such a domain structure is usually not realized, owing to the influence exerted on the position of the domain boundaries by mechanical stresses, inclusions, and other imperfections of the crystal structure. Therefore, to eliminate the influence of the domain structure on the results, we used in the calculation of constants from magnetostriction data in the weakly ferromagnetic state, as is customary, the difference between the transverse and longitudinal saturation magnetostrictions.

Below T_M, in the antiferromagnetic state, the antiferromagnetic domain structure does not influence the saturation magnetostriction (at $H \geq H_c$), for in this case the directions of the antiferromagnetism vector l differ by 180° (l is directed parallel or antiparallel to the z axis).

Our measurements have shown that the saturation magnetostriction of hematite in the weakly-ferromagnetic and antiferromagnetic states is well described by formulas (5) and (6). Figure 2 shows by way of an example plots (experimental and theoretical) for the transverse magnetostriction of samples out in the xz and yz planes, the theoretical curves in this figure being plotted by using the magnetostriction constants determined from measurements of the saturation magnetostriction along other directions. From the data on the saturation magnetostriction we determined the constants M, U, K − L, and R − Q. It turns out that,

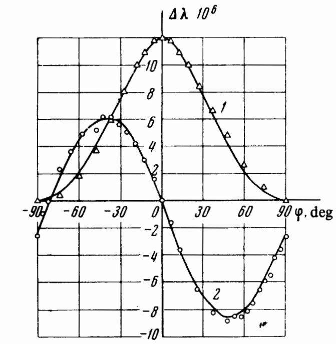

FIG. 2. Saturation magnetostriction of hematite against the direction of the magnetic field (φ – angle between the x axis and the projection of the field on the basal plane). Δ–difference between transverse and longitudinal magnetostrictions, measured along the direction lying in the yz plane at an angle 52° to the z axis; O–difference of transverse and longitudinal magnetostrictions, measured along the direction lying in the xz plane at an angle 40° to the z axis; 1, 2–theoretical curves based on formulas (5) and (6).

within the limits of experimental accuracy (approximately 10%), these constant do not depend on the temperature in the temperature interval 100–300°K. We present the values of the magnetostriction constants (multiplied by 10^6):

K–L	R–Q	M	U	N	V
5.6±0.6	–2.5±0.3	–3.4±0.4	–8.2±1.0	±14±3	±10±4

From the data on the saturation magnetostriction it is impossible, however, to determine the magnetostriction constants N and V, which are the coefficients of the terms of the form $\gamma_z\gamma_i$ (i = x, y) in formula (3), since these terms vanish both in the antiferromagnetic ($\gamma_x = \gamma_y = 0$) and in the weakly-ferromagnetic ($\gamma_z = 0$) state. They differ from zero only in the intermediate state and cause the appearance of maxima and minima on the $\lambda(H)$ curves when $H < H_c$ (see Fig. 1). To calculate the constants N and V it is necessary to know the dependence of the direction cosines γ_i on the field. If it is assumed, as already mentioned, that upon magnetization of the antiferromagnetic modification of hematite in the basal plane the vector of the antiferromagnetism l rotates in a plane perpendicular to the field, and that the angle of deviation of the vector l from the z axis does not depend on the orientation of the field in the basal plane relative to the axes x and y, then the magnetostriction depends in the following manner on the angle φ between the direction of the field in the basal plane and the x axis:

$$\lambda=\{(\alpha_x^2+\alpha_y^2)(K-L)+(R-Q)\alpha_z^2$$
$$-[(\alpha_x^2-\alpha_y^2)M+\alpha_y\alpha_z U]\cos 2\varphi$$
$$-[2\alpha_x\alpha_y M+2\alpha_x\alpha_z U]\sin 2\varphi\}(1-\gamma_z^2)$$
$$+2\{[(\alpha_x^2-\alpha_y^2)N+2V\alpha_y\alpha_z]\cos\varphi$$
$$-[2\alpha_x\alpha_y N+2\alpha_x\alpha_z V]\sin\varphi\}\gamma_z\sqrt{1-\gamma_z^2}. \tag{7}$$

From the experimental dependence of the magnetostriction on the field, plotted at measurements and field directions such that the magnetostriction depends only on $1-\gamma_z^2$, and there are no terms of the type $\gamma_z\gamma_i \sim \gamma_z\sqrt{1-\gamma_z^2}$ (for example, if $\alpha_z = \alpha_x = 0$ and $\varphi = \pi/2$), we can determine the dependence of $1-\gamma_z^2$ on the field. Knowing this dependence, we can calculate the contribution made to the magnetostriction, measured at all other field orientations and measurement directions, on the terms proportional to $1 - \gamma_z^2$. Subtracting this contribution from the experimentally observed dependence $\lambda(H)$, we obtain the field dependence of the part of the magnetostriction proportional to $\gamma_z\sqrt{1-\gamma_z^2}$. Figure 3 shows the dependence of the magnetostriction determined in this manner, proportional to $\gamma_z\sqrt{1-\gamma_z^2}$, on the field. Since the maximum value of the function $\gamma_z\sqrt{1-\gamma_z^2}$ is observed when the antiferromagnetism vector $\mathbf{l}$ deviates by 45° from the z axis and amounts to $1/2$, it is possible to determine the magnetostriction constants N and V from Fig. 3.

Since we do not know the direction of rotation of the vector $\mathbf{l}$ in the field (clockwise or counterclockwise), the values of N and V are determined apart from the sign. It must be noted that the magnetostriction described by terms of the type $\gamma_z\sqrt{1-\gamma_z^2}$ should be odd: it should reverse sign when the field is reversed. This is connected with the fact that when the sign of the field is reversed a change takes place in the direction of rotation of the antiferromagnetism vector, and consequently the sign of the projection of $\mathbf{l}$ on the basal plane is reversed.

In addition, this magnetostriction should depend on the antiferromagnetic domain structure by virtue of the difference in the sign of γ_z for antiferromagnetic domains with direction $\mathbf{l}$ parallel and antiparallel to the z axis. Our experiments have shown, however, that the odd magnetostriction is observed only in weak fields (smaller than approximately 10 kOe), and in stronger fields the magnetostriction does not depend on the sign of the field. A similar phenomenon was observed earlier in[15,16]. In these investigations, the vanishing of the odd magnetostriction in fields of the order of 10 kOe was attributed to realignment of the antiferromagnetic domain structure in the field: the application of such a field leads to the formation of a one-domain antiferromagnetic structure, and the reversal of the sign of the field involves a change in the sign of γ_z in the domain. In other words, only domains with a definite orientation relative to the crystallographic axes and of the field are stable in the field. Our results also agree with the proposed realignment of the domain structure in the field.

Using the obtained values of the magnetostriction constants and the values of the elastic moduli of hematite as given by Voigt[26], we determined by means of formulas (4) the magnetoelastic interaction constants of this antiferromagnet (in units of 10^6 erg/cm³):

$\delta_1+\delta_2$	$\delta_1-\delta_2$	δ_3	δ_4	δ_5	δ_6
-32 ± 4	17 ± 2	-3.9 ± 0.9	$\mp78\pm23$	$\mp56\pm13$	37 ± 3

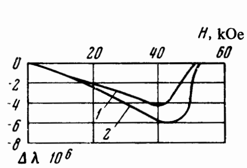

FIG. 3. Dependence of the magnetostriction, which is proportional to $\gamma_z\sqrt{1-\gamma_z^2}$, on the field. T = 230°K. Curve 1–difference between the transverse magnetostriction, measured along the direction lying in the xz plane at an angle 40° to the z axis, in a field H ∥ y, and the longitudinal magnetostriction along the same direction. Curve 2–difference between the transverse magnetostriction along the y axis, in a field H ∥ x, and the longitudinal magnetostriction in the same direction (with a minus sign).

CONTRIBUTION OF THE MAGNETOELASTIC INTERACTION ENERGY TO THE MAGNETIC ANISOTROPY ENERGY OF HEMATITE

Knowing the constants δ_i, we can estimate the influence of the energy of the magnetoelastic interaction on the anisotropy energy of hematite. It follows from Dzyaloshinskiĭ's work[7] that the anisotropy energy of hematite, which depends on the orientation of the antiferromagnetism vector $\mathbf{l}$ relative to the crystallographic axes, can be written (accurate to terms of fourth order in γ_i) in the form

$$E_{\text{аниз}} = \frac{a}{2}(1-\gamma_z^2) + \frac{b}{4}(1-\gamma_z^2)^2 + \frac{g}{2i}[(\gamma_x+i\gamma_y)^3 - (\gamma_x - i\gamma_y)^3]\gamma_z. \tag{8}$$

Using the expression for the magnetoelastic energy[24,25] and formulas (2) derived above for the dependence of the magnetostriction deformations on the orientation of the antiferromagnetism vector, we can obtain the following expression for the magnetoelastic energy:

$$\begin{aligned} E_{\text{му}} = {}& {}^1\!/_2[2\delta_4 V + 4\delta_5 N + 2\delta_3(R-Q)](1-\gamma_z^2) \\ &+ {}^1\!/_4[2(\delta_1+\delta_2)(K-L) + 2(\delta_1-\delta_2)M - 4\delta_4 V - 8\delta_5 N + 2\delta_6 U \\ &- 2\delta_3(R-Q)](1-\gamma_z^2)^2 \\ &+ \frac{1}{2i}[(\delta_1-\delta_2)N + \delta_5 M + \delta_6 V + \frac{1}{2}\delta_4 U][(\gamma_x+i\gamma_y)^3 - (\gamma_x-i\gamma_y)^3]\gamma_z. \end{aligned} \tag{9}$$

Comparing (8) and (9), we obtain for the magnetoelastic contributions to the anisotropy constants the expressions

$$\begin{aligned} \Delta a &= [2\delta_4 V + 4\delta_5 N + 2\delta_3(R-Q)], \\ \Delta b &= [2(\delta_1+\delta_2)(K-L) + 2(\delta_1-\delta_2)M - 4\delta_4 V - 8\delta_5 N \\ &\quad + 2\delta_6 U - 2\delta_3(R-Q)], \\ \Delta g &= [(\delta_1-\delta_2)N + \delta_5 M + \delta_6 V + {}^1\!/_2\delta_4 U]. \end{aligned} \tag{10}$$

From (10) we obtain, using the values of the magnetostriction constants and of the magnetoelastic interaction constants determined above, the following values of the magnetoelastic additions to the anisotropy constants of hematite:

$$\Delta a = -(4.7\pm2.8)\cdot10^3\ \text{erg/cm}^3 \quad \Delta b = (8.3\pm6)\cdot10^3\ \text{erg/cm}^3$$
$$\Delta g = \pm(1.1\pm0.3)\cdot10^3\ \text{erg/cm}^3$$

The anisotropy constants a and b of hematite in the antiferromagnetic phase at temperatures 20–30° below the Morin point, are equal to approximately 10^5 erg/cm³[12], which is larger by two orders of magnitude than the corresponding magnetoelastic additions, and consequently in this temperature region the magnetoelastic interaction has no appreciable influence on the properties of the hematite. However, near the Morin point, where uniaxial anisotropy decreases strongly, the influence of the magnetoelastic interaction becomes more appreciable.

The addition to the constant g, due to the magnetoelastic interaction, as well as the additions to the constants a and b, is of the order of 10^3 erg/cm³. The coefficient g characterizes the additional anisotropy energy, which depends on the orientation of the projection of the antiferromagnetism vector on the basal plane, and which appears in the case when the vector $\mathbf{l}$ is taken outside of this plane (see formula (8)). It was indicated above that in calculations of the magnetic properties of hematite in the antiferromagnetic state it is customary to take into account only interactions that are isotropic in the basal plane. A nonzero contribution of the magnetoelastic interaction to the constant g, comparable in magnitude with the magnetoelastic additions to the anisotropy constants a and b, indicates that interactions that are anisotropic in the basis plane must also be taken into account in the description of the behavior of the antiferromagnetic modification of hematite in the field. One should also note the fact that, as shown by an analysis of the expression given in[7] for the hematite energy, to explain the realignment of the antiferromagnetic domain structure observed in hematite in the field it is necessary to assume that the interactions that are anisotropic in the basal field differ from zero.

ON THE NATURE OF THE MAGNETOELASTIC INTERACTION IN HEMATITE

Artman et al.[27] have shown that the magnetic anisotropy of hematite is due to two causes: dipole-dipole interaction and single-ion anisotropy. The dipole-dipole interaction in the hematite was calculated together with its dependence on the parameters of the crystal cell. On the basis of the data of[27] it is easy to show that if the magnetoelastic interaction is due to the dependence of the dipole-dipole interaction on the interatomic distances, then the changes of the anisotropy constant a due to the deformations along the x and y axes in the basal plane ($u_{xx} = u_{yy}$) and along the z axis (u_{zz}) should have the following values:

$$\frac{\partial a}{\partial u_{xx}} = -66\cdot 10^6 \text{erg/cm}^3 \quad \frac{\partial a}{\partial u_{zz}} = 13\cdot 10^6 \text{erg/cm}^3$$

On the other hand, using the relations obtained in[24], we can express the dependence of the anisotropy constant a on the strains in the following manner in terms of the magnetostriction constants and the elastic moduli:

$$\frac{\partial a}{\partial u_{xx}} = -4[(K-L)(c_1+c_2)+(R-Q)c_4], \qquad (11)$$

$$\frac{\partial a}{\partial u_{zz}} = -2[2(K-L)c_4+(R-Q)c_3].$$

Substituting in (11) the values of the elastic moduli and the magnetostriction constants, we obtain for the dependence of the anisotropy constants on the strains values close to those given above:

$$\frac{\partial a}{\partial u_{xx}} = -(67\pm 4)\cdot 10^6 \text{erg/cm}^3 \quad \frac{\partial a}{\partial u_{zz}} = (8\pm 2)\cdot 10^6 \text{erg/cm}^3$$

Thus, it can be assumed that the magnetoelastic interaction in hematite is due to the dependence of the dipole-dipole interaction on the strains.

The authors are deeply grateful to K. P. Belov for interest in the work and valuable advice, A. M. Kadomtseva, V. I. Ozhogin, B. K. Ponomarev for fruitful discussions, and R. A. Voskanyan for supplying the samples for the measurements.

[1] C. Shull, W. Strausser, and E. Wollan, Phys. Rev. **83**, 333 (1951).
[2] S. Lin, J. Appl. Phys. **30**, 306S (1959).
[3] S. Lin, Phys. Rev. **116**, 1447 (1959).
[4] P. Besser, A. Morrish, and C. Searle, Phys. Rev. **153**, 632 (1967).
[5] A. Morrish, G. Johnston, and N. Curry, Phys. Lett. **7**, 177 (1963).
[6] R. Nathans, S. Pickart, H. Alperin, and P. Brown, Phys. Rev. **136**, A1641 (1964).
[7] I. E. Dzyaloshinskiĭ, Zh. Eksp. Teor. Fiz. **32**, 1547 (1957) [Sov. Phys.-JETP **5**, 1259 (1957)].
[8] J. Kaczer and T. Shalnikova, Proc. Int. Conf. on Magnetism, Nottingham, 1964, p. 589.
[9] G. Cinader and S. Strikman, Solid State Commun. **4**, 459 (1966).
[10] V. I. Ozhogin and V. G. Shapiro, ZhETF Pis. Red. **6**, 467 (1967) [JETP Lett. **6**, 7 (1967)].
[11] R. A. Voskanyan, R. Z. Levitin, and V. A. Shchurov, Zh. Eksp. Teor. Fiz. **53**, 459 (1967) [Sov. Phys.-JETP **26**, 302 (1968)].
[12] R. Z. Levitin and V. A. Shchurov, ZhETP Pis. Red. **7**, 142 (1968) [JETP Lett. **7**, 110 (1968)].
[13] H. Urquhart and J. Goldman, Phys. Rev. **101**, 1443 (1956).
[14] R. A. Voskanyan, R. Z. Levitin, and V. A. Shchurov, Zh. Eksp. Teor. Fiz. **54**, 790 (1968) [Sov. Phys.-JETP **27**, 423 (1968)].
[15] R. Scott and J. Anderson, J. Appl. Phys. **37**, 234 (1964).
[16] J. Anderson, R. Birss, and R. Scott, Proc. Int. Conf. on Magnetism, Nottingham, 1964, p. 597.
[17] V. P. Andratskiĭ and A. S. Borovik-Romanov, Zh. Eksp. Teor. Fiz. **51**, 1030 (1966) [Sov. Phys.-JETP **24**, 687 (1967)].
[18] N. Kawai and F. Ono, Phys. Lett. **21**, 279 (1966).
[19] H. Umebayashi, B. C. Frazer, G. Shirane, and W. D. Daniels, Phys. Lett. **22**, 407 (1966).
[20] R. C. Wayne and D. H. Anderson, Phys. Rev. **155**, 496 (1967).
[21] A. S. Borovik-Romanov and E. G. Rudashevskiĭ, Zh. Eksp. Teor. Fiz. **47**, 209 (1964) [Sov. Phys.-JETP **20**, 1407 (1964)].
[22] K. Mizushima and S. Iida, J. Phys. Soc. Japan **21**, 1521 (1966).
[23] B. K. Ponomarev and R. Z. Levitin, PTÉ No. 3, 188 (1966).
[24] A. S. Pakhomov, FMM **25**, 769 (1968).
[25] E. A. Turov and V. G. Shavrov, Fiz. Tverd. Tela **7**, 217 (1965) [Sov. Phys.-Solid State **7**, 166 (1965/66)].
[26] W. Voigt, Ann. Physik **22**, 129 (1907).
[27] J. Artman, J. Murphy, and S. Foner, Phys. Rev. **138**, A912 (1965).
[28] R. Z. Levitin, A. S. Pakhomov, and V. A. Shchurov, Phys. Lett. **27**, 603A (1968).

Translated by J. G. Adashko
144