ON THE NATURE OF THE MAGNETIZATION CURVES OF A SINGLE CRYSTAL OF SAMARIUM ORTHOFERRITE NEAR THE REORIENTATION TEMPERATURE

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The magnetization curves of a single crystal of samarium orthoferrite were measured from room temperature to the Curie point. On heating to 210°C, there is observed in samarium orthoferrite a reorientation of the magnetic moment from the a axis to the c axis of the orthorhombic crystal. In the temperature interval 150—300°C, the threshold fields of this compound do not exceed 20 kOe; to a first approximation, they increase linearly with distance from the reorientation temperature. Measurements made in pulsed magnetic fields showed that the threshold field of samarium orthoferrite at room temperature is about 50 to 60 kOe, whereas for europium and ytterbium orthoferrites the magnitude of the threshold field exceeds 200 kOe. The experimental magnetization curves near the reorientation temperature agree with calculated curves.

ORTHOFERRITES of rare-earth elements are antiferromagnetic with weak ferromagnetism. The weak ferromagnetism of these compounds occurs because of a noncollinear arrangement of the spins of the "iron" sublattices and is a consequence of their crystalline symmetry [1-3]. The spontaneous magnetic moment is oriented along a definite axis, and along the other two axes the crystal behaves like an ordinary antiferromagnet. Magnetization curves of orthoferrites along the various axes of the crystal were calculated by Turov and Naĭsh [3].

When an external magnetic field is applied along the axis of antiferromagnetism, at a certain threshold field the antiferromagnetism vector should suddenly set itself perpendicular to the magnetic field, and the spontaneous magnetic moment should at the same time orient itself along the field. According to a theoretical estimate [3], the magnitude of the threshold field for orthoferrites should be

$$h_t = \sqrt{h_0 h_a} \sim 10^5 \text{ Oe},$$

where h_0 is the effective exchange field and h_a is the magnetic-anisotropy field.

For samarium orthoferrite, however, a smaller value of the magnitude of the threshold field can be expected in a certain temperature interval. This is so because when samarium orthoferrite is heated to 210°C in the absence of a magnetic field, its magnetic moment is reoriented from the a axis to the c axis of the orthorhombic crystal, consequently, rotation of the magnetic moment becomes easier in the vicinity of the reorientation temperature. Because of this, the form of the magnetization curves should change in the vicinity of the reorientation temperature.

According to [3], the magnetic-energy density for orthorhombic weak ferromagnets—a group to which the orthoferrites belong—can be described approximately in the form

$$H = \tfrac{1}{2}Am^2 + \tfrac{1}{2}a_1 m_x^2 + \tfrac{1}{2}a_2 m_y^2 + \tfrac{1}{2}b_1 l_x^2 + \tfrac{1}{2}b_2 l_z^2 + d_1 m_x l_z - d_2 m_z l_x, \quad (1)$$

where $\mathbf{l}$ is the antiferromagnetism vector and $\mathbf{m}$ the magnetic vector:

$$\mathbf{l} = (\mathbf{M}_1 - \mathbf{M}_2) / 2M_0, \qquad \mathbf{m} = (\mathbf{M}_1 + \mathbf{M}_2) / 2M_0$$

($\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetic moments of the "iron" sublattices). The coefficients d_1 and d_2 are the Dzyaloshinskiĭ parameters, which are responsible for the occurrence of weak ferromagnetism. The natural axis of antiferromagnetism is oriented along one of the axes of the orthohombic crystal, determined by the size and sign of the coefficients b_1 and b_2.

For samarium orthoferrite below 210°C, when the antiferromagnetism vector is oriented along the c axis of the crystal, the energy of the anisotropy connected with rotation of the vector $\mathbf{l}$ can be written

$$\tfrac{1}{2}(b_1 - b_2) l_z^2 = K \cos^2 \nu,$$

where K is the anisotropy constant ($K > 0$) and ν is the angle between the vector $\mathbf{l}$ and the z axis. Then the energy H in a magnetic field h, directed along the z axis, can be represented in the form

$$H = {}^1/_2 Am^2 - K\cos^2\nu - dm - mh^*\sin\nu \qquad (2)$$

($h^* = h/M_0$). To simplify the problem of calculating the magnetization curve, we have here set $d_1 \approx d_2 = d$, which entails no conflict with our experimental data.

From the condition for equilibrium, we find

$$\sigma_z = \frac{\sigma_0^2 h}{2K(1-\chi_\perp h^2/2K)^2} \quad \text{for } h < h_t, \qquad (3)$$

$$\sigma_z = \sigma_0 + \chi_\perp h \quad \text{for } h > h_t. \qquad (4)$$

h_t is the value of the magnetic field at which a transition occurs from one relation, (3), to the other, (4). The value of the threshold field is found from the condition $\sin\nu = 1$:

$$h_t = (h_D^2/4 + h_0 h_a)^{1/2} - h_D/2, \qquad h_a = 2K/M_0, \quad h_0 = M_0/\chi_\perp, \quad h_D = dh_0/A \qquad (5)$$

(h_D is the Dzyaloshinskiĭ field). When the value of the anisotropy constant is very small ($h_a h_0 \ll h_D^2$), this field can be expressed in the form

$$h_t = h_a h_0 / h_D = h_a M_0/\sigma_0. \qquad (6)$$

Since $M_0/\sigma_0 \sim 10^2$, therefore near the reorientation temperature (that is, at small K) $h_t \sim 10^2 h_a$.

Figure 1 shows the theoretical magnetization curves (formulas (3) and (4)), $y = \alpha x(1 - \alpha x^2)^{-2}$, in the dimensionless variables $y = \sigma_z/\sigma_0$ and $x = \chi_\perp h/\sigma_0$, for three values of the parameter $\alpha = \sigma_0^2/2K\chi_\perp$.

We measured the magnetization curves of a single crystal of samarium orthoferrite along the c axis, in a constant magnetic field of up to 19 kOe, at various temperatures (Fig. 2). As is seen from the experimental curves, at temperatures below 210°C one can observe the effect of the field-induced transition of the magnetic moment from the a axis to the c axis of the crystal; the magnetization curves are consistent with the theoretical curves. For the magnitude of the threshold field, we take the value at which the rate of change of magnetization with field is greatest. As is clear from Fig. 2, the threshold field depends greatly on temperature. The highest temperature at which we were still able to produce a reorientation of the magnetic moment to the c axis was 142°C. At this temperature the threshold field attained a magnitude of about 16 kOe.

Figure 3 shows the temperature dependence of the magnetization along the c axis, measured for various values of the magnetic field. From the curves it is also possible to define a critical field as the field corresponding to the temperature of steepest rise of the $\sigma(T)$ curve. As was to be expected, the rise of the $\sigma(T)$ curves in a high field is displaced toward lower temperatures. The decrease of the magnetization in the neighborhood of 400°C corresponds to the Curie point of samarium orthoferrite.

We also measured magnetization curves along

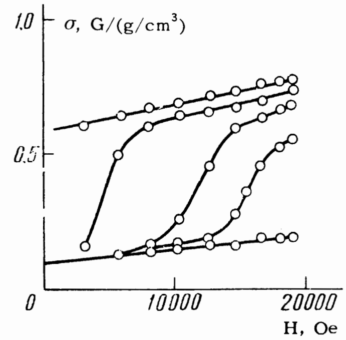

FIG. 2. Magnetization curves of a single crystal of samarium orthoferrite, measured along the c axis of the orthorhombic crystal at temperatures (from top to bottom) 237, 191, 174, 142, and 20°C.

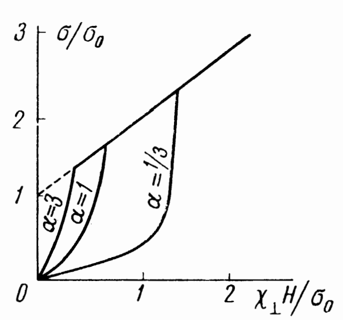

FIG. 1. Theoretical magnetization curves $y = \alpha x(1 - \alpha x^2)^{-2}$ in dimensionless variables $y = \sigma_z/\sigma_0$, $x = \chi_\perp H/\sigma_0$ for three values of the parameter $\alpha = \sigma_0^2/2K\chi_\perp$.

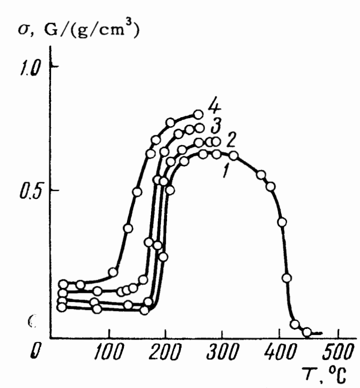

FIG. 3. Temperature dependence of the magnetization of a single crystal of samarium orthoferrite, measured along the c axis of the crystal in field: 1, 3000 Oe; 2, 5650 Oe; 3, 10 300 Oe; 4, 16 600 Oe.

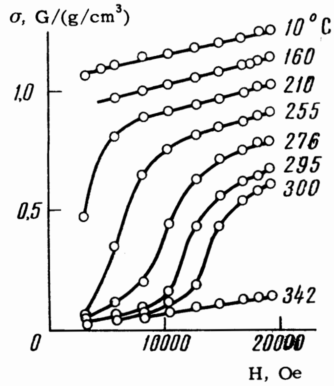

FIG. 4. Magnetization curves of a single crystal of samarium orthoferrite along the a axis at various temperatures.

the a axis at temperatures from 20 to 342°C (Fig. 4). Below 210°C, the magnetic moment is oriented along the a axis, and the magnetization curves conform to the usual relation for weak ferromagnets, $\sigma = \sigma_0 + \chi H$. At temperatures above 210°C, it is possible, by applying a sufficiently strong magnetic field along the a axis, to inhibit the reorientation of the magnetic moment to the c axis. This "inhibiting" field, which keeps the orientation of the magnetic moment along the a axis, increases rapidly with rise of temperature; and at 342°C, a magnetic field of 19 kOe is still not able to prevent the transition of the spontaneous magnetization to the c axis.

Figure 5 gives temperature-variation curves of the magnetization, taken at various values of the external magnetic field. From this figure it is also graphically evident that the larger the field, the higher the temperature of reorientation of the magnetic moment from the a to the c axis of the crystal.

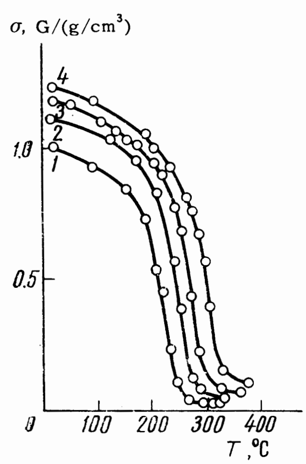

FIG. 5. Temperature dependence of the magnetization of single crystal of samarium orthoferrite, measured along the a axis in magnetic field: 1, 3000 Oe; 2, 5650 Oe; 3, 10 300 Oe; 4, 16 600 Oe.

The results obtained agree with data of a previous work[4] on measurement of the torque on a single crystal of samarium orthoferrite, in the (ac) plane, in fields up to 19 kOe at temperatures from room temperature to the Curie point. In a certain temperature interval, we observed absence of a rigid bond between the spontaneous magnetic moment and the a axis of the orthorhombic crystal, and correspondingly smaller values of the anisotropy constant.

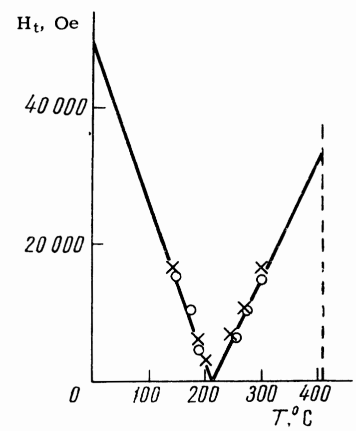

FIG. 6. Dependence of threshold field on temperature for samarium orthoferrite, calculated from the curves: o, σ(H); ×, σ(T).

The temperature dependence of the threshold and "inhibiting" fields, calculated from the curves of Figs. 2—5, is shown in Fig. 6. If we consider this dependence as linear, then at room temperature the threshold field should be about 50 kOe. It should be kept in mind that such an extrapolation is crude, since the values of the threshold fields were found in a narrow temperature region. In a similar approximation one can estimate also the value of the magnetic field (~30 kOe) in whose presence the magnetic moment would remain directed along the a axis clear to the Curie point, with no transition to the c axis of the crystal.

To determine the magnitude of the threshold field at room temperature, we made measurements of the magnetization of samarium orthoferrite in a pulsed magnetic field. The measurement of the magnetization was made by a ponderomotive method, based on the attractive force on the specimen in a nonuniform magnetic field[5] and on the dependence of the torque (proportional to the magnetization) on the field. Because of poor sensitivity, these measurements were of qualitative nature.

The magnitude of the threshold field, obtained from the break in the magnetization curve, was about 50 to 60 kOe.

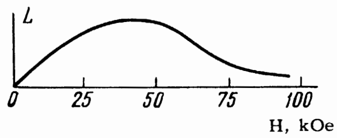

FIG. 7. Dependence of torque L on field for a single crystal of samarium orthoferrite: H ∥ c.

A similar value of the threshold field was also obtained from measurement of the torque due to the field (Fig. 7). In the measurement of the torque, the magnetic field was applied along the antiferromagnetism axis (the c axis of the crystal). In weak fields there is a twisting moment, due to the tendency of the crystal to turn so that the spontaneous moment, directed along the a axis, will be oriented along the field. In larger fields (~ 50–60 kOe), when the reorientation of the spontaneous moment from the a to the c axis (that is, along the field) has already occurred, the twisting moment diminishes.

In pulsed-field measurement of single crystals of europium and ytterbium orthoferrites, we detected no breaks in the magnetization curves up to 200 kOe; the threshold fields of these orthoferrites are therefore appreciably larger than for samarium orthoferrite.

In closing, we express our thanks to V. A. Timofeeva for growing the single crystals of orthoferrites.

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