Investigation of the effect of uniaxial pressure on antiferromagnetic resonance in $KFe_{11}O_{17}$ Crystals

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The deformation dependence of the resonance field in $KFe_{11}O_{17}$ single crystals was investigated by the AFMR method. The measurements were performed at $T=77$ K and $\nu=47.52$ GHz for two orientations of the external pressure. The experimental data are discussed in terms of a model of a very simple easy-plane antiferromagnet taking account of the elastic and magnetoelastic contributions to the thermodynamic potential. The magnetostriction, magnetoelastic, and elastic contants are calculated and the results are $\lambda=1.94\times10^{-5}$, $B_1=2.75\times10^8$ erg/cm^3, and $C_{11}-C_{12}=1.42\times10^{13}$ erg/cm^3, respectively. The values of these constants imply that the origin of the initial gap in the AFMR spectrum is not of magnetoelastic origin. © *1998 American Institute of Physics.* [S1063-7834(98)02403-4]

$KFe_{11}O_{17}$ has a hexagonal layered structure, belonging to the space symmetry group D_{6h}^4, like that observed in β-Al_2O_3.[1] Below the Néel temperature 800 K potassium ferrite is an easy-plane (EP) antiferromagnet.[2] In investigations of the orientational dependence of the low-frequency (LF) branch of the antiferromagnetic resonance (AFMR) in the basal plane of potassium ferrite crystals, it was observed that the amplitude and periodicity of the variation of the resonance field differed from sample to sample.[3] It was established that this is due to nonuniform strains induced in samples when they are glued to the quartz holder and to residual deformations arising when the solution in a melt cools during synthesis of the crystals. Moreover, the spectrum of the LF branch of AFMR has an isotropic energy gap, which, just as in other easy-plane antiferromagnets,[4] can be of magnetoelastic origin. For this reason, in the present work we investigated theoretically and experimentally the effect of uniaxial pressure on AFMR in potassium ferrite.

1. SAMPLES, EXPERIMENTAL CONDITIONS, AND RESULTS

The measurements were performed in an AFMR spectrometer with a pulsed magnetic field. The measuring section of the spectrometer was equipped with an apparatus that made it possible to apply a uniaxial pressure to the sample.[5] Single crystals grown by spontaneous crystallization from a solution in a melt[3] and prepared in the form of 1×0.3 mm rectangular wafers with plane parallel end planes were used as samples. To remove the induced residual strains, the samples were annealed for 7 h at 720 °C in air. The pressure on a sample placed in a quartz ampul was transmitted through a quartz rod. The ampul itself was placed inside a transmission-type resonator so that the sample was located at the antinode of the microwave field, whose flux lines were parallel to the applied pressure and perpendicular to the external magnetic field.

The deformation dependence of the LF AFMR was investigated at temperature 77 K and frequency 47.52 GHz for two orientations of the pressure relative to the crystallographic axes: $\mathbf{p}\|C_6$ and $\mathbf{p}\|C_2$, where C_6 is a six-fold principal axis of the crystal and C_2 is one of the two-fold axes passing through opposite sides of the hexagon characterizing the symmetry in the basal plane. In both cases the external magnetic field was oriented in the basal plane of the crystal along the other two-fold axis U_2, which was perpendicular to C_6 and C_2.

It was established that, to within the accuracy of the measurements, the pressure applied along the C_6 axis does not produce a shift of the resonance field, up to 4×10^8 dyn/cm^2. The figure displays the AFMR field versus pressure applied along C_2. This dependence can be described by a linear law.

2. DISCUSSION

The experimental data were analyzed using a phenomenological model of a two-sublattice antiferromagnet with

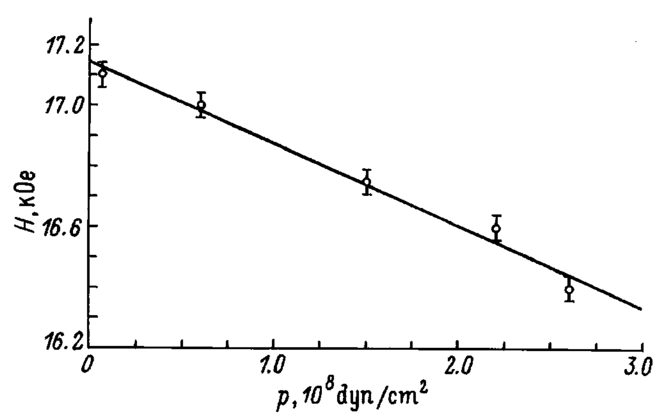

FIG. 1. Resonance field H versus external pressure p applied along one of the axes U_2.

easy-plane magnetic anisotropy. The thermodynamic potential for the experimental crystal can be written, on the basis of symmetry considerations, in the form

$$F=F_M+F_{ME}+F_E+F_{ES}, \qquad (1)$$

where

$$F_M=1/2(A\mathbf{m}^2)+1/2(a_1 l_z^2)-\mathbf{m}\cdot\mathbf{h} \qquad (2)$$

is the magnetic part of the thermodynamic potential, including the intersublattice exchange interaction, a second-order anisotropic invariant, and the Zeeman interaction, respectively, $\mathbf{m}=(\mathbf{M}_1+\mathbf{M}_2)/2M_0$ and $\mathbf{l}=(\mathbf{M}_1-\mathbf{M}_2)/2M_0$ are ferromagnetism and antiferromagnetism vectors, $\mathbf{M}_i$ are the sublattice magnetizations, $M_0=|\mathbf{M}_1|=|\mathbf{M}_2|$ is the saturation magnetization of the sublattices (the latter equalities are equivalent to the conditions $\mathbf{m}^2+\mathbf{l}^2=1$ and $\mathbf{m}\cdot\mathbf{l}=0$),

$$F_{ME}=B_1(U_{XX}l_X^2+U_{YY}l_Y^2+2U_{XY}l_Xl_Y)+B_2 \times(U_{XX}+U_{YY})l_Z^2+B_3U_{ZZ}l_Z^2+B_4(U_{XZ}l_Xl_Z +U_{YZ}l_Yl_Z) \qquad (3)$$

is the magnetoelastic part of the potential, B_i are magnetoelastic constants, u_{ij} are the strain,

$$F_E=C_{11}(U_{XX}^2+U_{YY}^2)/2+C_{12}U_{XX}U_{YY}+C_{13}(U_{XX}U_{ZZ} +U_{YY}U_{ZZ})+(C_{11}-C_{12})U_{XY}^2+C_{33}U_{ZZ}^2/2 +2C_{44}(U_{XZ}^2+U_{YZ}^2 \qquad (4)$$

is the elastic part of the potential, C_{ij} are the elastic constants,

$$E_{ES}=-\sigma_{ij}U_{ij} \qquad (5)$$

is the potential of the external stresses, $\sigma_{ij}=-|\mathbf{p}|\alpha_i\alpha_j$ is the stress tensor, and α_i and α_j are the direction cosines of the pressure vector. All phenomenological constants in the expression for the thermodynamic potential have the dimension of energy. The effective fields are expressed as follows: $H_E=A/2M_0$ is the effective exchange field, $H_{a2}=a_1/2M_0$ is the anisotropy field, $H=h/2M_0$ is the external magnetic field, and so on. The coordinate system of the problem was chosen so that $X\|U_2$, $Y\|C_2$, and $Z\|C_6$.

Let us examine the equilibrium states of the system for an external magnetic field directed along $U_2\|X$, using the standard procedure of minimizing the thermodynamic potential with respect to the components of the vectors **m** and **l** and the deformations u_{ij}. For the case $\mathbf{p}\|C_6$ ($\sigma=\sigma_{ZZ}$) we have

$$m_{OY}=0,\quad m_{OZ}=0,\quad l_{OX}=0,$$
$$l_{OY}=(1-H_X^2/H_E^2)^{1/2},\quad l_{OZ}=0,$$
$$(U_{XX}-U_{YY})^{(0)}=B_1l_{OY}^2/(C_{11}-C_{12}),$$
$$U_{XY}^{(0)}=0,\quad U_{XZ}^{(0)}=0,\quad U_{YZ}^{(0)}=0,$$
$$U_{ZZ}^{(0)}=[B_1C_{13}l_{OY}^2+(C_{11}+C_{12})\sigma_{ZZ}]/ [C_{33}(C_{11}+C_{12})-2C_{13}]. \qquad (6)$$

For the case $\mathbf{p}\|C_2$ ($\sigma=\sigma_{YY}$) we have

$$m_{OX}=H_X/H_E,\quad m_{OY}=0,\quad m_{OZ}=0,\quad l_{OX}=0,$$
$$l_{OY}=(1-H_X^2/H_E^2)^{1/2},\quad l_{OZ}=0,$$
$$(U_{XX}-U_{YY})^{(0)}=(B_1l_{OY}^2-\sigma_{YY})/(C_{11}-C_{12}),$$
$$U_{XY}^{(0)}=0,\quad U_{XZ}^{(0)}=0,\quad U_{YZ}^{(0)}=0,$$
$$U_{ZZ}^{(0)}=(B_1C_{13}l_{OY}^2-C_{13}\sigma_{YY})/[C_{33}(C_{11}+C_{12})-2C_{13}]. \qquad (7)$$

Solving the linearized Landau–Lifshitz equations for small uniform oscillations around a position of equilibrium and for an external magnetic field directed along the axis $U_2\|X$, we obtain for the characteristic frequencies of these oscillations

$$(\omega_1/\gamma)^2=(1-H_{a1}/2H_E)H_X^2+2H_EB_1 \times(u_{XX}-u_{YY})^{(0)}l_{OY}^2, \qquad (8)$$

$$(\omega_2/\gamma)^2=H_E[H_{a1}-2B_1U_{YY}^{(0)}+2B_2(u_{XX}-u_{YY})^{(0)} +2B_3U_{ZZ}^{(0)}]l_{OY}^2. \qquad (9)$$

In what follows we shall be interested only in the LF branch of AFMR and the particular cases of the equilibrium states (6) and (7) that are realized in the experiment.

If $\mathbf{p}\|C_6$, then

$$(\omega_1/\gamma)^2=(1-H_{a1}/2H_E)H_X^2+2H_EH_{MS}, \qquad (10)$$

where

$$H_{MS}=B_1^2/2M_0(C_{11}-C_{12})=\lambda_1B_1/2M_0 \qquad (11)$$

is the effective magnetoelastic field of spontaneous deformations and $\lambda_1=B_1/(C_{11}-C_{12})$ is one of four magnetostriction constants. In this case the pressure does not affect the AFMR parameters of the crystal, but spontaneous deformations make an isotropic contribution $2H_EH_{MS}$ to the initial gap. The frequency–field relation (10) is formally identical to the experimentally observed relation

$$(\omega/\gamma)^2=(1-H_{a1}/2H_E)H_X^2+\Delta^2, \qquad (12)$$

where $\Delta=4500$ Oe is the isotropic gap in the AFMR spectrum.

If $\mathbf{p}\|C_2$, then

$$(\omega_1/\gamma)^2=(1-H_{a1}/2H_E)H_X^2+2H_EH_{MS}+H_EH_\sigma, \qquad (13)$$

where

$$H_\sigma=-B_1\sigma_{YY}/2M_0(C_{11}-C_{12})=-\lambda_1\sigma_{YY}/2M_0 \qquad (14)$$

is the effective magnetoelastic field of the external stresses. In this case there is an external-pressure dependent additional anisotropic contribution $2H_EH_\sigma$ in the AFMR spectrum. It follows from Eqs. (13) and (14) that the external stress dependence of the resonance field has the form

$$H_X(\sigma)=[H_X^2(0)-H_E\lambda_1|\sigma_{YY}|/2M_0(1-H_{a1}/2H_E)]^{1/2} \approx H_X(0)-H_E\lambda_1|\sigma_{YY}|/2M_0H_X(0) \times(1-H_{a1}/2H_E), \qquad (15)$$

i.e., just as in the case of rhombohedral easy-plane antiferromagnets,[4,5] it is an approximately linear function of the applied stress (pressure).

Thus, in both cases the experimental pressure dependence of the resonance field is in complete qualitative agreement with the theoretical dependence. Comparing the relation (15) with the experimental data in the figure, we estimated the magnetostriction constant as $\lambda_1 = 1.94 \times 10^{-5}$. In so doing, we use the computed value $M_0 = 706$ G of the sublattice saturation magnetization and the values $H_{a1}/2H_E = 0.031$ and $H_E = 2.75 \times 10^6$ Oe obtained from the resonance and static magnetic measurements.[3,6] Next, using the value obtained for λ_1 and making the assumption that the initial splitting in the LF AFMR spectrum is of a purely magnetoelastic origin (i.e., the frequency versus field relation in the absence of external stresses is described by Eqs. (10)–(11)), we estimated the magnetoelastic and elastic constants $B_1 = 2.75 \times 10^8$ erg/cm^2 and $C_{11} - C_{12} = 1.42 \times 10^{13}$ erg/cm^3. It is evident from the estimates presented that each constant is approximately an order of magnitude greater than its typical value for related crystalline oxide compounds.[7] If these typical values ($B_1 \sim 10^7$ and $C_{ij} \sim 10^{12}$) are substituted back into the expression for H_{ME}, then it is found that only a fraction $\sim 1/7$ of the experimentally observed magnitude of the gap can be attributed to the magnetoelastic coupling.

In summary, LF AFMR in potassium ferrite is indeed very sensitive to the interaction of the spin and elastic subsystems of the crystal, but the existence of an initial splitting in the AFMR spectrum cannot be explained only by the magnetoelastic interaction.

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