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MAGNETIC FIELD INDUCED FIRST-ORDER TRANSITIONS IN DYSPROSIUM ORTHOFERRITE

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Abstract. – New type of magnetic first-order phase transition induced by external magnetic field applied in the \(ab\)-plane in DyFeO\(_3\) is investigated using different magnetooptic techniques. The phenomenological model of this transition is proposed. The phase diagram in \(H-T\) plane has been obtained for various \(H\) orientation in the \(ab\)-plane.

Introduction
Spin reorientation phase transitions in rare-earth orthoferrites RFeO\(_3\) (where \(R\) denotes Y or rare-earth element) induced by magnetic field parallel to \(a\), \(b\), \(c\)-axes have been attending great interest in the last two decades [1]. In DyFeO\(_3\) magnetic field \(H\) // \(a\) provides to spin reorientation \(\Gamma_1 (G_y) \rightarrow \Gamma_{12} (F_z G_y G_x) \rightarrow \Gamma_2 (F_z G_x)\) in temperatures lower than Morin point \((T_M)\), and to \(\Gamma_4 (F_x G_y) \rightarrow \Gamma_2 (F_z G_x G_y) \rightarrow \Gamma_2 (F_z G_x)\) at temperatures above the Morin point. Here \(\Gamma_i\) are the irreducible representations according to the notation given in [2]. \(G_i\) and \(F_i\) represent the basic antiferromagnetic and ferromagnetic spin-arrangement along the \(i\)-axis, respectively. In applied magnetic field \(H\) parallel to the \(a\)-axis the reorientations \(\Gamma_1 \rightarrow \Gamma_2\) and \(\Gamma_4 \rightarrow \Gamma_2\) usually occur through the continuous rotation of \(G\) and \(F\) and are completed by \(\Gamma_{12} \rightarrow \Gamma_2\) and \(\Gamma_{24} \rightarrow \Gamma_2\) second-order phase transitions, respectively. However, it was shown in [3] that in the vicinity of the Morin point \(T_M < T < T_c\) the \(\Gamma_4 \rightarrow \Gamma_2\) reorientation is realized in \(\Gamma_4 \rightarrow \Gamma_{24} \rightarrow \Gamma_{12} \rightarrow \Gamma_2\) sequence of phase transitions. In this sequence the \(\Gamma_{24} \rightarrow \Gamma_{12}\) transition is the first-order phase transition during which spins jump from \(ac\)-plane of the crystal to \(bc\)-plane. It is generally known, that in the orthorhombic crystal DyFeO\(_3\) a nature of phase transition induced by the applied magnetic field \(H\) // \(a\) differs from that for the case \(H\) // \(b\). Up to now, a phase transition induced by the field in the \(ab\)-plane has not been investigated. The main purpose of this paper was to study this case. Additionally, parameters of the critical point for the transition \(\Gamma_{24} \rightarrow \Gamma_{12}\) induced by the field \(H\) // \(a\) have been determined.

Experiment
The investigated DyFeO\(_3\) single crystals had the form of platelets 40 \(\mu\)m and 36 \(\mu\)m thick with \(c\)- and \(a\)-axis normal to the platelet surface, respectively. The samples were mounted in a helium cryostat in which the temperature could be stabilized with accuracy of 0.05 K. System of superconductive coils produced external magnetic field in the plane of the sample and along the normal to the plane. Sample could be also rotated along the axes perpendicular to the surface. The following experimental techniques have been applied: the polarizing microscope to observe the multiphase domain structure, and linear magnetic birefringence and Faraday effect to measure the magnetization discontinuity along the phase boundaries. From these measurements we obtained phase diagram in \(H-T\) plane for external magnetic field applied in \(ab\)-plane of the crystal \((H = (H_x, H_y, 0))\).

A phenomenological model of \(\Gamma_4 \rightarrow \Gamma_2\) phase transition in DyFeO\(_3\).

To describe the spin reorientation observed in magnetic field \(H = (H_x, H_y, 0)\), we have used thermodynamic potential of the form [4]:

\[
\Phi(\theta, \varphi) = K_{2ab}^b \cos^2 \theta \cos^2 \varphi + K_{2bc}^c \sin^2 \theta - m_0^2 H_x \sin \theta + 1/2 \chi_{zz}^x H_x H_y \cos^2 \theta \sin 2\varphi + K_4^{ab} \cos^4 \theta \cos^4 \varphi + K_4^{bc} \sin^4 \theta + K_4 \sin^2 2\theta \cos^2 \varphi,
\]

where \((\varphi, \theta)\) are the polar coordinates of \(G\);

\[
K_2^{ab} = K_2^{bc} + \chi_1^x H_x^2 - \chi_1^y H_y^2, \quad K_2^{bc} = K_2^{ab} - \chi_1^y H_x^2;
\]

\[
\chi_1^x = 1/2 \chi_{zz}^x (1 + \eta_x)^2; \quad \chi_1^y = 1/2 \chi_{zz}^x (1 + \eta_y)^2;
\]

\[
\chi_{zz}^x = \chi_0 (1 + \eta_x) (1 + \eta_y); \quad K_2^{ab}, K_2^{bc}, K_4^{ab}, K_4^{bc}, K_4, \]

are the second and fourth-order anisotropy constants for the \(ab\)- and \(bc\)-planes, respectively; \(\chi_x\) – perpendicular susceptibility; \(\eta_x, \eta_y\) – the amplification factors due to Dy\(^{3+}\) ions; \(m_0^2\) – the spontaneous magnetization. From the minimization of \(\Phi(\theta, \varphi)\) it results, that in low magnetic fields \((H \ll 2K_2^x/m_0^2)\) two stable magnetic states exist with the orientation of the G
vector given by:

\[ \sin \theta_i = \frac{m_i^0 H_z}{2 \left( \tilde{K}_2^{bc} - \tilde{K}_2^{ab} \cos^2 \varphi_i - \frac{1}{2} \chi^{xy}_{\perp} H_x H_y \sin 2\varphi_i \right)}; \]

\( (i = 1, 2); \)

\[ \varphi_1 \simeq \frac{1}{2} \arcsin \left( \frac{\chi^{xy}_{\perp} H_x H_y}{2 K_4^{ab}} \right); \] \( (2a) \)

\[ \varphi_2 \simeq \frac{\pi}{2} - \varphi_1; \] \( (2b) \)

It means, that on the contrary to all investigated hitherto phase transitions in orthoferrites and orthochromites the vector \( G \) is not localized in one of the \( ab-, ac- \) or \( bc- \) planes and all its components \( G_x, G_y, G_z \) are different from zero. This canted configuration is denoted by \( \Gamma_{124}(G_x, G_y, G_z) \).

### Experimental results

The lines for the first-order phase transition between magnetic configuration \( \Gamma_{124} \) and \( \Gamma''_{124} \) determined by the relation \( (2), (2a) \) and \( (2b) \) are obtained for different angles \( \alpha \) between external magnetic field \( H \) and \( a- \) axis by visual observation of phases coexistence or jumps of magnetooptical parameters. It may be well to add that for given \( H \) and \( \alpha \) values the phases coexistence region is very narrow keeping within 1 K. From these regions and additional magnetooptical measurements the phase diagrams in the planes \( H-T \) and \( H-\alpha \) were obtained. Figure 1 represents the phase diagram for the \( \Gamma'_{124} \rightarrow \Gamma''_{124} \) transition in \( H-T \) plane in vicinity of the Morin point. Continuous lines describe theoretical dependences obtained from an analysis of thermodynamical potential \( \Phi(\theta, \varphi) \). In order to describe all the experimental results one has to assume that parameter

\[ \tilde{\eta}_i(T) = \sqrt{\chi_{\perp}/2} \left[ 1 + \eta_i(T) \right] \quad (i = x, y) \]

depend on temperature. From the assumption:

\[ \eta_i(T) = \eta_i(T_M) + \frac{d\eta_i}{dT}(T - T_M) \]

it has been obtained:

\[ \tilde{\eta}_x(T_M) = 4.2 \times 10^{-3}, \quad \tilde{\eta}_y(T_M) = 2.2 \times 10^{-3}, \]

\[ \frac{d\tilde{\eta}_x}{dT} = -6.8 \times 10^{-5} \text{ K}^{-1}, \]

\[ \frac{d\tilde{\eta}_y}{dT} = -1.8 \times 10^{-4} \text{ K}^{-1}. \]

A good agreement of the theory with the experiment (Fig. 1) confirms an applicability of the proposed phenomenological model to the analysis of the phase transitions \( \Gamma_{124} \rightarrow \Gamma''_{124} \). The magnetooptical measurements performed on the plate perpendicular to the \( a- \) axis give the following values of the critical point parameters for the transition \( \Gamma_{24} \rightarrow \Gamma_{12} : H_{cr} \simeq 35 \text{ kOe}; \)

\[ T_{cr} \simeq 54.5 \text{ K}. \]

### Conclusions

In the paper for the first time the phase transitions in \( \text{DyFeO}_3 \) induced by the magnetic field in \( ab- \) plane were investigated. The first-order phase transition between the magnetic configurations of the \( \Gamma_{124} \) type with all non-zero components of the antiferromagnetic vector \( G \) have been observed. The proposed phenomenological model describes discussed phase transitions in a proper way.


