Topology of phase diagrams in spin-flip phase transitions and the antiferromagnetic resonance in dysprosium and yttrium orthoferrites

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A replacement of a rare-earth dysprosium ion by an yttrium ion in orthoferrite changes the combination sign of the "second" constants of the anisotropy if the signs of the "first" constants are the same. As a result, the topology of the phase diagram changes due to a magnetic-field-induced spin flip.

The energy gap in the spin-wave spectrum of an antiferromagnet in the case of a magnetic-field-induced spin flip is usually associated with a first-order phase transition. There is a situation, however, in which the softening mode is not directly related to those components of the order parameter which participate in forming the spin-wave spectrum. A finite energy gap can exist here even in the case of a second-order phase transition[1] because of the multicomponent nature of the order parameter[2] (we are considering here only the magnetic subsystem which is not related in any way to the other subsystems of the crystal).

It is accordingly of fundamental importance to consider all possible phase diagrams and the thermodynamic methods used to obtain these diagrams in the case of a magnetic-field-induced spin flip.

The Landau thermodynamic potential, written in accordance with the symmetry of orthorhombic crystals, is[1,3,4]

$$\Phi(\mathbf{M},\mathbf{L}) = \Phi_0(\mathbf{L}^2) + \frac{1}{2}B\mathbf{M}^2 + \frac{1}{2}D(\mathbf{ML})^2 + d(M_xL_z - M_zL_x) - \mathbf{MH}$$

$$+ \frac{1}{2}a_1L_x^2 + \frac{1}{2}a_2L_y^2 + \frac{1}{2}a_3L_z^2 + \frac{1}{4}a_{11}L_x^4 + \frac{1}{4}a_{22}L_y^4 + \frac{1}{4}a_{33}L_z^4$$

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$$+\frac{1}{2}a_{12}L_x^2L_y^2+\frac{1}{2}a_{13}L_x^2L_z^2+\frac{1}{2}a_{23}L_y^2L_z^2,$$

where, typically, $\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2$, $\mathbf{L}=\mathbf{M}_1-\mathbf{M}_2$, and $\mathbf{M}_1$ and $\mathbf{M}_2$ are the intensities of magnetization of the sublattices. We also assume that $\mathbf{L}^2=L_0^2$ (Ref. 5), where L_0 is the equilibrium value of the antiferromagnetic vector, $\mathbf{H}=(H_x,0,0)$ and $\mathbf{L}=(L_x,0,0)$ at $\mathbf{H}=0$.

Depending on the combination sign of the "second" constant of the anisotropy $a^{(2)}=a_{11}+a_{33}-2a_{13}$, there are two acceptable types of topologically different phase diagrams [Figs. 1(a) and 1(b)]. For $a^{(2)}>0$ a second-order phase-transition line (EF) applies and for $a^{(2)}<0$ both a second-order phase-transition line (AD) and a first-order phase-transition line (CA) apply.

Using very simple thermodynamic equations of motion[6,7] under the condition $\mathbf{L}^2=L_0^2$, we can find expressions for the antiferromagnetic-resonance frequencies $\nu=\nu_{0c}$ ($H_x=0$ and the vector $\mathbf{L}$ is parallel to the **a** axis of the orthoferrite) and $\nu=\nu_{0a}$ (ν_{0a} corresponds to an extrapolation to $H_x=0$ in the equation for the antiferromagnetic resonance when the vector $\mathbf{L}$ is oriented along the **c** axis)

$$\nu_{0c}^2=\Delta_c=\gamma^2(4\pi^2\chi_\perp)^{-1}[a_3-a_1+(a_{13}-a_{11})L_0^2]L_0^2,$$

$$\nu_{0a}^2=-\Delta_a=-\gamma^2(4\pi^2\chi_\perp)^{-1}[a_3-a_1+(a_{33}-a_{13})L_0^2]L_0^2$$

($\gamma=\gamma_0=ge/2mc$ was used for the kinetic coefficient γ in the calculations).

It follows from these expressions that the sign of $(\Delta_a-\Delta_c)$ is the same as the combination sign of the second constants $a^{(2)}$ of the anisotropy and thereby determines

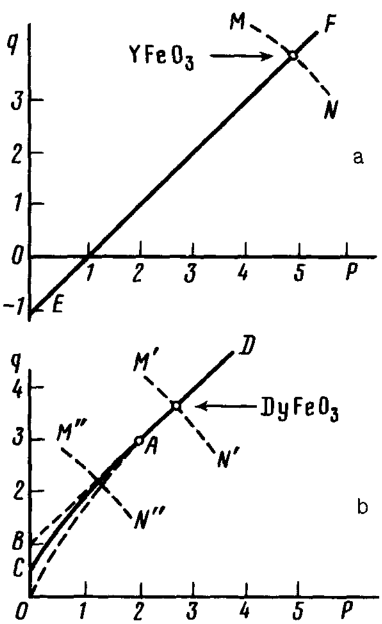

FIG. 1. Phase diagram corresponding to a change in the orientation of the vector $\mathbf{L}$ in the ac plane of the orthoferrite upon a change in the magnetic field. $q=[L_0^2a^{(1)}\chi_\perp^{-1}-(1-\chi_\parallel/\chi_\perp)H^2]/L_0^4|a^{(2)}|\chi_\perp^{-1}$, $p=HH_D/L_0^4|a^{(2)}|\chi_\perp^{-1}$, $a^{(1)}=a_3-a_1+L_0^2(a_{13}-a_{11})$, $H_D=dL_0$, $\chi_\perp^{-1}=B$, $\chi_\parallel^{-1}=B+DL_0^2$. The MN, $M'N'$, and $M''N''$ trajectories—Possible thermodynamic paths produced by changing the magnetic field and the temperature-dependent constant. The line equations are BD-$q=p+1_5$ CA-$p=(2\times3)^{-1}[\sqrt{6q-2}+2]^2[\sqrt{6q-2}-1]$, OA-$q=3(p/2)^{2/3}$.

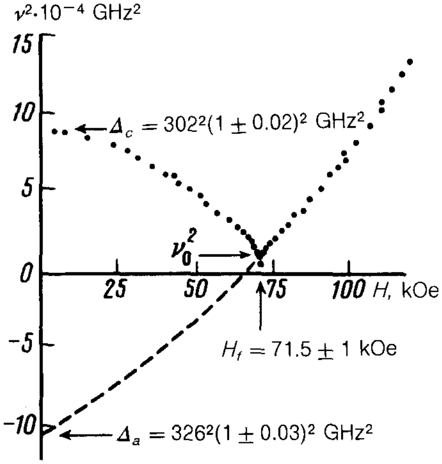

FIG. 2. The dependence $\nu^2(H)$ for $YFeO_3$ at $T = 293$ K, $\mathbf{H}\|a$.

which type of the phase diagram it belongs to. The experimental studies of the antiferromagnetic resonance in strong magnetic fields thus make it possible, in principle, to determine the topology of the phase diagram corresponding to a magnetic-field-induced spin flip.

In the present experiments we have studied the "low-frequency branches of the antiferromagnetic resonance in yttrium orthoferrite $YFeO_3$ and dysprosium orthoferrite $DyFeO_3$ when the magnetic field was oriented along the **a** axis of an orthorhombic crystal at $T = 293$ K. The measurement method used by us is similar to that described in Ref. 1. The results of the experiments are shown in Figs. 2 and 3. We see that the difference $\Delta_a - \Delta_c$ is positive for $YFeO_3$ and negative for $DyFeO_3$. We have thus determined experimentally that at room temperature $YFeO_3$ and $DyFeO_3$ correspond to topologically different phase diagrams which are illustrated in Figs. 1(a) and 1(b), respectively. The lines MN and $M'N'$ show the thermodynamic paths of these orthofer-

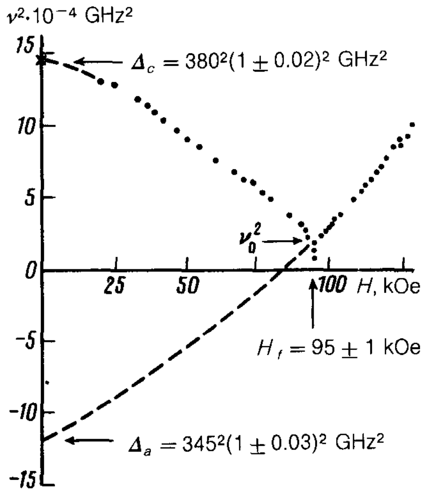

FIG. 3. The dependence $\nu^2(H)$ for $DyFeO_3$ at $T = 293$ K, $\mathbf{H}\|a$. The value of ν_{0c}^2 (*) is taken from Ref. 7.

rites produced by varying the magnetic field. We should point out that in $DyFeO_3$ and $YFeO_3$ the energy gap at $H = H_f$ is seen at the crossing of the second-order phase-transition line [the *AD* line in Fig. 1(b)].

A point that merits attention is the fact that a replacement of a rare-earth dysprosium ion by an yttrium ion, without changing the combination sign of the "first" constants of the anisotropy or the qualitative behavior of the $\nu^2(H)$ curve, leads to a change in the combination sign of the second constants $a^{(2)}$, which determines the topological features of the phase diagrams.

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