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THE FEATURES OF COBALT FLUORIDE STATES

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It was established by numerical solution that the change of magnetic subsystem phase from antiferromagnetic to angular occurs generally in restricted interval of magnetic fields, which is significantly less than the threshold field.

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1. INTRODUCTION

Study of the states of antiferromagnets (AFM) (see, for example, [1-4]), including states of AFM to which the Dzyaloshinskii interaction (see, for example, [5-7]) is inherent, is under great attention in connection with the possibility of the discovery of features of the physical properties. States of AFM cobalt fluoride in the external magnetic field arouse the interest of many researches during last years (see, for example, [8-14]).

The one of the reasons complicating the theoretical investigation of the phase transitions to CoF_2 and, consequently, impeding the description of the experimental data is (in contrast to MnF_2 crystal) the absence of small parameter because of a large value of the crystalline magnetic anisotropy. Anisotropy field H_A to exchange field H_e ratio does not satisfy the usual condition $H_A/H_e << 1$. Study [11, 12] of CoF_2 by measuring the magnetization, antiferromagnetic resonance, linear double refraction, and Faraday rotation of light propagating along the easy magnetization axis (EMA) has shown that with the increase in magnetic field $\mathbf{H} \parallel$ **EMA** instead of the usual transition of antiferromagnetism vector $\boldsymbol{l}$ from the state $\boldsymbol{l} \parallel$ **EMA** to the state $\boldsymbol{l} \perp$ **EMA**, transition of $\boldsymbol{l}$ from the antiferromagnetic phase to the angular one occurs. There were a lot of discussions if this transition occurs as the first- or the second-order phase transition. And the present work is devoted to this phase transition. The thermodynamic potential F and a number of variables which determine the state of magnetic subsystem are used in the work from [12]. However, some corrections are required.

2. THE SYSTEM OF EQUATIONS

We use the thermodynamic potential F in the following form:

$$F = 2M_0\left[\frac{1}{2}Em^2 + \frac{1}{2}G(ml)^2 - D(m_x l_x + l_x m_y) + F(ml)l_x l_y - mH + \right.$$
$$\left. + \frac{1}{2}A_1(l_x^2 + l_y^2) - \frac{1}{4}A_2(l_x^2 + l_y^2)^2\right], \tag{1}$$

where $m = (M_1 + M_2)/2M_0$; $l = (M_1 - M_2)/2M_0$; EMA $\parallel OZ$, E and G are the exchange constants; F, A_1, and A_2 are the anisotropy constants; and D is the Dzyaloshinskii constant.

Condition $ml = 0$ does not hold. We have to note that sign "–" is chosen in expression (1) before Dzyaloshinskii constant. Sign "–" is also chosen before constant A_2, in this case $A_2 > 0$.
Possible states denote that

$$l_x = l\sin\theta\sin\phi\,,\ \ l_y = l\sin\theta\cos\phi\,,\ \ l_z = l\cos\theta\,. \tag{2}$$

Therefore, it is necessary to write thermodynamic potential (1) in the form

$$\frac{F}{2M_0} = \frac{1}{2}E\left(m_x^2 + m_y^2 + m_z^2\right) + \frac{1}{2}Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + \right.$$
$$\left. + m_z\cos\theta\right)^2 - Dl\left(m_x\sin\theta\cos\phi + m_y\sin\theta\sin\phi\right) +$$
$$+ Fl^3\sin^2\theta\sin\phi\cos\phi(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta) -$$
$$-(m_x H_x + m_y H_y + m_z H_z) + \frac{1}{2}A_1 l^2\sin^2\theta - \frac{1}{4}A_2 l^4\sin^4\theta. \tag{3}$$

As follows from expression (3), thermodynamic potential is the function of five variables, i.e. $F = F(\theta, \phi, m_x, m_y, m_z)$, and using the necessary existence condition of the minimum of this function, we find that possible states of magnetic subsystem are determined from the following system of equations:

$$\frac{\partial F}{\partial\theta} = Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right)\times$$
$$\times\left(m_x\cos\theta\sin\phi + m_y\cos\theta\cos\phi - m_z\sin\theta\right) - Dl\cos\theta\left(m_x\cos\phi + m_y\sin\phi\right) +$$
$$+ Fl^3\sin^2\theta\sin\phi\cos\phi\left(m_x\cos\theta\sin\phi + m_y\cos\theta\cos\phi + m_z\sin\theta\right) +$$
$$+ \frac{1}{4}Fl^3\sin 2\theta\sin 2\phi\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right) +$$
$$+ \frac{1}{2}A_1 l^2\sin 2\theta - \frac{1}{2}A_2 l^4\sin 2\theta\sin^2\theta = 0, \tag{4}$$

$$\frac{\partial F}{\partial\phi} = Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right)\times$$
$$\times\left(m_x\sin\theta\cos\phi + m_y\sin\theta\sin\phi\right) - Dl\sin\theta\left(-m_x\sin\phi + m_y\cos\phi\right) +$$
$$+\frac{1}{2}Fl^3\sin^2\theta\sin2\phi\left(m_x\sin\theta\cos\phi - m_y\sin\theta\sin\phi\right) +$$
$$+Fl^3\sin^2\theta\cos2\phi\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right) = 0, \quad (5)$$

$$\frac{\partial F}{\partial m_x} = Em_x + Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right)\sin\theta\cos\phi -$$
$$-Dl\sin\theta\cos\phi + Fl^3\sin^3\theta\sin^2\phi\cos\phi - H_x = 0, \quad (6)$$

$$\frac{\partial F}{\partial m_y} = Em_y + Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right)\sin\theta\cos\phi -$$
$$-Dl\sin\theta\sin\phi + Fl^3\sin^3\theta\sin\phi\cos^2\phi - H_y = 0, \quad (7)$$

$$\frac{\partial F}{\partial m_z} = Em_z + Gl^2\left(m_x\sin\theta\sin\phi + m_y\sin\theta\cos\phi + m_z\cos\theta\right)\cos\theta +$$
$$-\frac{1}{2}Fl^3\sin^2\theta\sin2\phi\cos\theta - H_z = 0. \quad (8)$$

System of equations (4)-(8) is given in detail and purely mathematically more correct by the following reasons: firstly, this simplifies the analysis of possible states of magnetic subsystem; and, secondly, if find the values of m_x, m_y, m_z from equations (6)-(8) and substitute them into function (3) and use this function in the form of $F = F(\theta, \varphi)$, then if determine the sufficient existence conditions of the minimum of $F = F(\theta, \varphi)$, one can obtain the wrong conclusions.

Using (6)-(8), we find

$$\frac{\partial F}{\partial\theta} = -\frac{1}{E}H_yDl\cos\theta\sin\phi + \frac{1}{2}\sin2\theta\left\{-\frac{(Dl)^2}{E} + A_1l^2 - A_2l^4\sin^2\theta +\right.$$
$$+\frac{1}{E(E+Gl^2)}\left[H_y^2Gl^2\cos^2\phi - H_z^2Gl^2 + \frac{1}{2}\sin^2\theta\sin^2 2\phi(-E(Fl^3)^2 + 4EDlFl^3 +\right.$$
$$\left.\left.+4(Dl)^2Gl^2 + 3H_y\sin\theta\sin\phi\cos^2\phi(EFl^3 + 2DlGl^2)\right]\right\} +$$
$$+\frac{H_z\cos\phi}{E(E+Gl^2)}\left[H_yGl^2\cos2\theta + \sin\theta\sin\phi(EFl^3 + 2DlGl^2)(2\cos^2\theta - \sin^2\theta)\right] = 0, \quad (9)$$

$$\frac{\partial F}{\partial\phi} = -\frac{1}{E}H_yDl\sin\theta\cos\phi + \frac{1}{2E(E+Gl^2)}\left\{-H_y^2Gl^2\sin^2\theta\sin2\phi +\right.$$
$$+\sin^4\theta\sin2\phi\cos2\phi(-E(Fl^3)^2 + 4EDlFl^3 + 4(Dl)^2Gl^2) -$$
$$-H_yH_zGl^2\sin2\theta\sin\phi + 2H_y\sin^3\theta\cos\phi(EFl^3 + 2DlGl^2)(\cos^2\phi - 2\sin^2\phi) +$$
$$\left.+H_z\sin\theta\sin2\theta\cos2\phi(EFl^3 + 2DlGl^2)\right\}. \quad (10)$$

Equations (9) and (10), naturally, coincide with equations (9) and (10) obtained in the work [12] at $H_y = 0$.

3. ANALYSIS OF THE SYSTEM OF EQUATIONS

If in equations (9) and (10) direct the field **H** ∥ **EMA** ($H_y = 0$), then for CoF_2, according to [14], with the increase in the magnetic field, the state **I** ⊥ **EMA** ($\theta = \pi/2$, $\phi = \pi/2$) is not realized, in spite of the fact that it is the solution of equations (9) and (10), since this solution does not satisfy the minimum requirement of F. With the increase in the magnetic field **H** ∥ **EMA**, the states $\cos\theta \neq 0$ and $\cos 2\phi = 0$ are realized, i.e. the angular phase is realized.

To determine the further behavior of magnetic subsystem with the growth of magnetic field, we use the equation with respect to the angle θ at $\phi = \pi/4$.

$$\sin\theta\left\{\cos\theta\left[-\frac{H^2G}{E(E+Gl^2)}+\frac{2HGl}{E(E+Gl^2)}\left(D+\frac{FE}{2G}\right)\cos\theta - A_2l^2\sin^2\theta + \right.\right.$$
$$\left. + A_1 - \frac{D^2}{E} + \frac{1}{2E}\left(\frac{G}{E+Gl^2}(Fl^3-2Dl)^2 - Fl^2(Fl^2-4D)\right)\sin^2\theta\right] - \qquad (11)$$
$$\left. - \frac{HGl}{E(E+Gl^2)}\left(D+\frac{FE}{2G}\right)\sin^2\theta\right\} = 0.$$

It follows from equation (11) that the state $\theta = \pi/2$ is realized at $l = 0$, i.e. fields of the spin-flop and spin-flip transitions coincide. This conclusion agrees with the experimental data of the work [11], where authors have shown the absence of peculiarities of the dependence of the antiferromagnetic resonance frequency on the field between the threshold field H_c and the field of the spin-flip transition.

Equation (11) allows at $l \cong 1$ to find the numerical values of the angle θ substituting in it the values of the threshold field H_c and constants E, G, D, F, A_1, and A_2 obtained experimentally [11, 12]. These values of the angle θ versus the ratio H/H_c are represented in Table 1.

Table 1 *– Dependence of the orientation of antiferromagnetism vector on the magnetic field value*

H/Hc	1,025	1,05	1,1	1,15	1,2	1,25
θ, degrees	4,282	6,181	9,081	11,518	13,736	15,823

It follows from Table 1 that the strongest (and continuous) change of the angle θ with the increase in the magnetic field (starting from the threshold field H_c) occurs in the field range close to H_c, i.e. $|H - H_c| << 1$. This data agrees with the conclusions of the work [14], according to which the transition between the antiferromagnetic and the angular phases is the second-order transition.

4. CONCLUSIONS

1. The obtained solutions are of an interest for further experimental and theoretical investigations with the aim of the discovery of new features of the physical properties of the studied phase transition.

2. For the first time, it is discovered on the example of cobalt fluoride that the order parameter of the second-order phase transition (in the given case, it is angle θ) is changed in the vicinity of the critical (threshold) field so sharply with the change in the magnetic field value, that this result is of technical interest for the development of different relays.

3. Since giant magnetostriction discovered in intermetallic $TbFe_2$ and $DyFe_2$ compounds at room temperatures can not be used for the production of small-size and with high efficiency ultrasound sources because of the fact that these compounds possess large magnetocrystalline anisotropy, then the discovered peculiarities of the states in cobalt fluoride in the longitudinal magnetic field, firstly, open a prospect for use of cobalt fluoride as working part of the ultrasound source, and, secondly, indicate one of the research directions of the mentioned intermetallic compounds in order to find regions of high sensitivity to the external magnetic field action.

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