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COUPLED ELECTROMAGNETIC AND SPIN WAVES IN FERRODIELECTRICS NEAR THE CRITICAL POINT

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Coupled electromagnetic and spin waves in a ferrodielectric are considered near the critical point, at which the nature of the crystal's magnetic anisotropy changes. It is shown that, together with an abrupt increase of the activation energy for oscillations of the magnetic moment, a decrease occurs in the phase velocity of long-wave electromagnetic waves propagating in such a crystal.

IN this article we consider the propagation of electromagnetic oscillations in a ferromagnetic dielectric near the critical point, at which the character of the crystal's magnetic anisotropy changes. We shall be interested in long-wave electromagnetic oscillations in crystals having a small effective magnetic anisotropy, $|\beta^*| \ll 1$, where $\beta^* = \beta + (H_0/M_0)$; β is the constant of magnetic anisotropy; $\mathbf{M}_0$ is the equilibrium value of the density of the magnetic moment in an external field $\mathbf{H}_0$ ($\mathbf{H}_0 \parallel \mathbf{M}_0$).

The value of β^* and the magnetic symmetry of the ferromagnet determined by it may change, depending on the external conditions. In particular, crystals exist whose magnetic symmetry changes at a definite temperature (for example, magnetite[1]). In addition, one can achieve a change of magnetic symmetry for crystals having anisotropy of the easy plane type (and also for crystals with cubic symmetry) by gradually reducing the external magnetic field, which is directed at an angle to the axis of easiest magnetization.

If the external magnetic field is directed along the anisotropy axis of a uniaxial ferromagnet, then the dispersion equation for coupled electromagnetic and spin waves has the form (see, for example,[2]):

$$\frac{c^2q^2}{\omega^2\varepsilon} = \frac{1}{2}(\mu\sin^2\chi + \cos^2\chi)^{-1}\{\mu(1+\cos^2\chi) + (\mu^2 - \mu'^2)\sin^2\chi \pm \sqrt{(\mu^2 - \mu'^2 - \mu)^2\sin^4\chi + 4\mu'^2\cos^2\chi}\}, \quad (1)$$

where ω is the frequency, $\mathbf{q}$ is the wave vector of the oscillation, ϵ is the dielectric constant of the crystal,

$$\mu = 1 + \frac{4\pi g M_0 \Omega}{\Omega^2 - \omega^2}, \quad \mu' = \frac{4\pi g M_0 \omega}{\Omega^2 - \omega^2},$$

$\Omega = gM_0\beta^*$ (since we are interested in the region in which spatial dispersion of the high-frequency magnetic permeability is inessential, we neglect the term αq^2 in the expression for Ω), χ is the angle between the vector $\mathbf{q}$ and the anisotropy axis, and g is the gyromagnetic ratio.

According to Eq. (1) the frequency of one of the branches of coupled electromagnetic and spin waves in the long wavelength region ($q \ll 4\pi g M_0\sqrt{\epsilon}/c$) is given by

$$\omega_1 = 4\pi g M_0. \quad (2)$$

We note that if the coupling between spin and electromagnetic waves were not taken into consideration, then the frequency of the spin wave in the long-wave region would have the form

$$\omega_s = gM_0\sqrt{\beta^*(\beta^* + 4\pi\sin^2\chi)}.$$

Thus, owing to the coupling of spin waves with electromagnetic oscillations, the activation energy for oscillations of the magnetic moment increases abruptly near the critical point (by $\beta^{*-1/2}$ times, and in the case of waves propagating along the anisotropy axis—by β^{*-1} times).

For the two other branches of oscillations in the long-wave region ($q \ll 4\pi g M_0\sqrt{\epsilon}/c$) we obtain

$$\omega_{2,3} = \frac{cq}{8\pi g M_0 \varepsilon}\{\sqrt{c^2q^2 + (4\pi^{1/2}gM_0)^2\beta^*\varepsilon} \pm cq\}. \quad (3)$$

(For simplicity we confine ourselves to the case of waves propagating along the anisotropy axis.)

According to this formula, the dispersion law for electromagnetic oscillations near the critical point in the region

$$4^2\pi(gM_0)^2\varepsilon\beta^* \lesssim c^2q^2 \ll (4\pi g M_0)^2\varepsilon$$

differs substantially from the dispersion laws in both nonmagnetic media and in ferromagnetics with large magnetic anisotropy. Taking it into consideration that $4\pi g M_0 \sim 10^{11}$ sec^{-1}, we see that such a modification of the dispersion law must hold in the millimeter region.

In the region of very long waves ($4^2\pi(gM_0)^2\beta^*\epsilon \gg c^2q^2$) the electromagnetic oscillations are characterized, according to Eq. (3), by a linear dispersion law:

$$\omega_{2,3} = V_{ph}q, \quad V_{ph} = \frac{c}{\sqrt{\varepsilon}}\sqrt{\frac{\beta^*}{4\pi}}. \quad (4)$$

We see that near the critical point the phase velocity of the electromagnetic waves is appreciably smaller than the velocity of light (in contrast to the case of a ferromagnetic with large magnetic anisotropy, when $V_{ph} \sim c/\sqrt{\epsilon}$ (see [2])). Such a change of the phase velocity of the waves is associated with an abrupt increase of the crystal's magnetic susceptibility near the critical point.

Now let us dwell briefly on the case of oscillations propagating at an angle to the anisotropy axis ($\sin^2\chi \gg \beta^*/4\pi$). In this case only one of the branches of electromagnetic oscillations turns out to be slow; as before its phase velocity is determined by expression (4). As to the second branch of oscillations, in order of magnitude their phase velocity is equal to the velocity of light.

In particular, for $q \ll c^{-1}gM_0\sqrt{\epsilon}$

$$\omega = \frac{cq}{\sqrt{\varepsilon}}\sin\chi. \tag{5}$$

Experimental observation of the anomalous character of coupled electromagnetic-spin waves near the critical point is convenient to carry out, for example, in a crystal of magnetite at a temperature close to $T_C = 119°K$. (The size of the crystal should amount to several millimeters for this purpose.) In order that the velocity of the wave propagating along the anisotropy axis be 10^2 times smaller than the velocity of light, the temperature of the crystal should differ from T_C by an amount of the order of one degree.

An experiment with slow electromagnetic waves in such crystals may give valuable information about the nature of the phase transition axis—plane, in particular it may allow one to measure the temperature dependence of the magnetic anisotropy constant near the critical point more accurately than ordinary magnetic measurements.

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[1] L. R. Bickford, Phys. Rev. 78, 449 (1950).

[2] A. I. Akhiezer, V. G. Bar'yakhtar, and S. V. Peletminskiĭ, Spinovye volny (Spin Waves), Nauka, 1967, Sec. 9, p. 75 (English Transl., John Wiley and Sons, Inc., 1968).

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