SPIN WAVE DAMPING STIMULATED BY EXCHANGE INTERACTION AT SPIN-ORIENTATION PHASE TRANSITIONS IN HEXAGONAL FERROMAGNETS

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The types of phase transitions (PTs) and the conditions for them to occur in hexagonal ferromagnets (FMs) have been determined. The fundamental frequencies of the magnetization vector have been calculated for every ground state of a hexagonal FM. In order to take the dissipation processes in the system into account, a new form of the dissipation function proposed by Bar'yakhtar was used. The dispersion equation for oscillations of the magnetization vector in a hexagonal FM, taking the dissipation of the spin wave energy into account in the exchange approximation, has been derived, and the relevant fundamental frequencies have been calculated. The results obtained are in full agreement with those of the PT theory. The tensor of high-frequency magnetic susceptibility for a hexagonal FM has been calculated as well, which enables the crystal itself and the spin-orientation PTs in it to be described in detail.

1. Introduction

The Landau theory of the PTs of the second kind is a good approximation for the description of the spin-orientation transformations. It is so, because the latter are stimulated by the change of anisotropy, which, in its turn, is a consequence of relativistic interactions which are small in this case in comparison with the exchange interaction which governs the magnetization of the FM. Such PTs were considered in a lot of works (see, e.g., work [1]), so that the behavior of the spin wave spectrum in the vicinity of those PTs is well known. Nevertheless, the spin wave damping at spin-orientation PTs has not been taken into account until now. At the same time, it is obvious that the phenomenon of spin wave damping must be included into the self-consistent theory of PTs. If the damping turns out large, this circumstance will provide one more restriction, in addition to the Ginzburg—Levanyuk criterion, on the theory.

The investigation carried out in this work has shown that, in order to describe the spin wave damping, one has to use the FM dissipation function constructed with regard for both the symmetry of a crystal and the conservation law for the component of the magnetization vector directed along the symmetry axis of the crystal.

2. The Ground States of a Magnetic. Possible Spin-orientation Phase Transitions

Consider a ferromagnet, whose density of the total energy looks like

$$W = \frac{\alpha_{ik}}{2}\frac{\partial \vec{M}}{\partial x_i}\frac{\partial \vec{M}}{\partial x_k} + \frac{1}{2}K_1 M_z^2 + \frac{1}{4}K_2 M_z^4 + $$

$$+\frac{1}{8\chi_{\|} M_0^2}\left(\vec{M}^2 - M_0^2\right)^2, \qquad (2.1)$$

where $\vec{M}$ is the vector of the FM magnetization, M_0 is the saturation magnetization, α_{ik} are the exchange interaction constants, K_1 and K_2 are the constants of anisotropy, and $\chi_{\|}$ is the longitudinal magnetic susceptibility of the FM. This expression for the energy density corresponds to the main orders of the anisotropy energy expansion in a power series of $\vec{M}$ for crystals with hexagonal symmetry; such crystals can be considered as uniaxial if the terms of the sixth order in the expansion are neglected [2]. The term $\frac{1}{8\chi_{\|} M_0^2}\left(\vec{M}^2 - M_0^2\right)^2$ is responsible for the variation of the absolute value of the magnetic moment of the crystal $\vec{M}$; the constants that

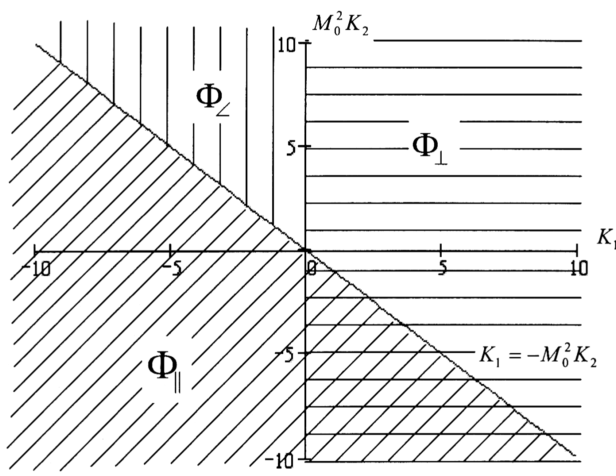

Diagram of the magnetization state stability of a uniaxial FM

enters into it obey the following conditions: $\frac{1}{\chi_\parallel M_0^2} > 0$, $\frac{1}{4\chi_\parallel} \gg K_1$, and $\frac{1}{2\chi_\parallel M_0^2} \gg K_2$.

For the FM of such a type, the following ground states are possible.

1) The "easy-axis" phase $\Phi_{||}$. Here,

$$\theta = 0, \quad M^2 = \frac{\frac{1}{2\chi_| M_0^2} M_0^2 - K_1}{\frac{1}{2\chi_| M_0^2} + K_2} \approx M_0^2.$$

The condition of phase stability is

$$K_1 < -M_0^2 K_2; \tag{2.2}$$

2) The "easy-plane" phase $\Phi_\perp$. Here,

$$\theta = \frac{\pi}{2}, \quad M^2 = M_0^2,$$

The condition of phase stability is

$$K_1 > 0; \tag{2.3}$$

3) The "angular" phase $\Phi_\angle$. Here,

$$\cos^2\theta = -\frac{K_1}{M_0^2 K_2}, \quad M^2 = M_0^2.$$

The condition of "angular"phase stability is

$$\begin{cases} K_2 > 0, \\ -M_0^2 K_2 < K_1 < 0. \end{cases} \tag{2.4}$$

It is convenient to analyze these data in the framework of the graphic method, by considering the common phase diagram for all the ground states of the uniaxial FM. We adopt the temperature as a parameter which governs the variation of the anisotropy constants K_1 and K_2 [3, 4]. From the diagram (see Figure), one can see that, if $M_0^2 K_2 < 0$, the stability regions of the phases $\Phi_\parallel$ and $\Phi_\perp$ overlap. In the region $0 < K_1 < -M_0^2 K_2$, the energies of both phases are minimal, and the phases are stable. As can be easily seen, the energies of these phases become equal if $K_1 = -\frac{1}{2} M_0^2 K_2$; but if we leave this line towards either side, the energy of either of these phases will be lower than that of the other. Therefore, one of the phases will be more profitable by energy, although the other still remains stable with respect to small perturbations.

Provided $K_1 > -\frac{1}{2} M_0^2 K_2$, the uniaxial FM changes from the phase $\Phi_\parallel$ to the phase $\Phi_\perp$; in this case, the moment undergoes a stepwise reorientation from the "easy axis" to the "easy plane" configuration. It means that the transformation from the phase $\Phi_\parallel$ to the phase $\Phi_\perp$ occurs as the PT of the first kind [1]. At $K_1 > -M_0^2 K_2$, the phase $\Phi_{||}$ becomes unstable, and only the phase $\Phi_\perp$ remains stable. If one moves in the opposite direction, the transition of the first kind will also occur, but now from the phase $\Phi_\perp$ to the phase $\Phi_{||}$.

On the contrary, if $M_0^2 K_2 > 0$, the regions of stability of the phases $\Phi_\parallel$ and $\Phi_\perp$ do not overlap. In the range $-M_0^2 K_2 < K_1 < 0$, there exists the third phase $\Phi_\angle$ we agreed to call "angular". Therefore, provided $K_1 < -M_0^2 K_2$, the value $\theta = 0$ and the phase $\Phi_{||}$ is stable, while, at $K_1 > -M_0^2 K_2$, the quantity θ becomes nonzero. The symmetry of the phase $\Phi_\angle$ is evidently lower than that of the phase $\Phi_{||}$, because, in the former, the moment deviates from the selected axis. Hence, the magnetization itself changes continuously in the course of the $\Phi_{||} \to \Phi_\angle$ transition, but the symmetry of the system drops down (the symmetry axis z disappears). Thus, the transition $\Phi_{||} \rightleftarrows \Delta\Phi_\angle$ is a typical PT of the second kind. The role of the order parameter at this transition is played by the angle θ. Analogously, one can easily verify that the transition $\Phi_\angle \rightleftarrows \Delta\Phi_\perp$ is also of the second kind.

Thus, if $M_0^2 K_2 > 0$, the transition from the phase $\Phi_{||}$ to the phase $\Phi_\perp$ occurs by means of two PTs of the second kind: $\Phi_{||} \rightleftarrows \Delta\Phi_\angle$ at $K_1 = -M_0^2 K_2$, and $\Phi_\angle \rightleftarrows \Delta\Phi_\perp$ at $K_1 = 0$ [5].

3. Dissipation of the Spin Wave Energy

For the theory of PTs to be consecutive in the framework of the spin wave theory, the problem of spin wave dissipation should be considered. The damping of spin waves in the ground state has evidently to be considerably smaller than their activation frequency, both becoming zero at the PT point [6].

As is known, the basic equation, which describes the dynamic and relaxation properties of the FM, is the Landau—Lifshits equation

$$\frac{\partial \vec{m}}{\partial t} = -\gamma\left[\vec{m}\vec{H}\right] + \frac{1}{M_0}R, \tag{3.1}$$

where $\vec{H} = -\frac{\delta W}{\delta \vec{M}}$ is the effective magnetic field. As was shown above, the modulus of the magnetization vector $\vec{M}$ can be considered constant, ($M^2 \approx M_0^2$), so that the unit vector of magnetization $\vec{m} = \vec{M}/M_0$ can be introduced.

Let us write down the phenomenological relaxation term in the Landau—Lifshits equation in the following form:

$$\vec{R} = \frac{\delta Q_m}{\delta \vec{H}}, \tag{3.2}$$

where Q_m is the dissipation function which was constructed taking the FM symmetry into account [7] and looks like

$$Q = \frac{\gamma M_0}{2}\lambda_e \left(\frac{\partial \vec{H}}{\partial x_i}\right)^2, \tag{3.3}$$

where λ_e is a constant which characterizes the relaxation processes caused by the exchange interaction. In this formula, the summation over the dummy index is implied.

In the case concerned, this dissipation function characterizes the dissipation of the spin wave energy only in the exchange approximation. In order to take the relaxation processes that are stimulated by the relativistic interaction into account, a corresponding term is to be introduced into Eq. (3.3). This will be made in the further works.

For carrying out the calculations, it is more convenient to pass to new variables. Let us rotate the Cartesian coordinate system in such a way that axis 3 should coincide with the direction of the magnetization vector in the ground state. This can be made with the help of the following transformation:

$$\begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}, \tag{3.4}$$

where θ is the polar angle; and m_1, m_2, and m_3 are the components of the magnetization vector in the new coordinate system. Note that the angle θ does not vary but accepts quite definite values determined by the direction of the magnetization vector $\vec{M}$. If axis 3 is taken for the axis of quantization, then $|\vec{m}| \approx m_3$, while m_1 and m_2 are small fluctuation-induced deviations from the equilibrium position.

Let us decompose Eq. (3.1) into its components, taking transformation (3.4) into account and using expression (2.1 for the energy density in the FM without the last summand which is responsible for the variation of the absolute value of the magnetic moment (since $M^2 \approx M_0^2$):

$$\dot{m}_1 = -\Omega_2 m_2 + \lambda_e \nabla^2 \Omega_1 m_1,$$

$$\dot{m}_2 = \Omega_1 m_1 + \lambda_e \nabla^2 \Omega_2 m_2. \tag{3.5}$$

Here, the notations

$$\Omega_1 = [K_1(\sin^2\theta - \cos^2\theta) +$$

$$+M_0^2 K_2 \cos^2\theta(3\sin^2\theta - \cos^2\theta)] - \alpha\nabla^2,$$

$$\Omega_2 = -[K_1\cos^2\theta + M_0^2 K_2 \cos^4\theta] - \alpha\nabla^2$$

are used; and $\dot{m}_1$ and $\dot{m}_2$ stand for the derivatives with respect to $\tau = \gamma M_0 t$.

Assuming that $m \sim \exp\left(-i\omega\tau + i\vec{\kappa}\vec{r}\right)$, the temporal and spatial Fourier transforms of Eqs. (3.5) look like

$$\left(-i\omega + \lambda_e \kappa^2 \Omega_1\right) m_1 + \Omega_2 m_2 = 0,$$

$$-\Omega_1 m_1 + \left(-i\omega + \lambda_e \kappa^2 \Omega_2\right) m_2 = 0. \tag{3.6}$$

Equations (3.6) bring easily about the law of spin wave dispersion

$$\omega = -\frac{i}{2}\lambda_e \kappa^2 \left(\Omega_1 + \Omega_2\right) \pm$$

$$\pm\frac{1}{2}\sqrt{-\lambda_e^2\kappa^4\left(\Omega_1 + \Omega_2\right)^2 + 4\Omega_1\Omega_2\left(\lambda_e^2\kappa^4 + 1\right)}. \tag{3.7}$$

Consider the frequencies of spin waves in the ground states of the FM. If the FM is in the $\Phi_{\parallel}$ state, we obtain

$$\omega = -i\lambda_e\kappa^2\left(\alpha\kappa^2 - (K_1 + M_0^2 K_2)\right) \pm$$

$$\pm\left(\alpha\kappa^2 - (K_1 + M_0^2 K_2)\right). \tag{3.8}$$

One can easily see that the condition

$$\frac{\omega_{\text{Im}}}{\omega_{\text{Re}}}\underset{\kappa\to 0}{=}\lambda_e\kappa^2\underset{\kappa\to 0}{\longrightarrow}0\ll 1, \tag{3.9}$$

for the spin waves to exist in the ground state $\Phi_{\parallel}$ is satisfied. Here, ω_{Im} and ω_{Re} are the imaginary and real parts of the spin wave oscillation frequency (3.8), respectively; the former characterizes the spin wave damping, and the latter determines the frequency of the spin wave activation. This state possesses a "gap", i.e. $\omega_{\text{Re}}(\kappa\to 0)\neq 0$.

In the cases where the FM is in the $\Phi_{\perp}$ or $\Phi_{\angle}$ ground state, the spin wave frequency looks like

$$\omega=-\frac{i}{2}\lambda_e\kappa^2\left(K_1+2\alpha\kappa^2\right)\pm$$

$$\pm\sqrt{-\lambda_e^2\kappa^4K_1^2+4\alpha\kappa^2(K_1+\alpha\kappa^2)} \tag{3.10}$$

for the phase $\Phi_{\perp}$ and

$$\omega=-\frac{i}{2}\lambda_e\kappa^2\left(-\frac{2K_1(K_1+M_0^2K_2)}{M_0^2K_2}+2\alpha\kappa^2\right)\pm$$

$$\pm\left(-\lambda_e^2\kappa^4\left(\frac{2K_1(K_1+M_0^2K_2)}{M_0^2K_2}\right)^2+\right.$$

$$\left.+4\alpha\kappa^2\left(-\frac{2K_1(K_1+M_0^2K_2)}{M_0^2K_2}+\alpha\kappa^2\right)\right)^{1/2} \tag{3.11}$$

for the phase $\Phi_{\angle}$. It is evident from expressions (3.10) and (3.11) that, in the ground states $\Phi_{\perp}$ and $\Phi_{\angle}$ which are gapless, the condition for the spin waves to exist, namely,

$$\frac{\omega_{\text{Im}}}{\omega_{\text{Re}}}\underset{\kappa\to 0}{=}\frac{\lambda_e\kappa}{F(K_1,\ K_2)}\underset{\kappa\to 0}{\longrightarrow}0\ll 1, \tag{3.12}$$

where $F(K_1,K_2)$ is a certain constant composed of the anisotropy ones, is also satisfied. The gap absence in the phases $\Phi_{\perp}$ and $\Phi_{\angle}$ is a consequence of the fact that the ground states of these phases are degenerate, being characterized by a continuous parameter of degeneration φ_0, the angle between the vector $\vec{M}_0$ and the x-axis in the base plane [8].

It should be noted that, if the relaxation term in the equation of the magnetic moment motion (3.1) is used in the Landau—Lifshits ($\vec{R}_{\text{LL}}=\lambda\gamma M_0\left[\vec{H}-\vec{m}(\vec{m}\vec{H})\right]$) or Gilbert ($R_{\text{G}}=\frac{a}{M_0}\left[\vec{M},\frac{\partial\vec{M}}{\partial t}\right]$) form, the spin wave damping ω_{Im} turns out independent of κ and, in the gapless ground states $\Phi_{\perp}$ and $\Phi_{\angle}$ of the FM, larger than the activation frequency ω_{Re} [7]:

$$\frac{\omega_{\text{Im}}}{\omega_{\text{Re}}}\underset{\kappa\to 0}{=}\frac{\lambda}{\kappa F(K_1,\ K_2)}\underset{\kappa\to 0}{\longrightarrow}\infty. \tag{3.13}$$

This means that, formally, the spin waves with $\kappa\to 0$ do not exist in the $\Phi_{\perp}$ and $\Phi_{\angle}$ phases. Therefore, the relaxation term in the Landau–Lifshits or Gilbert form does not describe the processes of the spin wave energy dissipation correctly. The reason is that these relaxation terms do not take a crystal symmetry into account.

While using the dissipation function in form (3.3), the condition for the spin waves to exist is satisfied in all the ground states of the uniaxial FM and at every value of κ. Therefore, form (3.3) for the relaxation function completely corresponds to the PT theory.

Note that the dissipation is considered inherently small in all the relaxation terms indicated above ($\lambda_e\ll\gamma M_0$, $\lambda\ll\gamma M_0$, and $a\ll\gamma M_0$), but it is the very form of the relaxation term, the Landau—Lifshits or the Gilbert one (in essence, proceeding from the general physical concepts, it is simply the moment of the friction forces), that brings us to contradictions in some cases.

It is worth noting that the indicated essence of this contradiction (the nonzero damping for spin waves at $\kappa\to 0$) and its absence in the case where the dissipation term is taken in form (3.3) require to be discussed in more detail. If form (3.3) is used, the zero damping arises in the cases of both gap and gapless spectra. To a great extent, this is a result of theoretical speculations in the framework of the selected model, where the dissipation term is written down in the exchange approximation only, form (2.1) is used for the density of the FM total energy, and no anisotropy in the base plane is taken into account. From the viewpoint of experimental manifestations in real magnetics, on the contrary, the zero damping at $\kappa\to 0$ in the nonzero-gap phase $\Phi_{\parallel}$ (formula (3.8)) has no physical meaning. Making allowance for the relativistic contributions to the spin wave energy dissipation (3.3) results in a finite value of the damping for the spin waves with $\kappa\to 0$. In the cases of degenerate states of the phases $\Phi_{\perp}$ and $\Phi_{\angle}$, both the existence of the gapless spin waves and the vanishing of their decay decrements at $\kappa\to 0$ are a consequence of the availability of a continuous parameter of degeneration φ_0 in these cases [8]. These requirements are satisfied by the choice of the dissipation term in form (3.3), unlike the results, which would be obtained if this term were selected in the Landau—Lifshits or Gilbert form. It is this circumstance that determines the advantage of representation (3.3).

4. Tensor of High-frequency Magnetic Susceptibility

In order to calculate the high-frequency susceptibility tensor, consider a uniaxial FM in an external magnetic field $\vec{H}_{\text{ext}}$. In this case, the expression for the energy density includes the term $W_H = -\vec{M}\vec{H}_{\text{ext}}$, so that Eqs. (3.6) look like

$$(-i\omega + L\Omega_1)\, m_1 + \Omega_2 m_2 = Lh_1 + h_2,$$

$$-\Omega_1 m_1 + (-i\omega + L\Omega_2)\, m_2 = Lh_2 - h_1, \tag{4.1}$$

where $L = \lambda_e \kappa^2$, and $h_1$and h_2 are the components of the external magnetic field in the new coordinate system $\left(\vec{h} = \vec{H}/M_0\right)$.

The components of the magnetization vector and those of the external magnetic field are coupled to each other: $m_i(\vec{\kappa}, \omega) = \chi_{ij}(\vec{\kappa}, \omega) h_j(\vec{\kappa}, \omega)$. Making use of Eqs. (4.1), we can calculate the tensor of magnetic susceptibility in the coordinate system (1, 2, 3):

$$\chi_{ij} = \begin{pmatrix} \frac{L(L\Omega_2 - i\omega)+\Omega_2}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & \frac{-i\omega}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & 0 \\ \frac{i\omega}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & \frac{L(L\Omega_1 - i\omega)+\Omega_1}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

Note that, in the absence of dissipation ($L = 0$), the tensor of magnetic susceptibility has the well-known value [8].

In the (x, y, z) coordinate system, the tensor of magnetic susceptibility looks like

$$\chi_{ij} = \begin{pmatrix} \frac{(L(L\Omega_2 - i\omega)+\Omega_2)\cos^2\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & -\frac{i\omega\cos\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & -\frac{(L(L\Omega_2 - i\omega)+\Omega_2)\cos\theta\sin\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} \\ \frac{i\omega\cos\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & \frac{L(L\Omega_1 - i\omega)+\Omega_1}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & -\frac{i\omega\sin\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} \\ -\frac{(L(L\Omega_2 - i\omega)+\Omega_2)\cos\theta\sin\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & \frac{i\omega\sin\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} & \frac{(L(L\Omega_2 - i\omega)+\Omega_2)\sin^2\theta}{(L\Omega_1 - i\omega)(L\Omega_2 - i\omega)+\Omega_1\Omega_2} \end{pmatrix}.$$

From this expression, one can always determine the form of the tensor of high-frequency magnetic susceptibility for each ground state of the FM. Knowing the tensor of magnetic susceptibility and following a standard routine [9], one can easily find the spectra of spin waves taking into account the dipole interaction for all the three ground states.

5. Conclusions

The use of the relaxation term in the Landau–Lifshits or Gilbert form for the description of the spin wave damping turns out incorrect in some cases. This is because those representations were constructed irrespectively of the crystal symmetry.

In this work, the dissipation function, which makes allowance for both the conservation law for the magnetization vector component along the axis of crystal symmetry and the specific symmetry of the crystal, was considered. The selected dissipation function has been shown to describe relaxation processes in the exchange approximation in total agreement with the PT theory (at an arbitrary value of the vector κ, the dissipation part of the spin wave oscillation frequency is much smaller than its activation part).

The dissipation function presented in the form, which was proposed by Bar'yakhtar taking into account Landau's speculations concerning the importance of the symmetry factor, produced correct results and brought us to the conclusion that the spin wave damping does not impose any restrictions on the Landau theory, when the latter is applied to the description of spin-orientation PTs. However, it is of importance that the results were obtained in the exchange approximation. For the relaxation processes in FMs to be described in more details, the term which is responsible for the relaxation caused by relativistic interaction is to be introduced into the dissipation function.

The tensor of high-frequency magnetic susceptibility of a hexagonal FM, which was calculated in this work taking into account the dissipation of the spin wave energy, enables one to describe more accurately and comprehensively both the crystal itself and the PTs that occur in it.

To summarize, the author tenders his sincere thanks to V.G. Bar'yakhtar for the formulation of the problem, valuable discussions, and his help in the work. The author is also grateful to Yu.I. Dzhedzherya for numerous important discussions.

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ЗАТУХАННЯ СПІНОВИХ ХВИЛЬ
ВНАСЛІДОК ОБМІННОЇ ВЗАЄМОДІЇ
ПРИ СПІН-ОРІЄНТАЦІЙНИХ ФАЗОВИХ ПЕРЕХОДАХ
У ФЕРОМАГНЕТИКАХ ГЕКСАГОНАЛЬНОЇ СИМЕТРІЇ

О.Г. Данилевич

Р е з ю м е

Визначено умови та типи фазових переходів (ФП) у гексагональному феромагнетику (ФМ). Розраховано власні частоти коливань вектора намагніченості для кожного основного стану ФМ гексагональної симетрії. Для врахування дисипативних процесів в системі, використано нову форму дисипативної функції, що була запропонована В.Г. Бар'яхтаром. Отримано дисперсійне рівняння та власні частоти коливань вектора намагніченості в гексагональному ФМ з урахуванням дисипації енергії спінових хвиль в обмінному наближенні. Одержані результати повністю відповідають теорії ФП. Також розраховано тензор високочастотної магнітної сприйнятливості для гексагонального ФМ, що дає можливість повніше описувати як сам кристал, так і спін-орієнтаційні ФП, що відбуваються в ньому.