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# Influence of the Mechanical Boundary Conditions on Dynamic and Static Properties of the Ferromagnetic with Competing Anisotropies

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The phase transitions on the material constants are investigated for the semi-infinite ferromagnetic with the mechanical boundary conditions and competing inclined single-axis and easy-plane anisotropies. The phase state soft he system and the dispersion laws of coupled magnetoelastic waves are determined. Analysis of the spectra of elementary excitations has allowed to plot the phase diagram of the system.

**Keywords:** Inclined Anisotropy, Magnetoelastic Interaction, Easy-plane Anisotropy.

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At microscopic description of the magnetic dielectrics, the terms like $S_n^i \beta_{ij} S_n^j$ appear in the Hamiltonian of the system ($S_n^i$ is the $i$th component of the spin operator at the $n$th site; $\beta_{ij}$ are the components of the tensor of the single-ion anisotropy). Such terms correspond to the energy of a single-ion anisotropy originating from the spin-orbit interaction. The simplest magnetic system exhibiting the single-ion anisotropy is the spin-1 magnet. Usually, the tensor of the single-ion anisotropy is diagonal in such a system. At this, $\beta_{zz} \neq \beta_{xx} = \beta_{yy}$. Such view of the tensor of the single-ion anisotropy leads to the formation of the single-axis single-ion anisotropy. This model has proved itself for many magnetic systems; however, the technological complexity appearing at the production of the magnetically ordered systems breaks the diagonality of the anisotropy tensor. Therefore, the more realistic model takes into account the non-diagonal components of the tensor of the single-ion anisotropy: $\beta_{xz} = \beta_{zx}$. This model describes both, the single-axis anisotropy, and the anisotropy in the XOZ plane with the axis of the easy-magnetization making angle $\varphi$ with the OZ axis. The last anisotropy is also called the inclined anisotropy. It should be noted that the single-ion anisotropy is not the only relativistic interaction, determined by the spin-orbit interaction. Thus, the magnetoelastic interaction also originates from the spin-orbit interaction. This spin-lattice interaction determines the coupling between the mechanical (elastic, acoustic, striction) and the magnetic characteristics of the system, and also essentially influence the critical behavior during the magnetic phase transitions. The account of the magnetoelastic interaction leads to the hybridization of the elastic and magnetoelastic excitations and to the origin of coupled magnetoelastic waves. This hybridized excitation determines the dynamic of the system near the orientation phase transitions, i.e., the transversely polarized quasiphonon branch of excitations becomes the soft mode in the vicinity of the orientation phase transitions; while, there appears the magnetoelastic gap in the quasimagnon spectrum. Besides, the account of the magnetoelastic interaction is crucial at the analysis of the experimental results, because one needs somehow to take into account the mechanical boundary conditions of the system. These boundary conditions determine the structure of the spontaneous strains of the magnetically ordered crystal. At the same time, the value and the structure of the spontaneous strains influence both, the thermodynamic, and the dynamic properties of the system, and, consequently, experimental results. Also, while producing the magnetic films, it is necessary to take into account the influence of the sublattice on the sample. The importance of this influence was mentioned by some authors, but this question is still investigated insufficiently.

The systems, described above, are rather well studied for the case of weak single-ion anisotropy. However, there is a great number of the magnetically ordered systems with strong single-ion anisotropy. The presence of strong single-ion anisotropy in the system leads to the whole set of effects which have purely quantum nature, and cannot be explained within the frameworks of the phenomenological models.

We consider a model of a semi-infinite ferromagnetic rigidly fixed at the ZOY plane. Without losing the generality of the considered problem, we suppose the spin of a magnetic ion equal to 1, as this is the minimal spin value at which the single-ion anisotropy can appear. Besides, it is supposed that the ferromagnetic has single-ion anisotropy of the easy-plane type (XOY is the basal plane), and the easy-axis anisotropy, oriented in the ZOX plane at some angle to the OZ axis (further, we will call it the inclined anisotropy for shortness). As the system is under strict bound conditions, then, in addition to the relativistic interactions, listed above, one also needs to take into account the magnetoelastic interaction. As the sample is rigidly fixed in the ZOY plane, there is no shifting of the magnetic ions along the OY and the OZ axes, i.e., $u_z = u_y = 0$. The boundary conditions were selected in such a way that the influence of the easy-plane and the inclined anisotropies is maximal. With the account of this, the Hamiltonian of the system can be presented as follows:

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$$\mathcal{H} = -\frac{1}{2}\sum_{n,n'} J_{nn'}\mathbf{S}_n\mathbf{S}_{n'} + \frac{\beta}{2}\sum_n (S_n^z)^2 - \frac{\beta_{zx}}{2}\sum_n O_{2n}^{zx} + \\ +\nu\sum_n \; u_{xx}(S_n^x)^2 + u_{xy}O_{2n}^{xy} + u_{zx}O_{2n}^{zx} \; + \\ +\int d\vec{r}\left\{\frac{\lambda+\eta}{2}u_{xx}^2 + \eta \;\; u_{xy}^2 + u_{zx}^2\right\}, \quad (1)$$

where $J_{nn'} > 0$ is the exchange integral; $S_n^i$ is the $i$th component of the spin operator at the $n$th site; $O_{2n}^{ij} = S_n^i S_n^j + S_n^j S_n^i$ are the Stevens operators; $\beta > 0$ is the constant of the easy-plane single-ion anisotropy (XOY is the basal plane); $\beta_{zx} > 0$ is the constant of the easy-axis single-ion inclined anisotropy in the XOZ plane; $\nu$ is the constant of the magnetoelastic coupling; $\lambda$ and $\eta$ are the elastic moduli; $u_{ij}$ are the components of the elastic strains tensor. We consider the low-temperature case ($T \ll T_C$, $T_C$ is the Curie temperature) when the studied effects are the most evident. Because the general solution is rather complex, we consider two cases:

1. $J_0 > \beta_{xz}, \beta$;
2. $J_0 < \beta_{xz}, \beta$.

Analysis of the spectra of elementary excitations and of the free energy of the system has shown that the properties of the system with the inclined anisotropy can be reduced to the behavior of the two-axis ferromagnetic. At this, depending on the material parameters of the system, two homogeneous phases can realize. At rather large exchange interaction (exceeding the anisotropy constants), the ferromagnetic (CFM) phase realizes. This phase is characterized by the magnetization vector, oriented in the XOZ plane. The equilibrium angle of magnetization vector orientation essentially depends on both, the spontaneous strains, and the relationship between the constants of the inclined and the easy-plane anisotropies. The spontaneous strains itself depend on the relationship between the constants of anisotropy. The magnetoelastic interaction is exhibited only statically in the CFM-phase, i.e., there is no dynamic softening of the quasiacoustic mode near the line of CFM-phase instability, but instead the additive term (the magnetoelastic gap) appears in the energy gap of the quasimagnons. This magnetoelastic gap is related with the spontaneous strains; at this, the magnetoelastic gap is considerably largerat $\beta_{xz} > \beta$, than at $\beta_{xz} < \beta$, which is because of the spontaneous strains dependence on the anisotropy constants.

Single-ion anisotropy constants increase ($J_0 < \beta_{xz}, \beta$) leads to the realization of the phase with zero magnetization (per site). First of all, this is related with the quantum reduction of the spin. This effect is usually exhibited at presence of the easy-plane anisotropy; however, in the present case, it is related with both, the inclined, and the easy-plane single-ion anisotropies, because they are related through the constants of the effective two-axis single-ion anisotropy. Also, the influence of the magnetoelastic interaction renormalizing the constants of the effective two-axis anisotropy plays important role. This phase state is not the paramagnetic, because the relationship $<(S^x)^2>=<(S^y)^2>=<(S^z)^2>=S(S+1)/3=2/3$ is not fulfilled, but instead $<(S^x)^2>=<(S^y)^2>=10$. This phase state is the quadrupolar (QU) phase, characterized by the components of the quadrupolar tensor. At this, the magnetoelastic interaction also does not soften the quasiphonon modes, and only renormalizes the speed of the quasiacoustic excitations. The additive term, determined by the magnetoelastic coupling, appears in the energy gap of the quasimagnon spectrum.

As it follows from the analysis of the spectra of elementary excitations, there is no direct transition between the CFM phase and the QU phase. The phase transition between these states is of the first order. The stability lines essentially depend on the relationship between the anisotropy constants. It should be noted that the line of stability loss for the QU phase is higher, than the corresponding line of stability loss for the CFM phase, which is common feature of the first order phase transitions.

The important feature of the investigated system is the absence of the quasiacoustic excitations softening in the vicinity of the stability line. This is related with the fact that the phase transition the CFM phase – the QU phase is not reorientation.

Analysis of the spectra of elementary excitations allows to plot the phase diagram of the ferromagnetic with competing inclined and easy-plane anisotropies on the ($\beta_{xz}$, $\beta$)-plane. This phase diagram is shown in fig. 1.

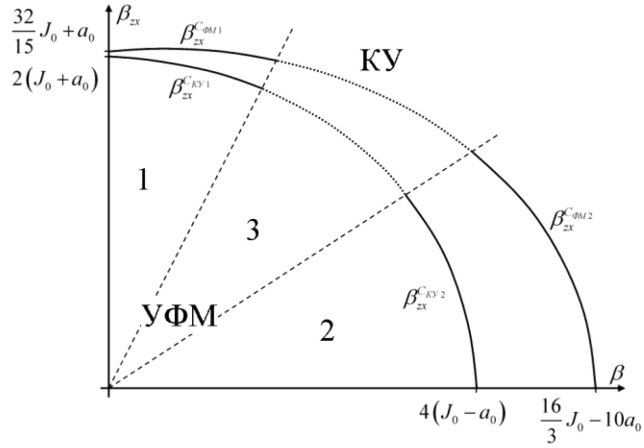


**Fig. 1** – Phase diagram of the semi-infinite strongly anisotropic ferromagnetic with the inclined anisotropy. Region 1 corresponds to the case $\beta_{xz} > \beta$, and Region 3 – to $\beta_{xz} < \beta$

As it was mentioned, the phase transition on the material constants, considered in the present investigation, if of the first order. TheRegion 1 atfig. 1 correspondstothecase$\beta_{xz} > \beta$, and Region 3 – to the case $\beta_{xz} < \beta$. Region 2 corresponds to the numerical approximation at arbitrary relationship between the anisotropy constants. The region in-between the stability lines of the QU and the CFM phases in fig. 1 is the region of phases' co-existence.

It should also be mentioned that the presence of the magnetoelastic coupling results in the considerable widening of the co-existence region of the CFM and the QU phases. As the mechanism of formation of the single-ion anisotropy and the magnetoelastic coupling is the spin-orbit interaction, the magnetoelastic coupling can be rather strong in the considered case of large values of the inclined and the easy-plane anisotropies, like it is observed in the rare-earth magnets.