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Influence of the mechanic boundary conditions on the dynamic and static properties of the ferromagnet with competing anisotropies

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ABSTRACT

The phase transitions on the material constants in a semi-infinite ferromagnet with mechanic boundary conditions and competing "inclined" ease-axis anisotropy and easy-plane anisotropy have been investigated. The phase states and the spectra of coupled magnetoelastic waves have been researched. The analysis of the spectra of elementary excitations allowed the construction of the phase diagram of the system.

1. Introduction

The terms proportional to $S_n^i \beta_{ij} S_n^j$ appear in the spin Hamiltonian at a microscopic description of the magnetic dielectrics. These terms correspond to single-ion anisotropy energy appearing due to the spin–orbit interaction (S_n^i is the i-th component of the spin operator in the n-th site; β_{ij} is the tensor of single-ion anisotropy). The simplest system possessing the single-ion anisotropy is the spin-1 magnet in which the singe-ion anisotropy tensor is usually diagonal and $\beta_{zz} \neq \beta_{xx} = \beta_{yy}$. Such kinds of single-ion anisotropy tensor components lead to the realization of easy-axis single-ion anisotropy or easy-plane single-ion anisotropy. In principle, the low symmetry of the ion position could lead to the appearance of non-diagonal tensor $\hat{\beta}$, but for unbordered media, isotropic with respect to its elastic properties, this tensor can be diagonalized. But for the real systems with borders, with accounting for long-ranged deformations caused by the surface, the principal axis of the tensor $\hat{\beta}$ can be inclined with respect to the surface. This is the case of the so-called "inclined anisotropy", which is unavoidable for many real magnets, e.g., the system of the type of "magnetic film on non-magnetic substrate". Therefore, accounting for the non-diagonal components of a single-ion anisotropy tensor ($\beta_{zz} \neq \beta_{xx} = \beta_{yy}$, $\beta_{zx} = \beta_{xz}$) describes a more realistic model for magnetic films and platelets. Such a model describes both the easy-plane anisotropy and the easy-axis anisotropy lying in the XOZ plane and makes some angle φ with the OZ-axis. Sometimes this anisotropy is called "inclined" anisotropy [1]. The interest in such systems is explained by the fact that they describe quite well the anisotropy energy of disordered ferrite-garnet films. For example, it was shown that "inclined" anisotropy is realized in (111) disordered films within the frameworks of a two-parametric model [2,3]. Also, both easy-axis anisotropy and the angle of disordering lie in the $(\bar{1}10)$ plane [2]. The analysis of the demagnetization processes of (112) films (the case of (111) disordered film) [4] shows that if the external field is along the $(\bar{1}10)$ plane, then the magnetization vector lies in the same plane. Thus, if we introduce the coordinates X and Z in $(\bar{1}10)$ plane, then we can show that the anisotropy energy is described by two constants: β_{zz} and β_{zx} [4,5].

Magnetically ordered systems with inclined orientation of easy-axis single-ion anisotropy have promising characteristics for application in magneto-optic devices, for defectoscopy, for the visualization of inhomogeneous magnetic fields, for the research of nanostructure magnetic materials, etc. [6–8]. For example, the investigations of the magnetic properties of nanogranular films with easy-axis anisotropy have immense scientific and practical importance because they are promising materials for the creation of high density information storage devices [9–12].

Singe-ion anisotropy is not the only interaction determined by the spin–orbit interaction. For example, magnetoelastic interaction originates from the spin–orbit interaction too. Spin–lattice interaction determines the coupling between the mechanic (elastic, acoustic, and strictional) and magnetic characteristics of the system [13], and also influences the critical behavior during the magnetic phase transitions [14–18]. The account for the magnetoelastic interaction leads to the hybridization of the elastic and the magnetoelastic excitations, and also to the appearance of coupled magnetoelastic waves. This hybrid excitation determines the system's dynamics in the vicinity of the orientation phase transitions, i.e., the transversely polarized quasi-phonon branch becomes the soft mode in the vicinity of the orientation phase

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transition, and the magnetoelastic gap appears in the quasimagnon spectrum. Besides, the account of the magnetoelastic interaction is important for the analysis of the experimental results because it is necessary to take into account imposed mechanic boundary conditions. These mechanic conditions define the structure of the spontaneous deformations of the magnetically ordered crystal. Both the value and the structure of the spontaneous deformations influence both the thermodynamic and the dynamic characteristics of the system, and, consequently, they affect the experimental results. In addition, it is necessary to take into account the substrate's influence on the sample. Many authors pay attention to the importance of the account of the mechanic boundary conditions, but nowadays this question is still studied insufficiently [18].

The systems, described above, are studied well for the case of magnets with the Heisenberg exchange and weak single-ion anisotropy interaction (see [19–21] and references in the review article [21]). For such magnets, the phenomenological approach based on the Landau–Lifshitz equation is adequate. However, there are a large number of magnets with strong single-ion anisotropy. For these magnets (non-Heisenberg magnets), some special effects, which cannot be explained in the framework of this phenomenological model, are present. In their static properties, these systems can demonstrate the effects of quantum spin reduction in the ground state. The competition between the exchange interaction and easy-plane single-ion anisotropy leads to quantum reduction of the spin, and at $\beta > J$ to the realization of the spin nematic state with zero magnetic moment, characterized by the tensor order parameter. In their dynamics, the additional spin wave modes corresponding to the longitudinal spin oscillations are present. The details of such quantum effects can be found in a review article [22] as well as recent articles [23–27] and references therein.

In the present work, the influence of the magnetoelastic interaction (mechanic boundary conditions) on dynamic and static properties of the system will be investigated. The account for mechanic boundary conditions leads to the appearance of non-diagonal components of the deformation tensor that is absent for the “free” sample. In this case, the procedure of diagonalization of the anisotropy tensor is not sufficient, and one needs to realize full diagonalization of the single-site Hamiltonian, with the inclusion of the energy of magnetoelastic interaction. This naturally leads to a model with inclined anisotropy, i.e., the anisotropy axis of the system is not parallel to the surface. It turns out that the account for the influence of the boundary (mechanic boundary conditions) leads to a shift of phase stability lines or phase transition points, as well as to a change of the area of phase existing and co-existing. The magnetoelastic interaction can significantly influence both the static and the dynamic properties of the system. And, if we take into account the boundary conditions, then such a contribution becomes even more significant. For example, the account of the magnetoelastic interaction can change the lines of the phase stability or the points of the phase transitions, can change the region of the phases' co-existence, and can be exhibited in some other ways. Also, it is important that the anisotropy can amplify magnetoelastic effects because of their common nature (spin–orbit interaction).

2. Model

Let us investigate the semi-infinity ferromagnet, fixed at the ZOX plane (Fig. 1). The spin of the magnetic ion equals unity ($S=1$) because this is the minimal value of the spin at which single-ion anisotropy appears. Besides, the ferromagnet possesses both easy-plane single-ion anisotropy (XOY is the basal plane) and easy-axis single-ion anisotropy lying in the ZOX plane and makes some angle with the axis of anisotropy and the OZ-axis (“inclined” anisotropy). Because strict boundary conditions are imposed on the system, it is necessary to take into account the magnetoelastic interaction. There are no elastic deformations along the OY-axis and the OZ-axis ($u_z = u_y = 0$) because the sample is fixed at the ZOY-plane. Such boundary conditions correspond to a slab, fixed at the ZOY-plane [28]. It means that the slab size along the OX-axis is less than the sizes along the OY-axis and the OZ-axis. However, we can use these boundary conditions for the system with a large length in the direction perpendicular to the fixed plane (along the OX-axis) [29] because the slab size along the OY-axis and the OZ-axis is not limited. Consequently, the system under investigation can be considered as the semi-infinity sample, $0 < X < \infty$, $-\infty < Y < \infty$, $-\infty < Z < \infty$ (Fig. 1). We chose the boundary condition to have maximum influence of both easy-plane anisotropy and “inclined” anisotropy. Thus, the Hamiltonian of the system can be represented in the following view:

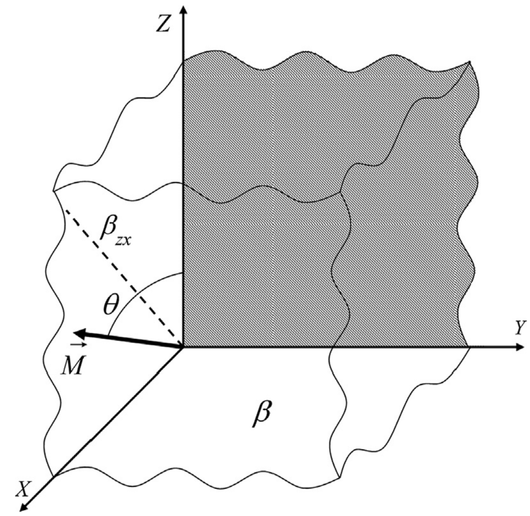

Fig. 1. The geometry of the model.

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

where $J_{nn'} > 0$ is the exchange integral; $O_{2n}^{ij} = S_n^i S_n^j + S_n^j S_n^i$ are the Stevens operators [30]; $\beta > 0$ is the constant of easy-plane single-ion anisotropy (XOY is the basal plane); $\beta_{zx} > 0$ is the constant of easy-axis single-ion “inclined” anisotropy acting in the ZOX-plane; ν is the constant of magnetoelastic coupling; λ and η are the elastic modules; and u_{ij} is the tensor of elastic deformations. We also consider the low temperature case ($T \ll T_C$, T_C is the Curie temperature).

The competing of the easy-plane and the “inclined” anisotropies leads to the fact that the magnetic moment lies in the ZOX-plane and makes some angle θ with the OZ-axis.

We will turn the coordinate system of the magnetic ion on the angle θ around the OY-axis to direct the magnetic moment along the OZ-axis, $U(\theta) = \prod_n \exp[i\theta S_n^y]$. Then, we will select the mean field and obtain the single-site Hamiltonian:

$$H_0(\theta) = -\overline{H}\sum_n S_n^z + B_2^0(\theta)\sum_n (S_n^z)^2 + B_2^2(\theta)\sum_n O_{2n}^2 + B_2^{xz}(\theta)\sum_n O_{2n}^{xz} + B_2^{xy}(\theta)\sum_n O_{2n}^{xy} + B_2^{yz}(\theta)\sum_n O_{2n}^{yz} + 2B_2^2(\theta). \tag{2}$$