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Influence of the next-nearest neighbor exchange interaction on the thin-film spin-wave spectrum

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ABSTRACT

We study the order of modes in the spin-wave spectrum of a ferromagnetic thin film. In our calculations we use the Heisenberg model taking into account the exchange interaction between the nearest (NN) and next-nearest (NNN) neighbors and including the single-ion anisotropy term. We elucidate the effect of the NNN exchange coupling on both the spectrum of propagating spin waves and the spin-wave resonance (SWR) spectrum. We show that with sufficiently strong antiferromagnetic NNN interaction the order of modes in the spin-wave spectrum is reversed at the center of the Brillouin zone, with the lowest mode optic and the highest one acoustic. This effect allows to infer the character of the NNN interaction from the resonance peak intensity pattern in the SWR spectrum. We also show that the reversed order of modes can be related to in-plane spin-wave propagation. Surprisingly, this dynamic reversal can occur even if both the NN and NNN exchange interactions are ferromagnetic. This effect should be observed in Brillouin light scattering and spin-polarized electron energy loss spectra as a collapse, followed by a spectrum with a reversed intensity pattern with changing wave-vector length.

1. Introduction

Magnetic thin films have remained the center of attention and subject of numerous studies for more than five decades [1–3]. This interest is stimulated by the huge progress in the fabrication technology of such structures and by their rich physics [4]. Besides, many properties of systems such as thin-film magnonic crystals or magnetic multilayers derive from the properties of the magnetic thin film [5–7]. For example, when combined with the propagation of spin waves parallel to the surface plane (in-plane propagation), the presence of the surface will result in surface localization. For exchange spin waves this effect was investigated both experimentally [8,9] and theoretically [10,11]. In the case of dipolar spin waves, the Damon–Eshbach localization [12] results in their non-reciprocity [13]. Another interesting effect related to in-plane propagation is the spin-wave spectrum collapse discovered by Lévy et al. [14] in semi-infinite ferromagnets, with a whole band of bulk modes degenerating to a single frequency. A study of this effect in thin films is presented in the paper [15].

In various investigations an important role is played by the interaction range [16–20]. Its extension from nearest (NN) to next-nearest (NNN) neighbors results in the occurrence of new effects in various systems [21–23]; in particular, in ferromagnetic thin films, it leads to subsurface localization [24] and the mode reversal considered in the present paper. Taking into account the long-range dipolar interaction will bring about vortex states in magnetic dots [25], cause the complete bandgap to open in magnonic crystals [26,27], and, in thin films, besides the above-mentioned Damon–Eshbach localization and non-reciprocity, lead to negative group velocity [28] and the splitting of the spectrum into subbands [29].

One of the most powerful experimental technique for studying the spin-wave properties is SPEELS, the spin-polarized electron energy loss spectroscopy, which gives possibility to observe the spin wave dispersion through the entire Brillouin zone [30]. The method allows experimental studies of different properties of magnetic ultrathin films such as exchange interactions [31], magnetic anisotropy [32], or thermal properties [33]. For example for iron films grown on different substrates SPEELS results show very different interactions as antiferromagnetic exchange [34] or Dzyaloshinskii–Moriya interactions [35].

In the present study we consider a homogeneous ferromagnetic thin film with the exchange interaction assumed to be strong enough for the effect of the dipolar interaction to be negligible. This assumption works well in the determination of the spin-wave spectrum of various systems, such as cobalt ultrathin films [8], Fe/Pt multilayers [36] or europium monochalcogenide magnetic semiconductors [37], and in the case of weakly nonlinear spin waves [38,39]. For the description of the considered system we use a microscopic model based on the Heisenberg Hamiltonian taking into account the exchange interaction between the nearest and next-nearest neighbors and the single-ion anisotropy (the model is described in detail in Section 2). By dividing the thin film into a system of lattice planes parallel to the surface the problem is reduced to a one-dimensional chain with effective interplane coupling. This effective coupling is reflected in the order of modes in the spin-wave spectrum. In the case of ferromagnetic (FM) coupling the

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lowest mode (the mode with the lowest energy) is 'acoustic', which means that the magnetic moments in neighboring planes precess with only a slight phase shift (below $\pi/2$); the highest mode is of 'optical' character, with the magnetic moments in neighboring planes precessing in antiphase. This we shall consider the normal order of modes. If the effective coupling is antiferromagnetic (AFM), the order of modes in the spectrum is reversed.

Widely discussed in the literature is the order of acoustic and optical modes in bilayers. In-phase and antiphase precession, respectively, of the resultant sublayer magnetizations is considered in such systems. For example, papers [40,41] present studies of a magnetic bilayer with purely dipolar coupling between sublayers. In the case of in-plane magnetization of the sublayers the coupling is antiferromagnetic, and the optical mode has a lower energy than the acoustic mode. In these papers the sublayer magnetization is referred to the oscillations of two coupled pendulums, which oscillate in phase in the mode with lower energy; thus, the order of modes in the spectrum of the bilayer with AFM coupling is reversed. A similar system is studied theoretically and experimentally in [42]. Mode reversal is apparent in the presented spin-wave resonance (SWR) spectra, in which the less intense peak, related to the optical mode, corresponds to a higher field than the high-intensity peak related to the acoustic mode. Mode reversal in the spin-wave spectrum has also been investigated in multilayer systems. The paper [43] considers an AFM superlattice divided into a system of parallel single-site planes so that the spin alignment is parallel within each plane and antiparallel between neighboring planes. In such an AFM multilayer system the coupling between neighboring planes favors optical modes. Papers [44,45] consider the order of acoustic and optical modes in a trilayer and a ferromagnetic chain.

In the present paper we investigate the influence of two factors, the NNN exchange interaction and the in-plane propagation of the spin wave, on the effective interplane coupling, with the ferromagnetic character of the NN interaction maintained. We formulate the conditions to be fulfilled by the NNN interaction to enable mode reversal. For non-propagating spin waves (at the center of the surface Brillouin zone, SBZ) we study the effect of the mode reversal on the SWR spectrum. For propagating spin waves we determine in which parts of the SBZ the mode order is normal or reversed. Also, we demonstrate that in-plane spin-wave propagation can reverse the order of modes in the spectrum even in the case of ferromagnetic NNN interaction.

2. The model

To study the ferromagnetic thin film under consideration we shall use the planar model described in details in several papers (see, e.g., Refs. [46,47]). Here we only present its most important points. The thin film is composed of L crystallographic planes (layers) parallel to the film surface. An external magnetic field is oriented perpendicularly to the surface, along the z direction, and strong enough to stabilize the homogenous ferromagnetic ground state. The wave vector can be decomposed into two components: an in-plane component $\vec{k}_{\parallel}=(k_x,k_y)$ parallel to the film surface, and a perpendicular component $\vec{k}_{\perp}$.

Our calculations are performed within the framework of the Heisenberg model taking into account the exchange interactions between nearest (NN) and next-nearest (NNN) neighbors, and the single-ion anisotropy term. The thin film is described by the Hamiltonian of the standard form:

$$\widehat{\mathcal{H}}=-2J\sum_{l\,\vec{j};l'\,\vec{j}'}\widehat{\vec{S}}_{l\,\vec{j}}\cdot\widehat{\vec{S}}_{l'\,\vec{j}'}-2J_N\sum_{l\,\vec{j};l'\,\vec{j}'}\widehat{\vec{S}}_{l\,\vec{j}}\cdot\widehat{\vec{S}}_{l'\,\vec{j}'}-\sum_{l\,\vec{j}}D_l\left(\hat{S}^z_{l\,\vec{j}}\right)^2. \tag{1}$$

J and J_N denoting the exchange integrals for NN and NNN interactions, respectively. The pair $l\,\vec{j}$ in the subscript describes the position of the spin in the crystal lattice: l denotes the layer number, and $\vec{j}$ is the position vector within the layer l ($\vec{j}\in l$). We assume that the single-ion anisotropy coefficient D_l can take different values at the surfaces and between them. Moreover, under the assumption of circular precession of spins the evenly distributed single-ion anisotropy shifts the energy spectrum uniformly, a significant effect being only produced by the difference between the surface and the bulk anisotropy. The Zeeman term is neglected, as it only results in a uniform shift of the energy spectrum, which is a consequence of the assumption of the sample saturation.

The diagonalization procedure of Hamiltonian (1) is described in detail in [46,47]. We perform a transformation of spin operators to second-quantization operators (the Holstein–Primakoff transformation) and subsequently, the Fourier transformation in the plane of the film (this step is justified by the assumption of in-plane periodicity of the film). Due to the spatial distribution of the NN and NNN in cubic thin films (i.e. thin films with spins arranged in the sites of the cubic lattice) of surface cuts (001) and (110), the diagonalization of the Hamiltonian (1) in these cases is equivalent to that of a seven-diagonal matrix of rank L (for a detailed analysis of the spatial distribution of the nearest and the next-nearest neighbors in cubic thin films, see our previous paper [47]). The explicit form of each element of the matrix depends on the parameters of the thin film, such as the crystallographic structure, the surface cut and the exchange integrals J and J_N, and on the in-plane wave vector $\vec{k}_{\parallel}$.

3. The mode order reversal in the spin-wave spectrum

In thin films with some particular surface cuts, e.g. sc(001), the nearest and the next-nearest neighbors of any spin lie no farther than in the adjacent atomic plane parallel to the film surface [47]. Consequently, the Hamiltonian matrix for these surface cuts is a 3-diagonal matrix of the following form:

$$\widehat{\mathcal{H}}=\begin{bmatrix} R-a & C & & & & \\ C & R & C & & & \\ & \ddots & \ddots & \ddots & & \\ & & C & R & C & \\ & & & C & R-b \end{bmatrix}. \tag{2}$$

Each element of matrix (2) depends on material parameters, such as the exchange integrals for the NN and the NNN interactions, and on the in-plane wave vector. This matrix describes the behavior of a chain with interaction only between neighboring sites. In our problem the role of the sites is played by the planes parallel to the surface; thus, even though both the NN and NNN interactions are allowed for from the point of view of the crystal structure, the effective coupling between planes is limited to the nearest neighboring planes (as implied by the spatial distribution of the NN and NNN in 3D structure). The diagonal elements of the matrix describe the energy at each chain site, or plane; the off-diagonal elements are related to the coupling between neighboring planes. It is noteworthy that the Zeeman energy, as an on-site energy, only affects the diagonal elements and thus shifts the whole spectrum of eigenvalues in a uniform way. So does the single-ion anisotropy; only the difference between its surface and bulk values changes the surface parameters a and b.

The off-diagonal element C describes the effective coupling between spin waves excited in adjacent atomic planes. If C is negative, the coupling is of ferromagnetic nature, leading to an in-phase precession in the lowest mode. Positive C implies antiferromagnetic effective coupling, conducive to a precession in antiphase in the lowest mode. Thus the order of modes in the spin-wave spectrum is determined by the off-diagonal element C. If $C<0$, the lowest mode is acoustic and the highest one optical, which means that the order of modes in the spin-wave spectrum is normal. However, for $C>0$ the reverse order occurs. A very interesting case is that of $C=0$, in which the whole band of