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Magnetic excitations in ferromagnetic glasses

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ABSTRACT

We have studied theoretically (including computer simulations) dynamical magnetic properties of aggregates of ferromagnetic amorphous nanogranules in the presence of direct exchange between the neighboring granules and random anisotropy fields. It was shown that in such structures there still exist delocalized magnetic excitations similar to magnons in the bulk materials, although at much lower frequencies. The excitations at high frequencies are localized within the corresponding granules. The details of spectrum of these excitations (including structural factors) are discussed.

1. Introduction

Nanostructured materials, of no doubt, are on the cutting edge both from scientific and technological points of view. In particular, it concerns aggregates of ferromagnetic nanogranules. On the one hand, here we deal with a new object with properties that can be significantly different from properties of a bulk material. On the other hand, the nanoparticle composites represent new promise for applications including e.g. memory devices. Recently in Ioffe Institute a new technology of fabrication of amorphous granular metals based on laser electrodeposition was developed [1].

The sizes of the granules are nearly fixed depending on the specific metal (to say, for Ni it correspond to ~ 2 nm). The properties of ensembles of nanoparticles (granules) depend on such factors as granules size and form, the strengths of intergranular exchange (which can be affected by tunneling interface) and dipolar interactions between the granules as well as on the anisotropy energies of different granules. In addition to the factors mentioned above, the properties of the films depend on the film thickness. In particular, it has appeared that relatively thin films (with a thickness less than 8 nm) exhibited properties of ensembles of superparamagnetic particles [2].

Earlier the theoretical studies (including computer simulations) of static magnetic properties of aggregates of ferromagnetic amorphous nanogranules in the presence of direct exchange between the neighboring granules and random anisotropy fields were made [3].

It was demonstrated (basing on analytical considerations as well as on the results of numerical simulations) that the system exhibits a random spatial distribution of granules magnetization which is smooth and characterized by a correlation length which is much larger than the granules size. Thus the regions with a size of the order of the correlation length correspond to nearly collinear orientation of magnetization and thus can be considered as "domains". The size of these domains (i.e. the correlation length) depends on the ratio of the exchange interaction and random anisotropy. Basing on these facts it was concluded that such a system can be considered as "ferromagnetic glass". Indeed, in contrast with well-known spin glasses here we deal with random distribution of large-scale magnetization rather than with the random order of elementary spins. In this paper we aim to consider (basing, again, on both analytical studies and on computer simulations) the character of magnetic excitations in such "ferromagnetic glasses". In contrast to bulk ferromagnets where we deal with exchange interactions between magnetic atoms, here we deal with interactions between relatively large granules having large magnetic moments. These interactions (involving only a group of surface atoms and, possibly, tunneling interface) are, naturally, weaker in comparison to the interatomic exchange in bulk materials. Thus we will show that the corresponding frequencies of intergranular magnetic excitations will be significantly lower than the typical magnon frequencies in bulk ferromagnets. Then, the random anisotropy imposes a soft gap for low-frequency excitations resulting from the fact that the magnon wavelength, in this case, cannot be bigger than the magnetization correlation length mentioned above.

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2. Theoretical model

The energy of the system:

$$E = E_{ex} + E_a \tag{1}$$

The exchange energy has a form

$$E_{ex} = -\frac{1}{M^2}\sum_{ij} J_{ij}\mathbf{M}_i\mathbf{M}_j, \tag{2}$$

where $\mathbf{M}_i$ and $\mathbf{M}_j$ are granule magnetizations and J_{ij} is exchange energy between them. We assume that all granule magnetizations has the same modulus M.

The exchange between neighbor atoms can be estimated as

$$J = J_0(S_{eff}/a^2)k_T^2 \tag{3}$$

Here J_0 is the interatomic exchange constant for ferromagnetic material, $S_{eff} < R^2$ is an effective area of the intergranular contact, R is the granule size, a is the lattice constant, k_T is the tunneling amplitude. Thus for a metallic sample $J > J_0$ while for an insulating sample $J < J_0$.[1]

It is important that the anisotropy energy of amorphous granules (which mostly originates from the granule shape) is characterized by a random distribution of the direction of the anisotropy axis. The corresponding energy term can be written as

$$E_a = -\frac{K_u V_g}{M^2}\sum_i (\mathbf{M}_i\mathbf{a}_i)^2, \tag{4}$$

where K_u is an anisotropy parameter, $V_g \sim R^3$ is the granule volume and $\mathbf{a}_i$ is a unit vector of anisotropy axis. We neglect a difference of volumes and anisotropy constants of various granules. We consider $K_u > 0$, which corresponds to the easy axis.

The dynamics of the magnetization can be described by the Landau-Lifshitz equation

$$\frac{d\mathbf{M}_i}{dt} = \gamma[\mathbf{M}_i \times \mathbf{H}_i] - \frac{\alpha\gamma}{M}[\mathbf{M}_i \times [\mathbf{M}_i \times \mathbf{H}_i]] \tag{5}$$

where γ is the electron gyromagnetic ratio, α is dimensionless damping factor and $\mathbf{H}_i$ is an effective magnetic field

$$\mathbf{H}_i = -\frac{\partial E}{\partial \mathbf{M}_i} = \frac{1}{M^2}\sum_{j\neq i} J_{ij}\mathbf{M}_j - \frac{2K_u V_g}{M^2}(\mathbf{M}_i\mathbf{a}_i)\mathbf{a}_i. \tag{6}$$

We have modeled a system of N magnetic particles situated within the sites of a square lattice with a lattice constant a. Within our model, we assumed that the particles are monodisperse while the anisotropy axis $\mathbf{a}_i$ for each particle is randomly oriented. While the simulations are obviously for 2D one, we have mentioned that actually for realistic ferromagnetic structures it is rather 3D one. However, from our point of view, we can consider as 2D any system where the correlation length is larger than the system thickness (larger than $\sim 4R$)—at least for excitations with wavelengths larger than the film thickness.

The equilibrium magnetization $\mathbf{M}_i^{(0)}$ was found by the minimization of the energy E using Nesterov's accelerated gradient descent.

2.1. Damping

The magnon-electron scattering time can be estimated as [4]

$$\frac{1}{\tau_{me}} = \frac{\tilde{g}^2}{\varepsilon_F}\omega \tag{7}$$

where

$$\tilde{g} = J_0^2\frac{k_F}{(\Delta k_F)^2 a} \tag{8}$$

Here J_0 is an exchange constant of the ferromagnet, k_F is the Fermi wave vector while Δk_F is the exchange splitting between minority and majority electrons. Note that while the initial estimates were made for damping of magnons within ferromagnetic layers while in our case the granule size is expected to be smaller than the magnon wavelength, this estimate holds since it is obtained with a neglect of magnon spatial dispersion within the ferromagnetic layer. Indeed, due to lifting of the momentum conservation law within the granule only energy conservation law controls the situation and the contributions of different granules to magnon damping are additive.

Then, we relate α to $1/\tau_{me}$ as $1/\tau_{me} = \alpha\omega$. Thus

$$\alpha = \frac{J_0^2}{\varepsilon_F^2}\frac{k_F}{(\Delta k_F)^2 a} \tag{9}$$

Estimating

$$\frac{\Delta k_F}{k_F} \sim \frac{J_0}{\varepsilon_F} \tag{10}$$

we have $\alpha \sim (k_F a)^{-1}$ which is expected to be of the order of 0.1. Realistically we have additional factor standing for the relative volume of the granules, but it is of the order of unity.

2.2. Correlation length

Now let us estimate the role of random anisotropy. According to [3] the correlation length for magnetization distribution is given as

$$\mathscr{L} = 6\pi^2\frac{(Rd)^{1/2}}{K}, \tag{11}$$

where $K = K_u V_g/J$ is the dimensionless anisotropy parameter and d is the film thickness. Since in our simulations we implied $d = R$, we will restrict ourselves by this case.

We calculate the spatial correlation function of the equilibrium granule magnetizations $\mathbf{M}_i^{(0)}$. The correlation length $\mathscr{L}$ is determined as a radius, at which the correlation function decreases two times from its maximum value. Fig. 1 shows $\mathscr{L} \sim K^{-0.9}$ which is close to $\mathscr{L} \sim K^{-1}$ predicted by Eq. (11).

It is natural to expect that the value of $\mathscr{L}$ gives a natural lower cutoff for the magnon wavevector. Thus we expect that there is a soft gap at low frequencies with a width $\propto \mathscr{L}^{-2}$. As it is seen from Fig. 2 indeed, this law holds with a good accuracy.

3. Near equilibrium dynamics

In the equilibrium, the magnetization $\mathbf{M}_i^{(0)}$ and induced effective magnetic field $\mathbf{H}_i^{(0)}$ minimize the energy E (it can be a local minimum). In this case the Landau-Lifshitz Eq. (5) is stationary and $\mathbf{M}_i^{(0)} \| \mathbf{H}_i^{(0)}$.

The deviation from the equilibrium can be written as

$$\mathbf{m}_i = \mathbf{M}_i - \mathbf{M}_i^{(0)}, \quad \mathbf{h}_i = \mathbf{H}_i - \mathbf{H}_i^{(0)}, \tag{12}$$

where $\mathbf{m}_i$ is perpendicular to $\mathbf{M}_i^{(0)}$. Since Eq. (6) is linear, we have

$$\mathbf{h}_i = \frac{1}{M^2}\sum_{j\neq i} J_{ij}\mathbf{m}_j - \frac{2K_u V_g}{M^2}(\mathbf{m}_i\mathbf{a}_i)\mathbf{a}_i. \tag{13}$$

[1] Indeed, the ratio (S_{eff}/a^2) gives the number of quantum channels between the granules while k_T^2 gives the tunneling transparency for each channel. Thus for insulating regime, the intergranular conductance is less than e^2/h, while for metallic regime it is larger than e^2/h.