Magneto-exchange resonance in small particles

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Results are presented of a theoretical calculation that shows that in small particles of nearly-single-domain size there can exist a special type of magnetic resonance, which, while having common features with the resonance in domain walls, differs substantially from the latter.

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In single-domain particles, just as in bulky samples, magnetic resonances takes place in the case of homogeneous precession of the magnetization. Thus, if the particle is a magnetically uniaxial spherical single crystal, then in the absence of an external magnetic field the frequency of such a resonance is $\omega_0 \approx 2K/I_s$, where K is the magnetic-anisotropy constant and I_s is the magnetization (see[1]).

We present in this article the results of a theoretical calculation that shows that in spherical, ellipsoidal, and cylindrical small particles with dimensions close to single-domain particles there can occur another type of magnetic resonance, which can be called magneto-exchange, having a frequency higher than ω_0. It can be observed in an ensemble of oriented particles, in an alternating magnetic field parallel or almost parallel to their easy axes. This resonance has features in common with the resonance in domain walls[2–5] and is due to the same physical causes, but differs substantially from the latter, namely, the region where the magnetization is inhomogeneous in the equilibrium state now extends over the entire volume of the particles, does not act as a boundary between domains, and does not move when the magnetic moments oscillates. Even the lowest natural frequency ω_0' of these oscillations depends on the parameter A of the exchange energy and is much higher than the natural frequency of the translational oscillations of the domain wall.

As shown by the author in[6], in small particles of the indicated shape, with dimensions exceeding but yet close to those of the corresponding dimensions of the single-domain particles, an equilibrium magnetic structure, dubbed "twisting" is produced (see Fig. 1). In the approximation where the magnetization distribution is assumed continuous, which is valid in the considered case, such a structure is described by the following dependence of the direction

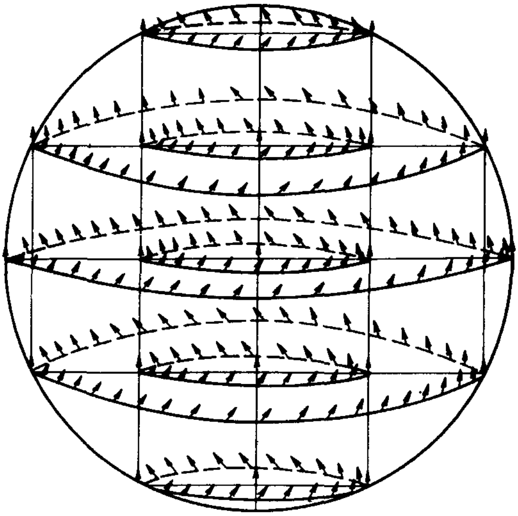

FIG. 1. Magnetic structure of "twisting" (the figure is taken from the article[6]).

cosines of this vector on the coordinates r, ϕ, and z in a cylindrical frame with origin at the center of the particle and with a z axis directed along the easy axis:

$$\mathbf{I} = I_s \vec{\alpha}, \quad \alpha_r = 0, \quad \alpha_\phi = \sin\epsilon, \quad \alpha_z = \cos\epsilon$$

$$\epsilon = \epsilon_1 \frac{r}{R_0}\left[1 - \kappa_1\left(\frac{r}{R_0}\right)^2 - \kappa_2\left(\frac{z}{R_0}\right)^2 + \dots\right], \tag{1}$$

where R_0 is the radius of the particle, a sphere or a prolate ellipsoid of revolution with easy axis along the major axis, ϵ_1 is a parameter that depends on R_0, on the external magnetic field H, on the constant K of the magnetic anisotropy, on I_s, and on the exchange energy constant A, while κ_1 and κ_2 are fractional numerical factors. The function $\epsilon(r,z)$ can be described with sufficient accuracy by the first three terms of formula (1). The boundary conditions for the magnetization, in the form $(\partial\alpha_i/\partial n)_{R=R_0} = 0$, are satisfied in this case if $\kappa_1 = \kappa_2 = 1/3$ for a sphere and $\kappa_1 = 1/3, \kappa_2 = 0$ for a cylinder.

In the equilibrium state, the vector $\mathbf{I}(r,z)$ is directed along the axis of the local effective field $\mathbf{H}_e(r,z)$, the components of which are equal to

$$H_{ei} = \frac{1}{I_s}\left(\mathrm{div}\frac{\partial\phi}{\partial(\nabla\alpha_i)} - \frac{\partial\phi}{\partial\alpha_i}\right), \tag{2}$$

where $\phi = d\Phi/d\Omega$ is the density of the thermodynamic potential Φ. When an alternating magnetic field $h = h_0\exp(i\omega t)$ is turned on, the vectors $\mathbf{I}$ are inclined away from the $\mathbf{H}_e$ axis, and the local demagnetizing and exchange fields are changed as a result. The principal role in the occurring magnetization oscillations are played by the alternating radial components ΔH_r^d of the demagnetizing field and ΔH_r^a of the exchange field, which are produced when the vectors **I** go out of their equilibrium positions. In these fields, the vectors **I** rotate around the radius vectors **r** and the angles ϵ increase and decrease alternately, while the magnetization lines twist and untwist alternately. The twisting is hindered by exchange forces and magnetic-anisotropy forces, and the untwisting is hindered by the action of the demagnetizing field.

We present below the results of calculations of the natural frequency of the oscillations and of the magnetic susceptibility κ in an alternating magnetic field for a quasi-one-domain particle in the simplest case, when the magnetic losses can be neglected. The calculations were made in a linear approximation in the small parameter ϵ_1 (see formula (1)). The function $\phi(r, z, \alpha_i)$ (see formula (2)) was determined from the expression for the thermodynamic potential Φ given in[6].

It is convenient in this case to solve the Landau and Lifshitz equations[1] by using local coordinate systems, in which the axes Z' are parallel to the vectors $\mathbf{H}_e^0$ in the equilibrium state. In these systems, in the linear approximation in ϵ_1, the components $E_{ez'}$ and $H_{ci'}$ are equal to

$$H_{ez'} = H_e^o = \left(\frac{2K}{I_s^2} + \frac{H_z}{I_s} - N_z\right) I_s, \quad \Delta H_{ez'} = 0$$

$$\Delta H_{er'} = -(N_e + \kappa_a^{-1})\Delta I_r, \qquad \Delta H_{e\phi'} = -\kappa_a^{-1}\Delta I_\phi, \tag{3}$$

where ΔI_i are the components of the alternating term of the magnetization, $H_z = H$, N_z is the demagnetizing factor of the particle along the Z axis, N_e is the effective demagnetizing factor along the radius, $N_e \approx 3\pi$ for spherical and cylindrical particles, $\kappa_a = c(R_0^2 I_s^2/A)$ is the susceptibility in the effective exchange field, $c = 0.15$ for cylindrical particles and $c = 0.12$ for spherical ones.

Substituting $H_e{}^0$ and $H_{ei'}$ in the Landau-Lifshitz equation, we get

$$i\omega\Delta I_r + \gamma I_s\left(\kappa_a^{-1} + \frac{2K}{I_s^2} + \frac{H}{I_s} - N_z\right)\Delta I_\phi = \gamma h_{\phi'} I_s \tag{4}$$

$$\gamma I_s\left(N_e + \kappa_a^{-1} + \frac{2K}{I_s^2} + \frac{H}{I_s} - N_z\right)\Delta I_r - i\omega\Delta I_\phi = 0,$$

where $h_{\phi'} = h_0 \sin\epsilon$ is the azimuthal component of the alternating magnetic field amplitude in the local coordinate system. Solving the system (4), we obtain the magnetic susceptibility $\kappa = \overline{\Delta I_z}/h_0$, where $\overline{\Delta I_z}$ is the value of $\Delta I_z = \Delta I_\phi \sin\epsilon$ averaged over the particle volume, and the resonant frequency ω_c'

$$\kappa = \kappa_o \left[1 - \left(\frac{\omega}{\omega_o'}\right)^2\right]^{-1} \tag{5}$$

$$\omega_0' = \gamma I_s \left[\left(N_e + \kappa_a^{-1} + \frac{2K}{I_s^2} + \frac{H}{I_s} - N_z\right)\left(\kappa_a^{-1} + \frac{2K}{I_s^2} + \frac{H}{I_s} - N_z\right)\right]^{1/2}, \tag{6}$$

where $\kappa_0 = k[\kappa_a^{-1} + (2K/I_s^2) + (H/I_s) - N_z]^{-1}$ at $\epsilon_1 = 0.25$, $k \approx 0.018$ for cylindrical particles, and $k \approx 0.0015$ for spherical particles. In the case when $\kappa_0 > 0$, resonance takes place at $\omega = \omega_0'$. If $\kappa_0 < 0$, there is no resonance.

For iron we have $A = 2\times10^{-6}$ erg/cm and $I_s^2 \approx 3\times10^6$ erg/cm^3. Cylindrical iron particles become single-domain at radii on the order of 100 Å (see[6]). Assuming for a quasi-one-domain particle $R_0 = 300$ Å, we obtain $\kappa_a^{-1} \approx 0.6$. In this case at $H = -1000$ Oe we have $\kappa_0 \approx 0.06$ and the resonant frequency is $\omega_0' \approx 2900\gamma$ (the corresponding wavelength is $\lambda \approx 4$ cm). For nickel at $H = -300$ Oe and $R_0 = 600$ Å we have $\kappa_a^{-1} \approx 0.6$, $\kappa_0 \approx 0.045$, $\omega_0' \approx 1000\gamma$ and $\lambda_0 \approx 10$ cm. We note that powder particles remain single-domain at larger radii than isolated particles. The value of κ_a^{-1} for powder is there smaller, and the same resonant frequencies should be observed in magnetic fields H of smaller absolute value.

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