Magnetostochastic resonance

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A magnetostochastic resonance is proposed for use in studying magnetization fluctuations in a ferromagnet, in particular, for observing a macroscopic quantum tunneling of the magnetic moment.

1. The stochastic resonance which was discovered by Benzi *et al.*[1] and studied extensively[2-6] might prove to be a very useful tool for studying systems with a bistable potential.

In this letter we examine the magnetostochastic resonance in a ferromagnetic and suggest some experiments in which this resonance would be used to study uniform fluctuations of a spin system.

We consider an easy-axis ferromagnetic (the easy axis runs along the z axis) with an anisotropy field H_α and a saturation magnetization M_0. We start with a dynamic equation for the magnetization in the Landau–Lifshitz form: $d\vec{M}/dt = -\gamma[\vec{M},\vec{H}_{\rm eff}] + \lambda(\vec{H}_{\rm eff} - \vec{M}(\vec{M}\vec{H}_{\rm eff})/M_0^2)$, where $\vec{M}$ is the magnetization vector, $\vec{H}_{\rm eff}$ is the effective field, and λ is the damping constant. When this equation is rewritten in terms of the angle (θ) between the magnetization vector and the z axis, in a periodic external magnetic field $\vec{H}_0 \| z$, with a Langevin source $\xi(t)(\langle\xi(t)\xi(t')\rangle = \delta(t-t'))$, it becomes

$$d\theta/dt = -\alpha\gamma(H_a \cos\theta + H_0\cos(\omega_0 t))\sin\theta + \sqrt{2D}\xi(t) = -\partial V/\partial\theta + \sqrt{2D}\xi(t), \quad (1)$$

where is the gyromagnetic ratio, $\alpha = \lambda/(\gamma M_0)$ is a dimensionless damping constant, D is the source strength, and $V(\theta,t) = \alpha\gamma(H_\alpha \sin^2\theta - H_0\cos(\omega_0 t)\cos\theta)$ is the effective bistable potential corresponding to (1). The Fokker–Planck equation corresponding to (1),

$$\frac{\partial\rho}{\partial t} = \frac{\partial}{\partial\theta}\left(\rho\frac{\partial V}{\partial\theta}\right) + D\frac{\partial^2\rho}{\partial\theta^2}, \quad (2)$$

has a steady-state solution $\rho = \exp(-V(\theta)/D)$ in the case $H_0 = 0$.

2. For thermal fluctuations of the magnetization we easily find $D_T = \alpha\gamma kT/(M_0 v)$, where v is the volume of the sample, by working from the energy of the fluctuations. Using (2), we find the Kramers time[3] for a transition between equilibrium positions $\theta = 0$ and $\theta = \pi$ ($kT < H_\alpha M_0 v$):

$$\tau_c = 1/\nu_c = \frac{\pi}{\alpha\gamma H_a}\exp\left(\frac{H_a M_0 v}{kT}\right). \quad (3)$$

Following Refs. 3 and 6, we find the magnetostochastic resonance, which is ordinarily found as the signal-to-noise ratio at the frequency of the periodic external field ($\omega_0 \ll \nu_c$):

$$R_T = \frac{\alpha\gamma H_a}{2\Delta_f} \left(\frac{H_0 M_0 v}{kT}\right)^2 \exp\left(-\frac{H_a M_0 v}{kT}\right), \tag{4}$$

where Δ_f is the bandwidth of the signal to be detected.

Selective detection in the absence of a magnetostochastic resonance [if the second maximum of the function $V(\theta)$ is ignored] gives us a signal-to-noise ratio

$$R_s = \frac{1}{2\Delta_f} \left(\frac{H_0}{H_a}\right)^2 \frac{M_0 v \omega_0^2}{\alpha\gamma kT}. \tag{5}$$

From (4) and (5) we find the ratio (Γ) of the signals at magnetostochastic resonance and in the absence of such a resonance for the same noise level:

$$\Gamma = \frac{R_T}{R_s} = \frac{H_a M}{kT} \left(\frac{\alpha\gamma H_a}{\omega_0}\right)^2 \exp\left(-\frac{H_a M_0 v}{kT}\right). \tag{6}$$

For estimates, we use some values typical of magnetic iron garnet crystals: $H_\alpha \cong 10^3$ Oe, $M_0 \cong 10^2$ Oe, $\gamma \cong 10^7$ Oe$^{-1}\cdot$s^{-1}, $\alpha \cong 0.1$, $v = 100\times100\times100$ Å^3, and $T = 300$ K. We then find $\nu_c = 3\times10^8$ Hz, $R_T = 5\times10^4$, and $R_s = 2\times10^{-2}$ with $\Delta_f = 1$ Hz and $\Gamma \cong 10^6$.

Consequently, for a given strength of the periodic magnetic field the response of a system with magnetostochastic resonance is considerably larger than that of a system without such a resonance; furthermore, it depends on the level of fluctuations in the system. In particular, the signal-to-noise ratio goes through a maximum at a noise power $D_T = 2\alpha\gamma H_\alpha$, which corresponds to a temperature $T = 2H_\alpha M_0 v/k$.

The magnetostochastic resonance thus presents a convenient experimental situation for studying uniform fluctuations of the average magnetization of a ferromagnet. Let us examine some possible applications.

3. There has been a discussion in the literature[7,8] of whether it would be possible to detect a macroscopic quantum tunneling of magnetization in a single-domain sample of a uniaxial ferromagnet (the z axis is the easy axis). The sample would be immersed in a uniform magnetic field H_x to lower the potential barrier for the tunneling and to achieve reasonable tunneling rates. The application of a weak harmonic magnetic field along the z axis would set the stage for a magnetostochastic resonance. In the case of quantum tunneling, the Kramers time is[7] $\tau_c = (\pi/\alpha\gamma H_\alpha) \times \exp[-(4M_0 v/\hbar\gamma)\epsilon^{3/2}]$, where $\epsilon = 1 - H_x/H_\alpha$, the strength of the quantum fluctuations is $D_q = (\alpha\hbar\gamma^2 H_\alpha)/(M_0 v)$, and the size of the magnetostochastic resonance is $R_q \cong 8\alpha\gamma H_\alpha \epsilon^3 (H_0 M_0 v/hH_\alpha)^2 \exp[-(4M_0 v/\hbar\gamma)\epsilon^{3/2}]$. The temperature at which the strength of a Langevin quantum source becomes comparable to the thermal strength, $T_q = \hbar\gamma H_\alpha/k \cong 1$ K, is low but still accessible. If the magnetization were detected in a volume $v = 10^{-21}$ cm^3, there would be no need to apply an additional field H_x.

Figure 1 shows the experimental layout for studying macroscopic tunneling with a magnetostochastic resonance. The distance from the ferromagnetic needle to the

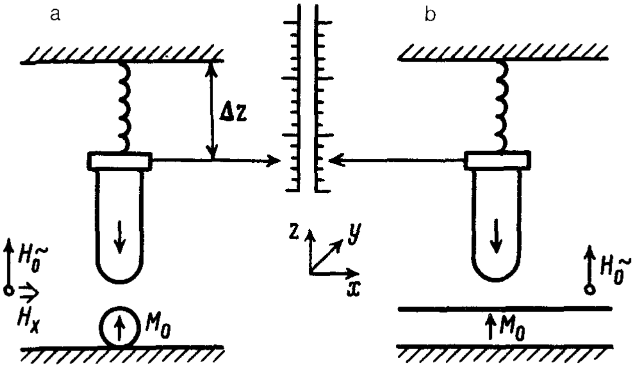

FIG. 1. Experimental layout for studying magnetic tunneling by means of a magnetostochastic resonance. a—Ferromagnetic sphere $\cong 100$ Å in diameter; b—thin magnetic film. The change in magnetization is detected by measuring Δz, the distance from the magnetic needle to the sample.

ferromagnetic sphere characterizes the magnetization of the sample. This distance is measured by interference methods.[9] The signal-to-noise ratio at the frequency of the applied alternating magnetic field H_0 gives rise to the magnetostochastic resonance. In addition to a sphere (Fig. 1a), one might use a thin ferromagnetic film, e.g., a film of an iron garnet (Fig. 1b), while the needle detecting the average magnetization might be the tip in a scanning atomic-force microscope.[9] The magnetization might also be detected by optical methods.

4. Another situation in which the magnetostochastic resonance might substantially simplify detection of the effect is a magnetization-dependent tunneling of electrons between two ferromagnetic layers separated by an insulator, as was studied in Ref. 10.

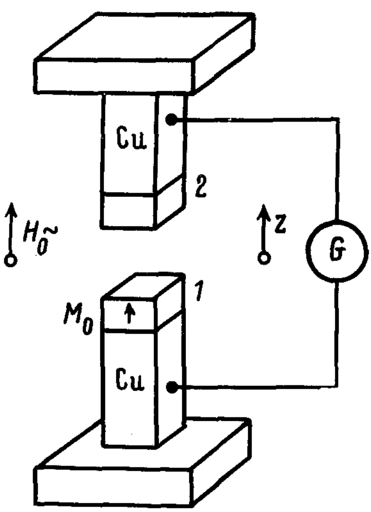

FIG. 2. Experimental layout for detecting a magnetization-dependent tunneling of electrons. The component of the tunneling current at the frequency of the magnetic field H_0 is measured. *1*—Thin layer of ferromagnet; *2*—thin layer of ferromagnet or antiferromagnet.

The experimental apparatus for this situation is shown in Fig. 2. A thin layer of a ferromagnet, with a uniaxial anisotropy along the z axis, is deposited on the surface of nonmagnetic conducting needles. The component of the tunneling current at the frequency of the periodic magnetic field applied along the z axis is measured. Because of the bistable potential set up by the uniaxial anisotropy, there would be a magnetostochastic resonance, and the component of the tunneling current at the frequency of the external field would be substantially larger than in the absence of a magnetostochastic resonance [as in (6)].

5. In conclusion, a magnetostochastic resonance in a uniaxial ferromagnet is a convenient tool for studying magnetization fluctuations, for detecting a macroscopic magnetic tunneling, for detecting a magnetization-dependent tunneling of electrons, and for detecting weak periodic magnetic fields.

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