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Thermal decay of the magnetization in two-dimensional nanoparticle ensembles

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Abstract

A method to numerically simulate the thermally induced magnetic relaxation in two-dimensional (2D) nanoparticle ensembles is generalized for the case of applied perpendicular magnetic fields. The influence of the correlations of the nanoparticle magnetic moments and of the external field on the relaxation law and on the relaxation rate is studied.

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The dipolar interaction between magnetic nanoparticles essentially changes the thermally induced decay of magnetization in nanoparticle ensembles. In the two-dimensional (2D) ensembles of uniaxial nanoparticles with large perpendicular anisotropy, which represent an important class of perpendicular magnetic recording media [1], the influence of the dipolar interaction on the magnetic relaxation, has been studied analytically, within the mean-field [2,3] and fluctuation [4] theories of magnetic relaxation, and numerically [5], in the case of zero applied field. These investigations showed that the correlations of the nanoparticle magnetic moments, arising from the dipolar interaction, play an important role in magnetic relaxation, and therefore for its correct description the correlation effects must be taken into account. The numerical method developed in Ref. [5] is applied to a considerably larger time interval than the time-quantified Monte Carlo method [6] and operates with real time t, not with the Monte Carlo steps as in Refs. [7–9], therefore it is a unique tool for investigation of magnetic relaxation in these ensembles.

In this paper we generalize our method in the case of the presence of an external magnetic field and we study its influence on the decay of magnetization in 2D nanoparticle ensembles. We assume that spherical nanoparticles of radius r occupy the sites of a hexagonal lattice with lattice spacing d, the easy axes of nanoparticles magnetization are perpendicular to the lattice plane (xy plane), the nanoparticles have magnetic moments $\mathbf{m}_i(t)$ (the index i labels the nanoparticles, $|\mathbf{m}_i(t)| = m$) and along the z axis on each nanoparticle acts a magnetic field H_0. If the thermal energy $k_B T$ (k_B is the Boltzmann constant, T is the absolute temperature) is much less than the heights of the potential barriers between the equilibrium directions of $\mathbf{m}_i(t)$, then the probability density of reorientation of $\mathbf{m}_i(t)$ is given by

$$w_{\sigma_i}(t;i) = \frac{2}{t_r}\sqrt{\frac{a}{\pi}}[1 - B_i^2(t)][1 + \sigma_i B_i(t)]\mathrm{e}^{-a[1+\sigma_i B_i(t)]^2} \qquad (1)$$

here $t_r = 2/\lambda\gamma H_a$, λ is the Landau–Lifshitz damping parameter, γ is the gyromagnetic ratio, H_a is the anisotropy field, $a = H_a m/2k_B T (a \gg 1)$, $B_i(t) = b_i(t) + b_0 (|B_i(t)| < 1)$, $b_i(t) = h_i(t)/H_a$, $h_i(t)$ is the z component of the dipolar field acting on $\mathbf{m}_i(t)$, $b_0 = H_0/H_a$ and $\sigma_i \equiv \sigma_i(t) = +$ or $-$. In this case the reduced magnetization $\rho(t) = 2N_+(t)/N - 1$ [$N_+(t)$ is the average number of positively oriented magnetic moments in a lattice region

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with $N(\gg 1)$ nanoparticles] on a sufficiently small time interval $(t, t+\tau)$ is written as

$$\rho(t+\tau) - \rho(t) = -\frac{2\tau}{N}\sum_{i=1}^{N}\sigma_i w_{\sigma_i}(t;i). \quad (2)$$

This equation is valid in the case that the probabilities of two and more reorientations of $\mathbf{m}_i(t)$ are negligibly small in the time interval $(t, t+\tau)$, and it can be applied if the ensemble state is known, i.e., $\sigma_i(t)$ for all i, at time t.

Using Eqs. (1) and (2), and the numerical procedure of Ref. [5] for the calculation of $\sigma_i(t+\tau)$, if $\sigma_i(t)$ is known, we have calculated $\rho(t)$ for different nanoparticle ensembles and different H_0. The plots of $\rho(t)$ for the ensemble of Co nanoparticles with parameters $m/V =$ 1400 G (V is the nanoparticle volume), $H_a = 6400$ Oe, $\lambda = 0.2$, $r = 4$ nm, $d = 3r$, $T = 300$ K, and $H_0 = 0$ and 500 Oe are shown in Fig. 1. In this figure, the plots of the mean-field reduced magnetization $\rho_{mf}(t)$, which satisfies the equation

$$\dot{\rho}_{mf}(t) = -\rho_{mf}(t)[w_+(t) + w_-(t)] - w_+(t) + w_-(t), \quad (3)$$

[$\rho_{mf}(0) = 1$, $w_\pm(t)$ is defined by Eq. (1), where it is necessary to replace $b_i(t)$ by $-11.034m\rho_{mf}(t)/H_a d$], are also shown, for comparison. As we can see from Fig. 1, the dipolar correlations of the nanoparticle magnetic moments, which are ignored within the mean-field approximation and are taken into account explicitly, in the numerical simulation, give rise to the distinctions between $\rho_{mf}(t)$ and $\rho(t)$. The function $\rho_{mf}(t)$ is changed almost logarithmically (quasilogarithmically) over six decades of time, whereas $\rho(t)$ has another functional form in this time interval. According to Ref. [2], the quasilogarithmic relaxation exists because the mean dipolar field decreases with time. On small times the actual magnetic relaxation occurs faster than the mean-field theory predicts, i.e., $\rho(t) < \rho_{mf}(t)$. The reason is that the reoriented and most of the non-reoriented magnetic moments are

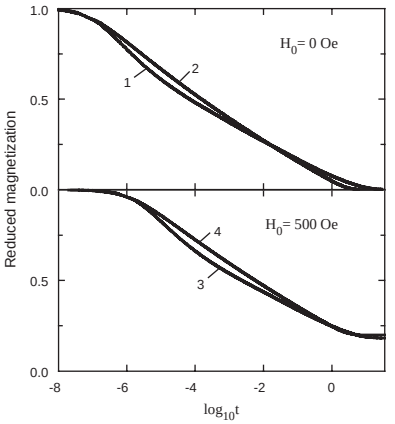

Fig. 1. Plots of the reduced magnetizations $\rho(t)$ and $\rho_{mf}(t)$ at $H_0 = 0$ Oe (curves 1 and 2, respectively) and $H_0 = 500$ Oe (curves 3 and 4).

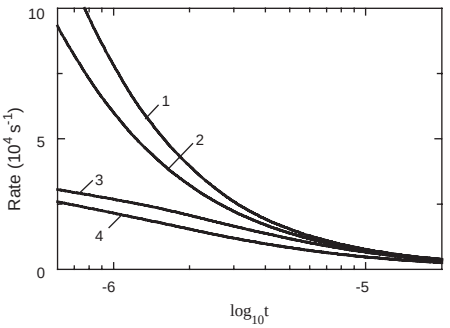

Fig. 2. Plots of the relaxation rates $u(t)$ and $u_{mf}(t)$ at $H_0 = 0$ Oe (curves 1 and 2) and $H_0 = 500$ Oe (curves 3 and 4).

under the action of the local dipolar fields, which exceed the mean dipolar field. To quantitatively characterize this feature, we have calculated $u(t) = |\dot{\rho}(t)/\rho(t)|$ and $u_{mf}(t)$ (see Fig. 2). They are decreasing functions of t, on the initial phase of magnetic relaxation the relaxation rates grow as H_0 decreases, and $u(t) > u_{mf}(t)$. Notice that for Debye relaxation, as in the case of non-interacting nanoparticles, the relaxation rate does not depend on t.

At $H_0 = 0$ and large times each magnetic moment is surrounded, on average, by four opposite and two similarly oriented magnetic moments. This means that on the final phase of magnetic relaxation the local dipolar fields are nonzero and have the same directions as the magnetic moments, whereas the mean dipolar field tends to zero. Therefore, $w_\pm(t;i) < w_\pm(t)$, and magnetic relaxation on large times occurs more slowly than for the mean-field theory. This feature of the relaxation rate causes the intersection of the curves $\rho(t)$ and $\rho_{mf}(t)$ at $t = t_1$ [$t_1 \approx 0.016$ s, $\rho_{mf}(\infty) = \rho(\infty) = 0$ for $H_0 = 0$]. If $H_0 > 0$, then the conditions $\rho_{mf}(\infty) > \rho(\infty) > 0$ hold [$\rho_{mf}(\infty) \approx 0.199$ and $\rho(\infty) \approx 0.181$ for $H_0 = 500$ Oe], and these curves intersect twice at $t = t_1$ and $t = t_2$ [$t_1 \approx 0.915$ s and $t_2 \approx 4.750$ s for $H_0 = 500$ Oe]. By increasing H_0 the time interval (t_1, t_2) is decreased, and $\rho_{mf}(t) > \rho(t)$ $(t > 0)$ for sufficiently large H_0. At $H_0 < 0$ the correlations of the nanoparticle magnetic moments lead to the conditions $\rho_{mf}(\infty) < \rho(\infty) < 0$ [$\rho_{mf}(\infty) \approx -0.199$ and $\rho(\infty) \approx -0.181$ for $H_0 = -500$ Oe], and curves $\rho(t)$ and $\rho_{mf}(t)$ intersect only once at $t = t_1$ [$t_1 \approx 4.13 \times 10^{-4}$ s for $H_0 = -500$ Oe].

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