Magnetization Switching in Single-Domain Ferromagnets

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Abstract

A model for single-domain uniaxial ferromagnetic particles with high anisotropy, the Ising model, is studied. Recent experimental observations have been made of the probability that the magnetization has not switched, $P_{\text{NOT}}$. Here an approach is described in which it is emphasized that a ferromagnetic particle in an unfavorable field is in fact a metastable system, and the switching is accomplished through the nucleation and subsequent growth of localized droplets. Nucleation theory is applied to finite systems to determine the coercivity as a function of particle size and to calculate $P_{\text{NOT}}$. Both of these quantities are modified by different boundary conditions, magnetostatic interactions, and quenched disorder.

Key words: Magnetization - reversal, Switching Fields, Metastable Phases, Ferromagnets - nanoscale

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Highly anisotropic single-domain ferromagnetic particles are candidates for applications in ultra-high density magnetic recording. Since such particles do not have internal domain walls in equilibrium, wall-motion descriptions of the switching dynamics are inadequate. Recent experimental observations, including $\mu$-SQUID [1] and Magnetic Force Microscopy [2], allow measurements on individual magnetic particles of the probability that the magnetization has not switched at time $t$, $P_{\text{NOT}}(t)$. Such experiments provide tests for theoretical predictions of the reversal mechanism for single-domain nanoscale magnetic particles. The theoretical approach emphasized here is that a ferromagnetic particle in an unfavorable field is in fact a metastable system [3], and that the switching is accomplished through the nucleation and subsequent growth of localized droplets.

To simulate the switching dynamics a kinetic Ising model with Hamiltonian $H = -J \sum_{\langle i,j \rangle} s_i s_j - HL^d m + DL^d m^2$, is used, where $s_i = \pm 1$ is the $z$-component of the local magnetization, $J > 0$ for these ferromagnetic systems, $H$ is the applied magnetic field times the single-spin magnetic moment, $D$ is a mean-field approximation for the demagnetizing field [4], and a $L \times L$ square lattice ($d=2$) with only nearest-neighbor exchange interactions is used. The dimensionless magnetization is $m = L^{-d} \sum_i s_i$, where the sum runs over all $L^d$ spins. The dynamic is to choose a spin at random, and then flip it with the Metropolis or with the Glauber spin-flip probability [3]. Time is measured in Monte Carlo steps per spin, MCSS. The simulation starts with all spins +1 and a negative field $H$, then $P_{\text{NOT}}(t)$ is measured. Fixing a waiting time, $t_w$, the switching field, $H_{\text{sw}}$, defined as the field at which $P_{\text{NOT}}(t_w) = \frac{1}{2}$, is also measured.

The simulations are performed at temperatures well below the critical temperature for the pure system, $T_c \approx 2.269 J$. There are at least four relevant length scales in the problem [3]: the lattice spacing (which is set equal to unity); the system size $L$; the radius of a critical droplet, $R_c$; and the typical distance between droplets that are critical or supercritical, $R_o$. This paper concentrates on three regimes [3,5]: the coexistence (CE) regime where $L < R_c$; the single-droplet (SD) regime where $R_c < L < R_o$; and the multi-droplet (MD) regime where $R_o < L$. Figure 1 presents $H_{\text{sw}}$ as a function of $L$ for various situations. The curves with bond dilution were simulated with the Glauber dynamic, while the Metropolis dynamic was used in the other curves. On this scale results interchanging the dynamics should be indistinguishable. The maxima in $H_{\text{sw}}$ are near the cross-over between the CE and SD regimes. The shapes of these curves for periodic [5] and other [6] boundary conditions have been predicted by detailed droplet-theory calculations. Results for quenched disorder have been presented recently [7].

In the SD regime [5] $P_{\text{NOT}}(t) = \exp(-t/\tau)$, where $\tau$ is the average lifetime
of the metastable state. However, in the MD regime [5]

\[ P_{\text{NOT}}(t) \approx \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{t - \tau}{L - d/2 \Delta t} \right) \right], \tag{1} \]

where for \( D=0 \) and periodic boundary conditions \( \Delta t \) has been obtained explicitly [5]. Figure 2 shows \( P_{\text{NOT}}(t) \) in the MD regime. The shape of \( P_{\text{NOT}}(t) \) is not changed for finite \( D \) or for randomness in the field.

In summary, magnetization switching in a finite system is complicated, even for the simplest highly anisotropic ferromagnetic model. There are always at least four length scales in the problem, and the switching mechanism is different in regimes with different relationships between these length scales. Even with no demagnetizing fields highly anisotropic single-domain magnetic particles exhibit a maximum in the switching field as a function of system size. The form for \( P_{\text{NOT}} \) is different in different regimes: in the SD regime it is an exponential while in the MD regime it is well approximated by an error function.

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Figure Captions

Fig. 1. The switching field with $D=0$, $t_w=30000$ MCSS, and temperature $T=1.3J$. Solid lines with $\times$ are for periodic boundary conditions and random bond dilution. Other data are for a circular system with free boundary conditions ($\circ$), and for a square system with periodic boundary conditions in one direction and free boundary conditions in the other direction ($\Box$).

Fig. 2. The probability of not switching, $P_{\text{NOT}}(t)$, in the multi-droplet (MD) regime for periodic boundary conditions; $L=100$, $T=0.8T_c\approx 1.815J$, using Glauber dynamics. The curves are from 1000 escapes from the metastable state. Curve (a) for $H=-0.34725J$ and $D=0$; (b) for $H=-0.34725J$ and $D=0.05J$, and (c) for $D=0$ and a uniformly distributed random field centered at $H=-0.34725J$ with a width of 0.34725J. This figure should be compared with Fig. 3c of [5], which is for the Metropolis dynamic, but has the same values for $L$, $T$, and $H$. 