MAGNETIC ANISOTROPY OF THIN ELONGATED FERROMAGNETIC NANO-ISLANDS

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1. Introduction and Motivation

⇒ Disordered and frustrated magnetic states like those studied in artificial spin ices [1] have deserved a great deal of efforts, mainly by virtue of their competing ground states, magnetic monopole and string-like excitations [2, 3, 4], and the difficulty to achieve thermal equilibrium.

⇒ Such systems are typically composed from elongated thin ferromagnetic ellipsoidal nano-islands grown or etched lithographically to a small height L_z on a substrate, whose geometric demagnetization effects lead to a strong magnetic anisotropy along the major diameter. This justify the general assumption that each island effectively behaves like a monodomain (Ising-like anisotropy), eventually yielding ice-rules, like "2-in/ 2-out" in square arrangements. However, such ice-rules are *energetic preferences*, not absolute statements about the allowed states.

⇒ Our intention here is investigate how fluctuations energetics take place away from this Ising anisotropic framework, trying to capture what is happening in the transition between these states. For that we focus on an individual ellipsoidal island from the spin ice system.

2. The island model and its energetics

- Consider a thin elliptical particle with dimensions $L_x \times L_y \times L_z$, partitioned into cells of sizes $a \times a \times L_z$ on a square grid with a saturation magnetization, M_s, within each cell. [Typically, $L_x \sim 2-4\times 10^2$ nm, $L_y \sim 60-80$ nm, and height $L_z \sim 15-25$ nm]. A given cell has a magnetic moment given by $\vec{m}_i = M_s a^2 L_z \hat{m}_i = \mu_{\rm cell}\,\hat{m}_i$ pointing along $\hat{m}_i$.
- Internal energy of the island is given by evaluating exchange and dipole-dipole terms. Using the approach of Ref.[5], based upon Green functions, one obtains ($\vec{h}_{M,i} = \vec{H}_M/M_s$ is the demagnetization field):

$$\mathcal{H}_{\rm int} = -J\left\{\sum_{(i,j)} \hat{m}_i\cdot\hat{m}_j + \left(\frac{a}{\lambda_{\rm ex}}\right)^2 \sum_i \left[\kappa(\hat{m}_i\cdot\hat{u})^2 + \frac{1}{2}\vec{h}_{M,i}\cdot\hat{m}_i\right]\right\}. \quad (1)$$

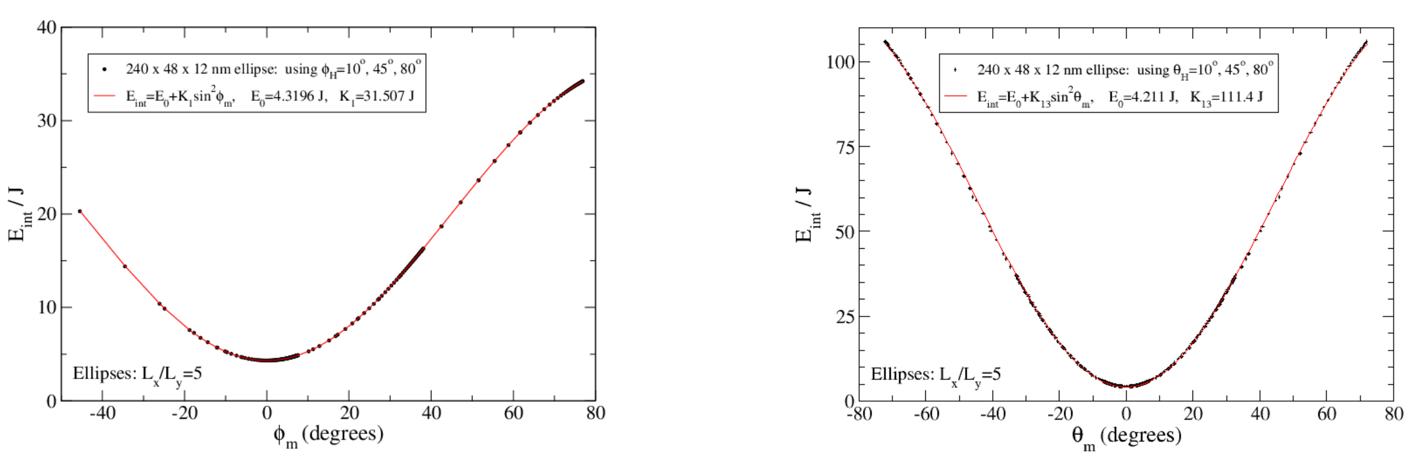
$\lambda_{\rm ex} = \sqrt{2A/\mu_0 M_S^2}$ ⟶ ferromagnetic exchange length;

$\kappa = K/\mu_0\, M_s^2$ ⟶ scaled dimensionless uniaxial anisotropy along $\hat{u}$.

- Permalloy parameters: $M_s \approx 860$ kA/m, $A \approx 13$ pJ/m, $K \approx 100$ J/m^3, giving $\lambda_{\rm ex} \approx 5.3$ nm and $\kappa \approx 1.1\times 10^{-4}$.
⟹Once κ is very small ⟹ intrinsic uniaxial anisotropy energy << other energies of the system.

- Most simulations: $a = 2.0$ nm ($a = 0.5$ nm for the smallest high aspect ratio particles).
⟹ a sufficiently less than $\lambda_{\rm ex}$ ⟹ reliable description of the internal magnetic structure.
- Local spin relaxation algorithm [6] ⟹ moves system towards the nearest local equilibrium, by pointing each $\vec{m}_i$ along its local effective magnetic field $\vec{B}_i$, as produced by the whole island.

3. Results and Discussion



Island internal energy calculated from Hamiltonian (1) and the best fittings (red curves). Island size and other relevant parameters are also shown.

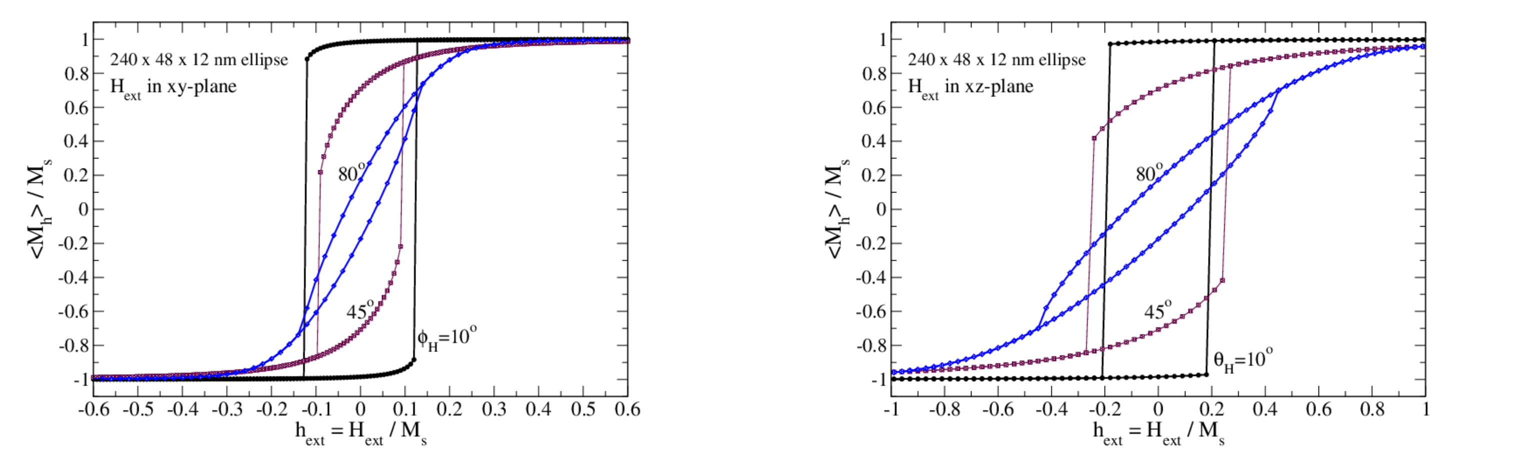
- Island effective internal energy, $E_{\rm int}$, appears to be very well fitted by (see Figure above):

$$E_{\rm int} = E_0 + K_1[1-(\hat{\mu}\cdot\hat{x})]^2 + K_3(\hat{\mu}\cdot\hat{z})^2 \quad (2)$$

K_1, K_3 ⟹ effective anisotropic parameters along x (easy-axis) and z (hard-axis), respectively ⟹ they account for the cost of tilting the island net magnetization from its ground-state; $K_{13} \equiv (K_1+K_3)$ is the net stiffness.

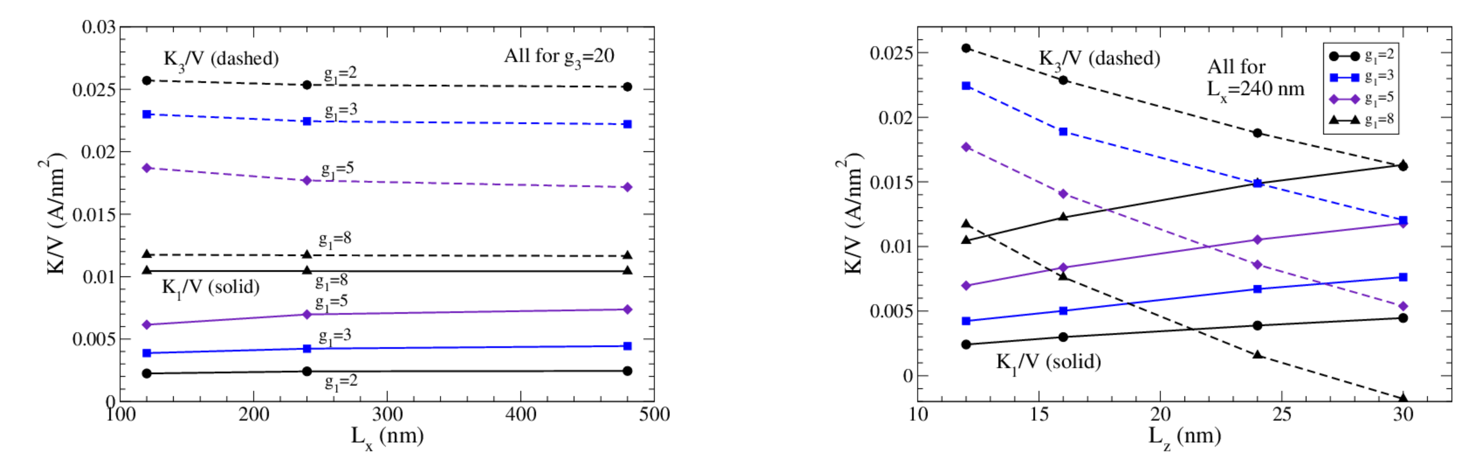
- In-plane potential: $E_{\rm int} = E_0 + K_1\sin^2\phi_m$ ⟶ tilt of ϕ_m to easy-axis x.
- Out-of-plane potential: $E_{\rm int} = E_0 + K_{13}\sin^2\theta_m$ ⟶ tilt of θ_m to hard-axis, z (stronger potential; see also hysteresis loops below).
- Contrary to Ising anisotropy, potentials above are smooth ⟹ smooth transitions between island allowed states.
⟹ More realistic simulations of artificial spin ice dynamics!

- Hysteresis loops: Another way to account for K_1, K_3, and related anisotropies.



Typical hysteresis loops for an ellipsoidal island with an applied field along xy (in-plane) at different angles, ϕ_H; similar results for a field applied along xz (out-of-plane), at distinct angles θ_H (on the right).

- How anisotropic constants, K_1 and K_3, vary with island dimensions



[Left] Aspect ratio, $g_3 = L_x/L_z = 20$ is fixed and K_1 increases while K_3 decreases with $g_1 = L_x/L_y$; they equal each other at high g_1 (needle-like limit). [Right] Their behavior with island volume (fixed $L_x = 240$ nm): Thicker island ⟶ weaker out-of-plane anisotropy, K_3; in contrast, K_1 increases due to thicker lateral edges effects.

- Lower aspect ratio islands, $g_1 < 2$ ⟶ smaller K_1;
As $g_1 \to 1$ ⟶ disk-shaped magnets ⟶ K_1 vanishes, as expected.

4. Conclusions and Prospects

Magnetization properties of typical ellipsoidal islands composing artificial spin ice arrangements have been studied, and we have realized that:

- The effective island internal energy may be described by smooth potentials like $E_{\rm int} = E_0 + K\sin^2\alpha$.
⟹This may be used for a more realistic investigation of transitions and dynamics observed in artificial spin ices systems[7].
- Anisotropic parameters, in-plane K_1 and out-of-plane K_3, may be tunned by choosing island dimensions. ⟹ Control of island geometric anisotropies⟶ Possible on demand transitions between allowed states.
⟹ Towards new protocols to achieve ground-state and to investigate elementary excitations properties in artificial spin ice systems .

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