Simulation of Hysteresis
In
Permalloy Films

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Looking for the \textit{classical} behavior of small magnetic systems under the influence of \textit{finite temperature}.

Important for understanding of: \textbf{Macroscopic Quantum Tunneling} Magnetic \textbf{Bit Stability}, and related topics.

Simulating Magnetic Systems in search for understanding of \textbf{Time} and \textbf{Temperature} Dependence of such systems.
Temperature included in simulations via Metropolis Monte Carlo techniques.

Can include finite temperature effects with the benefit that many different meta-stable states are available.

Potentially longer physical time scales can be simulated.

Lose information about physical time scale of simulation, although some dynamics can be realized.
The problem is to model the behavior of this permalloy bar to find such properties as the Long Axis Magnetization Remanence (M/Ms), and the Coercive Field (Hc).

We chose this problem to study to compare results to other work, as well as to study the Temperature dependence of the system.
Simulation Specifications

Monte Carlo Symmetric Transition Probability:

\[ W(A \rightarrow B) = \frac{P}{(1+P)} \]

where \( P = \exp\left[-\frac{E_A - E_B}{k_B T}\right] \)

and \( E = \sum_i m_i \cdot H_{\text{Tot}} \)

\( H_{\text{Tot}} \) includes the ANISOTROPY term which wants to align the moment along the easy axis, the EXCHANGE term which wants to align neighboring moments, the DIPOLE term which drives the demagnetization of the system, and the APPLIED FIELD term which wants to align the moments with the field.

The Monte Carlo Procedure will take the system into a meta-stable energy minimum of these competing terms.
Low Temperature Remanent States

Relaxation Simulation Results

Both Sets of Results show **end domains**, lowering the dipole energy at the ends of the bar, along with a large **central region of uniform magnetization**, minimizing exchange and anisotropic energies.
Monte Carlo seeks out many meta-stable energy states, it is important to follow the evolution of the system as a function of energy.

The System is driven primarily by dipole interactions between grains in the system; no external magnetic field is applied.
End domains begin to form, lowering energy due to magnetic pole density at the ends of the bar. Ends take different amounts of time to form domains due to the randomness of the Monte Carlo method.
Relaxation Simulation Results

End Domains Propagate into the center of the bar, setting up this herringbone structure.

Then a sudden irreversible step occurs, reversing a region of magnetization setting up a domain in the center of the bar.
Final Remanent State, along with blow up of domain wall structure. The energy of this state remains higher than that of the Landau Closure Pattern.
Hysteresis Results

Room Temperature Results:

Low Remanence $M/M_s = 0.5$
Coercive Field $H_c = 66$ Oe

Hysteresis shows jumps in the magnetization, similar to Barkhausen jumps.

Low Temperature Results: High Remanence $M/M_s = 0.85$, Coercive Field $H_c = 100$ Oe
**Hysteresis Results**

Field A: 80 Oe

*End Domains* have formed, magnetic field holds magnetization straight in the center. *Ends are aligned parallel* to each other.

Field B: 0 Oe

Remanent State shows the same structure as when relaxed in Zero applied field.
Hysteresis Results

Step 1: -64 Oe to -68 Oe

Magnetic Vortices move under the presence of an applied field toward the sides of the bar. This process reverses large regions of magnetization, accounting for the steps seen in the hysteresis loop.
**Hysteresis Results**

**Step 2: -166 Oe to -170 Oe**

Final Domain along left edge reverses under the influence of the field. **Sweeps out in stripe-like** fashion. Field continues to increase until the bar is essentially saturated in the opposite direction.
After Saturation is reached, the field is reversed. This image shows the configuration along the return path. Again end domains begin to form, and the field is strong enough to hold the magnetization in the center. Note that the end domains align themselves anti-parallel. This is the reason for the asymmetry in the Hysteresis Loop.

Compare to Field A image on Page 12.
With the ends anti-parallel, the reversal process shows less vorticity, setting up a shifted Landau-like pattern. The reversal process is shown to involve the **sweeping out of rows** along the edges of the bar.
Hysteresis Results

As the field is continued to increase, more rows are reversed by this sweeping process. The reversal of these domains leads to the steps seen in the Hysteresis Loop.

Step 4: 192 Oe to 196 Oe
**Hysteresis Results**

We follow the dynamics of the evolution of the magnetization in the presence of an applied field. This series of steps corresponds to the **final jump** in the Hysteresis Loop.

Field D: Evolution at 300 Oe

We see how the stripes are removed, through the **propagation of magnetic waves starting at the vortices** until they collide with one another. This set of images correspond to 1000 Monte Carlo Steps.
Parameter Games

Increased Anisotropy

$E_B$ clearly increases as $K$ increases, but $E_B$ increases as volume increases, $E_B$ decreases as $H$ is reversed, and $E_B$ decreases at $M$ increases.
Conclusions

Energy Barriers for Magnetization Reversal are lowered by:

Magnetic Fields, Large Magnetic Moments, and Small Sizes.

Thermal Fluctuations become important to study as the barriers to reversal shrink.

Future Work

Quantify Monte Carlo Time Step with Monte Carlo Clock.

Continue to Study Reversal Mechanisms in small magnetic systems