Vortices in ferromagnetic elements with perpendicular anisotropy

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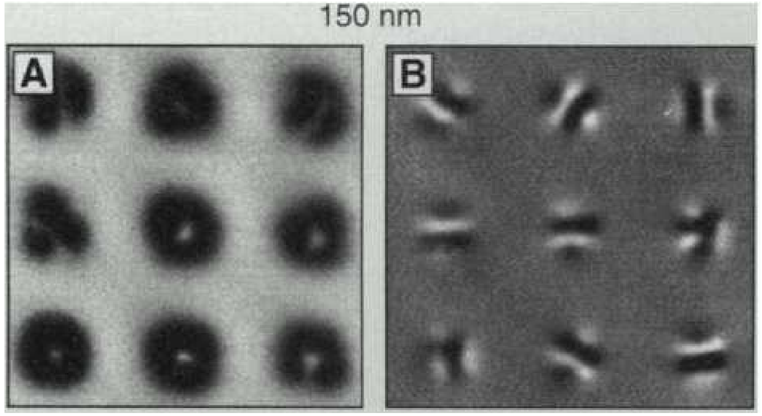
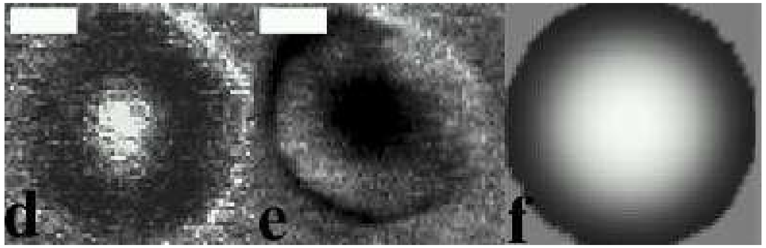
Magnetic elements with perpendicular anisotropy

Cobalt (hcp) dots. Thickness=150nm ($52\ell_{\rm ex}$), Diameter=500nm ($175\ell_{\rm ex}$).



[Hehn et al, Nature, 1996]

Nickel (tetragonally distorted) dots. Thickness=100nm ($12\ell_{\rm ex}$), Diameter=300nm ($36\ell_{\rm ex}$).



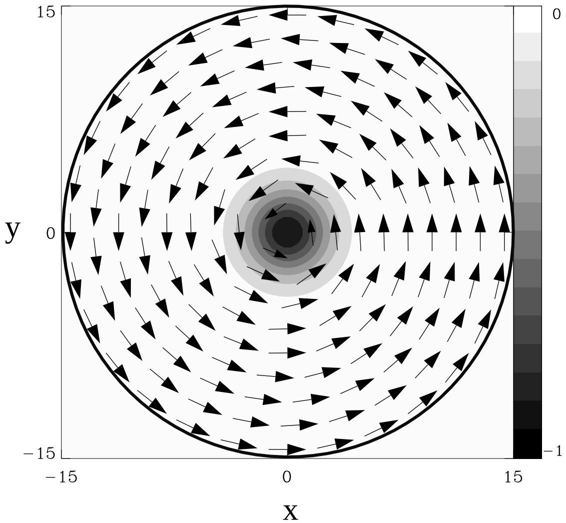
[Skidmore et al, Phys. Rev. B, 2004]

The magnetocrystalline anisotropy (with strength K) is perpendicular (along the axis of the dot).

The quality factor $Q \equiv K/(2\pi M_s^2) = 0.4$ in both cases.
Exchange length: $\ell_{\rm ex}({\rm Co}) \approx 3{\rm nm}$, $\ell_{\rm ex}({\rm Ni}) \approx 8{\rm nm}$.

[J.K. Ha, R. Hertel, and J. Kirschner, Europhys. Lett. (2003)]

A vortex (thin discs)



Disc thickness $t = 3\ell_{\rm ex}$, diameter $D = 30\ell_{\rm ex}$, and quality factor $Q = 0.4$. The arrows show the projection of the magnetization on the plane while the third component of the magnetization is coded in grey-scale.

Vortex profile

For very thin discs the magnetostatic energy becomes $E_m \to t/2 \int M_z^2\, dxdy$. Combine this with the magnetocrystalline easy-axis anisotropy:

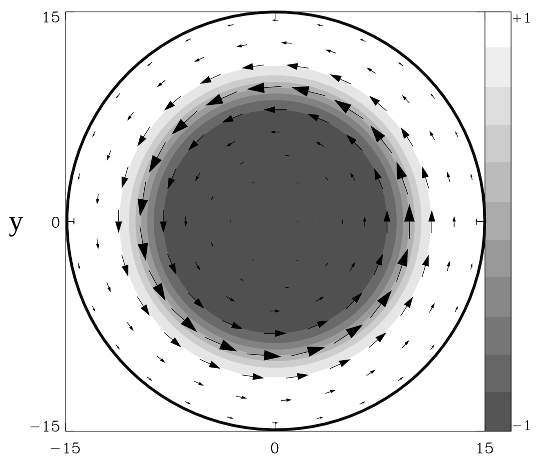
$$E_a + E_m = \frac{1-Q}{2}\, t \int M_z^2\, dxdy,$$

i.e., effective easy-plane anisotropy strength: $1 - Q$. Thus, vortex core size

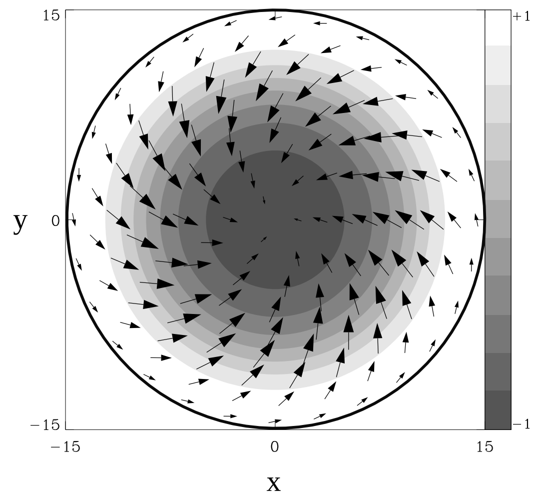
$$R_{\rm core} \sim \ell_{\rm ex}/\sqrt{1-Q}.$$

Bidomain states

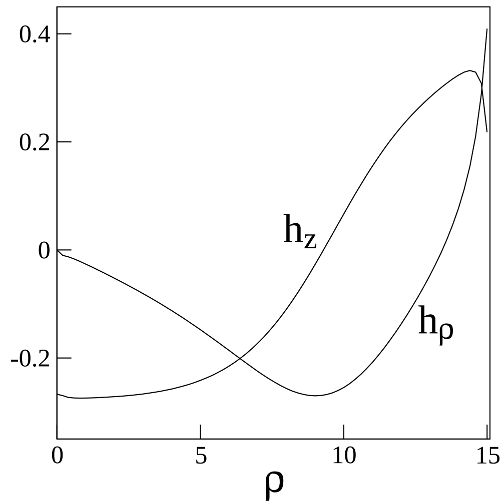
Middle plane of dot



Top surface of dot



Disc thickness $t = 11\ell_{\text{ex}}$ (diameter $D = 30\ell_{\text{ex}}$): a bidomain state is akin to a magnetic bubble. We have $\boldsymbol{M} = -M_s\hat{\boldsymbol{z}}$ at the disc center, $\boldsymbol{M} \approx M_s\hat{\boldsymbol{z}}$ at the periphery.

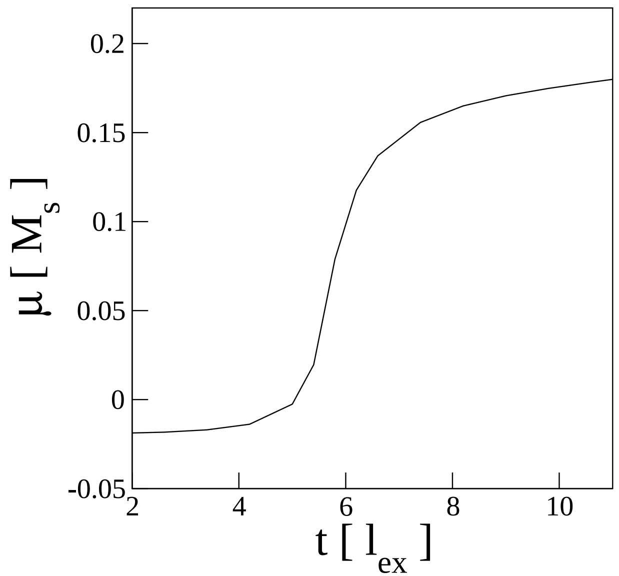


The magnetostatic field just above the top particle surface. It is axially symmetric.

From a vortex to a bubble

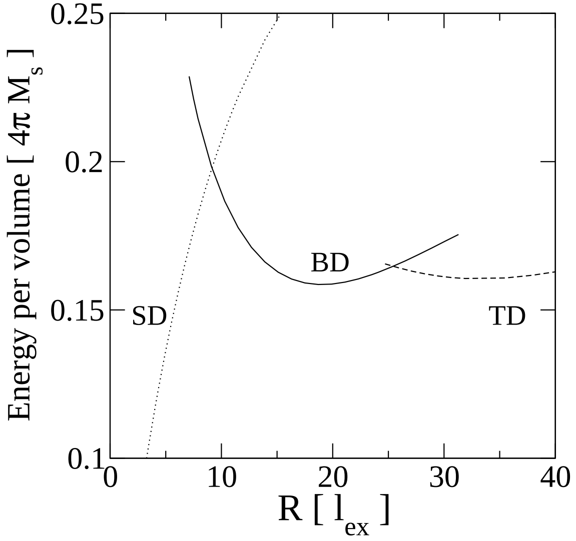
The perpendicular magnetization per unit volume:

$$\mu \equiv \frac{1}{V} \int m_z \, dV$$



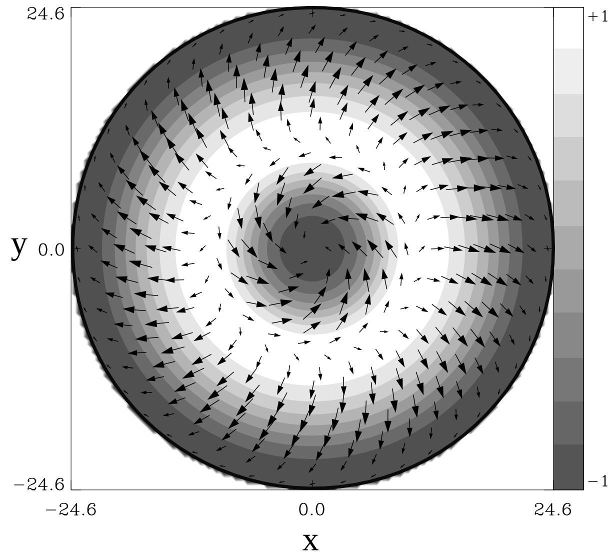
undergoes a transition from $\mu \approx 0$ (vortex) to a finite value (bidomain state), as a function of disc thickness t.

Bidomain and Three-ring states



Energy per volume versus disc radius, for Single-domain (SD), Bidomain (BD) and Three-ring (TD) states.

Top particle surface for a three-ring state.

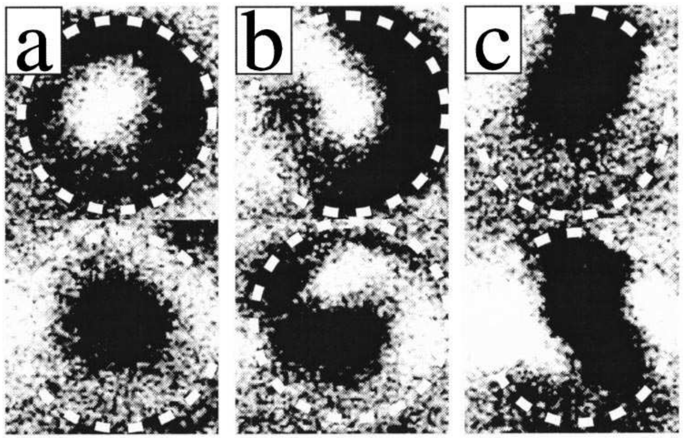


J.K. Ha, R. Hertel, and J. Kirschner, Europhys. Lett. (2003)

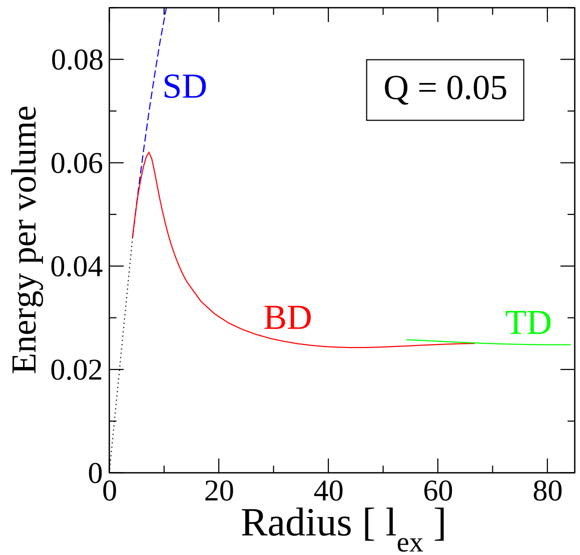
M. Buda et al, IEEE Trans. Mag. (2001).

Very weak anisotropy

Simulate thick ($t = 200\text{nm} = 33\ell_{\rm ex}$) NiFe discs with a very weak deposition induced perpendicular anisotropy.



[P. Eames, E.D. Dahlberg, JAP, (2002)]



Energy versus radius for disc particles (choose $Q = 0.05$).

The BD line:

corresponds to a bidomain for large radii ($R > 25\ell_{\rm ex}$),

resembles a vortex with a large core and small tail for $10\ell_{\rm ex} < R < 20\ell_{\rm ex}$,

approaches a single-domain state for $R < 10\ell_{\rm ex}$.

Conclusions

Magnetic states in perpendicular anisotropy elements can have a nontrivial and interesting magnetization structure.

Magnetic vortices, bubbles, and intermediate states can be stable.

These can be characterized by a topological charge, which turns out to be $\mathcal{N} \approx 1$ for the bidomain and $\mathcal{N} \approx 0$ for the three-ring state (for a vortex: $\mathcal{N} = 1/2$).

$\mathcal{N}$ is linked to vortex/bubble dynamics. We thus expect different dynamical behaviour for the two states. Thus, the scope for dynamics in magnetic elements is significantly expanded (compared to vortices in soft materials).