Rotating vortex dipoles in ferromagnets

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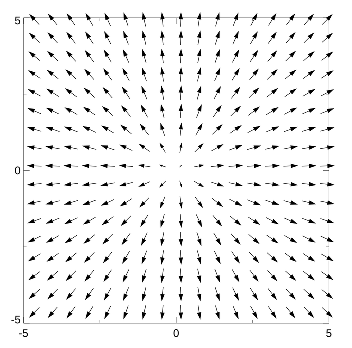
Nano
Magneto
Dynamics

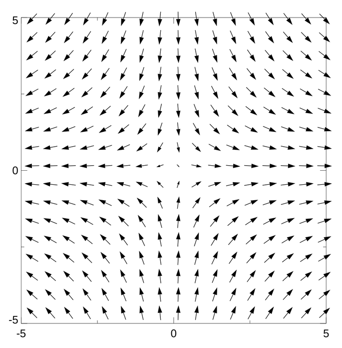
Abstract

Vortex-antivortex pairs are localized excitations and have been found to be spontaneously created in magnetic elements. In the case that the vortex and the antivortex have opposite polarities the pair has a nonzero topological charge, and it behaves as a rotating vortex dipole. We find theoretically, and confirm numerically, the form of the energy as a function of the angular momentum of the system and the associated rotation frequencies. We discuss the process of annihilation of the pair which changes the topological charge of the system by unity while its energy is monotonically decreasing. Such a change in the topological charge affects profoundly the dynamics in the magnetic system. We finally discuss the connection of our results with Bloch Points (BP) and the implications for BP dynamics.

1 Vortex and Antivortex

Vortex ($S=1$), Antivortex ($S=-1$)





This is a magnetisation $[\boldsymbol{m}=(m_1,m_2,m_3)]$ configuration of the form:

$$m_3=\lambda\,\cos\Theta(\rho),\quad m_1+i\,m_2=\sin\Theta(\rho)\,e^{iS(\phi-\phi_0)}.$$

(ρ,ϕ): polar coordinates
$S=1,2,\dots$ is the winding number
$\lambda=\pm 1$ is the vortex polarity
ϕ_0: constant, called the vortex orientation.

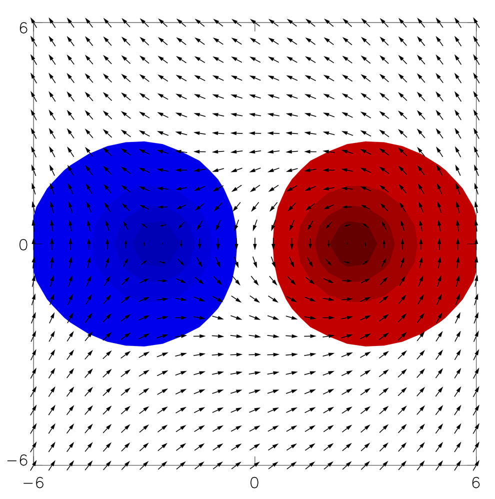
Topological charge

Definition:

$$\mathcal{N}\equiv\frac{1}{4\pi}\int n\,d^2x,\quad n\equiv\frac{1}{2}\epsilon_{\mu\nu}\,(\partial_\nu\boldsymbol{m}\times\partial_\mu\boldsymbol{m})\cdot\boldsymbol{m}.$$

For vortices: $\mathcal{N}=-\frac{1}{2}\,S\,\lambda$.

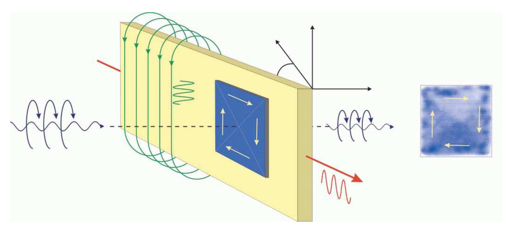
A vortex-antivortex pair



2 Experiments

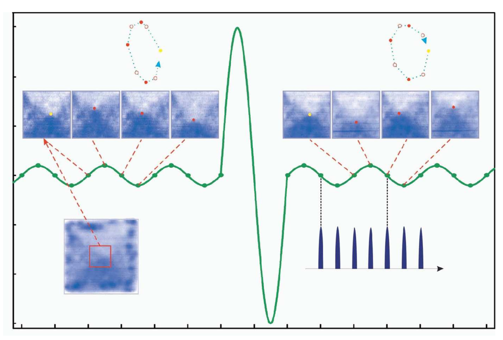
Sample

Square NiFe elements: $1.5\mu\mathrm{m}\times 1.5\mu\mathrm{m}\times 50\mathrm{nm}$ [1].
Circular Py elements: radius $R=500\mathrm{nm}$ [2].



Process [1]

Alternating magnetic field (250 MHz, 0.1 mT).
Add a "burst" of 1.5 mT, for one period.
Check (by XMCD) that you obtained vortex core switching!

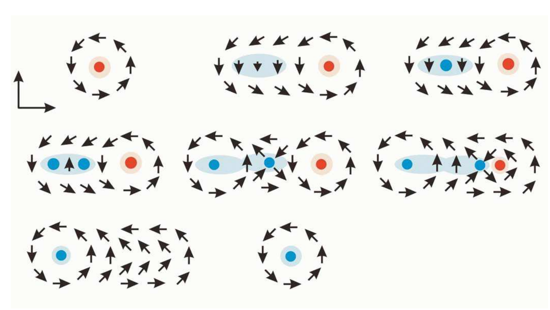


Process [2]

a.c. electrical current.
Vortex is initially set in motion.
Check (by MFM) that you obtained vortex core switching!

Mechanism

Dynamics of vortex-antivortex pairs.



3 Model

Energy (exchange and easy-plane anisotropy):

$$E=E_e+E_a,$$

$$E_e=\frac{1}{2}\int(\boldsymbol{\nabla}\boldsymbol{m})^2\,d^2x,\quad E_a=\frac{Q}{2}\int(m_3)^2\,d^2x.$$

Dynamics given by the Landau-Lifshitz equation (LLE):

$$\frac{\partial\boldsymbol{m}}{\partial t}=\boldsymbol{m}\times\boldsymbol{f},\quad \boldsymbol{f}\equiv\Delta\boldsymbol{m}-Q\,m_3\,\hat{\boldsymbol{e}}_3.$$

4 Dynamics of the vortex dipole

The angular momentum within LLE:

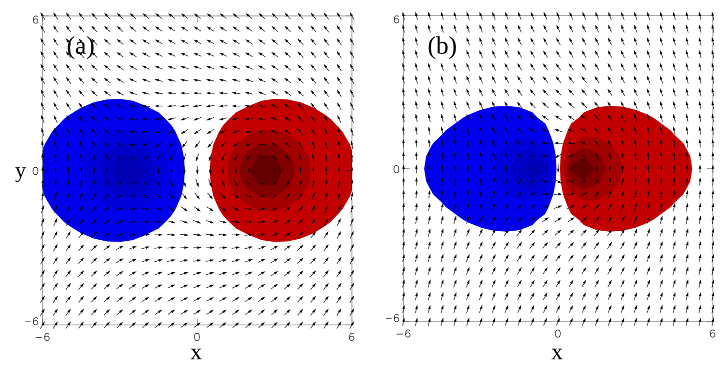
$$\ell=\frac{1}{2}\int\rho^2\,n\,dxdy,$$

and measures the size of the dipole.
Let d the distance between vortices, then $\ell\sim d^2$.

Since n is positive everywhere we have $\ell\neq 0$. Thus the dipole should be rotating.

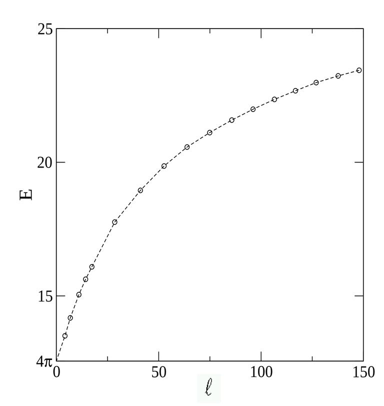
This is confirmed by
(i) a numerical simulation of the LL,
(ii) the result of the Thiele equations for this system.

Vortex dipoles rotating at a constant angular frequency ω.



Left figure: distance between vortices $d=2.7$ and $\omega=0.06$.
Right figure: distance between vortices $d=1.85$ and $\omega=0.17$.
(ω is in units $4\pi\gamma M_s$, Colours code the vortex polarity).

Energy and Angular momentum



Numerically calculated energy as a function of the angular momentum for vortex dipoles in steady state rotational motion.

Rotation frequency

We have

$$\omega=\frac{dE}{d\omega}$$

and is thus given by the slope of the $E(\ell)$ curve.

Now, use Derrick's scaling argument to find

$$E_a=\omega\,\ell.$$

For well-separated vortices:

$$\omega=\frac{\pi}{\ell}=\frac{2}{d^2}.$$

For a very small vortex dipole ($d\to 0$), one can use the exchange model solution

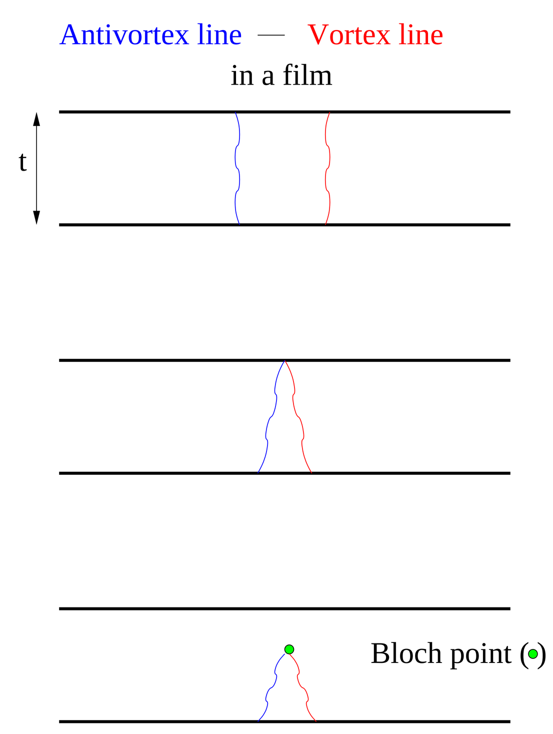
$$\Omega\equiv\frac{m_1+i\,m_2}{1+m_3}=\frac{\bar{\zeta}+a}{\bar{\zeta}-a},\quad \zeta\equiv x+i\,y,$$

and find

$$E_a=\frac{Q}{2}\,\ell\Rightarrow\omega=1/2,\qquad\text{for}\ \ d\to 0.$$

5 Bloch Points

- Suppose a film of finite thickness t where a vortex-antivortex line has been created [3]. (see next figure.)
- The vortex lines move towards one another in order to minimize energy, and they are annihilated first, say, on the upper film part.
- A Bloch Point has been created!
  ⇒ The dynamics of a Bloch Point should be related to vortex-antivortex dynamics.



References

[1] B. V. Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fähnle, H. Brückl, K. Rott, G. Reiss, I. Neudecker, D. Weiss, C. H. Back, and G. Schütz, Nature **444**, 461 (2006).

[2] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nature Materials **6**, 269 (2007).

[3] R. Hertel, S. Gliga, M. Fähnle, and C. M. Schneider, cond-mat/0611668.

[4] S. Komineas, arXiv:0705.2977v1 (2007).