Magnetic Vortex Stability, Reversal and Dynamics in Restricted Geometry

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San Sebastian view from Igeldo mountain. UPV/EHU is 1 km to the right.
Spiral galaxy in the universe

Atmospheric vortex

Vortex in nature

Magnetic vortex (skyrmion)

Vortex in the ocean
Outline of the talk

• Magnetic topological solitons (vortex & skyrmion)
• Classification of the soliton dynamic excitations
• Vortex gyrotrropic dynamics
• Vortex core polarization reversal
• Spin waves in the vortex state (briefly)
• Vortex modes in thick dots: vortex mass
• Summary
Topological magnetic solitons


Skyrmion number (topological charge)

\[ S = \frac{1}{4\pi} \int dxdy m \cdot (\partial_x m \times \partial_y m) \]

Vortex \( S = 1/2 \)
Skyrmion \( S = 1 \)
Skyrmions in ferroelectrics/ferromagnets

S. Seki et al., Science 336, 198 (2012)

(a) Lorentz TEM imaging of thin film single crystal Cu2OSeO3. Lateral magnetization distribution (Cu+2) on 10 nm scale
(b) Single magnetic skyrmion
(c) 2D magnetic skyrmion crystal
Patterned films: 2D regular arrays of magnetic dots

Dot radius $R \sim 100-500$ nm
Dot thickness $L \sim 10-50$ nm

Small flat magnetic particle = magnetic dot
Magnetic vortices in soft magnetic dots

Magnetic Vortex Integers:

Vorticity (topological charge): $q = \pm 1$
degree of mapping of $XY$ plane to the magnetization unit sphere

Chirality (CCW, CW): $C = \pm 1$

Polarization: $p = \pm 1$

Skyrmion number: $S = qp/2$

M-ground state depends on:

- Dot geometry and shape: $L$ and $R$
- Material: $A$, $K$ and $M_s$
Magnetic Vortex Integels

Vorticity (topolog. charge):

\[ q = \pm 1 \]

Chirality (CCW, CW):

\[ C = \pm 1 \]

Polarization:

\[ p = \pm 1 \]

Single domain state

Phase diagram for magnetically-soft circular nanodots:
Magnetic vortices in soft magnetic particles (dots)

MFM image of magnetic vortex

Guslienko et al., PRB 2002

Experimental observation of magnetic vortices

Magnetization reversal via vortex movement

1) Lorentz Microscopy on 200 nm Co disk
2) MFM on 1 μm Permalloy disk
3) SP-STM on 200 nm wide and 500 nm long Fe island

R ~ 100-500 nm
L ~ 10-50 nm

Magnetization, M/Ms
Field, mT

H

Vortex and antivortex structures

Vortex structure
- Curling structure of magnetization (M)
- Perpendicular component ($M_z$) at the core

Antivortex structure
- Cross-like lines of magnetization (M)
- Perpendicular component ($M_z$) at the core

Topological charge $q$: +1 (V) or -1 (AV)

Core polarization $p$: up/down
Magnetization dynamics in restricted geometry

Main features of spin excitations in restricted geometry:

a) the low-lying part of excitation spectra is quantized
b) magnetostatic interaction plays important role

Examples to focus on:

• Spin modes in Vortex (topol. soliton) state

Motivation:

1) Understanding of fundamentals of vortex dynamics in magnetic dots
2) Explanation of numerous experiments
3) Applications to magnetic recording and spin-torque devices
Spin Excitations of Magnetic Vortex: two kinds of eigenmodes

Low-frequency vortex eigenmodes, sub-GHz range
- Translation (gyrotropic) modes

High-frequency spin-waves, GHz range
- Radial modes
- Azimuthal modes

** Magnetostatic interactions dominate in sub-micron and micron-size dots **
Vortex equation of motion: 2D topological solitons

Traveling wave ansatz (rigid motion)

\[ M(r, t) = M(r - X(t)) \]

\[ -\frac{dM}{dt} = \frac{\alpha_G}{M_S} \left[ M \times \frac{dM}{dt} \right] - \gamma (M \times H_{\text{eff}}) \]

\[ G \times \dot{X} + \hat{D} \dot{X} - \frac{\partial W(X)}{\partial X} = 0 \]

Vortex Dynamics: Core Trajectory

Magnetic vortex in a potential well

Core position \( X(t) \)

\[ M(r, t) = M(r, X(t)) \]

Thiele’s equation

\[-G \times \frac{dX}{dt} - \hat{D} \frac{dX}{dt} + \frac{\partial W(X)}{\partial X} = 0\]

G : gyrovector \( G = -pq|G|\hat{z} \)

Core polarization \( p=+1 \)

Thiele’s equation is essentially more general than Thiele assumed. It’s valid not only for steady motion \( V=\text{const} \).
Vortex Dynamics: Frequency and Core Trajectory

Vortex moves along circular trajectory with angular frequency $\sim 100$ MHz

Vortex core trajectory $X(t)$

Vorticity $q=1$

$X = (X, Y)$

For thin dots $L \ll R$

$\omega_0 \sim 100$-500 MHz

$\omega_0 = \frac{5}{9\pi} \frac{L}{R} \omega_M$

$\omega_M = \gamma 4\pi M_s \approx 30$ GHz

Guslienko et al., JAP 91, 8037, 2002; PRL 96, 067205 (2006)
Comparison with FMR and PEEM experiments

Narrow linewidth ~ 2-11 MHz!

Beyond rigid vortex model: Distorted moving vortex - first stage of the vortex core reversal

Excellent agreement of theory/exp. for thin dots


PEEM: Guslienko et al., PRL (2006)
Vortex-Core Reversal and Spin-Waves in Geometrically Confined Magnetic Elements:
Vortex Core Reversal

Fast reversal on 10 ps time scale (core “up” -> core “down”) involving 10 nm size magnetic non-uniformity
Vortex dynamics in cylindrical magnetic dot under oscillating field or SP current

How to excite vortex motion and get core reversal?
by mag. field or SP current

$\omega \approx \omega_0$ Gyrotropic frequency

Linearly polarized in-plane field

$$H_y = H_0 \sin(\omega t)$$

Circularly polarized field

$$\mathbf{H} = H_0 (\cos(\omega t), \sin(\omega t))$$

Ultrafast vortex core reversal $\sim 50 \text{ ps}$ in relatively small a.c. field 10-20 Oe

(Static core reversal in perp. field of 3-4 kOe)

R. Hertel et al., PRL 2007; K. Lee et al., PR B 2007; K. Guslienko et al., PRL 2008
Vortex core reversal: switching field & time

$\Omega = \omega / \omega_0$

Switching time

\[ t_s(H_0) = -(d\omega_0)^{-1} \ln \left(1 - \frac{H_0^C}{H_0} \right) \]

Minimum switching field

\[ H_0^C(\Omega = 1) = 3\gamma V_c / \gamma R \]

Excitation field

\[ H(t) = H_0 \exp(i\omega t) \]

Criterion of VC reversal is reaching a critical velocity

\[ v_c \approx \gamma M_s L_{ex} = \gamma (2A)^{1/2} \]

Guslienko, PRL’08 \hspace{1cm} Exp. confirmed by Vansteenkiste, PRL 2008
Vortex core reversal: critical velocity

Critical velocity is only determined by exchange

\[ v_c \approx \gamma M_s L_{ex} = \gamma \left( 2A \right)^{1/2} \]
Vortex core switching field vs. frequency
X-Ray imaging experiment

Figure 2 | Three-dimensional representation of the experimentally observed vortex core profile, generated from the marked area in the last frame of Fig. 1b. The differential intensity is proportional to the

Figure 3 | Magnetic field amplitudes $B_{0,\text{thr}}$ and average vortex velocities $v_{\text{thr}}$ just below the threshold for core switching, determined for different excitation frequencies $f$ near the gyroscopic resonance of three 500 nm x 500 nm x 50 nm permalloy samples. The critical field required


Minimum of switching field vs. frequency & critical velocity were detected
Spin-wave radiation process related to Vortex core reversal (linear field polarization)

Magnetic field change

Vortex-antivortex pair nucleation

Vortex-antivortex pair annihilation

Spin-wave radiation

Choi et al., PRL 2007

Scheme of the strong Spin Waves generation with wave vectors $k>10^5$ cm$^{-1}$ by vortex core p-reversal in magnetic nanoelement
Vortex core polarization switching: the main

Very fast (10 ps time scale!), occurs in small variable field $H$

VC switching is pure dynamic process - no overcoming an energy barrier

Mechanism - creation and annihilation of the Vortex-AntiVortex pairs ($V$ escape)

Criterion of the reversal: Critical velocity of the vortex core

Vortex core reversal in perpendicular field

Mag. resonance force microscopy:
Vortex frequency vs. perpendicular field.
NiMnSb, \( L = 44 \) nm, \( R = 130 \) and \( 520 \) nm

Frequency jumps correspond to Vortex core polarization reversal

\[
\omega_0 ( H ) = \omega_0 (0) \left[ 1 + p H / H_s \right]
\]

G. de Loubens et al. PRL, 2009
Vortex core dynamics and spin waves

SW are classified by number of nodes along radial \((n)\) and azimuthal \((m)\) direct.

Moving vortex core strongly interacts with some spin waves (azimuthal) and influences their frequencies (frequency splitting and vortex mass).
Spin Wave Modes in the Vortex ground state

\[ \mathbf{M}(\rho, t) = \mathbf{M}_v(\rho) + \mu(\rho, t) \]

\[ |\mu| << M_s \]

\[ \mathbf{\mu} = (\mu_\rho, 0, \mu_z) \] - Dynamical magnetization

\[ \mu_z(\rho, t) = b_n(\rho) \sin(\omega t - m\varphi) \]

\[ \mu_\rho(\rho, t) = a_n(\rho) \cos(\omega t - m\varphi) \]

\[ \rho = (\rho, \varphi) \] - in plane radius vector

\[ \mathbf{\mu} \perp \mathbf{M}_v \]

Static vortex  Spin waves

Radial mode profile, index n  Azimuthal index, \( m \)

\( m=0 \) - Radial spin waves (standing)  \( m=+1/-1, +2/-2, \ldots \) - Azimuthal spin waves (propagating)

TR Kerr experiment
Buess et al. PRL 2004

2.8 GHz  n=0
3.9 GHz  n=1
4.5 GHz  n=2
Vortex core reversal induced by high-frequency driving field

Experimental (X-ray microscopy) diagram of VC reversal. Blue/red colors correspond to reversal after CW/CCW in-plane filed bursts. Minima in switching fields correspond to frequencies of the azimuthal spin waves with indices $m=+1/-1$. M. Kammerer et al., Nature Comm. 2011

Vortex interaction with azimuthal spin waves (any $n$, $m=+1/-1$)

RF pumping at SW frequencies leads to VC reversal at $H_0\sim5$-10 Oe-

Guslienko et al. PRB 2010

Proof of Vortex - SW coupling
Layered nanopillars and dot pairs

- Magnetostatic interactions between dots strongly affect dynamic excitations.
- Two gyrotrropic eigenfrequencies and complicated vortex core trajectories for tri-layer F/N/F dots and lateral dot pairs.

Two ferromagnetic (F) layers with nonmagnetic (N) spacer.

Ferromagnetic Dot Pair on a substrate.

Different polarizations and chiralities of vortices in F-layers.

Magnonics: Spin excitations in coupled 2D vortex dot arrays

A. Vogel et al., PRL 2010
Broadband FMR experiment

A. Awad et al., APL 2010
The detected by broadband FMR spin eigenfrequencies labelled by the mode indices \((n, m)\) vs. interdot separation
Collective excitations of vortex dot array (beyond dipolar approximation)

Dispersive relations for the square array of the vortex magnetic dots. The array period is $d$ in units of dot radius $R$. The frequency is normalised to the gyrotropic frequency of isolated dot $\omega_0$ (Sukhostavets et al., PRB 2013).
High order vortex gyromodes in thick dots: Vortex mass

Thick cylindrical magnetic dot in the vortex state
(Gyromode wave vector is quantized along the dot thickness)

Experimental (a)-(d) and simulated (e)-(h) FMR spectra of the dot arrays. $L=50$-100 nm. (i) Spatial distribution of eigenmodes for the dots with $L=60$ nm. Dot diameter is 300nm.


The modes are classified by number of the M-nodes along thickness ($n=0,1,...$)
Gyrotropic frequencies vs. dot thickness

\[ \omega_n \propto \frac{n^2}{L^2} \]

Consider this vortex Gyro-mode.
Scheme of vortex dynamics calculation

1) Moving frame related to the instant vortex magnetization

2) Gauge field leads to Vortex – SW interaction

3) Consequences of the V-SW interaction:
   a) vortex mass
   b) splitting of the azimuthal SW frequencies (not considered here)

4) Comparison with b-FMR experiment on Py dots:
   The vortex mass strongly depends on dot thickness and is large
   \[ \approx 10^{-18} \, g \] for thick dots (L= 100 nm)
Moving vortex is dressed by SW Azimuthal spin waves, dynamical magnetization

\[ \propto \cos(m\varphi - \omega t), \quad m = \pm 1 \]

\[ L_{\text{kin}}^{\text{int}} = \frac{M_s}{\gamma} \sin \Theta \Phi \vartheta \]

Moving vortex is deformed, the deformation increases with its velocity. The dynamical vortex energy depends on velocity:

This leads to definition of the vortex mass:

\[ E_{\text{kin}} = \frac{1}{2} M_v \nu^2 \]
Giant vortex mass for thick dots

Renormalized Vortex frequency of $n=0$ gyrotropic mode (accounting for vortex mass decreases the gyrofrequency)

$$\omega_n' = \gamma \left( \sqrt{1 + 4M_v^n \omega_n / \gamma^2} - 1 \right) / 2M_v^n$$

Vortex mass is sum of contributions of the azimuthal spin waves, $m=+1/-1$

For thin dots $L/R<<1$

$$M_v^0 = 1.5 / \gamma^2$$  K. Guslienko et al. PRB 81, 014414 (2010)

$$M_v^0 = 0.6 / \gamma^2$$  B. Ivanov, et al. JETP Lett. 91, 178 (2010)

$$M_v^0 L \approx 10^{-18} \gamma$$  for thickness $L=100$ nm (larger than Doring mass for DW)

Recent estimation of bubble-Skyrmion mass in Co/Pt dot by Buettner et al., Nature Phys 2015, is

$$M_{Sk} > 8 \cdot 10^{-19} \gamma$$
Fundamental gyrotrropic frequency vs. dot thickness

Inset: Vortex mass per unit length

Conclusions

1) Magnetic vortices are stable in **soft magnetic elements** with thickness several tens of nm and micron- and submicron in-plane sizes.

2) The vortex core trajectory and **vortex core reversal** strongly depend on the driving field (SP current) amplitude/frequency.

3) To describe vortex p-reversal we need to consider **internal vortex structure** (vortex core deformation, V/AV pairs creation/annihilation).

4) There are extra vortex gyrotropic modes in thick dots due to the wave vector quantization along the dot thickness.

5) The frequency of the fundamental gyromode mode is calculated by introducing **an inertia (mass) term**. The mass is anomalously large for thick dots and reflects moving vortex interaction with spin waves.
Summary

1) Mesoscopic magnetic structures provide now a wide testing area for concepts of nanomagnetism and prospective applications.

2) Magnetic vortex in a dot having two stable states of polarization and chirality is a promising candidate for high density magnetic recording (non-volatile data storage devices, VRAM).

3) Vortex dynamics is important for interpretation of SP current induced magnetization dynamics in nanopillars and nanocontacts.

4) The vortex core orientation reversal is extremely fast (~ tens of ps) and can be readily reached in small a.c. field. THz writing?

5) Understanding the stability and dynamic behavior of magnetic vortices and skyrmions is on the forefront of modern science.
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