COMPUTER SIMULATION STUDIES OF SKYRMIONIC TEXTURES IN HELIMAGNETIC NANOSTRUCTURES

Marijan Beg*, Hans Fangohr

Faculty of Engineering and the Environment, University of Southampton, Southampton, United Kingdom

*email: mb4e10@soton.ac.uk
OVERVIEW

1. Initial states (analytic model)
2. Equilibrium states in a nano disk
3. Ground state phase diagram
4. Robustness
5. Hysteretic behaviour (DMI anisotropy)
6. Reversal mechanism
7. Summary
SKYRMIONIC TEXTURES IN CONFINED HELIMAGNETIC NANOSTRUCTURES
MOTIVATION

• Magnetic skyrmions possess interesting properties promising for the development of future data-storage and information processing devices.

• One of the main problems, obstructing the development of skyrmion-based devices using helimagnetic materials, is their magnetic and thermal stability.

• In infinitely large thin film or bulk B20 helimagnetic samples, skyrmion phase is stabilised in presence of an external field.

• The motivation for this work is to explore the skyrmionic textures in finite size B20 helimagnetic nanostructures.

Yu et. al., Nature 465, 901-4 (2011)

Schematic  Lorentz TEM

Thin film phase diagram
SYSTEM UNDER STUDY

- Sample geometry is **10 nm thin film disk** with varying diameter
- Cubic **B20 helimagnetic FeGe**
  - $M_s = 3.84 \times 10^5 \text{ Am}^{-1}$
  - $A = 8.78 \times 10^{-12} \text{ Jm}^{-1}$
  - $D = 1.58 \times 10^{-3} \text{ Jm}^{-2}$
  - Helical period $4\pi A/D = 70 \text{ nm}$
- Finite elements mesh maximum neighbouring node spacing smaller than 3 nm.
- External field applied uniformly and **perpendicular to the film in $+z$ direction**.
- Zero temperature **micromagnetic model**

Finite size effects, stability, hysteretic behaviour, and reversal mechanism of skyrmionic textures in nanostructures,

Marijan Beg, Dmitri Chernyshenko, Marc-Antonio Bisotti, Weiwei Wang, Maximilian Albert, Robert L. Stamps, Hans Fangohr,

arxiv:1312.7665

MICROMAGNETIC MODEL
- HAMILTONIAN AND DYNAMICS -

• **FINMAG**
  • Finite elements based simulator.
  • successor of Nmag, [http://nmag.soton.ac.uk](http://nmag.soton.ac.uk)

• **HAMILTONIAN:**

\[
W = \int \left[ A(\nabla \mathbf{m})^2 + D \mathbf{m} \cdot (\nabla \times \mathbf{m}) - \mu_0 \mathbf{m} \cdot \mathbf{H} + w_d \right] \, d^3r
\]

• **No anisotropy** (isotropic helimagnetic B20 material).
• **Full 3D model** - no assumption about translational invariance of magnetisation in out-of-film direction which radically changes the skyrmion energetics [Rybakov et al., PRB 87, 094424 (2013)].
MAGNETISATION DYNAMICS

- Magnetisation dynamics is governed by the **LLG EQUATION**.

\[
\frac{\partial m}{\partial t} = \gamma^* m \times H_{\text{eff}} + \alpha m \times \frac{\partial m}{\partial t}
\]

**Precession**

\[
H_{\text{eff}} = H_{\text{eff}} + H_{\text{eff}}
\]

**Damping**

\[
H_{\text{eff}} = H_{\text{eff}} + H_{\text{eff}}
\]
ENERGY LANDSCAPE

- Initial state
- Relaxed state

**Energy**

Phase space

Metastable state (local energy minimum)

Ground state (global energy minimum)
SIMULATION METHOD

- $d$ and $H$ are **varied** in steps:

  $$\Delta d = 2 \text{ nm} \quad \mu_0 \Delta H = 2 \text{ mT}$$

- Gilbert damping $\alpha = 1$

- **System is relaxed** from multiple initial states by computing the magnetisation’s time development

- The relaxed state with the lowest energy is chosen as the **ground state** for the phase space point $(d, H)$.

- The **scalar parameter** $S_a$ is computed as:

  $$S_a = \frac{1}{4\pi} \left| \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial x} \right) \right| \, d^3 r$$

- **Phase diagram**: $S_a = f(d, H)$
INITIAL CONFIGURATIONS

A

B

C

D

E

H2

H3

H4

U

R

$\mathbf{m}(x)$

$\mathbf{x}$

$-d/2$ 0  $d/2$
DEFINING SKYRMIONIC INITIAL STATES – ANALYTIC MODEL

- The **chiral skyrmion profile** is approximated in cylindrical coordinates:

\[
\begin{align*}
m_r &= 0 \\
m_\theta &= \sin(kr) \\
m_z &= -\cos(kr)
\end{align*}
\]

- The **effective field** due to symmetric exchange and DMI (no external field, isotropic B20 material):

\[
\vec{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s} \frac{\delta w}{\delta \vec{m}} = 2 \frac{2}{\mu_0 M_S} \left[ A \nabla^2 \vec{m} - D (\nabla \times \vec{m}) \right]
\]

Yu et. al., Nature 465, 901-4 (2011)
ANALYTIC MODEL
- ZERO TORQUE EQUATION -

• In equilibrium state, the **torque is zero**: \( \mathbf{m} \times \mathbf{H}_{\text{eff}} = 0 \)

• Computing the **zero radial torque at** \( r=R \) **for assumed chiral skyrmion profile results in condition**:

\[
g(kR) \equiv -\frac{D}{kA} \sin^2(kR) - \frac{\sin(2kR)}{2kR} + 1 = 0
\]

• This equation **has solution if**:

\[
P = \frac{D}{kA} > \frac{2}{3} \quad \Rightarrow \quad D > \frac{2}{3} kA
\]

• Two scalar parameters are computed:

\[
S = \int \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) \, dx \, dy
\]

\[
S_a = \int \left| \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) \right| \, dx \, dy
\]
SOLUTION A

$m_r = 0$

$m_\theta = \sin(kr)$

$m_z = -\cos(kr)$
\[ m_r = 0 \]
\[ m_\theta = \sin(kr) \]
\[ m_z = -\cos(kr) \]
SOLUTION C

\[ m_r = 0 \]
\[ m_\theta = \sin(kr) \]
\[ m_z = -\cos(kr) \]
\[ m_r = 0 \]
\[ m_\theta = \sin(kr) \]
\[ m_z = -\cos(kr) \]
\[ m_r = 0 \]
\[ m_\theta = \sin(kr) \]
\[ m_z = -\cos(kr) \]
\[ m_r = 0 \]
\[ m_\theta = \sin(kr) \]
\[ m_z = -\cos(kr) \]
SIMULATION RESULTS
EQUILIBRIUM CONFIGURATIONS

- iSk
- Sk
- 2Sk
- 3Sk
- H2
- H3
- H4
- T

**iSk**
- $d=120$ nm
- $\mu_0H=0.2$ T

**Sk**
- $d=80$ nm
- $\mu_0H=0.3$ T

**T**
- $d=160$ nm
- $\mu_0H=0.22$ T

- **2Sk**
  - $d=160$ nm
  - $\mu_0H=0.6$ T

- **3Sk**
  - $d=172$ nm
  - $\mu_0H=0.8$ T

- **H2**
  - $d=120$ nm
  - $\mu_0H=0$ T

- **H3**
  - $d=160$ nm
  - $\mu_0H=0.1$ T

- **H4**
  - $d=172$ nm
  - $\mu_0H=0$ T
GROUND STATE PHASE DIAGRAM

- We select the state with the lowest energy
- Two different ground states.

FeGe thin film disk phase diagram
INCOMPLETE SKYRMION (ISK)

- No complete spin rotation.
- $|S| < 1$
- In literature also called “quasi-ferromagnetic” or “vortex” state.
ISOLATED SKYRMION (SK)

- Complete spin rotation present.
- Significant tilt of magnetisation at the edge which reduces $|S|$.

$d = 160\ \text{nm} \quad \mu_0 H = 0.3\ \text{T}$
ENERGIES OF METASTABLE STATES

\[ \Delta E / V (\text{mJ/m}^3) \]

\[ d \text{(nm)} \]

\[ \mu_0 H \text{(T)} \]

METASTABLE STATE (LOCAL ENERGY MINIMUM)

GROUND STATE (GLOBAL ENERGY MINIMUM)

PHASE SPACE
• Skyrmionic textures **able to adapt their size** to accommodate the size of a hosting nanostructure.
• This provides the **robustness** of technology built on skyrmions.
• iSk and Sk have **different core orientation**.
POSSIBLE STABILISING MECHANISM

Rybakov et al., PRB 87, 094424 (2013)

no demagnetisation
POSSIBLE STABILISING MECHANISM
HYSTERETIC BEHAVIOUR

<table>
<thead>
<tr>
<th></th>
<th>incomplete Skyrmion (iSk)</th>
<th>Skyrmion (Sk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iSk↑ orientation↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with dipolar interactions</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>no dipolar interactions</td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>iSk↓ orientation↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with dipolar interactions</td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>no dipolar interactions</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
</tr>
</tbody>
</table>
HYSTERETIC BEHAVIOUR (ISK)

Hysteretic behaviour remains in absence of magnetocrystalline anisotropy and dipolar-based shape anisotropy, suggesting the existence of Dzyaloshinskii-Moriya based shape anisotropy.
Hysteretic behaviour remains in absence of magnetocrystalline anisotropy and dipolar-based shape anisotropy, suggesting the existence of Dzyaloshinskii-Moriya based shape anisotropy.
REVERSAL MECHANISM

- Skyrmionic texture core reverses via Bloch point occurrence and propagation.
- Reversal from core down to core up.
- External field reduced abruptly from -210 mT to -260 mT.
- Magnetisation dynamics recorded for 1 ns.

REVERSAL MECHANISM

1. Core shrinks
2. Profile lowers
3. Core reverses
4. Size increases to adapt to the size of nanostructure.
**CORE REVERSAL MECHANISM**

**Bloch Point (BP):**
1. enters the sample at the top boundary,
2. propagates to the bottom boundary, and
3. leaves the sample.

$t=645.00$
DIFFERENT BLOCH POINT PROPAGATION

- One may ask whether different BP propagation direction is allowed.
- This process is stochastic and depends on simulation parameters.
- We choose 0.35 for Gilbert damping.
- Bloch point structure changes.

![Diagram](image.png)
SUMMARY

- In finite size B20 helimagnetic samples skyrmionic textures are ground state at zero field and in absence of magnetocrystalline anisotropy.
- Skyrmionic textures occur in a much wider range of external field values.
- Demagnetisation energy and magnetisation variance in out-of-plane direction crucial for the stability.
- Bistability: Two energetically equivalent configurations with different core orientation identified.
- Writability: Skyrmionic textures undergo hysteretic behaviour when the core orientation is changed using an external field.
  - Large hysteresis identified in absence of magnetocrystalline and dipolar-based shape anisotropies, suggesting the existence of DMI-based shape anisotropy.
- Skyrmionic textures reverse via Bloch-point occurrence and propagation.
- Results fully scalable for helimagnetic materials with different helical period.
- Presented stable skyrmionic textures could be used for hosting the information bit.

- Acknowledge the financial support from the EPSRC’s DTC grant EP/G03690X/1
- Acknowledge the help of Marijan Beg, Weiwei Wang, David Cortes, Rebecca Carey, Maximilian Albert, Dmitri Chernyshenko, Marc-Antonio Bisotti, Mark Vousden and Robert L. Stamps.
- email: mb4e10@soton.ac.uk
MICROMAGNETIC MODEL

• Energy density

\[ w(m) = A(\nabla m)^2 + Dm \cdot (\nabla \times m) - \mu_0 M_s m \cdot H + w_d \]

- Exchange
- DMI
- Demagnetisation
- Zeeman

• Effective field

\[ H_{\text{eff}}(m) = -\frac{1}{\mu_0 M_s} \frac{\delta w(m)}{\delta m} \]

- DMI
- Demagnetisation
- Zeeman

\[ H_{\text{eff}}(m) = \frac{2A}{\mu_0 M_s} \nabla^2 m - \frac{2D}{\mu_0 M_s} (\nabla \times m) + H + H_d \]

- Exchange

• LLG equation

\[ \frac{\partial m}{\partial t} = \gamma^* m \times H_{\text{eff}} + \alpha m \times \frac{\partial m}{\partial t} + u(|m| - 1)V(m) \]

- Precession
- Damping
- Norm correction
DEMAGNETISATION

- Magnetic scalar potential

\[ \phi(r') = \frac{M_s}{4\pi} \left( -\int_{\Omega} \frac{\nabla \cdot m(r')}{||r - r'||} \, dV + \int_{\partial\Omega} \frac{m(r') \cdot n}{||r - r'||} \, dS \right) \]

- Effective (demagnetisation) field

\[ H_d(r) = -\nabla \phi(r) \]

- Demagnetisation energy density

\[ w_d = -\frac{1}{2} H_d \cdot m \]