Imperial College London

MSc Independent Research Project

Presentation

Isolated skyrmion state stability exploration using mean-field model

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Date: September 15, 2022

Overview

- Introduction & Motivation
- Project Objectives
- Methodology
- Results and Discussion
- Conclusion

Skyrmion in Micromagnetics

Data storage $\xrightarrow[\text{economical}]{\text{most}}$ Magnetic storage

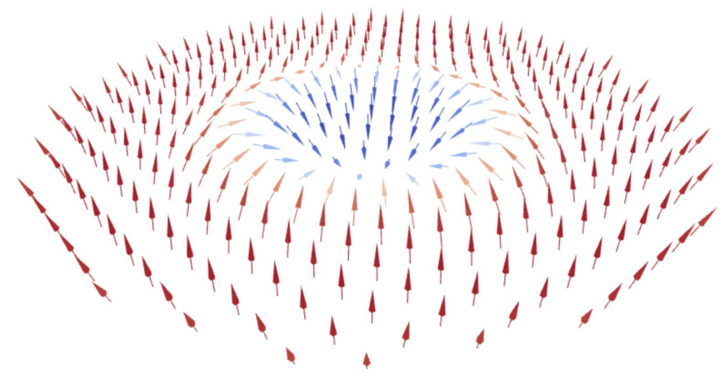


Figure 1: Two-dimensional chiral skyrmion configuration

Skyrmion
lowest energy

- small spin-polarized currents
- nanometer-scale
- stabilized easily

↓

Devices → High Density + Energy Efficient

↓

Challenges

- Thermal Stability — Thermodynamic beta : $\beta = \frac{1}{k_B T}$
- Magnetic Stability — External Magnetic Field : $\mathbf{B} = \mu_0 \mathbf{H}$

Does Skyrmion stable when applied T and B?

Discretised Magnetisation Field

ubermag
[1]

- Magnetisation is considered to be a continuous vector field.

- Magnetisation M is a function relevant to space r and time t.

$$\mathbf{M}(\mathbf{r}, t) = M_{\mathrm{S}}\mathbf{m}$$

- In finite-differences, magnetisation field M is discretised (at every time step) so that a single vector is assigned to each discretisation cell.

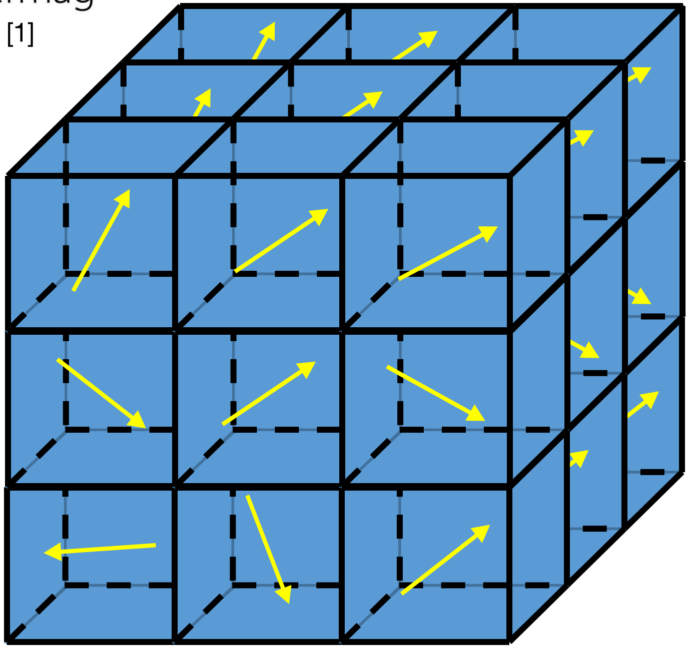


Figure 2: Three-dimensional continuous vector field

[1] M. Beg, M. Lang, and H. Fangohr, “Ubermag: Toward more effective micromagnetic workflows,” IEEE Transactions on Magnetics, vol. 58, no. 2, pp. 1–5, 2021.

Project Objectives

Initialize the continuous field M with magnetic moments

+

Implement energy terms

+

Implement mean-field model to find lowest energy state

+

Computational Simulation

=

Isolated skyrmion state stabilty exploration using mean-field model

Methodology

Methodology

Effective Field

Effective field can be expressed as

$$\mathbf{H}_{\text{eff}} = \frac{1}{\mu_0}\mathbf{B}_{\text{eff}} = \frac{1}{\mu_0}\left(-\frac{\delta E[\mathbf{m}]}{\delta \mathbf{M}}\right) = -\frac{1}{\mu_0 M_{\text{s}}}\frac{\delta E[\mathbf{m}]}{\delta \mathbf{m}}.$$

Three energy terms:

① Zeeman energy

② Exchange energy

③ Dzyaloshinskii-Moriya energy

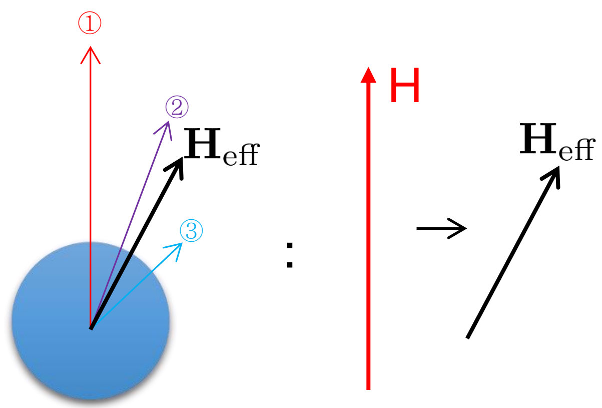


Figure 3: Schematic: effective field in this project

Alogrithm of Mean Field Model

Identify the lowest energy state of the magnetization.

λ = 0.005 --> change slowly

It changes the system at once.

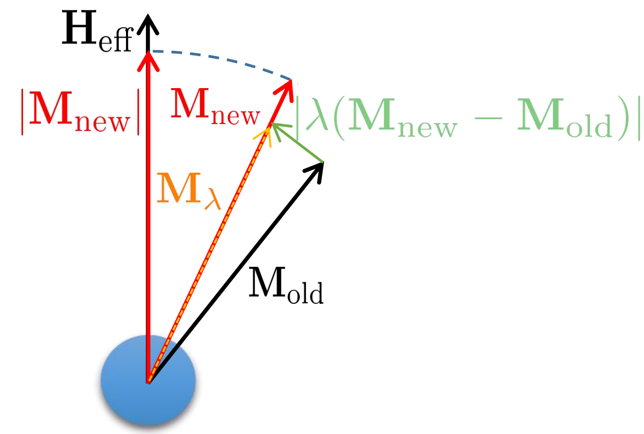


Figure 4: Schematic: how mean-field update M

Algorithm 1 Mean-Field Algorithm

Initialize the continuous vector field $\mathbf{M}$ in a well-defined state.
Calculate effective field of current magnetisation vector field $\mathbf{M}_{\text{old}}$: $\mathbf{H}_{\text{eff}} = \mathbf{H}^{\text{z}}_{\text{eff}} + \mathbf{H}^{\text{ex}}_{\text{eff}} + \mathbf{H}^{\text{dmi}}_{\text{eff}}$
while current iteration < 12500 iteration && tolerance < 1e-4 **do**
    Update magnitude of magnetisation $\mathbf{M}_{\text{new}} = M_S \cdot Langevin(\beta\mu_0|\mathbf{H}_{\text{eff}}|) \cdot \frac{\mathbf{H}_{\text{eff}}}{|\mathbf{H}_{\text{eff}}|}$
    Update direction of magnetisation $\mathbf{M}_{\lambda} = \mathbf{M}_{\text{old}} + \lambda(\mathbf{M}_{\text{new}} - \mathbf{M}_{\text{old}})$
    Renormalization the magnetisation $\mathbf{M}_{\text{new}} = \frac{\mathbf{M}_{\lambda}}{|\mathbf{M}_{\lambda}|} \cdot |\mathbf{M}_{\text{new}}|$
    Calculate effective field of updated magnetisation $\mathbf{M}_{\text{new}}$: $\mathbf{H}_{\text{eff}} = \mathbf{H}^{\text{z}}_{\text{eff}} + \mathbf{H}^{\text{ex}}_{\text{eff}} + \mathbf{H}^{\text{dmi}}_{\text{eff}}$
    Compare the difference $\mathbf{M}_{\text{new}} - \mathbf{M}_{\text{old}} = $ tolerance $\longleftarrow$ $\mathbf{m} \times \mathbf{H}_{\text{eff}} = 0$
end while

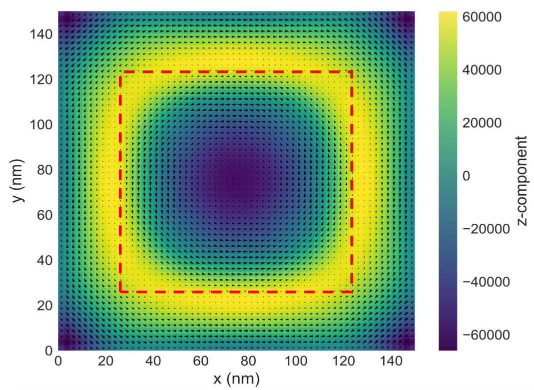
Output: Final state of magnetisation vector field $\mathbf{M}$ when energy is minimum.

RESULTS & DISCUSSION

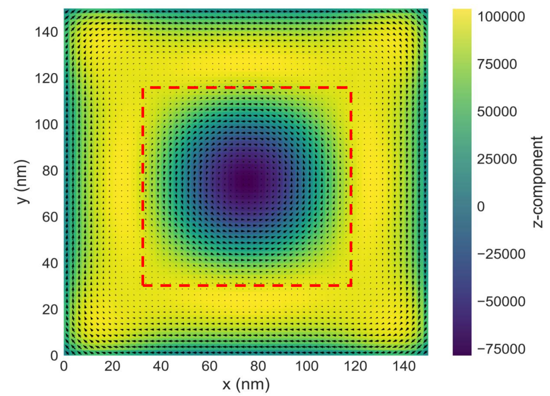
Results & Discussion

Skyrmion Stability

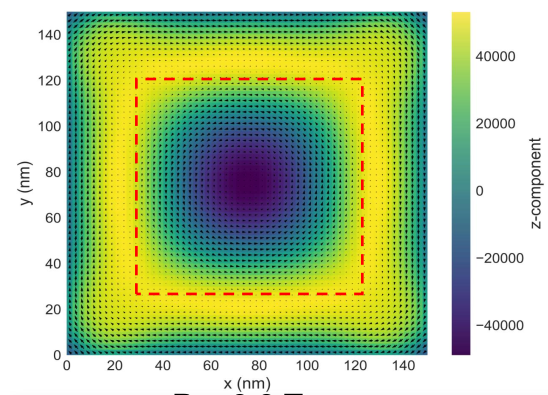
Apply β in the system, skyrmion exists in the minimal state.



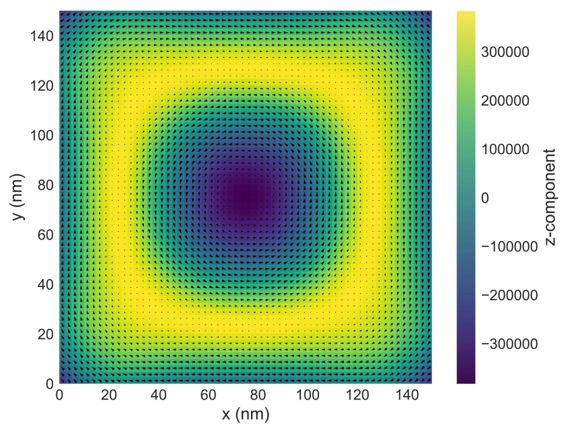
B = 0.2 T
β = 5000



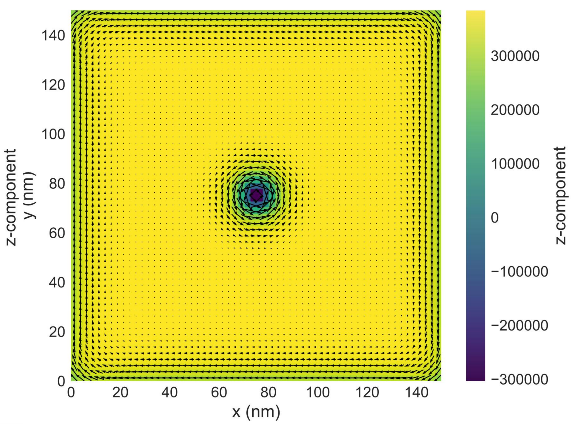
B = 0.8 T
β = 5000



B = 0.8 T
β = 2000



B = 0.2 T
β = infinity



B = 0.8 T
β = infinity

Figure 5: Skyrmion textures.

Skyrmion Number S

Skyrmions configurations are influenced by temperature and external magnetic field.

$$S = \frac{1}{4\pi}\int \mathbf{m}\cdot\left(\frac{\partial \mathbf{m}}{\partial x}\times\frac{\partial \mathbf{m}}{\partial y}\right)\mathrm{d}x\mathrm{d}y$$

β ↓ --> S increases and then decreases until skyrmions disappear.

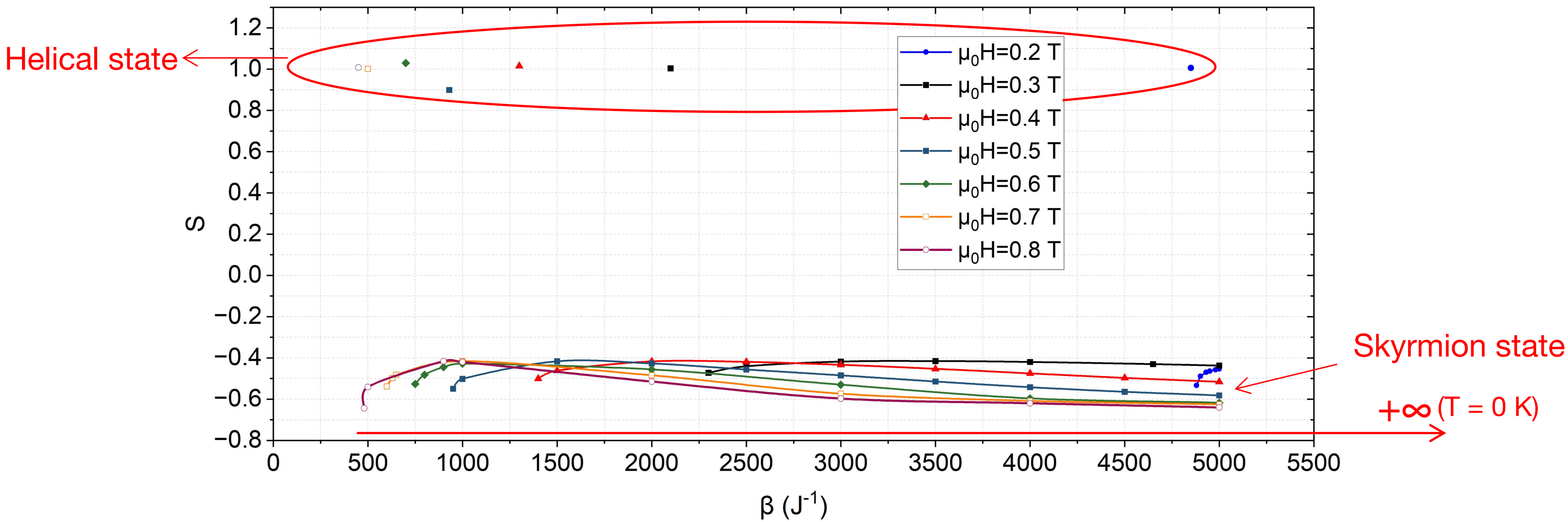


Figure 6: β and Skyrmion number S with different external magnetic field $\mu_0 H$.

Critical β Value

Critical β ↓ when magnetic field $\mu_0\mathbf{H}$ ↑

↓

Skyrmions in stronger magnetic fields over a wider temperature range.

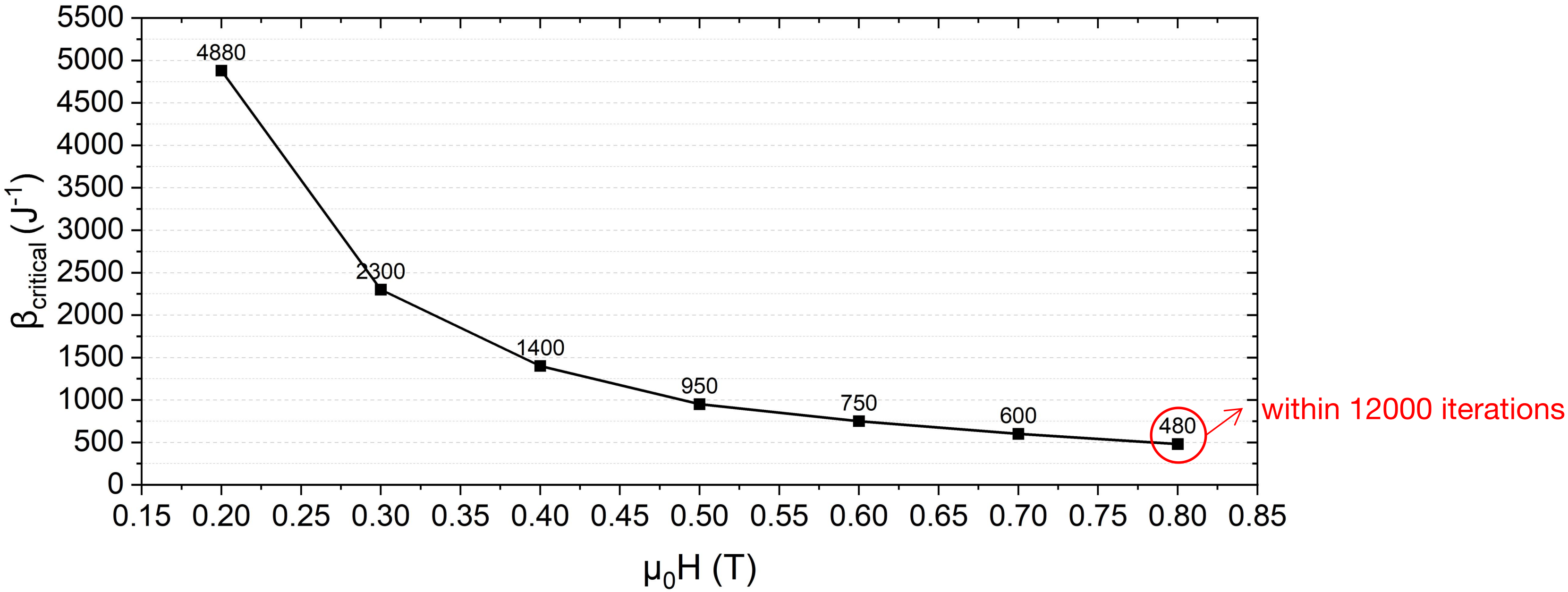


Figure 7: Relationship between critical β and external magnetic field $\mu_0 H$.

Conclusion

- Isolated skyrmion state has been observed at both zero and non-zero temperatures.
- Skyrmion number has been affected by different β and external magnetic field.
- Computational cost of mean-field is low based on the small number of iterations.

Thanks

Q&A