Micromagnetic simulations of skyrmion-skyrmion interactions in a ferromagnetic thin film

Nemanja Ninkovic
Center for Emergent Materials, The Ohio State University

Abstract

Interactions between two magnetic skyrmions on a ferromagnetic thin film were studied numerically by using micromagnetic simulations. Magnetic skyrmions are nanoscale configurations of spin that exhibit particle-like behaviors and have topological origin. Results show that skyrmions with the same core polarization repel. An interesting spiraling motion is also shown between skyrmions at close distances. This is predicted to be the result of a magnus force. Both the repulsion and magnus forces become extremely weak after a certain critical distance based on the properties of the material used. The simulations performed do not display any change in skyrmion size when skyrmions are in close proximities to each other. This goes against other literature and would be something to look into for future directions. Interactions between skyrmions are important to understand for applications and experimental studies of skyrmions.

1 Background

Magnetic skyrmions are nanoscale spin configurations of topological origin which exhibit particle-like behaviors.[1] They can be considered two dimensional objects which continue trivially along the third dimension. In a ferromagnetic medium, they are characterized by a continuously changing magnetization density where the core of the skyrmion is oriented opposite of the surrounding spins located around the edge.[2] Figure 1 shows an example of a skyrmion.

Applicable interest in skyrmions stems from their potential use in nanoscale information processing for new memory and computing technologies. The advantages attributed to magnetic skyrmions over other spintronic alternatives comes from their ability to be moved in low density currents (low power consumption), nanoscale size, stability, and particle-like behavior. The concept of the skyrmion was initially introduced in nuclear physics by Tony Skyrme to explain the stability of hadrons and eventually found uses in condensed matter.[1]

The main mechanism behind the stability of skyrmions is DMI or the Dzyaloshinskii-Moriya interaction. DMI is an anti-symmetric exchange interaction found in magnetic systems that lack inversion symmetry and that have a strong spin-orbit interaction.[3] DMI in thin films is called interfacial DMI.

Figure 1: Model of a Neel-type Skyrmion, which is characterized by the spins rotating in radial planes from the core to the periphery.[4]

The DMI Hamiltonian has the following form:

$$\mathcal{H}_{DM} = -D_{12} \cdot (S_1 \times S_2) \tag{1}$$

Where each S_1 and S_2 correspond to two different spins and D_{12} is the DM vector between the two spins. As a consequence of this equation, DMI causes a deviation from the parallel alignment of spins resulting from the Hamiltonian of the Heisenberg exchange interaction:

$$\mathcal{H} = -J_{12}(S_1 \cdot S_2) \tag{2}$$

Where J is the exchange constant and J > 0 for a ferromagnet. This leads to a competition between the DMI, which favors an angle between two spins, and the Heisenberg exchange, which favors a parallel alignment of two spins. Skyrmions form as a result of this competition.

As mentioned before, skyrmions exhibit particle-like behavior, therefore it is possible to study the interactions between them. In experiment, and application alike, there will be situations where skyrmions will be close to each other. Therefore, it is important to understand the interactions that can occur between them. For certain applications, it is important to know the critical separation distance where skyrmion interactions are minimized and do not effect the functionality of the device.

Simulations performed show how the separation distance between skyrmions effects their interactions, a spiraling motion between skyrmions when they are at close distances and how the size of a skyrmion is effected by interaction with another skyrmion.

2 Methods

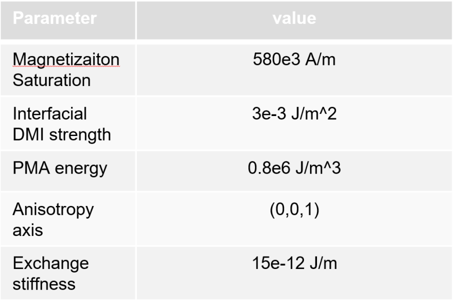
Micromagnetic simulations were numerically performed using MuMax3,[5] a GPU accelerated micromagnetic simulation program which solves the Landau-Lifshitz-Gilbert (LLG) equation:

$$-\frac{1}{\gamma}\frac{dM}{dt} = [M \times H_{eff}] - \frac{\alpha}{\gamma M_s}[M \times \frac{dM}{dt}] \tag{3}$$

Where α is the damping coefficient, M_s is the magnetization saturation, γ is the gyromagnetic ratio, H_{eff} is the effective field, and M is the magnetization. The LLG equation describes the precession, or rotation, of magnetization about the effective field of a magnetic system. The damping term on the right-hand side leads to the magnetization aligning with the effective field and therefore energy minimization.

In the simulations, the grid size was set to 400 x 400 x 1 nm^3 with a discretization of 1 x 1 x 1 nm^3 for the unit cells. Two Neel skyrmions were generated at an initial distance apart horizontally. They were then allowed to reach equilibrium states through solving the LLG equation. The default differential equation solver in MuMax3 uses the Prince-Dormand method. Parameters used in the simulations are shown in table 1.

MuMax3 offers multiple ways of reaching minimum energy in a system. The run() function runs the simulation for a specified amount of time and was used in simulations where time evolution was important. The relax() function tries to evolve the magnetization as closely as possible to the minimum energy state while turning off all excitations.



Parameter	value
Magnetizaiton Saturation	580e3 A/m
Interfacial DMI strength	3e-3 J/m^2
PMA energy	0.8e6 J/m^3
Anisotropy axis	(0,0,1)
Exchange stiffness	15e-12 J/m

Table 1: Parameters used in the simulations.

The anisotropy axis shown indicates that the ferromagnet wants to be aligned in the positive z-direction and therefore the core magnetization of each skyrmion is pointing in the negative z-direction.

Interactions between skyrmions were done with the run() function. The same simulations were done for multiple separation distances and for 2 nanoseconds at each distance. The relax() function was used to simulate a large number of separation distances in order to plot the energies as a function of distance. The distances between the skyrmions are displayed from center to center. The radius was automatically calculated by MuMax3 to be about 15 nanometers, for each skyrmion, based on the parameters.

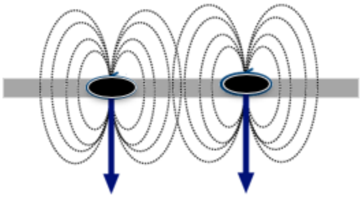


Figure 2: Visual depiction of skyrmions with negative core polarity and their magnetic fields. For results, only one was approximated as a point dipole.

Results from the simulations showed no change in skyrmion size as a function of distance. Therefore, in order to explain these results, skyrmions were approximated as magnetic dipoles and their interaction was simulated by applying an external field on a single skyrmion, as shown in figure 2. This shows the effect that the magnetic field of one skyrmion has on another.

3 Results

Results for the dynamics of skyrmions are shown in figure 3. There is a clear repulsive force between the two skyrmions that is best illustrated in the top row of figure 3.

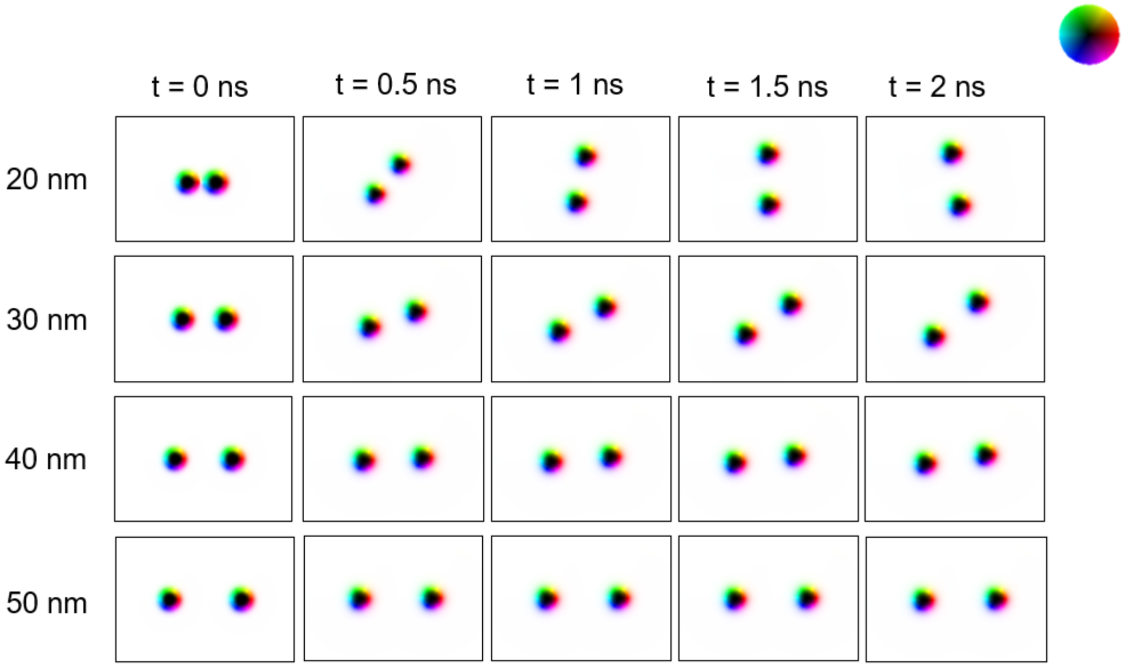


Figure 3: Time evolution of the dynamics between two skyrmions in 2 nanoseconds for multiple initial separation distances. The colors, shown in the color wheel on the top right, correspond to different directions of in-plane magnetization in the skyrmions. Each square is only a sliver of the actual grid to focus on the dynamics.

Owing to their particle-like behavior, this shows that skyrmions with the same core polarity will repel. There was also a spiraling motion that occurred between skyrmions at close distances. The two skyrmions rotated about each other in a counterclockwise motion. This is very similar to the effect of a magnus force.

A magnus force is a force that acts perpendicularly to the motion of a rotating object. The precession of the magnetization would seem to be analogous to a rotating object and, as the skyrmions repel, a perpendicular magnus force causes them to rotate about each other in a spiral. This effect gets weaker as the initial distance between the skyrmions is increased.

The repulsion force also gets weaker for greater initial distance. This can be illustrated well in figure 4. Repulsion weakens significantly after a certain distance. There is also a critical separation distance where the skyrmions fuse into a single skyrmion. This separation distance is not exactly when they overlap. The top row of figure 3 shows skyrmions with a slight overlap and they still repel. They have to be overlapping fairly significantly, to the point where the cores are overlapping, in order to cause a fusion.

As stated before, the size of the skyrmions did not change in a noticeable way for any of the simulations performed. This goes against other literature where there is a clear change in size based on the distance between skyrmions[6].[7] The cause of this inconsistency is unknown but the results can be validated by calculating the magnetic field applied from one skyrmion onto the other. The applied external magnetic field is approximated as the magnetic field of a point dipole.

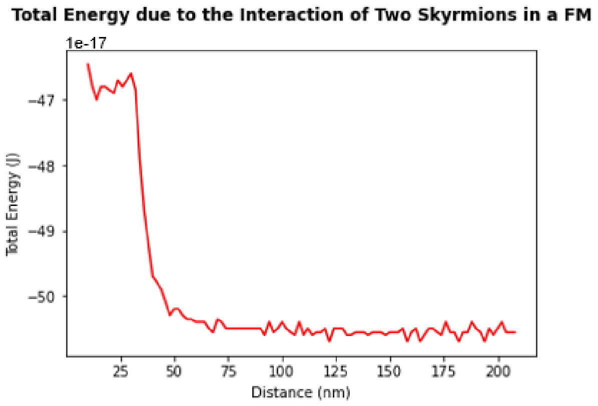


Figure 4: Total energy as a function of separation distance for the interactions of two skyrmions. There is a significant drop in energy around 30-40 nanometers, indicating the weak repulsion experienced thereafter.

The calculated value of the skyrmion based on this approximation came out to be 1.77 Gauss. This was then tested by applying an external field on a single skyrmion to simulate a skyrmion-skyrmion interaction. The results are shown in figure 5.

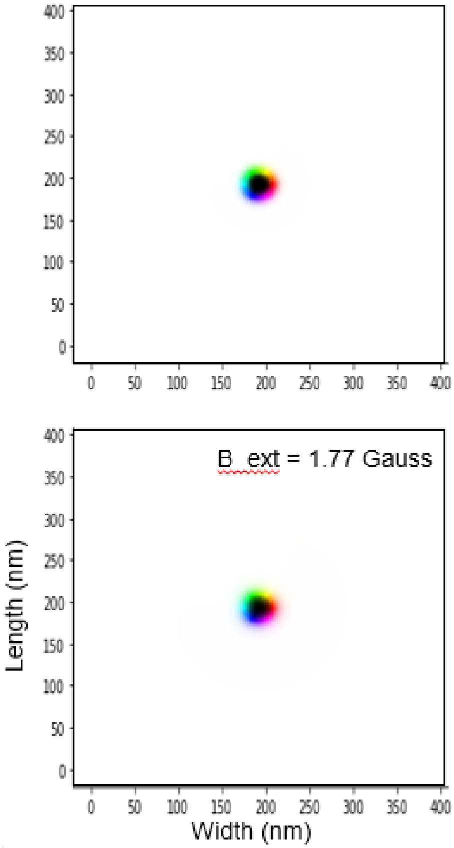


Figure 5: Externally applied field effect on skyrmion size to simulate skyrmion-skyrmion interaction effect on size. Top figure shows the size of the skyrmion when it is initially generated. The bottom figure shows the effect of the applied external magnetic field on the skyrmion. For the calculated value of 1.77 Gauss, the skyrmion shows no noticeable change in size.

It can be seen that there is no effect on the size of the skyrmion from figure 5. There is no noticeable change until the magnitude of the magnetic field of a skymrion reaches values in the hundreds of Gauss. More testing will need to be done to validate these results. MuMax3 may allow skyrmions to expand even when they are close to each other. Capic et. al.[6] applied an external magnetic field on the center of the skyrmion to avoid this, which could prove to be a useful test.

4 Conclusion

Interactions between skyrmions in a ferromagnetic thin film were studied using micromagnetic simulations. Interest in these interactions stems from usefulness in experiment as well as application. Results showed a repulsion between skyrmions with the same core polarity. In addition to this, a magnus effect was shown to be prevalent between skyrmions in close proximity to one another. This, along with the repulsion, caused a spiraling out between skyrmions until they reached a critical distance where the magnus and repulsion forces had a weak effect. For application, it is important to understand how these interactions can be avoided or beneficially used in a device.

One unexpected result was that the size of the skyrmions did not change as distance between skyrmions is changed. Approximating skyrmions as point dipoles and calculating the magnetic field strength applied from one skyrmion to the other supported this claim. However, this goes against many other studies. A future direction is to find out what caused this discrepancy. One possible route is to apply an external magnetic field on the center of each skyrmion to control their size and keep them pinned for each distance. It would be good to experimentally verify all of the results shown. Studying skyrmion interactions in antiferromagnets would also be interesting due to certain properties in antiferromagnets that make them better candidates for certain applications.

5 Acknowledgements

I would like to acknowledge and thank all of the advisors and students that helped me throughout this REU. Dr. Denis Pelekhov, Dr. Chris Hammel, Dr. Mohit Randeria, Jacob Freyermuth, Guanzhong Wu, and Matt Shmukler.

This research was primarily supported by the Center for Emergent Materials, an NSF MRSEC, under award number DMR-2011876.

References

[1] Naoto Nagaosa and Yoshinori Tokura. Topological properties and dynamics of magnetic skyrmions. *Nature Nanotechnology*, 8(12):899–911, December 2013.

[2] Börge Göbel, Ingrid Mertig, and Oleg A. Tretiakov. Beyond skyrmions: Review and perspectives of alternative magnetic quasiparticles. *Physics Reports*, 895:1–28, 2021.

[3] Bram Van Dijk. Skyrmions and the dzyaloshinskii-moriya interaction. Master's thesis, Utrecht University, 2014.

[4] I. Kezsmarki and Milde Bordacs. Neel-type skyrmion lattice with confined orientation in the po-

lar magnetic semiconductor GaVS. *Nature Mater*, 14:1116–1122, 2015.

[5] Arne Vansteenkiste and Ben Wiele. Mumax: A new high-performance micromagnetic simulation tool. *Journal of Magnetism and Magnetic Materials - J MAGN MAGN MATER*, 323:2585–2591, 11 2011.

[6] D Capic, D A Garanin, and E M Chudnovsky. Skyrmion–skyrmion interaction in a magnetic film. *Journal of Physics: Condensed Matter*, 32(41):415803, jul 2020.

[7] Xichao Zhang, GP Zhao, Hans Fangohr, J Ping Liu, WX Xia, J Xia, and FJ Morvan. Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory. *Scientific reports*, 5:7643, January 2015.