Nonlinear Dynamics of Skyrmion in Helical Lanes

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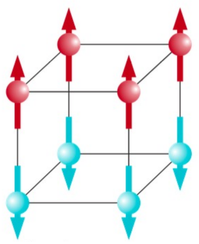
Introduction

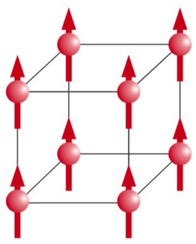
Spin is the key to determine magnetic properties of the macroscopic matter with specific symmetry. Skyrmion is a vortex-like non-colinear spin orientation found in magnetic materials[1-3]. It exhibits nano-sized particle-like behavior stabilized at finite temperatures. Therefore, it is a promising building block for next generation information storage and memory devices.

Conventional Colinear States

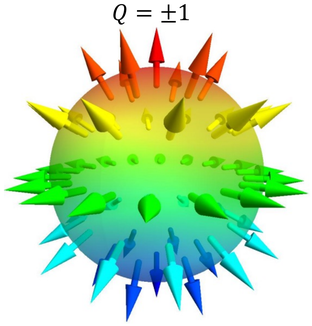
Antiferromagnet



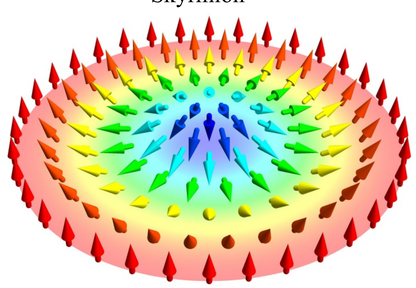
Ferromagnet



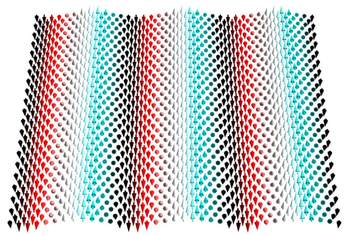
$Q = \pm 1$



Skyrmion



Helical Phase

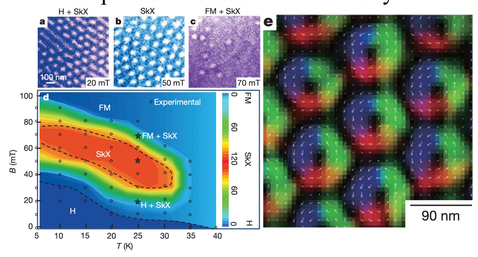


Topological Skyrmion Number

$$Q = \frac{1}{4\pi}\int_{u.c.} \frac{\partial\hat{\Omega}}{\partial x} \times \frac{\partial\hat{\Omega}}{\partial y} \cdot \hat{\Omega}\, dS$$

Skyrmions could be "bits" in future memory devices

Experimental Observation of Skyrmion



Theory of Skyrmion's Nonlinear Dynamics

We explore the dynamics of skyrmion under electric current $\boldsymbol{j}$ by solving the equation of motion. A skyrmion under a current with no external potential behaves as a massless particle, with the current proportional to its velocity.

The Equation of Motion for Skyrmion

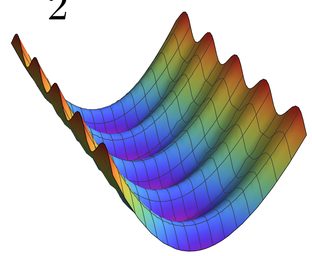
$$\boldsymbol{G} \times (\boldsymbol{u} - \dot{\boldsymbol{r}}) + D(\beta\boldsymbol{u} - \alpha\dot{\boldsymbol{r}}) - \nabla U = \boldsymbol{0}$$

$$\boldsymbol{G} = 4\pi Q\hat{\boldsymbol{z}}$$

$$\boldsymbol{u} \propto -\boldsymbol{j}$$

The Potential in Our Model

$$U = \frac{1}{2}ky^2 - V_0\cos(Kx)$$



$$m_{sk}\ddot{x} + \gamma\dot{x} = F_p - V_0K\sin(Kx)$$

$$m_{sk} = \frac{G^2 + D^2\alpha^2}{k}$$

- In our model, the potential is the helical potential, which is *locally harmonic* in the y-direction, plus the impurity potential.
- Our attempt is to model the impurity potential as a simple cosine periodic function, which is *nonlinear*.
- It has been assumed that skyrmions behave as massless particles, but our model shows that they are described as *massive* particles.

The equations of motion are in the form of a mixture of coordinates x and y. However, by eliminating y, we obtain a second-order differential equation for x alone. This allows the one-dimensional motion of skyrmion to be extracted.

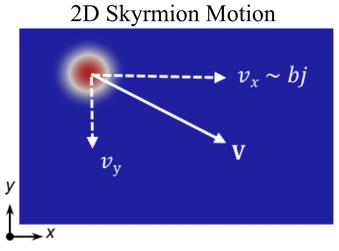
Emergence of skyrmion mass in helical lanes

1D-Motion of Skyrmion in Helical Lanes

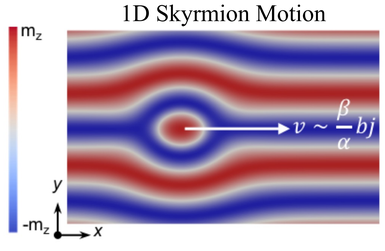
- In the recent study, it has been suggested to confine skyrmions in quasi-1D lanes [4-6], made of helical phase. In Ref. [7], a skyrmion confined to one-dimensional helical lanes was experimentally studied in FeGe compounds.
- Skyrmion is driven parallel to the applied current, but also perpendicular to it. In helical lanes, it moves parallel along the current.
- The experiment showed that the helical lane is not merely a path that confine skyrmion to one dimension, but also a highway that boost the speed of skyrmion.
- The figure on the right shows the current-velocity relation of skyrmion, with the slope being larger for 1D motion.
- This groundbreaking dynamic properties unique to skyrmion confined in helical lanes, and it is essential to understand them theoretically.

Skyrmions in HL move straight in 1D and faster than 2D-motion

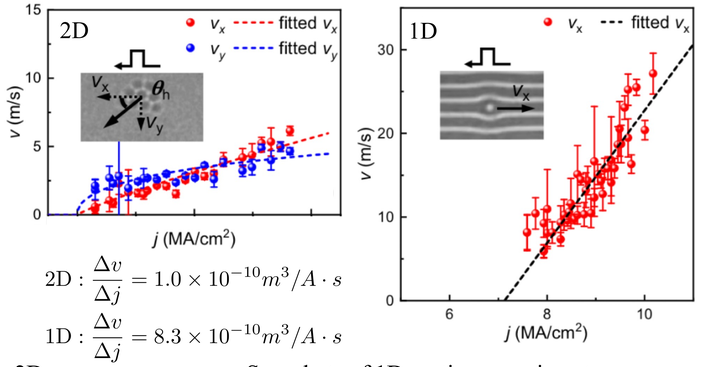
2D Skyrmion Motion



1D Skyrmion Motion



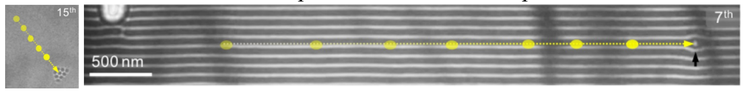
Current-Velocity Relation in Different Dimension



$$2D: \frac{\Delta v}{\Delta j} = 1.0 \times 10^{-10} m^3/A \cdot s$$

$$1D: \frac{\Delta v}{\Delta j} = 8.3 \times 10^{-10} m^3/A \cdot s$$

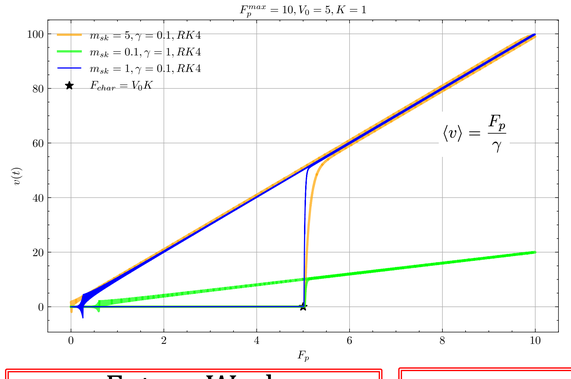
2D Snapshots of 1D motion experiment



Hysteresis: Consequence of Massive Behavior

We have confirmed numerically that, as a consequence of non-zero skyrmion mass, its motion exhibits *hysteresis* with the current density.

We predict that skyrmion mass leads to a hysteresis in current-induced motion



Conclusion

- Our model shows that the skyrmion behaves like a particle with emergent mass and induce its hysteresis.
- From the washerboard potential, we determined the current density required to overcome the potential, not pinned by impurity potential.
- In the range greater than such current densities, there is a linear relationship that is generally inversely proportional to the dissipation factor.

Future Work

- We will explore the application limits of our model and the response of more general impurity potentials and dissipation terms.
- We will work with experimentalists to verify the prediction of the hysteresis.

References

[1] N.Nagaosa and Y.Tokura, *Nature Nanotechnology* 8, 899 (2013).
[2] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, *Science* 323, 915 (2009).
[3] X. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, *Nature* 465, 7300, 901 (2010).
[4] J. Müller, J. Rajeswari, P. Huang, Y. Murooka, H. M. Rønnow, F. Carbone, and A. Rosch, *Physical Review Letters* 119, 13, 137201 (2017).
[5] R. Knapman, D. R. Rodrigues, J. Masell, and K. Everschor-Sitte, *Journal of Physics D: Applied Physics* 54, 40 404003 (2021).
[6] L. Kong, X. Chen, W. Wang, D. Song, and H. Du, *Physical Review B* 104, 21, 214407 (2021).
[7] D. Song, W. Wang, J.-X. Yu, P. Zhang, S. S. Pershoguba, G. Yin, W. Wei, J. Jiang, B. Ge, X. Fan, *et al.* (2022).