Nucleation, stabilization and manipulation of magnetic skyrmions

Xiuzhen Yu
RIKEN Center for Emergent Matter Science
Electronic States Microscopy Research Team (ESMRT)

Microscope in RIKEN CEMS

Magnetic skyrmion
Multifunctional TEM/STEM (HREM, DPC-STEM, Lorentz TEM, EELS, EDS, SAED)

- Temperature range: 5K – 500 K
- DC current: $0 \pm 100$ mA
- DC voltage: $0 \pm 40$ V
- CCD camera, CMOS camera
- He holder with ten electrodes
Lorentz TEM (Fresnel mode) is a useful technique to realize magnetization texture

\[
\nabla \phi \quad M(x,y)
\]

◆Lorentz TEM sample geometry: 2D thin film
(sample thickness \( t < 200 \text{ nm} \) is much smaller than the sample size (from several tens to several hundreds micrometers)

\[
I(x, y, z_0 + \Delta z) \quad I(x, y, z_0 - \Delta z)
\]

\[
\frac{\partial I}{\partial z} \approx \frac{I(x, y, z_0 + \Delta z) - I(x, y, z_0 - \Delta z)}{2\Delta z}
\]

\( I(x, y, z) \): Electron intensity at image planes

\[
\frac{2\pi}{\lambda} \frac{\partial I(xyz)}{\partial z} = \nabla_{xy} [I(xyz) \nabla_{xy} \phi(xyz)]
\]

\( \phi(x,y,z) \): The phase distribution of electron wave


\[
\nabla \phi(xyz) = - \frac{e}{\hbar} (M \times n)t
\]

\( M \): Spontaneous magnetization in the sample
\( t \): Thickness of the sample
Magnetic twins can be projected by Lorentz TEM

In-plane (2D) spin texture of helical structure can be projected by LTEM

Schematic of helical structure

Lorentz TEM observations for skyrmion within magnetic field

Problems:
- The original Lorentz TEM is used to perform the spontaneous magnetic domain structure for the magnetic materials without bias fields by using the special Lorentz transmission electron microscope.
- However, we need bias fields to create skyrmions in B20 compounds.

Improvements:
- Lorentz TEM performance is carried out in commercial transmission electron microscopes.
- The tunable magnetic field is induced with changing the objective lens-current.

Changes of the lens-current

The tunable magnetic field is induced by the objective magnetic lens:

\[ B_z \approx \frac{B_0}{1 + \left( \frac{z}{a} \right)^2} \]

- \( B_0 \): a maximum field (\( Z = Z_0 \))
- \( a \): the half-width at half maximum of \( B_z \)

\[ B_0 \propto I_{\text{obj}} \]

Skyrmion: topological spin texture

Bloch-type skyrmion  Neel-type skyrmion

$\Omega$: solid angle  Berry phase $\rightarrow$ effective fictitious field

$N_s = \frac{1}{4\pi} \int \tilde{n} \cdot \left( \frac{\delta\tilde{n}}{\delta x} \times \frac{\delta\tilde{n}}{\delta y} \right) \delta x \delta y$

$\tilde{n} = \frac{\tilde{M}(r)}{|\tilde{M}(r)|}$

Emergent field

$B_{\text{eff}}^z = -\phi_0 / A$

$\phi_0 = h/e$

$A$: Surface area of skyrmion

Emergent field is in inverse proportional to the square of skyrmion radius

- Topological particle
- Emergent field

Nontrivial emergent phenomena

Electromagnetic induction
Moving magnetic flux produces the transverse electric field

\[ e = -\frac{1}{c} [V \parallel \times h] \]

Topological Hall effect

Ultra-low Current-driven SkX motion in FeGe thin plate

J. Zhang, et al., PRL (2011)

Skyrmion Hall motion

\[ J_{c, Sk} \sim 10^5 \text{ A/m}^2 \ll J_{c, FM} \]
Magnetically-induced the formation of skyrmion lattice in B20 compounds

Crystal structure
- Cubic
- Noncentrosymmetric

Spin Hamiltonian
\[ H = \int \, dr \left[ \frac{J}{2} (\nabla \mathbf{M})^2 + \alpha \mathbf{M} \cdot (\nabla \times \mathbf{M}) \right] \]

Ground state:
spiral with \( q \sim \alpha J \)

Magnetically-induced the formation of SkL

Phase diagram in a bulk MnSi
- First observation for SkL in a prototype skyrmion material
- It is hardly to confirm the topological spin texture for a single skyrmion by SANS
- Narrow window for SkL phase in a bulk MnSi

We need a imaging technique to confirm the topological nature of skyrmions as well as their lattice forms.
Nucleation of magnetic skyrmions in chiral-lattice magnets under magnetic field

A chiral-lattice FeGe, 260 K

The $B \perp \text{the plate plane}$ induces the phase transition in two magnetic systems:

Stripes $\rightarrow$ SkX $\rightarrow$ FM

First real-space observation of magnetic skyrmion in a chiral-lattice magnet Fe$_{0.5}$Co$_{0.5}$Si

Skyrmions in a (001) Fe$_{0.5}$Co$_{0.5}$Si thin plate

- 2D SkL is robust in a thin chiral-lattice magnet
- Isolated skyrmions have been realized

In collaborations with Profs. Tokura, Nagaosa, Onose, Han; Drs. Matsui, Kanazawa
Realization of isolated skyrmions

One to one correspondence of skyrmion helicity and crystal chirality in chiral-lattice systems


Over-focused image plane

Electron beam

B

RT, 240 mT

100 K, 50 mT

50 nm

150 nm

XY & Y. Tokura, JEOL news (2015)
The thinner the sample is, the more stable SkX is.

Phase diagram in a bulk MnSi

MnSi thin plates

$\lambda$: period of helical structure

- $t \sim 5 \lambda$
- $t \sim 3 \lambda$
- $t < 3 \lambda$


- The thinner the crystal plate is, the wider SkX phase is in the T-B plane.
- Compared to Sk phase in (110) and (001) films, Sk phase shirked in the thicker (111) MnSi film (>75nm).
Transformation of square to triangular SkL in a Co-Zn-Mn

\[(001) \text{Co}_8\text{Zn}_9\text{Mn}_3\]

\[T = 295\text{K}\]
Transformation of a square lattice to a triangular lattice at the RT

(001) $\text{Co}_8\text{Zn}_9\text{Mn}_3$

$B = 20 \text{ mT}$

$B = 55 \text{ mT}$

$H_Z$

$K (D^2/J)$

I : spin spiral
II: squire lattice of skyrmions
III: hexagonal lattice of skyrmions
IV: spin spiral conical structure


XY, et al. in preparation
Various states of skyrmion aggregate at RT

20 mT
65 mT
90 mT
150 mT
Skyrmion strings at 250 K

$B = 90 \text{ mT}$

$B = 110 \text{ mT}$

Scale bars are 100 nm
**Topic I -2: Nucleation of magnetic skyrmions under current excitation**


Dc current-induced the formation of skyrmions
Electric current-induced topological phase transition

FeGe, 180 K, 160 mT

Co-Zn-Mn, RT, 100 mT

Conical phase
(q ⊥ plate plane)

Uniform contrast in defocused Lorentz TEM image

Skyrmion

500 nm

200 nm

Estimation of Joule heating effect

2~3 K @ 4 mA
Robust zero-field SkX in a FeGe thin plate

$B = 0, T = 6 \text{ K}$
Changes of the quenched SkX with an increase of the bias-field

XY, et al. in preparation

2017/7/27

SPICE Mainz
Crystallization of skyrmions and phase separation with a decrease of the bias field $T = 6$ K
Topic Ⅱ-1: skyrmion Hall motion with electric current flow

Skyrmion & Skyrmion lattice (observed by DPC-STEM)

B = 160 mT
T = 210 K

XY, et al. in preparation

\[ J = 7.8 \times 10^7 \text{ A} \cdot \text{m}^{-2} \]

\[ J = 8 \times 10^7 \text{ A} \cdot \text{m}^{-2} \]
Skyrmion Hall motion with electric current flow

FeGe, $J_C \sim 10^8 \text{A} \cdot \text{m}^{-2}$

$J = 7.8 \times 10^7 \text{A} \cdot \text{m}^{-2}$

$J = 8 \times 10^7 \text{A} \cdot \text{m}^{-2}$

$T (K)$

$J_C (10^8 \text{A} \cdot \text{m}^{-2})$

$500 \text{ nm}$

210 K  160 mT

$t = 0$

$t = 50 \text{ ms}$

$t = 100 \text{ ms}$

$t = 150 \text{ ms}$

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SPICE Mainz
Unidirectional rotation of SkL in a Cu$_2$OSeO$_3$ thin plate

$\textbf{Cu}_2\textbf{OSeO}_3$: $d_{\text{sk}} \sim 50 \text{ nm}$  $T = 35 \text{ K}, B \otimes = 65 \text{ mT}$

- Concentric thermal gradient created by electron beam
- Unidirectional rotational motion of skyrmion lattice

Summary

- 2D SkX as well as isolated skyrmions has been realized over a wide temperature range (6K~350 K) by means of Lorentz TEM.
- The fertile lattice forms as well as the bound skyrmions have been realized with tuning magnetic anisotropy in chiral-lattice compounds.
- Zero-field SkX can be stabilized with quenching of thermodynamically stable SkX in chiral-lattice magnets.
- Magnetic skyrmions can be excited by electric current.
- The *in-situ* Lorentz TEM observations have demonstrated a current-induced dynamical phase transition from a non-topological phase (conical phase) to a topological SkX phase.
- Lorentz TEM observations captured the skyrmion Hall motion with low-current (∼10^8 A/m^2) and thermal current.
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Thank you for your kind attention!

We are recruiting the young researchers who are interested in topological spin texture

yu_x@riken.jp