See also talks online by Tokura, Tchernyshyov

Magnetic skyrmions

Rembert Duine

with Marianne Knoester (UU)
Jairo Sinova (Texas A&M, Mainz)

ArXiv 1310.2850

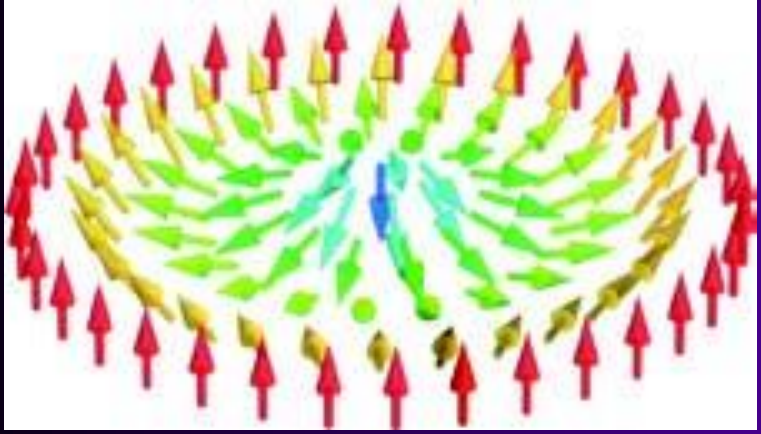
Institute for Theoretical Physics
Utrecht University

Outline:

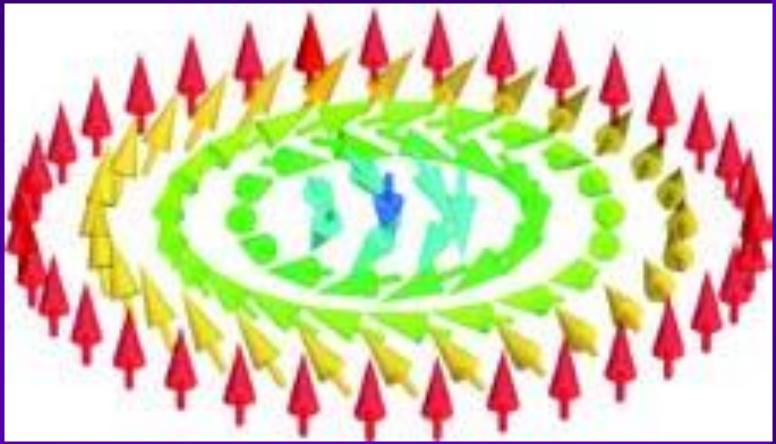
- What are magnetic skyrmions?: topology and energetics
- Skyrmion lattices and single skyrmions
- Interactions between skyrmions and current – weak and strong spin-orbit coupling
- (My) motivation: skyrmions are testing ground for current-magnetization interaction

Single magnetic (baby-)skyrmion

"hedgehog"



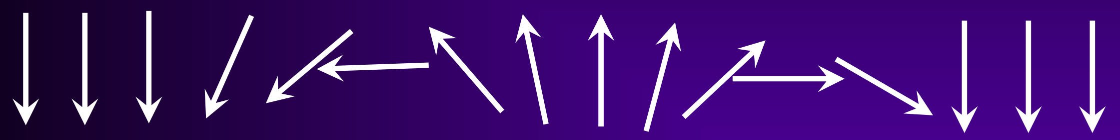
"vortex-like"



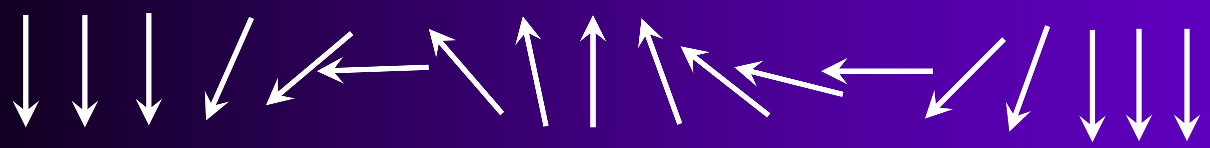
- Spins down at core, up everywhere else, homogeneous in z-direction
- Topological excitation, characterized by winding number: $4\pi W = \int d\vec{x}\, \Omega \cdot \frac{\partial \Omega}{\partial x} \times \frac{\partial \Omega}{\partial y}$

Pictures from Fert et al., Nature Nanotechnology (2013)

Even topologically speaking, not all bubbles are skyrmions…



$W=1$
chiral

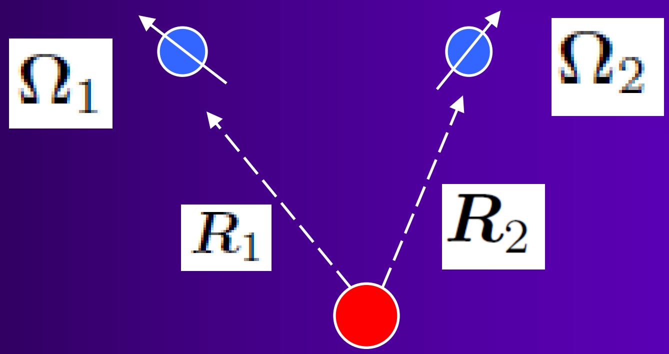


$W=0$
Not chiral

Skyrmion energetics (I)

- Chirality set by Dzyaloshinskii-Moriya interactions:

$$E_{\mathrm{DMI}} = \boldsymbol{D} \cdot \boldsymbol{\Omega}_1 \times \boldsymbol{\Omega}_2$$ with $$\boldsymbol{D} \propto \boldsymbol{R}_1 \times \boldsymbol{R}_2$$



magnetic atoms

non-magnetic,
strong spin-orbit coupling

Need inversion asymmetry
\+ spin-orbit coupling

Fert/Levy (1980)

Skyrmion energetics (II)

- Example of energy with bulk DM-interaction (MnSi) – favors vortex-like skyrmions:

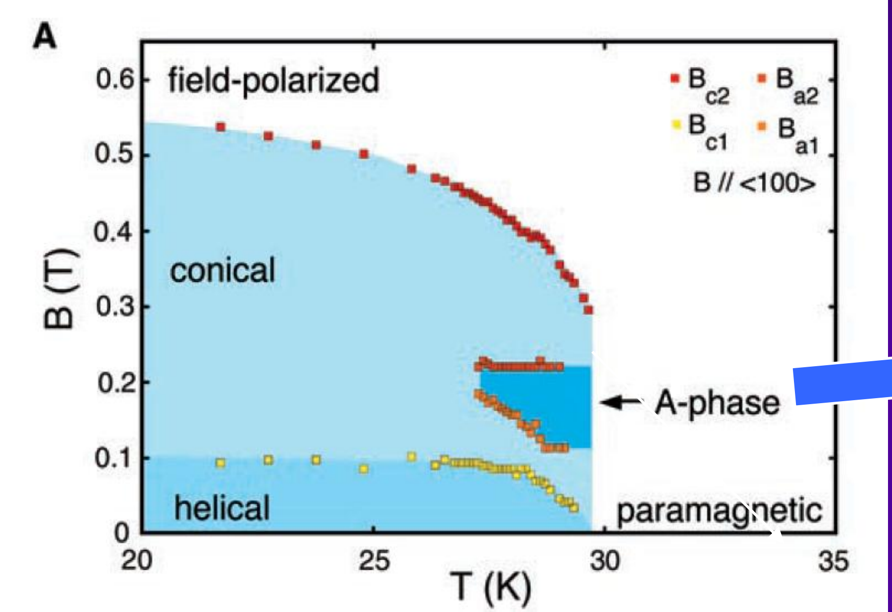
$$E = \int d\boldsymbol{x} \left\{ -\frac{J_s}{2} \boldsymbol{\Omega} \cdot \nabla^2 \boldsymbol{\Omega} + D \boldsymbol{\Omega} \cdot \nabla \times \boldsymbol{\Omega} - H \boldsymbol{\Omega}_z - \boldsymbol{\Omega} \cdot \boldsymbol{H}_d \right\}$$

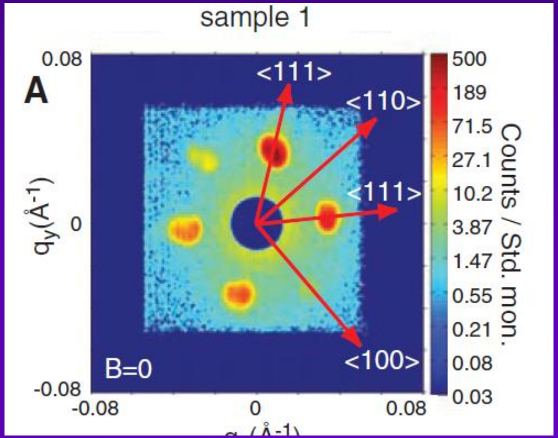
Size of spiral/skyrmion: $\sim J_s/D$

Skyrmions stable for fields: $H \sim J_s D^2$

Bogdanov/Hubert (1994)

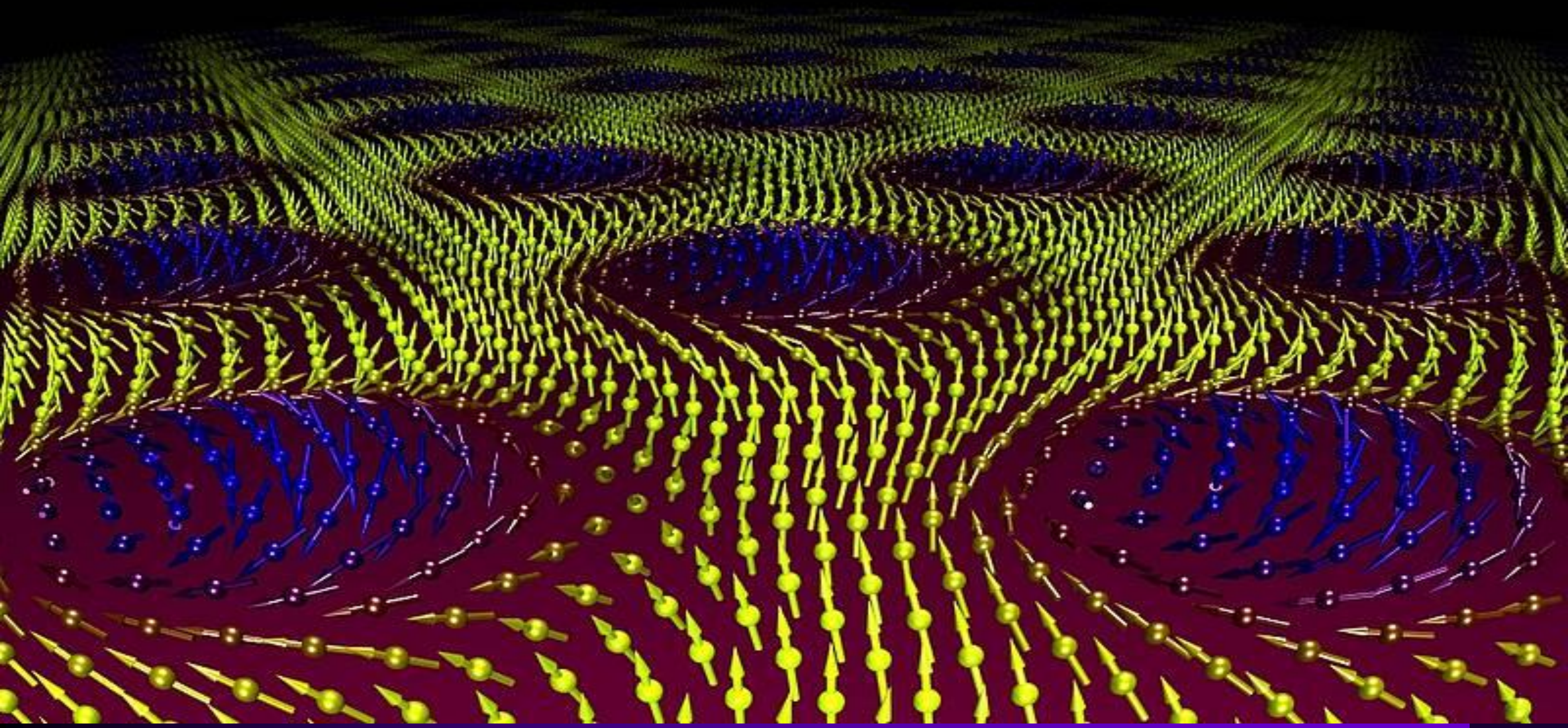
Skyrmion lattices





Neutron scattering experiments

Mühlbauer et al., (2009); Tokura/Wiesendanger groups



Mühlbauer et al., (2009)

Skyrmions/bubbles/vortices

- Skyrmions: topological (*W*=integer), exchange vs. DM interactions
- Bubbles: strictly speaking do not have to be topological, exchange vs. surface stray fields
- Magnetic vortices: exchange vs. dipolar field in magnetic disk, *W*=half-integer ("meron")

What about interaction with current?

Current-magnetization interaction

- Assume weak intrinsic spin-orbit coupling:

$$\left.\frac{\partial \mathbf{\Omega}}{\partial t}\right|_{\mathrm{current}} = a\left(\mathbf{j}\cdot\nabla\right)\mathbf{\Omega} + a'\mathbf{\Omega}\times\left(\mathbf{j}\cdot\nabla\right)\mathbf{\Omega}$$

⟷ Onsager

$$j_\alpha^{\mathbf{\Omega}} = \frac{\sigma M}{\gamma}\left\{a\frac{\partial \mathbf{\Omega}}{\partial x_\alpha}\cdot\left(\mathbf{\Omega}\times\frac{\partial \mathbf{\Omega}}{\partial t}\right) - a'\frac{\partial \mathbf{\Omega}}{\partial x_\alpha}\cdot\frac{\partial \mathbf{\Omega}}{\partial t}\right\}$$

Volovik, Bazaliy, Zhang/Li, Barnes/Maekawa, Brataas/Bauer/Tserkovnyak, RD, Tserkovnyak/Mecklenburg, …

Not restricted to solid state

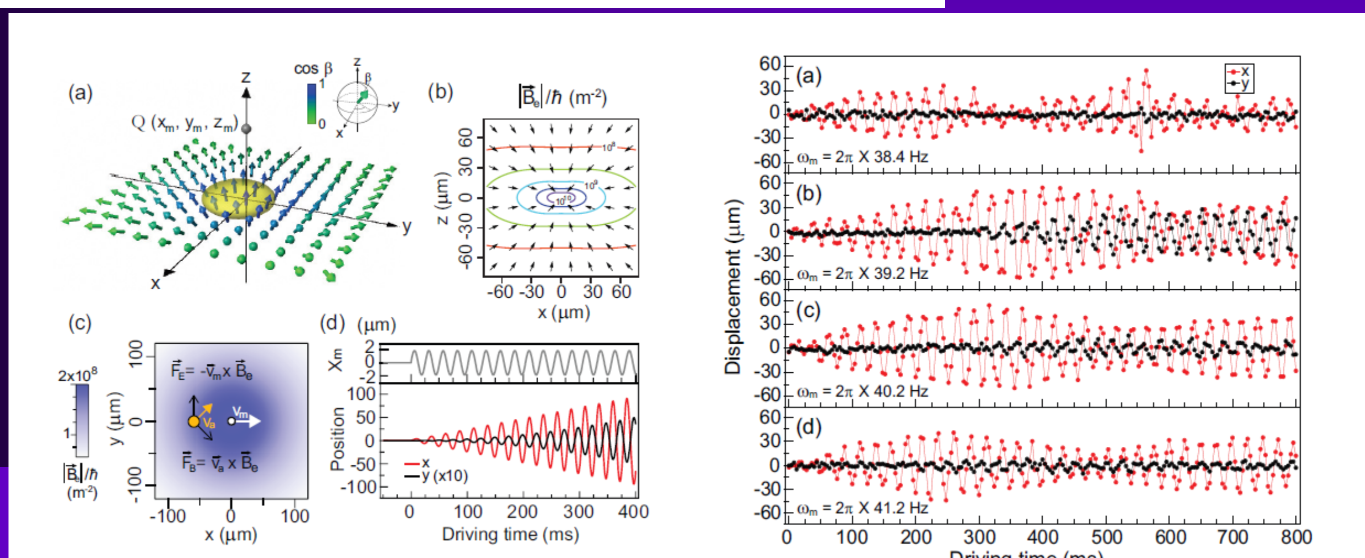
PRL 110, 260404 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Magnetization Relaxation and Geometric Forces in a Bose Ferromagnet

J. Armaitis,* H. T. C. Stoof, and R. A. Duine
Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, The Netherlands
(Received 27 March 2013; published 26 June 2013)

Observation of a Geometric Hall Effect in a Spinor Bose-Einstein Condensate

Jae-yoon Choi, Seji Kang, Sang Won Seo, Woo Jin Kwon, and Yong-il Shin*
Center for Subwavelength Optics and Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea



Current-magnetization interaction

- Assume negligible intrinsic spin-orbit coupling:

$$\left.\frac{\partial \boldsymbol{\Omega}}{\partial t}\right|_{\text{current}} = a\left(\mathbf{j}\cdot\nabla\right)\boldsymbol{\Omega} + a'\boldsymbol{\Omega}\times\left(\mathbf{j}\cdot\nabla\right)\boldsymbol{\Omega}$$

⟺ Onsager

$$j_\alpha^{\boldsymbol{\Omega}} = \frac{\sigma M}{\gamma}\left\{a\frac{\partial \boldsymbol{\Omega}}{\partial x_\alpha}\cdot\left(\boldsymbol{\Omega}\times\frac{\partial \boldsymbol{\Omega}}{\partial t}\right) - a'\frac{\partial \boldsymbol{\Omega}}{\partial x_\alpha}\cdot\frac{\partial \boldsymbol{\Omega}}{\partial t}\right\}$$

Volovik, Bazaliy, Zhang/Li, Barnes/Maekawa, Brataas/Bauer/Tserkovnyak, RD, Tserkovnyak/Mecklenburg, Tatara/Shibata/Kohno…

Experimental results: Current-driven rotation of skX

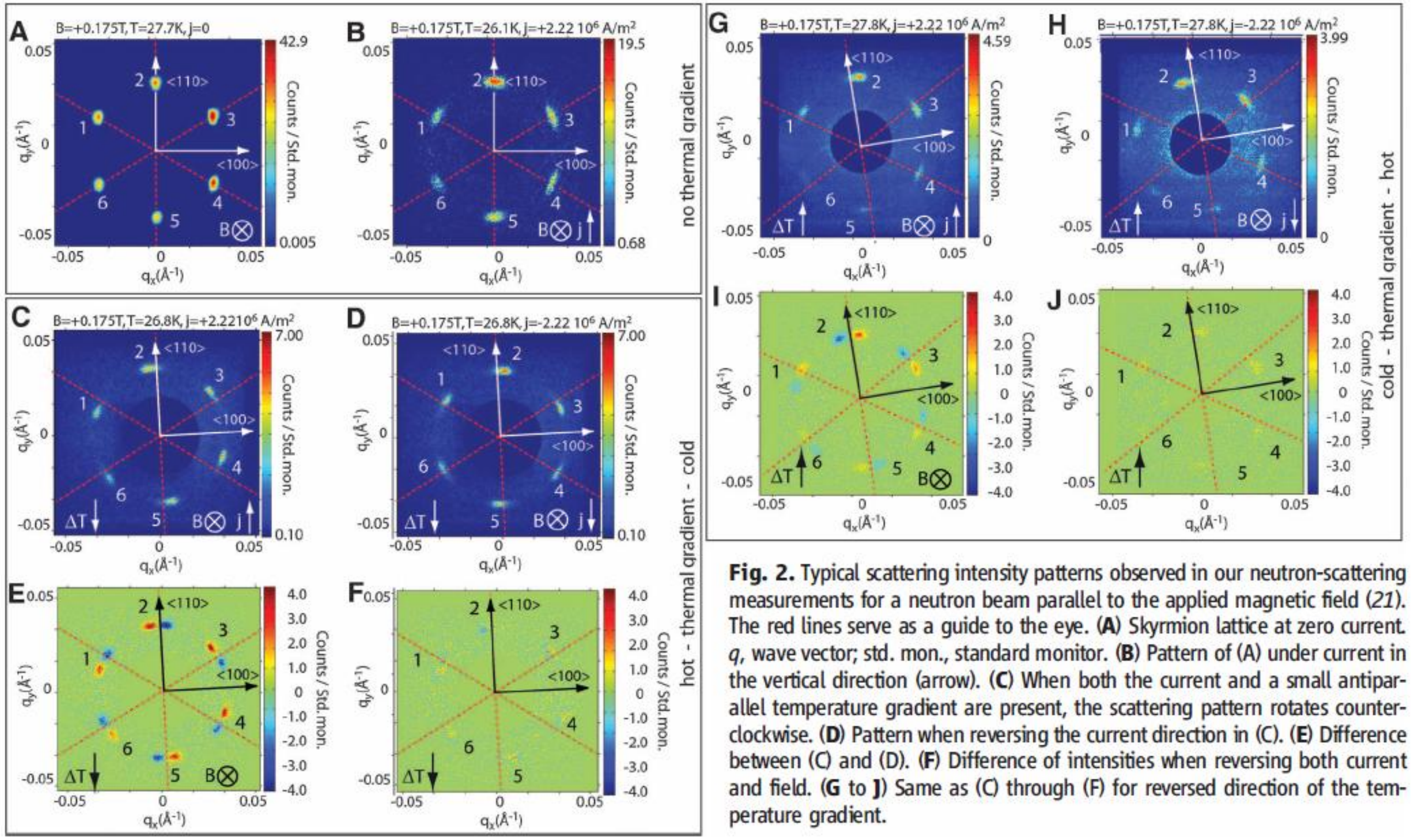
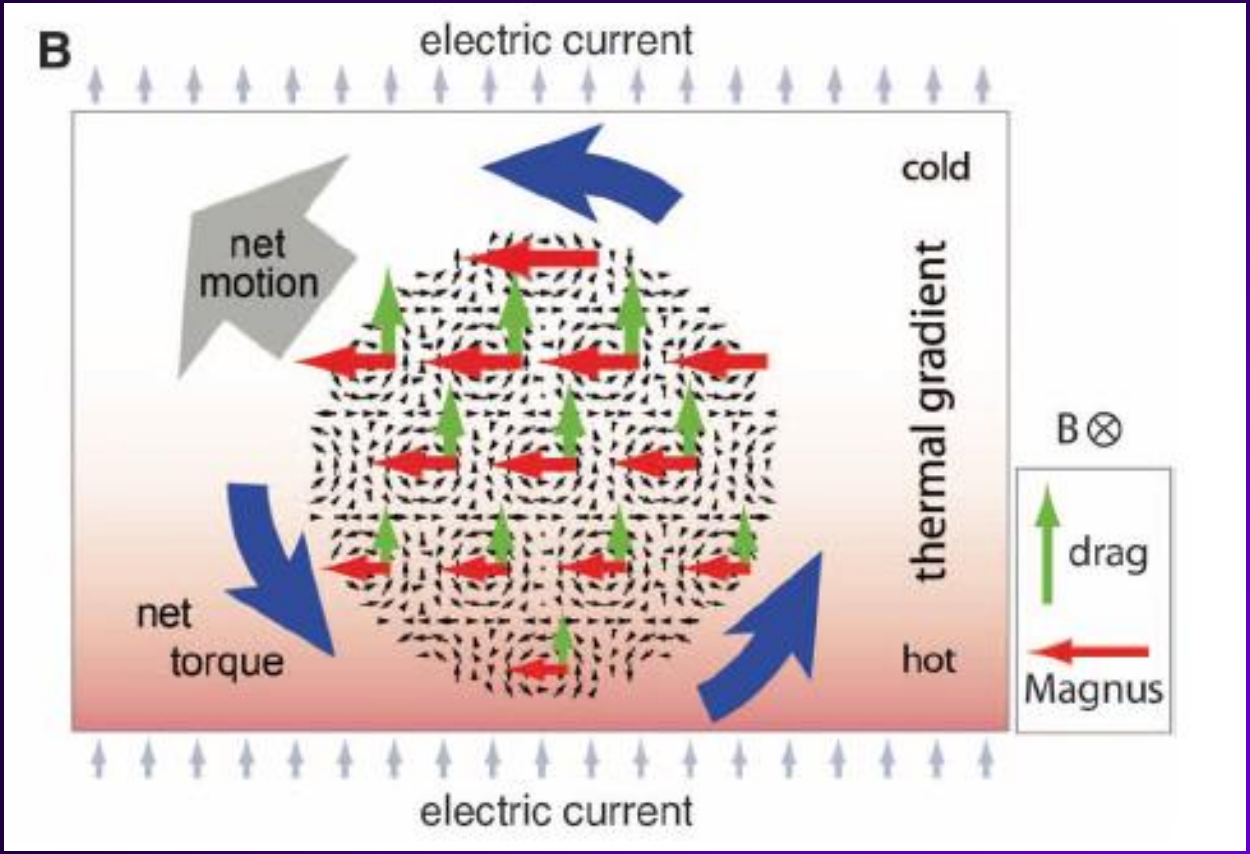


Fig. 2. Typical scattering intensity patterns observed in our neutron-scattering measurements for a neutron beam parallel to the applied magnetic field (*21*). The red lines serve as a guide to the eye. **(A)** Skyrmion lattice at zero current. *q*, wave vector; std. mon., standard monitor. **(B)** Pattern of (A) under current in the vertical direction (arrow). **(C)** When both the current and a small antiparallel temperature gradient are present, the scattering pattern rotates counterclockwise. **(D)** Pattern when reversing the current direction in (C). **(E)** Difference between (C) and (D). **(F)** Difference of intensities when reversing both current and field. **(G** to **J)** Same as (C) through (F) for reversed direction of the temperature gradient.

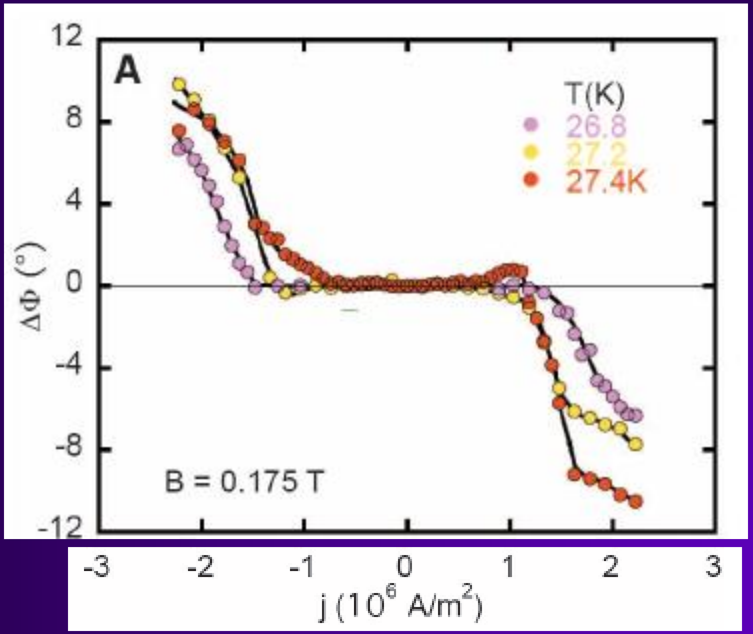
Jonietz, …RD, Pfleiderer, Rosch (2010)

Interpretation



Jonietz, …RD, Pfleiderer, Rosch (2010)

Critical current



Orders of magnitude smaller than for current-driven domain walls: skyrmion lattice weakly pinned to lattice, couples to current globally

Jonietz, …RD, Pfleiderer, Rosch (2010)

Topological Hall effect detection

Consider equation for the current:

$$j_\alpha^{\boldsymbol{\Omega}} = \frac{\sigma M}{\gamma} \left\{ a \frac{\partial \boldsymbol{\Omega}}{\partial x_\alpha} \cdot \left(\boldsymbol{\Omega} \times \frac{\partial \boldsymbol{\Omega}}{\partial t} \right) - a' \frac{\partial \boldsymbol{\Omega}}{\partial x_\alpha} \cdot \frac{\partial \boldsymbol{\Omega}}{\partial t} \right\}$$

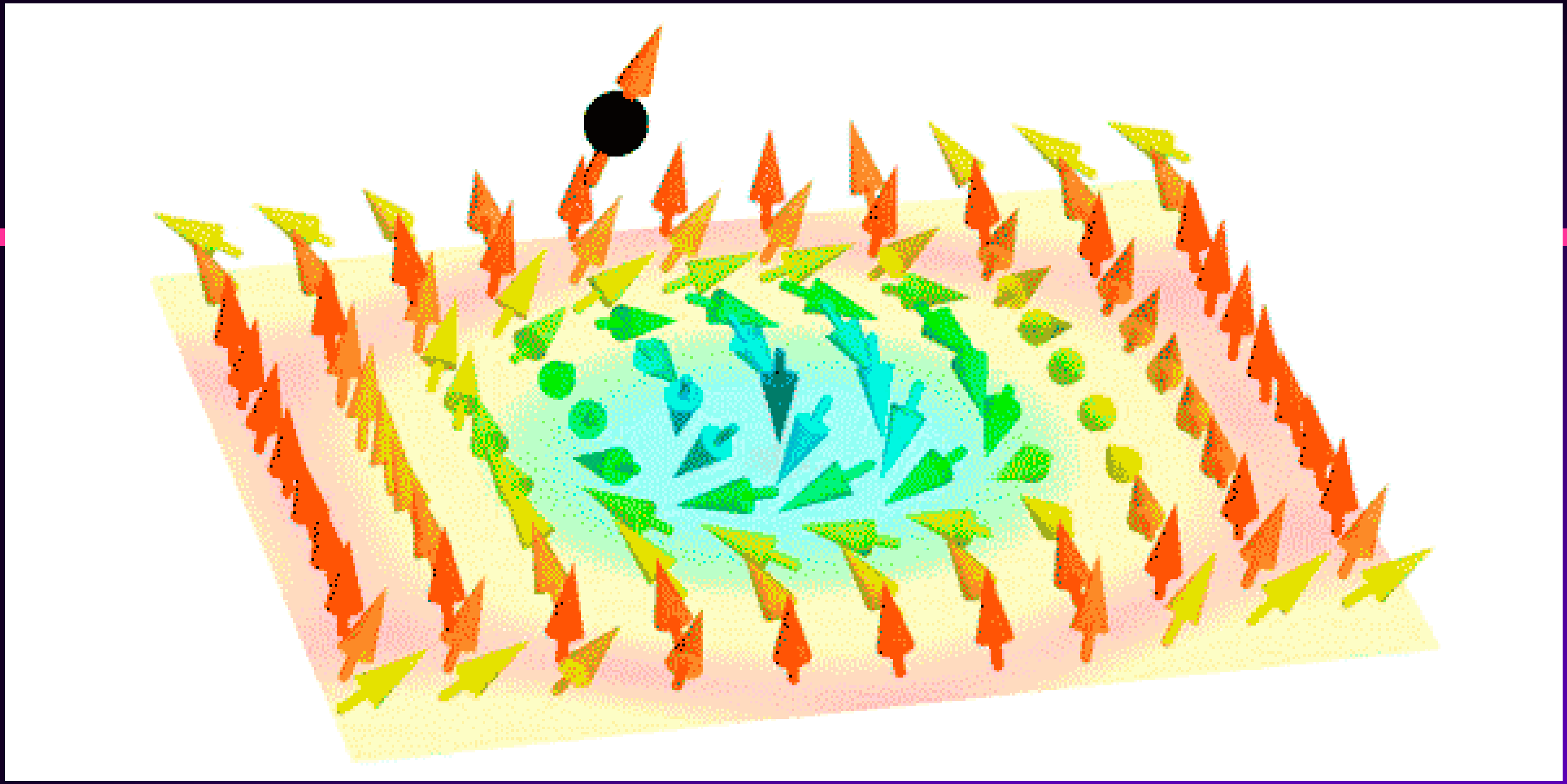
Allow for skyrmion motion and external current:

$$\frac{\partial}{\partial t} \to \cancel{\frac{\partial}{\partial t}} + \left(\boldsymbol{v}_{\mathrm{skyrmion}} - \boldsymbol{v}_{\mathrm{drift}} \right) \cdot \boldsymbol{\nabla}$$

$$\boldsymbol{j}^{\boldsymbol{\Omega}} \propto aW\hat{z} \times \left(\boldsymbol{v}_{\mathrm{skyrmion}} - \boldsymbol{v}_{\mathrm{drift}} \right)$$

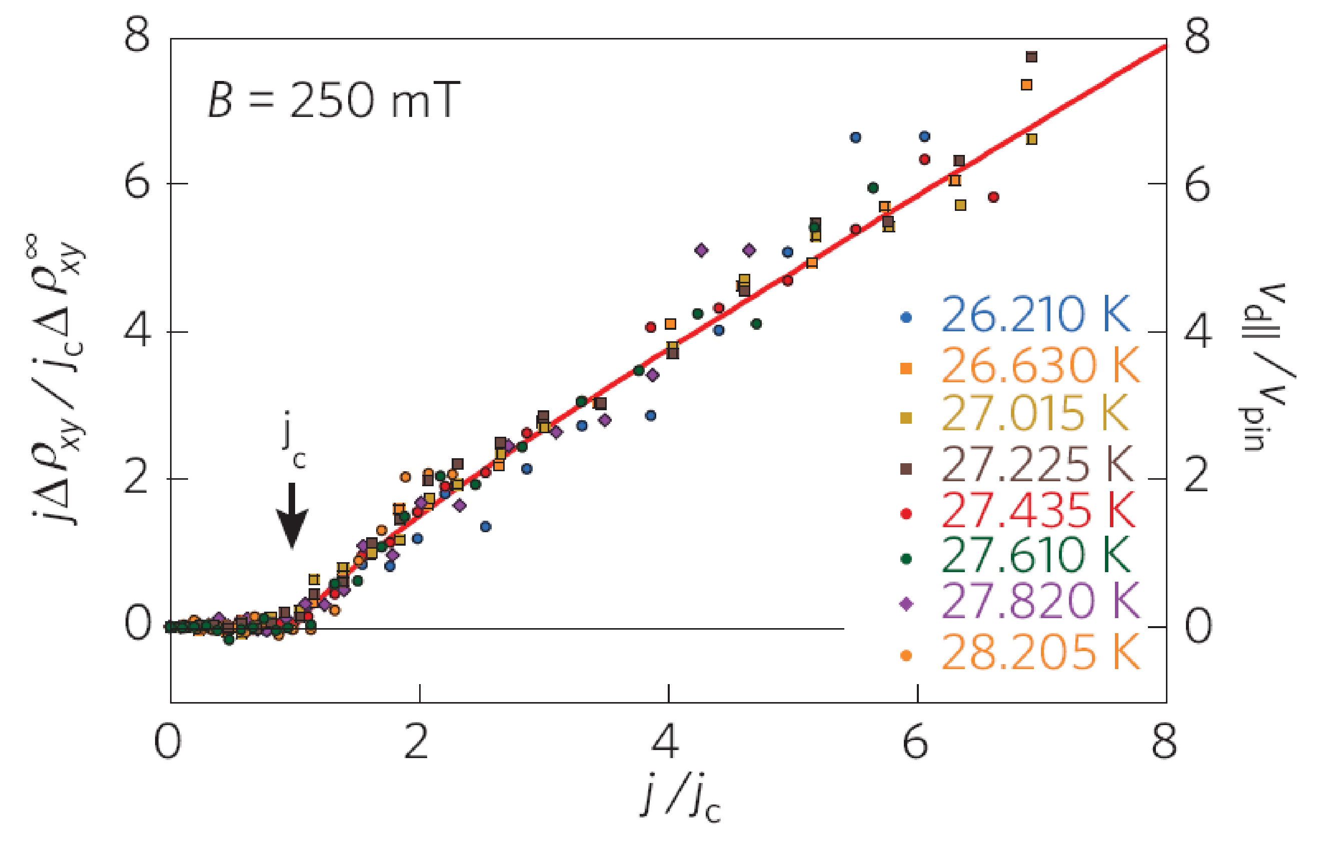
Hall signal drops when skyrmions move!

Same phenomenology applies to thermal transport (Van Hoogdalem, et al., PRB (2012))



Topological contribution Hall effect;
Reduces when skyrmion lattice slides

Pfleiderer, Rosch (2012)



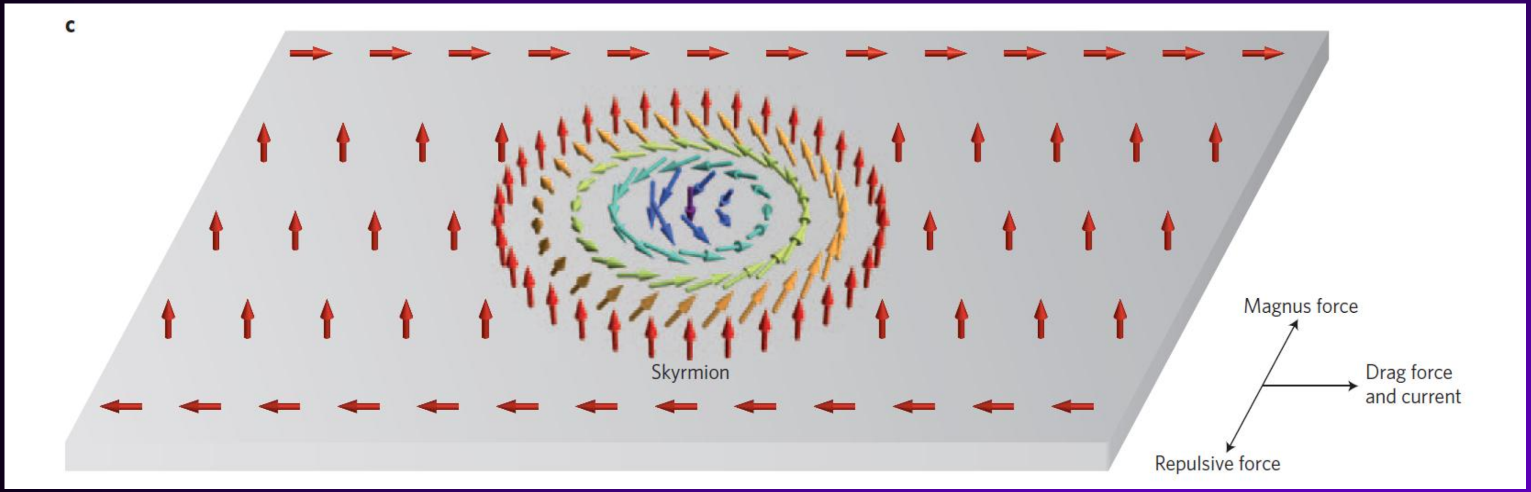
Experimental proof skyrmion lattice is sliding (neutron scattering proved rotation only)

Nature Phys. 8, 301 (2012)

What about single skyrmions?

Motion of single skyrmions

RD, N&V (2013)

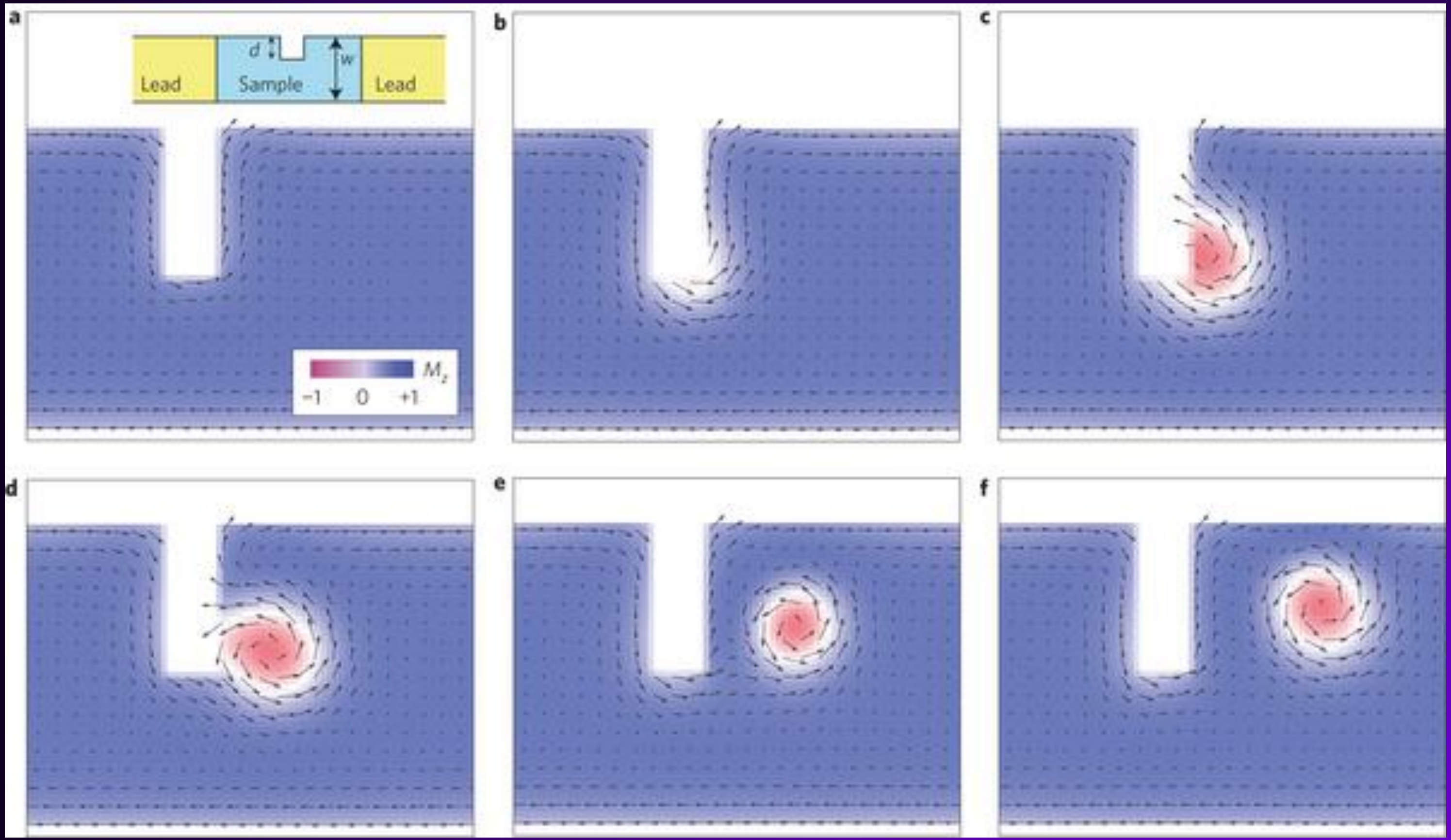


DM interactions lead to repulve force from edge that balances Magnus force; drag most important:

$$|\boldsymbol{v}_{\mathrm{skyrmion}}| \propto \frac{F_{\mathrm{drag}}}{\mathrm{damping}}$$

Nagaosa et al. (2013)
Cros/Sampaio/Fert/Thiaville (2013)

Skyrmion nucleation (I)



Nucleation only for one current direction

Nagaosa et al. (2013)

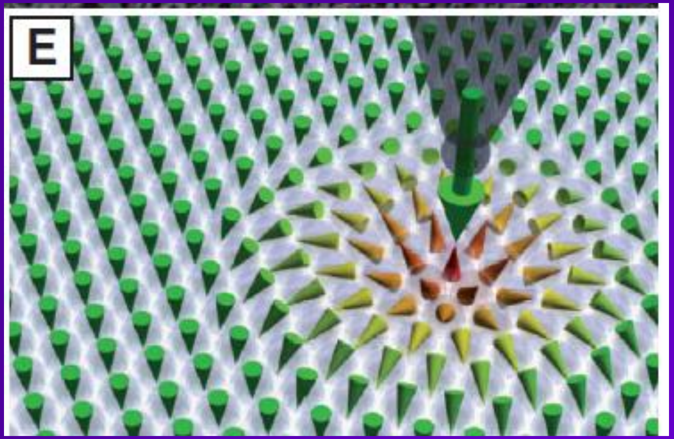
Skyrmion nucleation (II)

Writing and Deleting Single Magnetic Skyrmions

Niklas Romming, Christian Hanneken, Matthias Menzel, Jessica E. Bickel,* Boris Wolter, Kirsten von Bergmann,† André Kubetzka,† Roland Wiesendanger

Science (2013)

- Spin-polarized STM
- Low *T*



Summary (so far:)

- Skyrmion lattices (theory and experiments):
  - current-driven motion: low *T* + near room *T*
  - electrical detection: topo Hall effect (low *T* + near room *T*)
  - nucleation/destruction: STM at low *T*
- Single skyrmions
  - current-driven motion (theory)
  - nucleation: notches (theory)
  - electrical detection: ?

Rest of talk

- Motivated by experiments on chiral domain walls: skyrmions in system with inversion asymmetry in one (=z) direction: perpendicular magnetic anisotropy (PMA) materials
- Include intrinsic spin-orbit coupling in current-skyrmion coupling [for MnSi; Hals/Brataas (2013)]
- Skyrmions allow for classification in powers of spin-orbit coupling of phenomenological terms

Phenomenological energy from symmetry:

Now: look at strong SO coupling + breaking of inversion in z-direction (due to interface)

Dzyaloshinkii-Moriya (DM) interaction

Anisotropy:

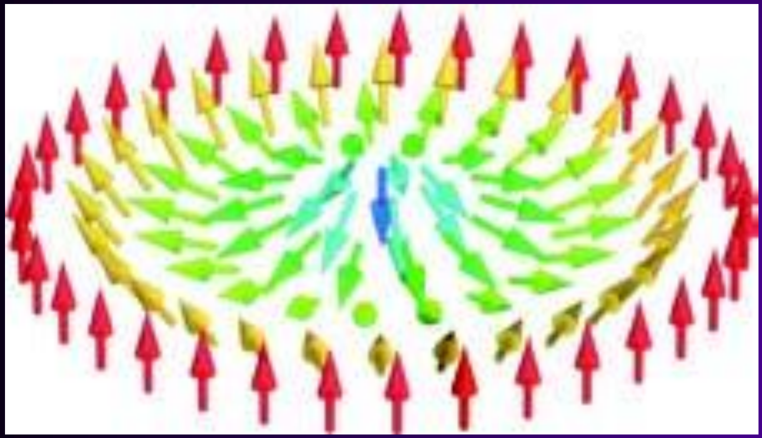
$$E = \int d\vec{x} \left\{ -J\vec{\Omega}.\nabla^2\vec{\Omega} - K\left(\hat{z}\cdot\vec{\Omega}\right)^2 + D\left(\hat{z}\times\vec{\Omega}\right)\cdot\left(\nabla\times\vec{\Omega}\right) \right\}$$

Only term allowed without SO coupling (anisotropy in *J*=ignored)

Experimental motivation:
Miron et al., Beach et al., Parkin et al., Ralph/Burhman et al., ...

Skyrmions in PMA materials

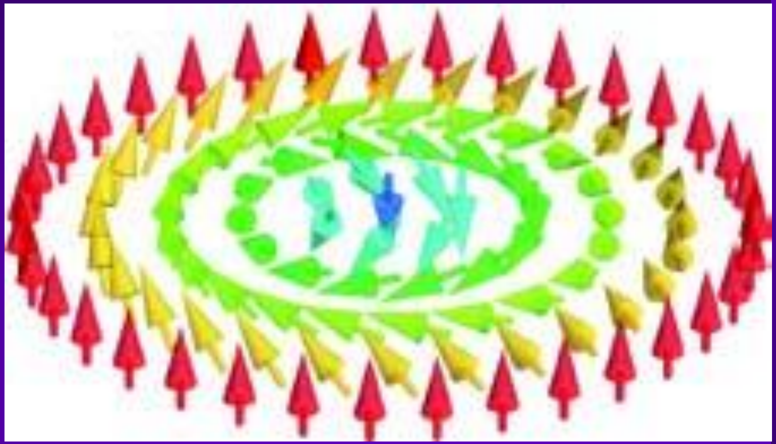
Favoured by interface DM interaction

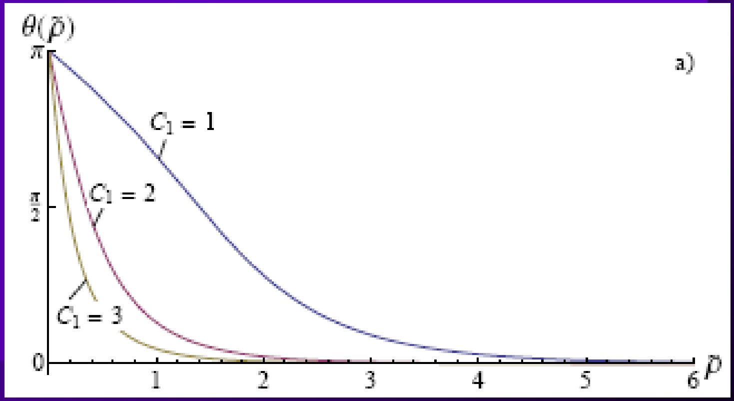


↑

Parameters of Beach et al.: these are the ones in PMA materials

Favoured by bulk DM interaction (MnSi), dipole-dipole





Size: J/D~10 nm
gradient~SOC^1

Knoester, Sinova, Duine, ArXiv (2013)

Phenomenological point-of-view

First: Current-induced torques on homogeneous magnetization (linear in electric field):

$$\left.\frac{\partial\vec{\Omega}}{\partial t}\right|_{current} \propto \vec{\Omega}\times\left(\vec{E}\times\hat{z}\right)+\beta'\vec{\Omega}\times\left(\vec{\Omega}\times\left(\vec{E}\times\hat{z}\right)\right)$$

- spin-orbit coupling: spatial and spin vectors allowed to "mix"
- Broken inversion symmetry: torques allowed to depend on $\hat{z}$
- Parity: each electric field comes with $\hat{z}$
- Microscopically: due to spin-current injection via SHE or Rashba spin-orbit couplin, or Berry-``field" (cf. Sinova et al.)

Garate/MacDonald (2009), Manchon & Zhang (2009), Kim et.al. (2012), Pesin & MacDonald (2012).

Phenomenological point-of-view

Current-induced torques on inhomogeneous magnetization:

$$\left.\frac{\partial\vec{\Omega}}{\partial t}\right|_{current} \propto \vec{\Omega}\times\left(\vec{E}\times\hat{z}\right)+\beta'\vec{\Omega}\times\left(\vec{\Omega}\times\left(\vec{E}\times\hat{z}\right)\right)$$
$$+\vec{\Omega}\times\left(\vec{\Omega}\times\left(\vec{E}\cdot\nabla\right)\vec{\Omega}\right)+\beta\vec{\Omega}\times\left(\vec{E}\cdot\nabla\right)\vec{\Omega}$$

This can –from symmetry point-of-view – not be the complete description, for e.g., domain-wall motion!! There should be torques from combination of gradients and SO coupling!

Phenomenological point-of-view

Current-induced torques on inhomogeneous magnetization:

$$\left.\frac{\partial\vec{\Omega}}{\partial t}\right|_{current} \propto \vec{\Omega}\times\ldots$$

…=any pseudovector that:

- One can build from $\hat{z}$, ∇, $\vec{\Omega}$, and/or $\vec{E}$
- Is first order in electric field (linear response) and/or gradients

Van der Bijl/Duine, PRB (2012)
Hals/Brataas, ArXiv, (2013)

Examples of symmetry-allowed torques:

$$\left.\frac{\partial\vec{\Omega}}{\partial t}\right|_{current} \propto \#\ldots + \#\vec{\Omega}\times\ldots$$

$$\sum_{j=x,y,z}\left(\vec{\Omega}\times\vec{E}\right)_j\left(\vec{\Omega}\times\nabla\right)\Omega_j$$

$$\left(\vec{E}\cdot\nabla\right)\vec{\Omega} \qquad \left(\vec{\Omega}\cdot\vec{E}\right)\left(\vec{\Omega}\cdot\nabla\right)\vec{\Omega}$$

$$\left(\vec{\Omega}\times\vec{E}\right)\left(\nabla\cdot\vec{\Omega}\right)$$

$$\left(\left(\vec{\Omega}\times\vec{E}\right)\cdot\nabla\right)\vec{\Omega}$$

$$\sum_{j=x,y,z} E_j\left(\vec{\Omega}\times\nabla\right)\Omega_j \qquad \left(\vec{\Omega}\times\vec{E}\right)\vec{\Omega}\cdot\left(\nabla\times\vec{\Omega}\right)$$

14 symmetry-allowed torques, not including z-direction yet..., some have straightforward interpretation, some don't ...

Power-counting of current-induced torques:

*Order: SOC^1 * gradient^0*

$$\left.\frac{\partial\vec{\Omega}}{\partial t}\right|_{current} \propto \vec{\Omega}\times\left(\vec{j}\times\hat{z}\right)+\beta'\vec{\Omega}\times\left(\vec{\Omega}\times\left(\vec{j}\times\hat{z}\right)\right)$$

$$+\vec{\Omega}\times\left(\vec{\Omega}\times\left(\vec{j}\cdot\nabla\right)\vec{\Omega}\right)+\beta\vec{\Omega}\times\left(\vec{j}\cdot\nabla\right)\vec{\Omega} \;+\; many\ more$$

*Order: SOC^0 * gradient^1*

*Order: SOC^1 * gradient^1*

Order SOC^1 for skyrmions!

Order SOC^2 for skyrmions!

Thiele equation for position of skyrmion:

Phenomenologuy of current-skyrmion coupling
to first order in SO coupling (other torques 2nd order):

$$\left.\frac{\partial \mathbf{\Omega}}{\partial t}\right|_{\text{current}} = a\left(\mathbf{j}\cdot\nabla\right)\mathbf{\Omega} + a'\mathbf{\Omega}\times\left(\mathbf{j}\cdot\nabla\right)\mathbf{\Omega}$$
$$+b\mathbf{\Omega}\times\left(\mathbf{j}\times\hat{z}\right) + b'\mathbf{\Omega}\times\left[\mathbf{\Omega}\times\left(\mathbf{j}\times\hat{z}\right)\right] \;,$$

Thiele equation:

$$\epsilon_{\alpha\beta}\left(\dot{X}_\beta + a j_\beta\right) =$$
$$-D_{\alpha\beta}\left(\alpha_G\dot{X}_\beta + a' j_\beta\right) + b\lambda I_{\alpha\beta} j_\beta + b'\lambda I'_{\alpha\beta} j_\beta$$

Estimates (only *b'*): speed~1-100 m/s

Resistivity due to current-skyrmion coupling

Topological Hall

Drag effects (Wong/Tserkovnyak)

$$\Delta\rho_{\alpha\beta} = -\frac{Ma}{\gamma ne}\frac{\partial\mathbf{\Omega}}{\partial x_\alpha}\cdot\left(\mathbf{\Omega}\times\frac{\partial\mathbf{\Omega}}{\partial x_\beta}\right) + \frac{Ma'}{\gamma ne}\frac{\partial\mathbf{\Omega}}{\partial x_\alpha}\cdot\frac{\partial\mathbf{\Omega}}{\partial x_\beta}$$
$$+\frac{Mb}{\gamma ne}\left(\hat{z}\times\frac{\partial\mathbf{\Omega}}{\partial x_\beta}\right)_\alpha - \frac{Mb'}{\gamma ne}\left[\hat{z}\times\left(\frac{\partial\mathbf{\Omega}}{\partial x_\beta}\times\mathbf{\Omega}\right)\right]_\alpha .$$

Texture+SO coupling induced Hall contribution

Texture+SO coupling induced contribution

Current generation of PMA (domain wall materials):

a=a'=b=0 [Beach's experiments]

Discussion

- Skyrmions attractive for controlled study of current-magnetization interaction [extra info via charging effects; cf. Bamler et al. (2013)]
- Are skyrmions more attractive then domain walls? (electrical detection, nucleation, speed, stability, interactions…?)
- What are the best materials for room *T* skyrmions?