Skyrmionic cocoons in magnetic multilayers

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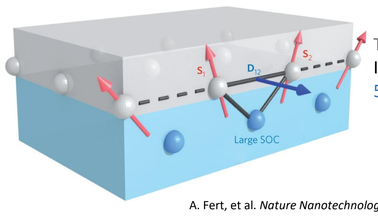
In aperiodic magnetic multilayers, we report the existence and characterization of skyrmionic cocoons, a novel 3D topological magnetic textures with a typical ellipsoid shape, which only extends along a fraction of the total thickness. Their vertical confinement can be controlled by optimizing the multilayer architecture or with an external magnetic field. Interestingly, they can coexist with more usual magnetic texture, like columnar skyrmions, which is an important asset for potential applications.

M. Grelier, et al. "Three-dimensional skyrmionic cocoons in magnetic multilayers." arXiv preprint arXiv:2205.01172 (2022). Under review at Nat. Comm.
M. Grelier, et al. "X-ray Fourier transform holography of skyrmionic cocoons in aperiodic magnetic multilayers." Submitted to APL Materials.

Skyrmions and beyond

Interfacial Dzyaloshinskii-Moriya Interaction (DMI)

- Antisymmetric analogue of the Heisenberg exchange interaction
- Requirements → Breaking of inversion symmetry; Spin-Orbit Coupling (SOC)



Thin 3d metal
Interface to break inversion symmetry
5d metal: indirect exchange, strong SOC

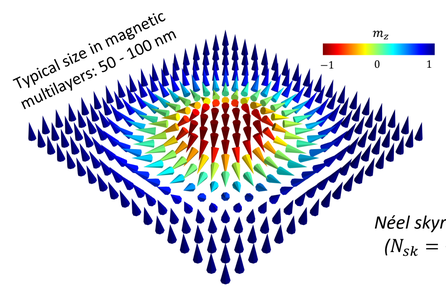
$$H_{DMI} = -D_{12} \cdot (S_1 \times S_2)$$

A. Fert, et al. *Nature Nanotechnology* 8.3 (2013): 152-156.

Favours **non-collinear arrangement** of the spins

Skyrmions

Two-dimensional **whirling** of the magnetization



Néel skyrmion ($N_{sk} = -1$)

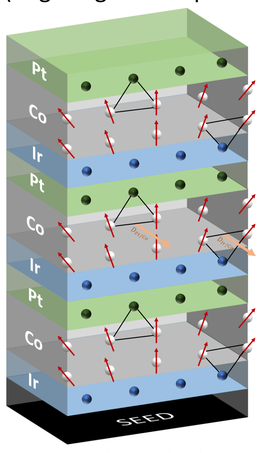
- Topologically non-trivial:

$$N_{sk} = \frac{1}{4\pi}\int_S \hat{m} \cdot \left(\frac{\partial \hat{m}}{\partial x} \times \frac{\partial \hat{m}}{\partial y}\right) dx\, dy = \pm 1$$

- Results of the interplay of various magnetic interactions: exchange, anisotropy, dipolar, DMI, Zeeman…

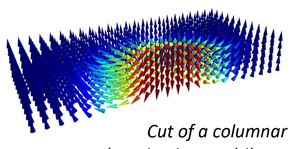
Magnetic multilayers

Stabilization of hybrid **columnar skyrmions** with larger thermal stability and easier to characterize (larger signal in experiments).



Typical multilayer structure
C. Moreau-Luchaire, et al. *Nature Nanotechnology* 11. (2016): 444-449.

If the two interfaces are the same, the DMI cancels out. With materials of opposite DMI sign, it adds up.

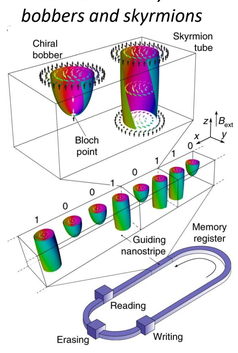


Cut of a columnar skyrmion in a multilayer

Exploring the third dimension

- Variations over the vertical dimension
- More possibility for potential applications

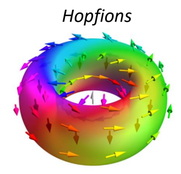
Racetrack memory with bobbers and skyrmions



Zheng, Fengshan, et al. *Nature Nanotechnology* 13.6 (2018): 451-455.

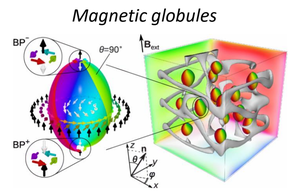
Truncated skyrmions, skyrmion braids…

Hopfions



Göbel, Börge, et al. Physical Review Research 2.1 (2020): 013315.

Magnetic globules



Müller, Gideon P., et al. *Physical Review B* 101.18 (2020): 184405.

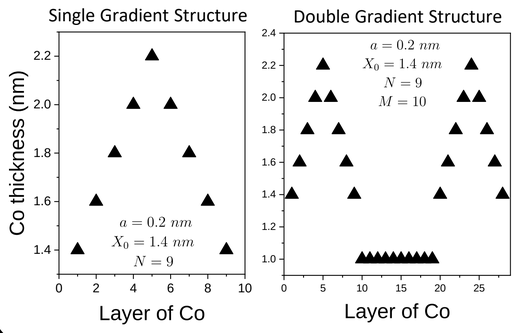
Towards 3D objects

Engineering of complex multilayers

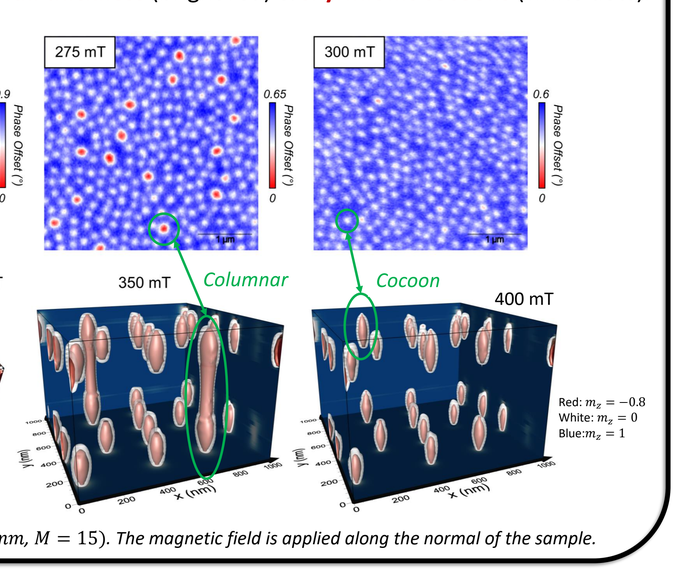
- Use **variable thickness of the ferromagnetic material** to induce a non-uniform effective anisotropy.
- Typical evolution for the Co thickness X_i:

$$X_{i+1} = \begin{cases} X_i + a \;\; for \;\; i \leq N/2 \\ X_i - a \;\; for \;\; i > N/2 \end{cases}$$

a: Thickness step ; N: number of magnetic layers; X_1 fixed



Schematic of the main architectures susceptible to host skyrmionic cocoons



Single Gradient (SG)
Repetitions of N trilayers Pt/Co/Al with variable Co thickness

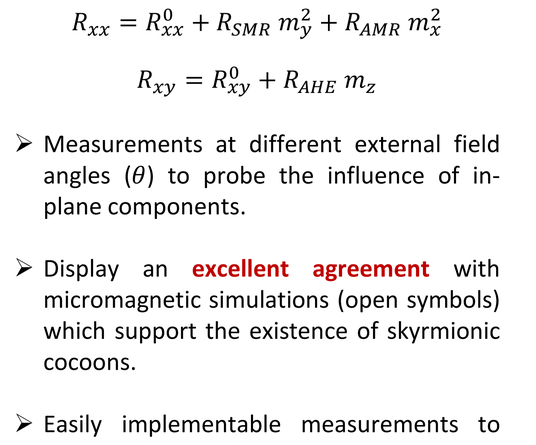
Double Gradient (DG)
Two gradients sandwich a block made of M trilayers with thin Co

Controlling the vertical confinement

- Ability to **tune the height** of the skyrmionic cocoons that are only present in a fraction of the layers in SG.

With an out-of-plane magnetic field

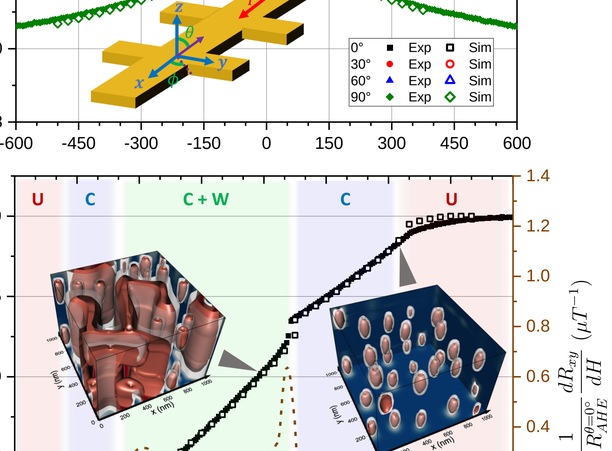
Evolution from columnar skyrmion to skyrmionic cocoon that possesses a typical ellipsoidal shape



Columnar skyrmion *Skyrmionic cocoon*

With the thickness step *a*

Strong impact of the gradient for equivalent magnetic field and average thickness



Signature of skyrmionic cocoons

- Magnetic Force Microscopy (MFM) to probe the stray field. Correlation with micromagnetic simulations.
- Different contrasts: **textures extending over the full thickness** (bright red) & **skyrmionic cocoons** (white dots).

Measurement on a DG structure ($X_1 = 2.0\ nm$, $N = 13$, $a = 0.1\ nm$, $M = 15$). The magnetic field is applied along the normal of the sample.

X-Ray Fourier Transform Holography

- Lensless transmission technique in reciprocal space measuring the interferences between an object hole and various reference holes. A simple Fourier Transform of the resulting holograms yields a signal closely related to m_z **averaged over the thickness**.
- Typical resolution defined by the reference holes size (typically 30nm) and the numerical aperture of the setup. **Phase Retrieval** process used to improve the contrast and resolution.
- Evidence of **various 3D objects** (different contrasts) and **magnetic phase transitions** (coloured ellipses).

Field dependency of the real-space reconstruction for a DG multilayer ($X_1 = 2.0\ nm$, $N = 13$, $a = 0.1\ nm$, $M = 15$) with a 800 nm object hole

Electronic transport

- Probe the **averaged magnetic properties** while sweeping the magnetic field.
- Multiple contributions to the resistance:
  - Spin Hall magnetoresistance (SMR)
  - Anisotropic magnetoresistance (AMR)
  - Anomalous Hall Effect (AHE)

$$R_{xx} = R^0_{xx} + R_{SMR}\, m_y^2 + R_{AMR}\, m_x^2$$

$$R_{xy} = R^0_{xy} + R_{AHE}\, m_z$$

- Measurements at different external field angles (θ) to probe the influence of in-plane components.
- Display an **excellent agreement** with micromagnetic simulations (open symbols) which support the existence of skyrmionic cocoons.
- Easily implementable measurements to detect 3D magnetic textures.
- Identification of the **various magnetic phases** (see coloured background): uniform (***U***), skyrmionic cocoons (***C***) and skyrmionic cocoons along with textures extending over the full thickness (***C+W***).

Magneto-transport measurements in a DG structure ($X_1 = 2.0\ nm$, $N = 13$, $a = 0.1\ nm$, $M = 15$).

Summary

- Stabilized skyrmionic cocoons, a novel 3D topological magnetic texture with an ellipsoidal shape, able to coexist with columnar skyrmions and whose vertical confinement can be controlled by various means.
- Their existence is supported by very different measurements (MFM, magneto-transport, holography, XRMS) correlated with micromagnetic simulations.
- X-Ray **laminography** experiment have also been performed to reconstruct experimentally the 3D magnetization, confirming the existence of magnetic textures displaying a limited vertical extension.
- Next studies: topological phase transitions, current-induced dynamics…

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