Dzyaloshinskii-Moriya Interaction

You Spin me round…

Pierre Géhanne – IDMAG
Cookies club – 14/06/2018

Outline

1. Magnetism : a short introduction
2. What is DMI ?
3. Effects of DMI

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1. Magnetism : a short introduction

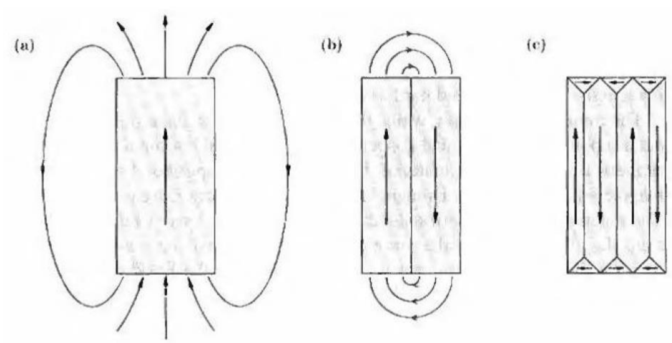
- Back to basics

Iron…
- can be strongly magnetized
- but not above a certain temperature T_c

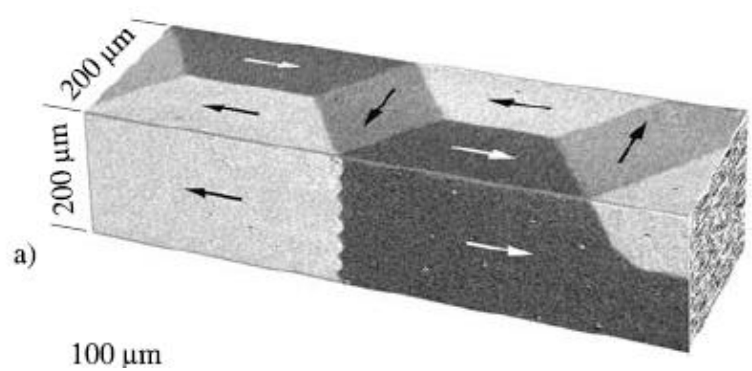
A magnet cut in halves = two magnets

Some interaction holds microscopic magnets together -> exchange

How can a ferromagnet have zero magnetization under T_c ?
-> domains



Blundell (Oxford, 2001)



Hubert & Schäffer (Springer, 2009)

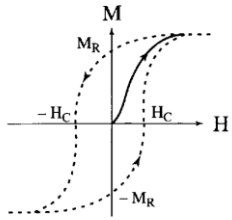
Magnetic domains

Heisenberg exchange (spins // to each other)

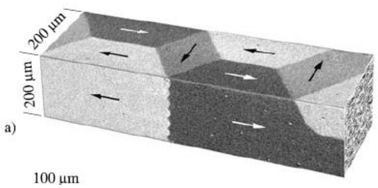
Dipole-dipole interaction (stray field cost energy)

1. Magnetism : a short introduction

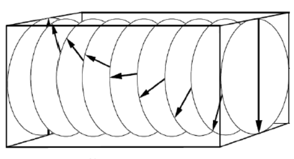
- The many scales of magnetism



Macroscopic magnetim

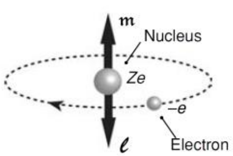


Domains (> 1 µm)
Mesoscopic arrangement of magnetization



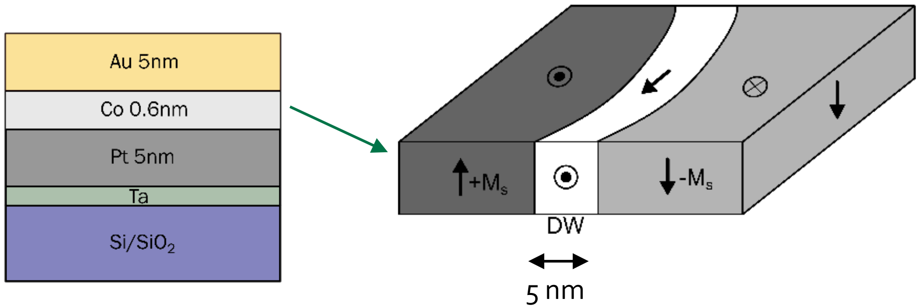
Domain walls (1 nm to 1 µm)
Boundaries between areas of same magnetization

Atomic level(< 1 nm)
Elementary magnetic moments (localized or travelling electrons)

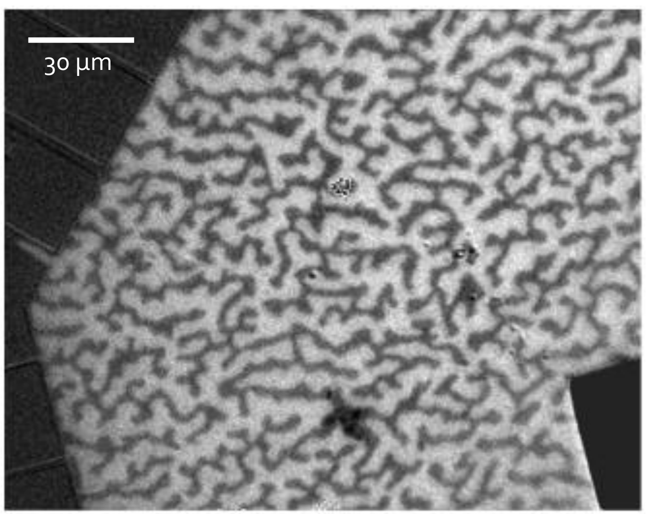


Hubert & Schäffer (Springer, 2009)
du Trémolet de Lacheisserie et al. (EDP Sciences, 2000)
Coey (Cambridge, 2009)

Magnetism of nearly 2D magnets :



Thin film = A few mono layers of FM on top of a substrate, possibly sandwiched between other metals or oxydes.



V. Jeudy, J. Curiale, A. Lemaitre

Stripe domains in (Ga,Mn)/As
(MOKE microscopy)

Magnetic domains

Heisenberg exchange
(spins // to each other)

Dipole-dipole interaction
(stray field cost energy)

Anisotropy
(spins // easy axis, defined by the lattice or surface effects)

Type of domain walls

Preferred spins direction

Outline

1. Magnetism : a short introduction
2. What is DMI ?
3. Effects of DMI

2. What is DMI ?

- Exchange : symmetric

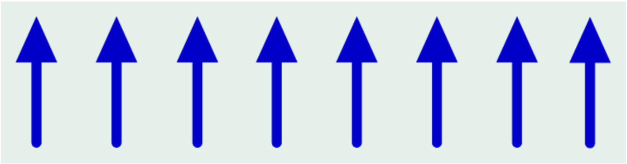
Exchange interaction :

$$H = \sum_{<i,j>} \underbrace{-J\vec{S}_i \cdot \vec{S}_j}_{\text{Heisenberg}}$$

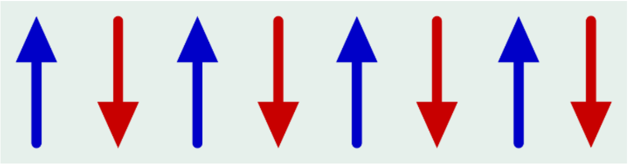
Heisenberg term (symmetric) :
favors parallel spins

$J > 0$ Ferromagnetic order

$J < 0$ Antiferromagnetic order



$J > 0$



$J < 0$

2. What is DMI ?

- Exchange : symmetric and antisymmetric

Exchange interaction :

$$H = \sum_{<i,j>} [-J\vec{S}_i \cdot \vec{S}_j + \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)]$$

Heisenberg DMI

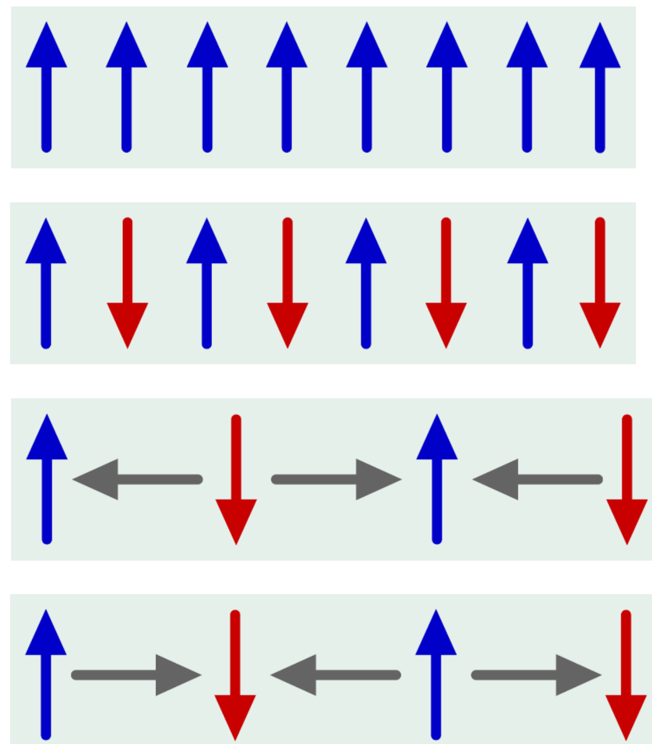
Heisenberg term (symmetric) :
favors parallel spins

$J > 0$ Ferromagnetic order

$J < 0$ Antiferromagnetic order

Dzyaloshinskii-Moriya term (antisymmetric) :
favors perpendicular spins.

The spins curl around the D vector, whose direction depends on the sign of the spin-orbit coupling and on the geometry.



$J > 0$

$J < 0$

$\odot \ \vec{D}_{ij}$

$\otimes \ \vec{D}_{ij}$

2. What is DMI ?

- History of DMI

In the 50's : some antiferromagnets display a small macroscopic magnetization… (e.g. hematite, α-Fe_2O_3).

Dzyaloshinskii : some canting of the spins is allowed if there is no inversion symmetry in the crystal

-> asymmetric term $\overrightarrow{D_{ij}} \cdot (\overrightarrow{S_i} \times \overrightarrow{S_j})$

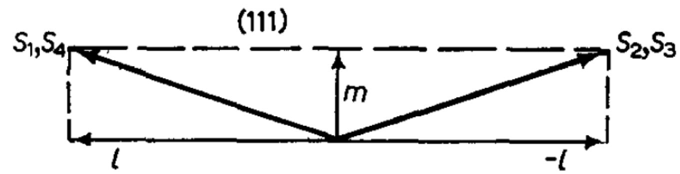


FIG. 2. Projection of ion spins on (1) for α-Fe_2O_3.

Moriya : precise rules of symmetry to have $\vec{D} \neq \vec{0}$ and two-site model based on superexchange to calculate its value.

Fert & Levy : 3-site model based on RKKY interaction with Spin-Orbit Coupling

Dzyaloshinskii, J.Phys.Chem.Solids (1958)
Moriya, Phys.Rev. (1960)
Fert & Levy, Phys.Rev.Lett. (1980)

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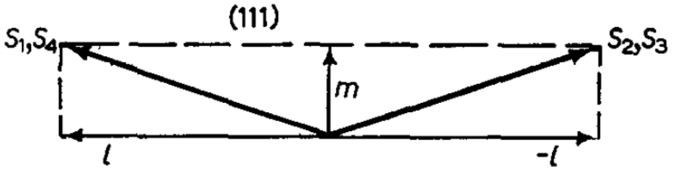

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Dzyaloshinskii, J.Phys.Chem.Solids (1958)
Moriya, Phys.Rev. (1960)
Fert & Levy, Phys.Rev.Lett. (1980)

For theoreticians only !

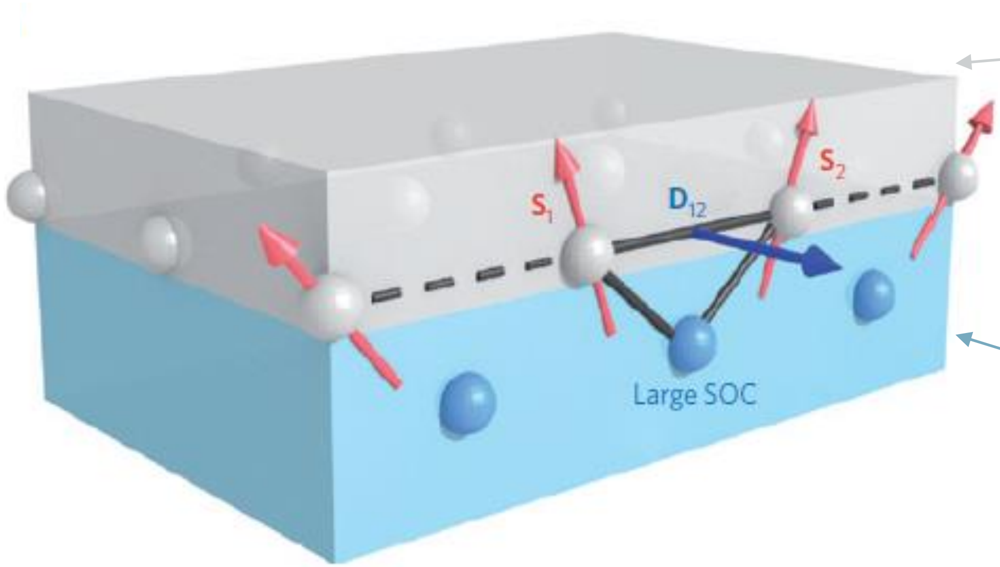
2. What is DMI ?

- It’s always better with a picture

DMI appears only when inversion symmetry is broken :

- Low-symmetry lattices
- Surface and interfaces

Interfacial DMI :



Ferromagnetic layer (Fe, Co…)

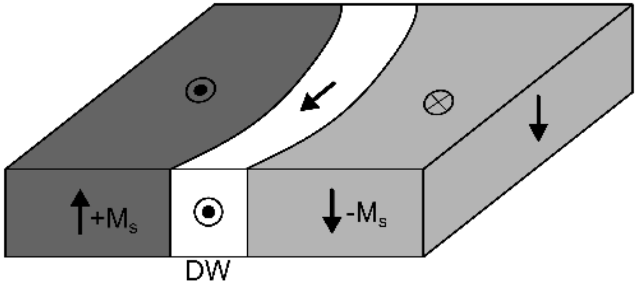
Heavy metal (Pt, Ir…)

Fert et al., Nat.Nano. (2013)

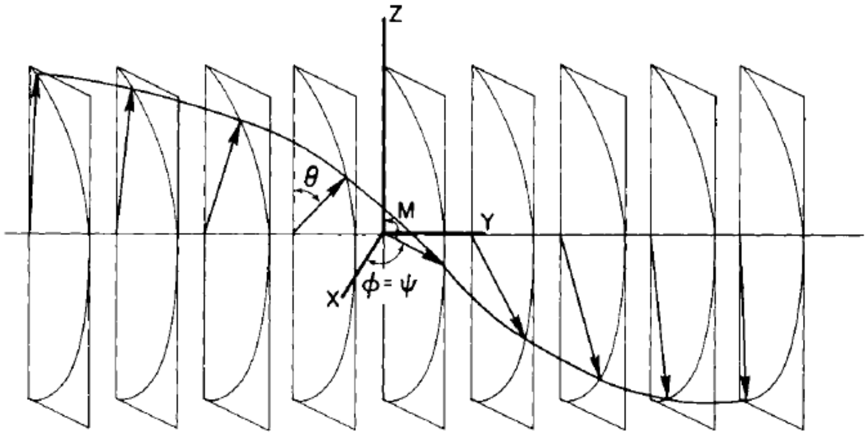
Outline

3. Effects of DMI

- Domains walls



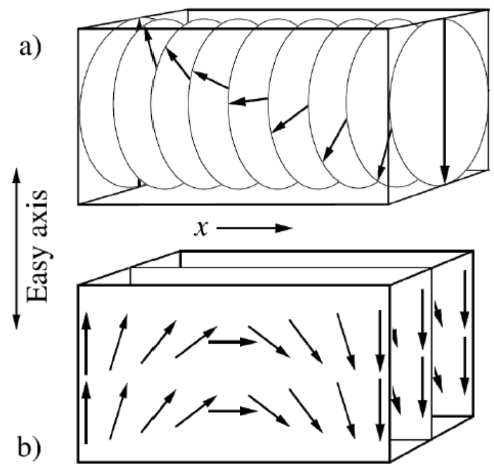
Domain wall = transition from an up to a down domain
Size ≈ 10 nm



Malozemoff & Sloncewski (A.P. 1979)

Without DMI : the Bloch wall minimizes the stray field

With DMI : If D is larger than the stray field energy, Néel wall with a fixed chirality



Parois de Bloch (a) et de Néél (b).

Hubert & Schäffer (Springer, 2009)

3. Effects of DMI

- Dzyaloshinskii Domain Walls

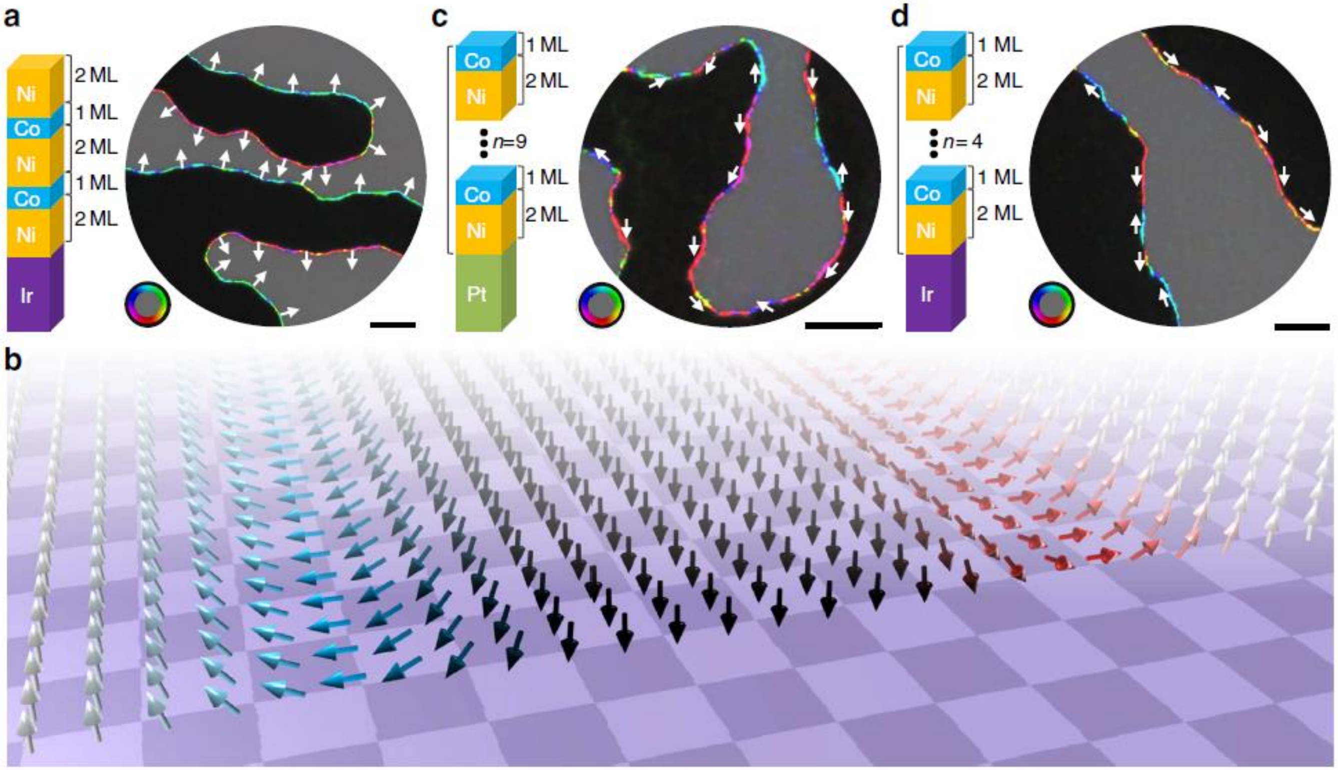
Chen *et al.*, Nat.Com. (2013) : Tailoring the chirality of magnetic DW by interface engineering

SP-LEEM observation of $[Co/Ni]_n$ stacks on Pt or Ir

DMI
(Ni/Heavy metal interface)

↕

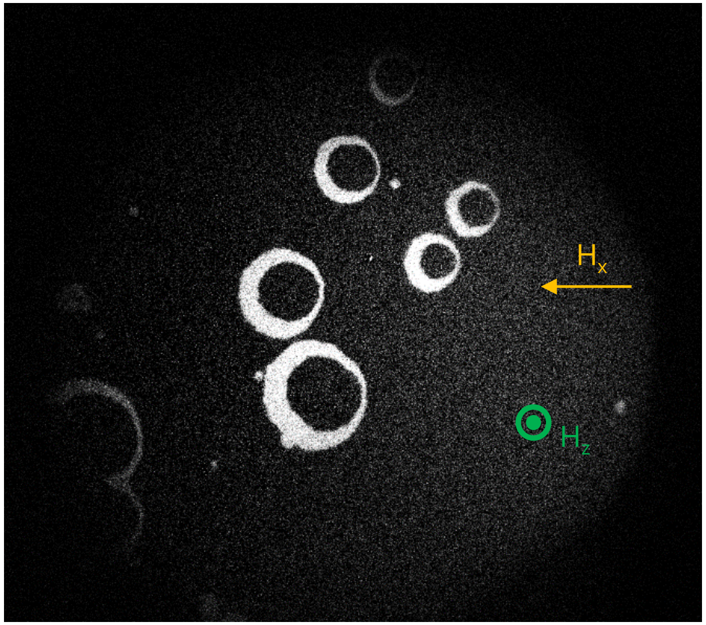
Stray field energy
(grows with the thickness of the [Co/Ni] stack)



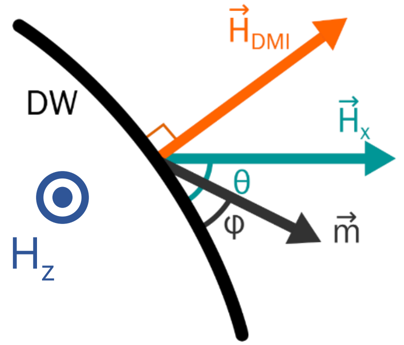
3. Effects of DMI

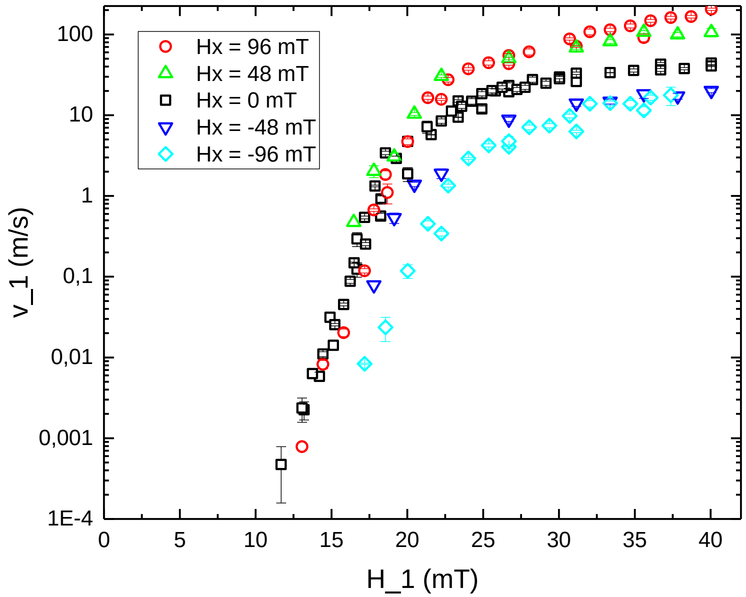
- DDW dynamics

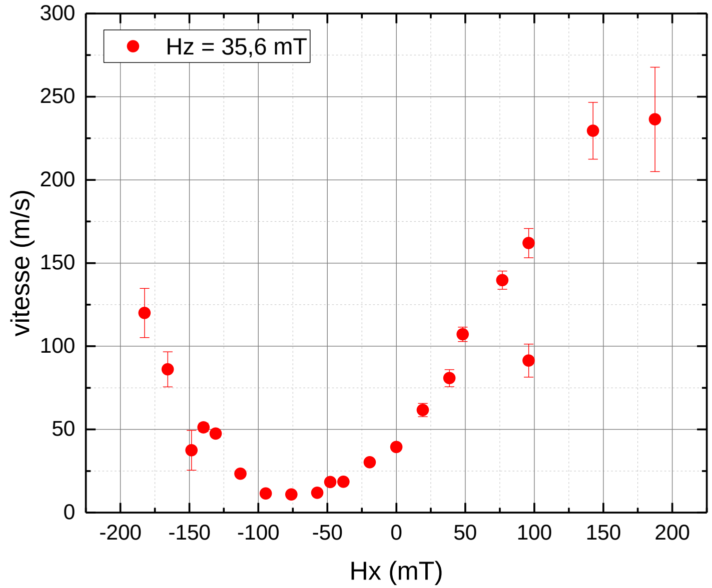
Motion of Dzyaloshinskii domain walls



Asymmetric domain growth in Pt/Co/Au

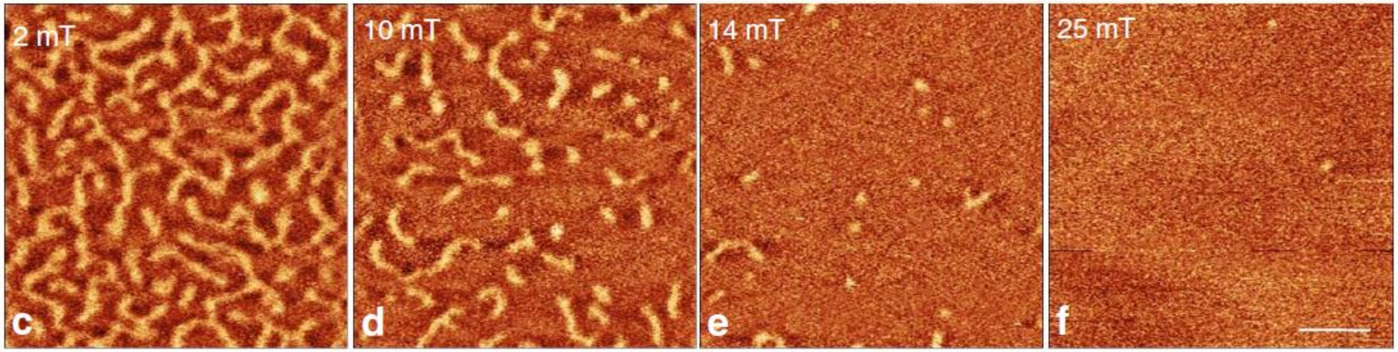






3. Effects of DMI

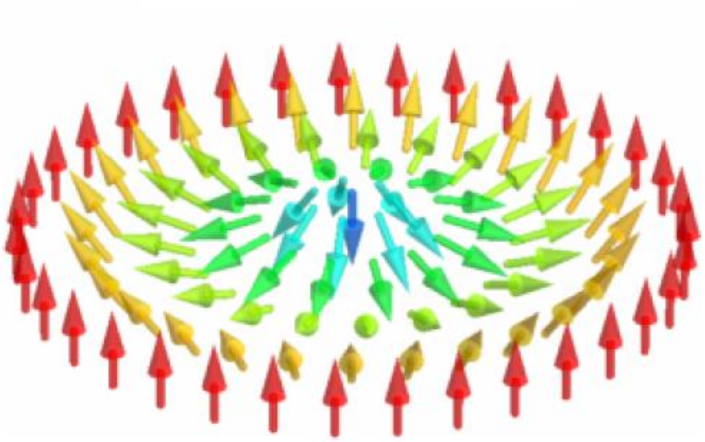
- Skyrmions



Hrabec *et al*. Nat.Com. (2017) Stabilization of isolated hedgehog skyrmions in Pt/Co/Au/Co/Pt, observed by MFM.

Hedgehog skyrmion
= Néel wall loop

-> Nice topological properties



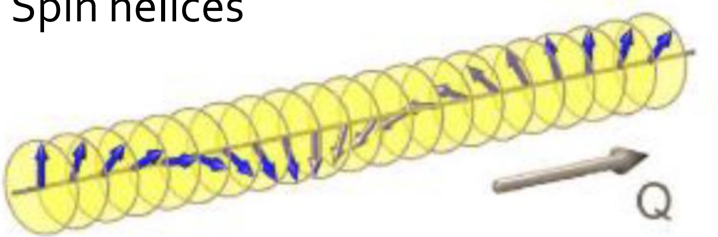
Everschor, PhD thesis (2012)

3. Effects of DMI

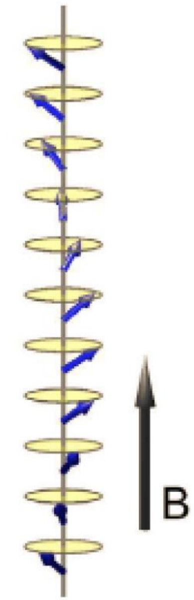
- Bulk chiral magnetic phases : MnSi

The interplay between Heisenberg exchange and DMI give rise to 3D chiral magnetic structures

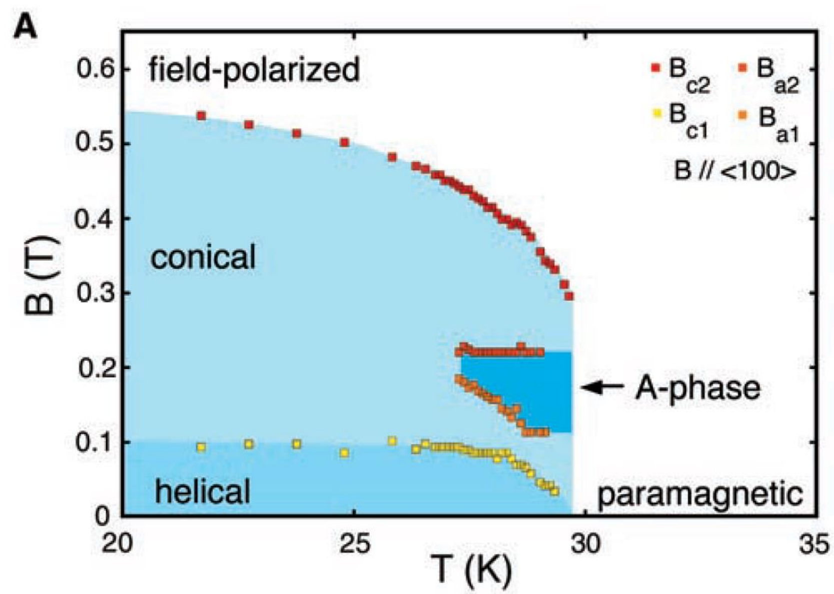
Spin helices



Conical helices

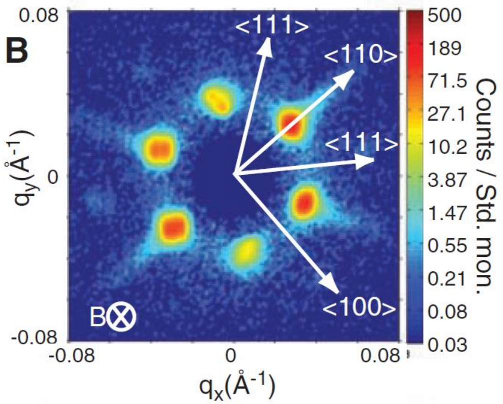


Mühlbauer *et al.*, Science (2011) :
Phase diagram of MnSi under a magnetic field (neutron diffraction)



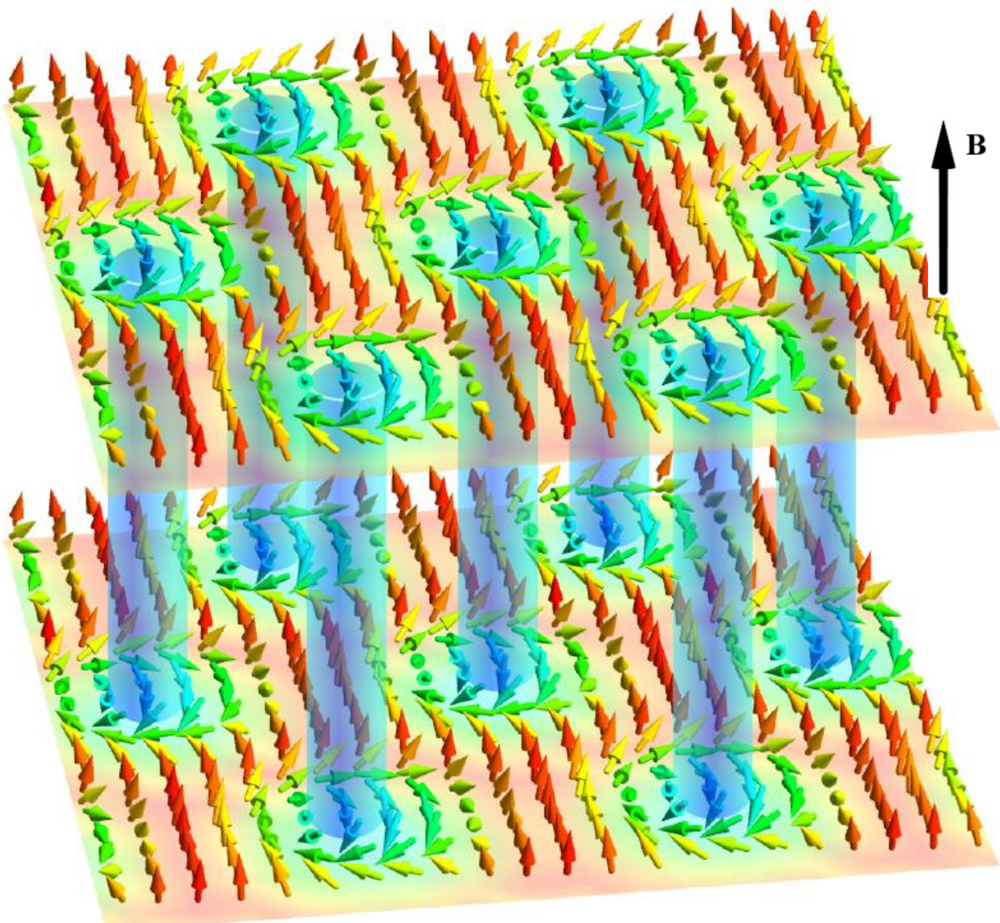
- Bulk chiral magnetic phases : MnSi

A-phase : 6-fold symmetry -> Skyrmion lattice



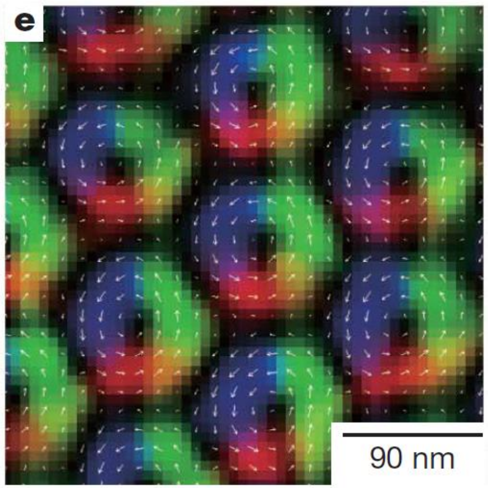
Mühlbauer *et al.*, Science (2009)

B20 cubic lattice constant : a = 4.56 Å
Skyrmion lattice constant : λ = 190 Å



Everschor, PhD thesis (2012)

Observed in real space by Lorentz TEM on $Fe_{0.5}Co_{0.5}Si$



Yu *et al.*, Nature (2010)

The end !

Micromagnetism = mesoscopic description of spin configurations and dynamics

Individual spins $\vec{S}_i$ ⟶ (Average over a few nm) Local magnetization $\vec{M} = M_S\vec{m}$

Heisenberg exchange :

$$H = -J\sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j \longrightarrow e_{ex} = A\int \left[\left(\vec{\nabla}m_x\right)^2 + \left(\vec{\nabla}m_y\right)^2 + \left(\vec{\nabla}m_z\right)^2\right] dV$$

Dipole-dipole interaction and anisotropy ⟶ $e_K = K_{eff}(\vec{m}\cdot\vec{e}_K)^2$+ higher order terms

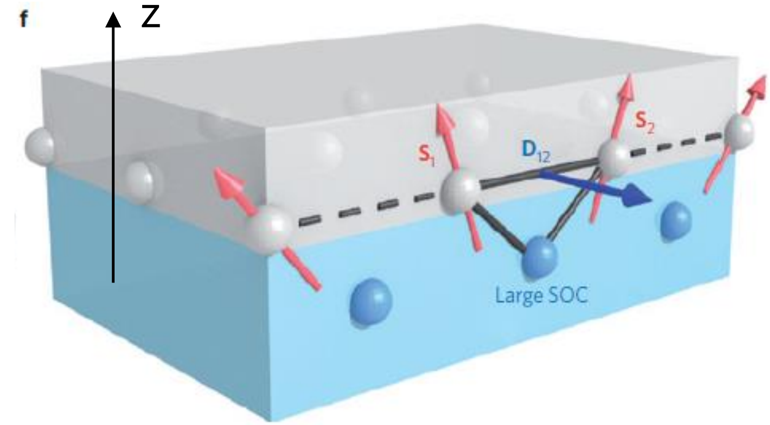
More slides

- Micromagnetism of thin-films

Interface between a ferromagnet and a heavy metal

$$\vec{D}_{ij} = D\hat{u}_{ij} \times \hat{u}_z$$

D lies in the plane of the interface



$$H_{DMI} = \sum_{<i,j>} \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$$

$$e_{DMI} = D_S \left[\left(m_x \frac{\partial m_z}{\partial x} - m_z \frac{\partial m_x}{\partial x} \right) + \left(m_y \frac{\partial m_z}{\partial y} - m_z \frac{\partial m_y}{\partial y} \right) \right]$$

Rohart *et al.*, Phys.Rev.B (2013)