

School overview : a short story 😊

Olivier FRUCHART



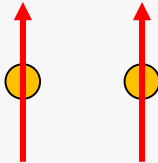


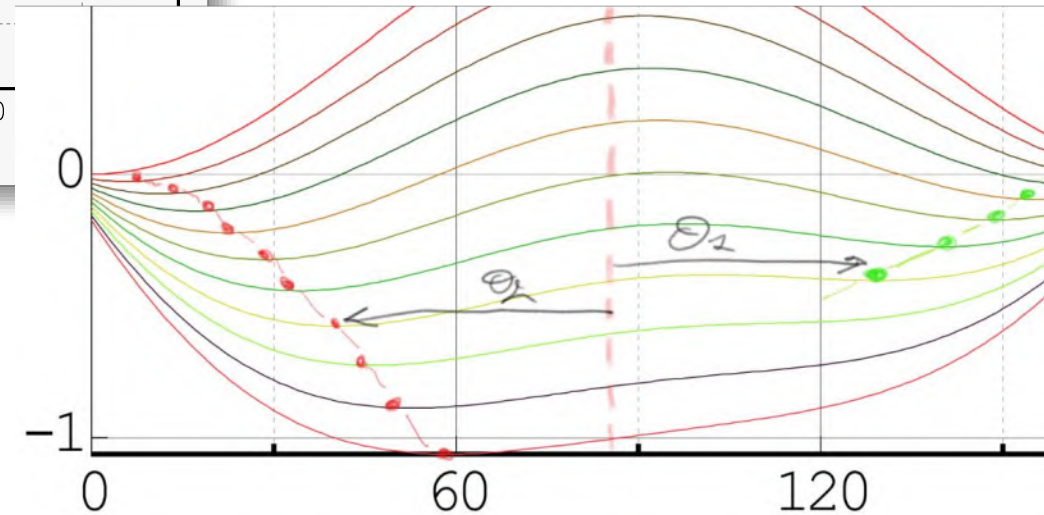
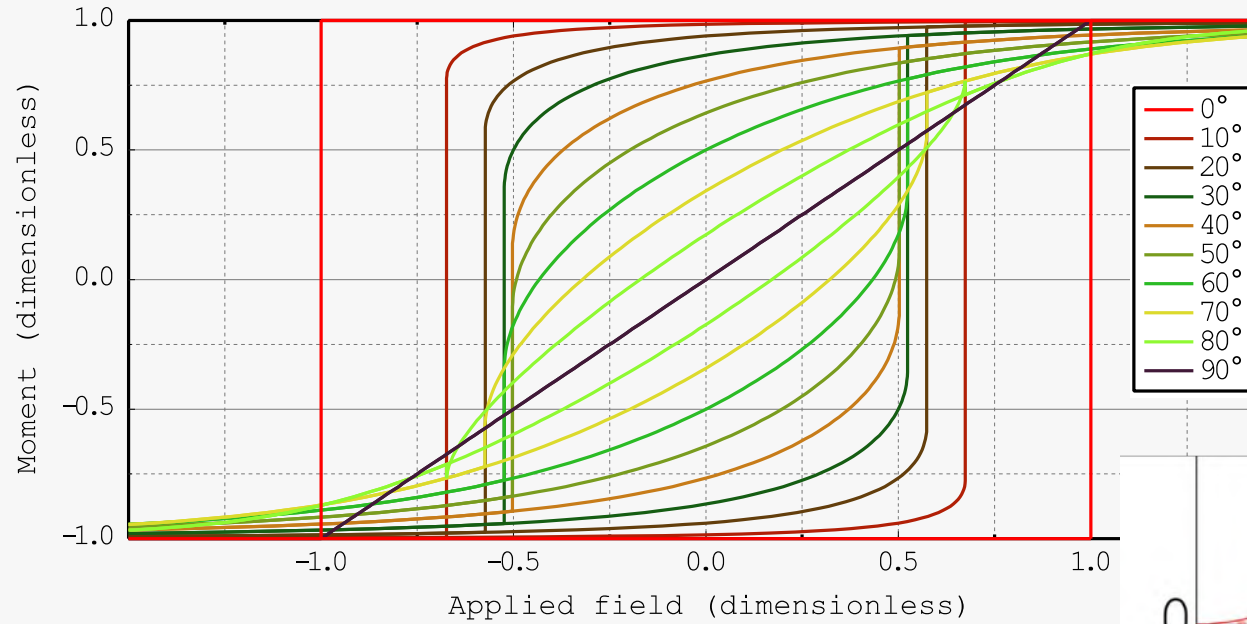
Diagram showing two parallel magnetic dipoles (yellow circles with red arrows pointing up) separated by a distance r . The energy $\mathcal{E}$ is given by:

$$\mathcal{E} = + \frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$

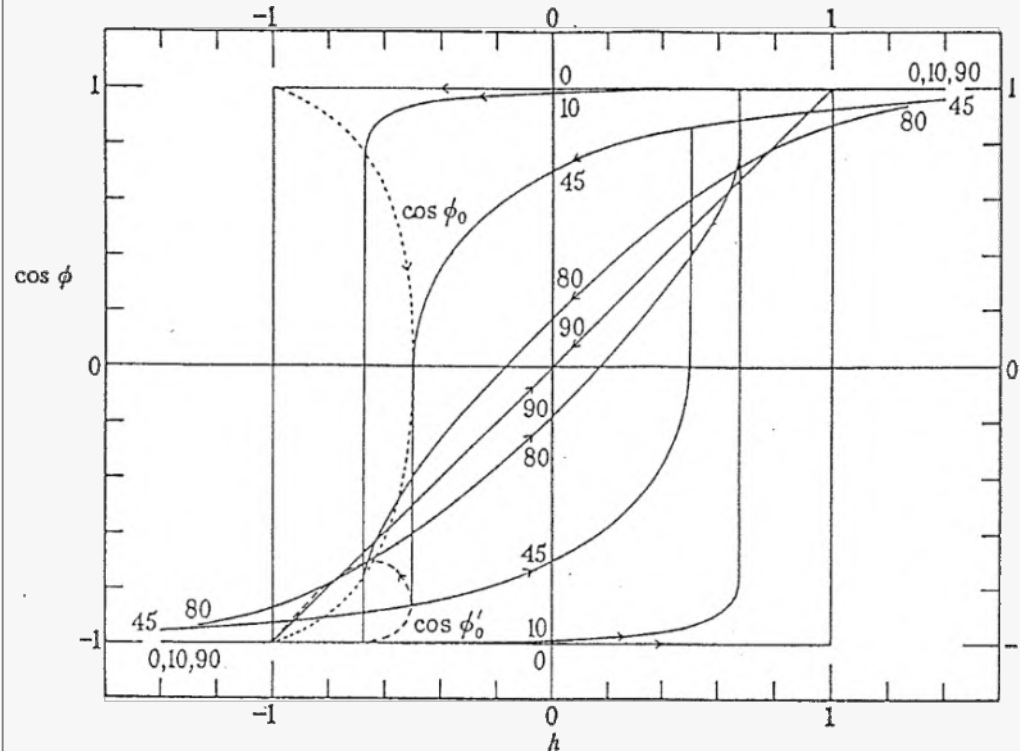


Diagram showing two parallel magnetic dipoles (yellow circles with red arrows pointing up) separated by a distance r . The energy $\mathcal{E}$ is given by:

$$\mathcal{E} = -2 \frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$



Stoner-Wohlfarth model



E. C. Stoner & E. P. Wohlfarth, Phil. Trans. Roy. Soc. London A240, 599 (1948)

A review from a contemporary author

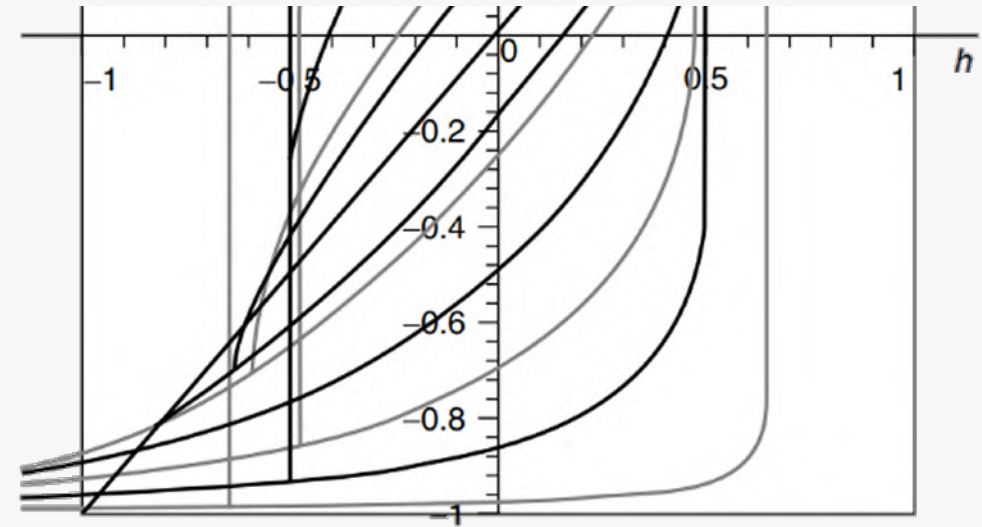


Figure 2. Longitudinal M - H hysteresis loops for 0 (innermost line through the origin, hard axis), 5, 10, 30, 45, 60, 85, and 90 (outermost square loop, easy axis) degrees away from the hard axis for the case of a twofold anisotropy.

Magnetic Periodic Table

Atomic Number → **66 Dy** ← Atomic symbol
Typical ionic charge → **3+ 4+** ← Atomic weight
Antiferromagnetic T_N (K) → **17 85** ← Ferromagnetic T_C (K)

1 H 1.00																	2 He 4.00	
3 Li 6.94 1-2s ⁰	4 Be 9.01 2-2s ⁰																	10 Ne 20.18
11 Na 22.99 1-3s ⁰	12 Mg 24.31 2-3s ⁰																	18 Ar 39.95
19 K 39.10 1-4s ⁰	20 Ca 40.08 2-4s ⁰	21 Sc 44.96 3-3d ⁰	22 Ti 47.88 4-3d ⁰	23 V 50.94 3-3d ⁰	24 Cr 52.00 3-3d ⁰	25 Mn 54.94 2-3d ⁰	26 Fe 55.85 3-3d ⁰	27 Co 58.93 2-3d ⁰	28 Ni 58.69 2-3d ⁰	29 Cu 63.55 2-3d ⁰	30 Zn 65.39 2-3d ⁰	31 Ga 69.72 3-3d ⁰	32 Ge 72.61 4-4d ⁰	33 As 74.92 4-4d ⁰	34 Se 78.96 4-4d ⁰	35 Br 79.90 4-4d ⁰	36 Kr 83.80	
37 Rb 85.47 1-5s ⁰	38 Sr 87.62 2-5s ⁰	39 Y 88.91 2-4d ⁰	40 Zr 91.22 4-4d ⁰	41 Nb 92.91 5-4d ⁰	42 Mo 95.94 5-4d ⁰	43 Tc 97.9 6-4d ⁰	44 Ru 101.1 3-4d ⁰	45 Rh 102.4 3-4d ⁰	46 Pd 106.4 2-4d ⁰	47 Ag 107.9 1-4d ⁰	48 Cd 112.4 2-4d ⁰	49 In 114.8 3-4d ⁰	50 Sn 118.7 4-4d ⁰	51 Sb 121.8 4-4d ⁰	52 Te 127.6 4-4d ⁰	53 I 126.9 4-4d ⁰	54 Xe 131.3	
55 Cs 132.9 1-6s ⁰	56 Ba 137.3 2-6s ⁰	57 La 138.9 3-4f ⁰	58 Ce 140.1 4-4f ⁰	59 Pr 140.9 3-4f ⁰	60 Nd 144.2 3-4f ⁰	61 Pm 145 4-4f ⁰	62 Sm 150.4 3-4f ⁰	63 Eu 152.0 2-4f ⁰	64 Gd 157.3 3-4f ⁰	65 Tb 158.9 3-4f ⁰	66 Dy 162.5 3-4f ⁰	67 Ho 164.9 3-4f ⁰	68 Er 167.3 3-4f ⁰	69 Tm 168.9 3-4f ⁰	70 Yb 173.0 3-4f ⁰	71 Lu 175.0 3-4f ⁰		
87 Fr 223	88 Ra 226.0 2-7s ⁰	89 Ac 227.0 3-5f ⁰	90 Th 232.0 4-5f ⁰	91 Pa 231.0 5-5f ⁰	92 U 238.0 4-5f ⁰	93 Np 237.0 5-5f ⁰	94 Pu 244 5-5f ⁰	95 Am 243 5-5f ⁰	96 Cm 247 5-5f ⁰	97 Bk 247 5-5f ⁰	98 Cf 251 5-5f ⁰	99 Es 252 5-5f ⁰	100 Fm 257 5-5f ⁰	101 Md 268 5-5f ⁰	102 No 269 5-5f ⁰	103 Lr 260 5-5f ⁰		

Nonmetal

Metal

Radioactive

Diamagnet

Paramagnet

Magnetic atom

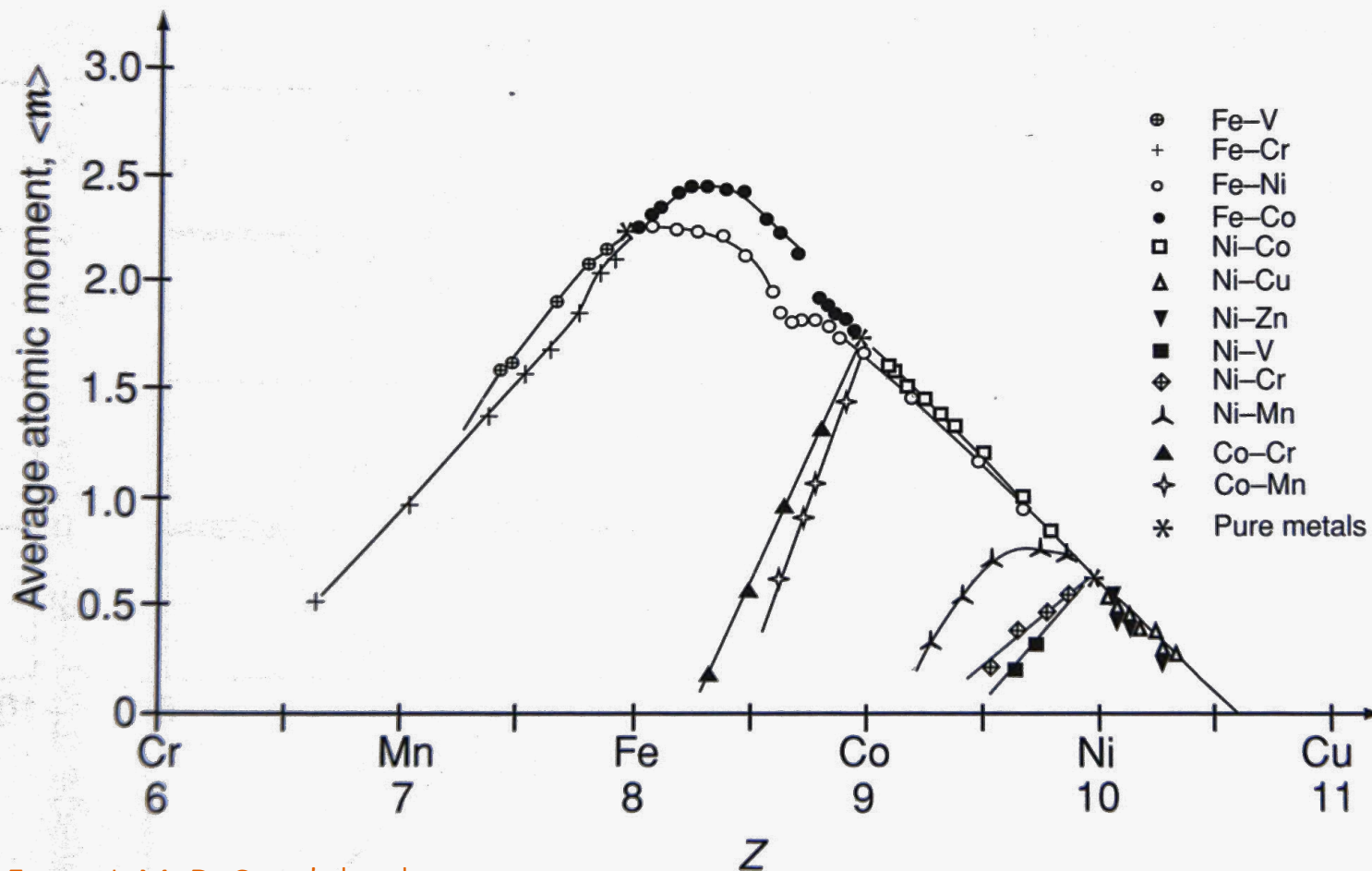
Ferromagnet $T_C > 290K$

Antiferromagnet with $T_N > 290K$

Antiferromagnet/Ferromagnet with $T_N/T_C < 290 K$

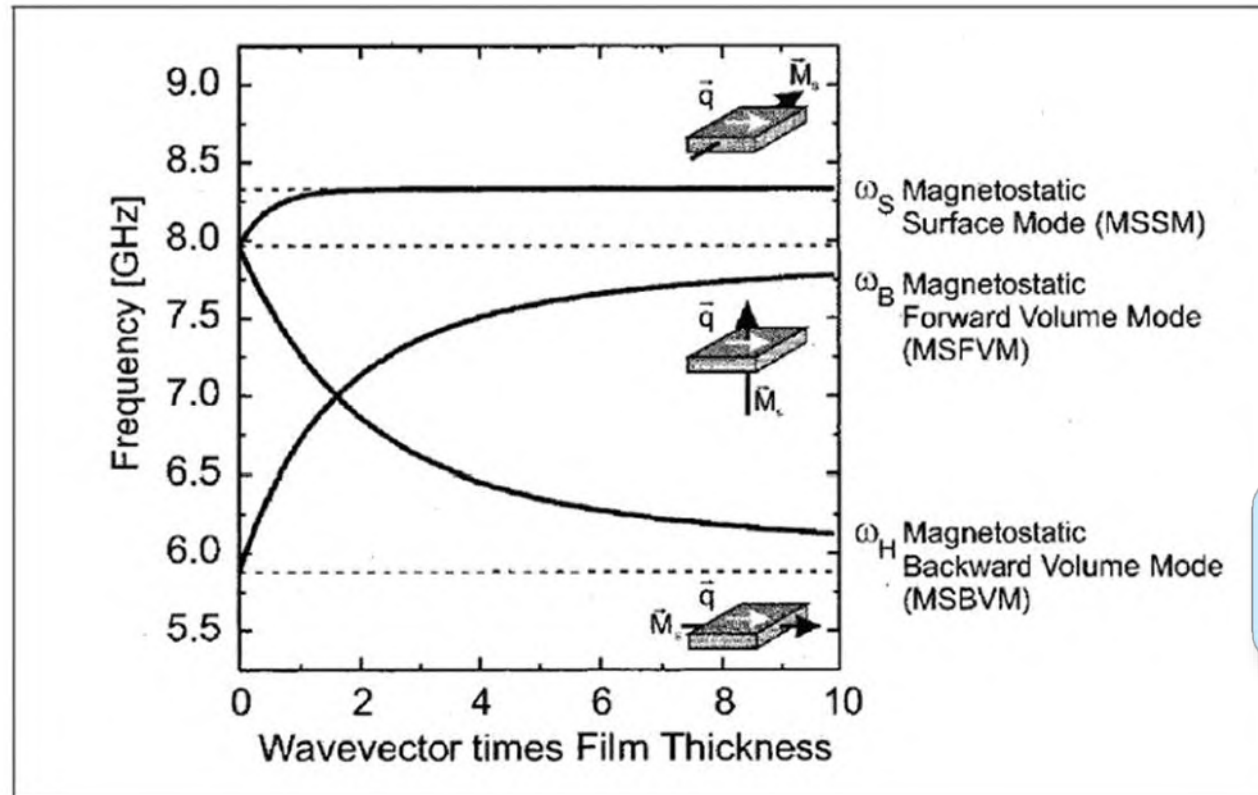
Why is Cu diamagnetic and not paramagnetic? (3d⁹)

Slater-Pauling curve



From: J. M. D. Coey's book

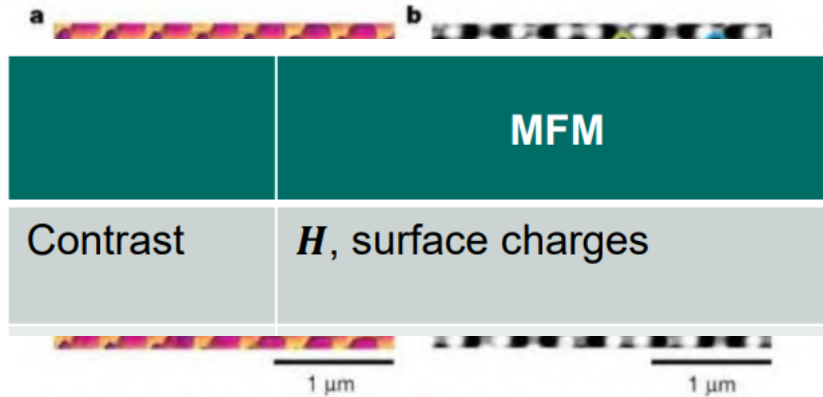
Excited spin-waves depend on measuring geometry



Why does a dispersion curve bends downwards with q ?

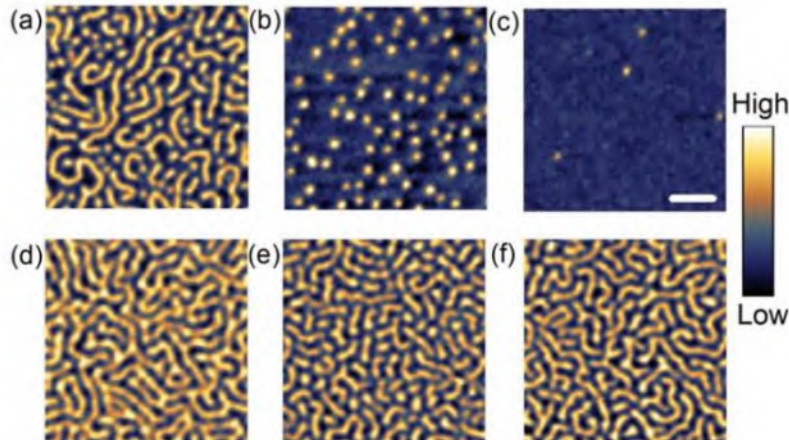
Nanomagnet arrays:

Wang et al., Nature (2006)



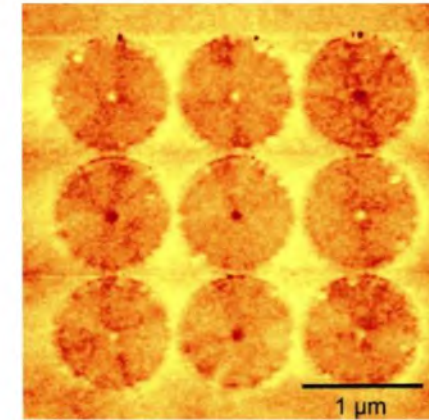
Magnetic domains, skyrmions:

Duong et al., APL (2019)



Patterned magnetic micro/nanostructures:

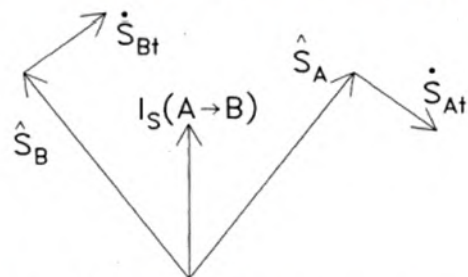
Magnetic vortices



Shinjo et al., Science (2000)

Contrast of Magnetic Force Microscopy
Why disks in a vortex state appears dark?

Spin torque in magnetic tunnel junctions



“Since S_A -polarized electrons impinge on magnet B, surely S_B must relax **toward**

$$J_S \sim S_A + S_B$$

$$\partial_t S_A = -S_A \times (J_S \times S_A)_A$$

$$\partial_t S_A \propto S_A \times (S_A \times S_B) \quad 6$$

Slonczewski, Physical Review B39, 6995 (1989)

$$P_{\text{trans}} = P \frac{J}{|e|} \mu_B$$



$J \leftarrow$

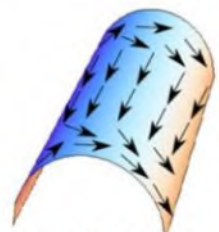
$$\frac{d\mathbf{m}_2}{dt} = -|\gamma_0| \mathbf{m}_2 \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m}_2 \times \frac{d\mathbf{m}_2}{dt} - \frac{P_{\text{trans}}}{M_2} \mathbf{m}_2 \times (\mathbf{m}_2 \times \mathbf{m}_1)$$

J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1-7(1996)

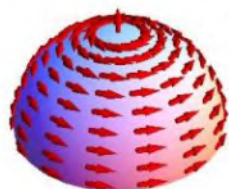
Spin-transfer is odd with current. How does it work when electrons flow from the free layer to the reservoir layer?

Impact of curvature on a magnetic system

Magnetic interactions in the anisotropic Heisenberg ferromagnet:



Cylindrical surfaces



Spherical surfaces

$$E = L \int_S \left[A \sum_{i=x,y,z} (\nabla m_i)^2 + K(\mathbf{m} \cdot \mathbf{n})^2 \right] dS$$

Exchange energy Anisotropy energy

In a curvilinear basis, micromagnetic energy can be rewritten:

$$\mathcal{E}_{ex} = [\nabla\theta - \Gamma(\varphi)]^2 + \left[\sin\theta (\nabla\varphi - \Omega) - \cos\theta \frac{\partial\Gamma(\varphi)}{\partial\varphi} \right]^2$$

$$\mathcal{E}_{ex} = \mathcal{E}_{ex}^0 + \mathcal{E}_{ex}^A + \mathcal{E}_{ex}^D \quad \mathcal{E}_{ex}^0 = (\nabla\theta)^2 + \sin^2\theta (\nabla\varphi)^2$$

Induced anisotropy responses:

$$\mathcal{E}_{ex}^A = \Gamma^2 + \sin^2\theta \Omega^2 + \cos^2\theta (\partial_\varphi \Gamma)^2$$

Quadratic in curvature

Induced chiral responses:

$$\mathcal{E}_{ex}^D = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$$

$$\mathcal{E}_{ex}^D = -2 [(\nabla\theta \cdot \Gamma) + \sin\theta \nabla\varphi \cdot (\Omega + \cos\theta \partial_\varphi \Gamma)]$$

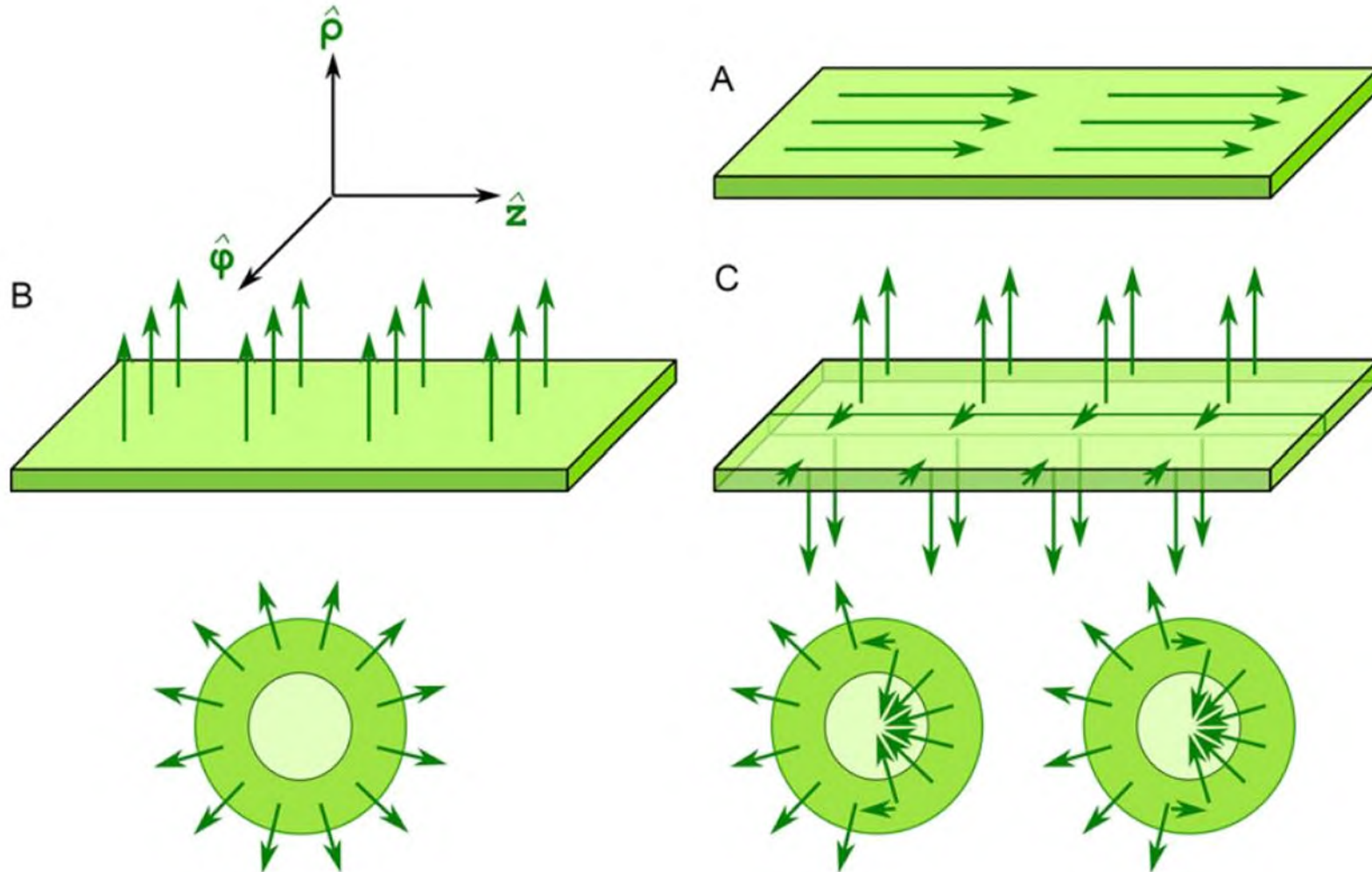
Linear in curvature

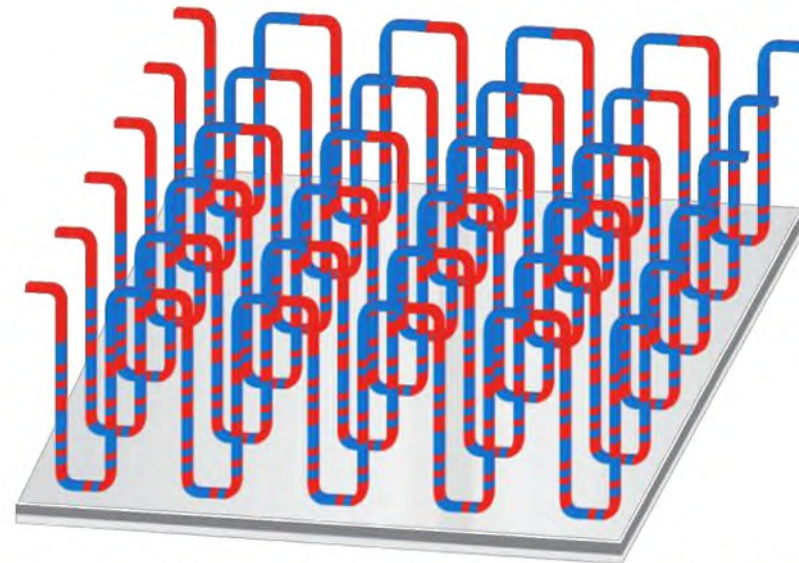
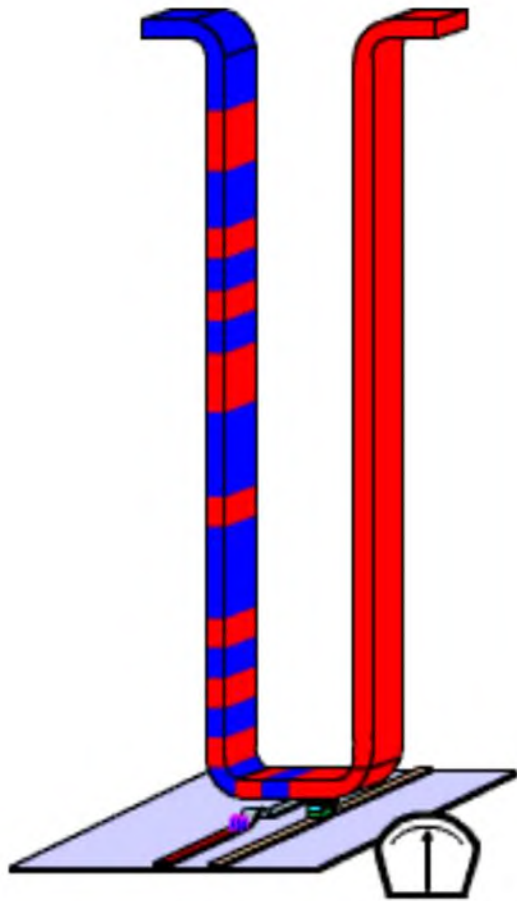
How do you understand curvature-induced magnetic anisotropy and Dzyaloshinskii-Moriya interactions in a simple manner?

Gaididei et al., *PRL* ('14); Pylypovskiy, DM et al., *PRL* ('15); Kravchuk, DM et al., *PRL* ('18); Volkov, DM et al., *PRL* ('19)...

Member of the Helmholtz Association

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Dreaming of a 3D storage device

What are the
bottlenecks to build a
3D race-track memory?

S. S. P. Parkin, Science 320, 190 (2008) + patents (IBM)

Thank you for your attention !

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