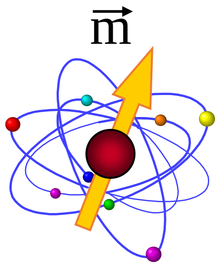
Lecture 5

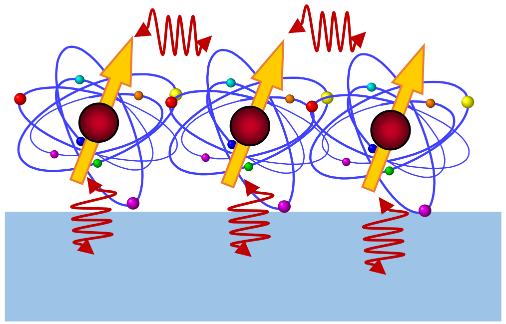
Thermal and magnetic field induced dynamics

The spintronics “goose game”

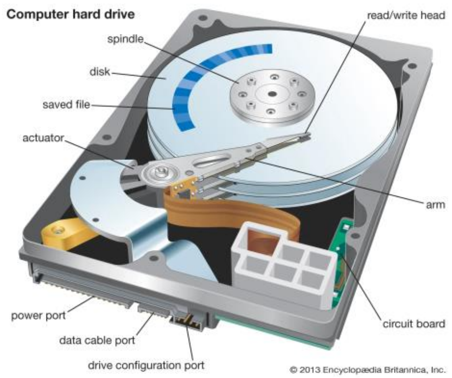
Atom magnetism

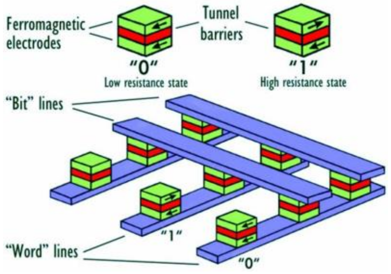


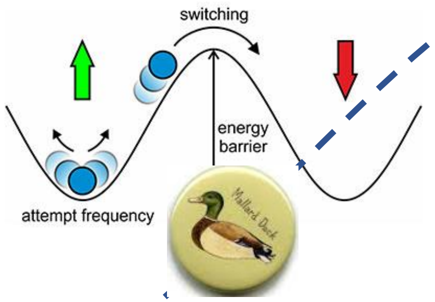
interactions between spins and with the supporting substrate



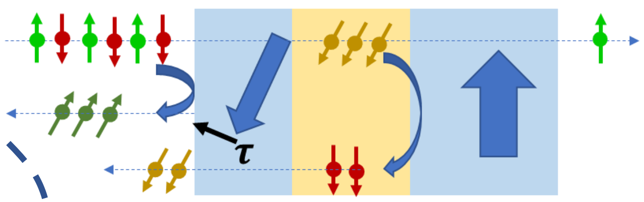
applications

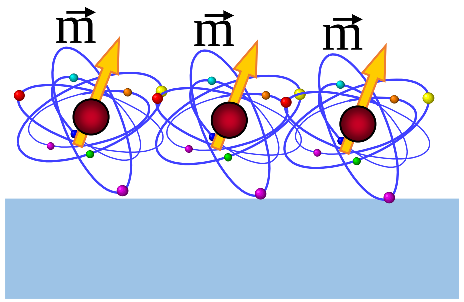




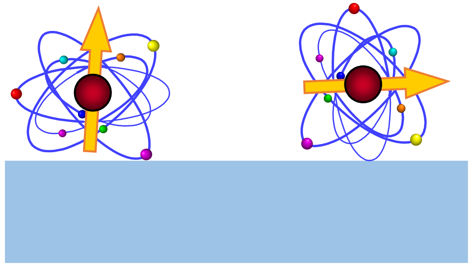


STT - SOT

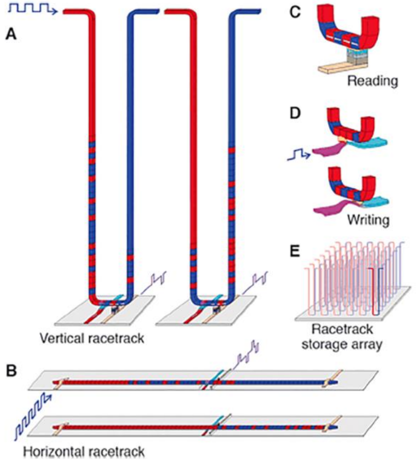




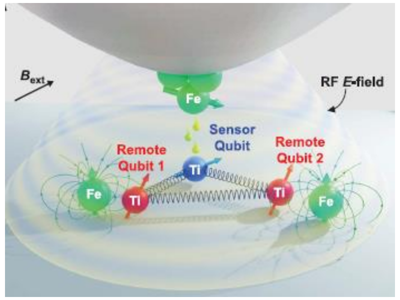
magnetic moment in a cluster and/or on a support

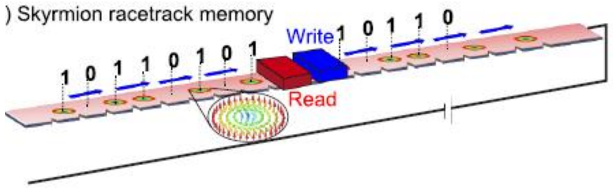


Magnetization easy axis



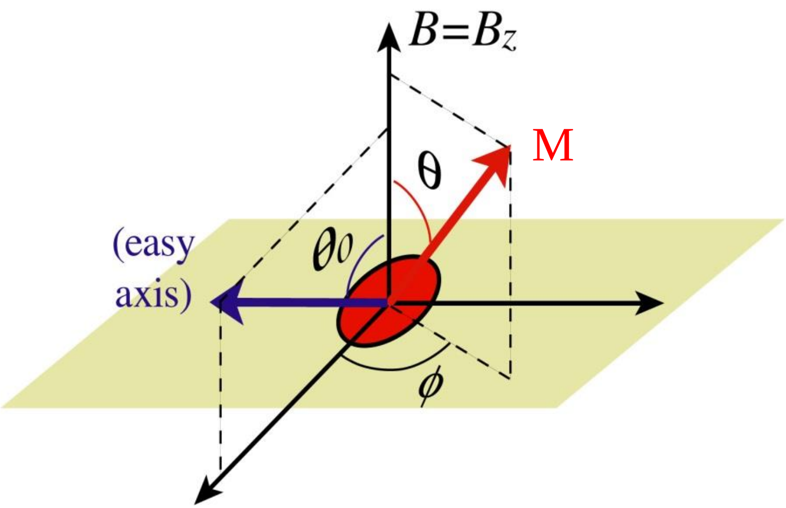
Future

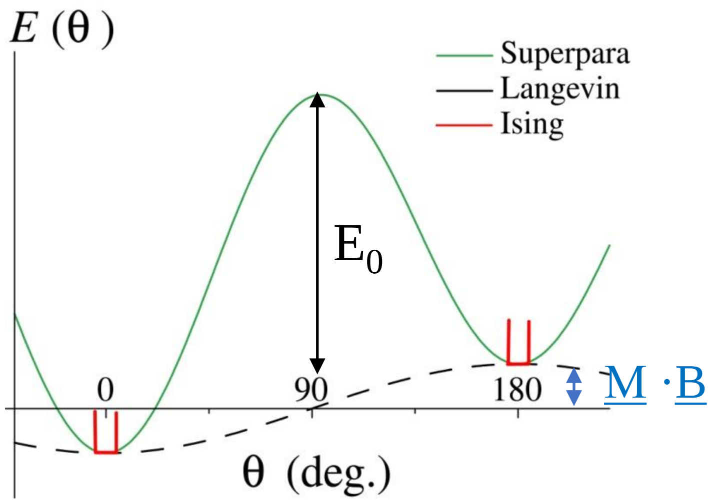




Bit magnetization reversal

A bit is a binary system where 1 and 0 correspond to the magnetization being up or down → Magnetization along a defined axis: easy magnetization axis





$$E(\theta,\theta_0,\phi) = -\mathbf{M}\cdot\mathbf{B} - E_0 \cos^2(\textbf{easy axis}\cdot\mathbf{M})$$

Simplified phenomenological expression for the MAE for uniaxial easy axis

E_0 is the magnetization reversal energy barrier at B = 0

E_0 = MCA (crystal field) + shape anisotropy (= $\frac{1}{2}\mu_0 M^2$) assuming:

a) a single magnetic domain bit

b) coherent magnetization reversal (i.e. all spins in the bit turn at the same time)

Coherent magnetization reversal at T = 0

Single-domain particles: the Stoner-Wohlfart model

Magnetization of a single-domain particle in an external field.

$E = E_{Zeeman} + E_{mc} + E_{dm}$ E_{dm} = shape anisotropy

Suppose $\mu = MV$ = const. for any H value (coherent rotation) and, for simplicity, $E_{dm} = 0$. Φ = const.

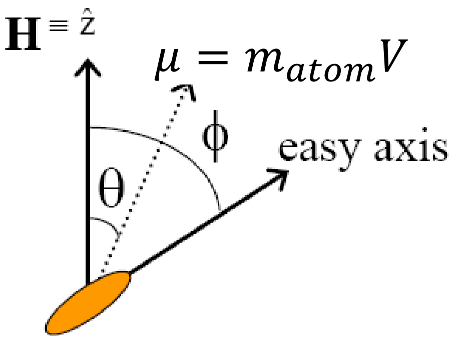
$E = -\mu H\cos\theta - K_1 V\cos^2(\theta-\phi)$ $E_0 = KV$

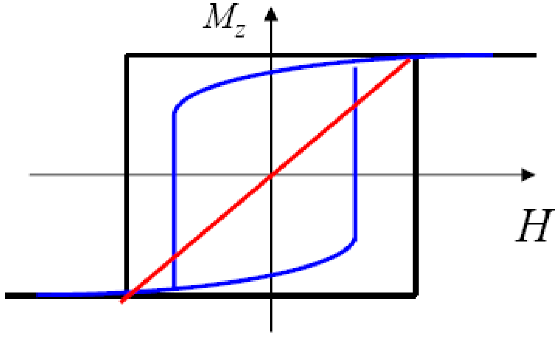
The magnetiic moment $\mu = MV$ will point along a direction that makes E a minimum:

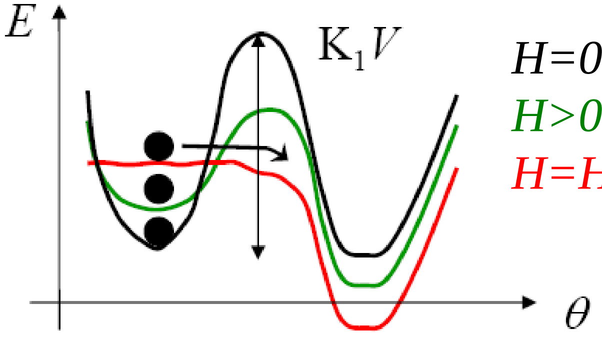
$$\frac{\partial E}{\partial \vartheta} = \mu H\sin\vartheta + K_1 V\sin(2(\vartheta-\varphi)) = 0 \quad (2)$$

Eq. 2 can be solved for θ and we can plot $M_z = M\cos\theta$ (this is what one usually measures) as a function of H.

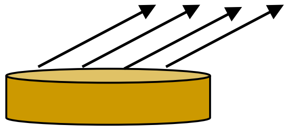
The reversal field is the field at which the energy minimum in eq. (1) vanishes ($\partial^2 E/\partial\vartheta^2 = 0$)







Coherent reversal:
During the magnetization reversal all the atom spins in the particle stay aligned



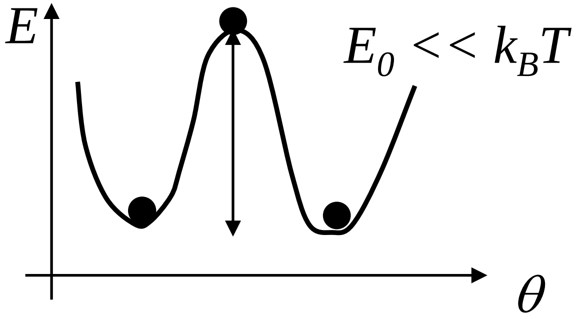
$\phi = 0$:
$M(H)$ curve for H along easy axis

H_{rev} is the field required to reverse the magnetization i.e. to write a bit

$$H_{rev} = \frac{2K}{m_{at}} = \frac{2E_0}{m_{at}V}$$

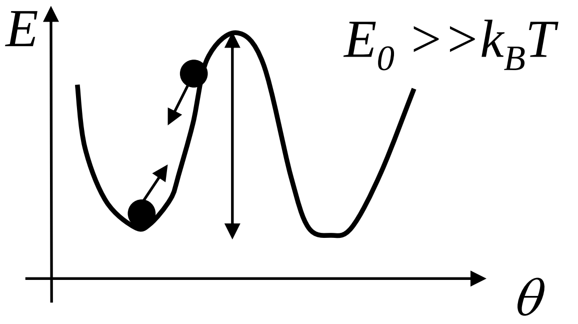
See exercise: 5.1

B = 0 → $E(\theta,\theta_0,\phi) = -E_0 \cos^2(\textbf{easy axis} \cdot \textbf{M})$



$E_0 << k_BT$
the magnetization vector isotropically fluctuates in the space.

Information **can not** be stored



$E_0 >> k_BT$
the magnetization vector can not switch the direction

Information **can** be stored

- μ_o is the permeability of vacuum
- K is the uniaxial MAE
- $\gamma = g_e\mu_0\mu_B/\hbar$ is the gyromagnetic ratio in units of Hz/(A/m)
- M is the saturation magnetization
- α is the Gilbert damping parameter for a given material (from 0.3 to 0.001 depending on the coupling of the spin system to the lattice)

Relaxation time = Avg. time needed to jump from one minimum to the other:

$$\tau = \tau_0 \exp(E_0/k_BT) \qquad \tau_0 \approx 10^{-10}\,\mathrm{s}$$

$$\tau_0 = \frac{1+\alpha^2}{\alpha}\frac{\mu_0 M}{2\gamma K}\sqrt{\frac{\pi k_B T}{K}}$$

τ = 1 year → $E_0 = 40\,k_BT$
τ = 1 second → $E_0 = 23\,k_BT$

***E_0* determines the thermal stability of the magnetization direction**

W.F. Brown, Phys. Rev. 130, 1677 (1963)

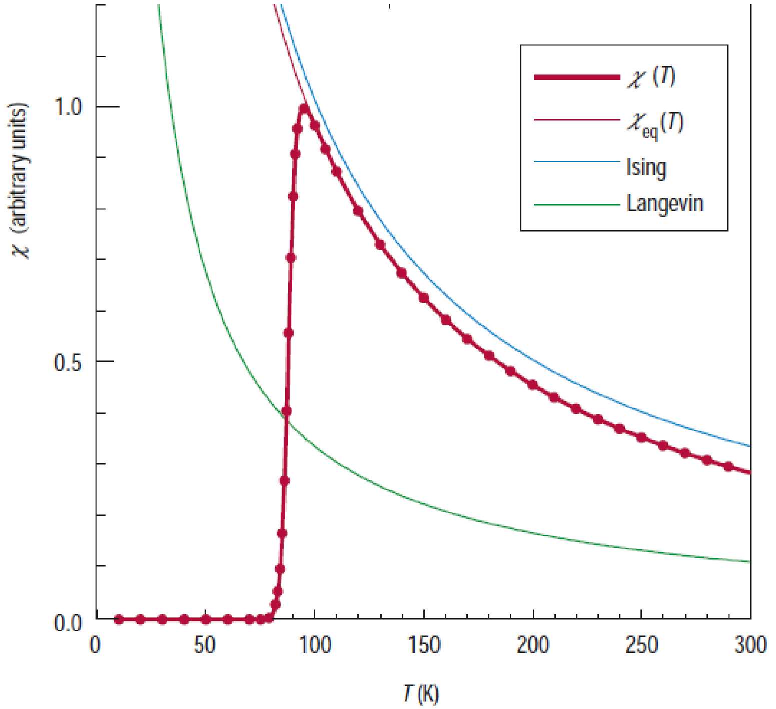
Zero field magnetic susceptibility

Magnetization oscillating due to $B = B_0 \cos \omega t$

Zero field magnetic susceptibility:

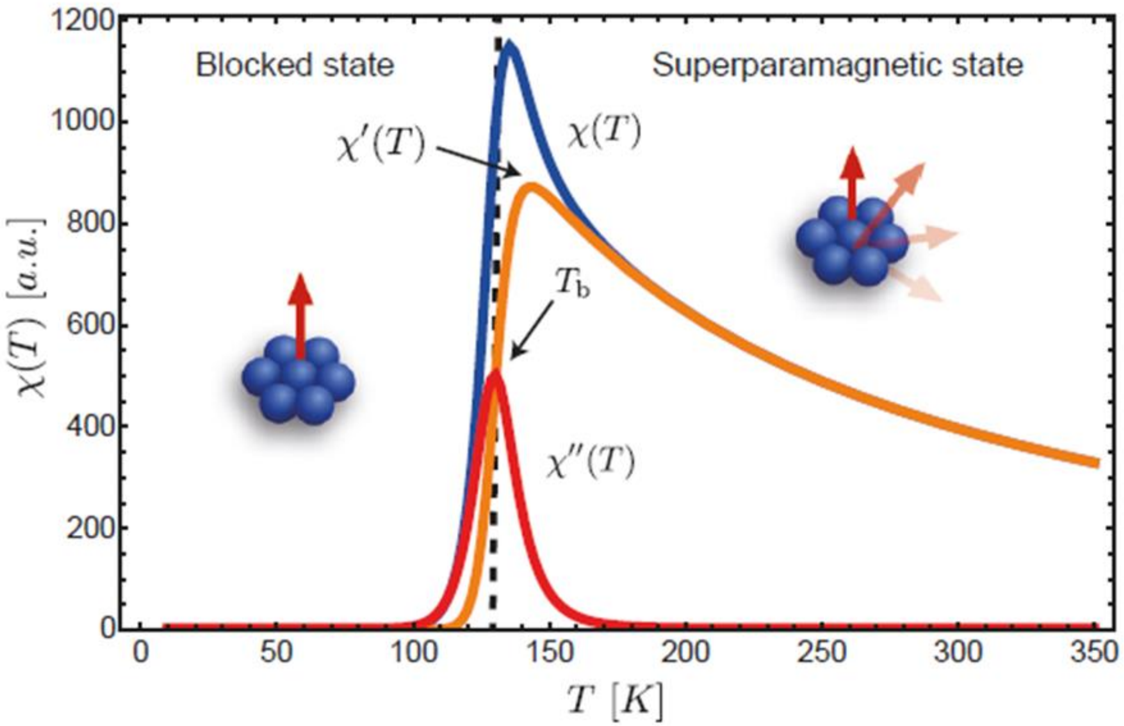
$$\chi = \frac{dM}{dB} = \frac{1}{1+i\omega\tau}\chi_{eq}(T) = \chi' + i\chi''$$

$$\chi_{eq}(T) = M^2\left[\frac{\exp(K/k_BT)}{\sqrt{\pi K k_B T}\,\mathrm{Erfi}\left(\sqrt{K/k_BT}\right)} - \frac{1}{2K}\right]$$



$$\chi_{eq}(T) \propto \frac{1}{k_B T}$$

$$\chi_{eq}(T) \propto \frac{1}{3k_B T}$$



$$\chi' = \frac{\chi_{eq}(T)}{1+\omega^2\tau^2}$$

$$\chi'' = -\omega\tau\frac{\chi_{eq}(T)}{1+\omega^2\tau^2}$$

doi:10.1038/nmat930; D. Mousadakos, EPFL these n° 7877

The superparamagnetic limit

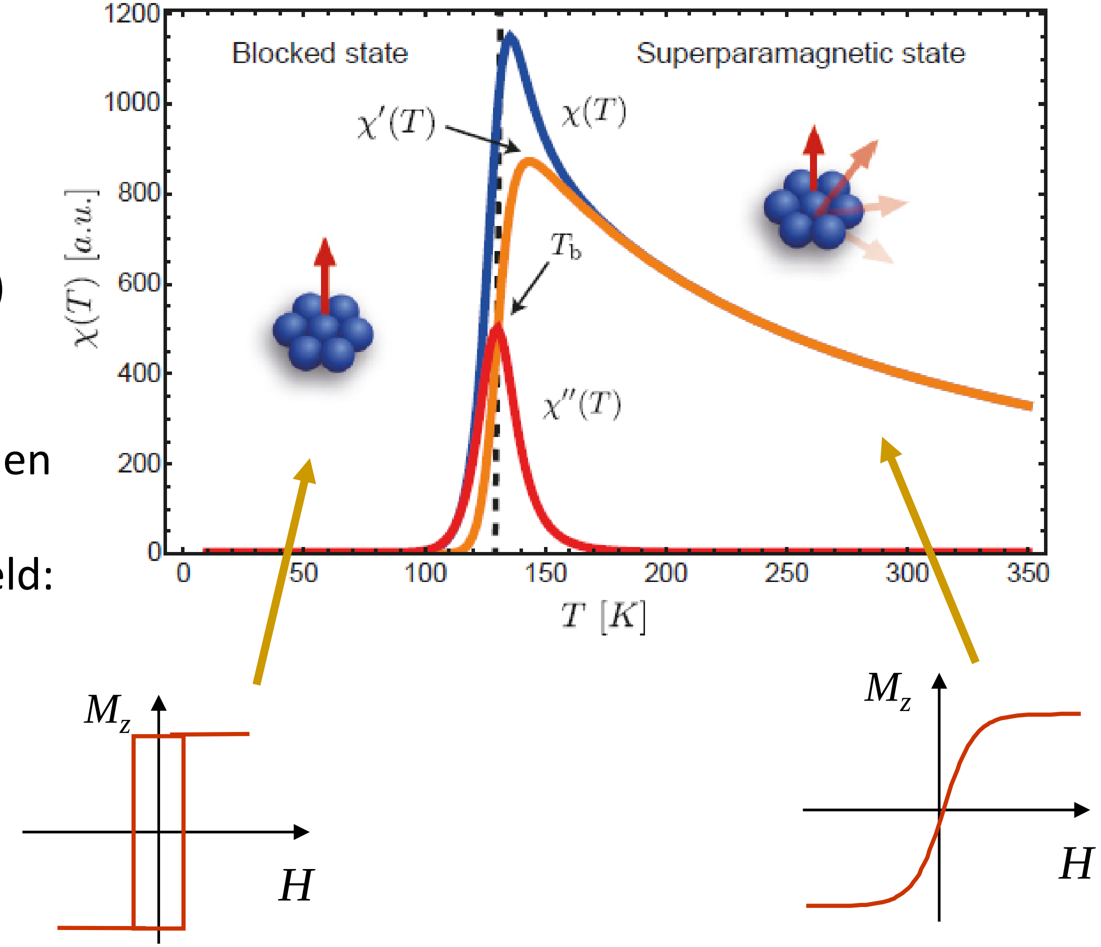
Blocking temperature T_b -> a way to measure E_0

Superparamagnetism:
- The atom spins in the clusters are coupled by exchange to form a macrospin.
- The macrospin fluctuates similarly to the spin of a paramagnetic atom

T_b is defined by the peak position in the zero field susceptibility (χ) *vs* T curve

The macrospin feels:
1) Thermal agitation $\tau = \tau_0 \exp(E_0/k_B T)$
2) External field $B = B_0 \cos \omega t$

The susceptibility peak is observed when the thermal agitation equals the oscillations induced by the external field:
$1/\omega \approx \tau_0 \exp(E_0/k_B T_b)$



$$T_b = \frac{E_0}{k_B} \ln\left(\frac{1}{\omega \tau_0}\right)$$

Blocking: E_0/kT >>30

Superparamagnetic: E_0/kT <<30

Magnetization reversal of a particle ensemble: B and T $\neq$ 0

Ensemble of noninteracting monodomain particles (macrospin *m*) with uniaxial anisotropy K

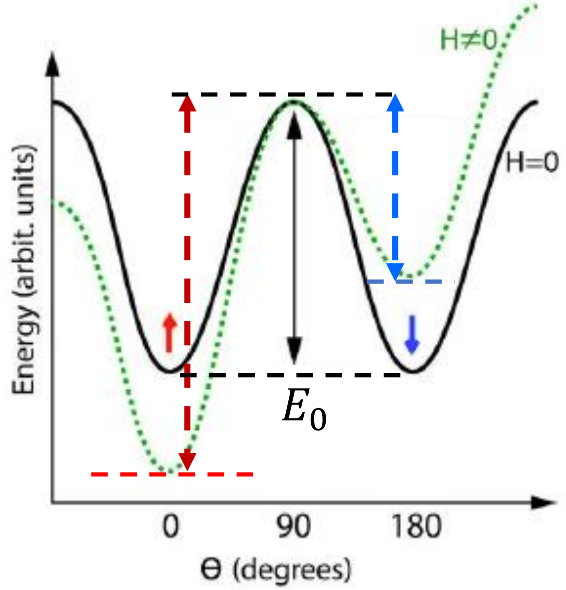
The magnetization curve represents the asymmetry in the number of particles pointing up ($n\uparrow$) or down ($n\downarrow$) changing over time with the applied field

Transition rates

$$\frac{dn_\uparrow}{dt} = -\kappa_{\uparrow\downarrow} n_\uparrow + \kappa_{\downarrow\uparrow} n_\downarrow \qquad \kappa_{\uparrow\downarrow} = \nu_0 e^{-E_{\uparrow\downarrow}/k_B T}$$

$$E_{\uparrow\downarrow} = K\sin^2\vartheta - mH\cos(\vartheta - \varphi)$$

$$E_{rev,\uparrow} = K(1+h)^2 \qquad E_{rev,\downarrow} = K(1-h)^2$$



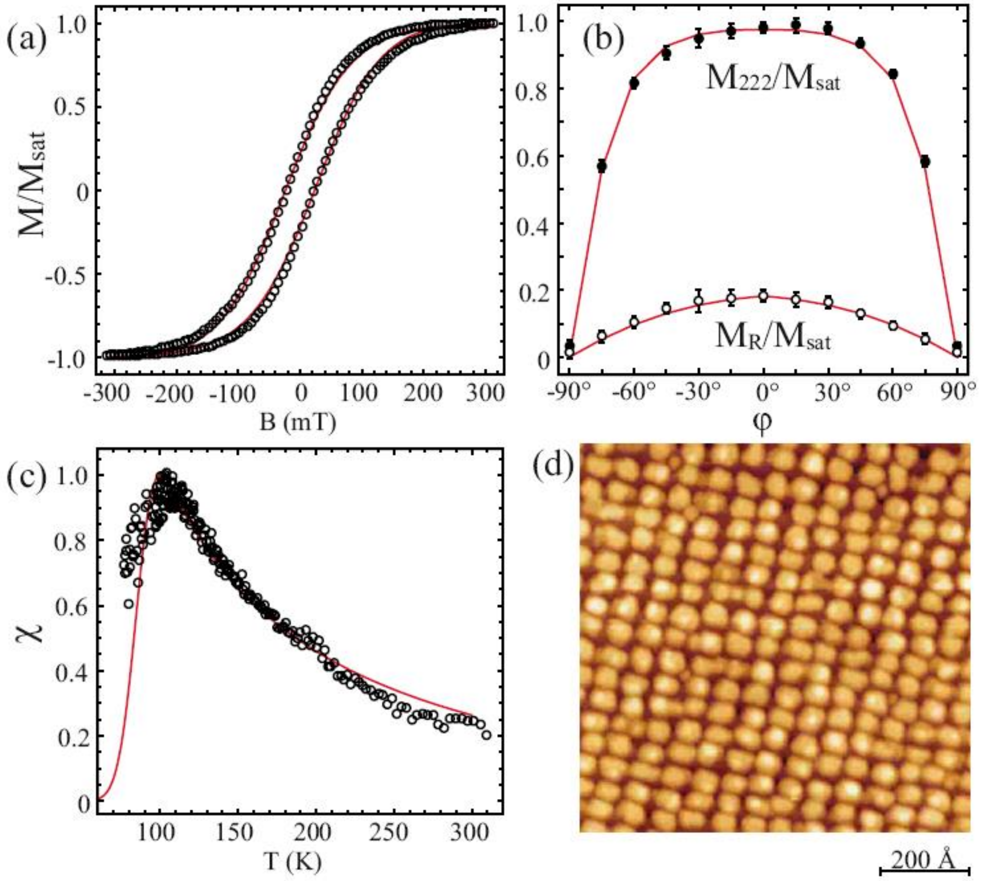
J. J. Lu *et al.*, J. Appl. Phys. **76**, 1726 (1994)

Distribution of writing fields

(experimentally we have a distribution of K and *m*)

1.1 ML Co/Au(11,12,12)

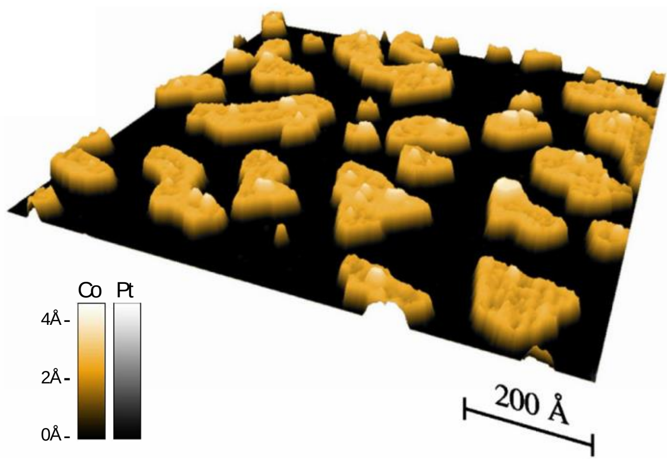
Two atomic layer high particles; mean size = 600 atoms



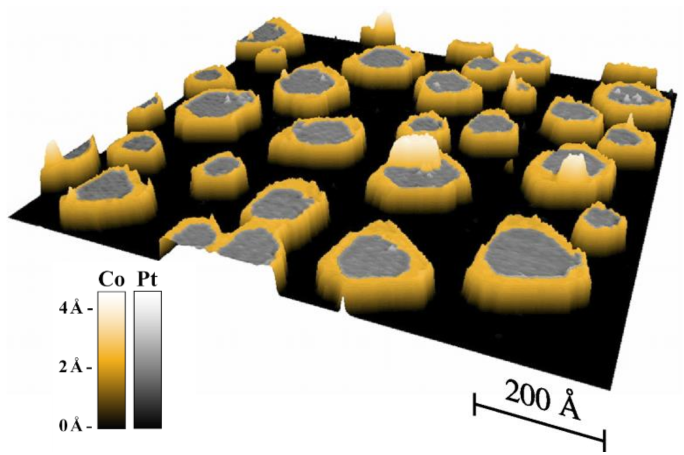
A. Lehnert *et al.*, Rev. Sci. Inst. **80**, 023902 (2009)

MAE: the edge does the job

Co islands

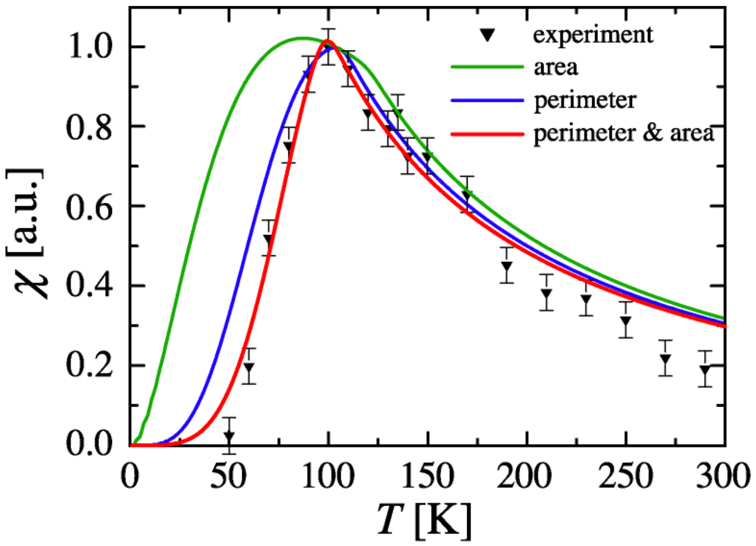


Pt core and Co shell

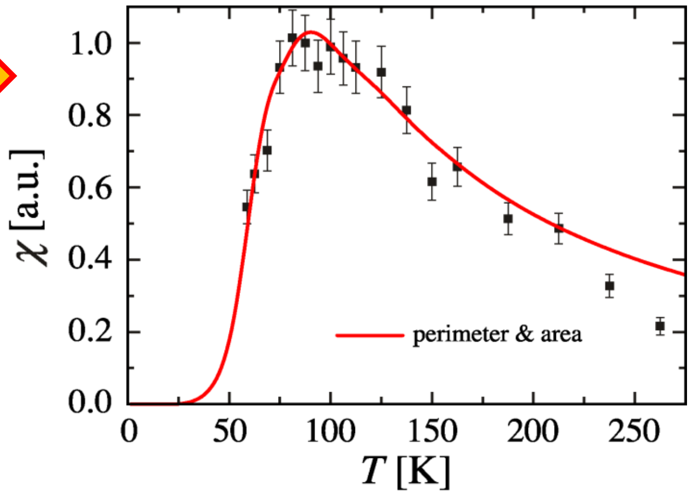


1 atomic layer high islands
Size about 1000 atoms

Out-of-plane easy axis



Same blocking temperature
T_b = 100 K



MAE originates from the edge:
ΔL is larger at low coordination sites

S. Rusponi *et al.*, Nature Mat. **2**, 546 (2003).

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ARTICLE

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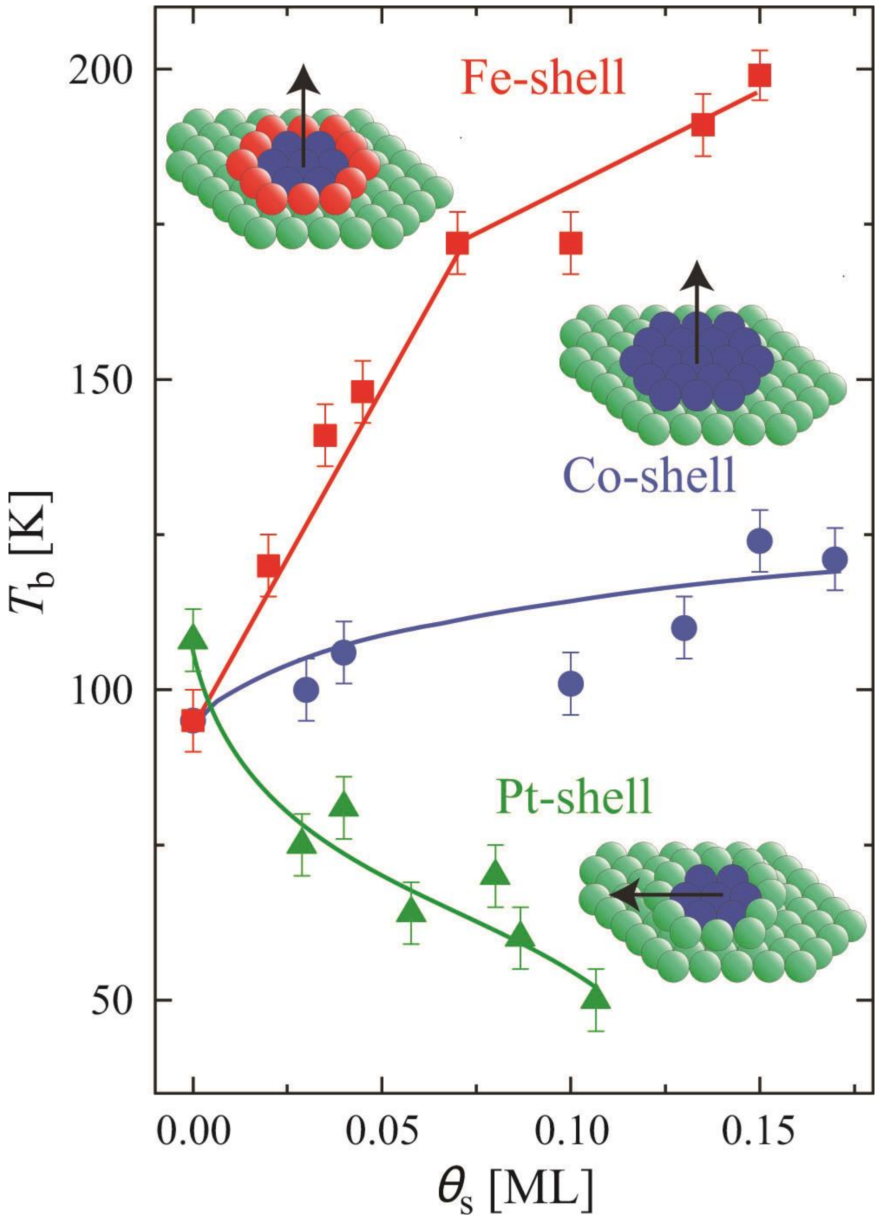
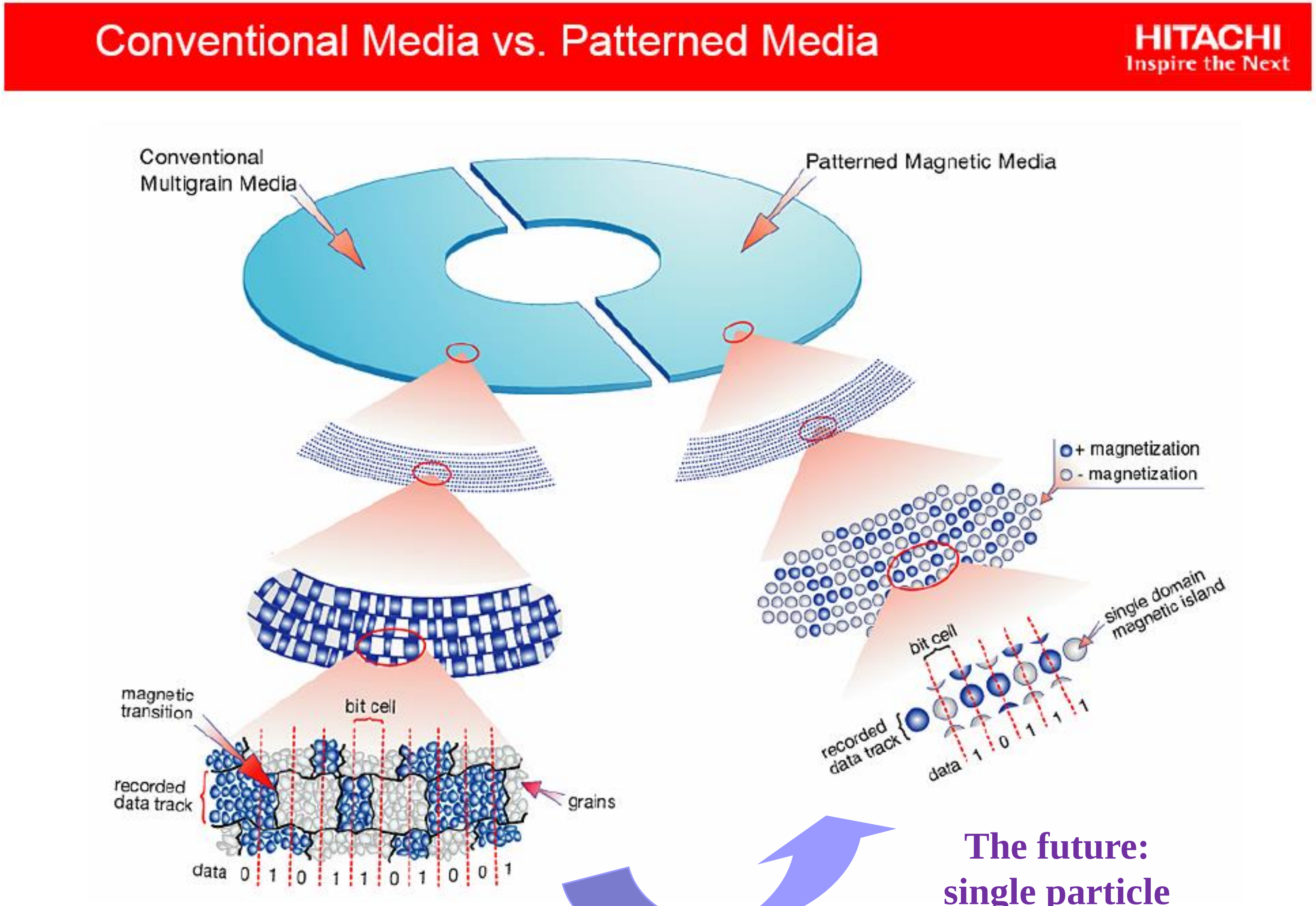
Atomic-scale engineering of magnetic anisotropy of nanostructures through interfaces and interlines

S. Ouazi[1,*,†], S. Vlaic[1,*], S. Rusponi[1], G. Moulas[1], P. Buluschek[1], K. Halleux[1], S. Bornemann[2], S. Mankovsky[2], J. Minár[2], J.B. Staunton[3], H. Ebert[2] & H. Brune[1]



Island size
about 1000 atoms

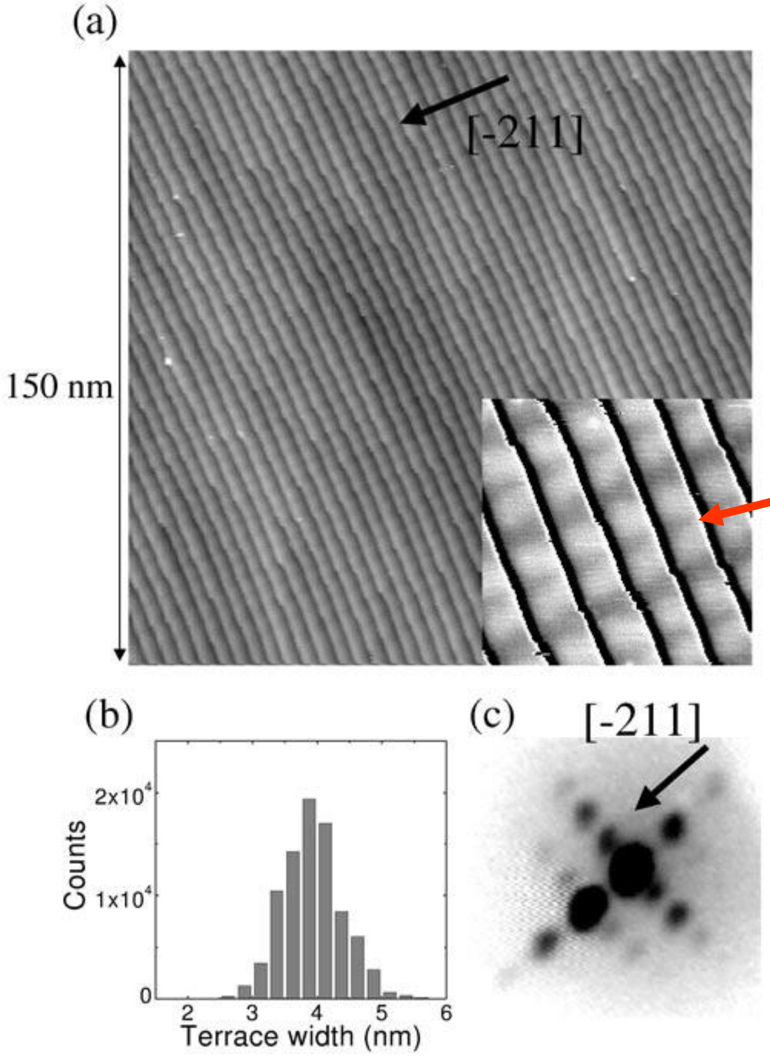
Storage media: present and future



The future: single particle per bit

Model system for ultra high density recording media

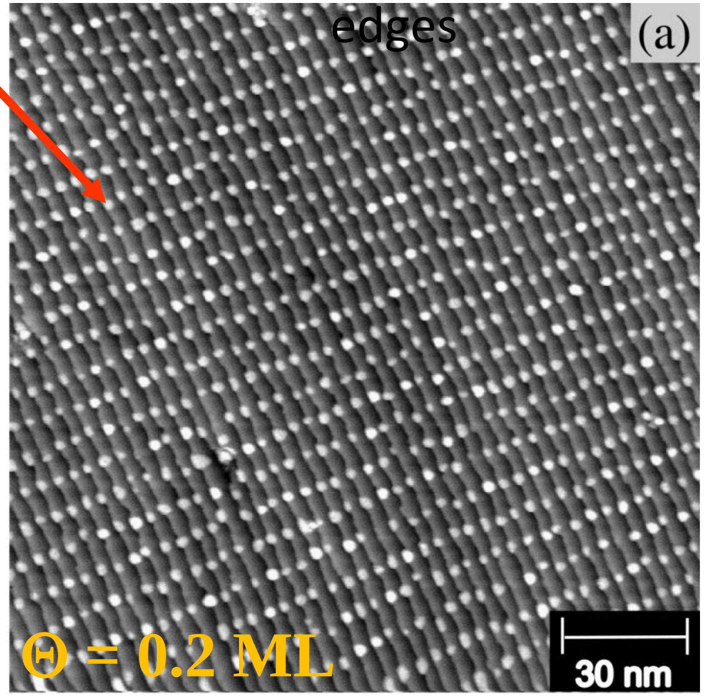
Au(788) vicinal surfaces



(111)-oriented terraces with reconstruction lines perpendicular to step edges

Surface reconstructions on two consecutive terraces are coherent

Co nucleates in bi-layer dots at the positions where the reconstruction lines cross the step edges



26 Tdots/in^2

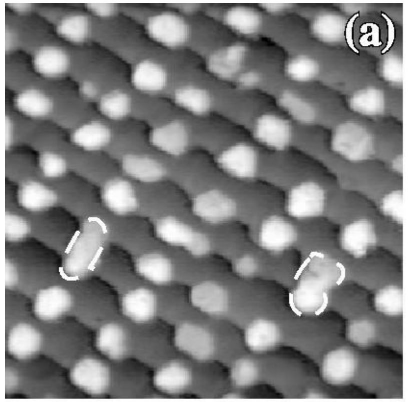
V. Repain et al. Europhys. Lett. **58**, 730 (2002)

Negligible dipolar interaction at 26 Tdots/in²

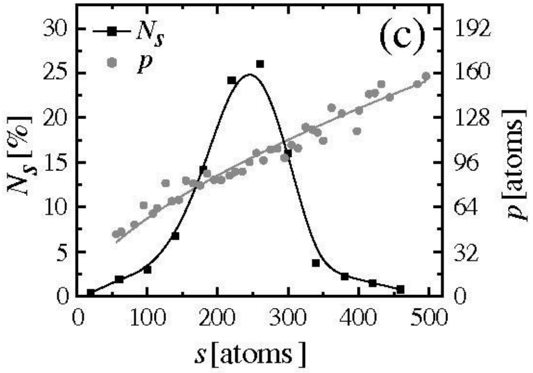
$\chi = dM/dB$ is the magnetic susceptibility

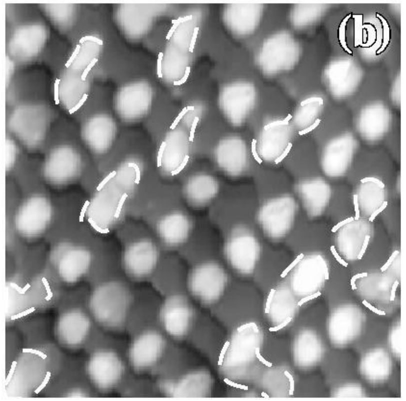
$(B = B_0 \cos(\omega t))$

0.75 ML Co

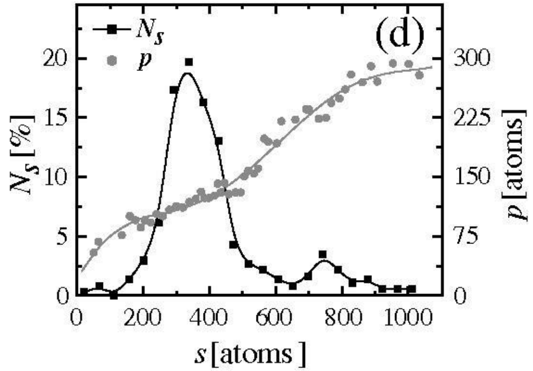


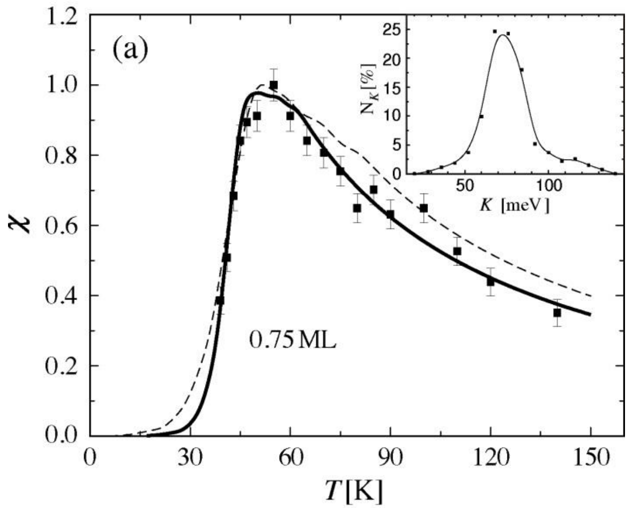
monodisperse
size distribution

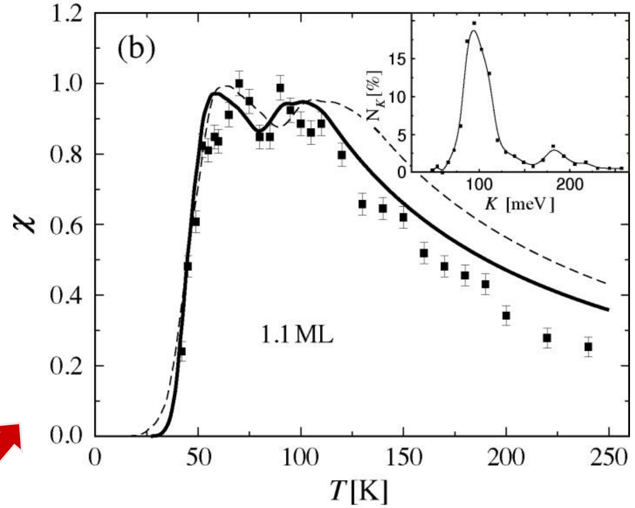




1.1 ML Co







χ(T) is maximal at the temperature at which the island magnetic moment oscillates in phase with B

χ(T) shows a single peak

χ(T) shows two peaks

Big and small particles are independent: No coupling

Bimodal size distribution

Bimodal χ vs. T

N. Weiss, *et al*. Phys. Rev. Lett. **95**, 157204 (2005).

Magnetization reversal mechanisms: coherent *vs.* incoherent reversal

$$\mathcal{E} = \int_{-L/2}^{L/2} dx \left\{ \frac{A}{M_0^2} \left[(\partial_x M_x)^2 + (\partial_x M_y)^2 + (\partial_x M_z)^2 \right] + \frac{K_h}{M_0^2} M_z^2 - \frac{K_e}{M_0^2} M_x^2 - H_{\mathrm{ext}} M_x \right\}$$

Exchange

Zeeman

Magnetic anisotropy (including the dipolar)

Coherent reversal: $E_{rev} = K\,L\,W$

Reversal by domain wall creation and displacement: $E_{rev} = 4\,W\sqrt{AK}$

$A = 2J_{ex}S^2/a$ is the stiffness (a is the atomic pitch)

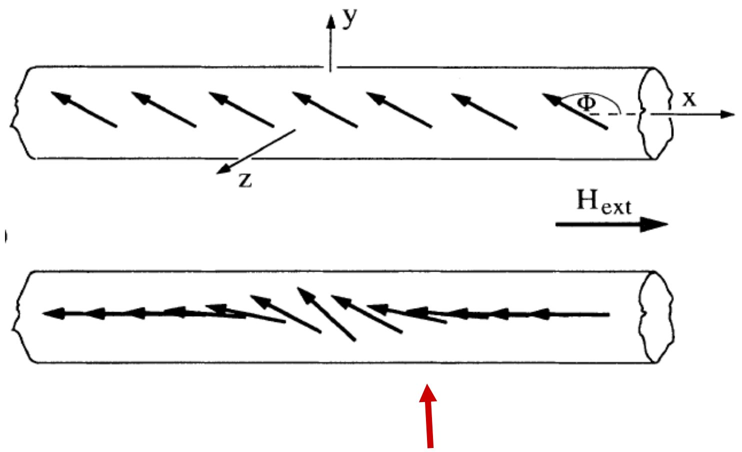
Domain wall displacement is favored if:

$$4\,W\sqrt{AK} < K\,L\,W$$

⇓

$$L_{cr} > 4\sqrt{A/K}$$

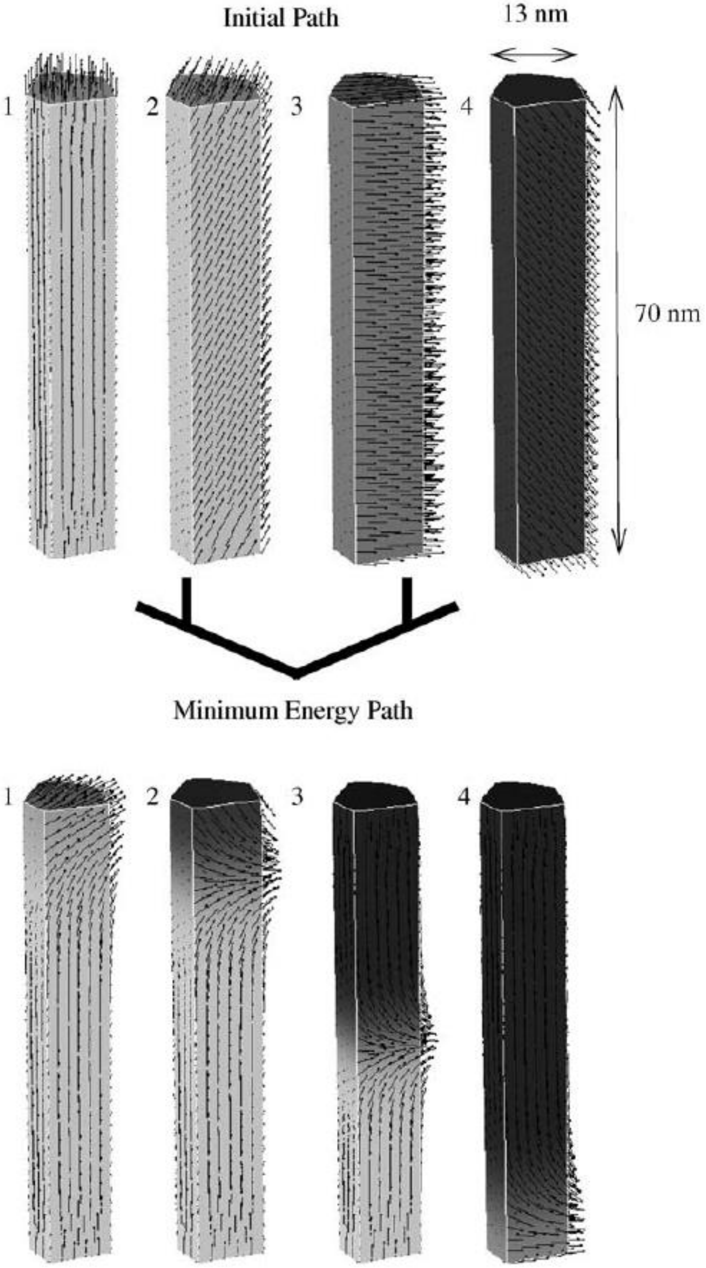
Wire with length *L*, section *W*, lattice parameter *a*.
Each atom contributes with a MAE = K

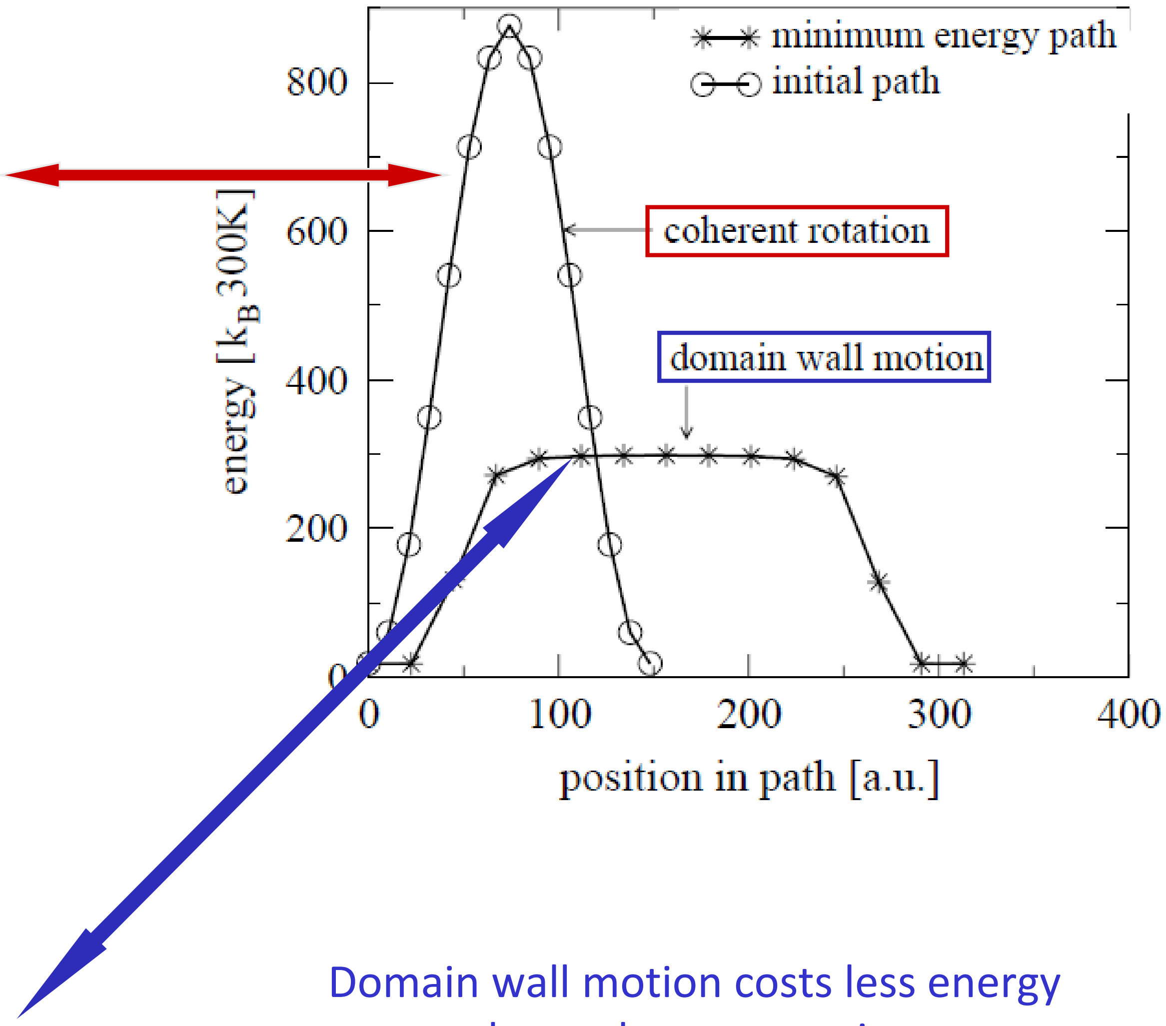


This solution is true in the limit of H_{ext} -> 0

H.-B. Braun Phys. Rev B **50**, 16502 (1994); H.-B. Braun Phys. Rev B **50**, 16485 (1994);
H.-B. Braun Phys. Rev Lett. **71**, 3557 (1993); H.-B. Braun J. Appl. Phys. **85**, 6172 (1999);

Particle shape affects magnetization reversal



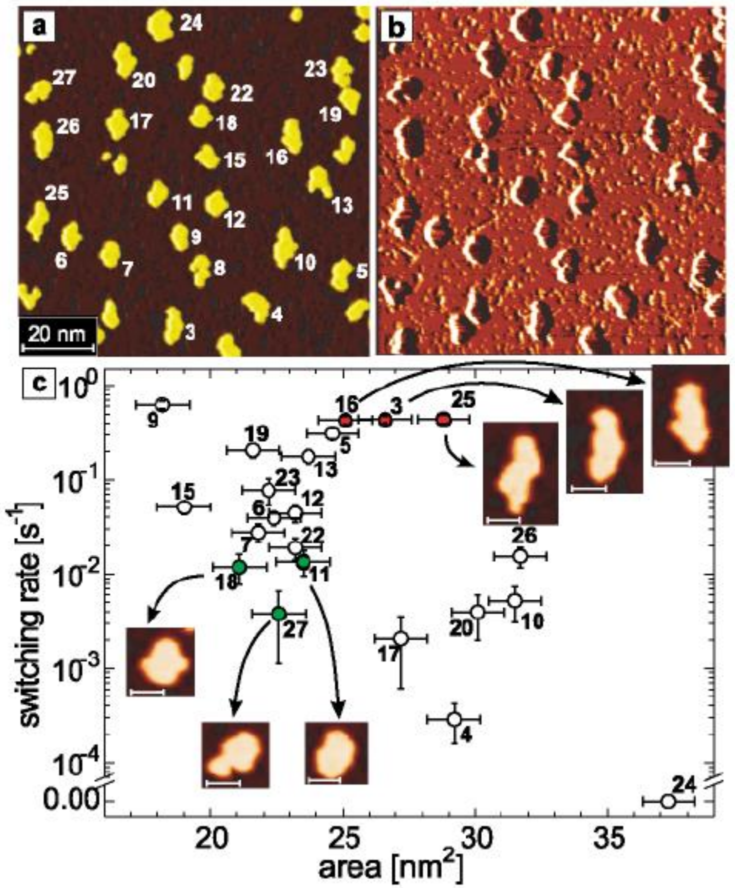


Domain wall motion costs less energy than coherent rotation

R. Dittrich *et al.* J. Magn. Magn. Matter. **250**, L12 (2002)

See exercise: 5.2

Elongated islands switch faster than compact islands: different reversal mechanism

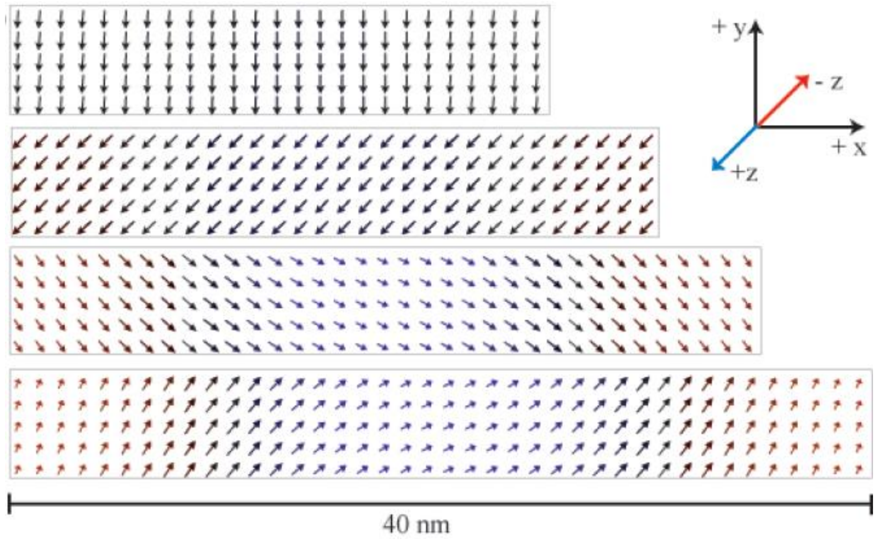


Spin Polarized-STM image of monolayer high Fe islands on Mo(110)

$L_{crit} \cong 5$ nm for Fe/Mo(110)

$L < L_{crit}$ -> Coherent rotation
$L > L_{crit}$ -> domain wall motion

$L_{crit} = 4\sqrt{A/K}$ if $K >> \mu_0 M^2$

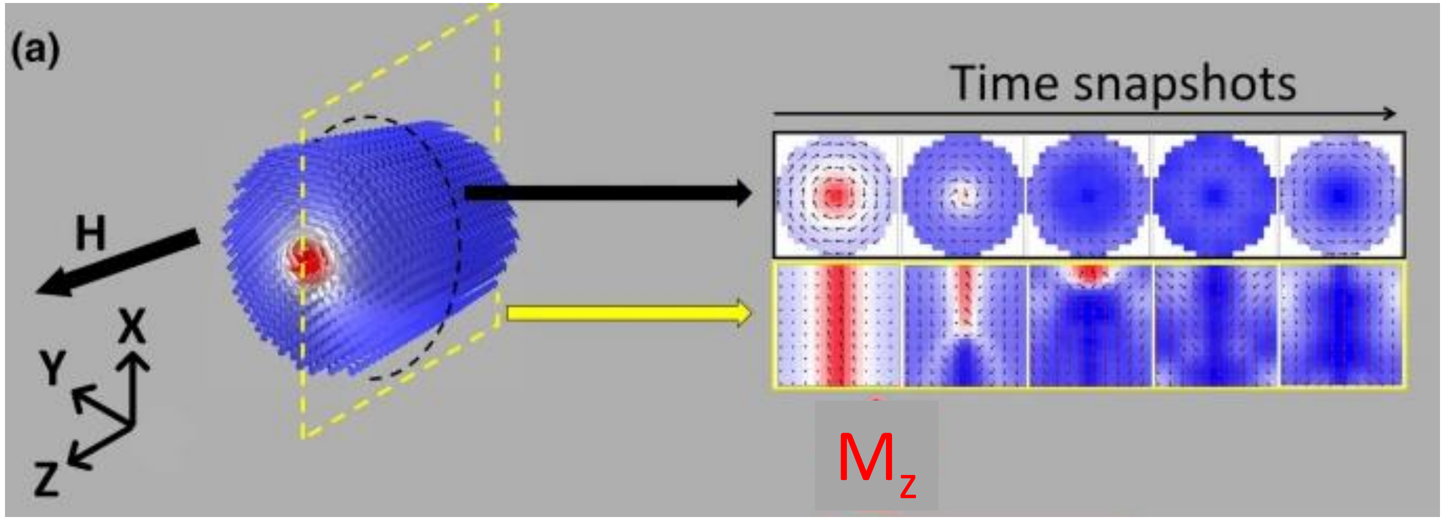


Micromagnetic simulation for Co islands on Pt(111)

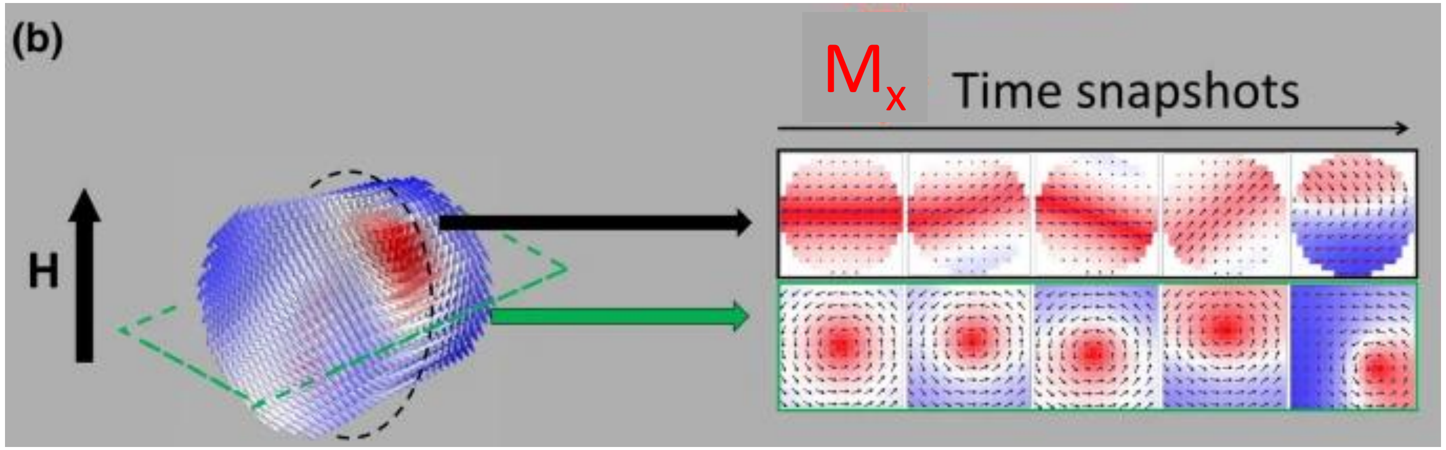
M. Bode et al. Phys.Rev. Lett. **92**, 067201 (2004)

DOI: https://doi.org/10.1103/PhysRevB.90.144427

Magnetic reversal modes in cylindrical nanostructures

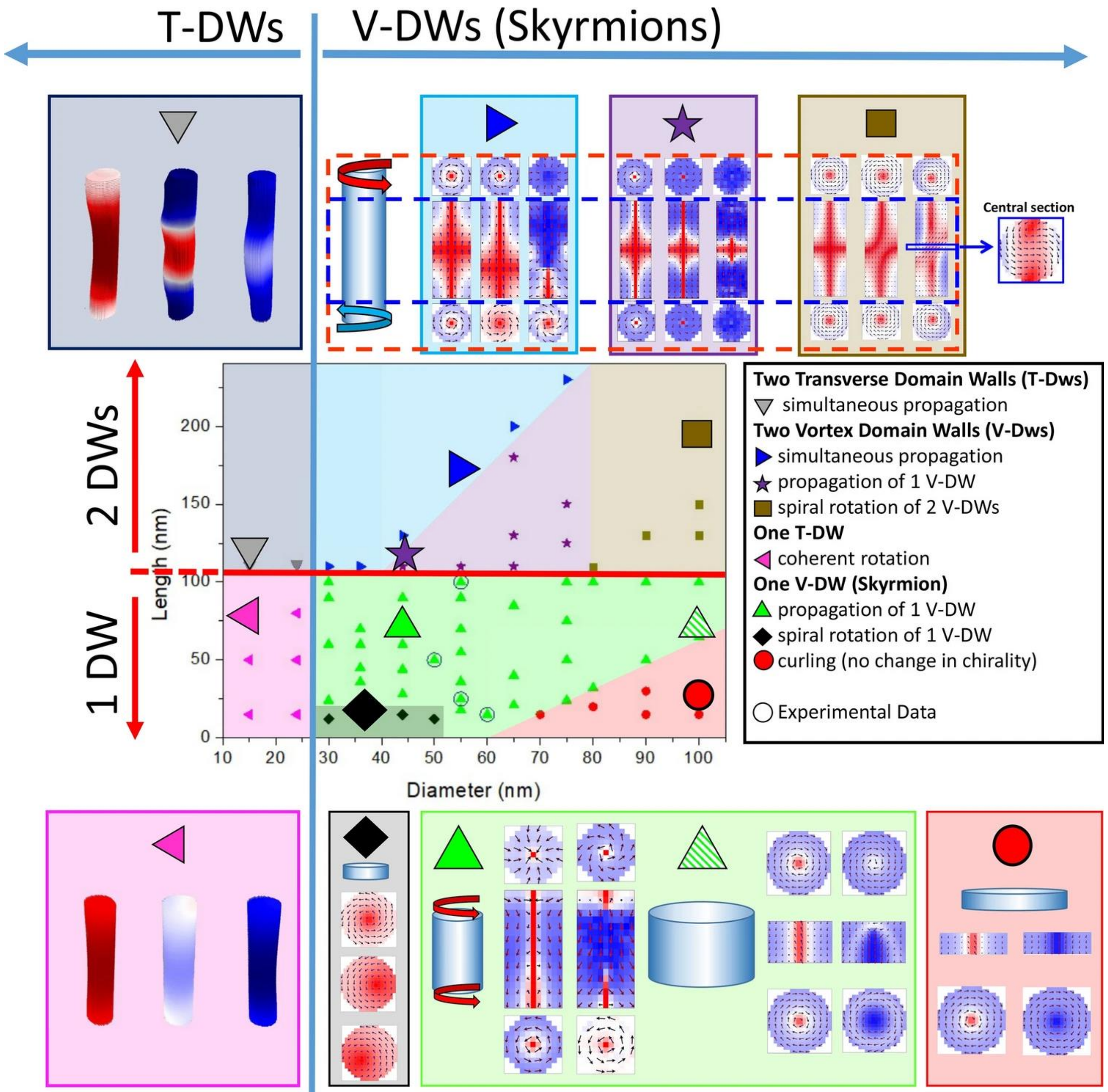


(**a**) and (**b**) 3D and cross-sectional representations (central x-, y- and z-slices) of time snapshots during magnetization reversal of an individual Ni NW with 50 nm in length and 50 nm in diameter, when applying the magnetic field (**a**) parallel and (**b**) perpendicular to the NWs' long axis. (**a**) Illustrates the formation of a skyrmion tube and the propagation of a vortex domain wall with alternating chirality from clockwise to counter-clockwise; while (**b**) illustrates reversal by spiral rotation of a vertical vortex.



https://doi.org/10.1038/s41598-021-89474-z

Magnetic reversal modes in cylindrical nanostructures



https://doi.org/10.1038/s41598-021-89474-z

Landau-Lifshitz-Gilbert (LLG) equation

See exercise: 5.3

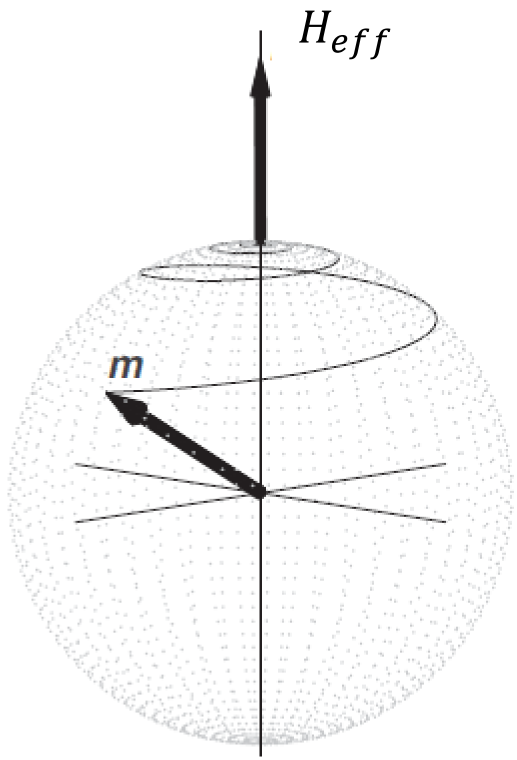
LLG equation describes the temporal evolution of a magnetic moment ***m*** or magnetization ***M*** = ***m***/*V* , assuming that the magnitudes |***m***| or |***M***| remain constant in time

Basic speaking: ***m*** is described as a vector of constant length (classical description) moving on the surface of a sphere

The effective field responsible for the spin dynamics contains several terms in addition to the external magnetic field *H*:

$$H_{eff} = H + H_{exc} + H_{MCA} + H_{dip}$$

temperature can also be included (described by a random magnetic field)



[St&Sie06]

https://demonstrations.wolfram.com/PrecessionOfMagnetizationUsingTheLandauLifshitzEquation/

[Aha00] pages 174-182

Landau-Lifshitz-Gilbert (LLG) equation

See exercise: 5.4

Classical description of magnetization dynamics (spin described as a rotating vector)

$$\frac{d\boldsymbol{m}}{dt} = -\frac{\gamma}{1+\alpha^2}(\boldsymbol{m} \wedge \boldsymbol{H}_{eff}) - \frac{\gamma}{1+\alpha^2}\frac{\alpha}{m}(\boldsymbol{m} \wedge [\boldsymbol{m} \wedge \boldsymbol{H}_{eff}]) \quad \Longleftrightarrow \quad \frac{d\boldsymbol{m}}{dt} = -\gamma(\boldsymbol{m} \wedge \boldsymbol{H}_{eff}) + \frac{\alpha}{m}\left(\boldsymbol{m} \wedge \frac{d\boldsymbol{m}}{dt}\right)$$

$\boldsymbol{H}_{eff} = \frac{d\mathcal{E}}{d\boldsymbol{M}}$ $\mathcal{E}$ is the magnetic energy density

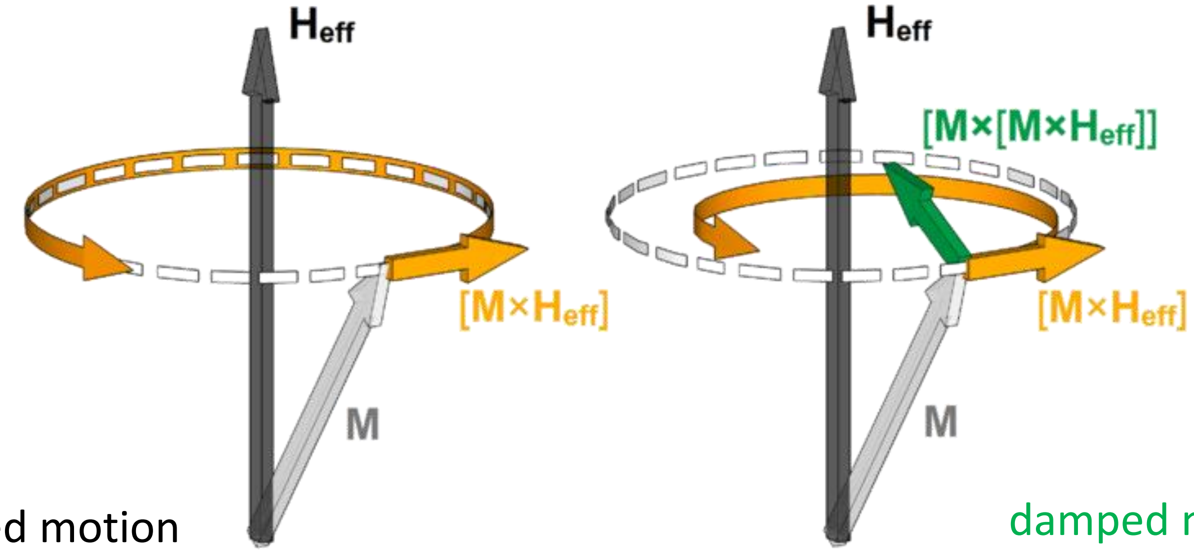
$\boldsymbol{m} = \frac{\boldsymbol{M}}{M_{sat}}$

$\gamma = -\frac{g_e e}{2m_e} = -\frac{2\mu_B}{\hbar} = -1.76\ 10^{11}$ rad s^{-1} T^{-1}= 28 GHz/T

α is the Gilbert damping parameter

$\boldsymbol{m} \wedge \boldsymbol{H}_{eff}$ describes the magnetization precession around the effective magnetic field

$\boldsymbol{m} \wedge \frac{d\boldsymbol{m}}{dt}$ describes the damping process leading the magnetization to the state with minimum energy (parallel to the effective field)



undamped motion

damped motion

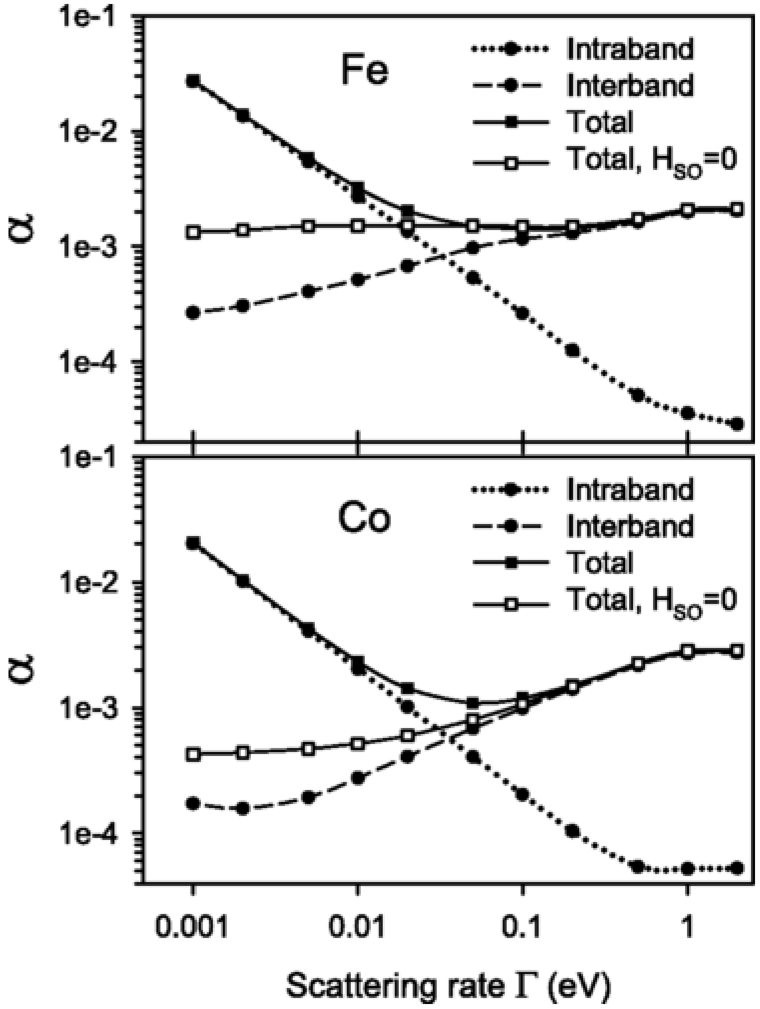
https://www.iue.tuwien.ac.at/phd/makarov/dissertationch5.html

Origin of the Gilbert damping parameter: spin-orbit + lattice scattering

The only energy that changes with the magnetization direction is the spin-orbit energy H_{soc}.

Damping is due to variations $\frac{\partial H_{\text{soc}}}{\partial \theta}$ in the energies $\mathcal{E}_{n,k}$ of the single-particle states with respect to the spin direction θ. The states are labeled with a wave vector k and band index n.

1) As the magnetization precesses, the spin-orbit interaction changes the energy of the electronic states, pushing some occupied states above the Fermi level and some unoccupied states below the Fermi level. Thus, electron-hole pairs are generated near the Fermi level even in the absence of changes in the electronic populations.
2) The electron-hole pairs created by the precession exist for some lifetime τ before relaxing through lattice scattering. The amount of energy and angular momentum dissipated to the lattice depends on how far from equilibrium the system gets; thus, damping by this mechanism increases linearly with the electron lifetime.



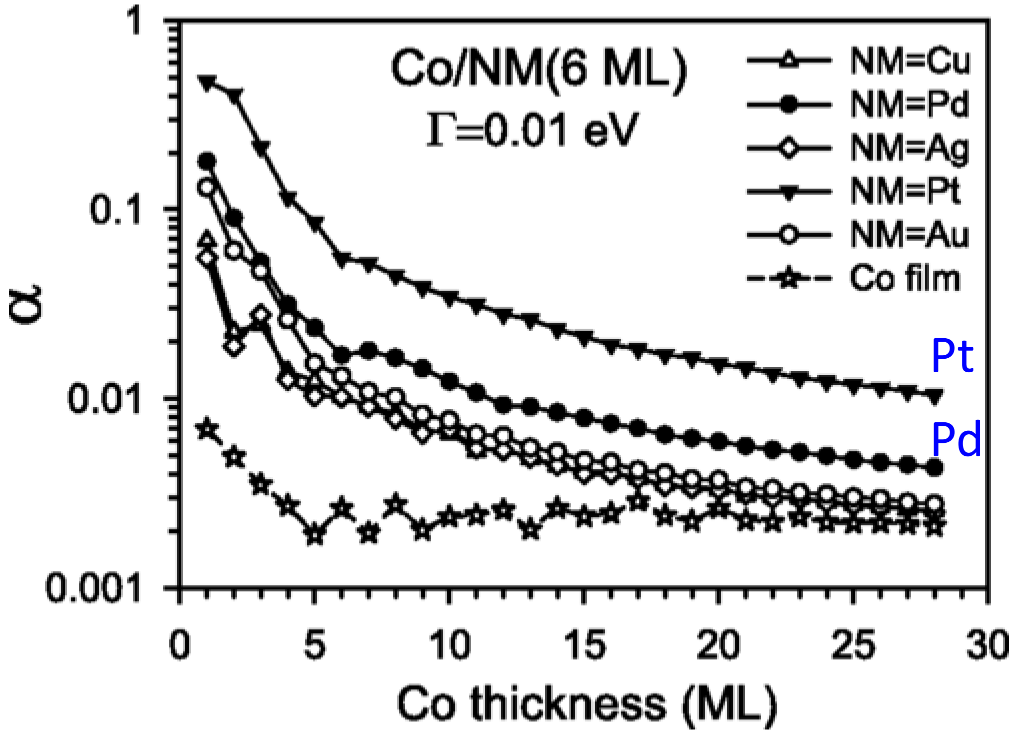
Gilbert damping constant α (solid lines) and its intraband (dotted line) and interband (dashed line) terms vs scattering rate $\Gamma = \frac{\hbar}{\tau}$ for bulk Fe and Co found with (solid symbols) and without (open squares) the SO interaction H_{SO}

https://doi.org/10.1103/PhysRevLett.99.027204

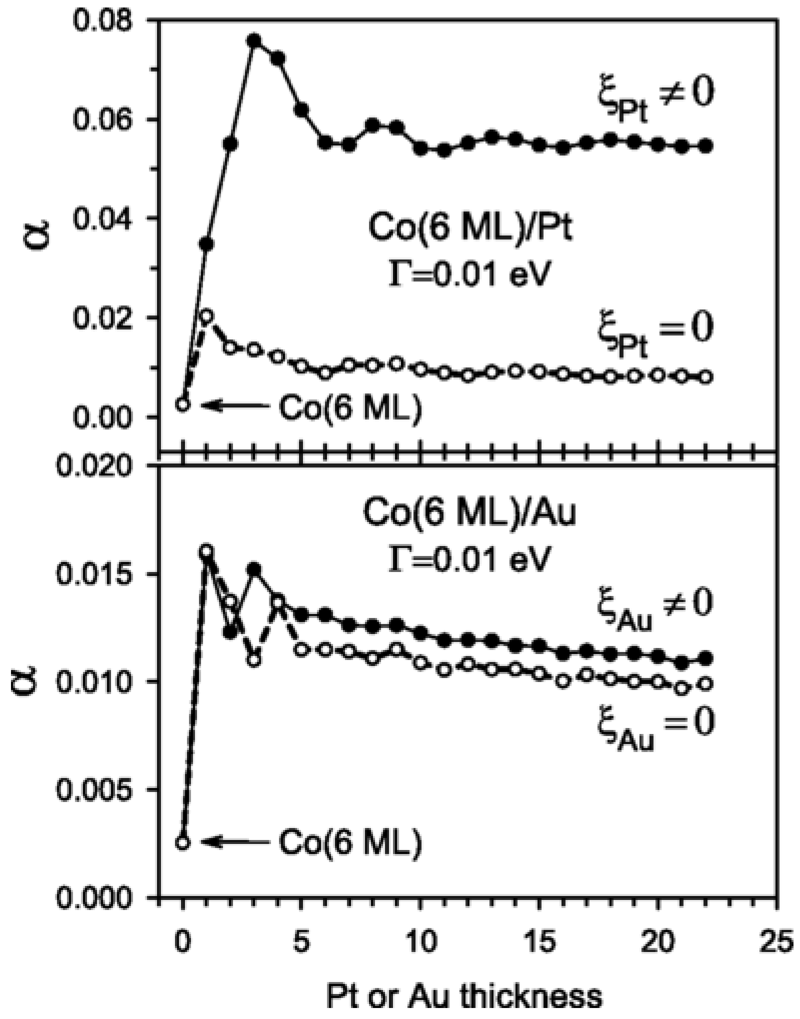
DOI: https://doi.org/10.1103/PhysRevB.90.014420

Effect of SOC on damping

Strong damping enhancement for Pd and Pt caps: combined effect of the large spin-orbit couplings of Pd and Pt and the simultaneous presence of d states at the Fermi level



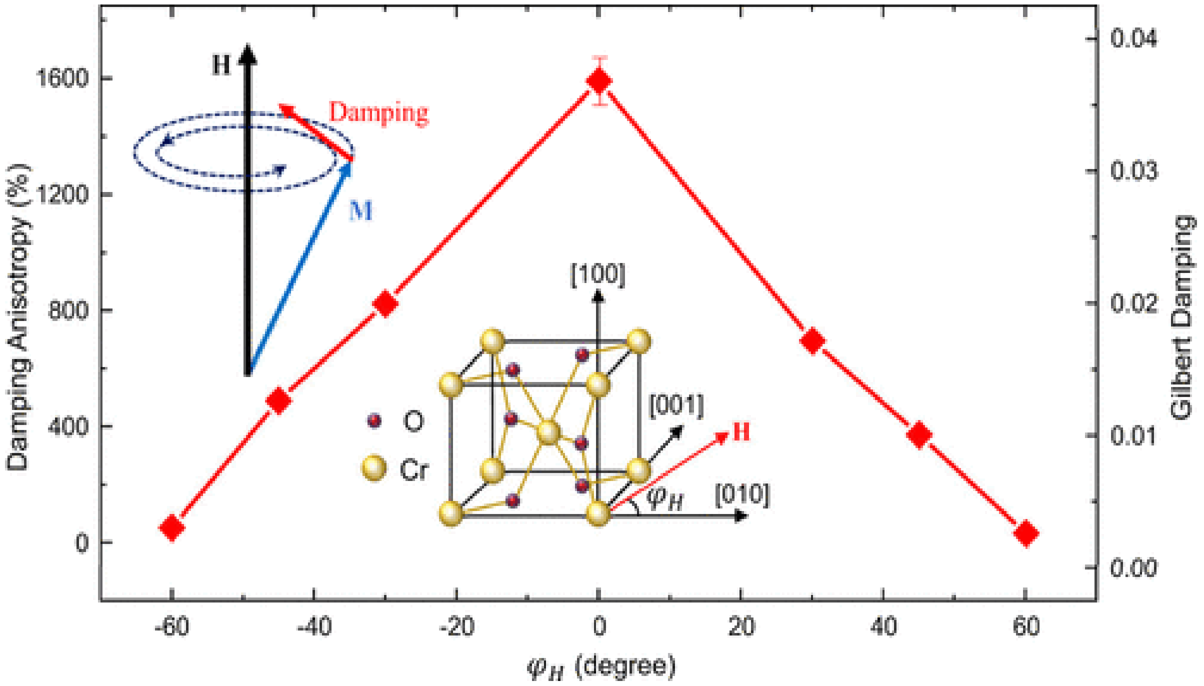
Gilbert damping constant vs Co thickness in (001) fcc Co/NM(6 ML) bilayers; Γ=0.01 eV.

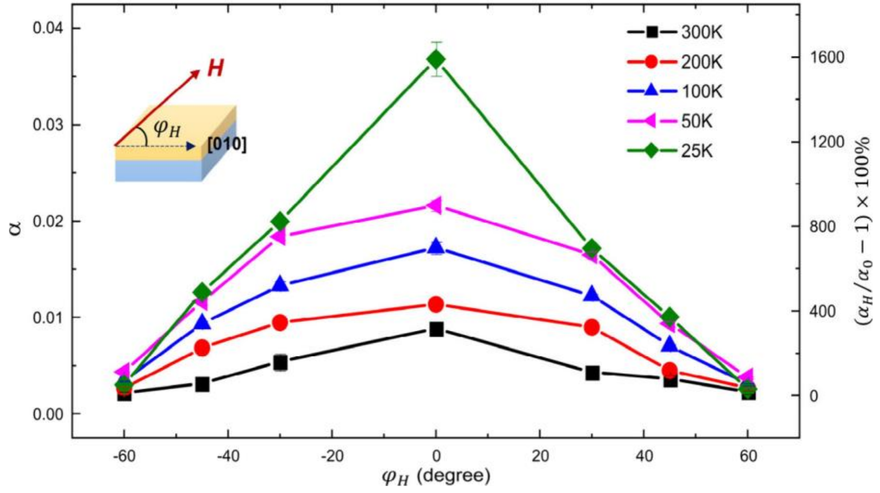


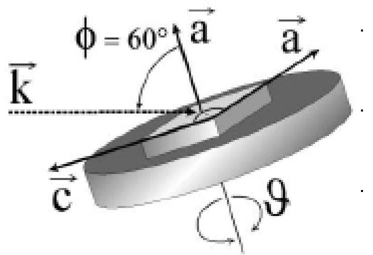
Gilbert damping constant vs NM cap thickness in (001) fcc Co(6 ML)/NM bilayer (NM=Pt and Au), in the presence (solid circles) and the absence (open circles) of the SO coupling in NM; Γ=0.01 eV.

DOI: https://doi.org/10.1103/PhysRevB.90.014420

Extremely Large Anisotropy of Effective Gilbert Damping in Half-Metallic CrO_2







strong SOC anisotropy of the half-metallic CrO_2

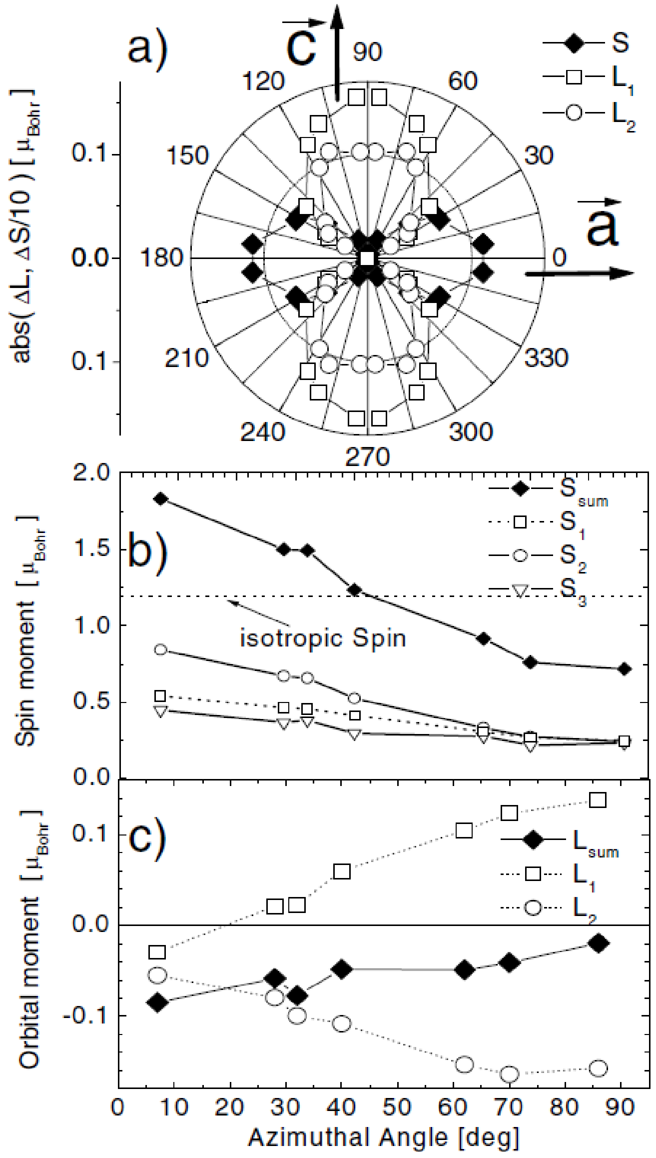
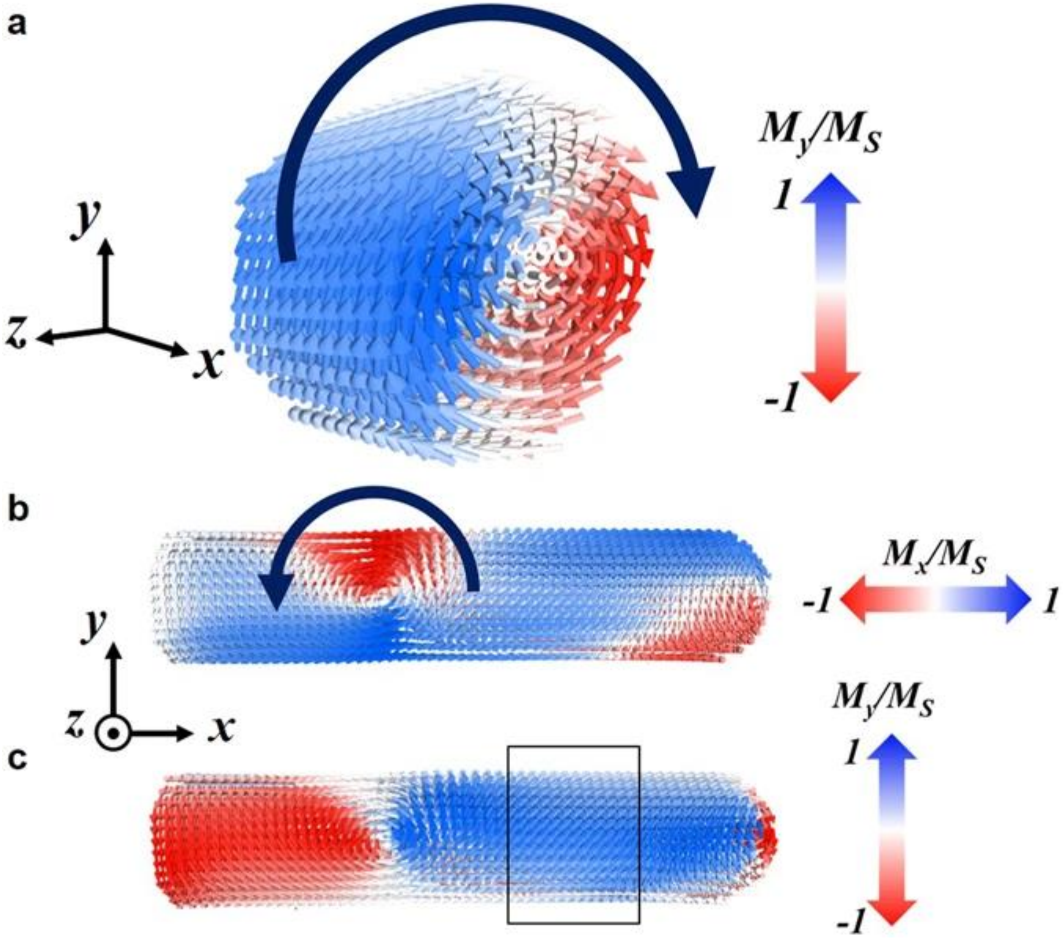


FIG. 4. (a) Fit results for the absolute changes in the spin (solid diamonds; divided by 10) and orbital projections (open squares and circles). Fit results for the (b) spin and (c) orbital projections of Cr 3*d* electrons by variation of the azimuthal angle ϑ.

Nano Lett. 2024, 24, 51, 16436–16442

Phys. Rev. Lett. **88,** 207203 (2002)

Micromagnetic simulations



- The magnetic object is divided into small volumes δV having uniform magnetization ***m***

- Assumption: the spins of the atoms inside δV are coupled by exchange to form a macrospin ***m*** (each macrospin is represented by an arrow in the sketch)

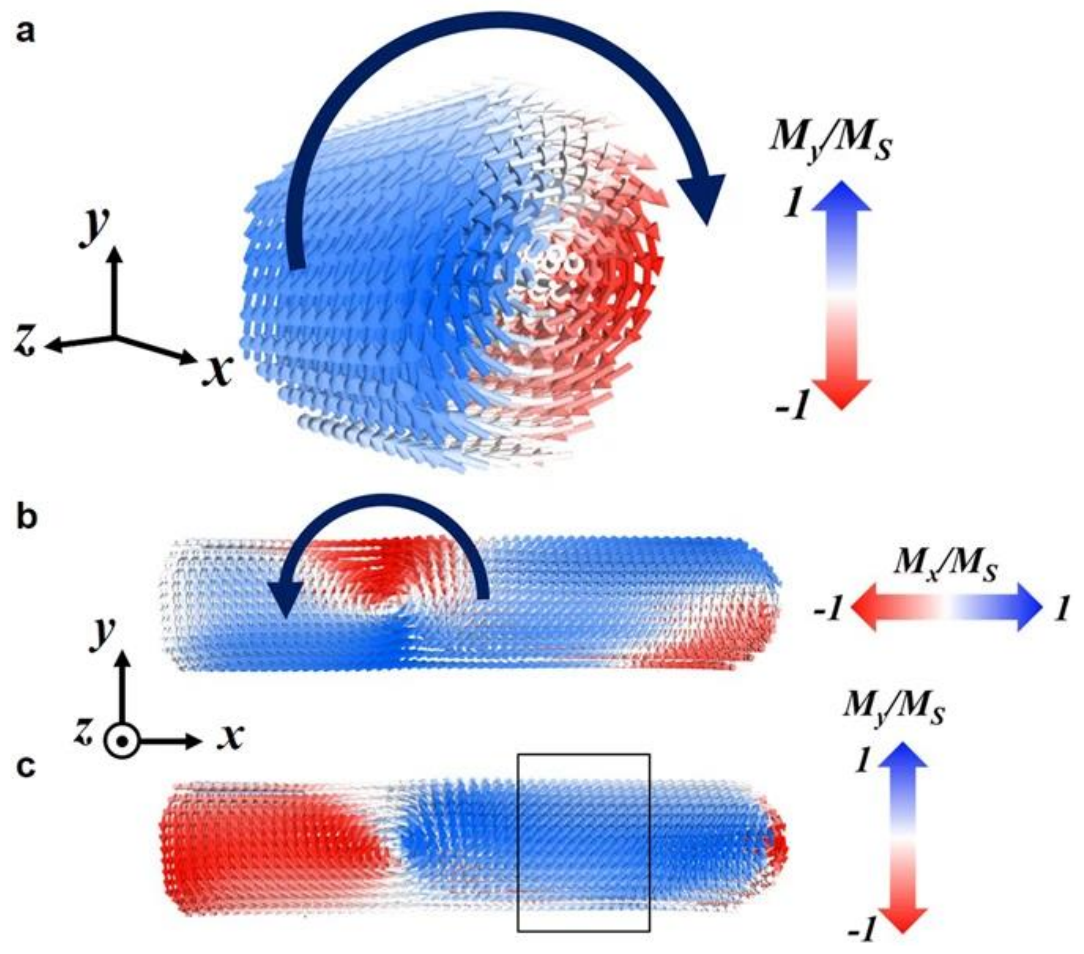
- The dynamics of each macrospin ***m*** is described by the LLG equation with the provided parameters

- Typical parameters:
  - temperature (described by a random magnetic field varying from macrospin to macrospin)
  - external magnetic field
  - magnetic moment per atom (or volume unit)
  - stiffness (= exchange coupling)
  - MCA
  - DMI
  - object dimension
  - δV dimension (Warning: δV must be small compared to DW size

https://doi.org/10.1038/s41598-017-05909-6

Micromagnetic simulations

EPFL



https://doi.org/10.1038/s41598-017-05909-6

Several codes available (list not complete)

Name	Release	FE/FD	GPU capable?	Free?	References
LLG micromagnetics simulator	1997	FD	No	Commercial	29
OOMMF	1998	FD	No	Free	27
micromagus	2003 [a]	FD	No	Commercial	30
magpar	2003	FE	No	Free	31
Nmag	2007	FE	No	Free	32
GPMagnet	2010	FD	Yes	Commercial	26
FEMME	2010	FE	No	Commercial	33
tetramag [b]	2010	FE	Yes	Commercial	34
finmag [c]	2011	FE	No	Free	35
Fastmag	2011	FE	Yes	Commercial	36
Mumax	2011	FD	Yes	Free	37
micromagnum	2012	FD	Yes	Free	38
magnum.fd [d]	2014	FD	Yes	Free	39
magnum.fe	2013	FE	No	Commercial	40
mumax [3]	2014	FD	Yes	Free	41
LLG micromagnetics simulator v4.	2015	FD	Yes	Commercial	29
Grace	2015	FD	Yes	Free	42,43
OOMMF (GPU version)	2016	FD	Yes	Free	44
fidimag	2018	FD	No	Free	45
commics	2018	FE	No	Free	46

https://doi.org/10.1063/1.5093730