Basic concepts on magnetization reversal (1)

Static properties : coherent reversal and beyond

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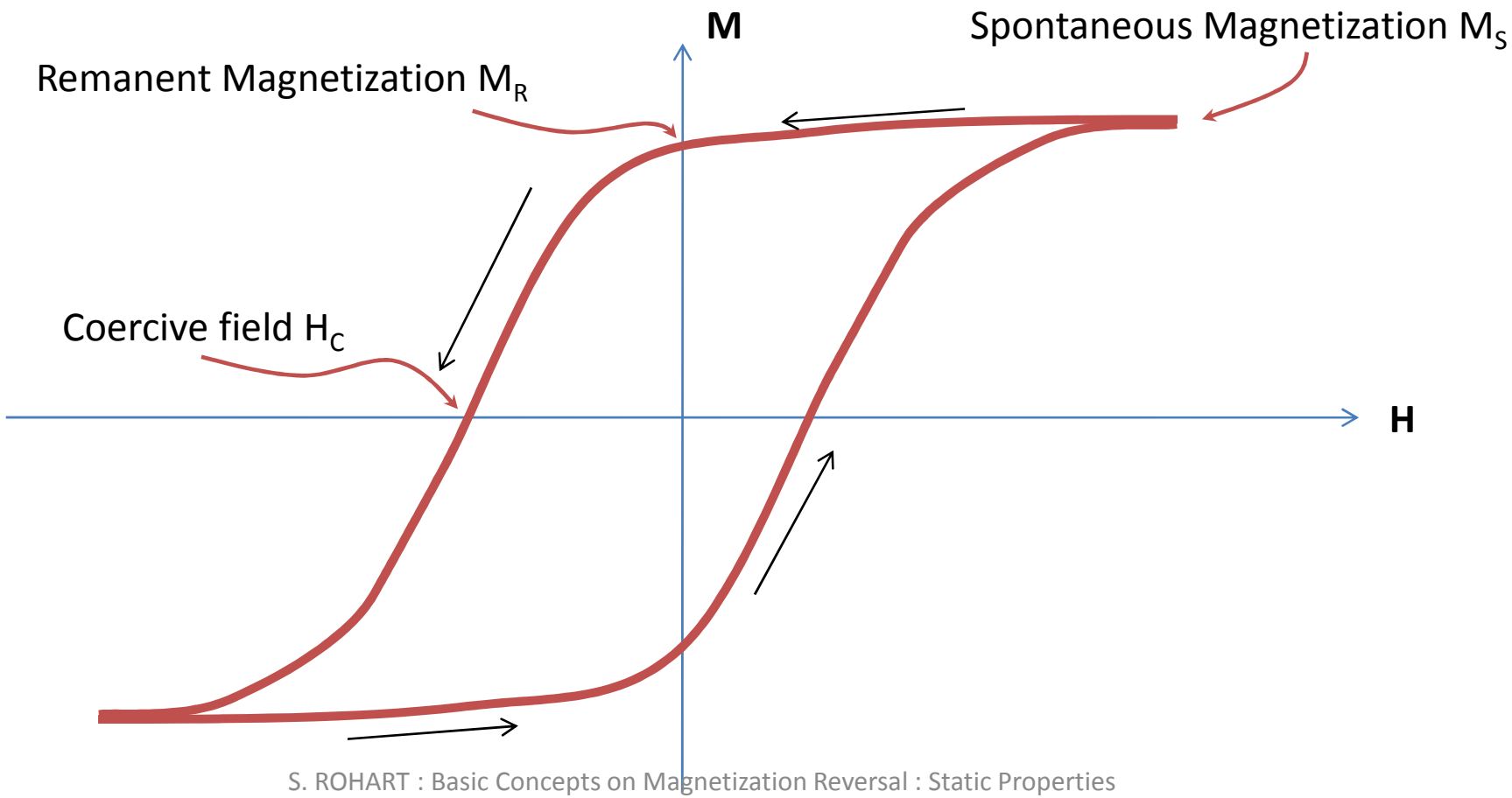
Introduction: Hysteresis loop

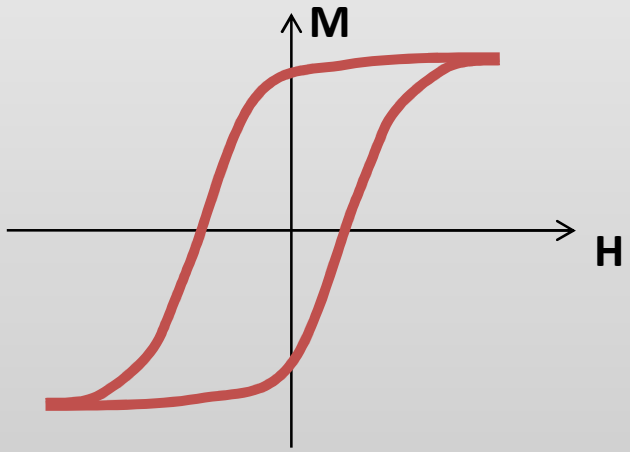
Manipulation of a magnetization :
Application of a magnetic field

Zeeman energy : $E_z = -\mu_0 \mathbf{H}.\mathbf{M_S}$



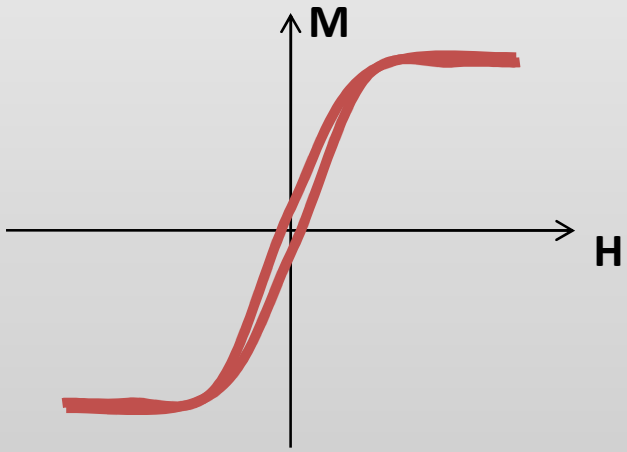
Introduction: Soft and Hard materials

Hard Materials



Applications : Permanent magnets, motors, magnetic recording
Ex: Cobalt, NdFeB, CoSm, Garnets

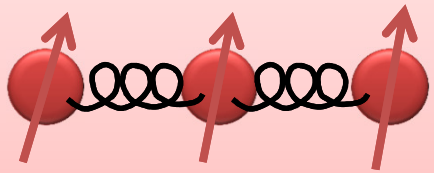
SoftMaterials



Applications : Transformer, flux guide (for electromagnets…), magnetic shielding
Ex : Iron, FeCo, Permalloy ($Fe_{20}Ni_{80}$)

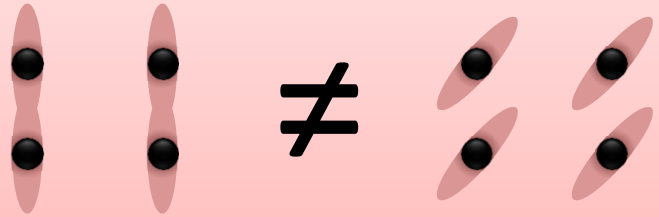
Introduction: Energies in magnetic systems

Exchange energy



$$E_{ex} = -J\vec{S}_i\vec{S}_j$$
$$= A(\nabla\theta)^2$$

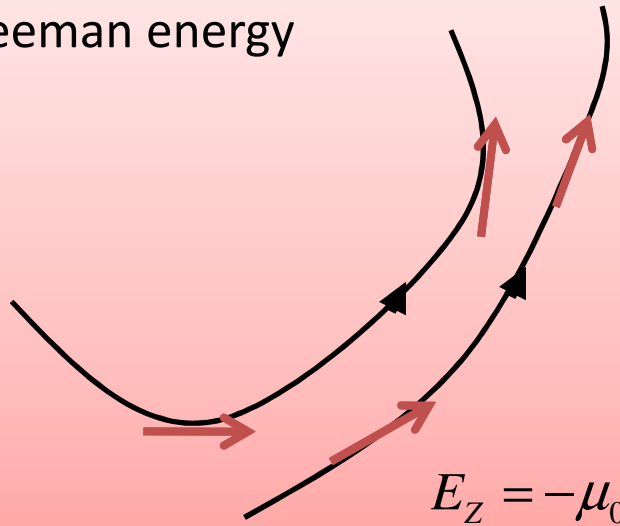
Magnetocrystalline anisotropy energy



$$E_{MC} = K(\vec{m}.\vec{e})^2$$

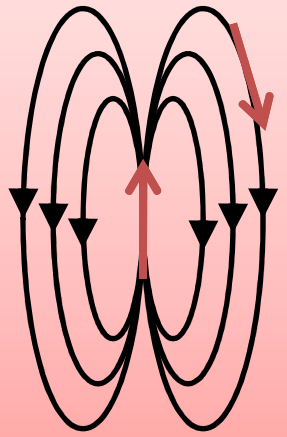
(simplest form, may be more complicated)
reflects the cristal symmetry

Zeeman energy



$$E_Z = -\mu_0\vec{M}.\vec{H}$$

Dipolar energy



$$E_D = -\frac{\mu_0}{4\pi}\left(\frac{3(\vec{m}_i.\vec{r}_{ij})\vec{r}_{ij}}{r_{ij}^5} - \frac{\vec{m}_i}{r_{ij}^3}\right).\vec{m}_j$$

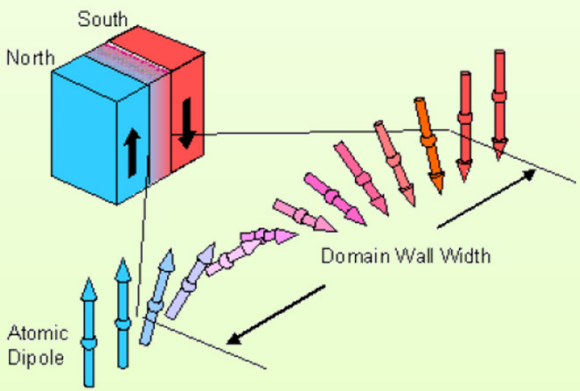
For practical use :
shape anisotropy

$$E_D = -\frac{1}{2}\mu_0\vec{M}.\vec{H}_d$$
$$= -\frac{1}{2}\mu_0\vec{M}.[N]\vec{M}$$

Introduction: Micromagnetism: Typical Length Scales

Bloch wall

-> Anisotropy vs. Exchange



$$E = A\left(d\theta/dx\right)^2 + K\sin^2\theta$$

Bloch wall parameter $\delta_B = \sqrt{A/K}$

Bloch wall width $d_B = \pi\sqrt{A/K}$

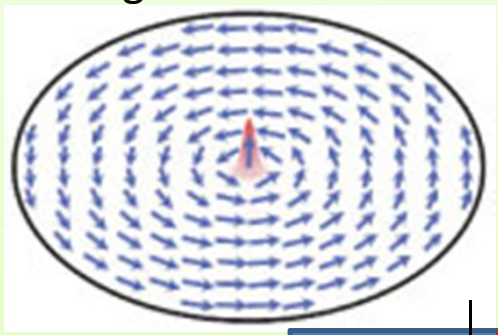
Bloch wall energy $\sigma_B = 4\sqrt{AK}$

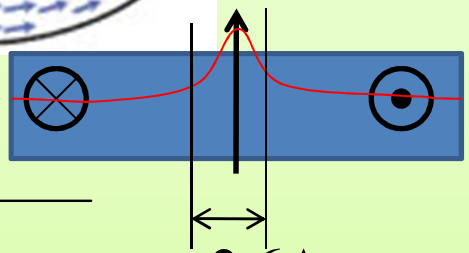
Typical value : 2-3 nm (hard)
-> 100-1000 nm (soft)

Exchange length

-> Dipolar coupling vs. Exchange

Ex : Magnetic vortex





$$\Lambda = \sqrt{2A/\mu_0 M_S^2} \qquad \sim 2.6\Lambda$$

Typical value : 5-10 nm

Quality factor

$$Q = 2K/\mu_0 M_S^2 = \left(\Lambda/\delta\right)^2$$

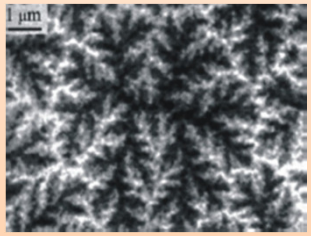
$Q > 1$ hard

$Q << 1$ soft

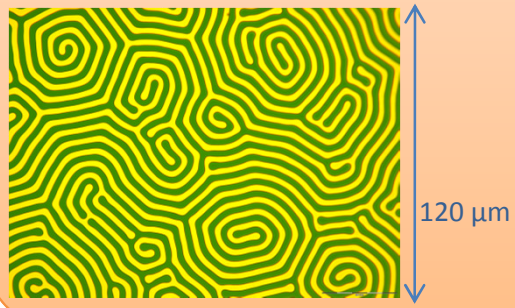
Introduction: Magnetic Domains

Bulk materials

Complex magnetic paterns

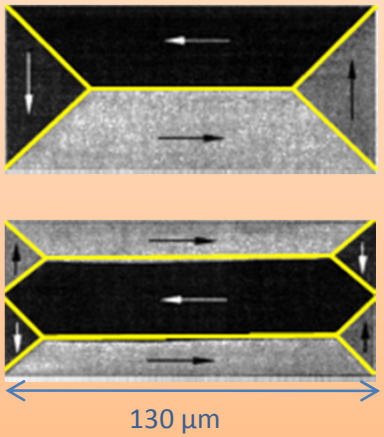


Self organization of domains



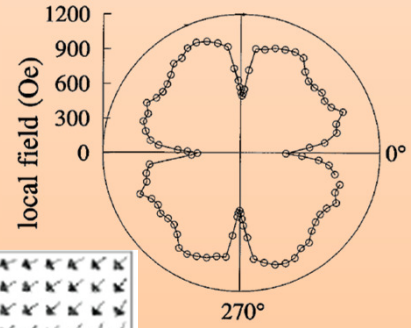
Mesoscopic scale

Small number of possible configuration.
Well defined states



Nanometric scale

Magnetic single domain but non collinearities are still possible
True collinear state at very reduced dimensions
(< few Λ)



(square dots – 500 nm)

Cowburn et al. PRL 81, 5414 (1998)
Cowburn J.Phys.D: Appl. Phys. 33, R1 (2000)

•Except at very small scales, dipolar energy plays an essential role [competition between dipolar energy (long range) and domain wall energy (local)].
•Single domain state is observed well below 1 µm or for hard material .

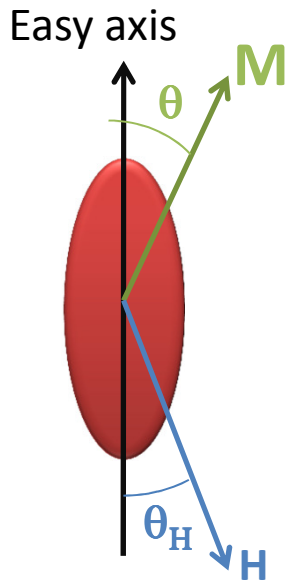
Contents

Coherent reversal: Macrospin hypothesis

Hypothesis : **m**(**r**)=cte=M (strong approximation)

Exchange energy is constant
Dipolar energy equivalent to anisotropy energy

$$E = G(\vec{M}) - \mu_0 \vec{M}.\vec{H}$$



Simplest model : Stoner and Wohlfarth

$$E = K_{eff} \sin^2\theta - \mu_0 M_S H \cos(\theta + \theta_H)$$

$$K_{eff} = K_{mc} + k_d$$

Anisotropy field : $H_K = 2K_{eff} / \mu_0 M_S$

Dimensionless equation : $e = \sin^2\theta - 2h\cos(\theta + \theta_H)$

Different names : Uniform rotation, coherent rotation, macrospin, Stoner and Wohlfarth model…

Coherent reversal: Equilibrium states and switching

$\theta_H = 0$ (Field aligned with the anisotropy axis)

$$e = \sin^2\theta - 2h\cos\theta$$

$$\frac{\partial e}{\partial \theta} = 2\sin\theta(\cos\theta + h)$$

$$\frac{\partial e}{\partial \theta} = 0 \Rightarrow \begin{array}{l} \cancel{\cos\theta = -h : \theta = \theta_m} \\ \sin\theta = 0 : \theta = 0 \; or \; \pi \end{array}$$

Stability

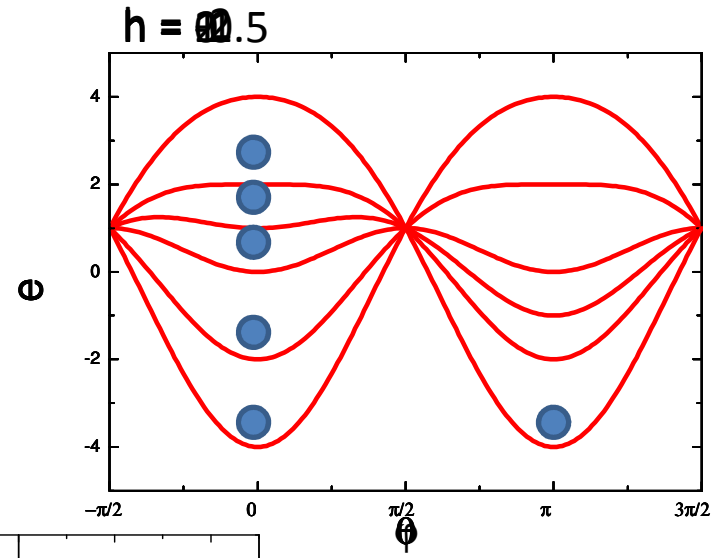
$$\frac{\partial^2 e}{\partial \theta^2} = -2\sin^2\theta + 2\cos^2\theta + 2h\cos\theta$$

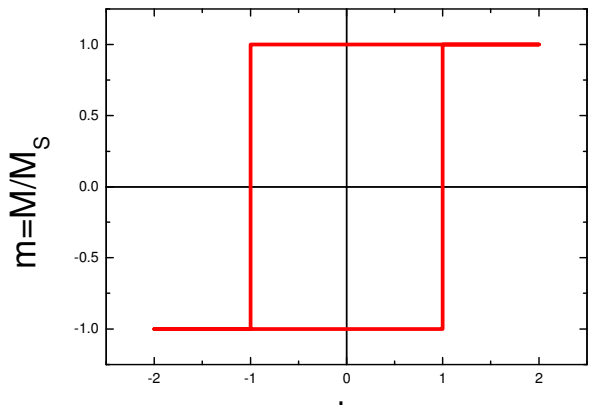
$$= 4\cos^2\theta - 2 + 2h\cos\theta$$

$$\boxed{\frac{\partial^2 e}{\partial \theta^2}(0) = 2(1+h) \quad \cancel{<}0}$$

$$\frac{\partial^2 e}{\partial \theta^2}(\theta_m) = 2(h^2 - 1) \quad > 0$$

$$\boxed{\frac{\partial^2 e}{\partial \theta^2}(\pi) = 2(1-h) \quad >0}$$





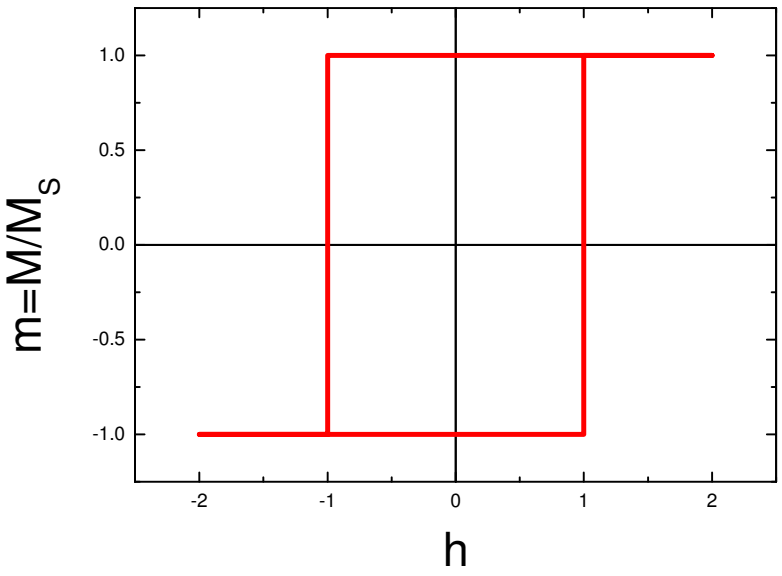
Square hysteresis loop

$H_{switch} = H_K$

Coherent reversal: Equilibrium states

$$e = \sin^2\theta - 2h\cos\theta$$

•Square hysteresis loop
->$H_{switch} = H_K$



Energy barrier

$$\Delta e = e(\varphi_m) - e(0)$$
$$= \left(1 - h^2 + 2h^2\right) - \left(-2h\right)$$
$$= \left(1 + h\right)^2$$

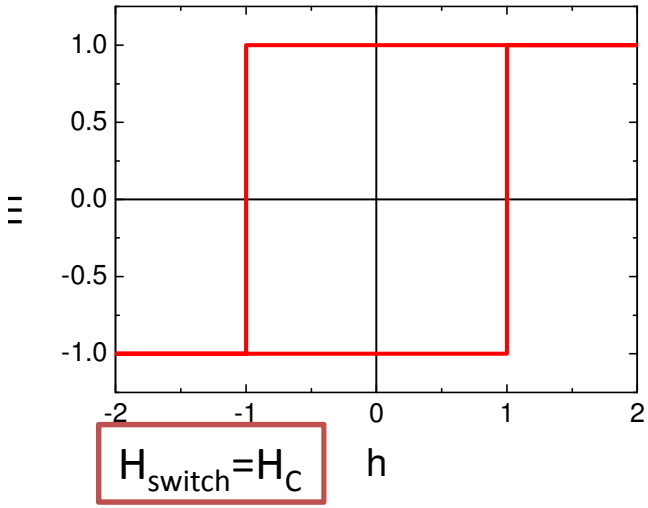
Important for thermally activated switching

For arbitrary angle :
•no analytical solution
•$H_K/2 < H_{switch} < H_K$
•$\Delta e = (1-h)^{\alpha}$ with $\alpha = 1.5$

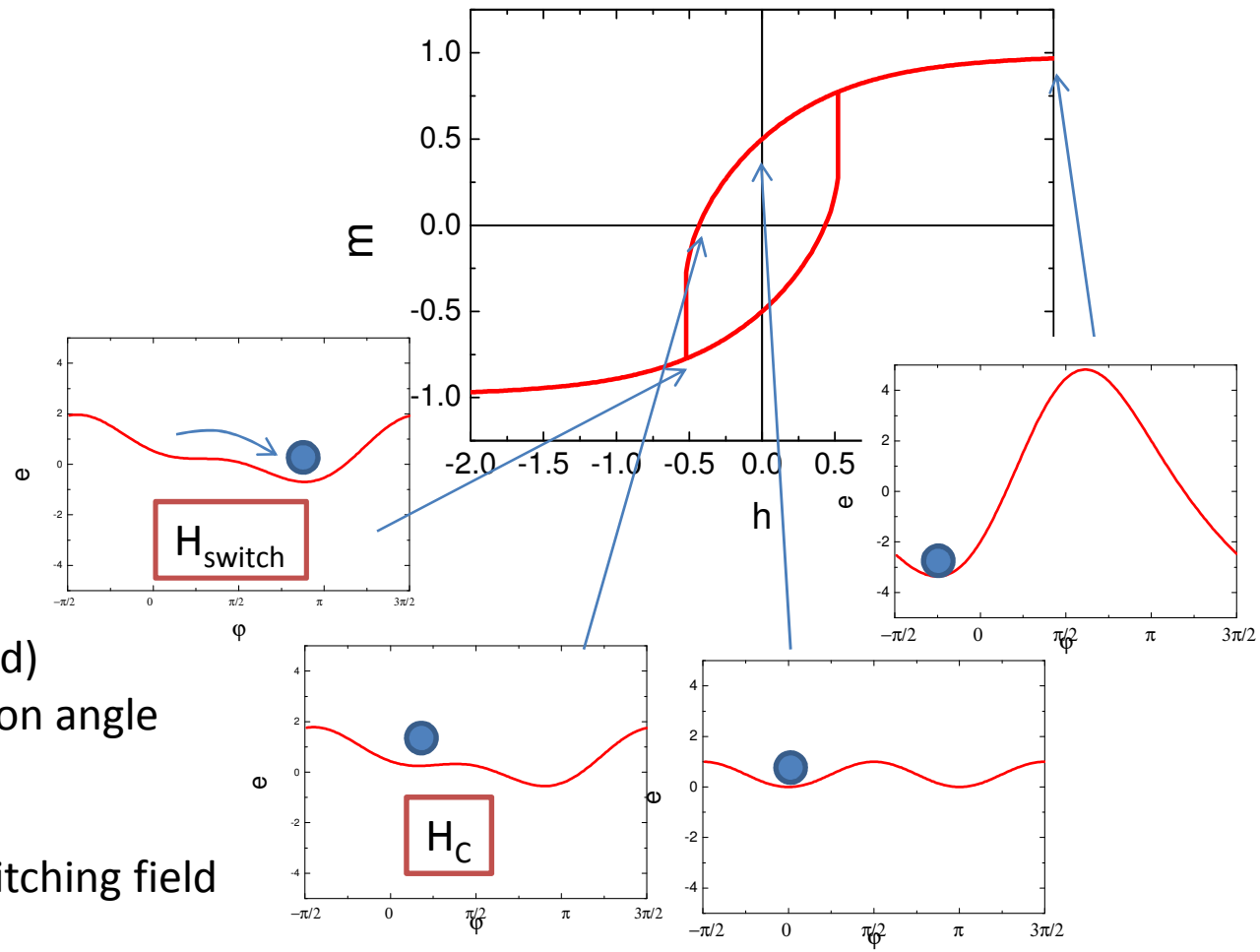
Coherent reversal: Hysteresis Loops

$$e = \sin^2\theta - 2h\cos(\theta + \theta_H)$$

θ = 0



$\theta_H = \pi/3$



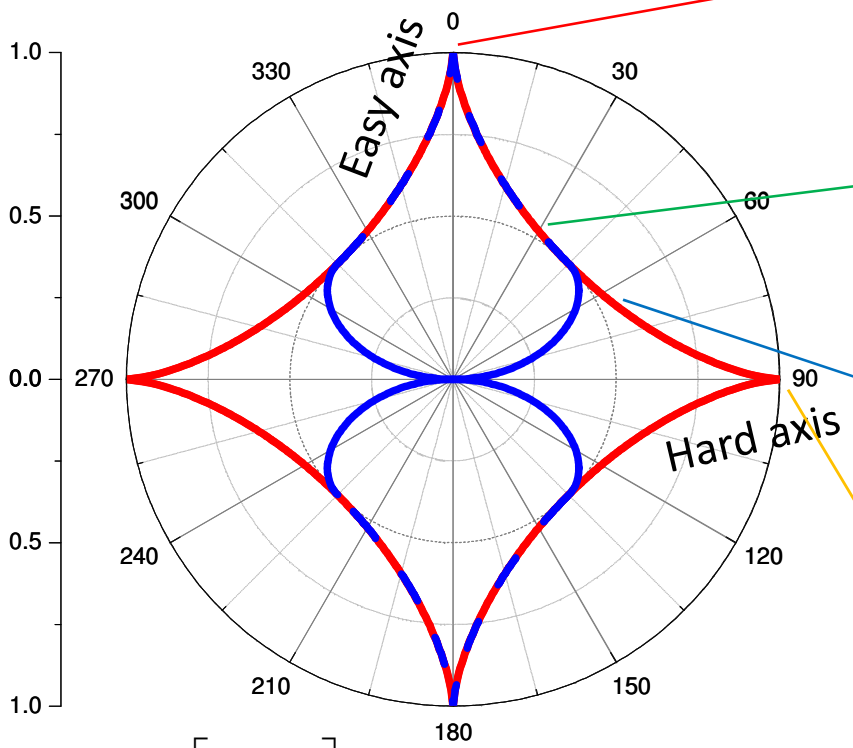
Switching field (or reversal field)
-> abrupt jump of magnetization angle

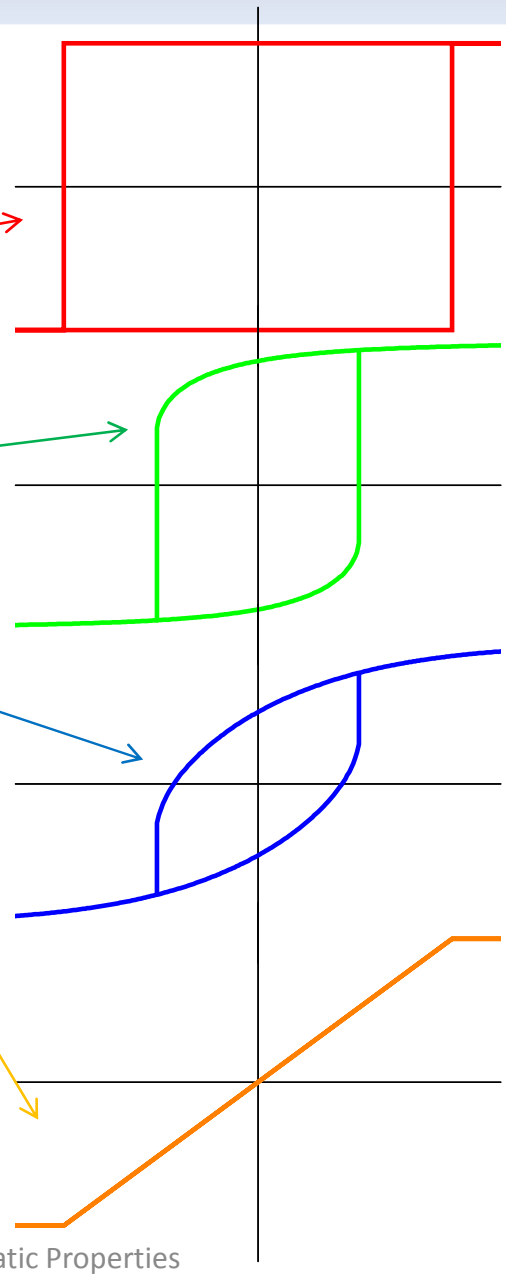
Coercive field : **M.H** = 0
-> may not be equal to the switching field

Coherent reversal: Switching field plot : astroids

Astroid curve :
Polar plot of H_{switch}

$$H_{switch} = \frac{H_K}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$





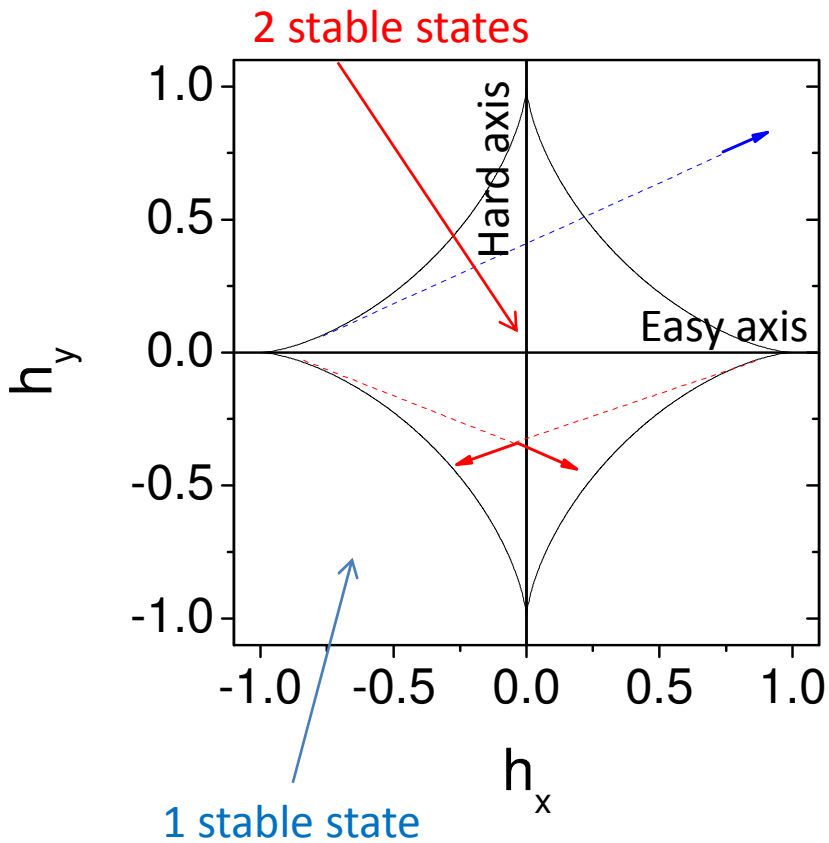
$$H_C = \begin{cases} H_{switch} & if\ \theta_H \in \left[-\frac{\pi}{4};\frac{\pi}{4}\right] @\ [\pi] \\ \frac{1}{2}\left|\sin 2\theta_H\right| & if\ \theta_H \in \left[\frac{\pi}{4};\frac{3\pi}{4}\right] @\ [\pi] \end{cases}$$

J.C. Slonczewski (1956)

Coherent reversal: Switching field plot : astroids

$$e = G(\vec{m}) - 2\vec{h}.\vec{m}$$

$$\vec{m} = (\cos\theta, \sin\theta)$$



Equilibrim condition

$$\frac{de}{d\theta} = G'(\vec{m}) - 2\vec{h}.\vec{e} = 0 \quad \text{with } \vec{e} = (-\sin\theta, \cos\theta)$$

-> For given *m* : Straight line in the field space, tangente to the critial astroid curve, directed along *m*

Stability condition

$$\frac{d^2e}{d\theta^2} = G''(\vec{m}) + 2\vec{h}.\vec{m} > 0$$

->For given *m* : Only one part of the line is stable

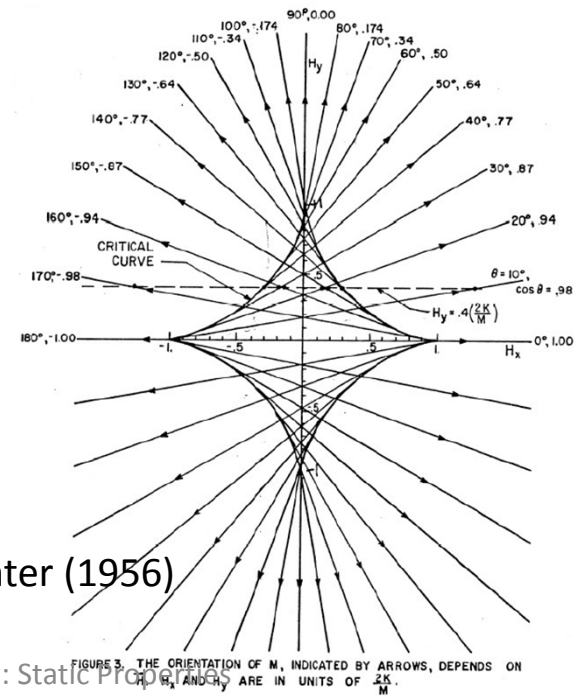


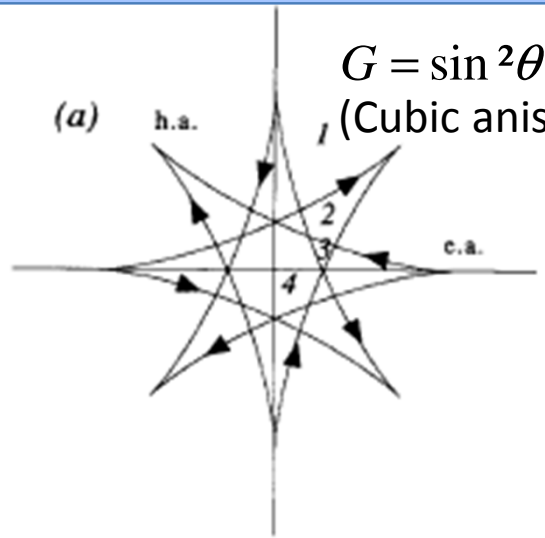
FIGURE 3. THE ORIENTATION OF M, INDICATED BY ARROWS, DEPENDS ON H_x AND H_y ARE IN UNITS OF $\frac{2K}{M}$.

J.C. Slonczewski Research Memo RM 003.111.224, IBM Research Center (1956)
A. Thiaville JMMM 182, 5, (1998)

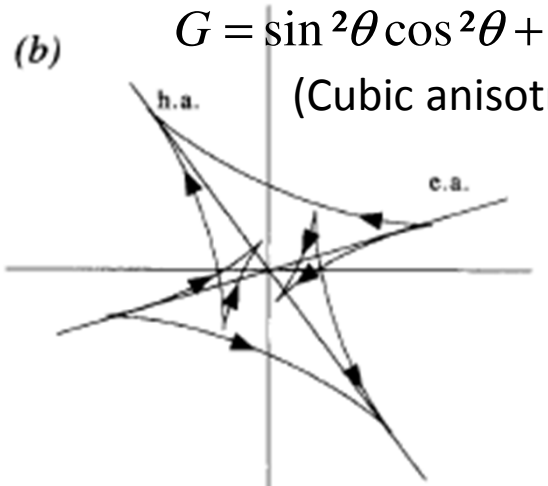
Coherent reversal: Switching field plot : astroids

-> To go further :
•Complex type of anisotropy

$$G = \sin^2\theta \cos^2\theta$$
(Cubic anisotropy)

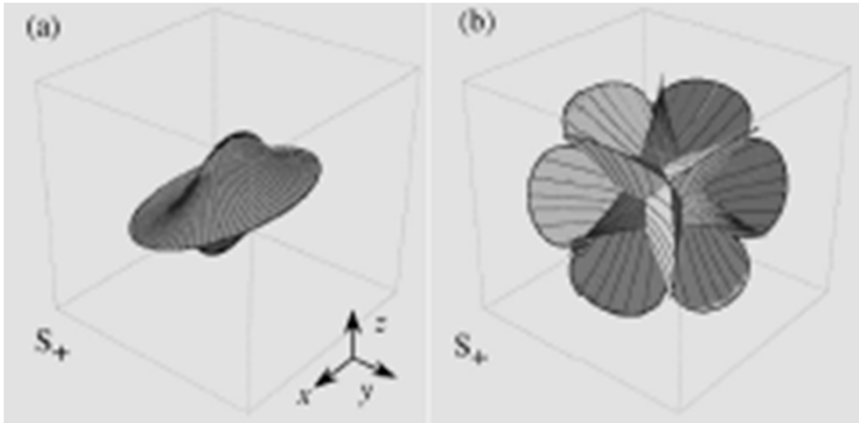


$$G = \sin^2\theta \cos^2\theta + \sin^2(\theta + \pi/6)$$
(Cubic anisotropy + uniaxial)



Thiaville JMMM 182, 5, (1998)

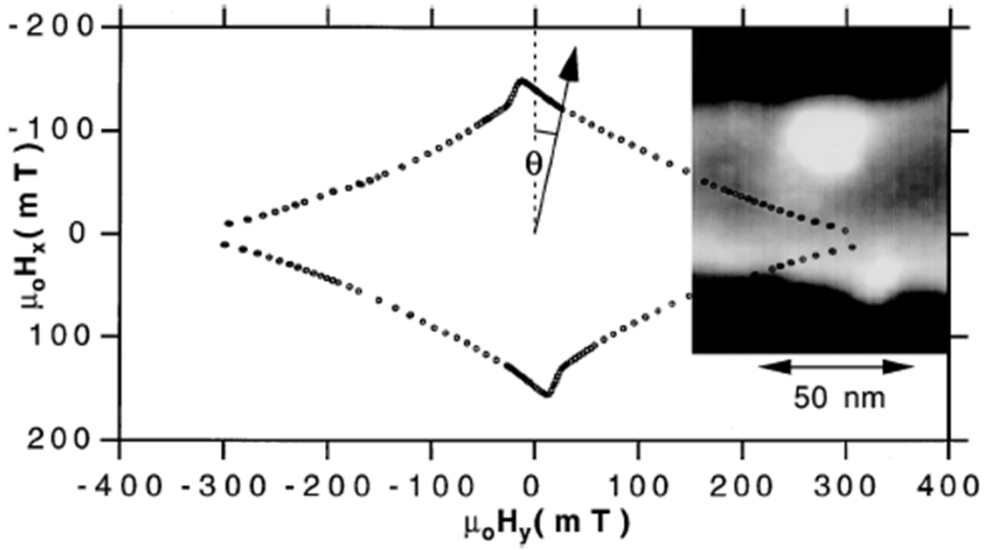
•Three dimensionnal extension



Thiaville PRB 61, 12221 (2000)

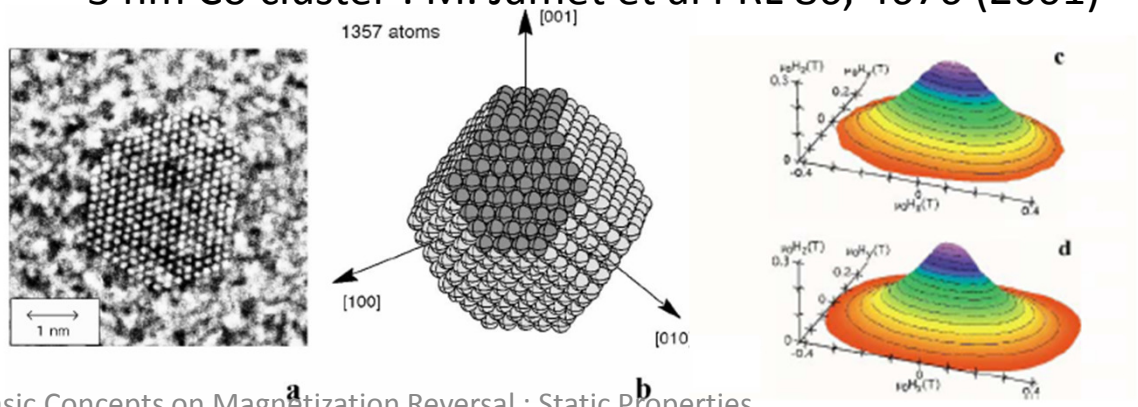
Coherent reversal: Experimental relevance

First observation (2D) : Co (D = 25 nm) cluster
Wernsdorder et al. PRL 78, 1791 (1997)



In 3 D: (same Co cluster) E. Bonnet et al PRL 83, 4188 (1999)

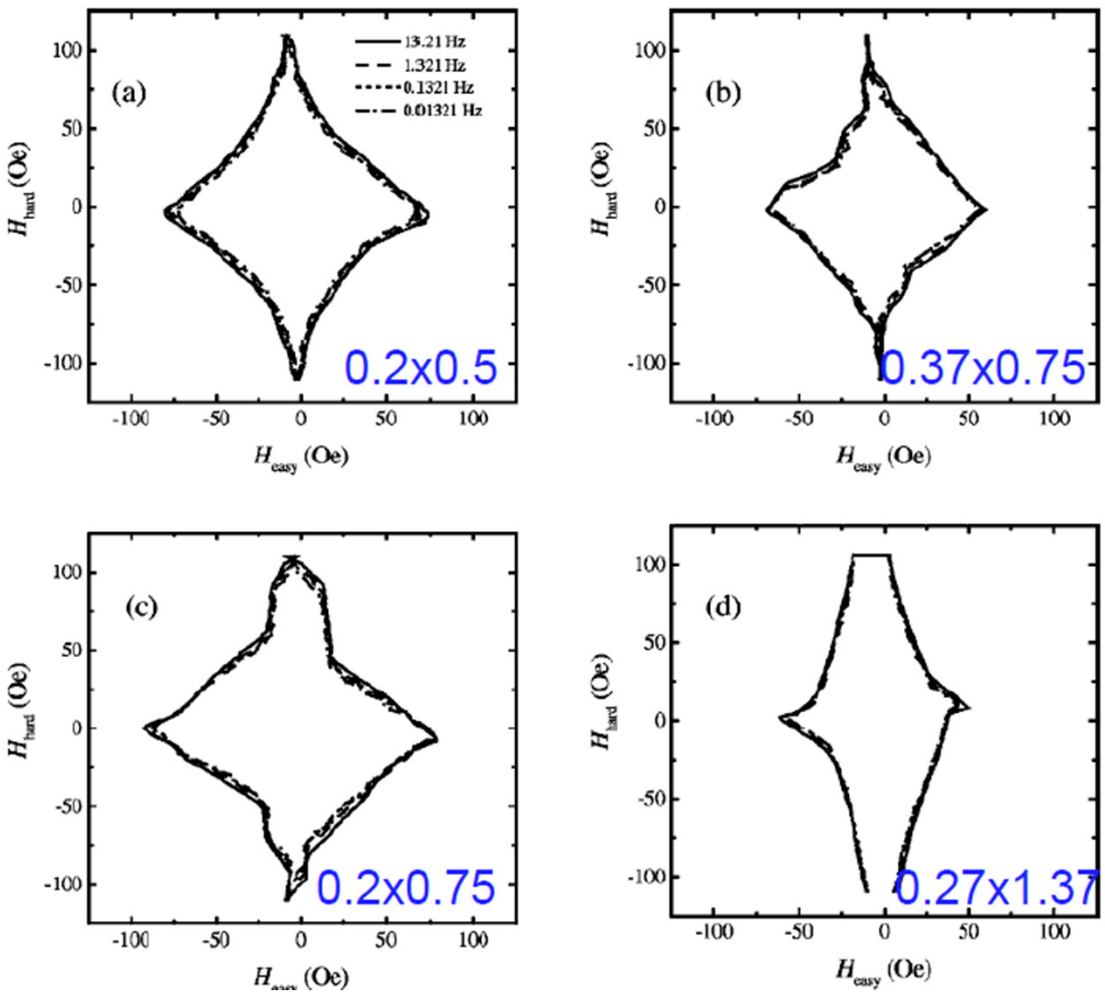
3 nm Co cluster : M. Jamet et al PRL 86, 4676 (2001)



Coherent reversal: Experimental relevance

In technological application : memory cells

Measurements of the astroids of elliptical M-RAM cells
(Dimensions in µm)



Conclusion :
Good agreement with coherent rotation only for smallest elements.

⇒Apply coherent reversal with great care!
⇒In most systems $H_{switch} << H_K$
«Brown's paradox»

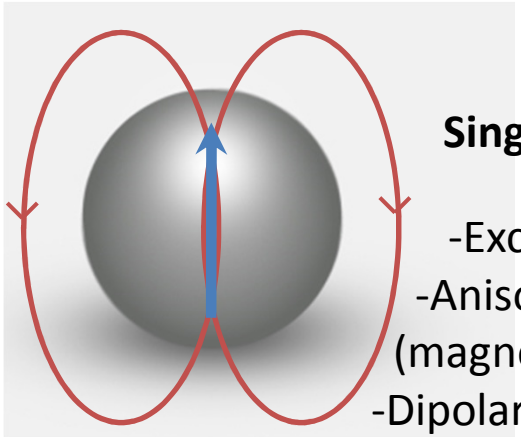
Sun et al. APL 78, 4004 (2001)

Magnetization reversal in nanoparticles

- Is the coherent reversal model applicable to nanoparticles?
- Is a uniform magnetized ground state sufficient for coherent magnetization reversal?
- Can we go further than coherent magnetization reversal?

Nanoparticles: Phase diagram of nanostructures

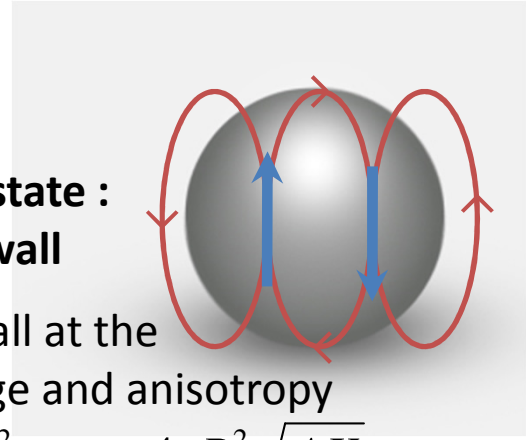
1. Single domain ground-state criterion



Single domain state

-Exchange energy is minimum
-Anisotropy energy is minimum (magnetization along easy axis)
-Dipolar energy :

$$E_d^{SD} = \frac{NV}{2}\mu_0 M_S^2 = \frac{1}{6}\mu_0 M_S^2 \times \frac{4}{3}\pi R^3$$



Non uniform state :
1 domain wall

-Bloch domain wall at the centre -> exchange and anisotropy cost : $E_{DW} = \pi R^2 \sigma_{BW} = 4\pi R^2 \sqrt{AK}$
-Dipolar energy gain : magnetic flux is closed in two domains: $E_d^{DW} = E_d^{SD}/2$

$$R_{SD} \Leftrightarrow E_d^{SD} = E_d^{DW} + E_{DW}$$

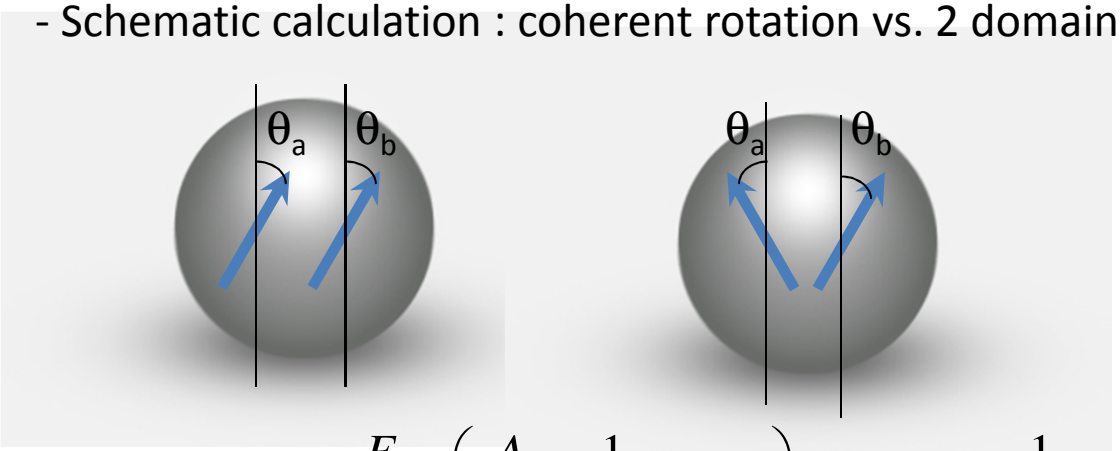
$$R_{SD} = \frac{36\sqrt{AK}}{\mu_0 M_S^2}$$

Domain wall width is neglected -> calculation adapted for high anisotropy materials

Nanoparticles: Phase diagram of nanostructures

2. Coherent/Incoherent rotation criterion

- Schematic calculation : coherent rotation vs. 2 domain rotation



Hypothesis : 2 localized moments

$m_{a/b} = M_S V/2$ at $x_{a/b} = \pm R/2$

$$\frac{E}{V} = \left(\frac{A}{R^2} - \frac{1}{24}\mu_0 M_S^2\right)(\theta_a - \theta_b)^2 + \frac{1}{4}(2K - \mu_0 M_S H)(\theta^2{}_a + \theta^2{}_b)$$

Stability analysis :
diagonalize the 2x2 matrix $\left[\frac{\partial^2 E}{\partial\theta_i \partial\theta_j}\right]$ and find *H* that changes the sign of one eigenvalue

The two eigenmodes are : $\theta_a = \theta_b \Rightarrow H_{coh} = H_K$ (coherent rotation)

$$\theta_a = -\theta_b \Rightarrow H_{incoh} = H_K - \frac{M_S}{3} + \frac{8A}{\mu_0 M_S R^2}$$

$H_{incoh} < H_{incoh}$ if $R > \sqrt{\frac{24A}{\mu_0 M_S^2}}$

Remarks :

$R_{coh} < R_{SD}$ for real materials

anisotropy does not enter in the criterion

Nanoparticles: Phase diagram of nanostructures

2. Coherent rotation criterion

$$\frac{E}{V} = \left(\frac{A}{R^2} - \frac{1}{24}\mu_0 M_S^2\right)(\theta_a - \theta_b)^2 + \frac{1}{4}(2K - \mu_0 M_S H)(\theta^2{}_a + \theta^2{}_b)$$

Exchange : the two moments are distant of *R* and the angle variation is $\Delta=\theta_a-\theta_b$. The exchange energy density is $A(dm/dx)^2 \sim A(\theta_a-\theta_b)^2/R^2$

Dipolar energy : if $\theta_a=\theta_b$, the dipolar energy is $\mu_0 M_S^2/6$. If the two angles are different, the total magnetization is lower so that E_d decreases by
$-[\mu_0 M_S^2/6]\cos(\theta_a-\theta_b)/2 \sim -[\mu_0 M_S^2/24](\theta_a-\theta_b)^2$

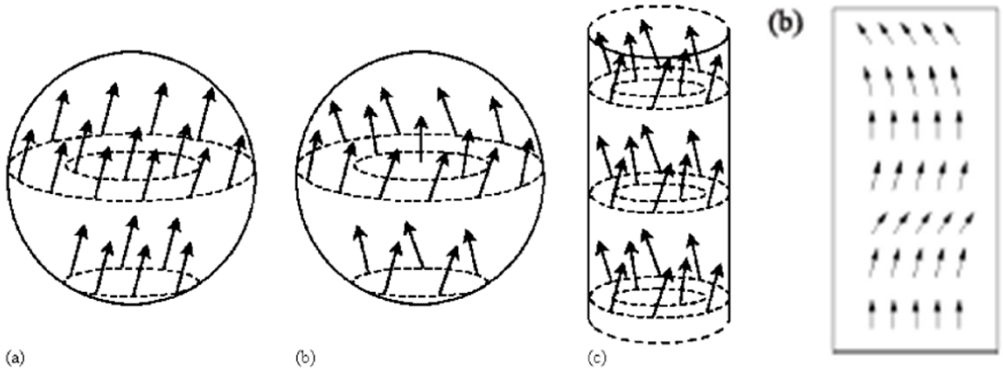
Anisotropy energy : each hemisphere of volume V/2 has the anisotropy energy
$K[\sin^2\theta]*V/2 \sim 2K\theta^2 V/4$

Zeeman energy : each hemisphere of volume V/2 has the Zeeman energy
$-\mu_0 M_S H[\cos\theta]*V/2 \sim -\mu_0 M_S H\theta^2 * V/4$

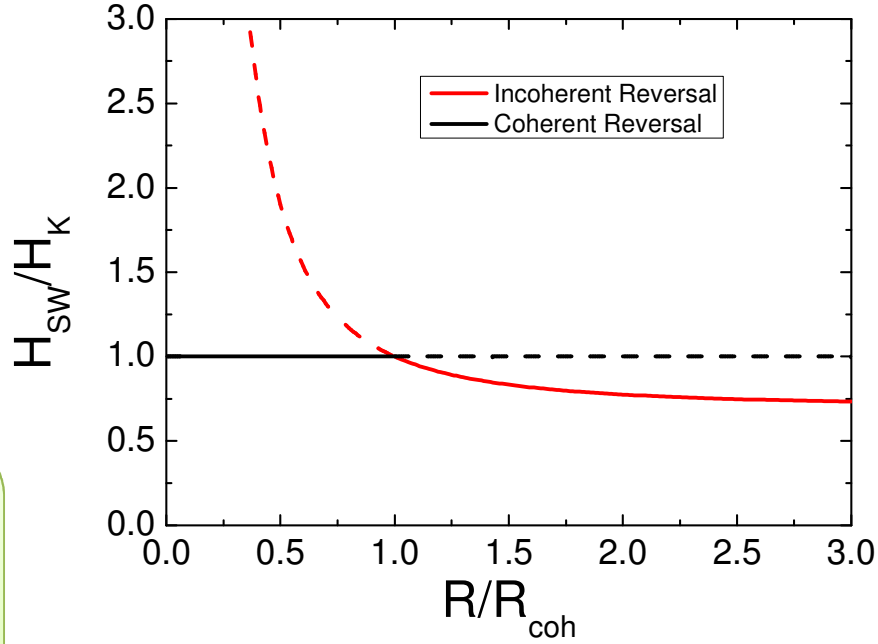
Nanoparticles: Phase diagram of nanostructures

2. Coherent/Incoherent rotation criterion

Real reversal mechanisms :



Coherent Curling, Buckling



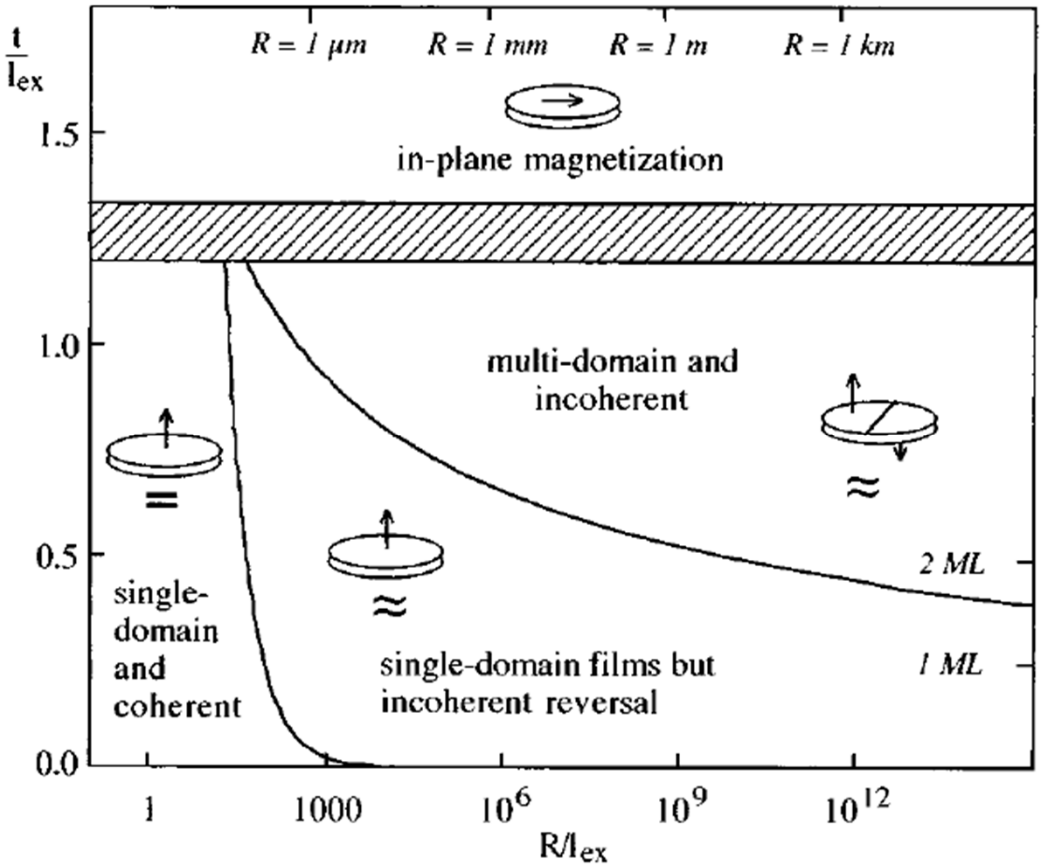
For curling : $$H_{sw} = H_K - \frac{M_S}{3} + \frac{8.67A}{\mu_0 M_S R^2}$$

$$R_{crit} = \sqrt{\frac{26A}{\mu_0 M_S^2}}$$

See: Aharoni *Introduction to the theory of Ferromagnetism (1996)*
Skomski and Coey *Permanent Magnetism* (1999)

Nanoparticles: Phase diagram of nanostructures

Phase diagram for a flat disk with surface anisotropy

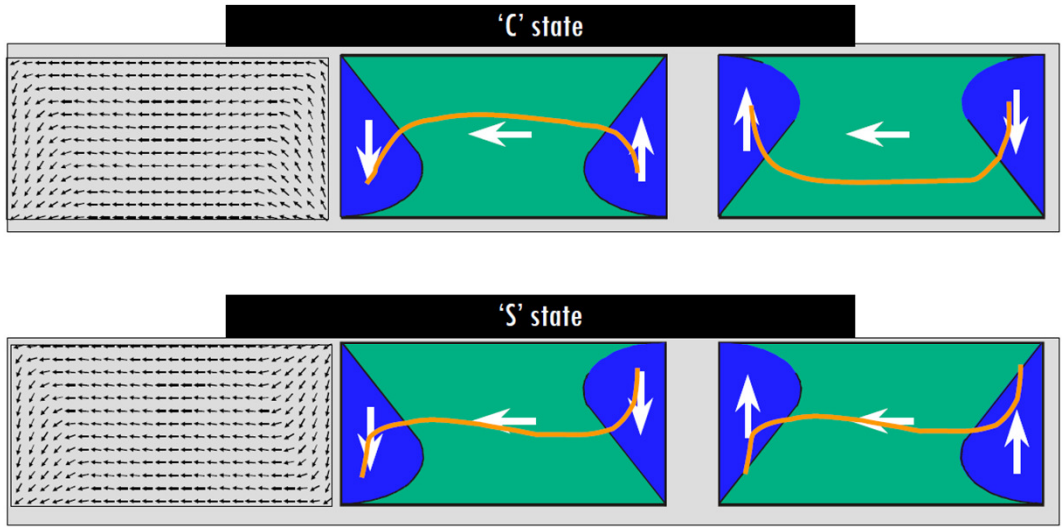


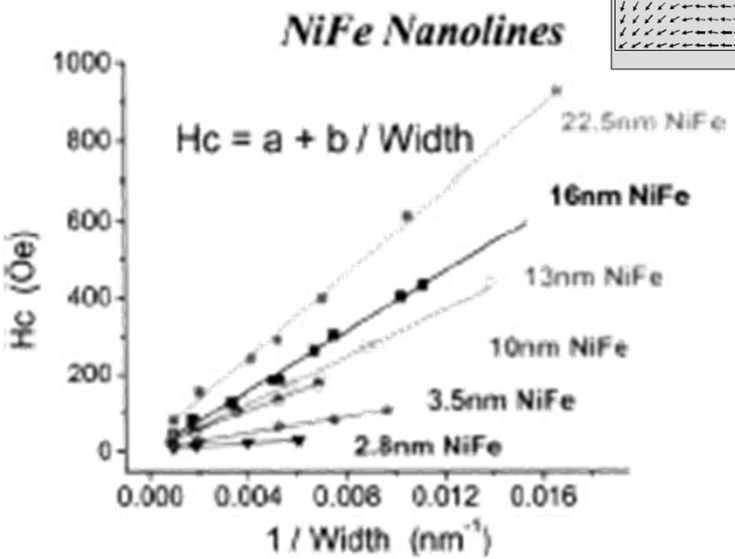
Skomski et al. PRB 58, 3223 (1998)

Nanoparticles : Influence of nanostructure inhomogeneity

Dipolar field effect

-> Soft elements: flux closure domains faciliate magnetic reversal





$$H_K = 5000 Oe$$

$$H_C = 3M_S \frac{t}{W} + cte$$

Shape anisotropy ~ M_S *L/W*
but switching field intependant of *L*

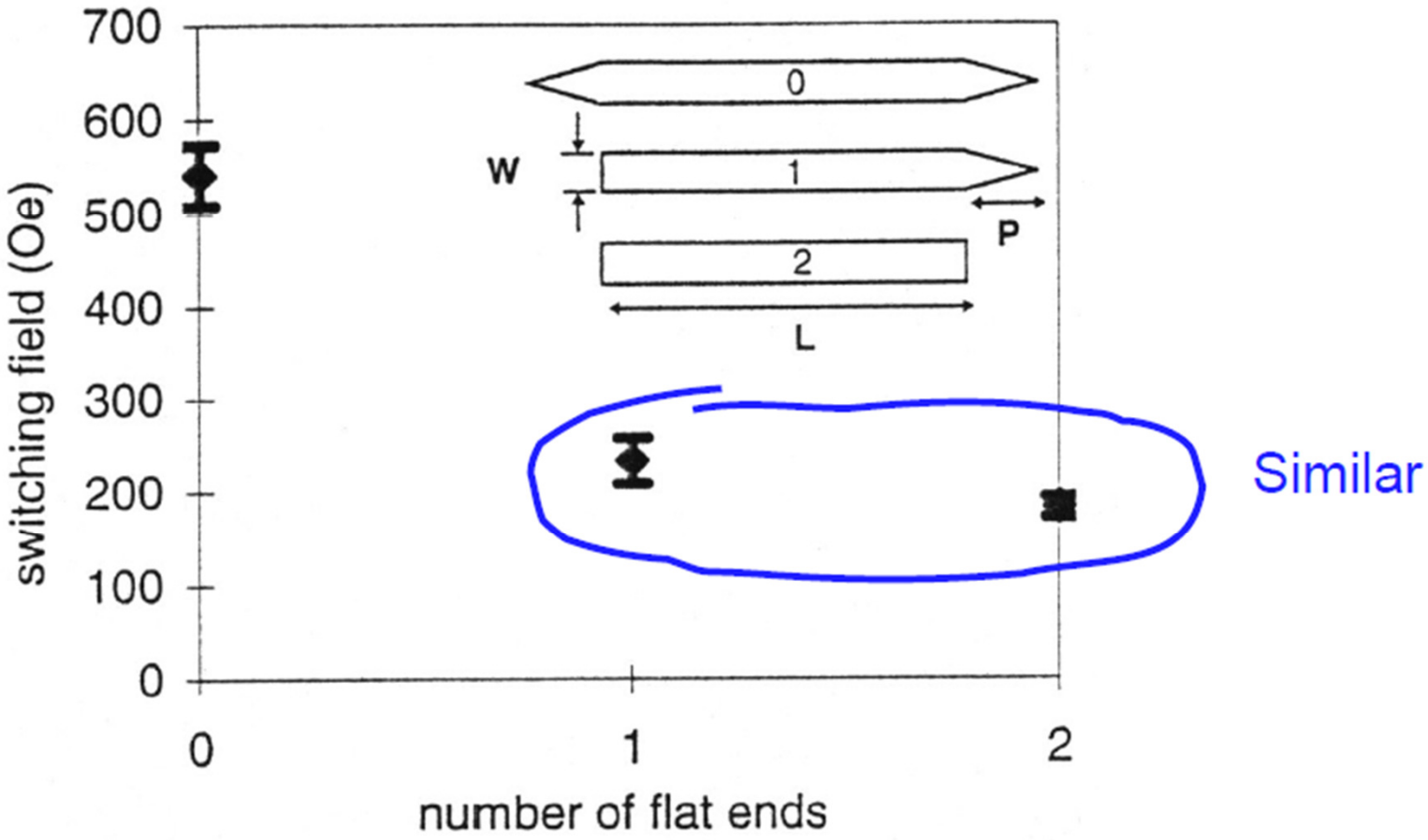
Uhlig and Shi APL 84, 759 (2004)

Nanoparticles : Influence of nanostructure inhomogeneity

Dipolar field effect

-> Soft elements

K.J. Kirk et al., J. Magn. Soc. Jap., 21 (7), (1997)

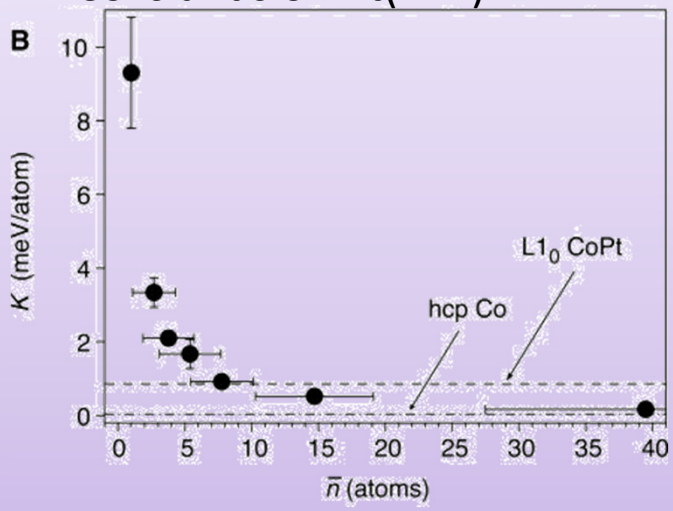


Nanoparticles : Influence of nanostructure inhomogeneity

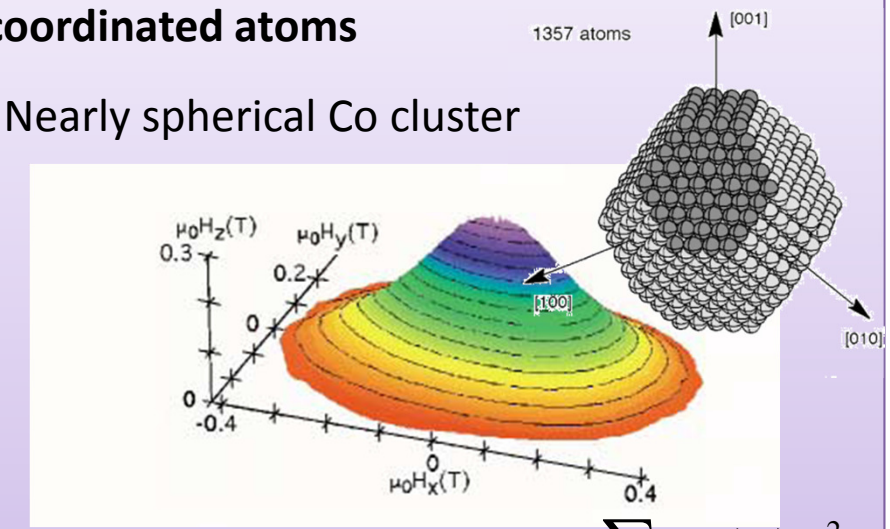
Edge and surface anisotropy in very small elements

Origin : enhanced magnetic anisotropy at low coordinated atoms

Co islands on Pt(111)



Nearly spherical Co cluster



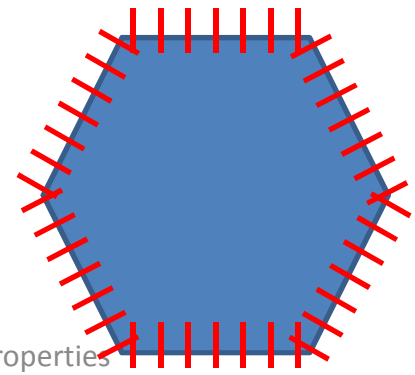
Néel pair anisotropy model $E_a = \sum_{\substack{<i,j> \\ n.n.}} L(\vec{m}.\vec{u}_{ij})^2$

Gambardella et al. Science 300, 1130 (2003)

Jamet et al. PRL 86, 4676 (2001)

On spherical clusters, atom anisotropy axis are perpendicular to the local surface

-> Hedgehog like orientation of anisotropy axis



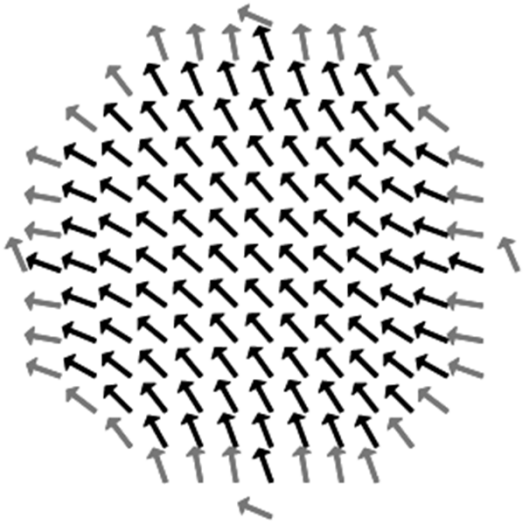
Kachkachi and Dimian PRB 66,174419 (2002)

Néel J. Phys. Radium 15, 225 (1954)

Nanoparticles : Influence of nanostructure inhomogeneity

Edge and surface anisotropy in very small elements

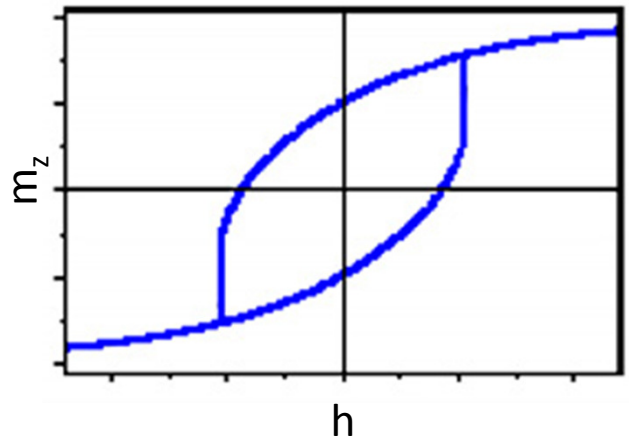
Consequence of surface anisotropy axis distribution



Non colinear magnetic configuration
Atomic simulation : L/J=2
(unphysically strong surface anisotropy!)

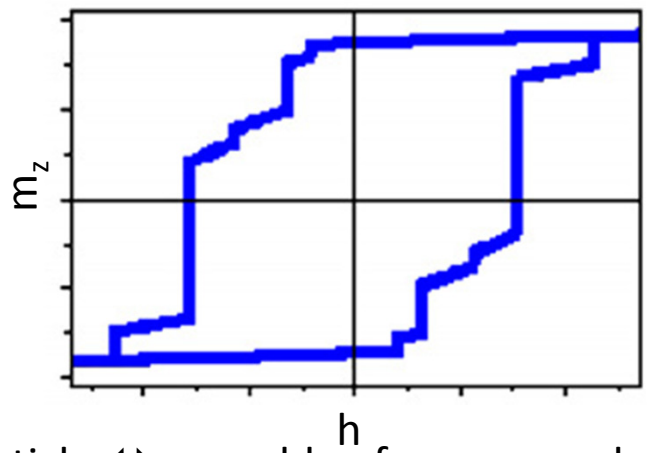
Kachkachi and Dimian PRB 66,174419 (2002)
Garanin and Kachkachi PRL 90 065504 (2003)

$J >> K_{surface} = K_{volume}$



1 particle ⇔ 1 macrospin

$J \sim K_{surface} >> K_{volume}$



1 particle ⇔assembly of many coupled spins

Nanoparticles : Influence of nanostructure inhomogeneity

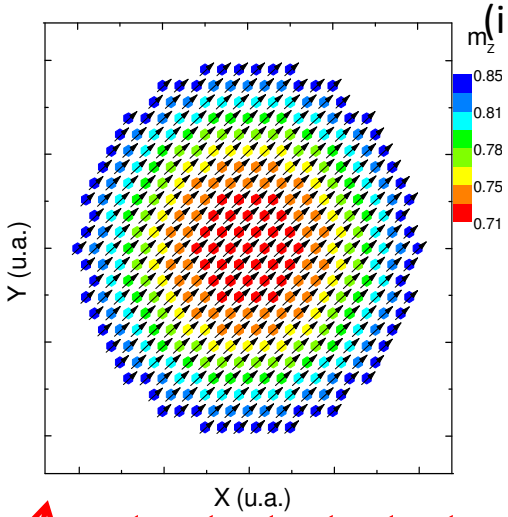
Edge and surface anisotropy in very small elements

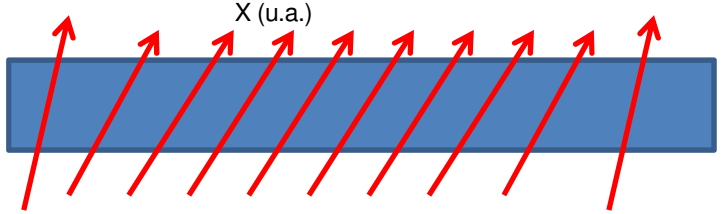
Effective anisotropy model

Example: flat disk with edge anisotropy

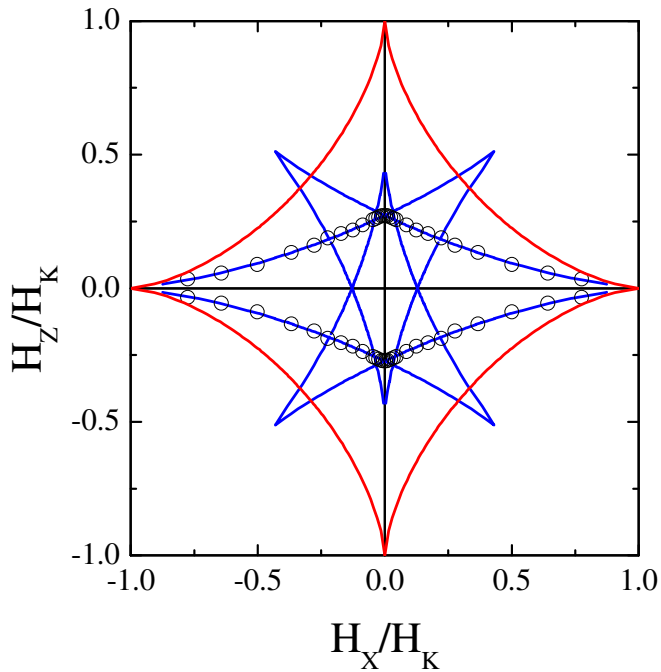
$$\frac{E[\theta(r)]}{2\pi t} = \int_0^R \left\{ A\left(\frac{d\theta}{dr}\right)^2 + K_d \cos^2\theta \right\} r dr + R K_S \sin^2\theta$$

Exchange — Shape anisotropy (in plane) — Edge anisotropy (out of plane)





Twisted inhomogeneous configuration



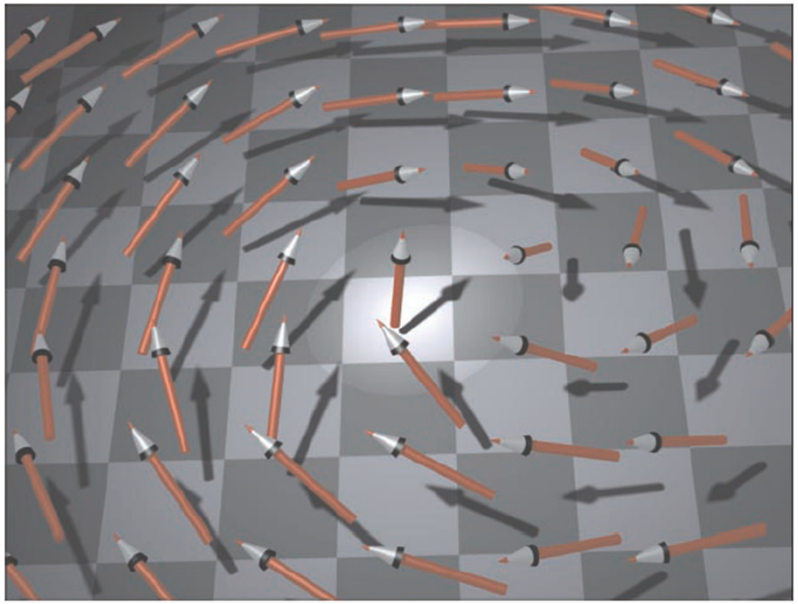
Typical astroid with a 4th order anisotropy

$$E_a^{\text{eff}}(\theta) = \langle K \rangle \sin^2\theta + K_4 \sin^4\theta$$

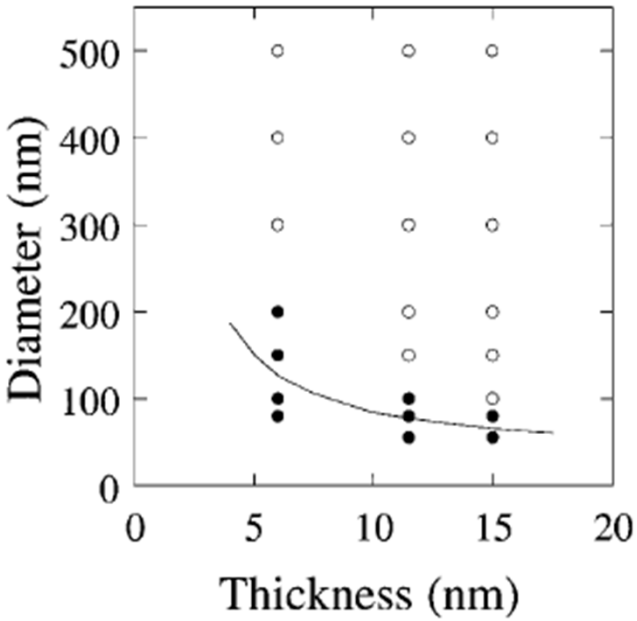
Rohart et al. PRB 76, 104401 (2007)
Garanin and Kachkachi PRL 90 065504 (2003)

Nanoparticles: Vortices

⇒Strongly inhomogeneous magnetic state



Wachowiak et al. Science 298 577 (2002)

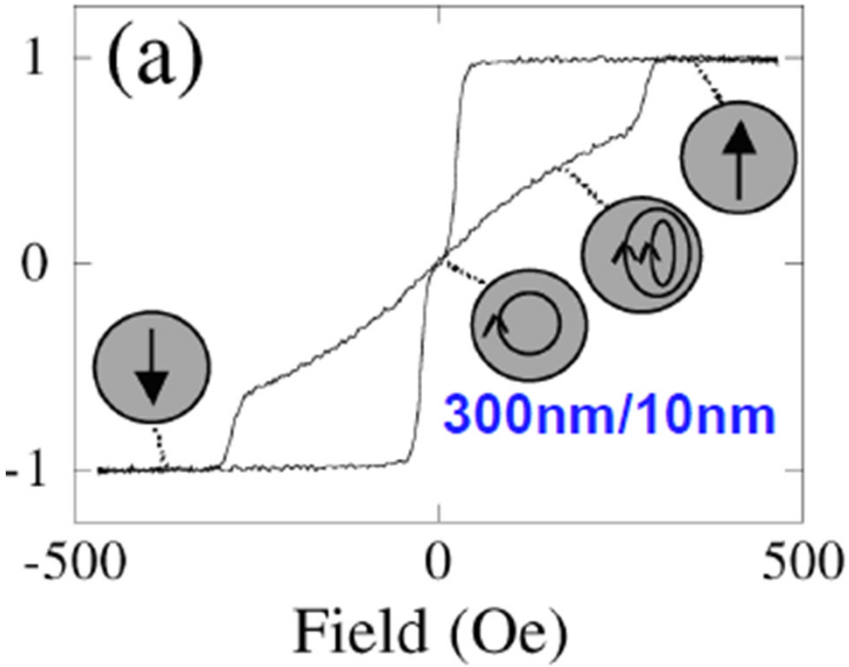


Cowburn et al. PRL 83, 1042 (1999)

Four degenerated states :
-<u>vortex cirulation</u> (clock wise vs. Counter clock wise)
-> difficult to manipulate with magnetic field
-<u>Vortex core</u> (up vs. Down) -> easily coupled to magnetic field

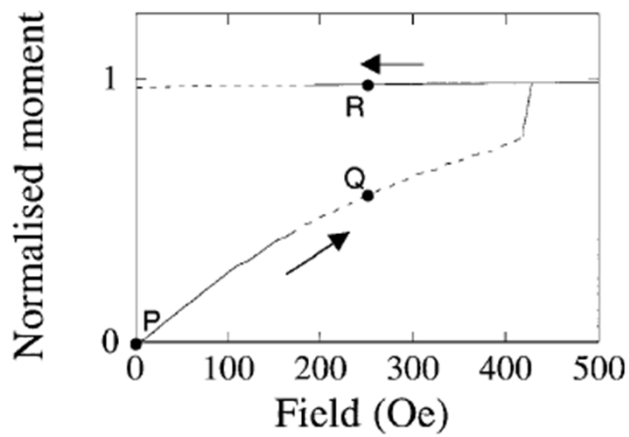
Nanoparticles: Vortices

Hysteresis loop with IN PLANE magnetic field

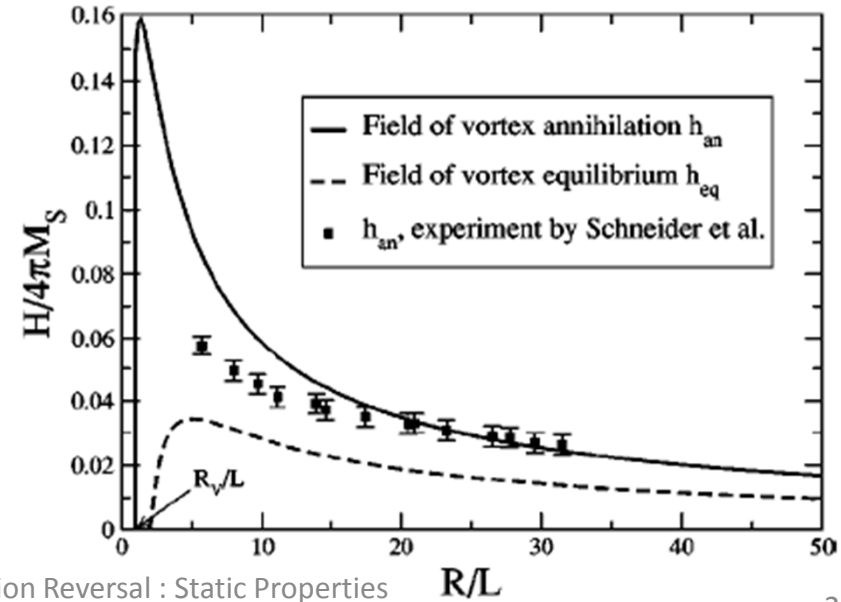


Cowburn et al. PRL 83, 1042 (1999)
Guslienko and Metlov PRB 63, 100403R (2001)

Stable vortex state → ← Stable uniform state



The energy cost to expell the vortex core out of the disk creates an hysteresis



Nanoparticles: Vortices

Vortex core magnetization reversal

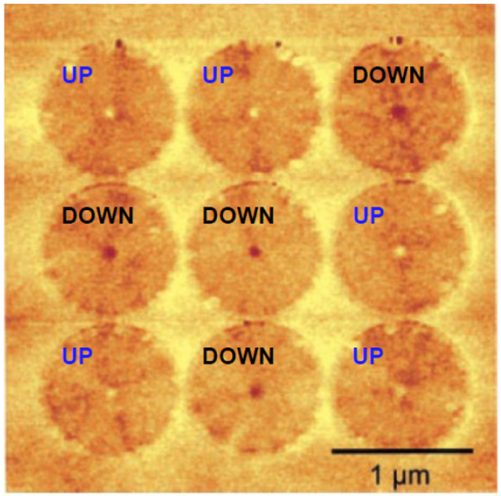
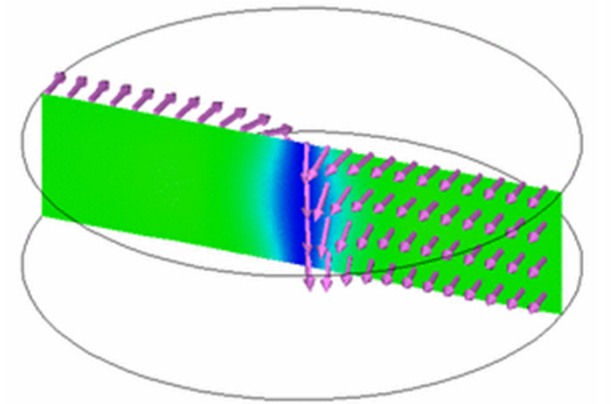


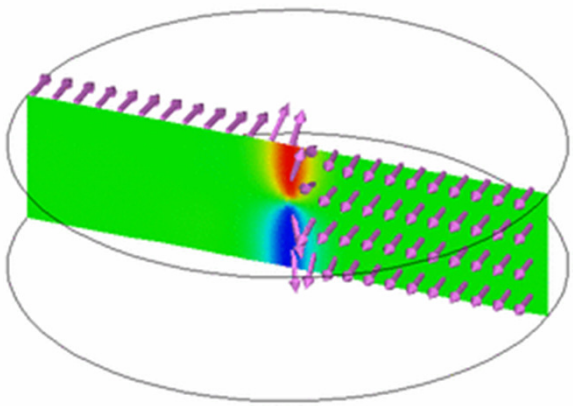
Fig. 2. MFM image of an array of permalloy dots 1 μm in diameter and 50 nm thick.

Shinjo et al. Science 289, 930 (2000)

Magnetic field is coupled to the vortex core only but coherent reversal of vortex core magnetization is topologically impossible



Normal vortex state : magnetization is perpendicular to minimize exchange energy



Vortex with Bloch point: magnetic moment are all almost in plane**, mean magnetization is zero at the core**

Beyond micromagnetism

$$E_{ex}(r) = 2A/r$$

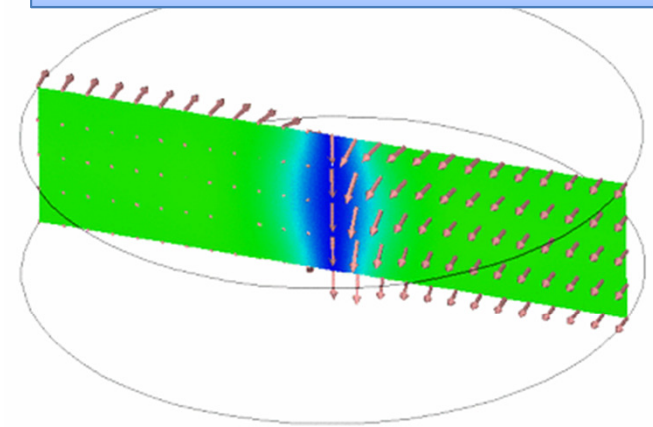
$$E_{BP} = \iiint E_{ex}(r) r^2 \sin\theta dr d\theta d\varphi = 8\pi AR$$

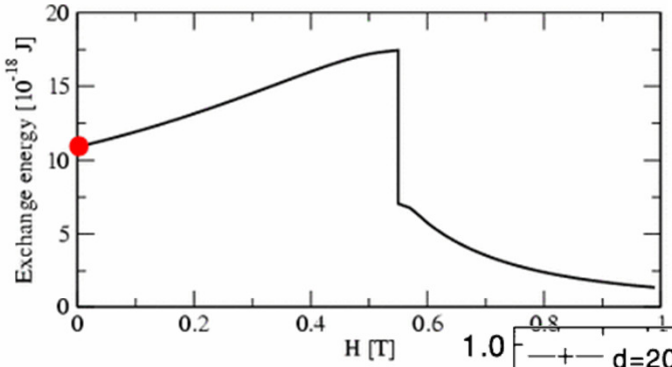
Thiaville et al. PRB 67, 094410 (2003)

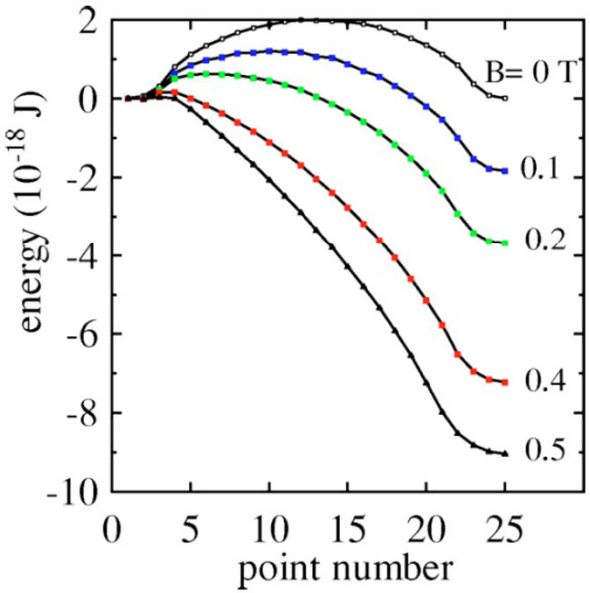
Images from R. Dittrich http://magnet.atp.tuwien.ac.at/gallery/bloch_point/index.html

Nanoparticles: Vortices

Vortex core magnetization reversal







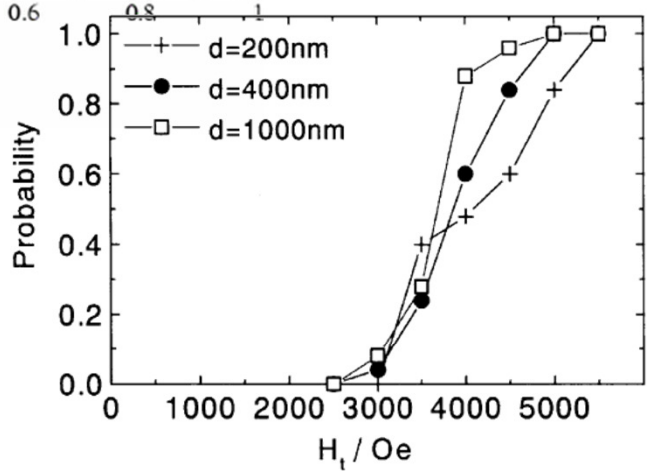


Fig. 5. Switching probability of a turned-up magnetization in circular dots with the diameter of 0.2, 0.4 and 1 μm as a function of magnetic field normal to the sample plane. The average switching field is 4100, 3900 and 3650 Oe in the sample of 0.2, 0.4 and 1 μm in diameter, respectively.

Experiments : Okuno et al. JMMM 240, 1 (2006)

Thiaville et al. PRB 67, 094410 (2003)

Images from R. Dittrich http://magnet.atp.tuwien.ac.at/gallery/bloch_point/index.html

Magnetization reversal in thin films

Is the macrospin model relevant for thin films ?

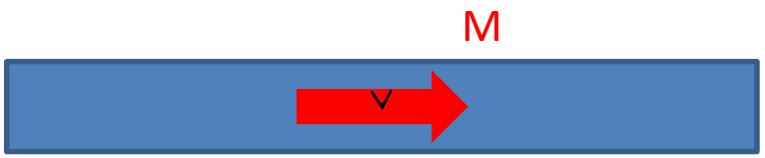
-Lateral dimension >> Micromagnetic lengthes
-Experimental observation : $H_C << H_K$ in most systems

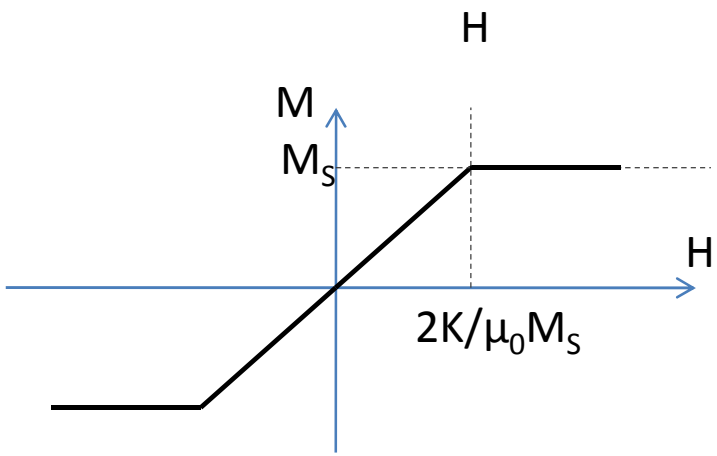
⇒ Brown's paradox

⇒Coherent reversal is unreallistic : need for micromagnetic modelling.
⇒Defect (even at very low density) may drive the switching field if domain wall propagation is involved

Thin Films: Hard axis hysteresis loops

In some cases, coherent reversal can be applied to hard axis hysteresis loops





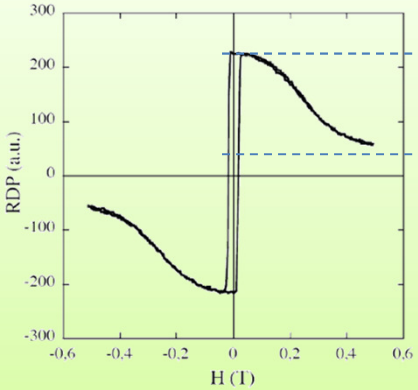
-**In hard axis loop, domain nucleation is prevented** (the two orientation energies are the same) and coherent rotation is possible.

=> **Application: determination of magnetic anisotropy and M_S**

Example1: Soft magnetic film
Permalloy thin film
- -no magnetocristalline anisotropy
- -in plane magnetization due to the shape anisotropy $E_d = \frac{1}{2}\mu_0 M_S^2$
- => Loop with perpendicular field yields a saturation field of M_S

Example2: « Anisometry »
Ga(Mn)As thin film
(with perpendicular magnetization)
- •Polar Kerr effect measurment with quasi in plane field (α)

$$H = \frac{\sin 2\theta K_{eff}}{M_S \cos(\theta + \alpha)} \quad ; \quad M = M_s \cos\theta$$



-> K_{eff} = 272 mT
J.P. Adam PhD. Thesis 2008

Principle/Application:
Grolier et al. J. Appl. Phys. 73, 5939 (1993)

Thin Films: Brown's paradox

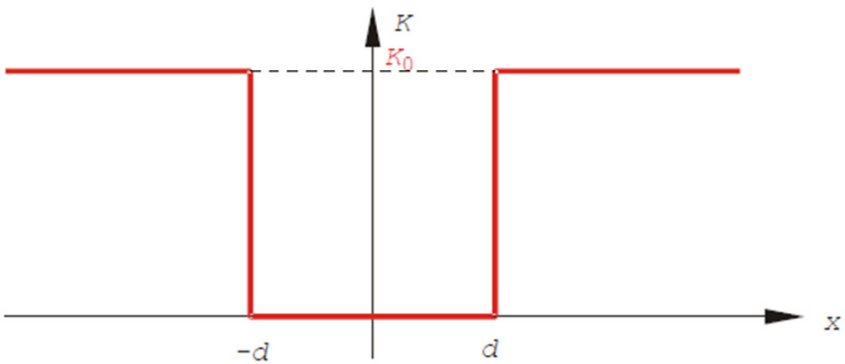
Origin of the lower coercivity : magnetic defects, temperature

PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

Reduction in Coercive Force Caused by a Certain Type of Imperfection

A. AHARONI
Department of Electronics, The Weizmann Institute of Science, Rehovot, Israel
(Received February 1, 1960)

As a first approach to the study of the dependence of the coercive force on imperfections in materials which have high magnetocrystalline anisotropy, the following one-dimensional model is treated. A material which is infinite in all directions has an infinite slab of finite width in which the anisotropy is 0. The coercive force is calculated as a function of the slab width. It is found that for relatively small widths there is a considerable reduction in the coercive force with respect to perfect material, but reduction saturates rapidly so that it is never by more than a factor of 4.



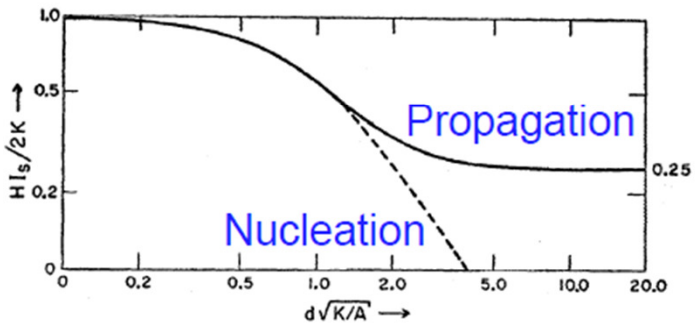
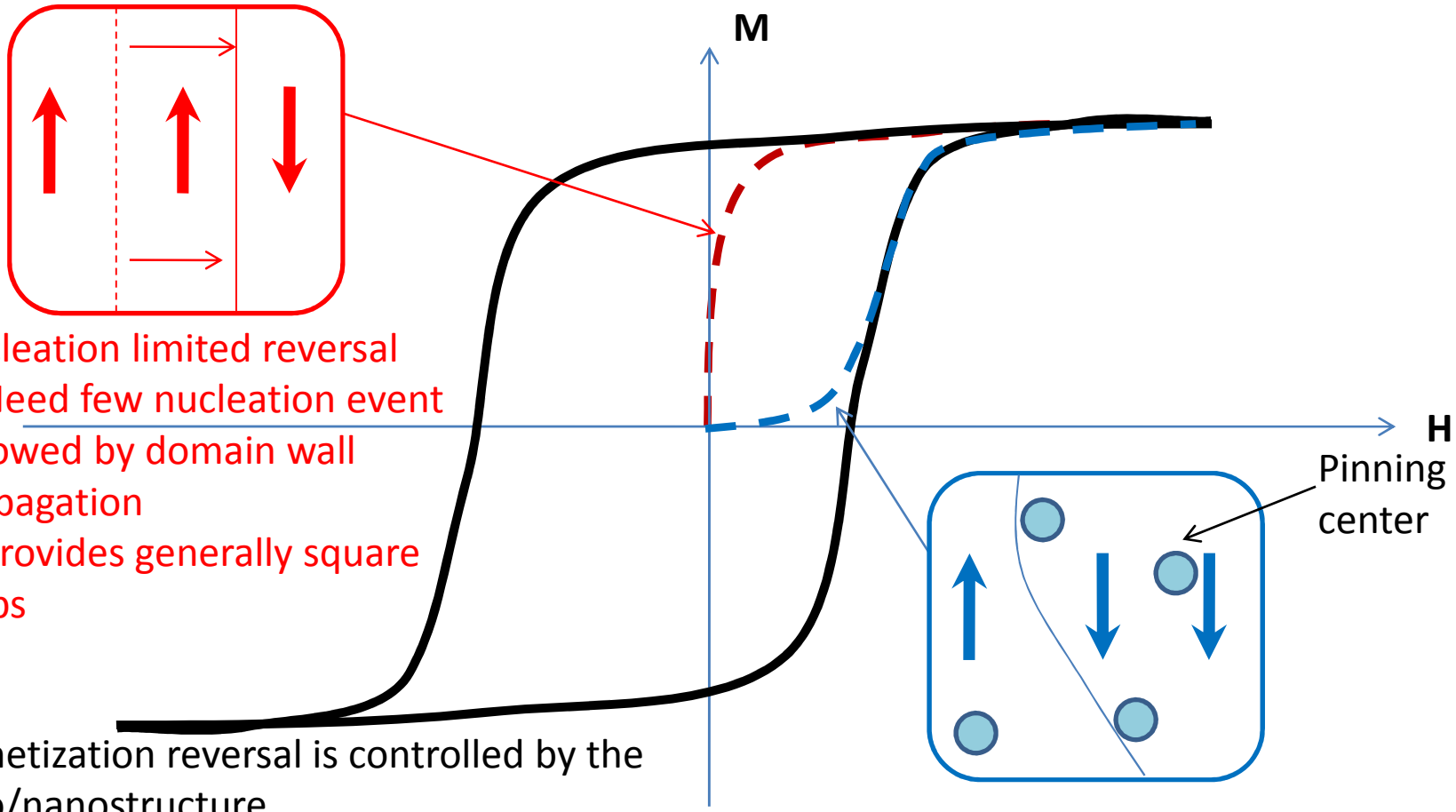


FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

Thin Films: Nucleation vs. Propagation

First magnetization curve indicates the type of coercivity



Nucleation limited reversal
-> Need few nucleation event followed by domain wall propagation
-> Provides generally square loops

Magnetization reversal is controlled by the micro/nanostructure
->Soft inclusion, misoriented grains…
create nucleation centers
->Hard inclusion,crystalline defect…
create pinning centers

Propagation limited reversal
-> Need many nucleation events
-> Provides generally rounded loops
Ex : Recording media

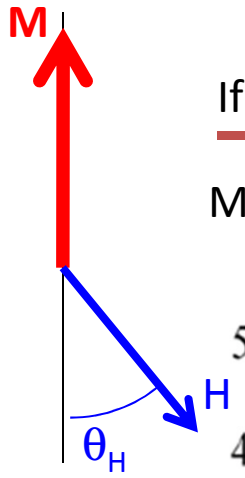
Thin Films: Nucleation – « 1/cos θ_H law »

Nucleation of a reversed domain on defect -> Nucleation volume

- $v \approx \delta^3$ for bulk hard magnets Givord et al. JMMM 258, 1 (2003)
- Droplet theory for thin films Barbara JMMM 129, 79 (1994)

Nucleation cost (domain wall, anisotropy energy) E_0

is compensated by Zeeman energy gain (plus thermal energy)

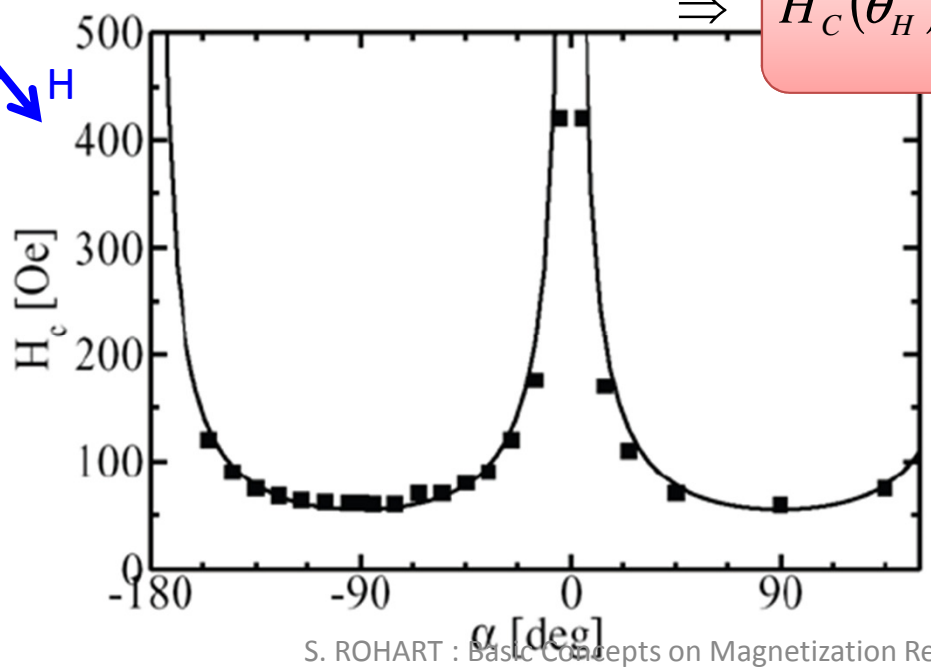


If $H_c << H_K$: M is aligned with easy axis $\Delta E_z = -2\mu_0 M_S v H \cos\theta_H$

Magnetization reversal if $\Delta E_z = E_0 - 25kT$

$$\Rightarrow \quad H_C(\theta_H) = \frac{H_{C,\theta_H=0}}{\cos\theta_H}$$

Kondorsky, J. Exp. Theor. Fiz. 10, 420 (1940)
See also : Givord JMMM 72, 247 (1988)



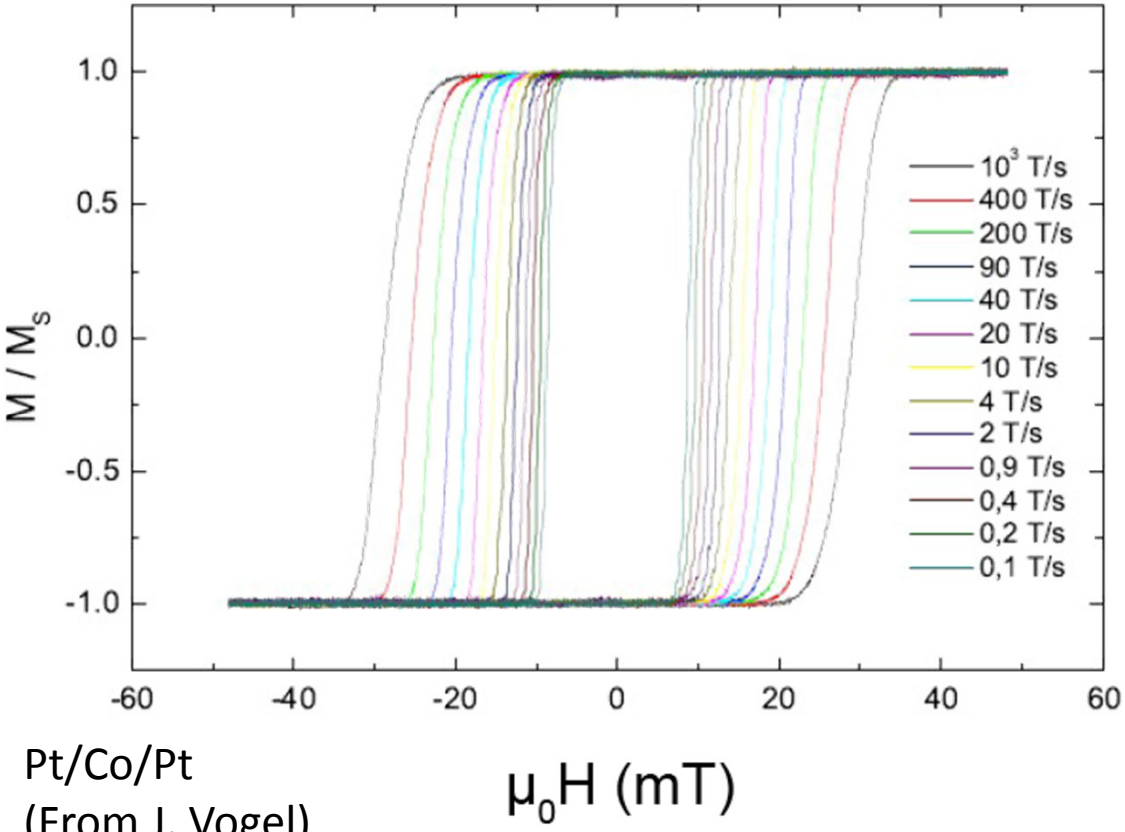
Switching field of a Co(1 nm) film grown on Au(233)
-> In plane magnetization with well defined in plane anisotropy (step edges)

G. Baudot PhD. Thesis, unpublished (2003)

Thin Films: Nucleation vs. DW propagation

Importance of dynamics

Key ingredient :
-> Nucleation rate
-> Domain wall propagation dynamics



Pt/Co/Pt
(From J. Vogel)

Coercive field may not be an intrinsic property
(ie. only linked to micromagnetic parameters)
-> depend on temperature
-> depend on sweeping rate

See second part of the lecture on temperature activation and slow dynamics

Conclusion

Take home messages

•Coherent (uniform) magnetization reversal only takes place in very small particles
•Micromagnetism is powerfull to determine the switching mode in nanoparticles
•In thin films: Importance of micro/nano structure of magnetic films to determine the reversal mechanism
•Coercive field may be ambiguous (different from switching field, not intrinsic…)

To go further

•Temperature influence and slow dynamics
•Precessionnal magnetization reversal (ns time scale, need loweer magnetic fields)
•Ultra fast magnetization reversal (beyond micromagnetism hypothesis **M**=**cte**)
•New driving forces for magnetization reversal (spin polarized currents, electrical field…)

Some readings

•Skomski and Coey *Permanent magnetism (*Taylor & Francis Group 1999)
•Hubert and Schäfer *Magnetic domains* (Springer 1999)
•Aharoni *Introduction to the theory of ferromagnetism* (Oxford 1996)
•Skomski *Nanomagnetics* J. Phys. Cond. Mat. **15**, R841 (2003)
•Fiorani *Surface effects in Magnetic Nanoparticles* (Springer 2005)
•Fruchart and Thiaville *Magnetism in reduced dimensions* CR Physique **6** 921 (2005)