Introduction to magnetism
Part II – Magnetization reversal

Olivier Fruchart
Institut Néel (CNRS-UJF-INPG)
Grenoble - France
http://neel.cnrs.fr

The European School on Magnetism

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Latest news

- [2010-05-25] Repository of lecture notes opens.
- [2010-05-25] Next ESM: Sep.2011: *Time-dependent phenomena in Magnetism*. Web site opens soon.
- [2010-05-25] Latest ESM : 2009: *Models in magnetism : from basic aspects to practical uses*.

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Link to the Schools

- 2011: Time-dependent phenomena in magnetism, Targoviste, Romania. Web site opens by Summer 2010.
- 2009: Models in magnetism : from basic aspects to practical uses, Timisoara, Romania.
- 2007: New magnetic materials and their functions, Cluj-Napoca, Romania.
- 2005: New experimental approaches to Magnetism, Constanta, Black Sea, Romania.
- 2003: Magnetism of Nanostructured Systems and Hybrid Structures, Brasov, Romania.

Webmaster

URL: http://esm.neel.cnrs.fr/index.html

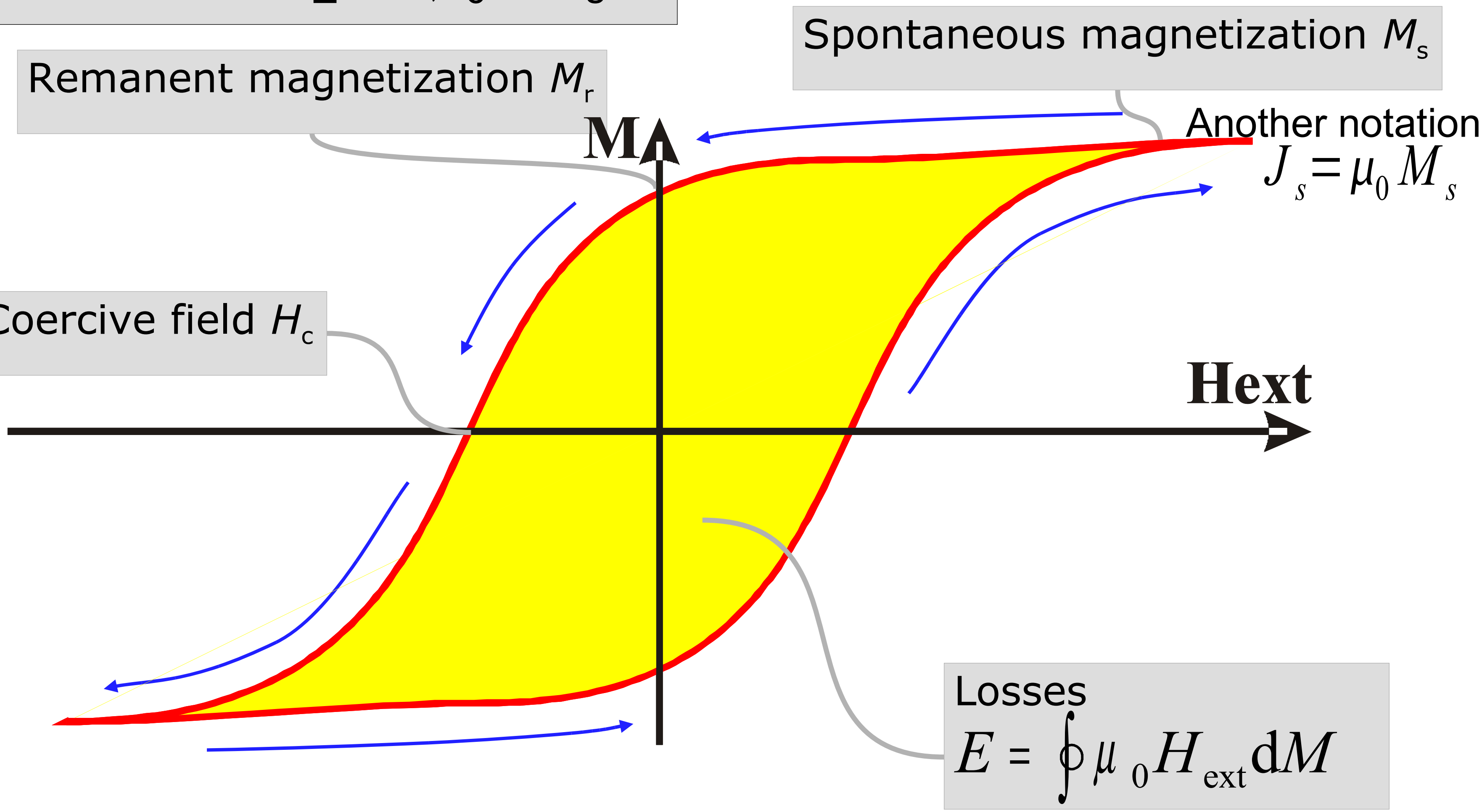
Optimized for Firefox

Manipulation of magnetic materials:

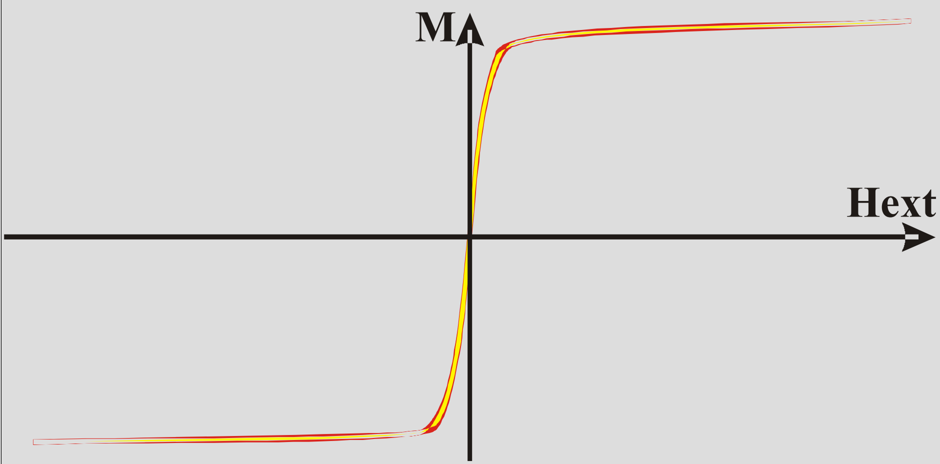
↳ Application of a magnetic field

Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}_s$

Spontaneous ≠ **S**aturation



Soft materials

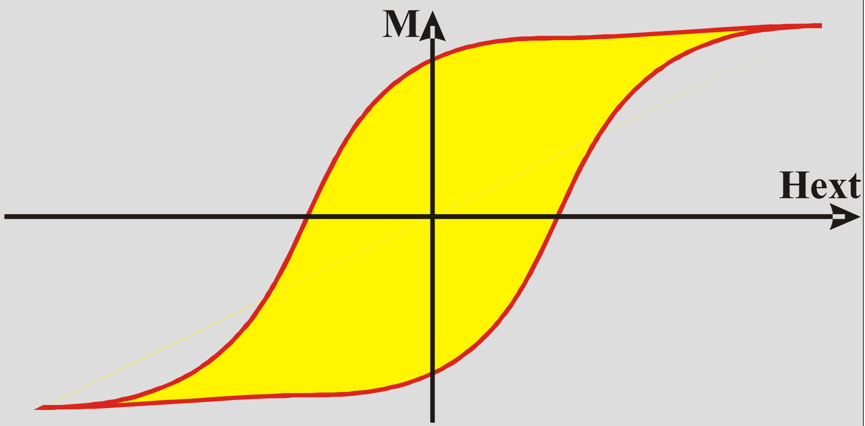


Transformers

Flux guides, sensors

Magnetic shielding

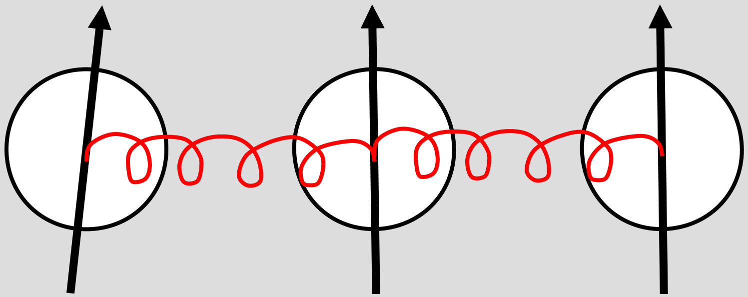
Hard materials



Permanent magnets, motors

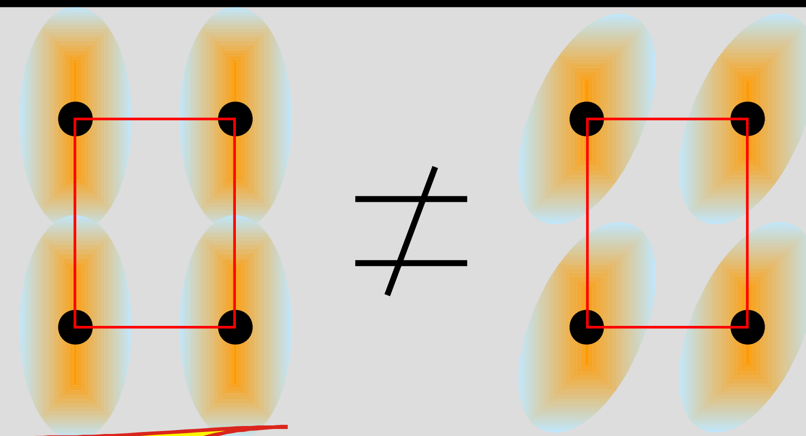
Magnetic recording

Echange energy

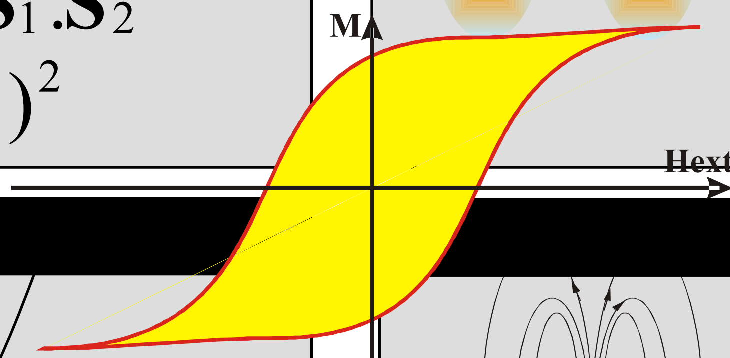


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2$$
$$= A(\nabla\theta)^2$$

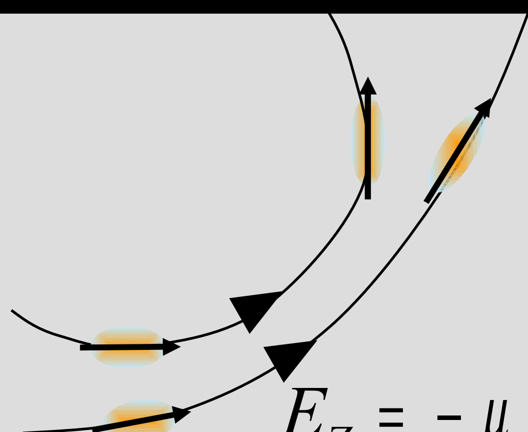
Magnetocrystalline anisotropy energy



$$E_{\mathrm{mc}} = K\sin^2(\theta)$$

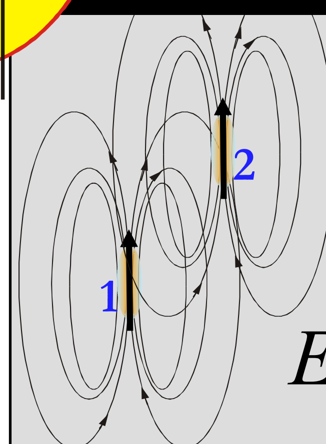


Zeeman energy (enthalpy)



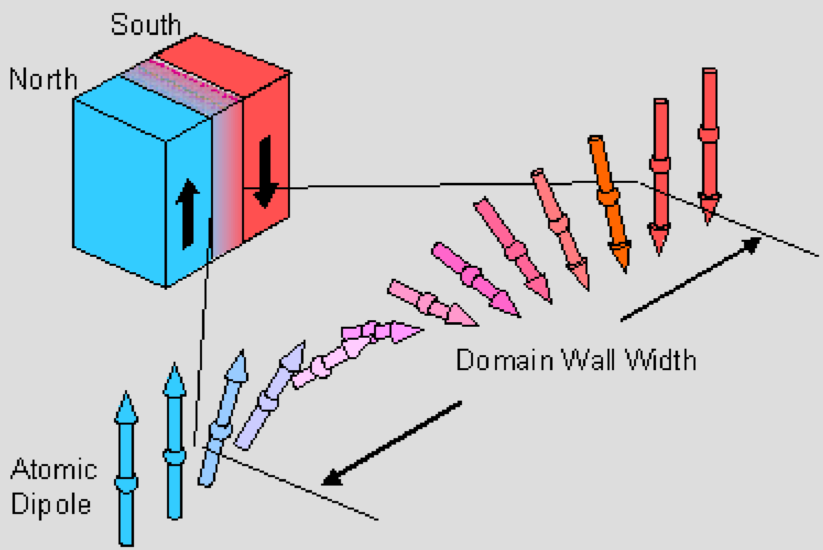
$$E_{\mathrm{Z}} = -\mu_0 \mathbf{M}_{\mathrm{S}} . \mathbf{H}$$

Dipolar energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}_{\mathrm{d}}$$

Typical length scale: Bloch wall width λ_B



$$e = A(d\theta / dx)^2 + K\sin^2\theta$$

Exchange $\rightarrow$ J/m

Anisotropy $\rightarrow$ J/m^3

Numerical values

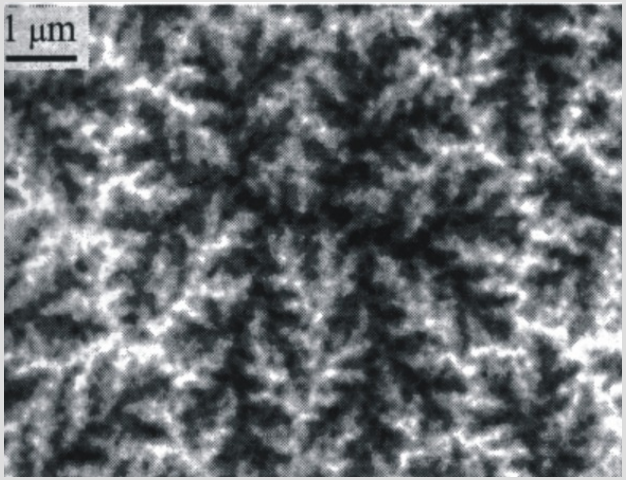
$$\lambda_B = \pi\sqrt{A/K}$$

λ_B = 2 - 3 nm $\longrightarrow$ $\lambda_B \geq$ 100 nm

Hard Soft

Bulk material

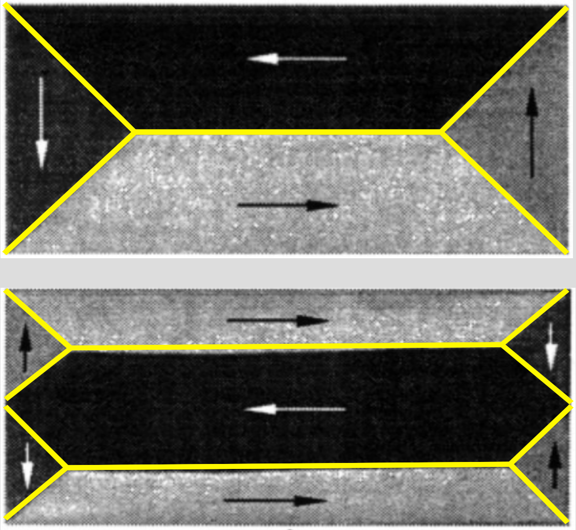
Numerous and complex magnetic domains



Co(1000) crystal – SEMPA
A. Hubert, *Magnetic domains*

Mesoscopic scale

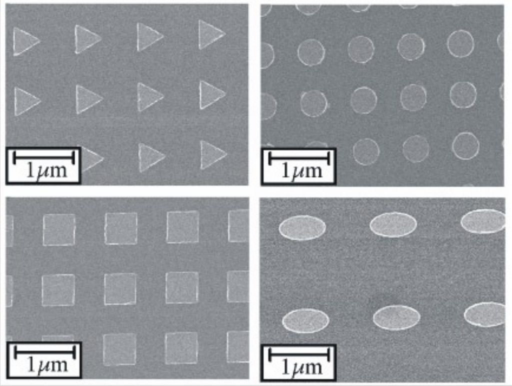
Small number of domains, simple shape

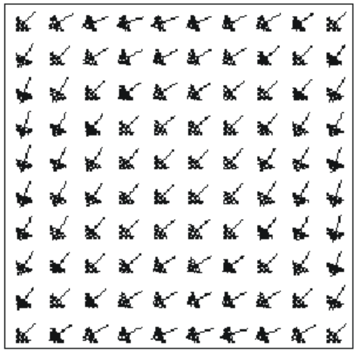


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

Nanomagnetism ~ mesoscopic magnetism

Framework

Approximation: $\vec{\mathbf{m}}(\vec{\mathbf{r}}) = \vec{\mathbf{M}} = Cte$

(strong!)

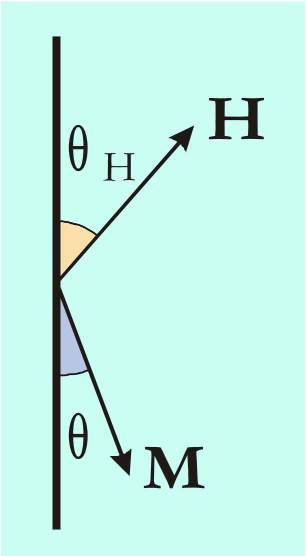
$$E_{tot} = V\left[K_{eff}\sin^2\theta - \mu_0 M_S H_{ext}\cos(\theta - \theta_H)\right]$$

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

Dimensionless units:

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

$$\begin{pmatrix} e = E/VK \\ h = H/H_a \\ H_a = 2K/\mu_0 M_S \end{pmatrix}$$

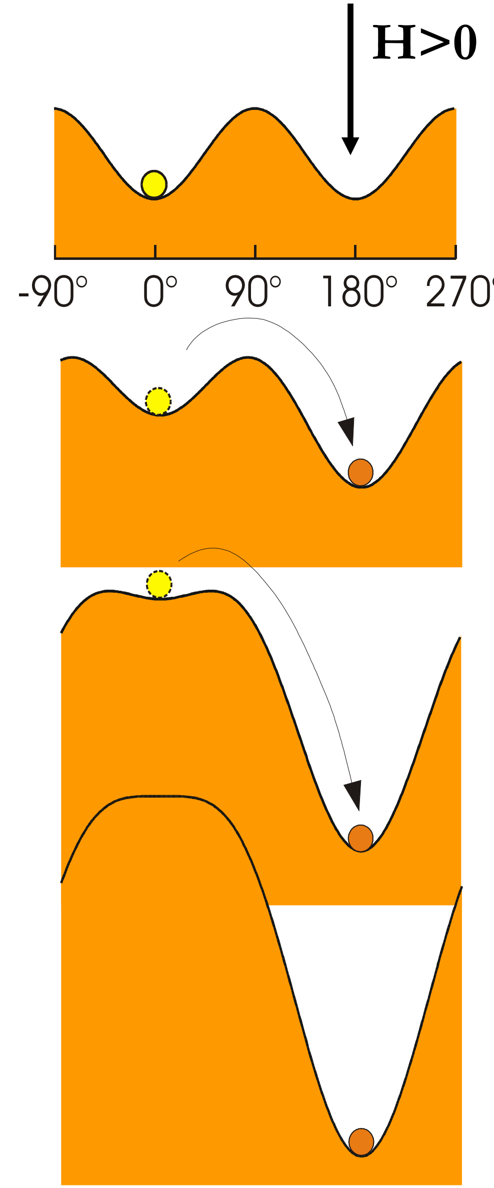


L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

- Uniform rotation / magnetization reversal
- Coherent rotation / magnetization reversal
- Macrospin etc.

$$e = \sin^2(\theta) + 2h\cos(\theta) \qquad (\theta_H = 180^\circ)$$



Equilibrium states

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

$$\frac{\partial e}{\partial \theta} = 0 \Rightarrow \cos(\theta_m) = h$$

$$\theta \equiv 0\,[\pi]$$

Stability

$$\frac{\partial^2 e}{\partial \theta^2} = 2\cos 2\theta - 2h\cos\theta = 4\cos^2\theta - 2 - 2h\cos\theta$$

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

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

$$\frac{\partial^2 e}{\partial \theta^2}(\pi) = 2(1+h)$$

Energy barrier

$$\Delta e = e(\theta_{max}) - e(0) = 1 - h^2 + 2h^2 - 2h = (1-h)^2$$

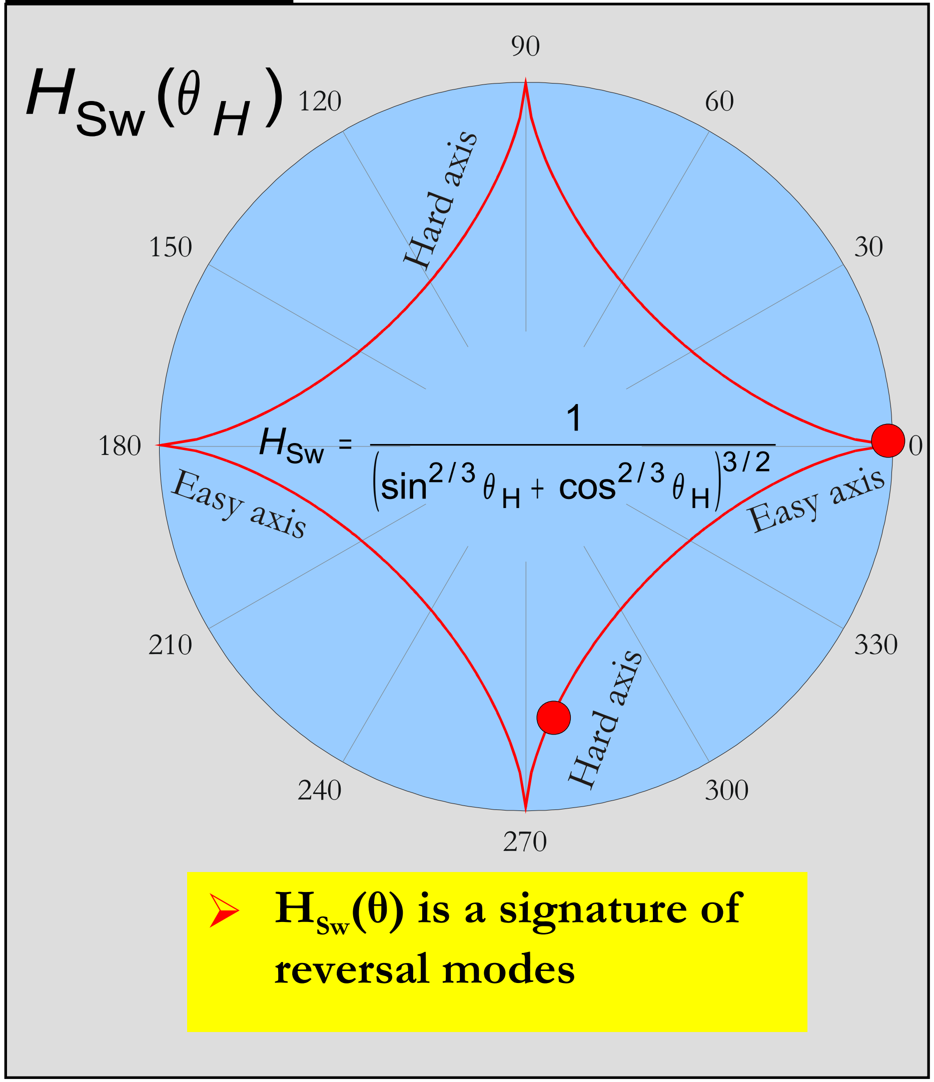
Switching

$h = 1$

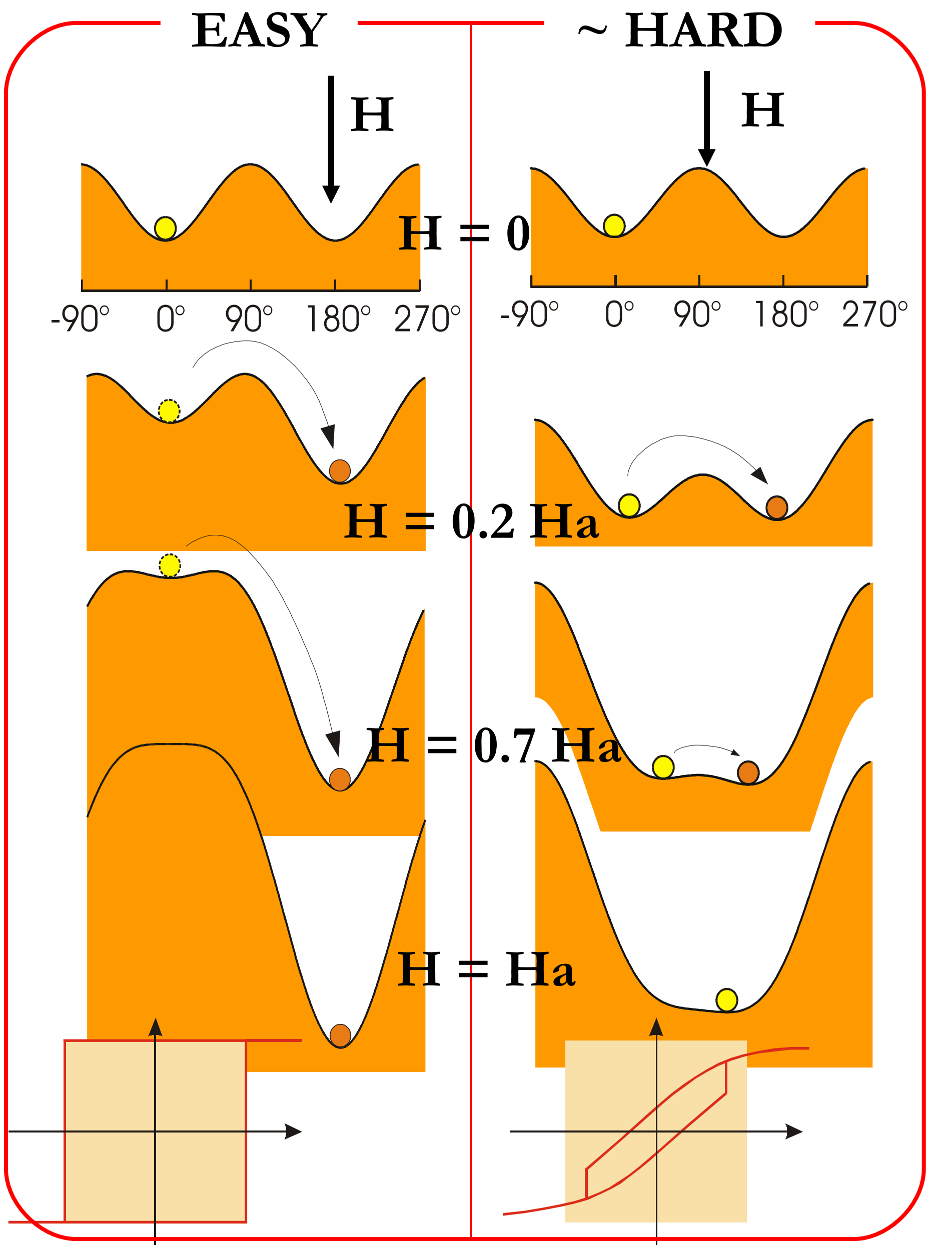
$H = H_a = 2K/\mu_0 M_s$

$(1-h)^\alpha$ with exponent 1.5 in general

'Astroid' curve



- $H_{Sw}(\theta)$ is a signature of reversal modes



J. C. Slonczewski, Research Memo RM 003.111.224, IBM Research Center (1956)

Switching field = Reversal field

A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.

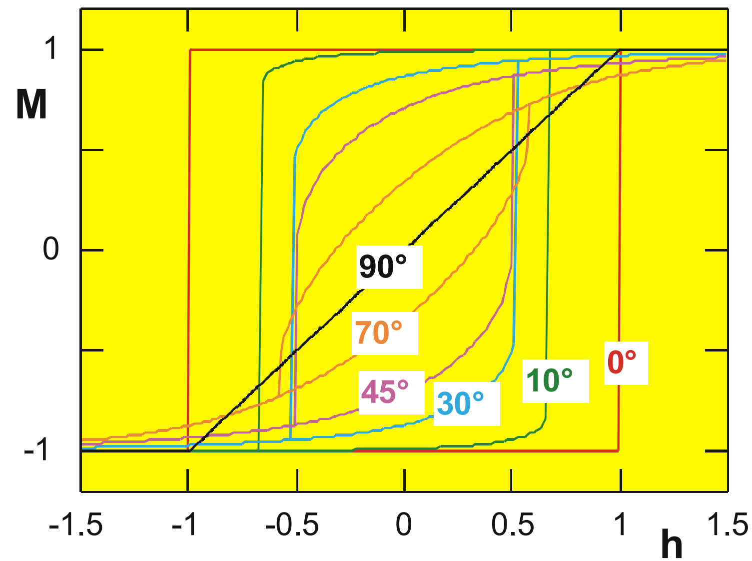
Can be measured only in single particles.

Coercive field

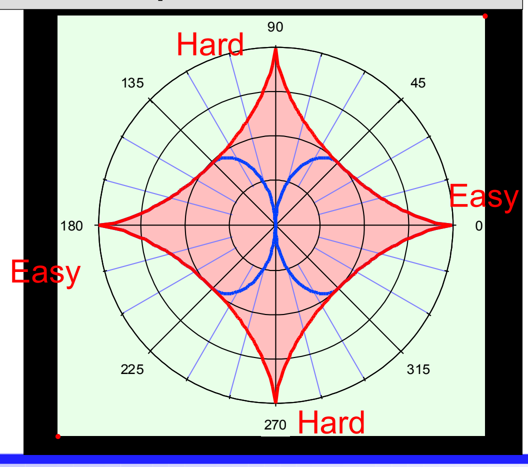
The value of field at which **M.H=0** ($\theta=\theta_H\pm\pi/2$)

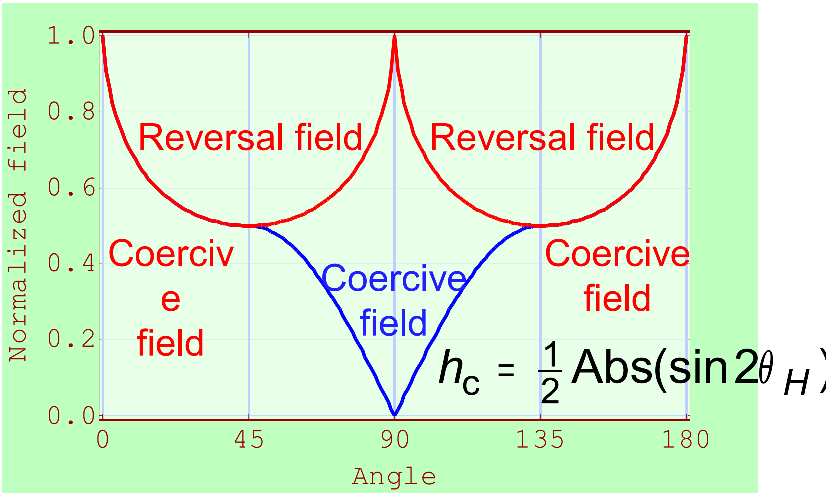
A quantity that can be measured in real materials (large number of 'particles').

May be or may not be a measure of the mean switching field at the microscopic level

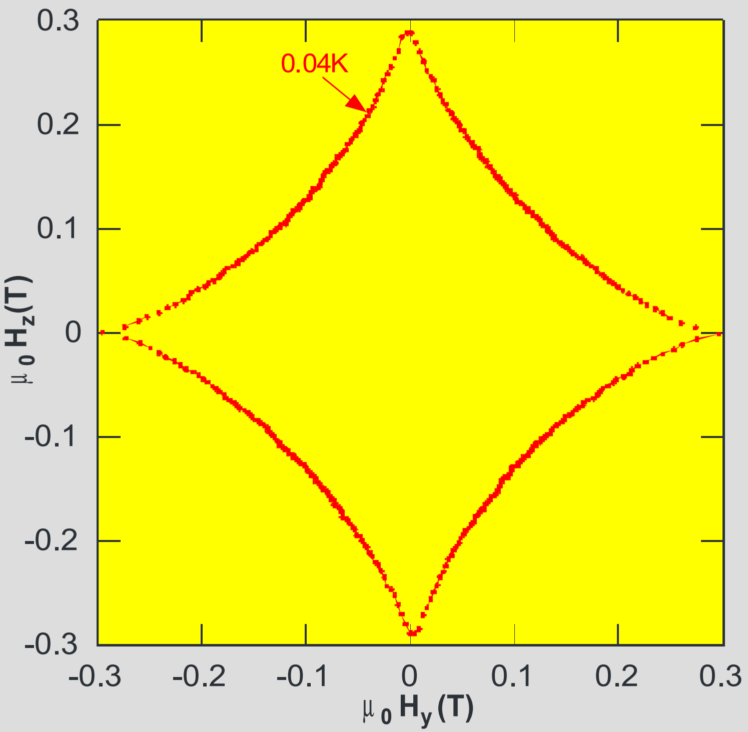


$$h_{Sw} = \frac{1}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$

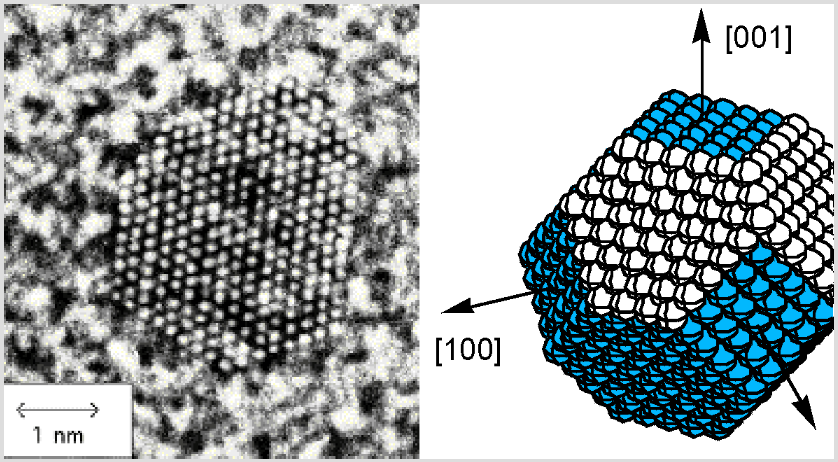




Experimental evidence

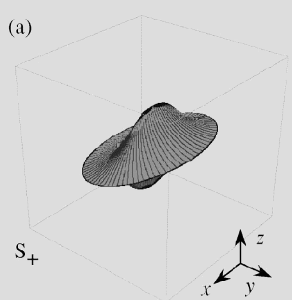


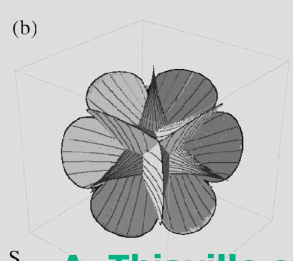
First evidence: W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)



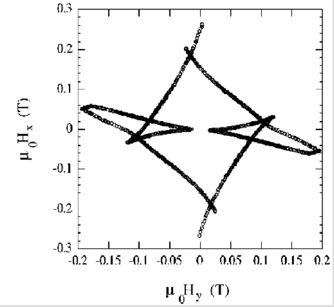
M. Jamet et al., Phys. Rev. Lett., 86, 4676 (2001)

Extensions: 3D, arbitrary anisotropy etc.





A. Thiaville et al., PRB61, 12221 (2000)

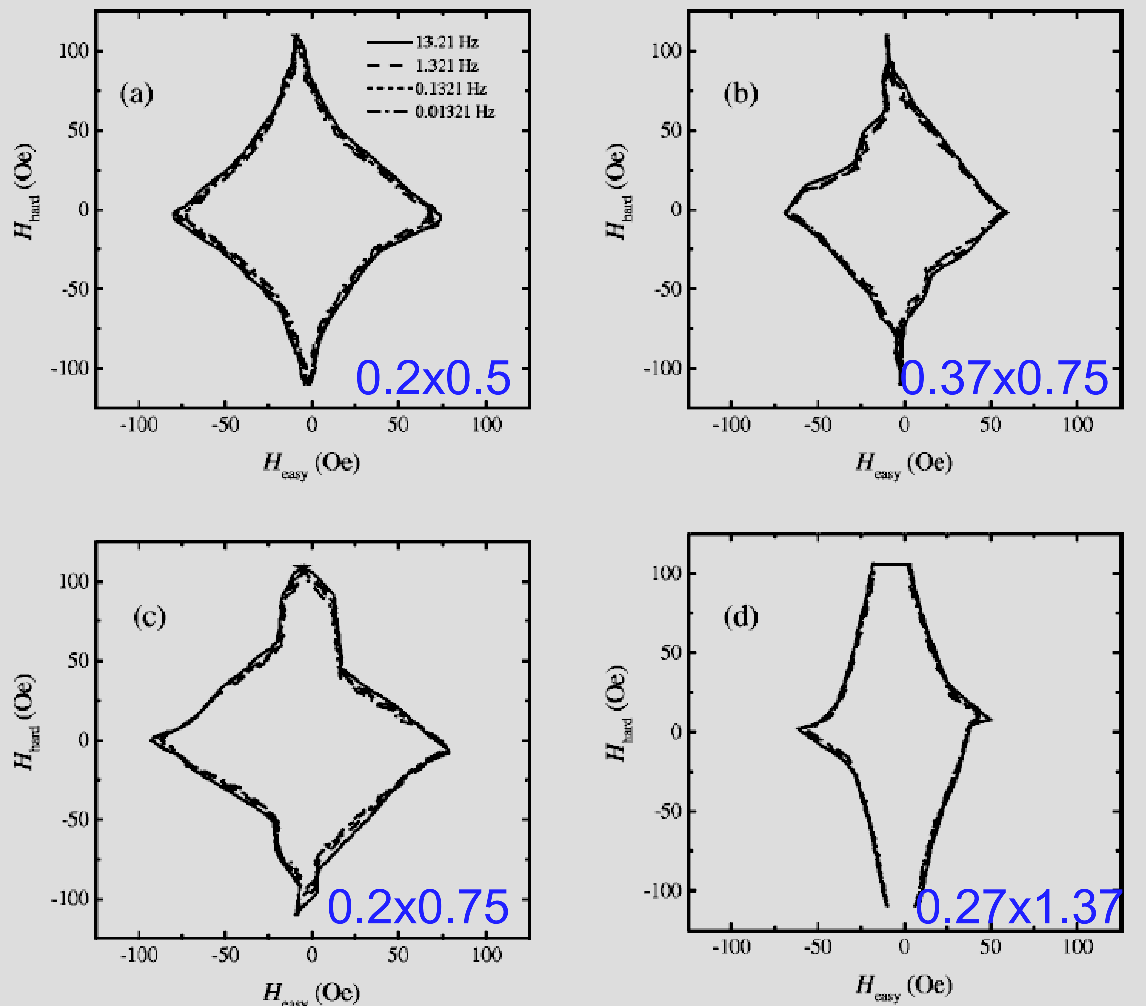


M. Jamet et al., PRB69, 024401 (2004)

Size-dependent magnetization reversal

Size in micrometers

Astroids of flat magnetic elements with increasing size



J. Z. Sun et al., Appl. Phys. Lett. 78 (25), 4004 (2001)

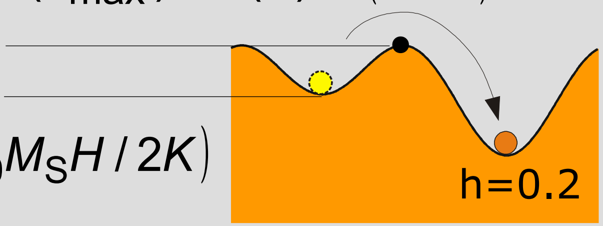
Conclusion over coherent rotation

- The simplest model
- Fails for most systems because they are too large: **apply model with great care!..**
- Hc<<Ha for most large systems (thin films, bulk): **do not use Hc to estimate K!**
  Early known as **Brown's paradox**

Barrier height

$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$

$$(h = \mu_0 M_S H / 2K)$$



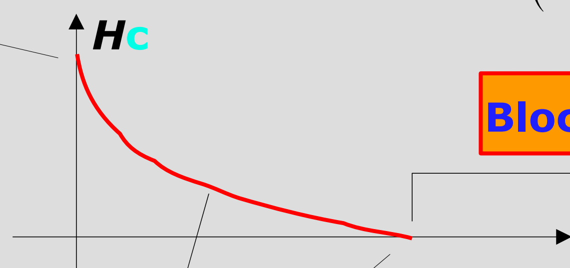
Thermal activation

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

$$\tau = \tau_0 \exp\left(\frac{\Delta E}{k_B T}\right) \Rightarrow \Delta E = k_B T \ln(\tau / \tau_0)$$

Lab measurement : $\tau = 1\mathrm{s}$ $\qquad \sim 25 k_B T$

$$H_c = \frac{2K}{\mu_0 M_S}\left(1 - \sqrt{\frac{25 k_B T}{KV}}\right)$$

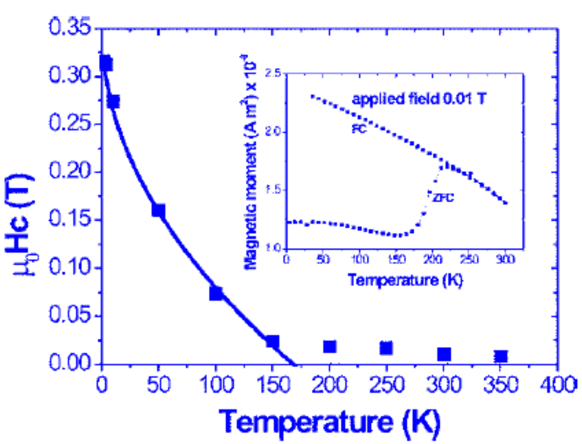


Blocking temperature

$T_b \approx KV / 25 k_B$

Information about anisotropy density

J. Appl. Phys. **99**, 08Q514 (2006)



Information about total effective anisotropy

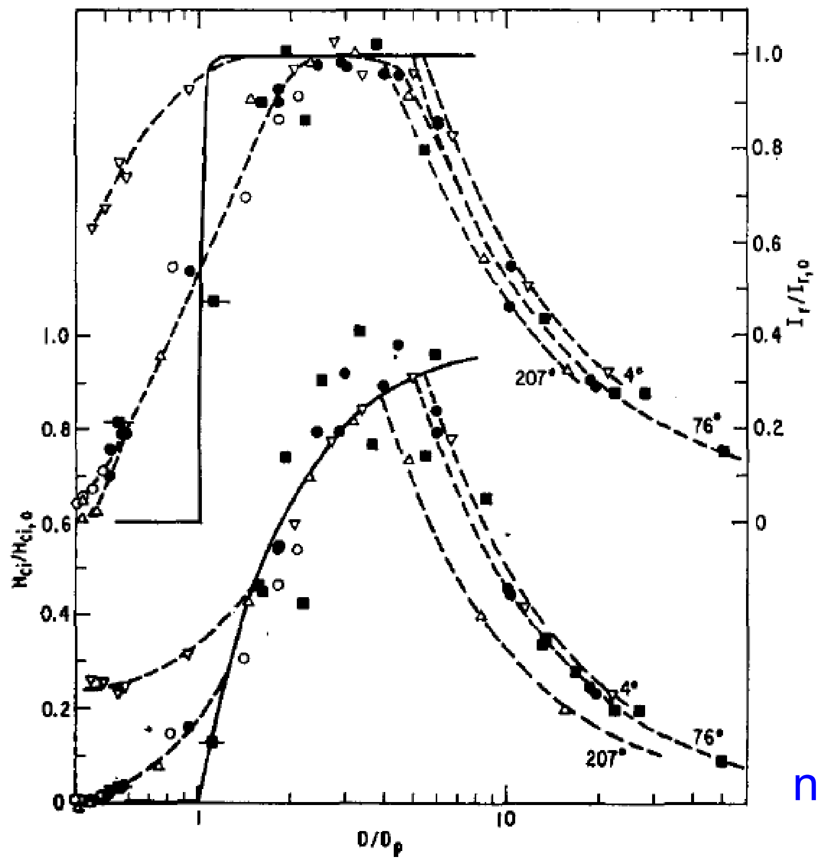
E. F. Kneller, J. Wijn (ed.) Handbuch der Physik XIII/2: Ferromagnetismus, Springer, 438 (1966)

M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

Notice, for magnetic recording : $t \approx 10^9\mathrm{s}$ $\qquad KV_B \approx 40 - 60 k_B T$

2. SINGLE-DOMAIN REVERSAL – Magnetic length scales

Towards suparamagnetism



Towards nucleation-propagation and multidomain

FIG. 1. Particle size dependence of essentially spherical, randomly oriented, iron particles. Calculated curve given by solid line. Diameters $D=\hat{d}_v$. Data at 76°K obtained from electron microscopic examination ■, calculated from I_r/I_s vs temperature O, and from smoothed data of H_{ci} vs D ●.

E. F. Kneller & F. E. Luborsky,
Particle size dependence of coercivity and remanence of single-domain particles,
J. Appl. Phys. 34, 656 (1963)

Magnetization

Magnetization vector **M** $\longrightarrow$ $$\mathbf{M} = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = M_s \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

Can vary in time and space.

Modulus is constant (hypothesis in micromagnetism) $\longrightarrow$ $$m_x^2 + m_y^2 + m_z^2 = 1$$

Mean-field approach possible: $M_s = M_s(T)$

Density of dipolar energy $E_\mathrm{d}(\mathbf{r}) = -\frac{1}{2}\mu_0 \mathbf{M}(\mathbf{r}).\mathbf{H}_\mathrm{d}(\mathbf{r})$

By definition $\mathrm{div}(\mathbf{H}_\mathrm{d}) = -\mathrm{div}(\mathbf{M})$. As $\mathbf{curl}(\mathbf{H}_\mathrm{d}) = \mathbf{0}$ we have (analogy with electrostatics):

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = -M_\mathrm{s} \iiint_\mathrm{space} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^3 r'$$

$\rho(\mathbf{r}) = -M_\mathrm{s}\mathrm{div}[\mathbf{m}(\mathbf{r})]$ is called the volume density of magnetic charges

To lift the divergence that may arise at sample boundaries a volume integration around the boundaries yields:

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = M_\mathrm{s}\left(-\iiint_\mathrm{space} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^3 r' + \iint_\mathrm{sample} \frac{[\mathbf{m}(\mathbf{r}').\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi \left\|\mathbf{r}-\mathbf{r}'\right\|^3} \mathrm{d}^2 r' \right)$$

$\sigma(\mathbf{r}) = M_\mathrm{s}\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ is called the surface density of magnetic charges, where n(r) is the outgoing unit vector at boundaries

Do not forget boundaries between samples with different M_s

Some ways to handle dipolar energy

Integrated dipolar energy:

$$\mathcal{E} = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{M}.\mathbf{H}_\mathrm{d}.\mathrm{d}V$$

Notice: six-fold integral over space: non-linear, long-range, time-consuming.

Bottle-neck of micromagnetic calculations

Usefull theorem for finite samples:

$$\mathcal{E} = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{M}.\mathbf{H}_\mathrm{d}.\mathrm{d}V = \frac{1}{2}\mu_0 \iiint_{\text{space}} \mathbf{H}_\mathrm{d}^2.\mathrm{d}V$$

⇨ $\mathcal{E}$ is always positive

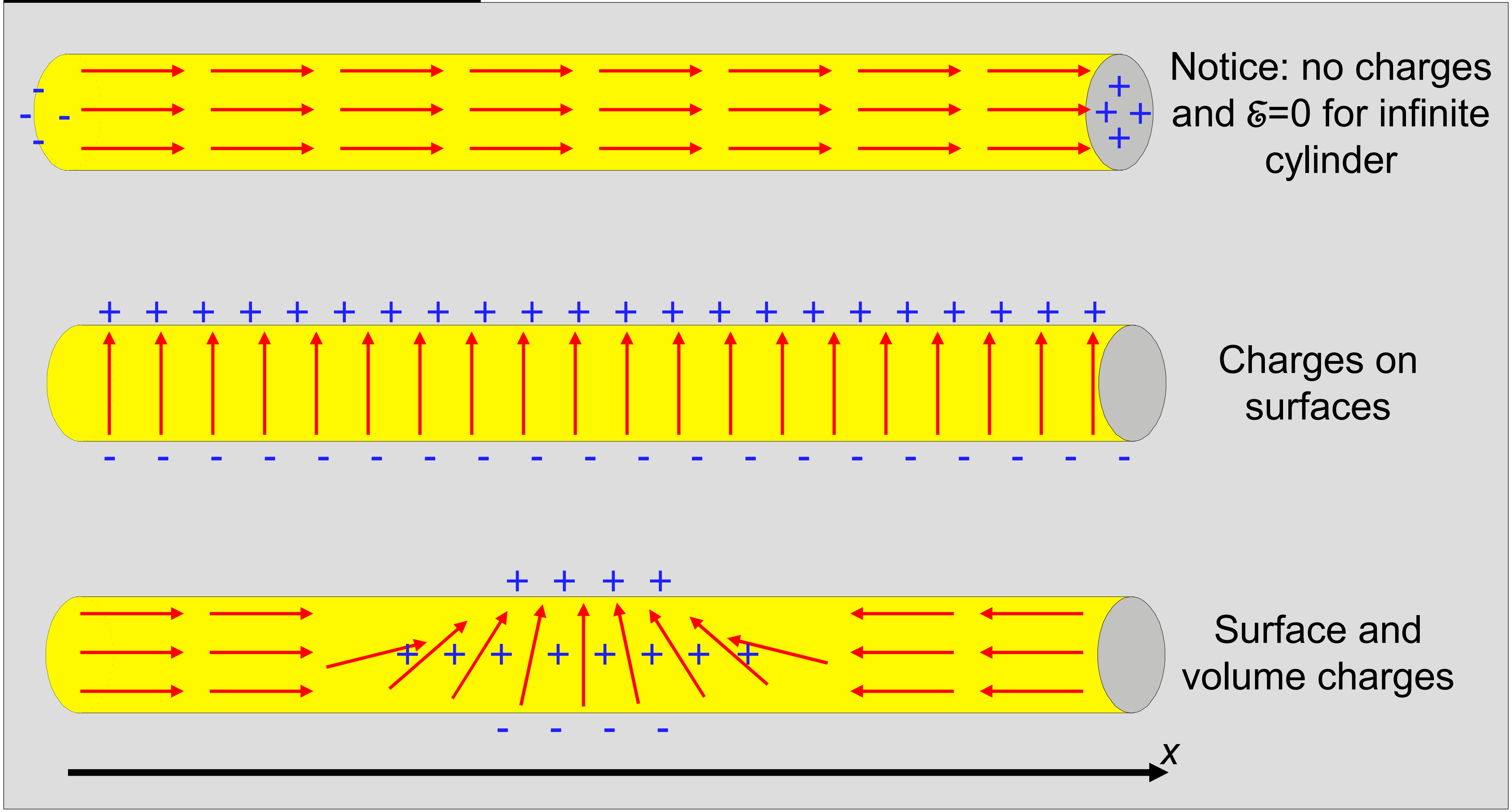
⇨ Significance of (BHmax) for permanent magnets

$$-\frac{1}{2}\mu_0 \iiint_{\text{sample}} (\mathbf{M}+\mathbf{H}_\mathrm{d}).\mathbf{H}_\mathrm{d}.\mathrm{d}V = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{B}.\mathbf{H}_\mathrm{d}.\mathrm{d}V$$

$$= \frac{1}{2}\mu_0 \iiint_{\text{space}\backslash\text{sample}} \mathbf{H}_\mathrm{d}^2.\mathrm{d}V$$

Energy available outside the sample, ie usefull for devices

Examples of magnetic charges



Assume uniform magnetization $\mathbf{M}(r) \equiv \mathbf{M} = M_s\left(m_x\mathbf{x} + m_y\mathbf{y} + m_z\mathbf{z}\right) = M_s m_i \mathbf{u}_i$

$$\mathbf{H}_d(\mathbf{r}) = M_s \iint_{\text{sample}} \frac{[\mathbf{m}.\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2r'$$

$$= M_s m_i \iint_{\text{sample}} \frac{n_i(\mathbf{r}').(\mathbf{r}'-\mathbf{r})}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2r'$$

$$\mathcal{E}_d = -\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{H}_d(\mathbf{r}).\mathbf{M}.\mathrm{d}^3\mathbf{r}$$

$$= -\frac{1}{2}\mu_0 M_s^2 m_i \iiint_{\text{sample}} \mathrm{d}^3\mathbf{r} \iint_{\text{sample}} \frac{n_i(\mathbf{r}').[\mathbf{m}.(\mathbf{r}'-\mathbf{r})]}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2\mathbf{r}'$$

$$= -K_d m_i m_j \iiint_{\text{sample}} \mathrm{d}^3\mathbf{r} \iint_{\text{sample}} \frac{n_i(\mathbf{r}').(r_j'-r_j)}{4\pi\left\|\mathbf{r}-\mathbf{r}'\right\|^3}\mathrm{d}^2\mathbf{r}'$$

$$\mathcal{E}_d = K_d V N_{ij} m_i m_j = K_d V \mathbf{m}.\overline{\overline{\mathbf{N}}}.\mathbf{m}$$

See more detailed approach: M. Beleggia and M. De Graef, J. Magn. Magn. Mater. 263, L1-9 (2003)

$$\mathcal{E}_{\mathrm{d}} = K_{\mathrm{d}} N_{ij} m_i m_j = K_{\mathrm{d}}\, {}^t\mathbf{m}.\overline{\overline{\mathbf{N}}}.\mathbf{m}$$

N is a positive second-order tensor

$$\langle \mathbf{H}_{\mathrm{d}}(\mathbf{r}) \rangle = -M_{\mathrm{s}} \overline{\overline{\mathbf{N}}}.\mathbf{m}$$

...and can be defined and diagonalized for any sample shape

$$N = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$$

$$\mathcal{E}_{\mathrm{d}} = K_{\mathrm{d}}(N_x m_x^2 + N_y m_y^2 + N_z m_z^2)$$

$$\langle H_{\mathrm{d,i}}(\mathbf{r}) \rangle = -M_{\mathrm{s}} N_i$$

Valid along main axes only!

$$N_x + N_y + N_z = 1$$

What with ellipsoids???

Self-consistency: the magnetization must be at equilibrium and therefore fulfill $\mathbf{m}//\mathbf{H}_{\mathrm{eff}}$

- Assuming $\mathbf{H}_{\mathrm{applied}}$ and $\mathbf{H}_{\mathrm{a}}$ are uniform, this requires $\mathbf{H}_{\mathrm{d}}(\mathbf{r})$ is uniform. This is satisfied only in volumes limited by polynomial surfaces of order 2 or less:
slabs, cylinders, ellisoids (+paraboloïds and hyperboloïds).
J. C. Maxwell, Clarendon 2, 66-73 (1872)

Ellipsoids

$$N_x = \tfrac{1}{2}abc\int_0^\infty \left[(a^2+\eta)\sqrt{(a^2+\eta)(b^2+\eta)(c^2+\eta)}\right]^{-1} d\eta$$

General ellipsoid:
main axes (a,c,c)

$$N_x = \frac{\alpha^2}{1-\alpha^2}\left[\frac{1}{\sqrt{1-\alpha^2}}\,\mathrm{Asinh}\left(\frac{\sqrt{1-\alpha^2}}{\alpha}\right)-1\right]$$

$$N_x = \frac{\alpha^2}{\alpha^2-1}\left[1-\frac{1}{\sqrt{\alpha^2-1}}\,\mathrm{Asin}\left(\frac{\sqrt{\alpha^2-1}}{\alpha}\right)\right]$$

For prolate revolution ellipsoid:
(a,c,c) with α=c/a<1

$$N_y = N_z = \tfrac{1}{2}(1-N_x)$$

For oblate revolution ellipsoid:
(a,c,c) with α=c/a>1

Cylinders

$$N_x = 0; \quad N_y = c/(b+c); \quad N_z = b/(b+c)$$

For a cylinder along x

J. A. Osborn, Phys. Rev. 67, 351 (1945).

For prisms, see: **A. Aharoni, J. Appl. Phys. 83, 3432 (1998)**

More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**

Magnetization loop of a macrospin along a hard axis

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

Dipolar energy: $H = h.H_a$, $H_a = 2K/\mu_0 M_s$, $K = N_i K_d$

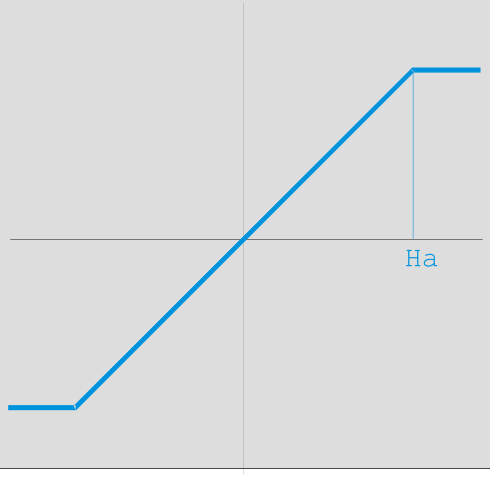
Hard axis: $\theta_H = \pi/2$

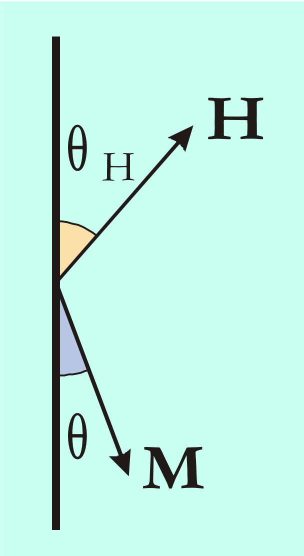
$$e = \sin^2(\theta) - 2h\sin(\theta)$$

$$\frac{\partial e}{\partial \theta} = 2\cos\theta\left(\sin\theta - h\right)$$

$$h = \sin\theta = \cos(\theta - \theta_H) = \mathbf{m.u_h}$$

Equilibrium position





Case of a bulk soft magnetic material

Hypotheses:

1. Use an ellipsoid, cylinder or slab along a main direction so that the demagnetizing field may be homogeneous.

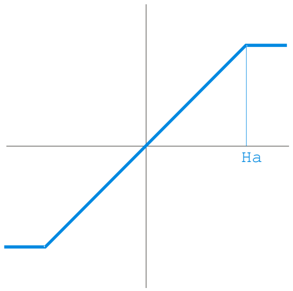
2. Domains can be created to yield a uniform and effective magnetization Meff

Density of energy:

$$E_{\mathrm{tot}} = E_{\mathrm{d}} + E_{\mathrm{Z}} = \frac{1}{2}\mu_0 N\mathbf{M}_{\mathrm{eff}}^2 - \mu_0 \mathbf{M}_{\mathrm{eff}} H_{\mathrm{ext}}$$

Minimization:

$$\frac{\partial E_{\mathrm{tot}}}{\partial \mathbf{M}_{\mathrm{eff}}} = \mu_0 N\mathbf{M}_{\mathrm{eff}} - \mu_0 H_{\mathrm{ext}} \Rightarrow \boxed{\mathbf{M}_{\mathrm{eff}} = \frac{1}{N}\mu_0 H_{\mathrm{ext}}}$$

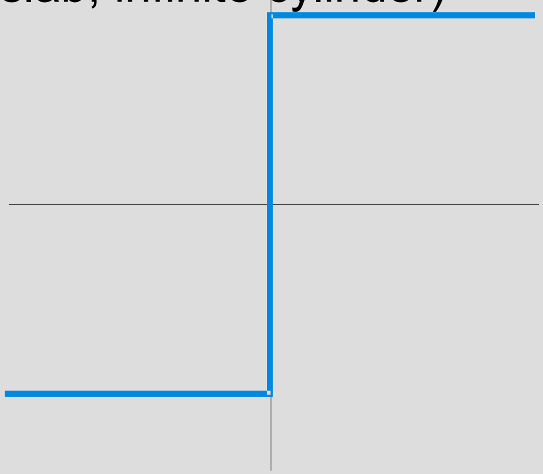


Conclusion for soft magnetic materials

Susceptibility is constant and equal to 1/N

Ideally soft

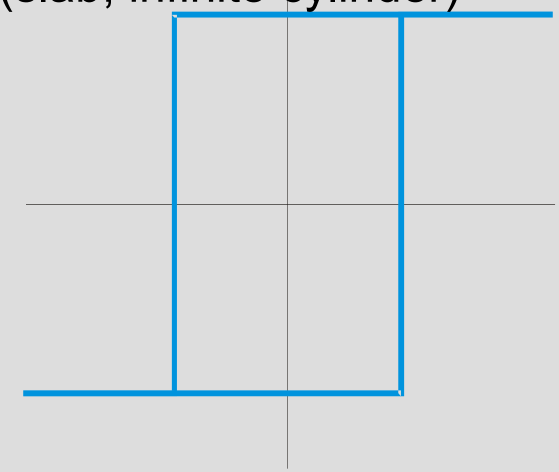
N=0 (slab, infinite cylinder)



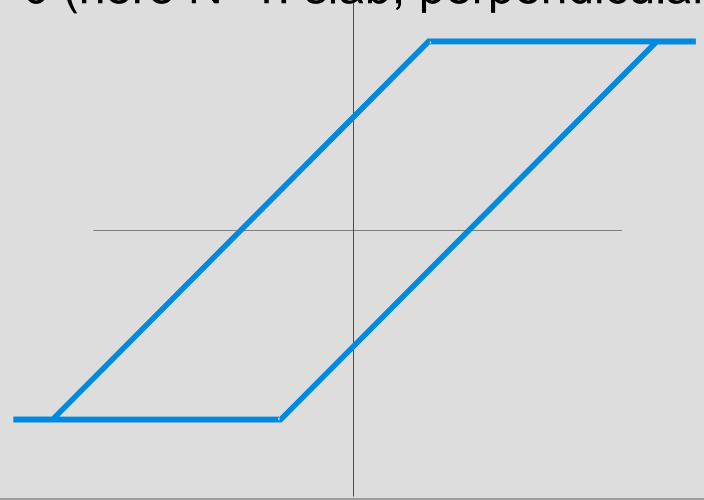
N>0 (here N=1: slab, perpendicular)

Easy axis, coercitive

N=0 (slab, infinite cylinder)

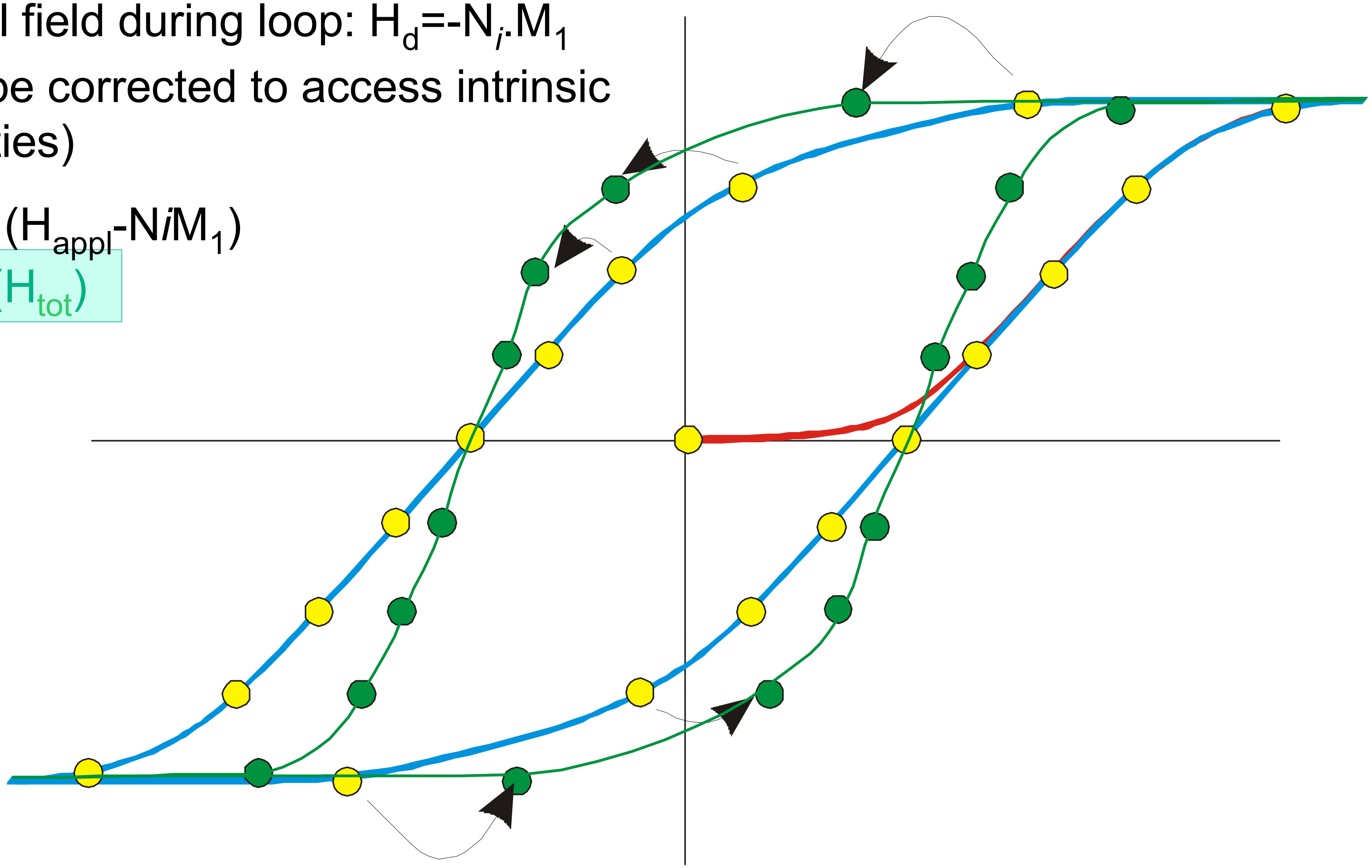


N>0 (here N=1: slab, perpendicular)



1. Measure a hysteresis loop $M_1(H_{appl})$
2. Internal field during loop: $H_d=-N_i.M_1$ (must be corrected to access intrinsic properties)
3. Plot $M_1(H_{appl}-N_iM_1)$

   ➡ $M_2(H_{tot})$



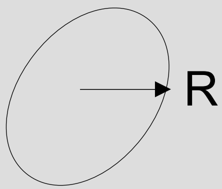
Upper bound for dipolar fields in 2D

Estimation of an upper range of dipolar field in a 2D system

$$\left\|\mathbf{H}_{\mathrm{d}}(R)\right\| \leq \oint \frac{2\pi r dr}{r^3}$$

Integration

Local dipole: $1/r^3$

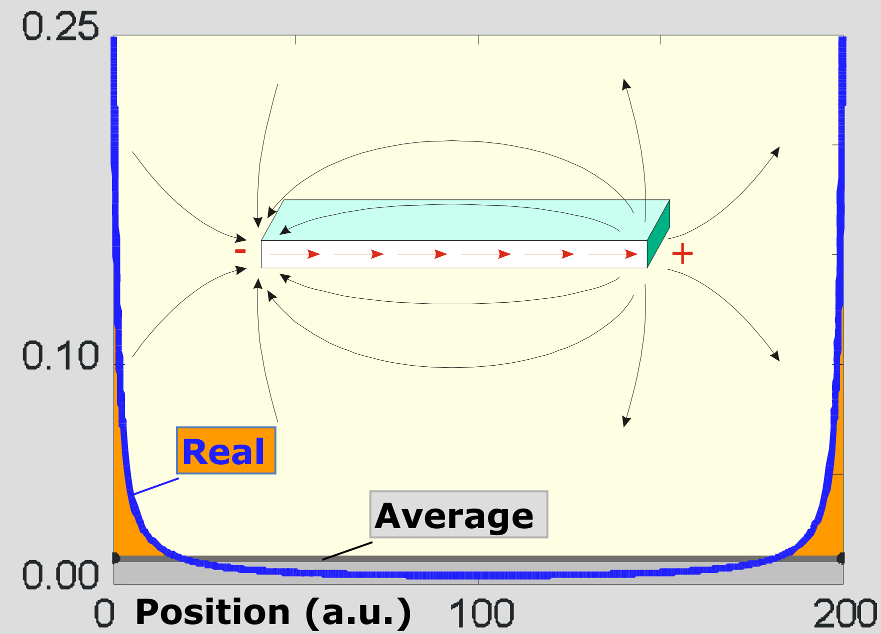


$$\left\|\mathbf{H}_{\mathrm{d}}(R)\right\| \leq \mathrm{Cte} + 1/R$$

Convergence with finite radius (typically thickness)

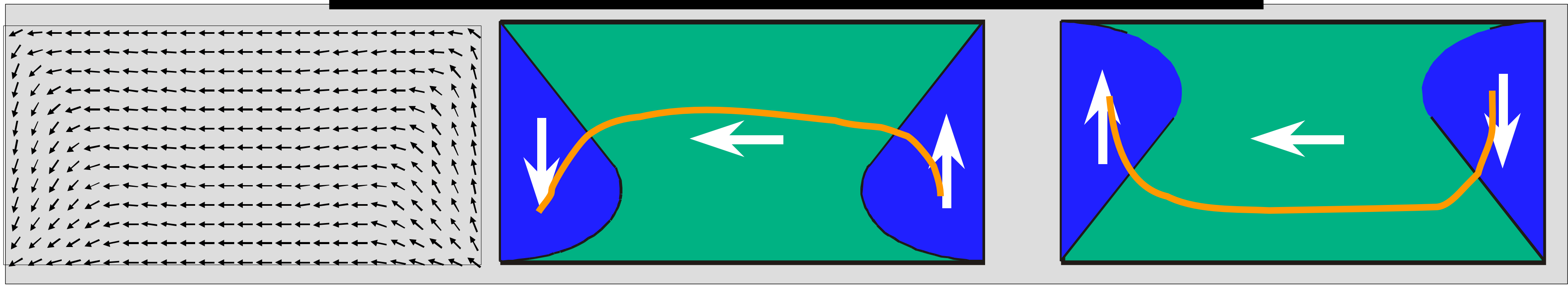
Non-homogeneity of dipolar fields in 2D

Example: flat stripe with thickness/height = 0.0125

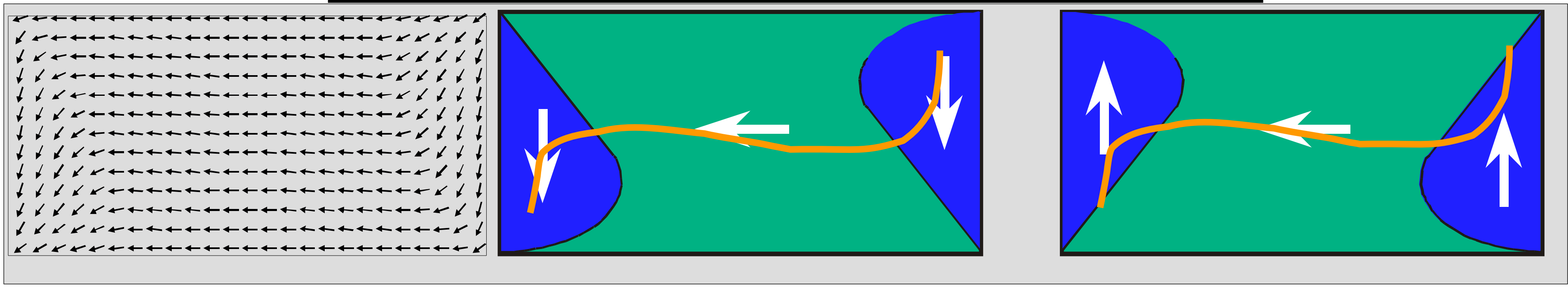


- Dipolar fields are weak and short-ranged in 2D or even lower-dimensionality systems
- Dipolar fields can be highly non-homogeneous in anisotropic systems like 2D
- Consequences on dot's non-homogenous state, magnetization reversal, collective effects etc.

'C' state



'S' state

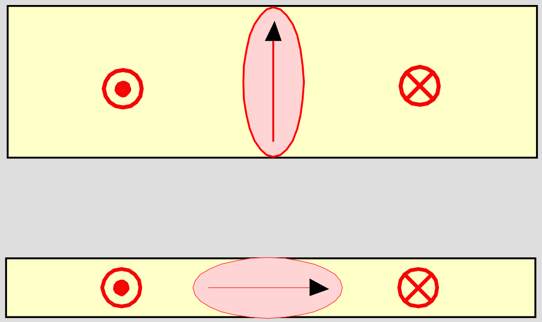


- At least 8 nearly-equivalent ground-states for a rectangular dot
- Issue for the reproductibility of magnetization reversal

Bloch versus Néel wall

Crude model: wall is a uniformly-magnetized cylinder with an ellipsoid base

Bloch wall



$$E_d = K_d \frac{W}{2t}$$

Thickness t

Wall width W

Néel wall

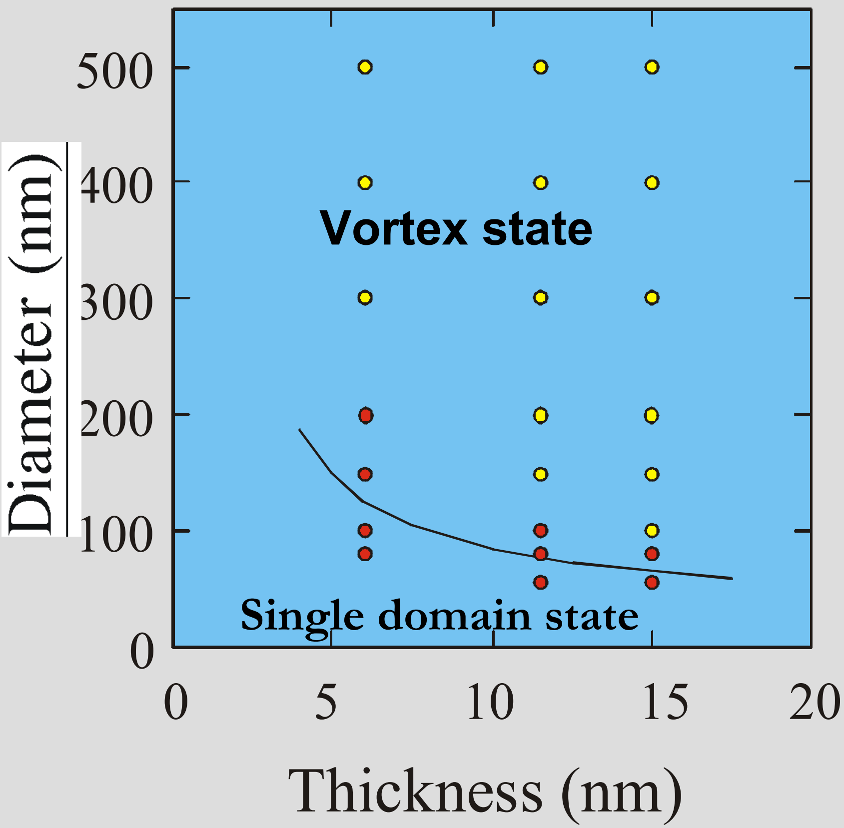
$$E_d = K_d \frac{t}{2W}$$

L. Néel, Énergie des parois de Bloch dans les couches minces, C. R. Acad. Sci. 241, 533-536 (1955)

Conclusion

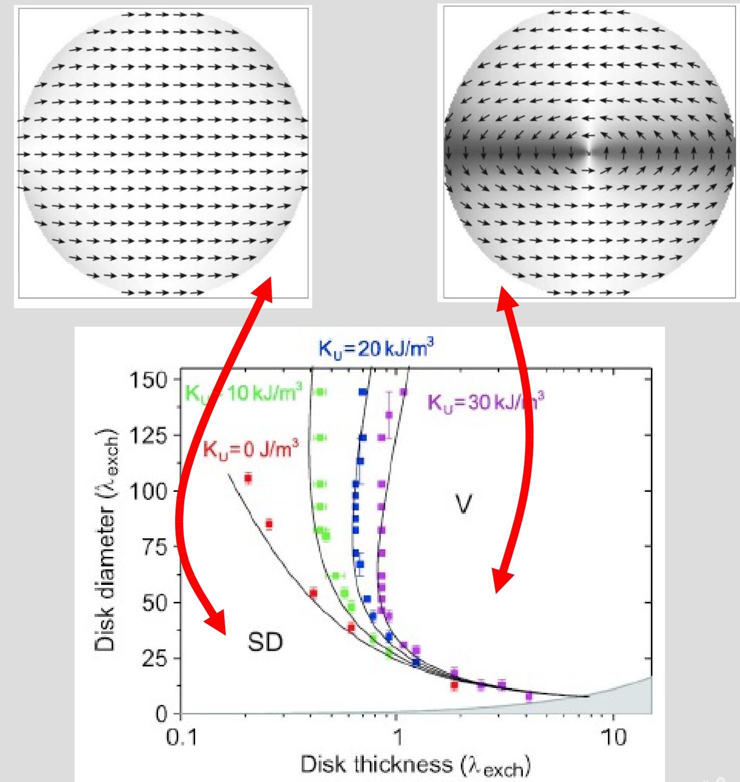
- At low thickness (roughly $t \approx W$) Bloch domain walls are expected to turn their magnetization in-plane > Néel wall
- Model needs to be refined
- Domain walls not changed for films with perpendicular magnetization

Experiments



R.P. Cowburn,
J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Theory / Simulation

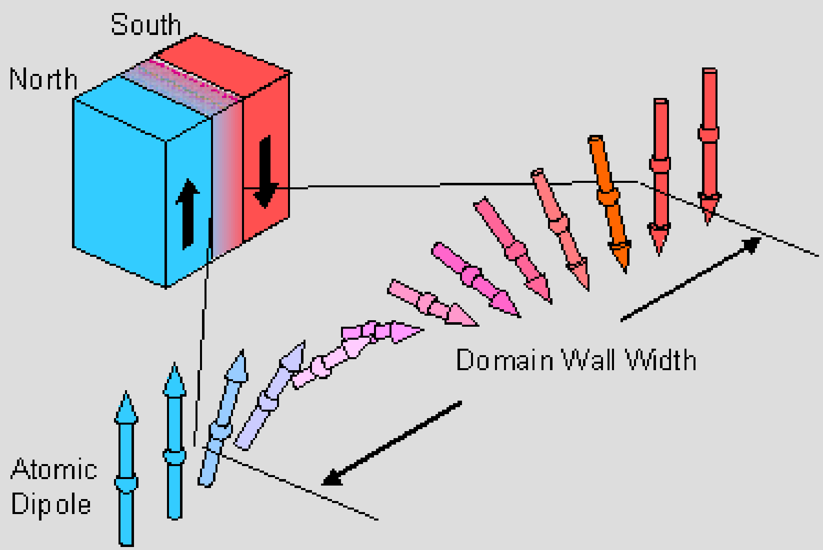


P.-O. Jubert & R. Allenspach,
PRB 70, 144402/1-5 (2004)

Zero-field cross-over $t.D \approx 20\lambda_{ex}^2$

- Vortex state (flux-closure) dominates at large thickness and/or diameter
- The size limit for single-domain is much larger than the exchange length
- Experimentally the vortex may be difficult to reach close to the transition (hysteresis)

Typical length scale: Bloch wall width λ_B



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

Exchange → J/m

Anisotropy → $\mathrm{J/m^3}$

Numerical values

$$\lambda_B = \pi\sqrt{A/K}$$

λ_B = 2 - 3 nm ⟶ $\lambda_B \geq$ 100 nm

Hard — Soft

$\Delta = \sqrt{A/K}$ is often called the Bloch wall parameter. Notice also that several definitions of Bloch wall width have been proposed, e.g. with $\pi\iota$ or 2 as prefactor

Typical length scale: Exchange length λ_{ex}

$$e = A(d\theta / dx)^2 + K_d \sin^2\theta$$

$A(d\theta/dx)^2$: Exchange, J/m

$K_d \sin^2\theta$: Dipolar energy, J/m³

$$\lambda_{ex} = \sqrt{A/K_d} = \sqrt{2A/\mu_0 M_s^2}$$

$$\lambda_{ex} = 3 - 10\ \mathrm{nm}$$

Critical size relevant for nanoparticules made of soft magnetic material

$$D_c \approx \pi\sqrt{3}\lambda_{ex}$$

Generalization for various shapes

$$D_c \approx \pi\sqrt{6A/(N\mu_0)M_s^2}$$

Quality factor Q

$$e = -K\sin^2\theta + K_d \sin^2\theta$$

$-K\sin^2\theta$: m.c., J/m

$K_d \sin^2\theta$: Dipolar energy, J/m³

$$Q = K / K_d$$

Relevant e.g. for stripe domains in thin films with perpendicular magnetocristalline anisotropy

Critical size for hard magnets

$$D_c \approx 6E_w / K_d \approx 2.5Q\lambda_B$$

$$E_w \approx 4\sqrt{AK} \text{ for hard magnetic materials}$$

Notice:

Other length scales: with field etc.

Brown's paradox

In most systems $H_c \prec\prec \dfrac{2K}{\mu_0 M_s}$

Micromagnetic modeling

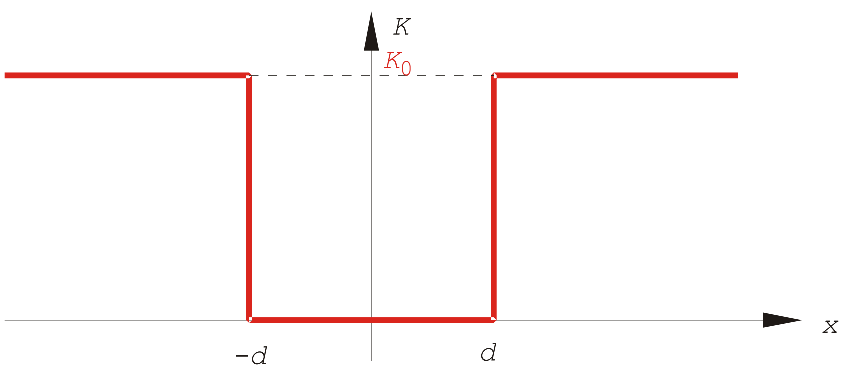
Exhibit analytic however realistic models for magnetization reversal

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.



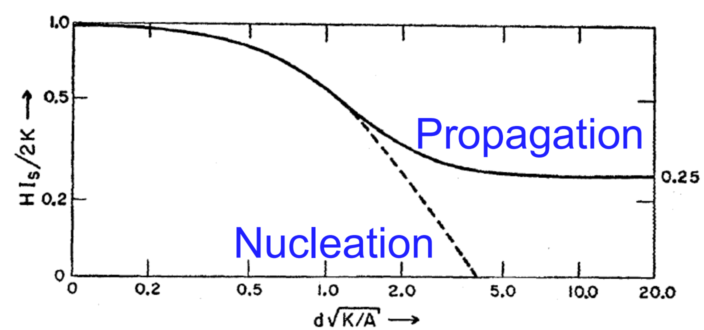
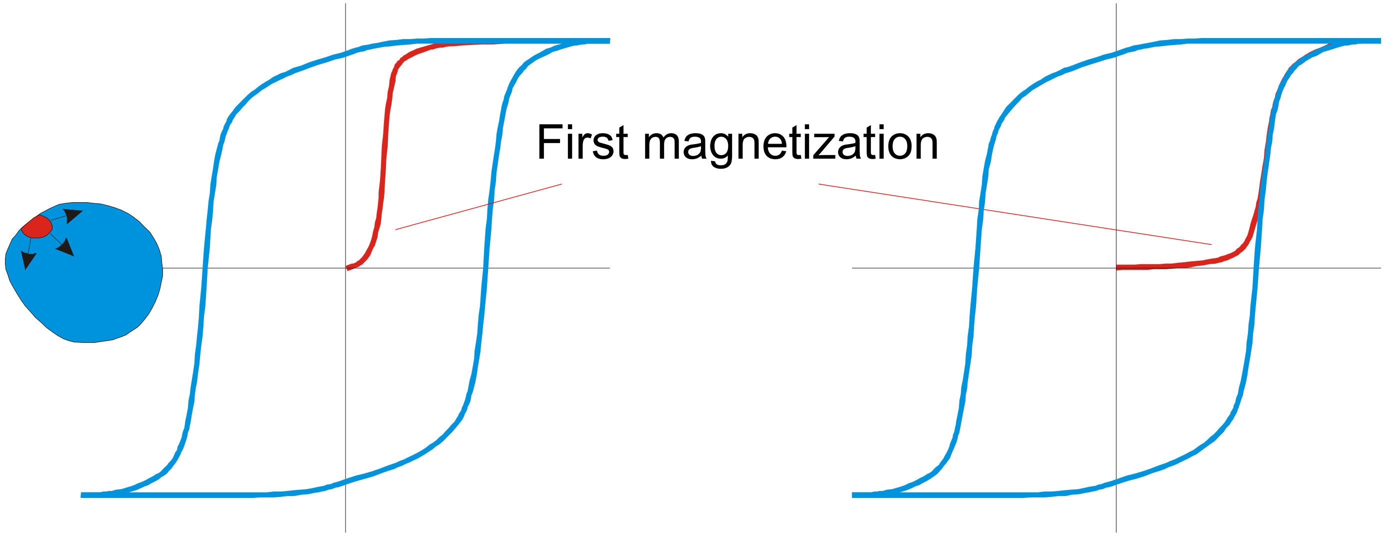


Fig. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, *d*.

Use first-magnetization curves to determine the type of coercivity

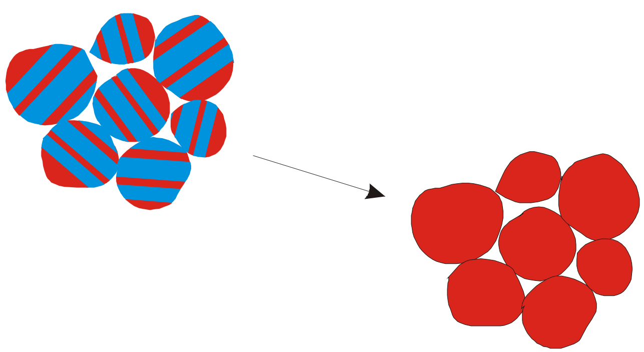


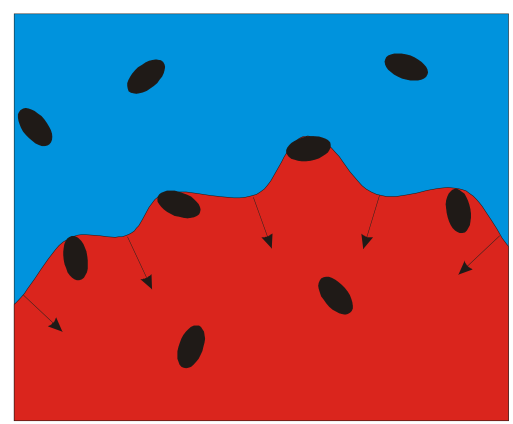
Nucleation-limited

Ex: Sm_2Co_{17}

Propagation-limited

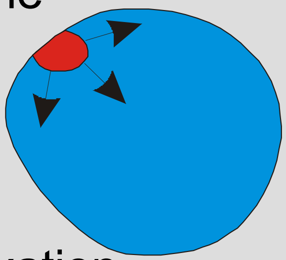
Ex: $SmCo_5$





Activation volume

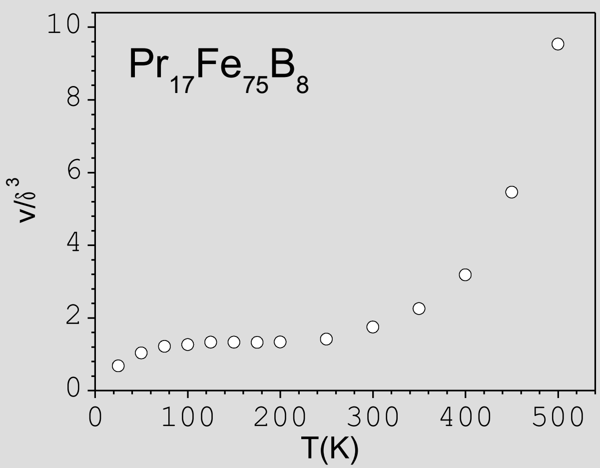
Also called: nucleation volume



Can be used for:

- Estimating Hc(T)
- Estimating long-time relaxation
- Determination of dimensionality

Note: of the order of domain wall width δ



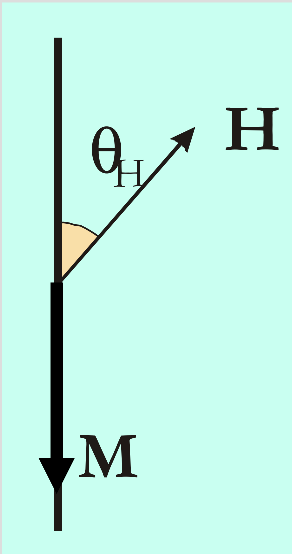
More detailed models:

D. Givord et al., JMMM258, 1 (2003)

$1/\cos\theta_H$ law

E. J. Kondorsky, J. Exp. Theor. Fiz. 10, 420 (1940)

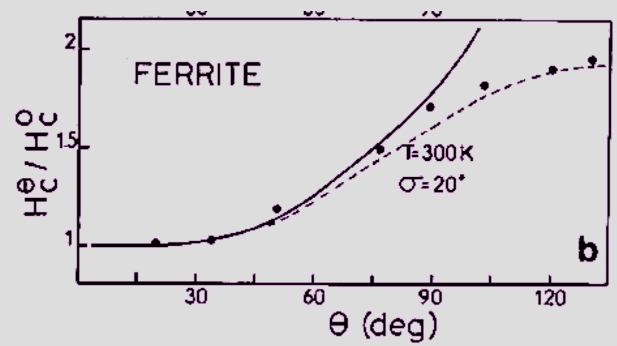
Hypothesis:



- Based on nucleation volume
- Hc<<Ha

Energy barrier E_0 overcome by gain in Zeeman energy plus thermal energy

$$E_0 = -\mu_0 M_s v_a H \cos(\theta_H) + 25 k_B T$$



D. Givord et al., JMMM72, 247 (1988)

Nucleation of new reversed domains

Fatuzzo/Labrune/Raquet model

$$dN = (N_0 - N)R\,dt$$

$$\Rightarrow N = N_0\left[1 - \exp(-Rt)\right]$$

N: number of nucleated centers at time t

N_0: total number of possible nucleation centers

R: rate of nucleation

Radial expansion of existing domains

$$\sigma_n = \sigma - \sigma_c = (v_0^2/T)[t_0 + t]^2 - \pi r_c^2/T$$

$$A = \int_0^t \left(\frac{dN}{dt}\right)_s (\sigma_n)_{t-s}\,ds + \frac{\pi r_c^2}{T} N(t)$$

Growth of existing nuclei

New nuclei

R_c: radius of critical nucleus

T: total area of sample

V_0: speed of propagation of domain wall

E. Fatuzzo, Phys. Rev. 127, 1999 (1962)

Model: fraction area not yet reversed

$$B(t) = \exp\Big(-2k^2\Big(1 - (Rt + k^{-1}) + \tfrac{1}{2}(Rt + k^{-1})^2 - e^{-Rt}(1 - k^{-1}) - \tfrac{1}{2}k^{-2}(1 - Rt)\Big)\Big),$$

$k = v_0 /(Rr_c)$

k is a measure of the importance of wall propagation versus nucleation events

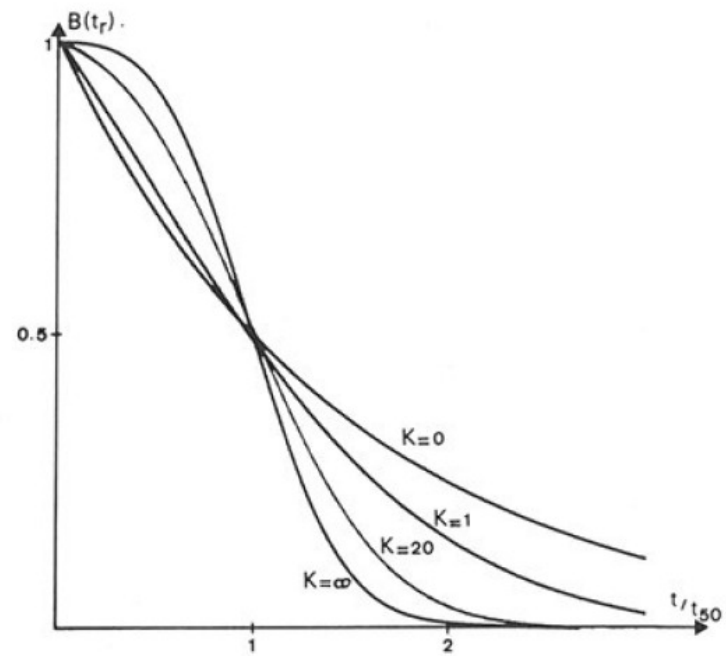


Fig. 6. Theoretical magnetization reversal curves (eq. (6)) for different values of the parameter k.

M. Labrune et al., J. Magn. Magn. Mater. 80, 211 (1989)
E. Fatuzzo, Phys. Rev. 127, 1999 (1962)

Depending on structural defects

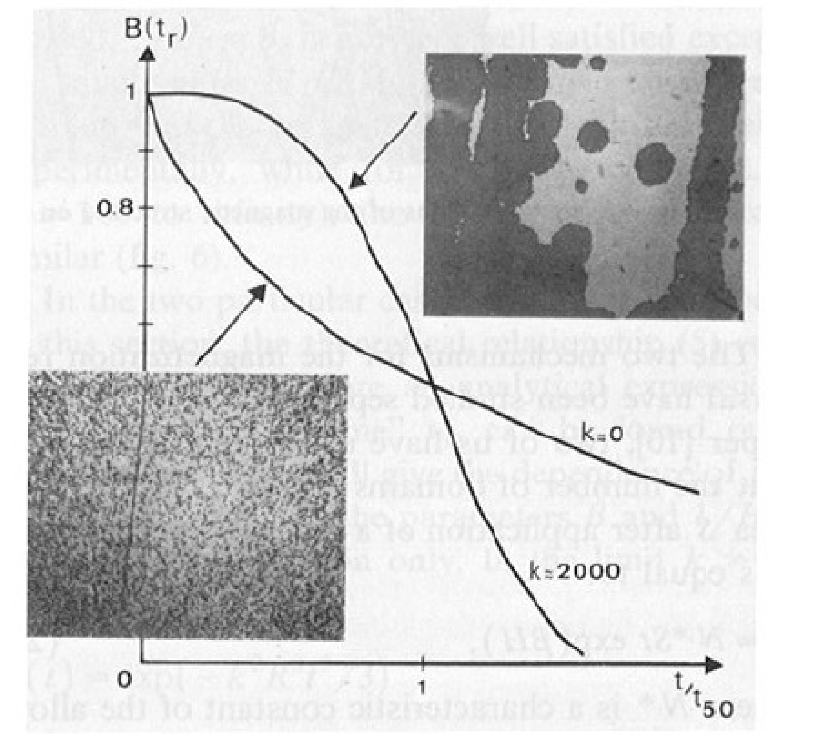
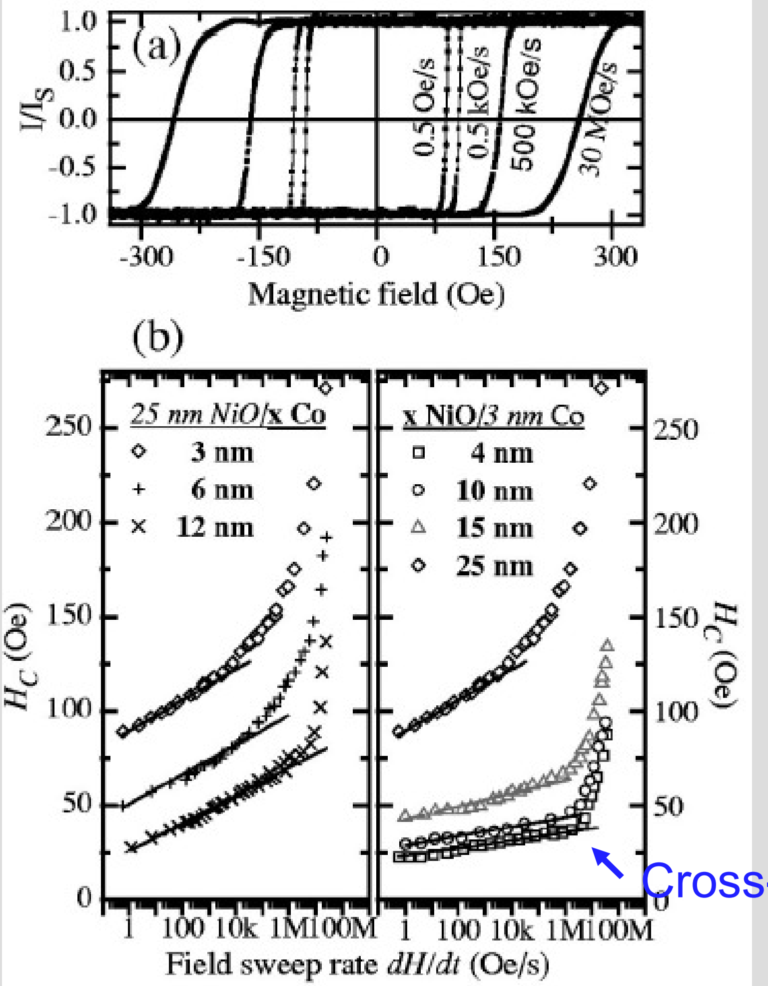


Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \approx 2000$) and a TbCo one ($k \approx 0$), corresponding domain structure observed by Kerr effect.

M. Labrune et al., J. Magn. Magn. Mater. 80, 211 (1989)

Depending on measurement dynamics



Cross-over

J. Camarero et al., PRB64, 172402 (2001)

Note also for fast propagation of domain walls: breakdown of propagation speed (Walker)

SOME READING

[1] Magnetic domains, A. Hubert, R. Schäfer, Springer (1999, reed. 2001)

[2] R. Skomski, Simple models of Magnetism, Oxford (2008).

[3] R. Skomski, *Nanomagnetics*, J. Phys.: Cond. Mat. **15,** R841–896 (2003).

[4] O. Fruchart, A. Thiaville, *Magnetism in reduced dimensions*, C. R. Physique **6**, 921 (2005) [Topical issue, Spintronics].

[5] O. Fruchart, *Couches minces et nanostructures magnétiques*, Techniques de l'Ingénieur, E2-150-151 (2007)

[6] Lecture notes from undergraduate lectures, plus various slides: http://perso.neel.cnrs.fr/olivier.fruchart/slides/

[7] G. Chaboussant, Nanostructures magnétiques, Techniques de l'Ingénieur, revue 10-9 (RE51) (2005)

[8] D. Givord, Q. Lu, M. F. Rossignol, P. Tenaud, T. Viadieu, Experimental approach to coercivity analysis in hard magnetic materials, J. Magn. Magn. Mater. 83, 183-188 (1990).

[9] D. Givord, M. Rossignol, V. M. T. S. Barthem, The physics of coercivity, J. Magn. Magn. Mater. 258, 1 (2003).

[10] J.I. Martin et coll., *Ordered magnetic nanostructures: fabrication and properties*, J. Magn. Magn. Mater. **256**, 449-501 (2003).

Basics of precessional switching

Démonstration: 1999

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{d\mathbf{M}}{dt} = -\gamma_0\left[\mathbf{M}\times\mathbf{H}_{eff}\right] + \frac{\alpha}{M_s}\left[\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right]$$

γ_0 Gyromagnetic factor

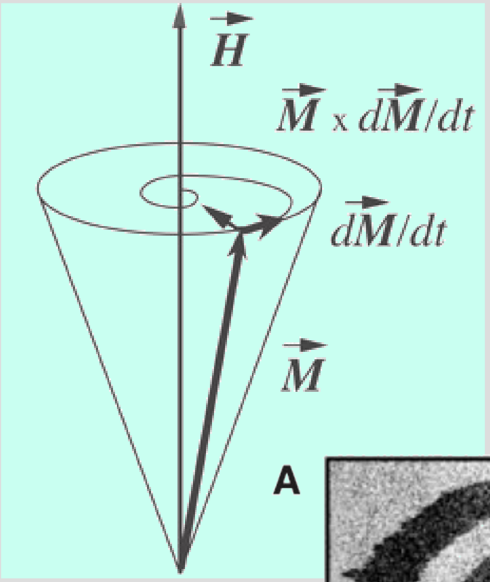
$$\gamma_0 = \mu_0\gamma \qquad \gamma = \frac{gq}{2m}$$

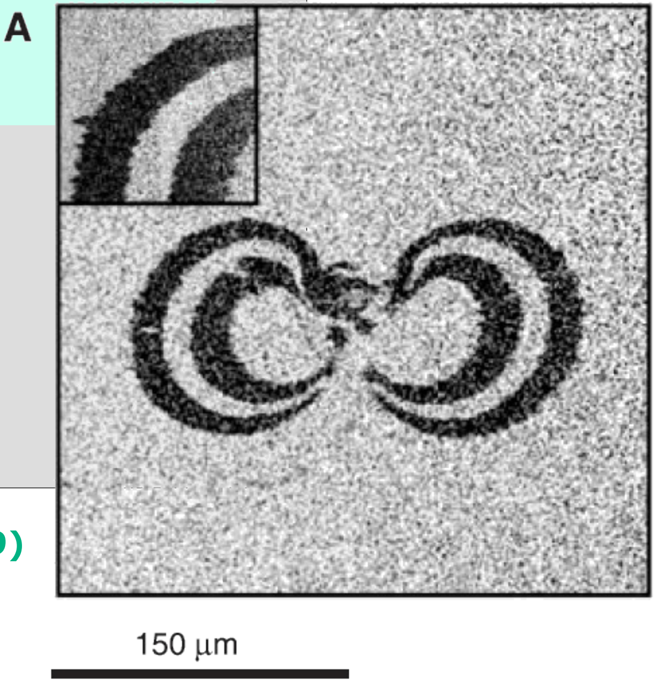
$$\gamma/2\pi = 28\,\mathrm{GHz/T}$$

H_{eff} Effective field (including applied)

$$\mu_0 H_{\mathrm{eff}} = -\frac{\partial E_{\mathrm{mag}}}{\partial \mathbf{M}}$$

α Damping coefficient ($10^{-3} > 10^{-1}$)





C. Back et al., Science 285, 864 (1999)

Precessional trajectories using energy conservation

(1) $E = \frac{1}{2}\mu_0 M_s^2 N_z m_z^2 - K m_x^2 - \mu_0 M_s H m_y$ In-plane uniaxial anisotropy

(2) $m_x^2 + m_y^2 + m_z^2 = 1$

Starting condition: $m_x = 1$

(1) ➡ $e = \frac{1}{2} N_z m_z^2 - h_K m_x^2 - h m_y$

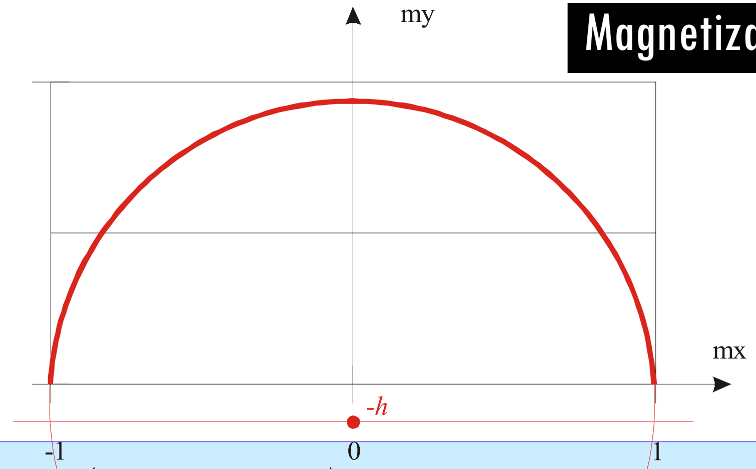
Using (2) ➡ $m_x^2 = 1 - \frac{2h}{N_z + h_K} m_y - \frac{N_z}{N_z + h_K} m_y^2$

Can be rewritten: $m_x^2 + \frac{\left(m_y + h / N_z\right)^2}{1 + h_K / N_z} = 1 + \frac{h^2}{N_z (N_z + h_K)}$

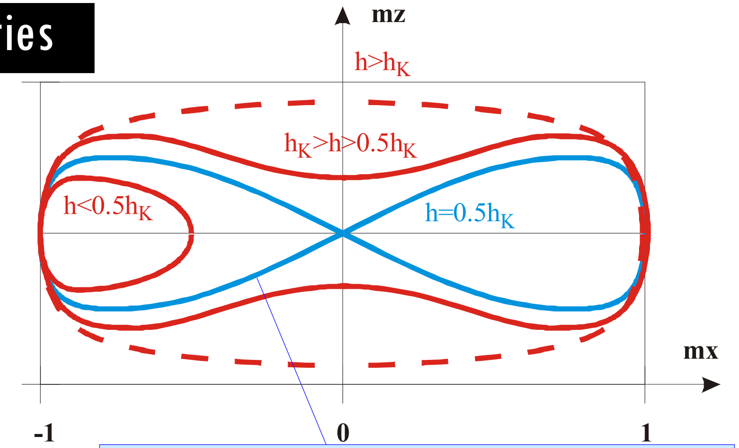
Using (2) ➡ $m_z^2 = \frac{2h}{N_z + h_K} m_y - \frac{h_K}{N_z + h_K} m_y^2$

Can be rewritten: $\frac{m_z^2}{\left(\frac{h_K}{N_z + h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$

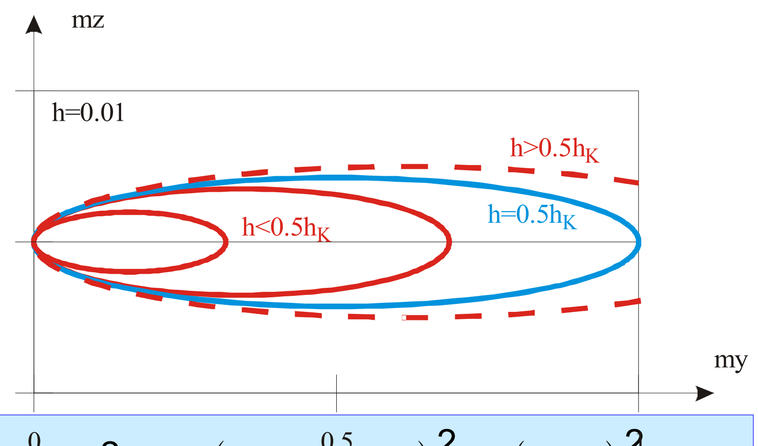
Magnetization trajectories



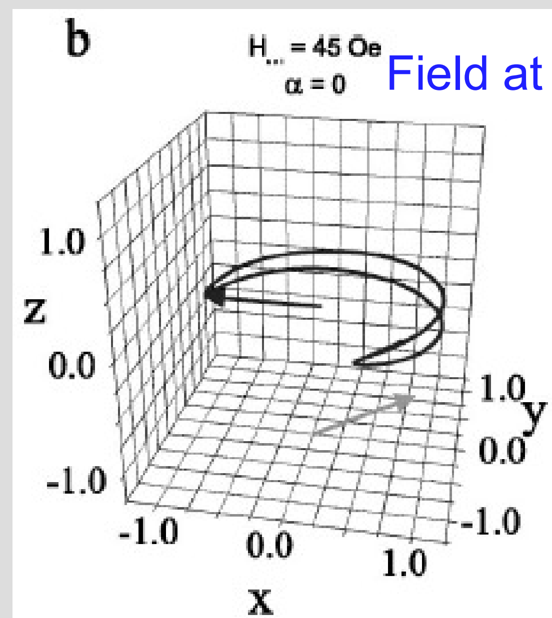
$$m_x^2 + \frac{(m_y + h/N_z)^2}{1+ h_K/N_z} = 1+ \frac{h^2}{N_z(N_z + h_K)}$$



$$\omega \approx 0.847\gamma_0\sqrt{M_s(H - H_K)/2}$$



$$\frac{m_z^2}{\left(\frac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$

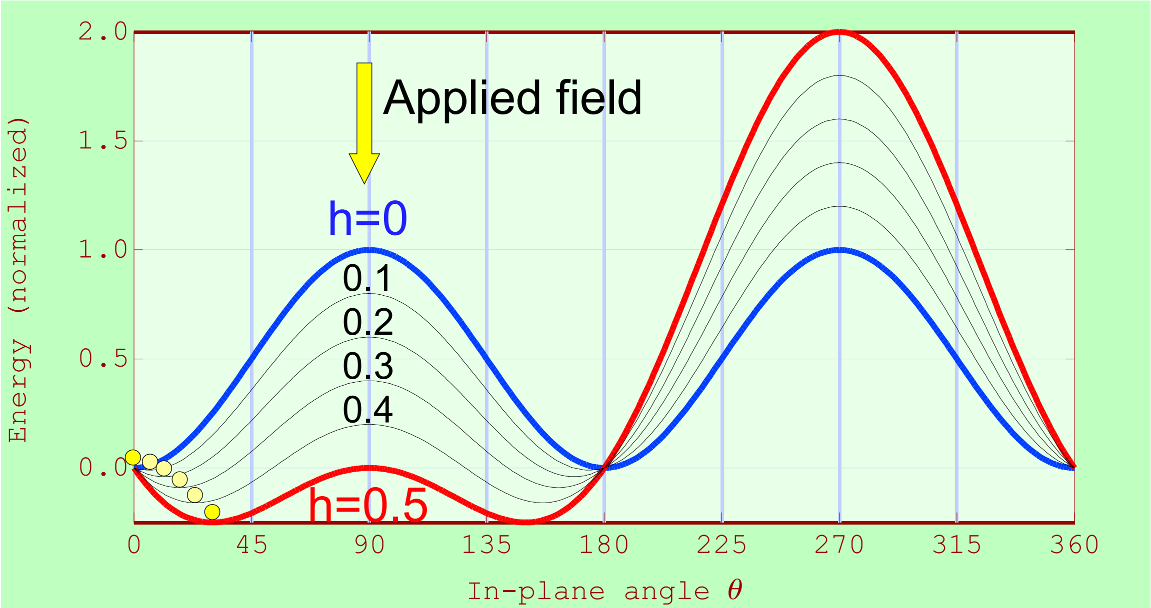


M. Bauer et al., PRB61, 3410 (2000)

Stoner-Wohlfarth versus precessional switching

Stoner-Wohlfarth model: describes processes where the system follows quasistatically energy minima, e.g. with slow field variation

Precessional switching: occurs at short time scales, e.g. when the field is varied rapidly



Relevant time scales

Precession period

$2\pi / \gamma = 35$ ps.T

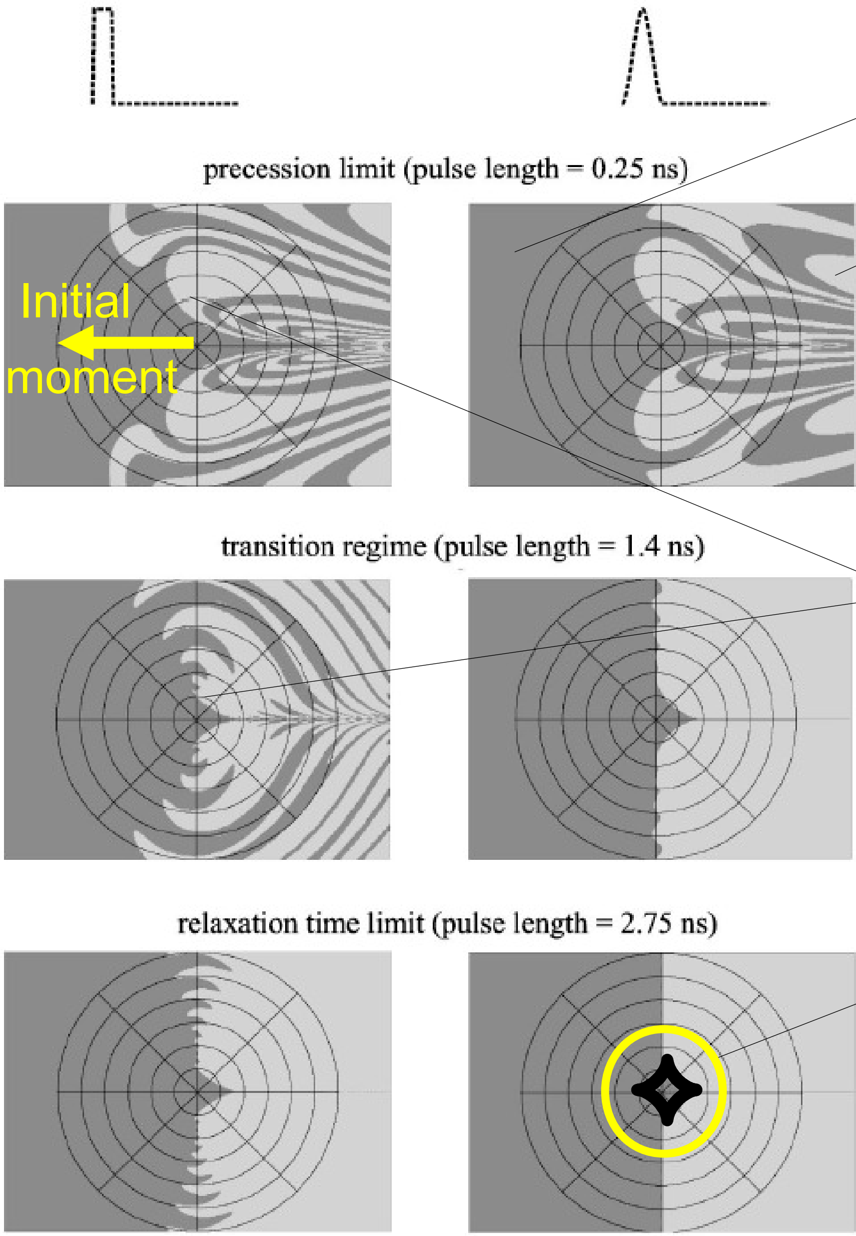
⇒ 25 - 500 ps

Precession damping

$1/(2\pi\alpha)$ per period

($\alpha = 0.01 - 0.5$)

Notice Magnetization reversal allowed for $h>0.5h_K$ (more efficient than classical reversal



Non-switched

Switched

Reversal below the quasistatic value h=1 for hy, and even for m.h>0!

Stoner-Wohlfarth astroid

(quasistatic limit)

M. Bauer et al., PRB61, 3410 (2000)

Conclusion on precessional switching

- Most efficient for field applied perpendicular to the easy axis
- Analytical or near-analytical descriptions
- Beyond the simple example given here: field pulse in one or several directions, finite damping, spin-valves etc.

Analytical models

C. Serpico et al., *Analytical solutions of Landau–Lifshitz equation for precessional switching*, J. Appl. Phys. 93, 6909 (2003)

G. Bertotti et al., *Comparison of analytical solutions of Landau–Lifshitz equation for ''damping'' and ''precessional'' switchings*, J. APpl. Phys. 93, 6811 (2003)

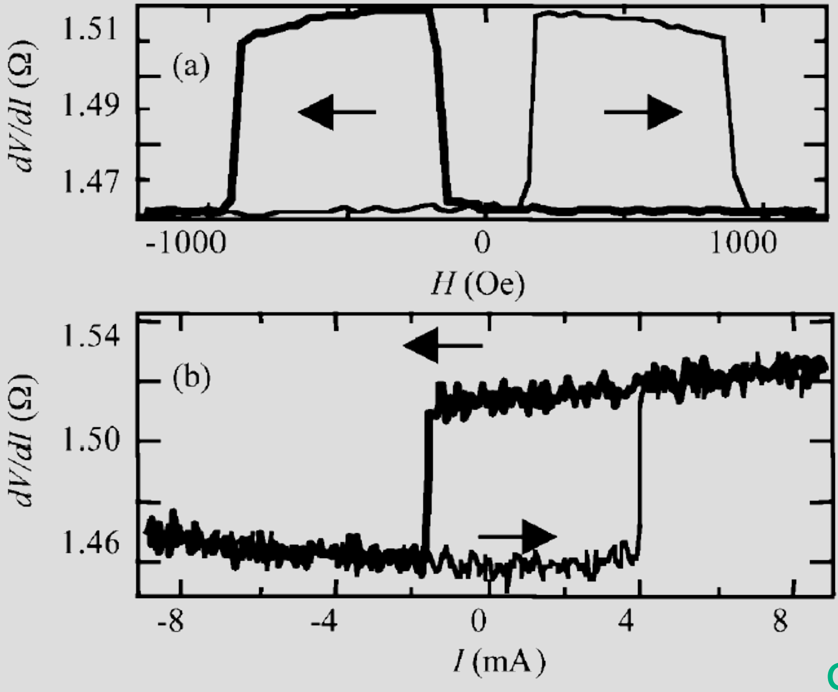
T. Devolder et aL, *Precessional switching of thin nanomagnets: analytical study*, Eur. Phys. J. B 36, 57–64 (2003)

T. Devolder et aL, *Spectral analysis of the precessional switching of the magnetization in an isotropic thin film*, Sol. State Com. 129, 97 (2004)

Basics

Can be viewed as the GMR-reversed effect

J. C. Slonczewski (1996)
L. Berger (1996)



Conventionnal hysteresis loop

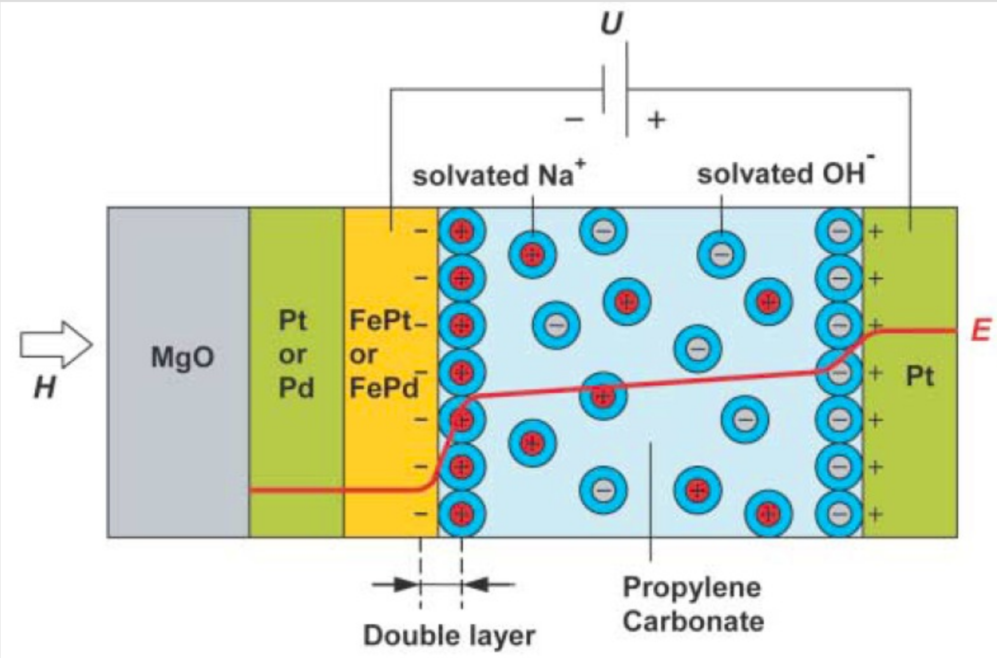
Current-induced magnetization reversal

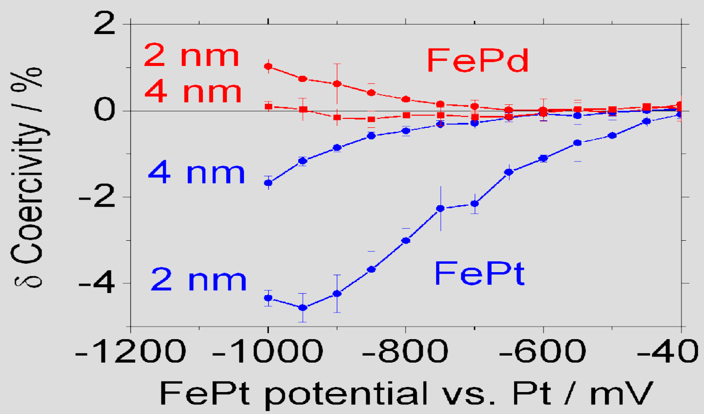
Group Myers et Ralph, Cornell University (2000)

Motivations

- Simplified architectures (MRAMs etc.)
- Fully electronic read/write
- Devices making use of domain wall motion (memory, logic)
- Devices using stationnary GHz oscillators

Electric modification of intrinsic properties





M. Weisheit et al., Science 315, 349 (2007)

See also: magnetic semiconductors, multiferroics etc.

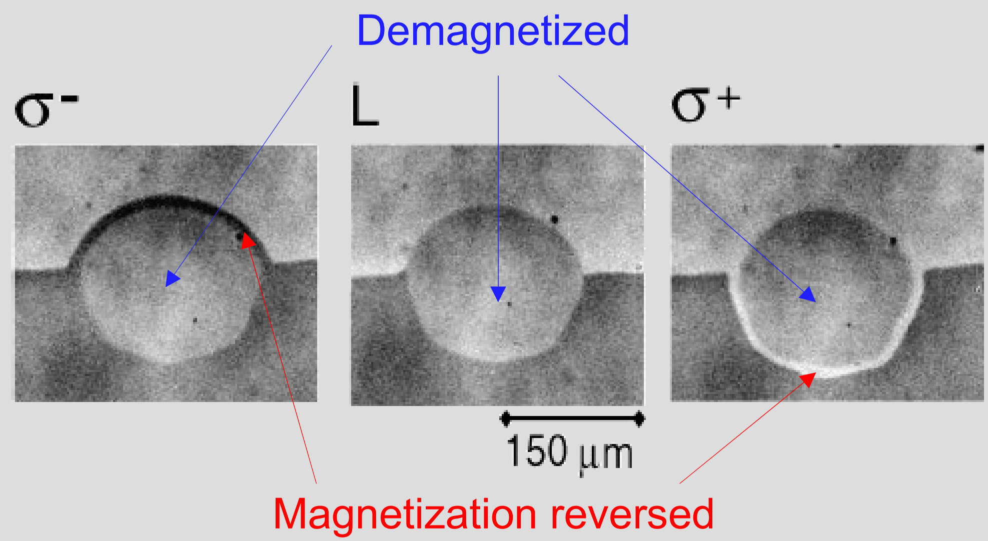
Principle

Combined heating
+ inverse Faraday effect

Magneto-optical material. Tc=500K
$Gd_{22}Fe_{74.6}Co_{3.4}$

Ti:S laser:
λ=800nm; $\Delta\tau$=40fs.

Preliminary: one shot with large power



Local reversal with controlled power

C. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007)