Introduction to nanomagnetism – I. Magnetization reversal

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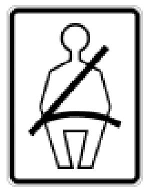
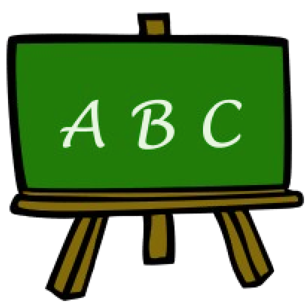
http://neel.cnrs.fr

Common language

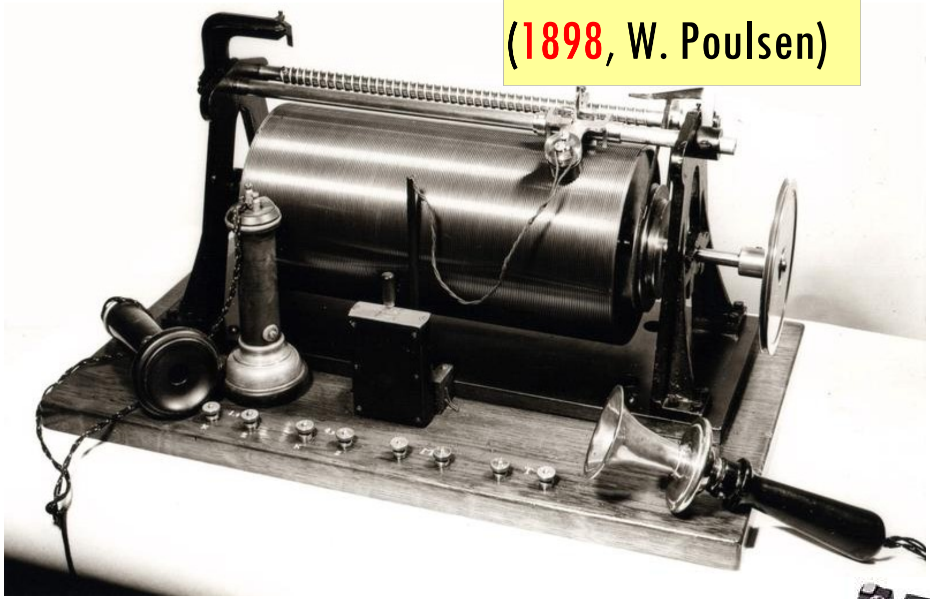


Advanced point: fasten seat belt

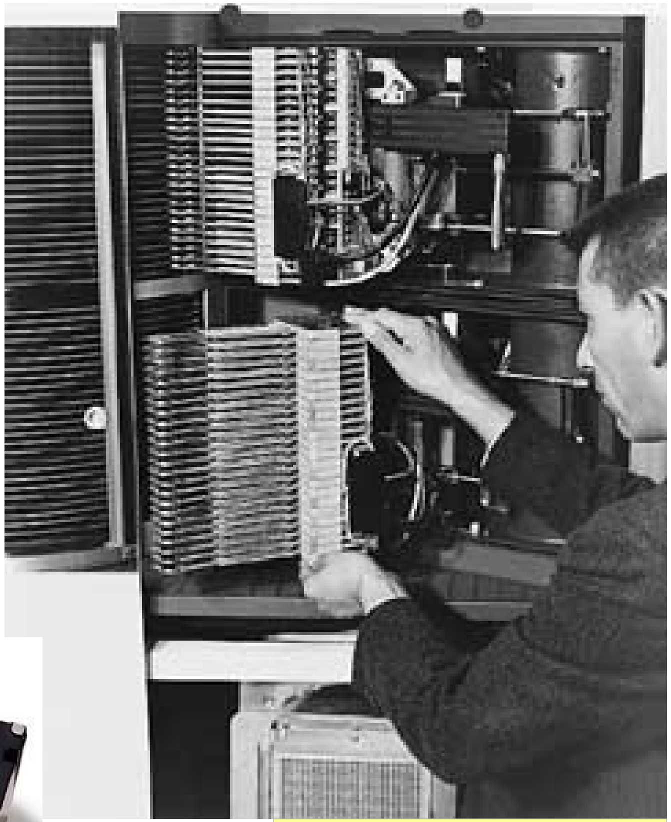
Slippery topic: be cautious



Blackboard explanation



Telegraphone
(1898, W. Poulsen)

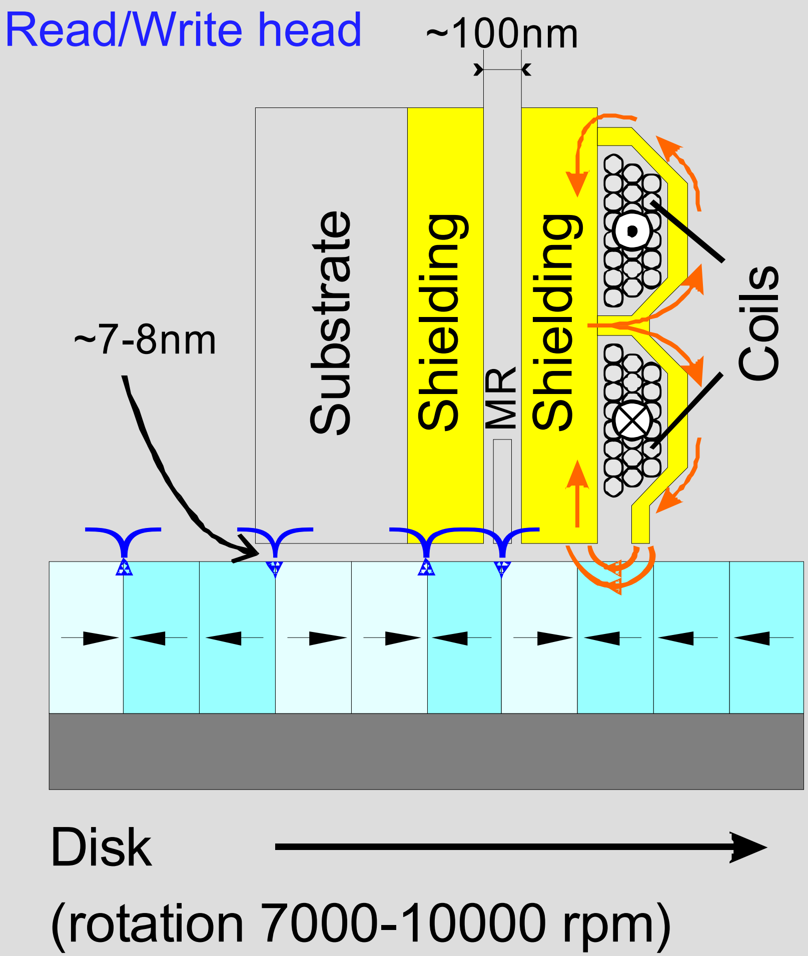


RAMAC (IBM, 1956)
2 kbit/in^2
50 disks Ø 60 cm
Total 5Mo

- Same concept over 100 years
- Technological innovation?
- New science?

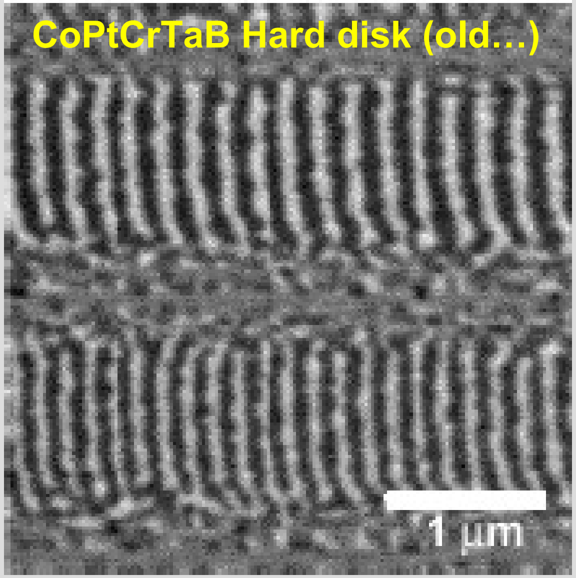
Modern hard disk drive (>1 To)

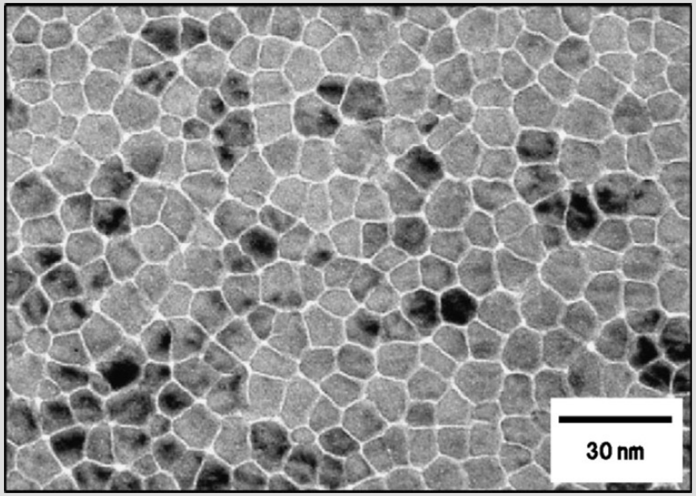
Principle of hard-disks



See lecture: L. Ranno

Magnetic bits

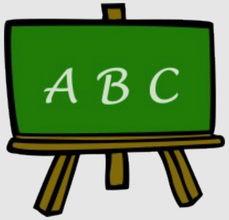




S. Takenoiri, J. Magn. Magn. Mater. 321, 562 (2009)

Fundamental issues for nanomagnetism

⇨ Is a small grain (ferro)magnetic?

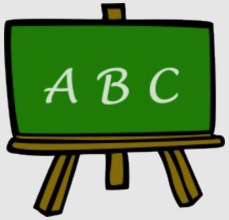


Count number of surface atoms

⇨ Is a small grain stable against thermal fluctuations?

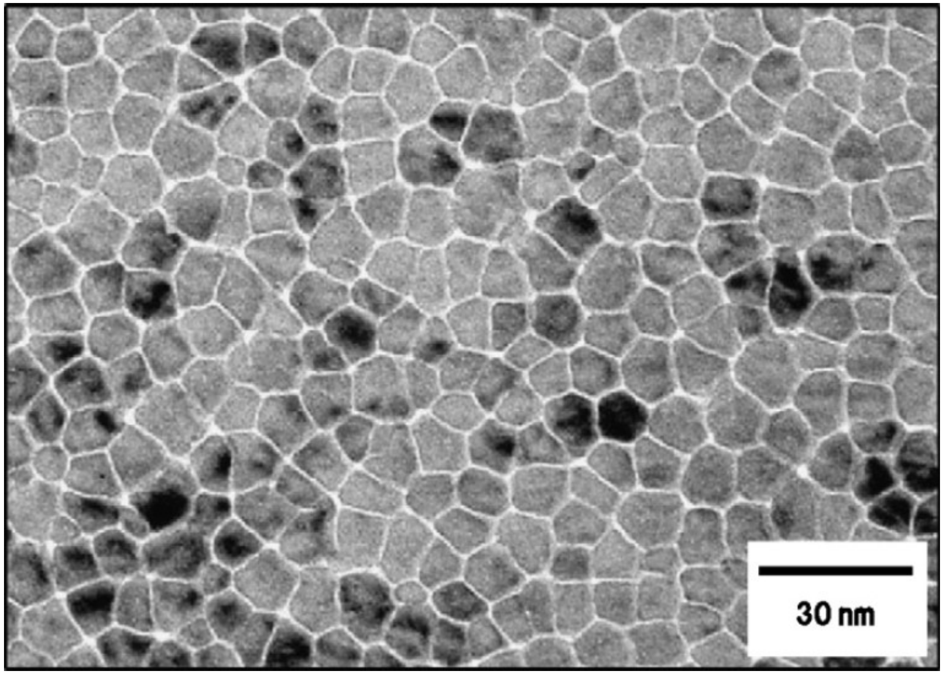
$$k_B T(300\ \mathrm{K}) \approx 4\times 10^{-21}\ \mathrm{J} \approx 25\ \mathrm{meV}$$

$$100\, k_B T(300\ \mathrm{K}) \approx 2.5\ \mathrm{eV}$$



Derive from macroscopic arguments

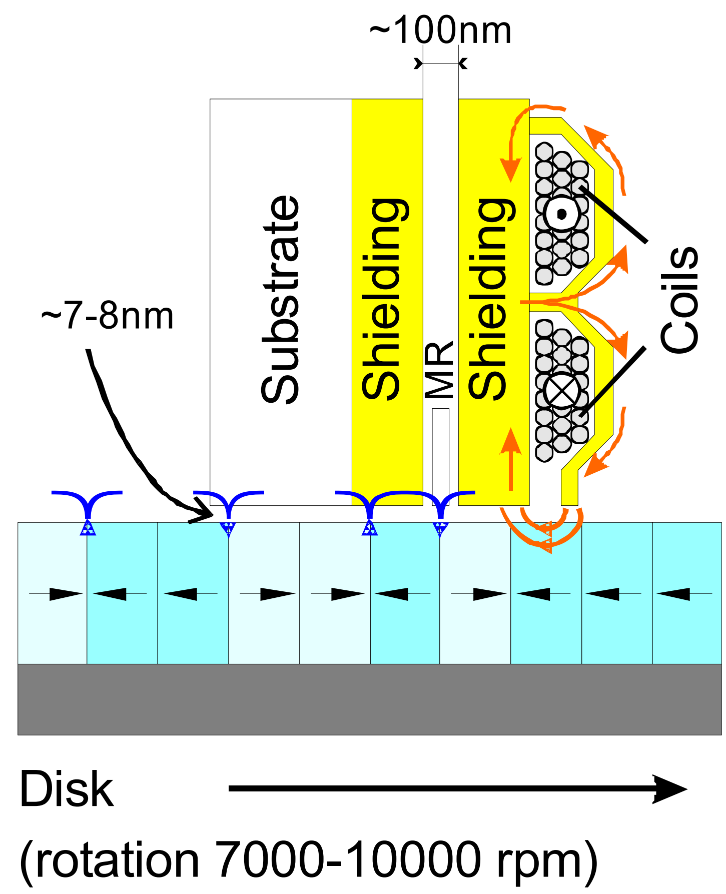
⇨ Are there domains, domain walls?
→ See later on...



Decades-old (yet still modern) topic

The technological need for spin electronics

- How to read information?
  → Convert magnetic information to electric signal
- Field of spin electronics
  - Magneto-transport.
  - Requires nanometer length scales



Official birth: discovery of magneto-resistance

N. M. Baibich, Phys. Rev. Lett. 61, 2472 (1998)
G. Binach, Phys. Rev. B 39, 4828 (1989)

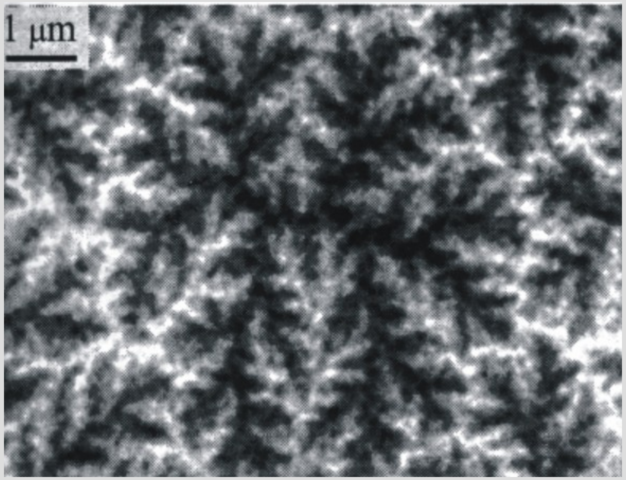
Novel prize 2007: A. Fert & P. Grünberg

See lecture: L. Ranno

Magnetic domains: from macroscopic to small systems

Bulk material

Numerous and complex magnetic domains

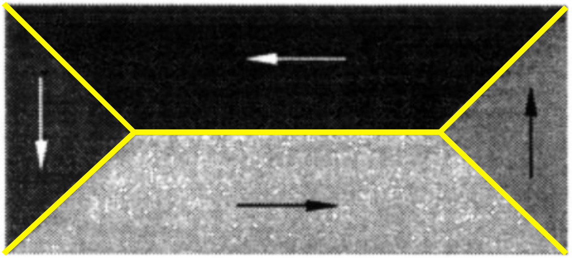


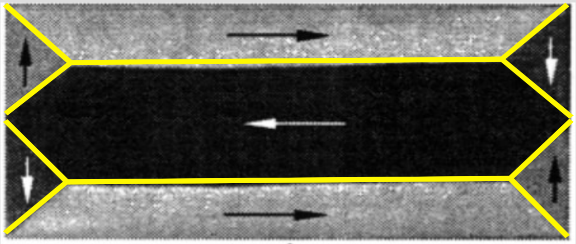
Co(1000) crystal – SEMPA

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape



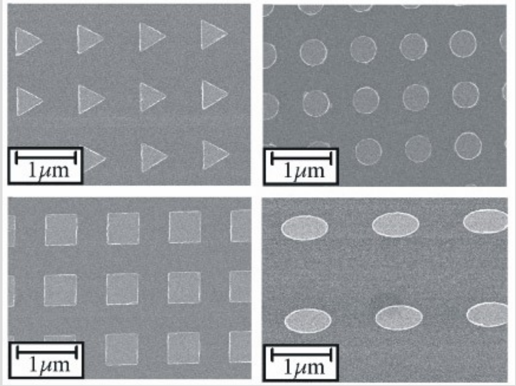


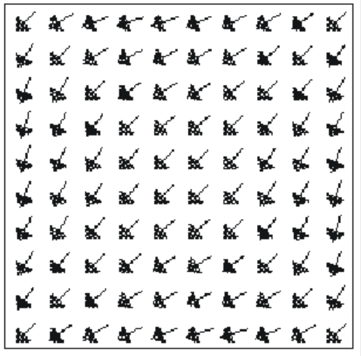
Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





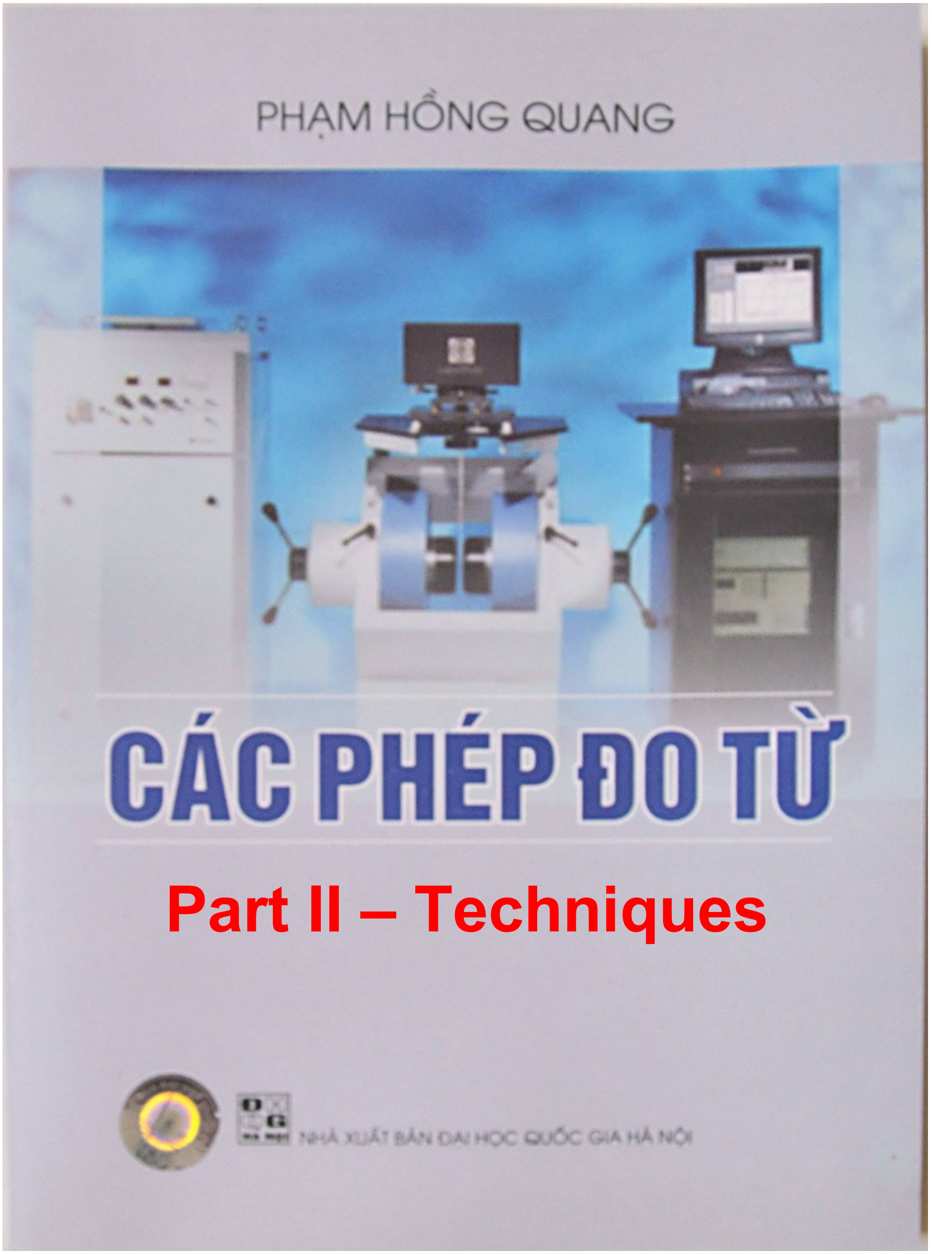
R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

Micromagnetism ~ mesoscopic magnetism

Part I – Magnetization reversal

Part II – Techniques

Part III – Atomic-scale properties


PHẠM HỒNG QUANG
CÁC PHÉP ĐO TỪ
Part II – Techniques
NHÀ XUẤT BẢN ĐẠI HỌC QUỐC GIA HÀ NỘI

Manipulation of magnetic materials:

Application of a magnetic field

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

Spontaneous ≠ **S**aturation

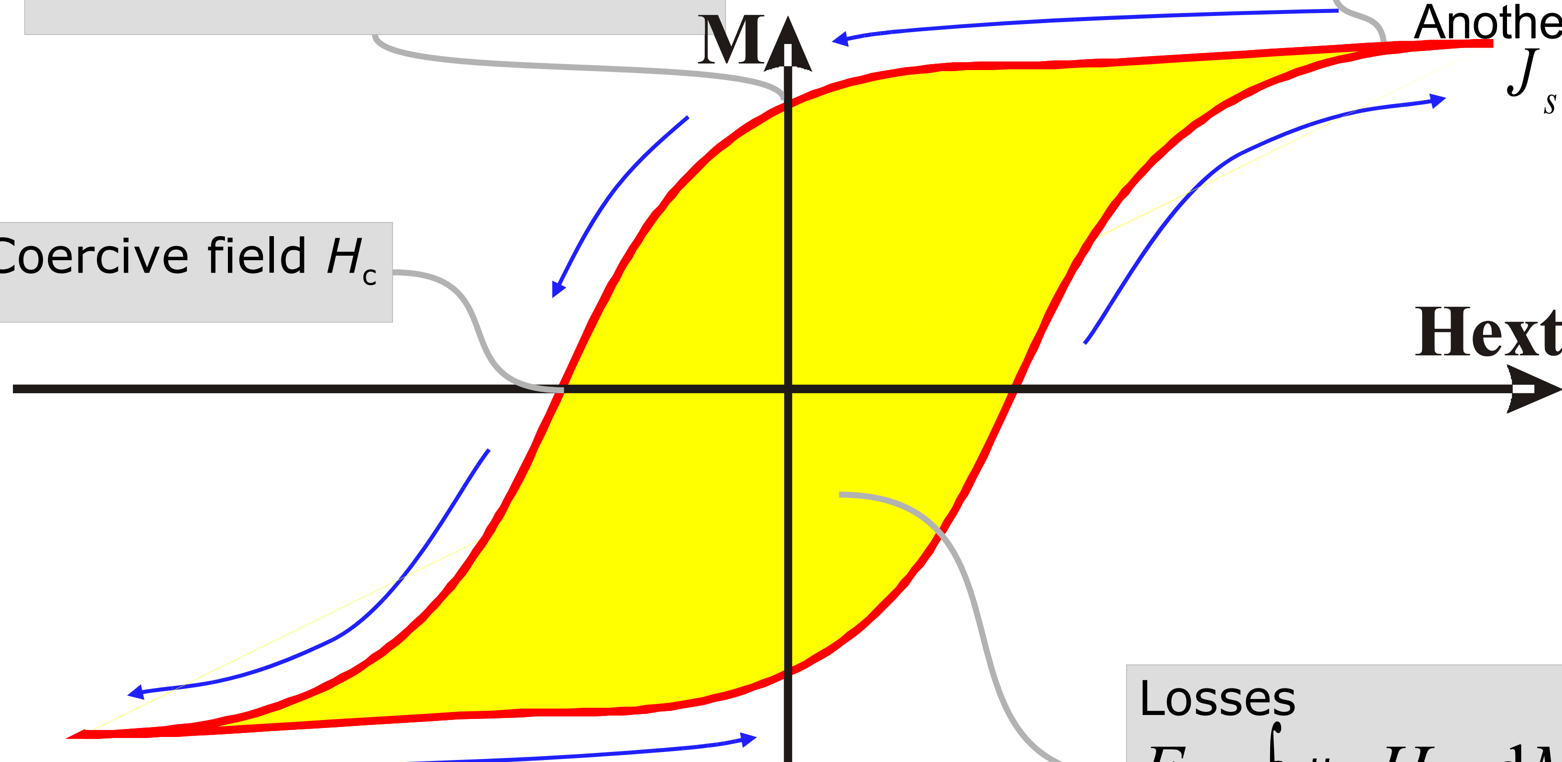
Spontaneous magnetization M_s

Remanent magnetization M_r

Another notation

$J_s = \mu_0 M_s$

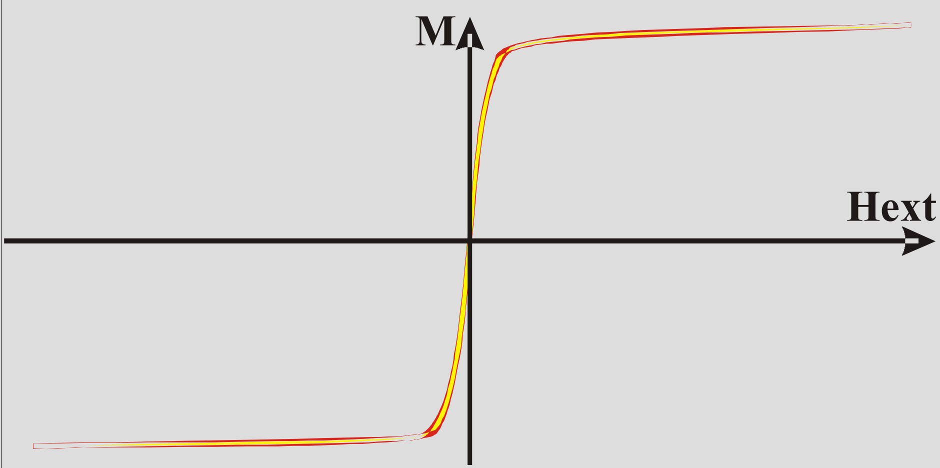
Coercive field H_c



Losses

$E = \oint \mu_0 H_{ext} \mathrm{d}M$

Soft materials

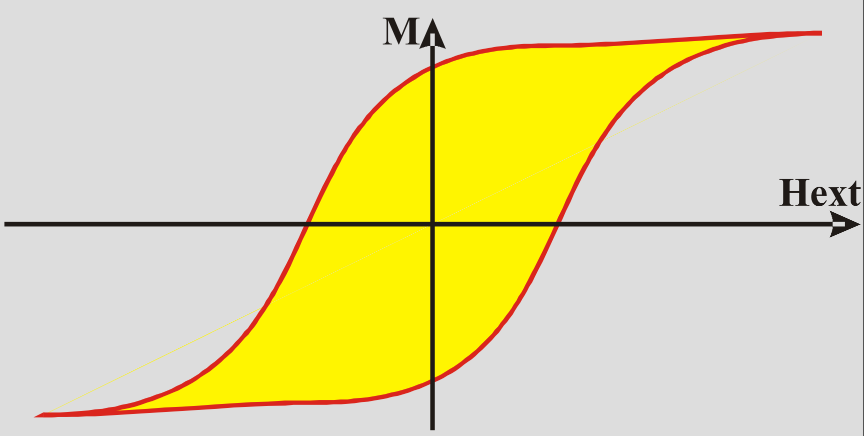


Transformers

Flux guides, sensors

Magnetic shielding

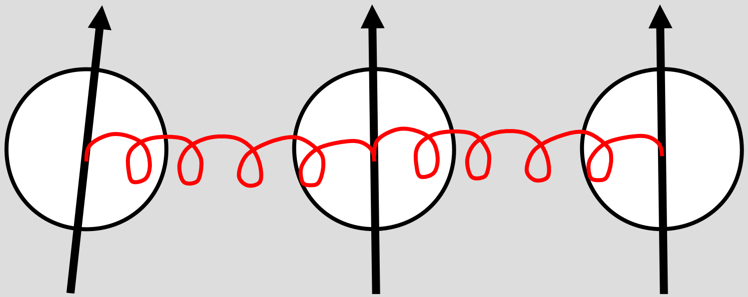
Hard materials



Permanent magnets, motors

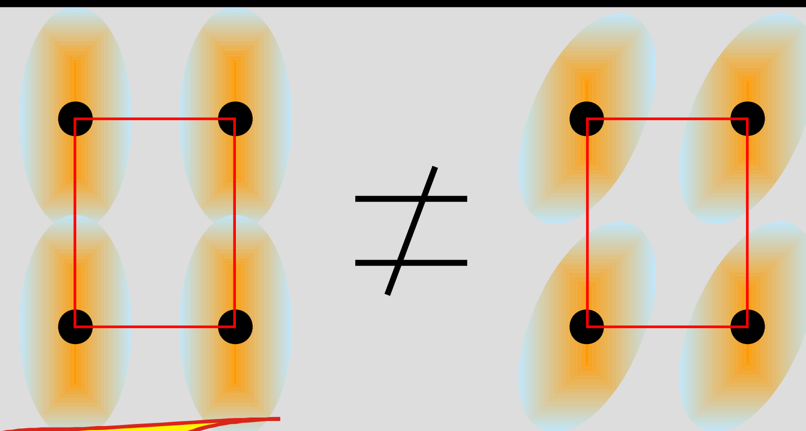
Magnetic recording

Echange energy

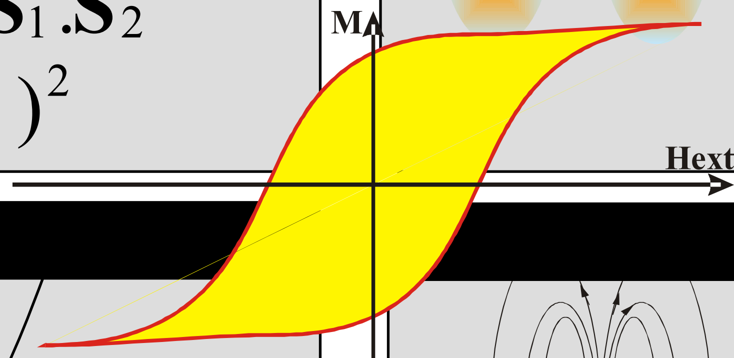


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2 = A(\nabla\theta)^2$$

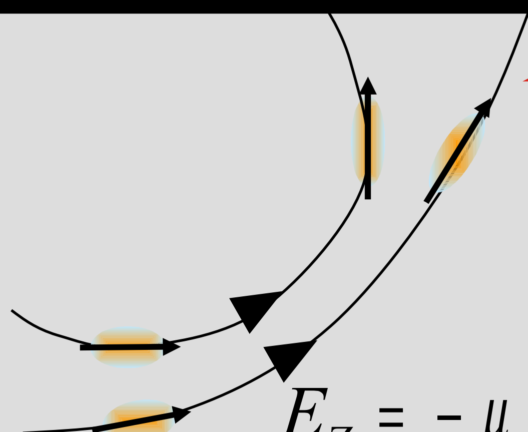
Magnetocrystalline anisotropy energy



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

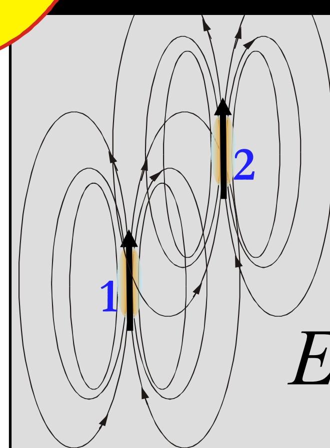


Zeeman energy (enthalpy)



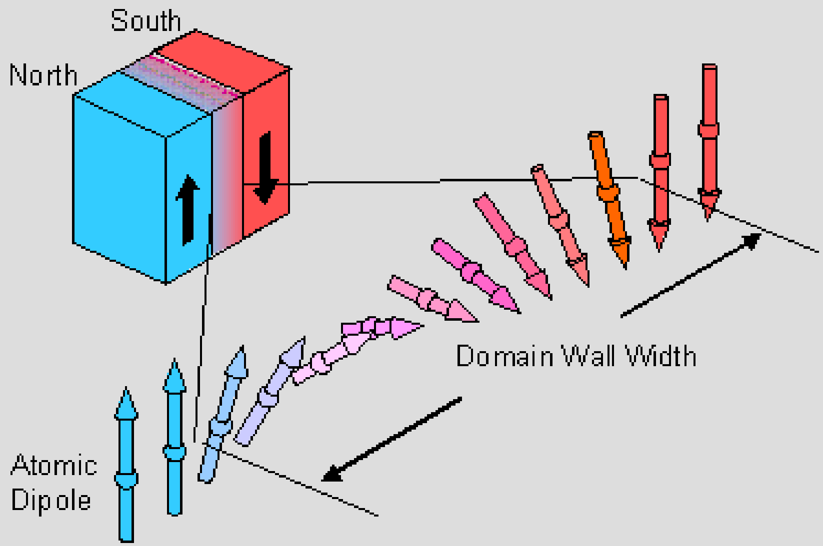
$$E_{\mathrm{Z}} = -\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

Dipolar energy



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

Typical length scale: Domain wall width



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

Exchange → J/m

Anisotropy → $\mathrm{J/m^3}$

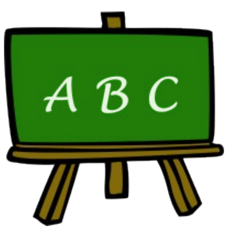
Numerical values

Bloch parameter: $\Delta = \sqrt{A/K}$

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

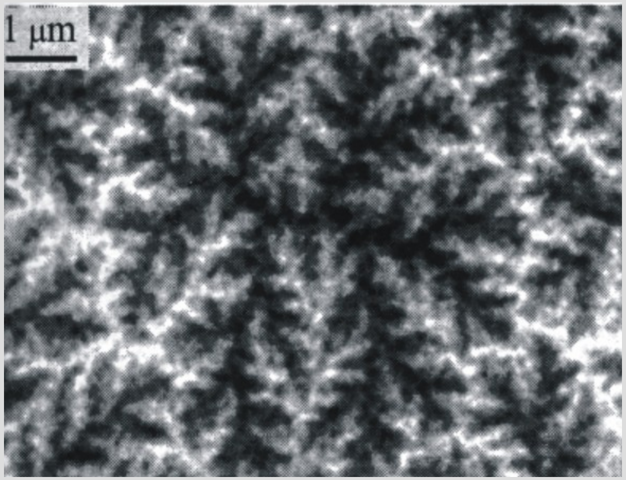
$\Delta \approx 1$ nm → $\Delta \geq 100$ nm

Hard — Soft



Bulk material

Numerous and complex magnetic domains



Co(1000) crystal – SEMPA

A. Hubert, *Magnetic domains*

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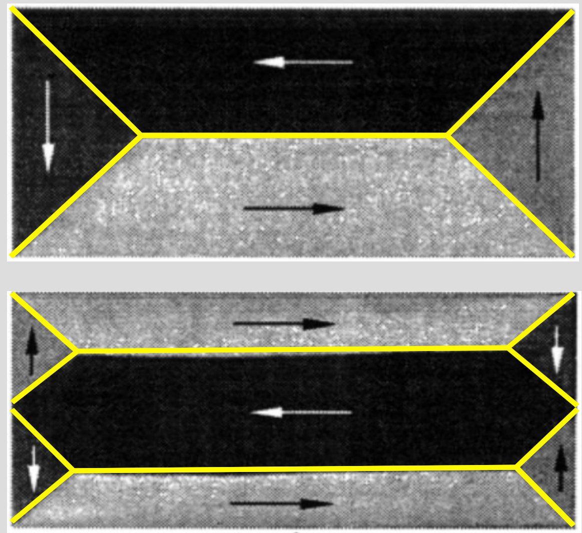

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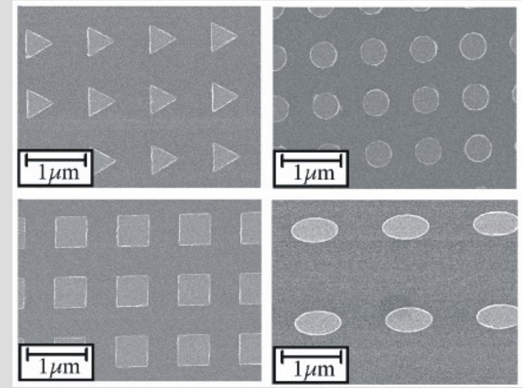
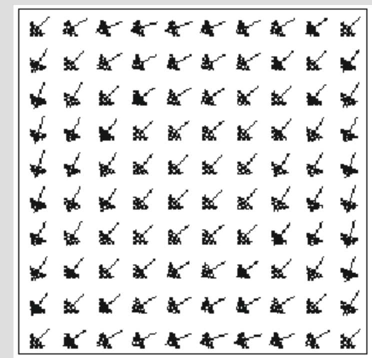
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





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

Nanomagnetism ~ mesoscopic magnetism

Framework

Approximation: $\partial_{\mathbf{r}}\mathbf{m}=\mathbf{o}$ (uniform magnetization)
(strong!)

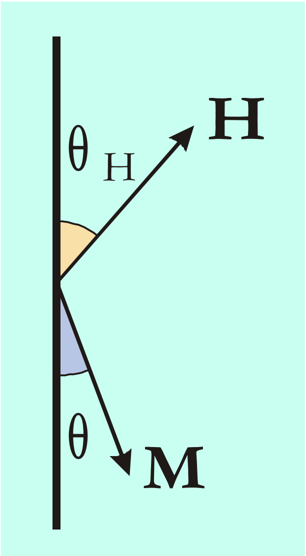
$$\mathcal{E}=EV=V\left[K_{\mathrm{eff}}\sin^2\theta-\mu_0 M_{\mathrm{S}} H\cos(\theta-\theta_H)\right]$$

$$K_{\mathrm{eff}}=K_{\mathrm{mc}}+K_{\mathrm{d}}$$

Dimensionless units:

$$e=\mathcal{E}/KV$$
$$h=H/H_{\mathrm{a}}$$
$$H_{\mathrm{a}}=2\mathrm{K}/\mu_0 M_{\mathrm{S}}$$

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

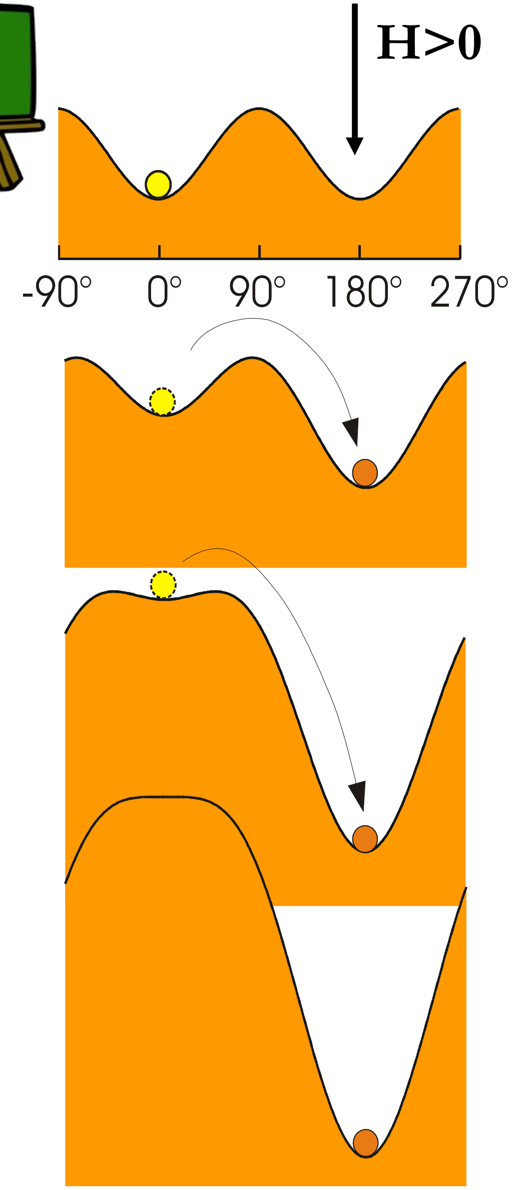


L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

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

Example for $\theta_H = 180°$ → $e = \sin^2\theta + 2h\cos\theta$



Equilibrium states

$$\partial_\theta e = 2\sin\theta(\cos\theta - h) \qquad \partial_\theta e = 0 \Longrightarrow \left| \begin{array}{l} \cos\theta_m = h \\ \theta \equiv 0[\pi] \end{array} \right.$$

Stability

$$\begin{aligned} \partial_{\theta\theta} e &= 2\cos 2\theta - 2h\cos\theta \\ &= 4\cos^2\theta - 2 - 2h\cos\theta \end{aligned}$$

$$\begin{aligned} \partial_{\theta\theta} e(0) &= 2(1-h) \\ \partial_{\theta\theta} e(\theta_m) &= 2(h^2-1) \\ \partial_{\theta\theta} e(\pi) &= 2(1+h) \end{aligned}$$

Energy barrier

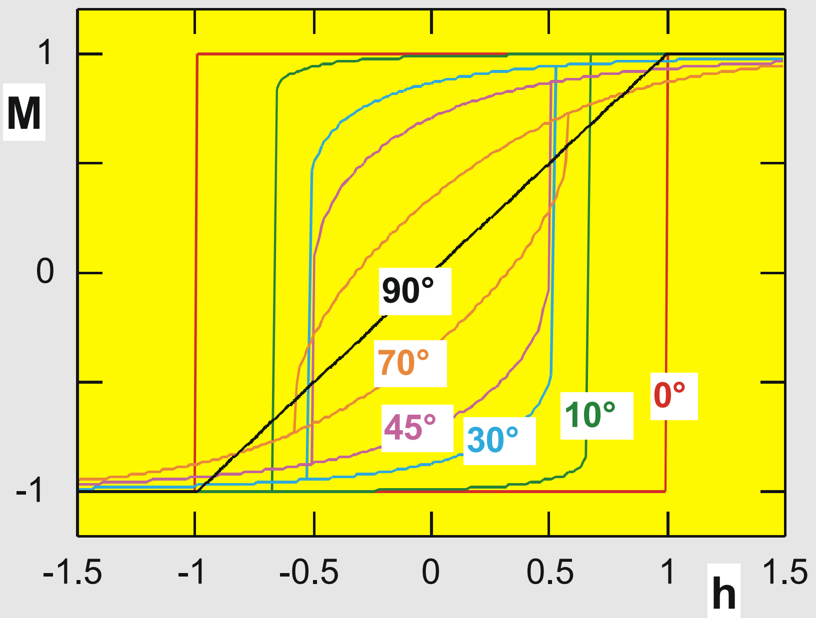
$$\begin{aligned} \Delta e &= e(\theta_{max}) - e(0) \\ &= 1 - h^2 + 2h^2 - 2h \\ &= (1-h)^2 \end{aligned}$$

Switching

$$\begin{aligned} h &= 1 \\ H &= H_a = 2K/\mu_0 M_s \end{aligned}$$

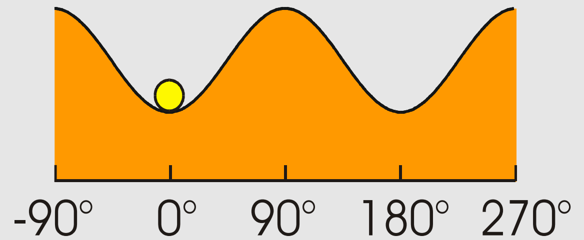
$(1-h)^\alpha$ with exponent 1.5 in general

Hysteresis loops



$\theta_H=0$ ⇨ Easy axis of magnetization

$\theta_H=\pi/2$ ⇨ Hard axis of magnetization



Switching field = Reversal field

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

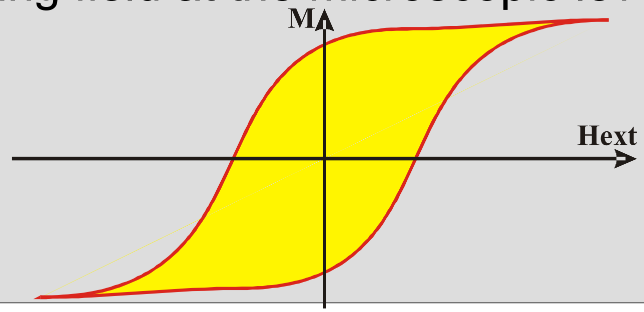
Can be measured only in single particles.

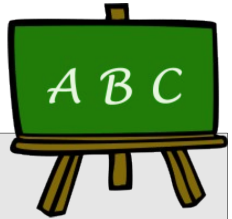
Coercive field

The field for which $\mathbf{M.H}=0$ $(\theta=\theta_H\pm\pi/2)$

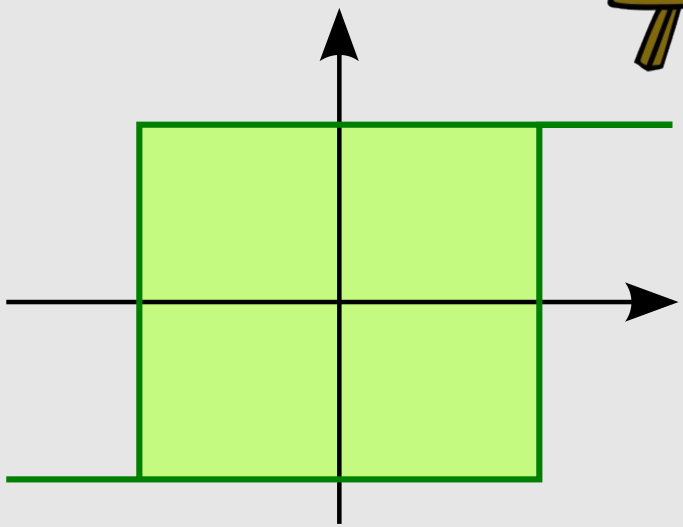
Used to characterize real materials (large number of 'particles').

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





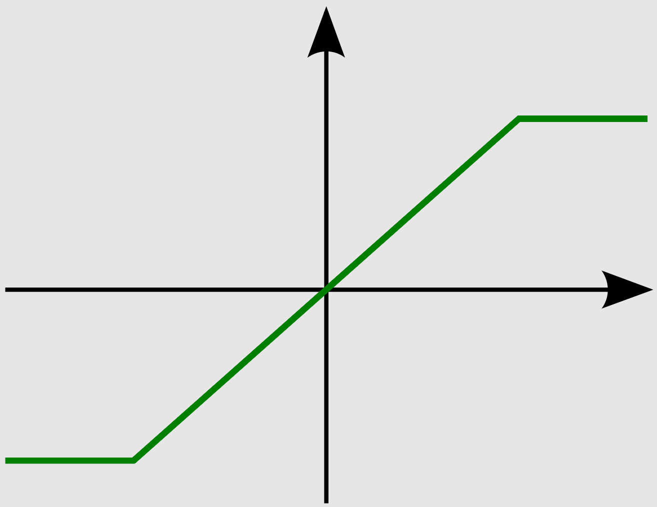
Easy axis



- High +/- remanence
- Coercivity

Memory, permanent magnet etc.

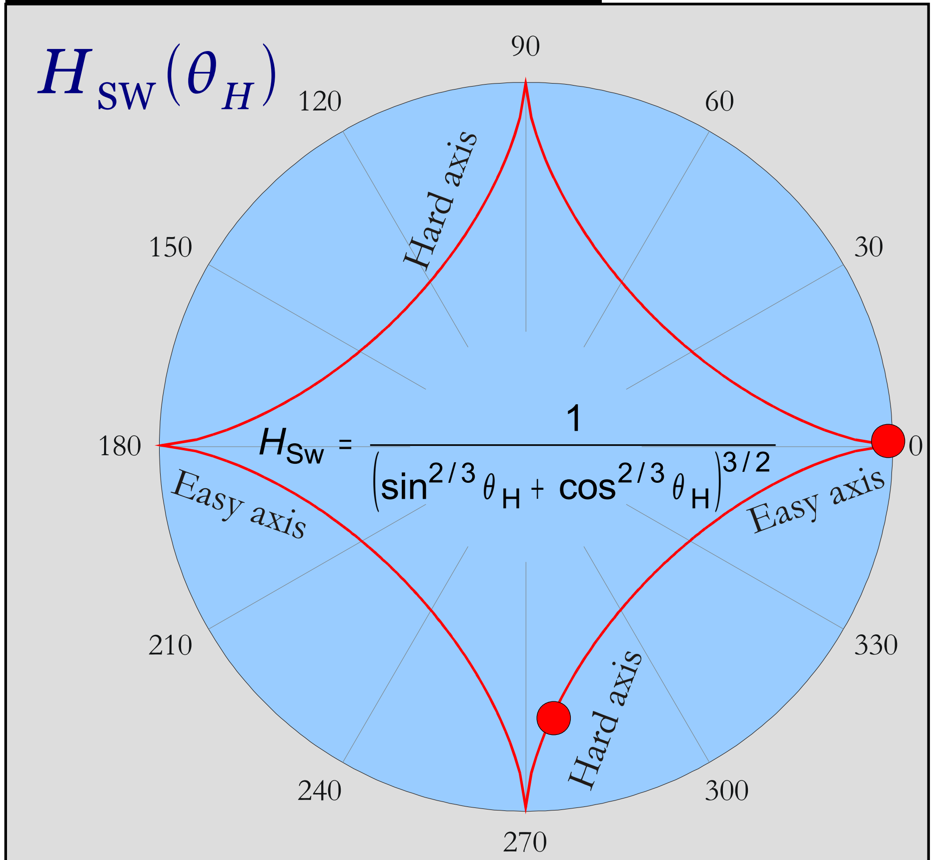
Hard axis



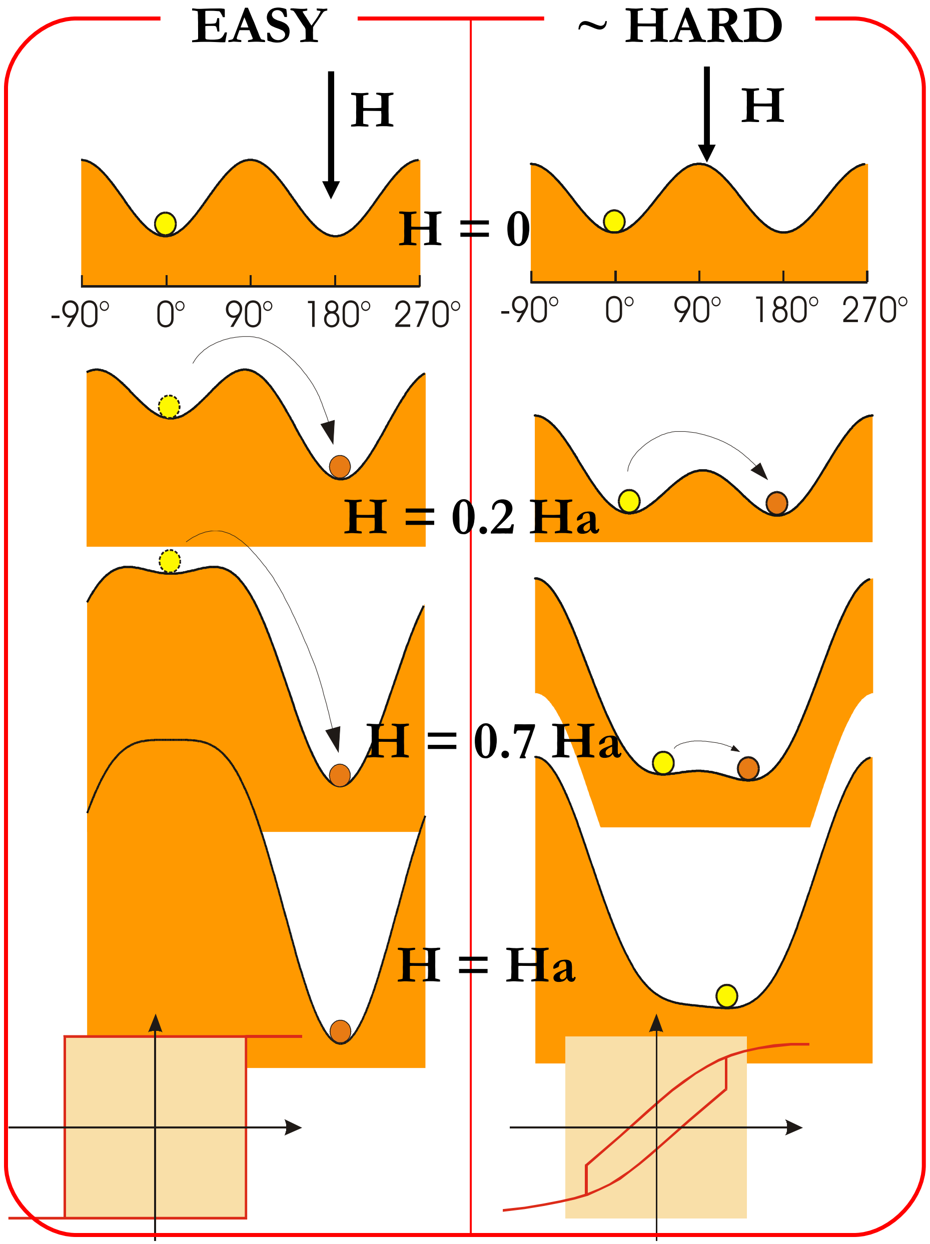
- Reversibility
- Linearity

Sensor, shielding etc.

'Astroid' curve: switching field



➢ $H_{SW}(\theta_H)$ is one signature of reversal modes

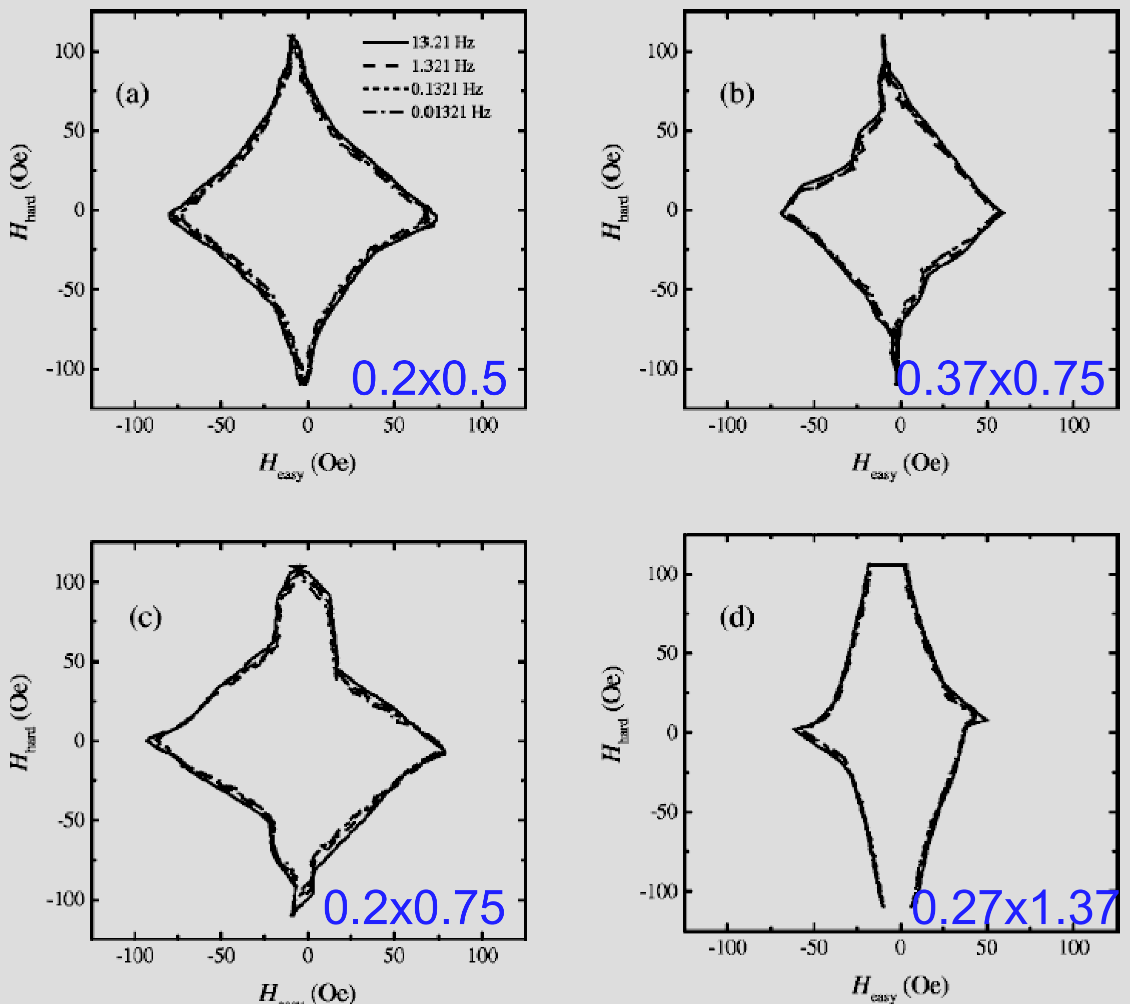


J. C. Slonczewski, Research Memo RM 003.111.224, IBM Research Center (1956)

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

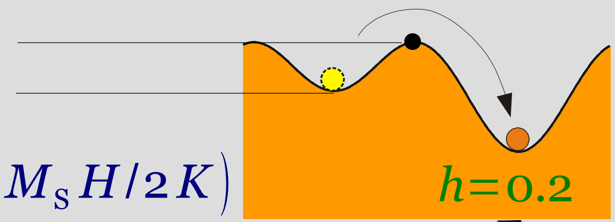
- The simplest model
- Fails for most systems because they are too large: **apply model with great care!..**
- Hc<<Ha for most large systems (thin films, bulk): **do not use Hc to estimate K!**

Early known as **Brown's paradox**

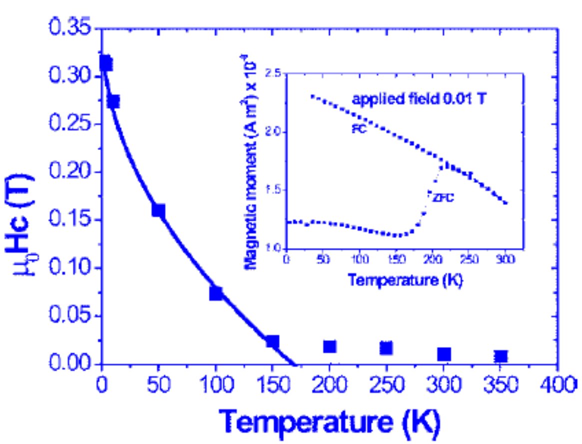
Barrier height

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

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



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



Thermal activation

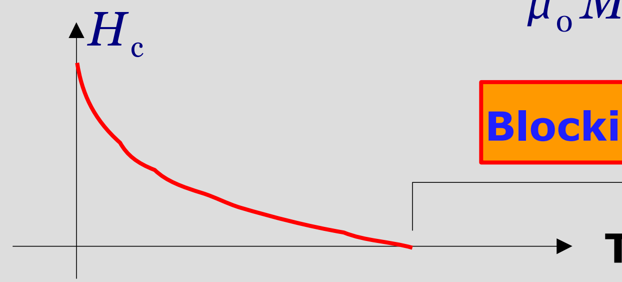
Brown, Phys.Rev.130, 1677 (1963)

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

$$\tau_0 \approx 10^{-10}\ \mathrm{s}$$

Lab measurement : $\tau \approx 1\ \mathrm{s} \Longrightarrow \Delta \mathcal{E} \approx 25 k_B T$

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



Blocking temperature

$$T_b \approx KV / 25 k_B$$

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 : $\tau \approx 10^9\ \mathrm{s}$ $\quad KV_b \approx 40-60 k_B T$

Formalism for superparamagnetism

C. P. Bean & J. D. Livingston, J. Appl. Phys. 30, S120 (1959)

Energy

$$E = KV.f(\theta,\varphi) - \mu_0\mu H$$

$$\beta E = d.f(\theta,\varphi) - h\mu$$

Partition function

$$Z = \sum \exp(-\beta E)$$

Average moment

$$<\mu> = \frac{1}{\beta\mu_0 Z}\frac{\partial Z}{\partial H}$$

Isotropic case

$$Z = \int_{-M}^{M} \exp(-\beta E)\mathrm{d}\mu$$

Note: equivalent to integration over solid angle

$$<\mu> = M\left[\mathrm{cotanh}(x) - 1/x\right]$$

Langevin function

Infinite anisotropy

$$Z = \exp(\beta\mu_0 MH) + \exp(-\beta\mu_0 MH)$$

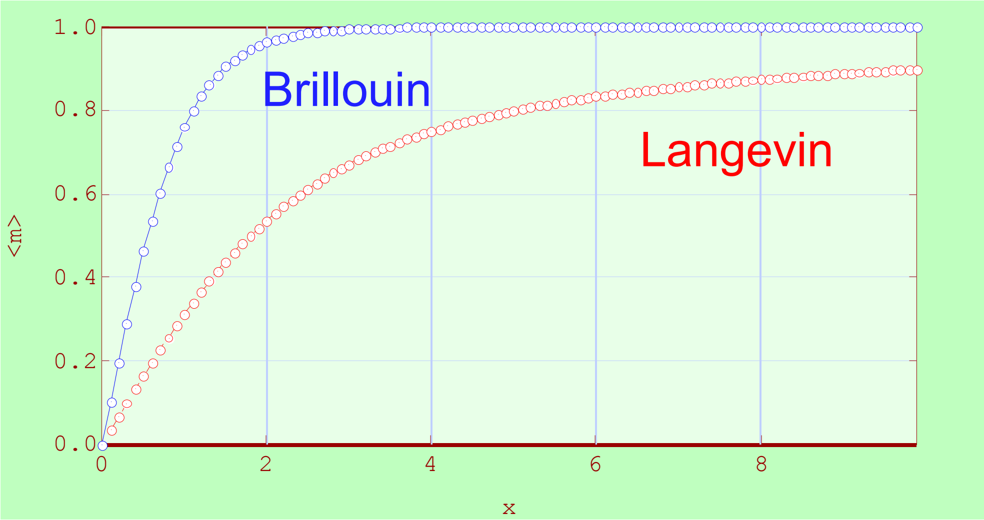
$$<\mu> = M.\tanh(x)$$

Brillouin ½ function

Note:

Use the moment M of the particule, not spin ½ .

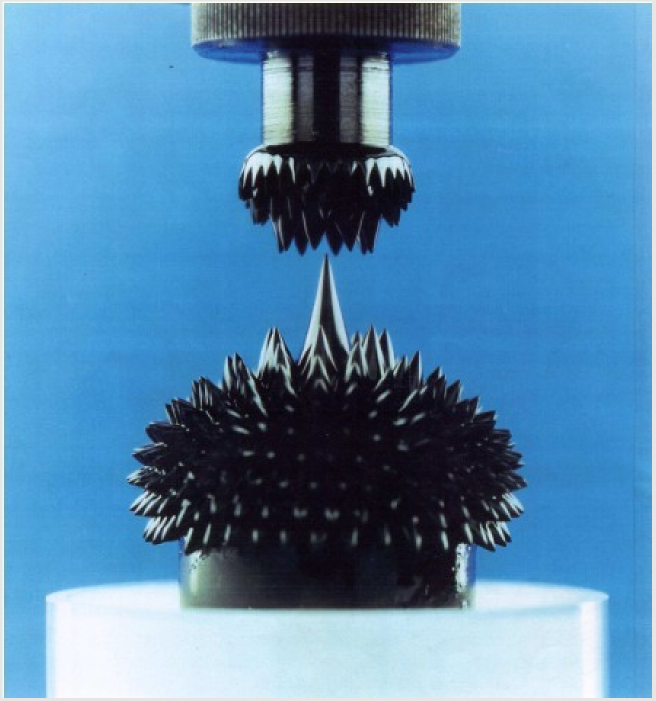
$$x = \beta\mu_0 MH$$



Ferrofluids

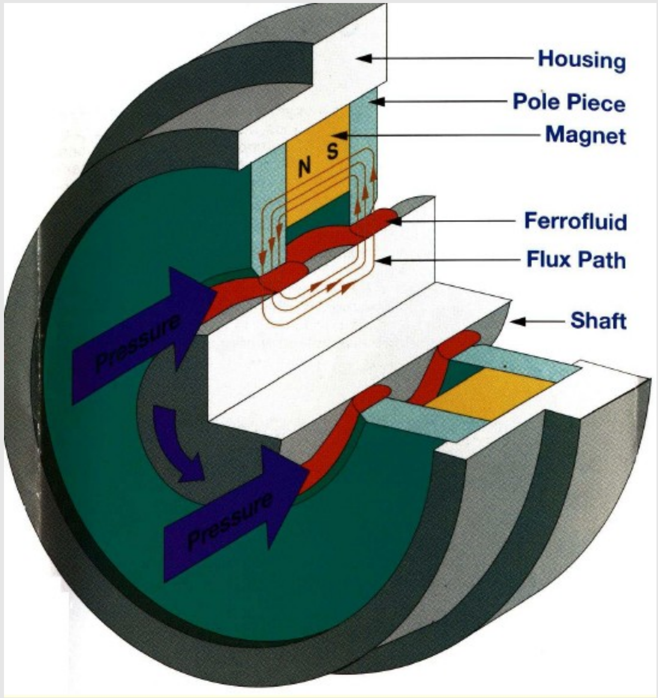
⇨ Principle

Surfactant-coated nanoparticles, preferably superparamagnetic
→ Avoid agglomeration of the particles
→ Fluid and polarizable



⇨ Example of use

Seals for rotating parts



R. E. Rosensweig, Magnetic fluid seals, US patent 3,260,584 (1971)

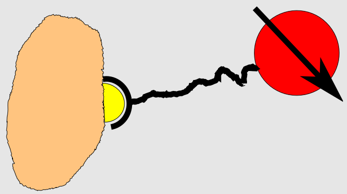
http://esm.neel.cnrs.fr/2007-cluj/slides/vekas-slides.pdf

Health and biology

Beads = coated nanoparticles, preferably superparamagnetic
→ Avoid agglomeration of the particles

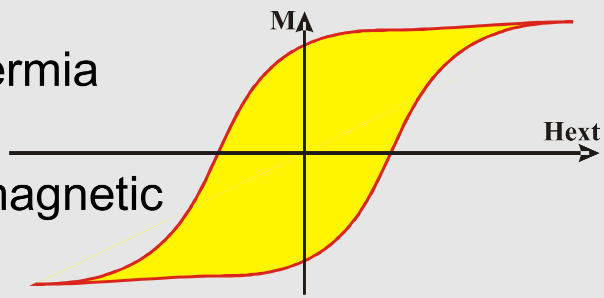
⇨ Cell sorting

$$\mathbf{F} = \nabla \boldsymbol{\mu}.\mathbf{B}$$



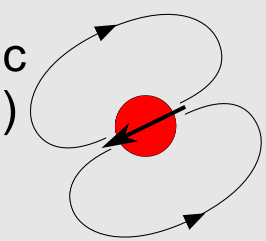
⇨ Hyperthermia

Use ac magnetic field



$$H_c = H_{c,0}\left(1 - \sqrt{\frac{\ln(\tau/\tau_0)k_B T}{KV}}\right)$$

⇨ Contrast agent in Magnetic Resonance Imaging (MRI)



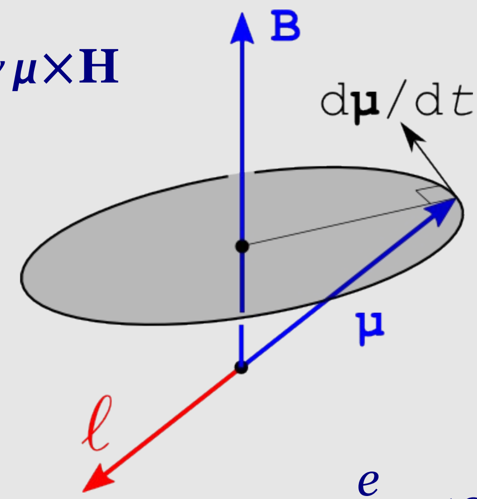
RAM (radar absorbing materials)

⇨ Principle

Absorbs energy at a well-defined frequency (ferromagnetic resonance)

$$\frac{d\boldsymbol{\ell}}{dt} = \boldsymbol{\Gamma} = \mu_0 \boldsymbol{\mu} \times \mathbf{H} = \mu_0 \gamma \boldsymbol{\ell} \times \mathbf{H}$$

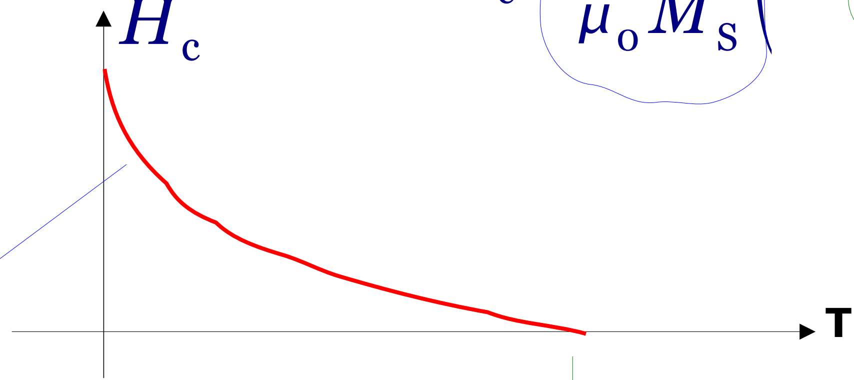
$$\frac{d\boldsymbol{\mu}}{dt} = \mu_0 \gamma \boldsymbol{\mu} \times \mathbf{H}$$



$$\gamma = -g_J \frac{e}{2m_e} < 0$$

$$\gamma_s / 2\pi \approx 28\ \mathrm{GHz/T}$$

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



Estimate for K

If K known,
estimate for V

Magnetization

Magnetization vector **M**

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

May vary over time and space.

Modulus is constant
(hypothesis in micromagnetism)

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

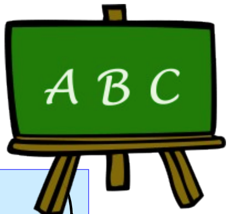
Mean-field approach possible: $M_s = M_s(T)$

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

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.

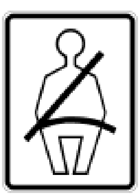
Bottle-neck of micromagnetic calculations

Usefull theorem for finite samples:

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

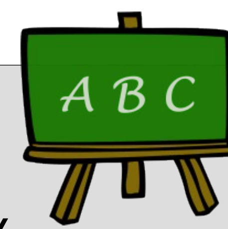
⇨ $\mathcal{E}$ is always positive

Significance of (BHmax) for permanent magnets



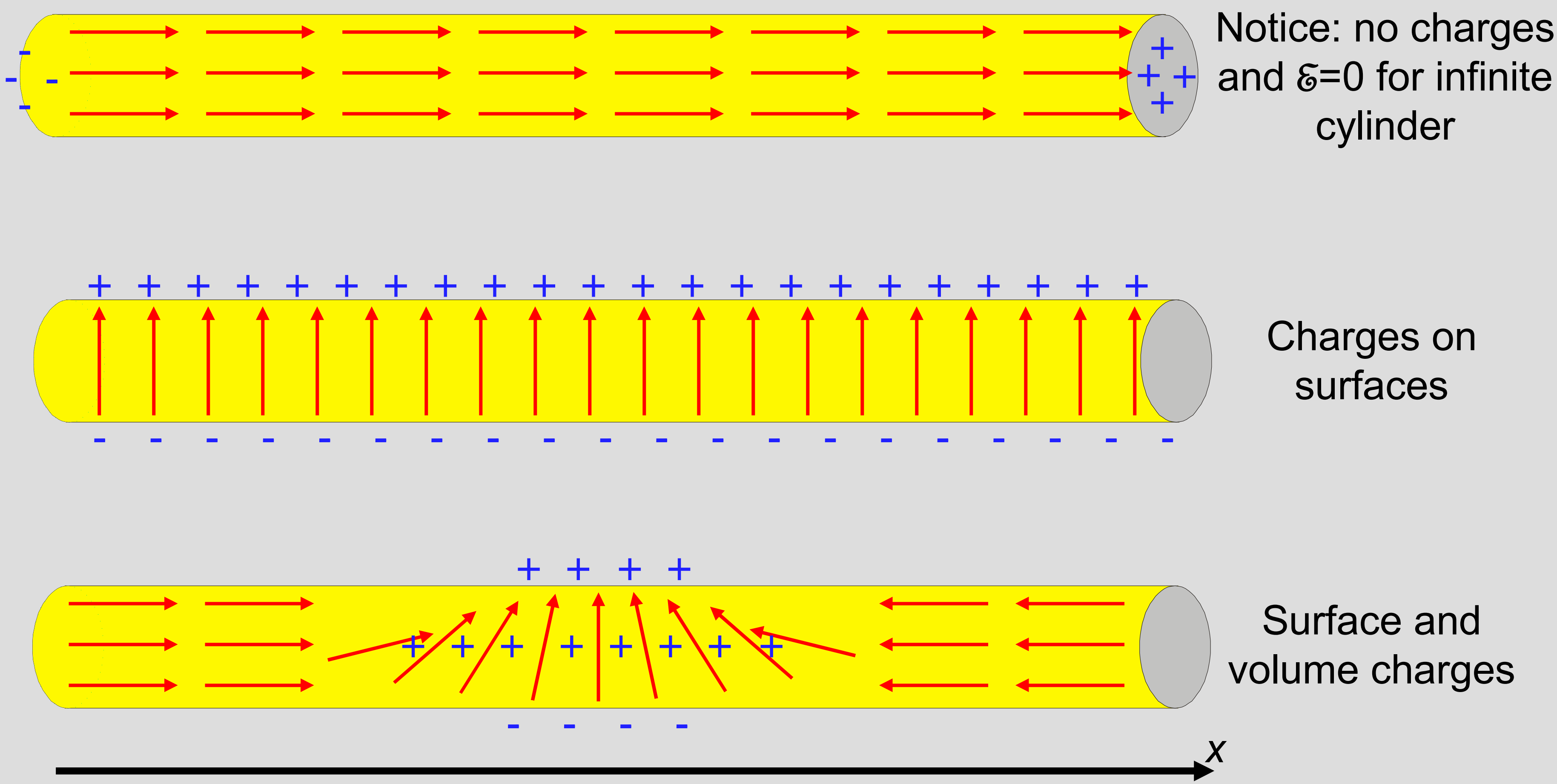
$$-\frac{1}{2}\mu_0 \iiint_{\text{sample}} (\mathbf{M}+\mathbf{H}_\mathrm{d}).\mathbf{H}_\mathrm{d}.\mathrm{d}V = \boxed{-\frac{1}{2}\mu_0 \iiint_{\text{sample}} \mathbf{B}.\mathbf{H}_\mathrm{d}.\mathrm{d}V}$$

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



Energy available outside the sample, ie usefull for devices

Examples of magnetic charges



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

Reminder

Density of surface charges

$\sigma(\mathbf{r}) = -M_s\mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$

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

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

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

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

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

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

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

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

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

N is a positive second-order tensor

…and can be defined and diagonalized for any sample shape

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

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

$$< H_{\mathrm{d},i}(\mathbf{r}) > = -M_\mathrm{s} N_i$$ ← 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

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

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

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

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

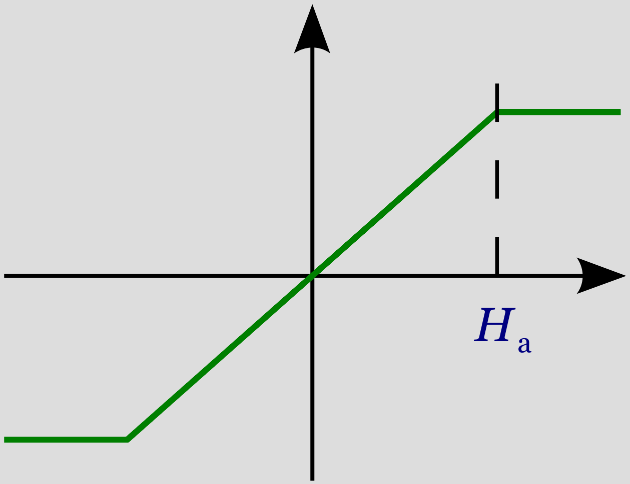
J. A. Osborn, Phys. Rev. 67, 351 (1945).

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

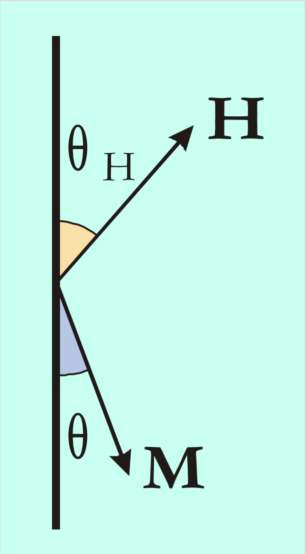
More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**

Magnetization loop of a macrospin along a hard axis

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



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



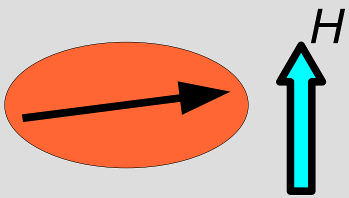
$$K = N_i K_d$$

with: $K_d = \frac{1}{2}\mu_0 M_s^2$

$$\Rightarrow H_a = 2K/\mu_0 M_s = N_i M_s$$

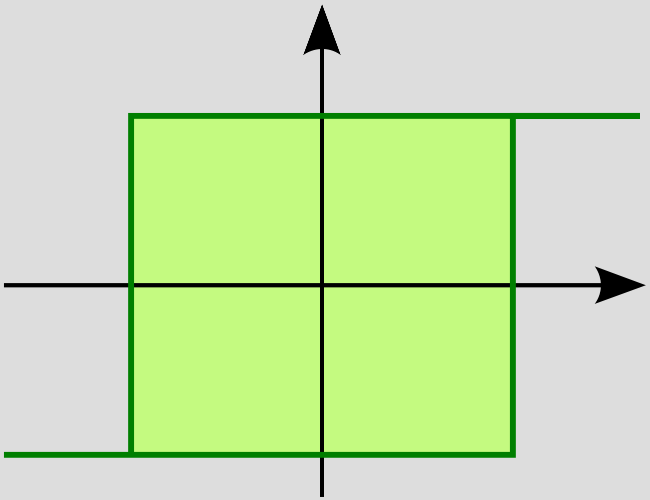
Example for sensor

- Large Ni → Large linear range → Low susceptibility & sensitivity
- Small Ni → High susceptibility & sensitivity → Small linear range



Magnetization loop of a macrospin along an easy axis

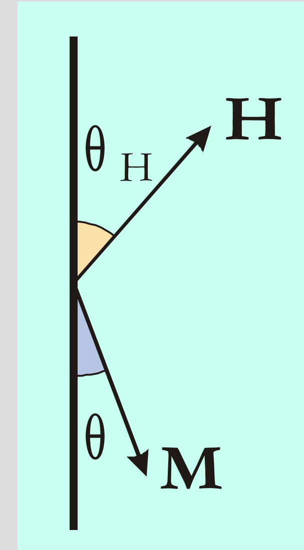
$$e = \sin^2\theta - 2h\cos(\theta - \theta_H)$$



Easy axis: $\theta_H = \pi$

$$K = N_i K_\mathrm{d}$$

with: $K_\mathrm{d} = \frac{1}{2}\mu_0 M_\mathrm{s}^2$

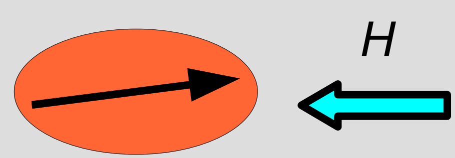


Reversal field $H_\mathrm{c} \approx 2\mathrm{K}/\mu_0 M_\mathrm{s} \approx N_i M_\mathrm{s}$

Thermal stability $\Delta\mathcal{E} = KV = k_\mathrm{B} T \ln(\tau/\tau_0)$

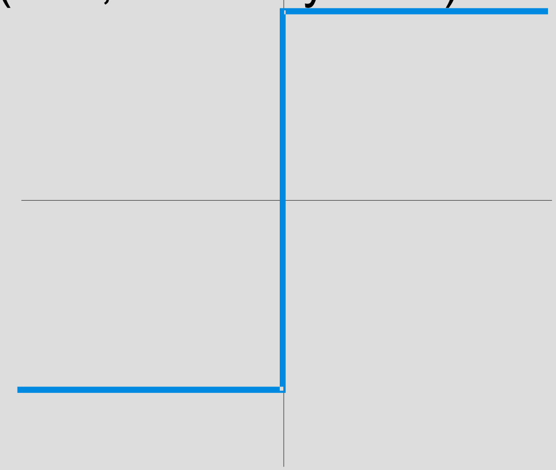
Example for memory

- Small Ni → Low switching field (low power!)
- Large Ni → Good thermal stability



Ideally soft

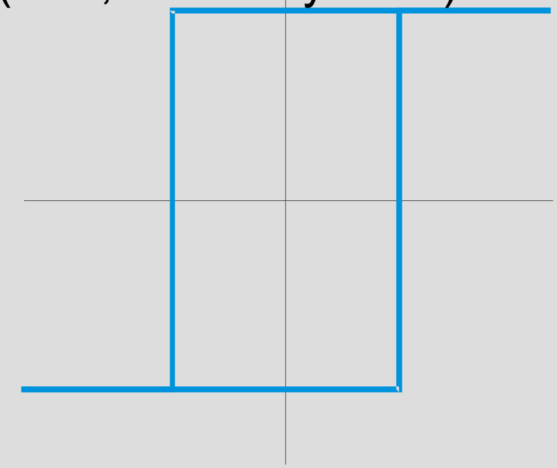
N=0 (slab, infinite cylinder)



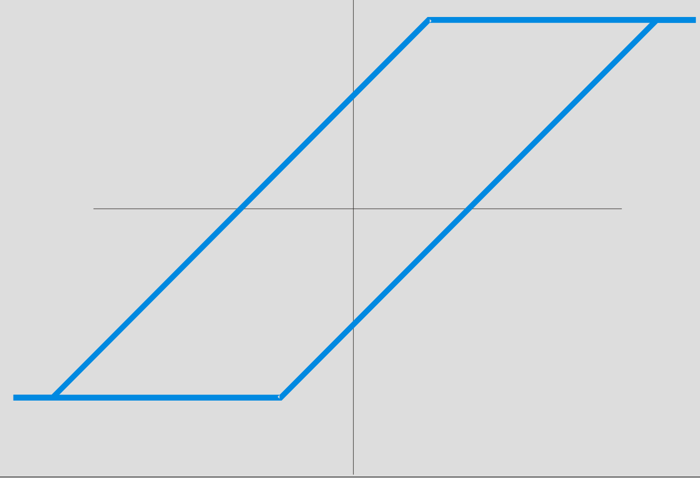
N>0 (here N=1: slab, perpendicular)

Easy axis, coercitive

N=0 (slab, infinite cylinder)



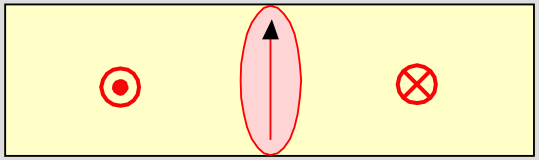
N>0 (here N=1: slab, perpendicular)



Bloch versus Néel wall

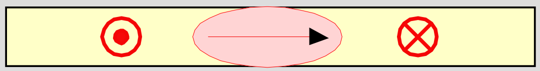
Crude model: wall is a uniformly-magnetized cylinder with an ellipsoid base

Bloch wall



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

Néel wall



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

Thickness t

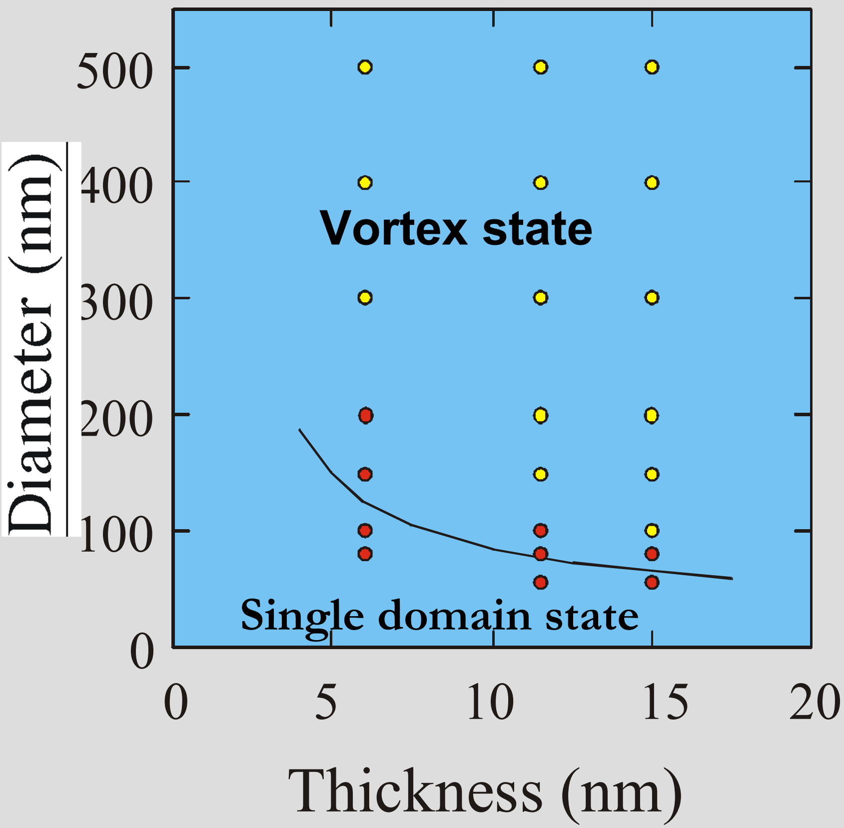
Wall width W

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

Conclusion

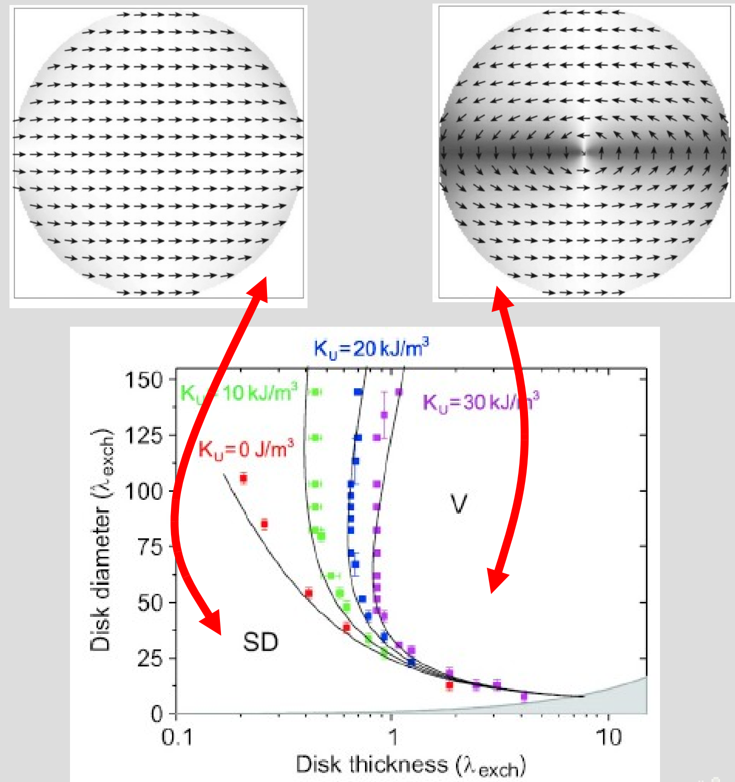
- At low thickness (roughly $t \approx W$) Bloch domain walls are expected to turn their magnetization in-plane > Néel wall
- Model needs to be refined
- Domain walls not changed for films with perpendicular magnetization

Experiments



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

Theory / Simulation

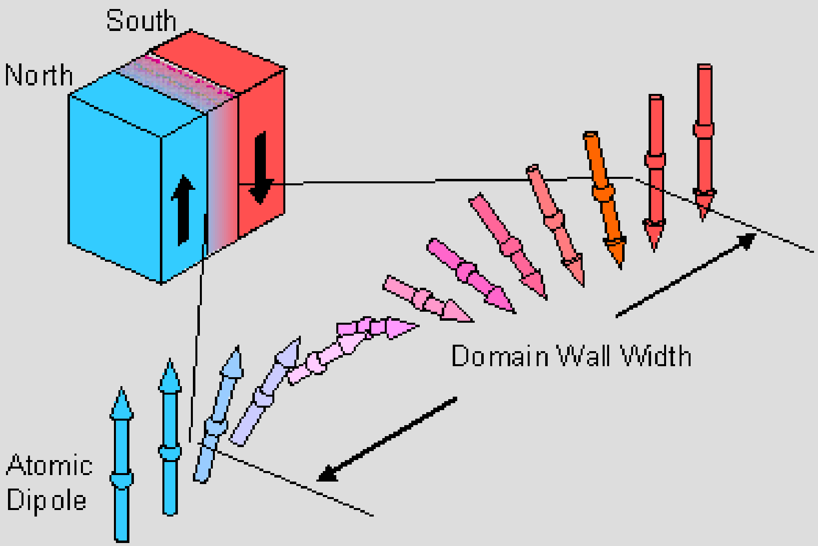


P.-O. Jubert & R. Allenspach,
PRB 70, 144402/1-5 (2004)

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: Domain wall width



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

Exchange → J/m

Anisotropy → J/m^3

Numerical values

Bloch parameter: $\Delta = \sqrt{A/K}$

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

$\Delta \approx 1\ \mathrm{nm} \rightarrow \Delta \geq 100\ \mathrm{nm}$

Hard Soft

Notice that several definitions for the Bloch wall width have been proposed, e.g. with π or 2 as prefactor

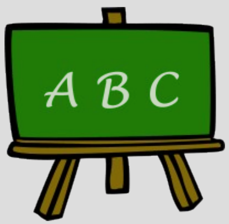
Typical length scale: Exchange length λ_{ex}

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

Exchange $\rightarrow$ J/m

Dipolar energy $\rightarrow$ J/m^3

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



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

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

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

m.c. $\rightarrow$ J/m

Dipolar energy $\rightarrow$ J/m^3

$$Q = K/K_d$$

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

Critical size for hard magnets

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

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

Notice:

Other length scales: with field etc.

Brown's paradox

In most systems $H_c \ll \dfrac{2K}{\mu_0 M_S}$

Micromagnetic modeling

Exhibit analytic however realistic models for magnetization reversal

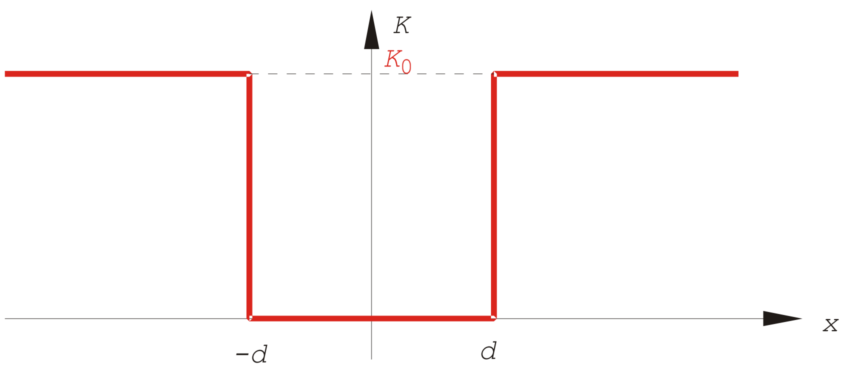
PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

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.



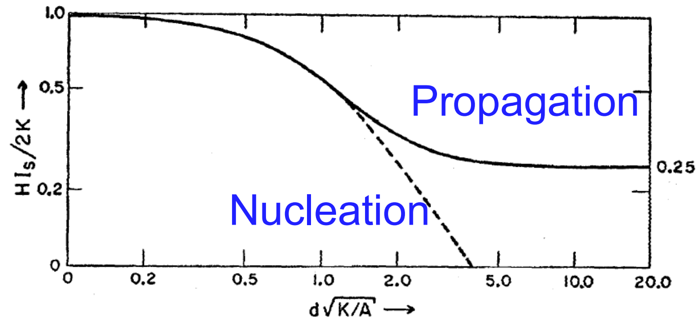
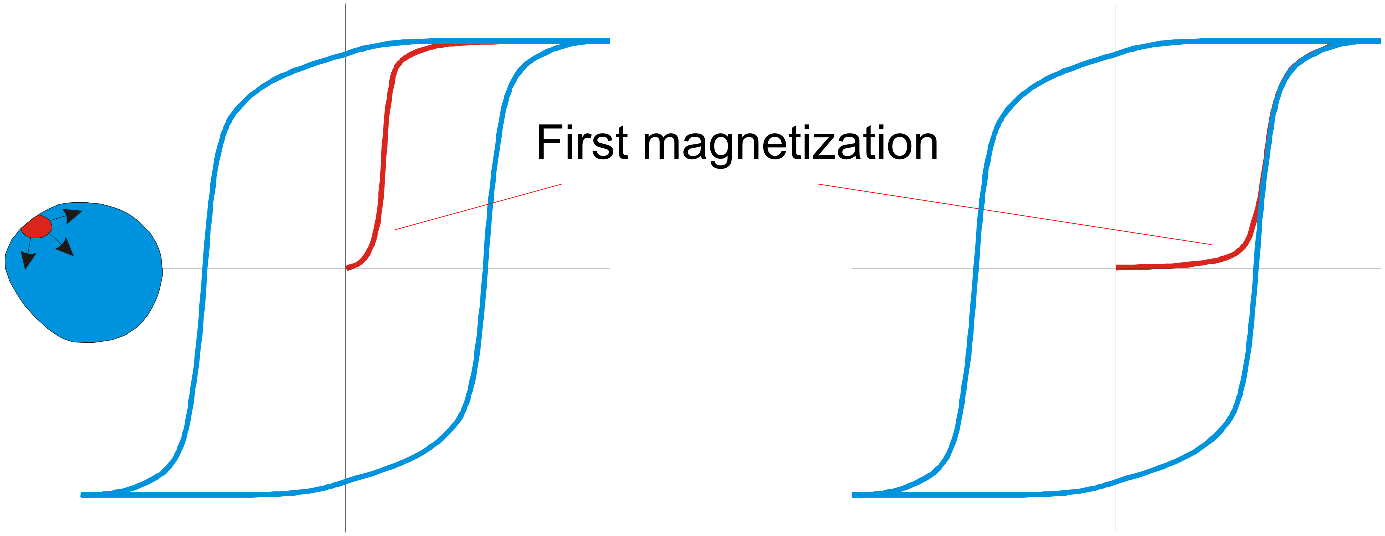


FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

Earlier: E. Kondorski, On the nature of coercive force and irreversible changes in magnetisation, Phys. Z. Sowjetunion 11, 597 (1937)

Use first-magnetization curves to determine the type of coercivity

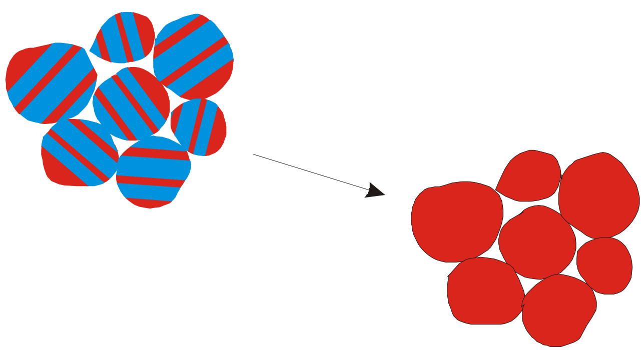


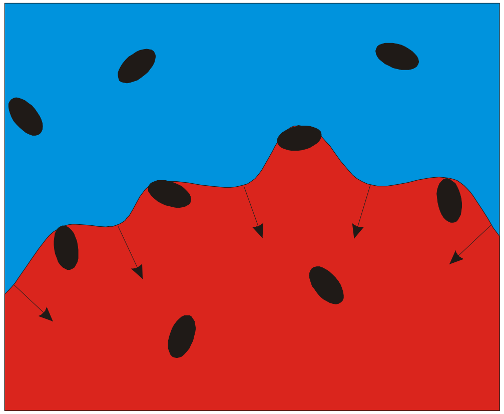
Nucleation-limited

Ex: Sm_2Co_{17}

Propagation-limited

Ex: $SmCo_5$





Courtesy: D. Givord

Depending on structural defects

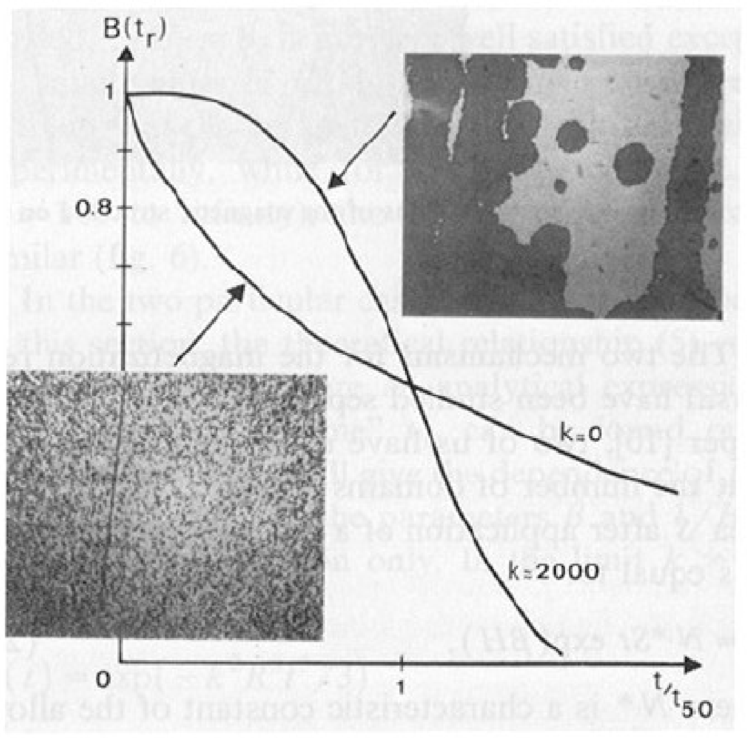
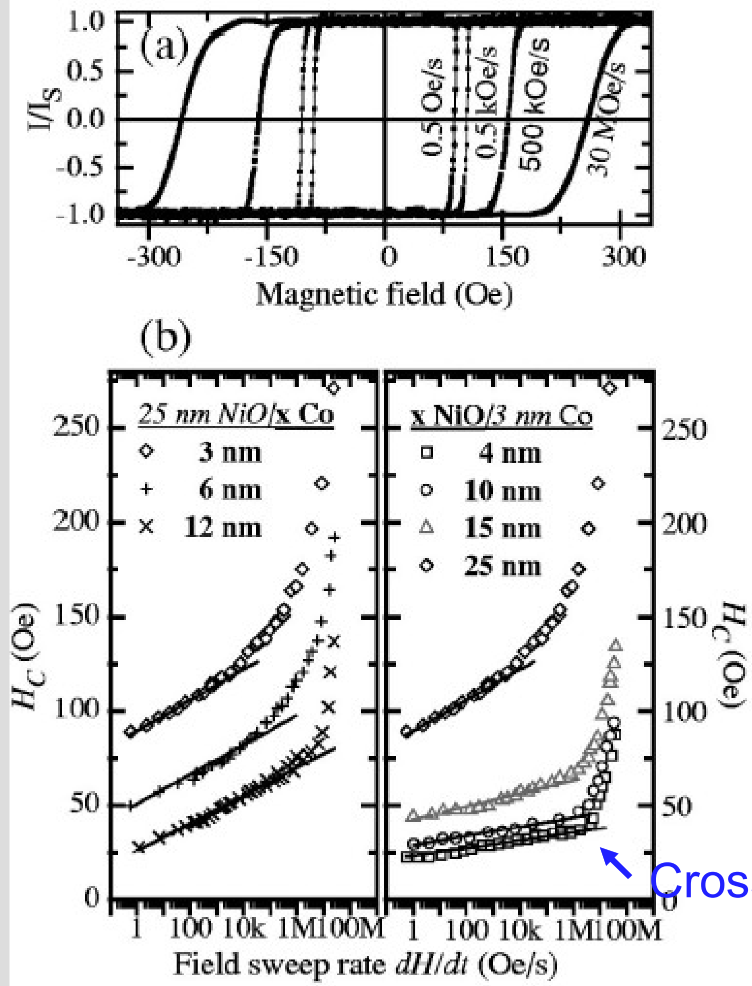


Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \approx 2000$) and a TbCo one ($k \approx 0$), corresponding domain structure observed by Kerr effect.

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

Depending on measurement dynamics



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

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

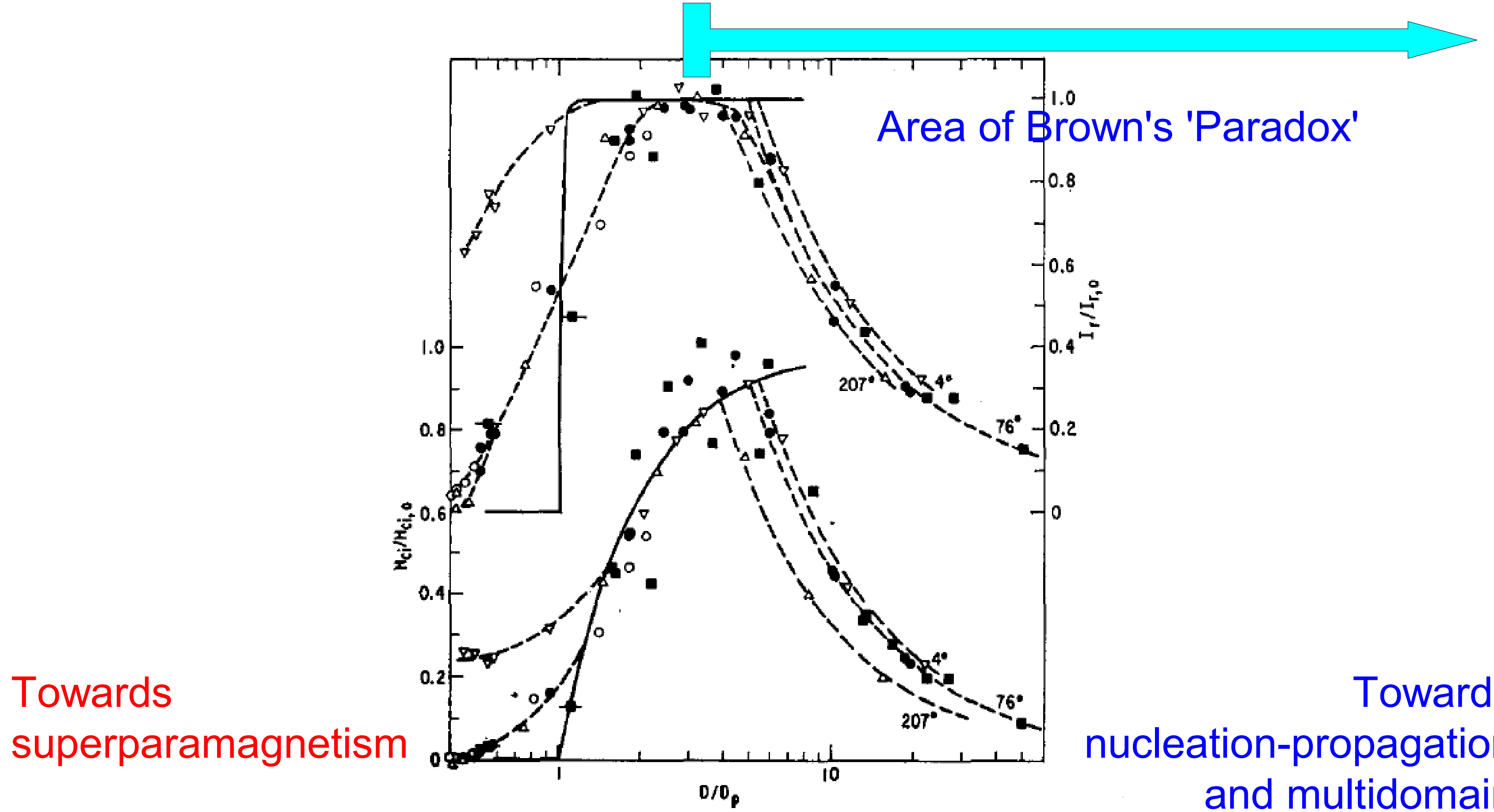


FIG. 1. Particle size dependence of essentially spherical, randomly oriented, iron particles. Calculated curve given by solid line. Diameters $D=\hat{d}_v$. Data at 76°K obtained from electron microscopic examination ■, calculated from I_r/I_s vs temperature O, and from smoothed data of H_{ci} vs D ●.

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

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) [FRENCH]

[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)

[11] Lecture notes in magnetism: http://esm.neel.cnrs.fr/repository.html

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- Magnetic field and moments
- Exchange, magnetic ordering, magnetic anisotropy
- Temperature effects and excitations
- Correlated systems
- Transport
- Magnetization processes
- Simulations
- Materials
- Nanoparticles, microstructures etc
- Nanomagnetism and spintronics
- Techniques
- Applications and interdisciplinary magnetism
- Open sessions

Magnetic field and moments

- **[2009]** Magnetic field, Origin of magnetism, Spin and orbital magnetic moments, Crystal field, Magnetism of free electrons - Paramagnetism etc.: JOHN MICHAEL COEY, *TCD-Dublin, Ireland*. [Abstract pt.1 | pt.2] [Slides pt.1 | pt.2 | pt.3-4]
- **[2007]** Fundamental properties: EKKES BRÜCK, , *Amsterdam, The Netherlands* [Abstract | Slides pt.1 | Slides pt.2]
- **[2005]** Basis and magnetic materials: K.H. MÜLLER [Abstract | Slides (2.2MB)]
- **[2003]** Magnetism of matter - Basic interactions and magnetization processes: D. GIVORD [Abstract | Slides]

Exchange, magnetic ordering, magnetic anisotropy

Exchange and magnetic ordering

- **[2009]** Exchange interactions: exchange, super-exchange, RKKY, Stoner ferromagnetism: TOMASZ DIETL, *Warsaw, Poland*. [Abstract | Slides]
- **[2009]** Magnetic Order: different types, dimensionality effects, number of components (Ising, XY, Heisenberg): PETER DE CHATEL, *Amsterdam, The Netherlands*. [Abstract | Slides]
- **[2009]** Magnetism at finite temperature: molecular field, phase transitions: CLAUDINE LACROIX, *Institut Néel - Grenoble, France* [Slides].

Magnetic anisotropy

- **[2009]** Magnetic anisotropy and how it can be controlled: DIRK SANDER, *MPI-Halle, Germany*. [Abstract | Slides]

Low-dimensional and surface magnetism

- **[2003]** Low dimensional magnetism - experiments: O. FRUCHART [Abstract | Slides]
- **[2003]** Low dimensional magnetism : the role of the electronic structure: H. DREYSSÉ [Content | Abstract]
- **[2003]** From the atom to magnetic nanoparticles: E. BONET [Abstract | Slides]