

Nanomagnetism

Part 1 - Macrospins



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Micro-NanoMagnetism team : <http://neel.cnrs.fr/mnm>

Email to esm@magnetism.eu on Aug.19 2009 18:55

hi, i was investigating about magnetism in the human body and i used a speaker with a plug connected to it and then i started touching my body with the plug to hear how it sounds, i realized that when i put the plug in my nipples it made a louder sound which means that the magnetics were bigger in that area, i have asked about this but i get no answer why, there is no coverage about this subject on the internet either, please if you know about this let me know, my theory is that our nipples are our bridge of expulsing magnetics and electric signal to control the energy outside our bodies, hope this helps with some research, thank you...

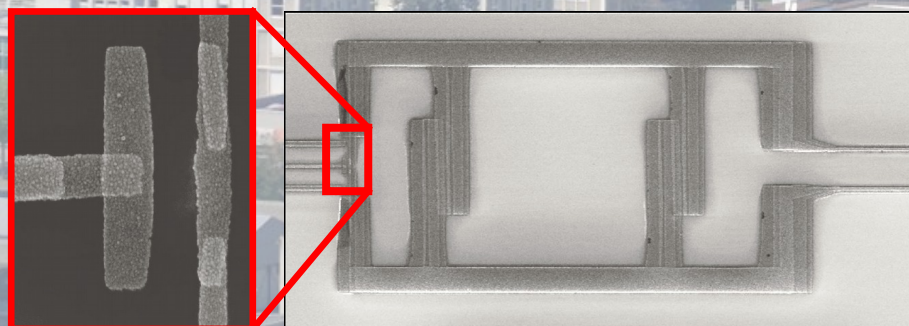


Facts

- ➡ Core of Condensed Matter Physics
- ➡ 180 full-staff scientists, 130 technical staff
- ➡ 40 PhD / year

Internal structure

- ➡ Research teams + technological support groups
- ➡ Three scientific departments
 - Condensed Matter – Low Temperatures
 - Condensed Matter – Functional Materials
 - Nanosciences





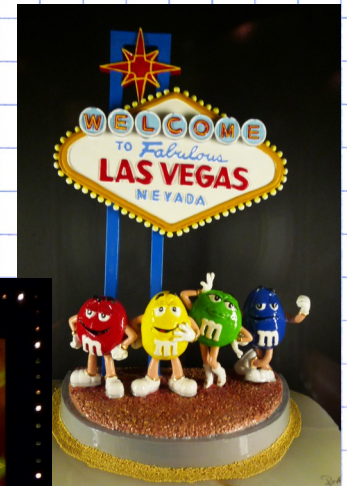
Credits: O. Fruchart

New-York

Las Vegas



Credits: C. Haranczyk



Credits: V. Chaumont

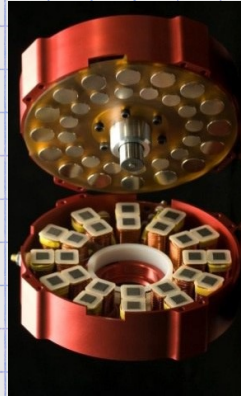
London



Modern applications of (Nano)magnetism

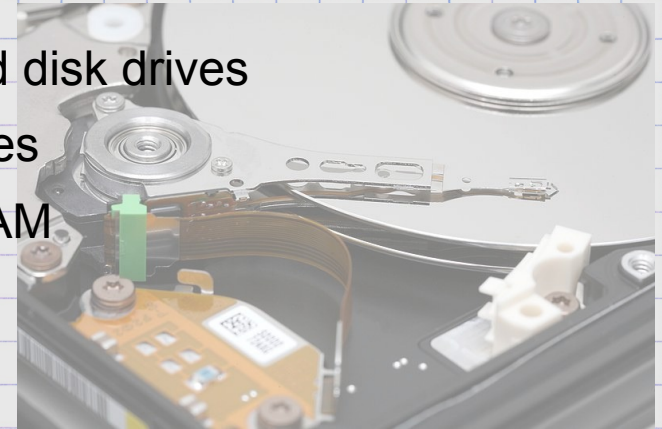
Materials

- ⇒ Magnets
(→ motors and generators)
- ⇒ Transformers
- ⇒ Magnetocaloric



Data storage

- ⇒ Hard disk drives
- ⇒ Tapes
- ⇒ MRAM



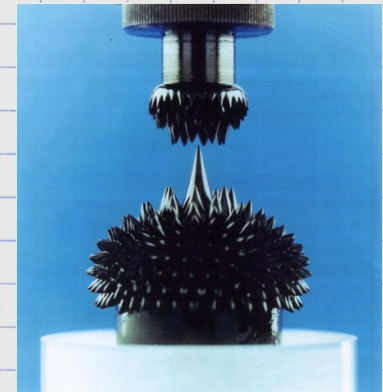
Sensors

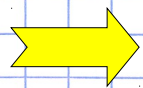
- ⇒ Compass
- ⇒ Field mapping
- ⇒ HDD read heads



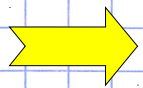
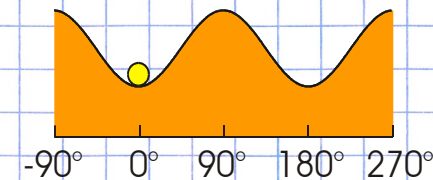
Nanoparticles

- ⇒ Ferrofluids
- ⇒ MRI contrast
- ⇒ Hyperthermia
- ⇒ Sorting & tagging

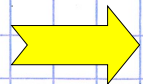
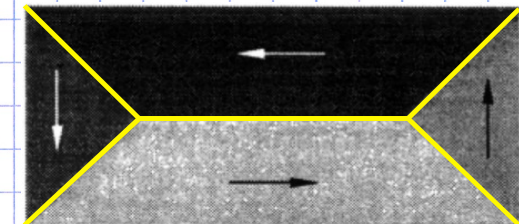




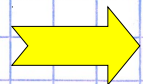
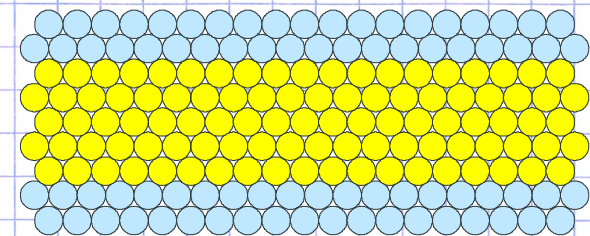
Part 1 : basics of micromagnetism – Simple models of magnetization reversal



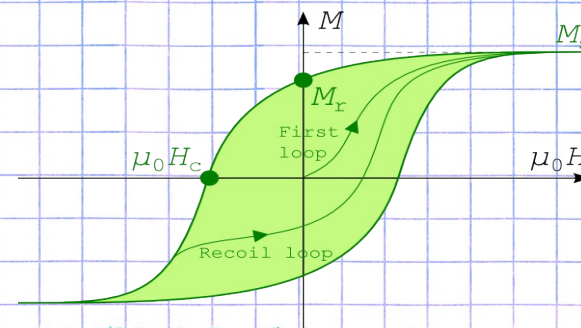
Part 2 : non-uniform magnetization in nanostructure: domains, domain walls



Part 3 : Low-dimensions, interfaces and heterostructures



Part 4 : Learn from hysteresis loops





Definitions

SI system

Meter m
Kilogram kg
Second s
Ampere A

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ SI}$$

cgs-Gauss

Centimeter cm
Gram g
Second s
Ab-Ampere ab-A = 10A

$$\mathbf{B} = \mathbf{H} + 4\pi \mathbf{M}$$

$$\mu_0 = 4\pi$$

Conversions

Field	$\mathbf{H}$	1 A/m	↔	$4\pi \times 10^{-3}$ Oe (Oersted)
Moment	μ	1 A.m ²	↔	10 ³ emu
Magnetization	$\mathbf{M}$	1 A/m	↔	10 ⁻³ emu/cm ³
Induction	$\mathbf{B}$	1 T	↔	10 ⁴ G (Gauss)
Susceptibility	$\chi = M/H$	1	↔	1/4π

Notations

Practical on units : <http://magnetism.eu/esm/2013/abs/fruchart-tutorial.pdf>

Microscopic quantity E

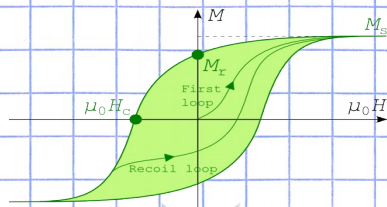
Dimensionless quantity $e = E/E_0$

Global quantity

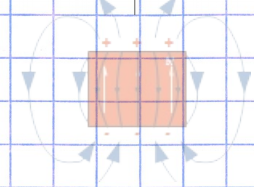
Vector quantity $\mathbf{B}$

$$\mathcal{E} = \iiint E \cdot dV$$

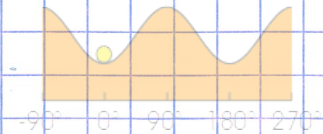
Numerics = 1 A.m²



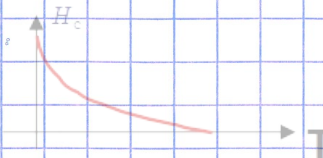
⇒ Motivation for understanding magnetization switching



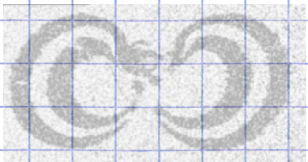
⇒ Magnetostatics



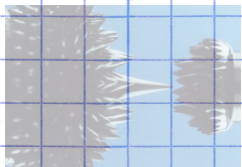
⇒ Stoner-Wohlfarth model



⇒ Thermal activation



⇒ Precessional switching



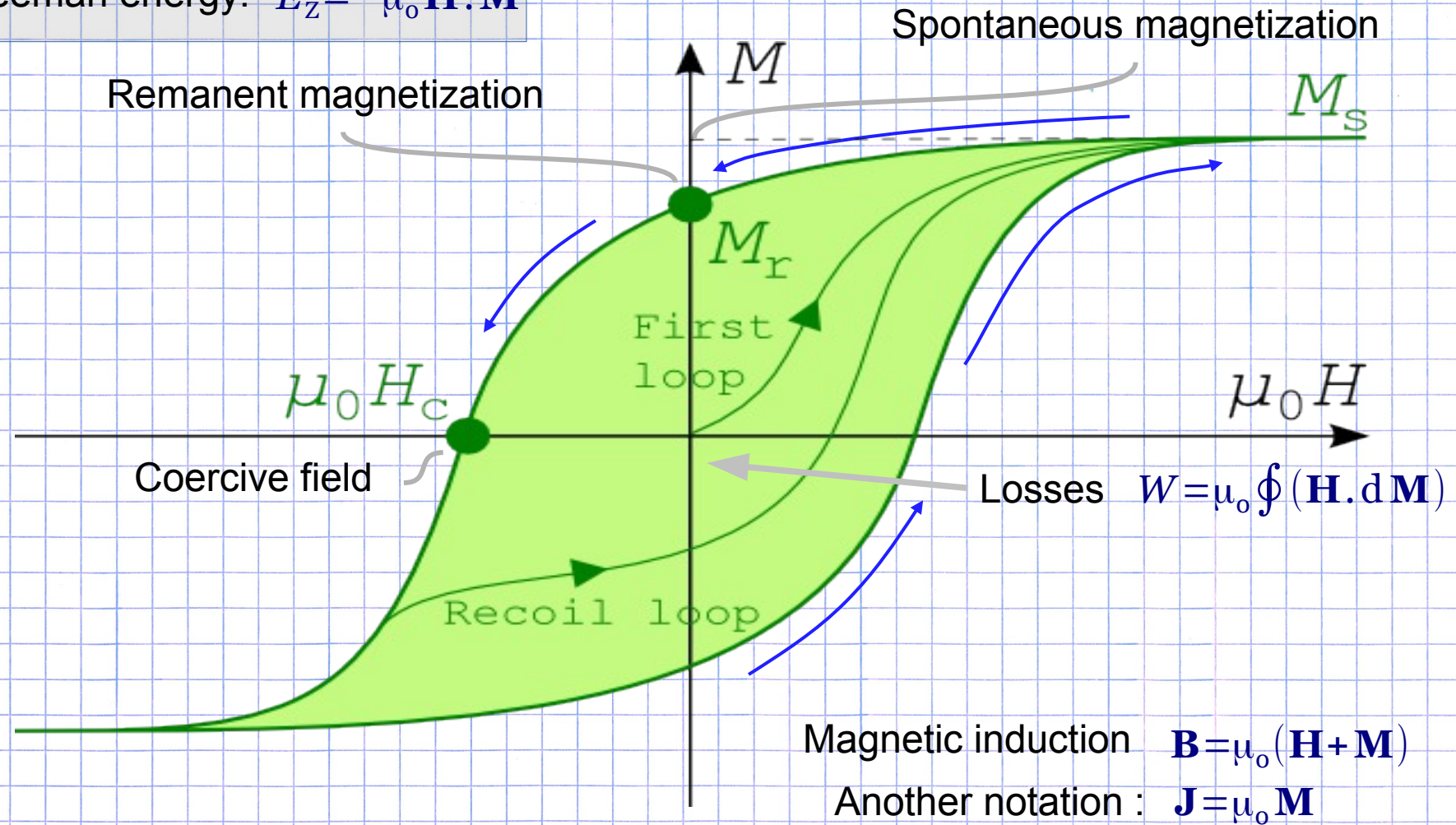
⇒ Applications of macrospins (nanoparticles)



Manipulation of magnetic materials:

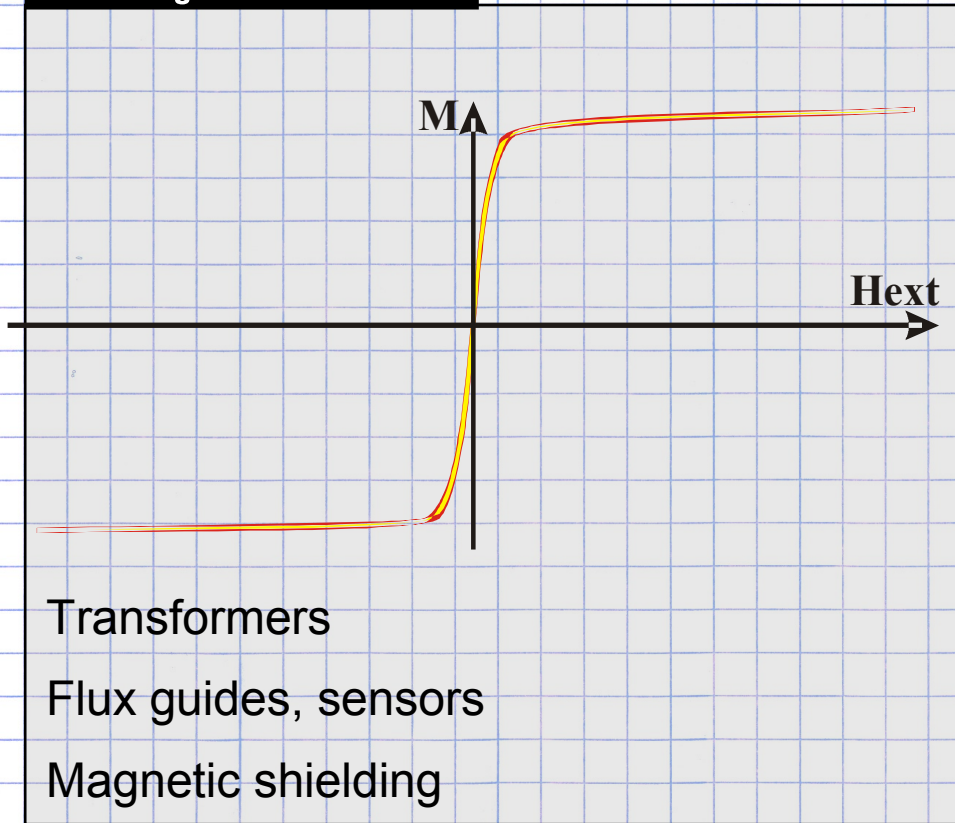
→ Application of a magnetic field

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

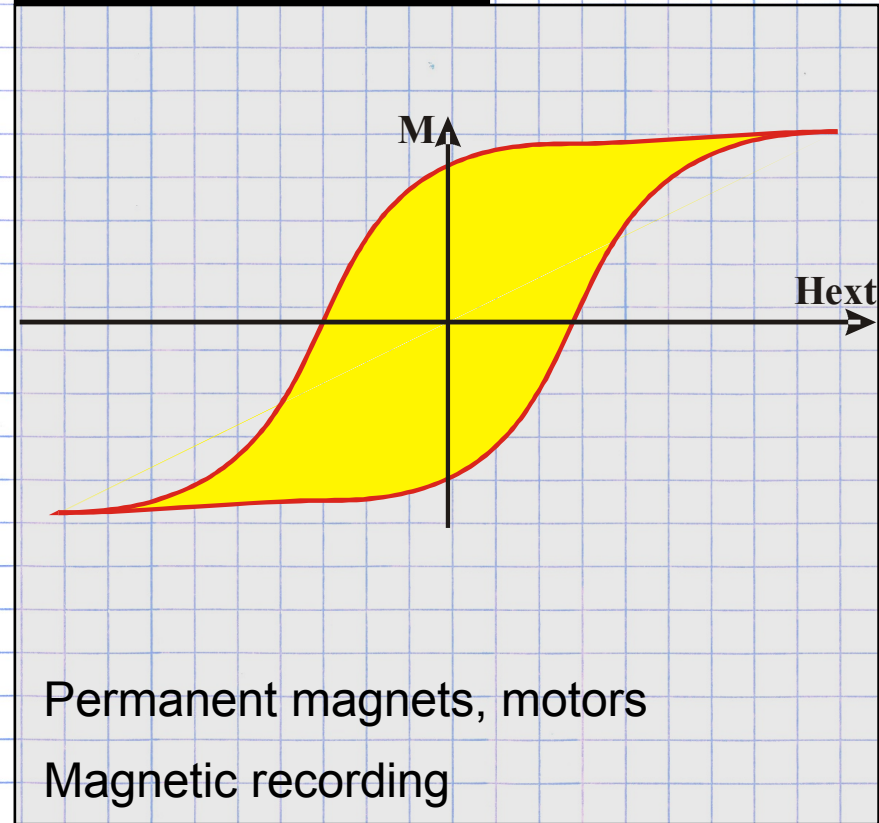




Soft magnetic materials

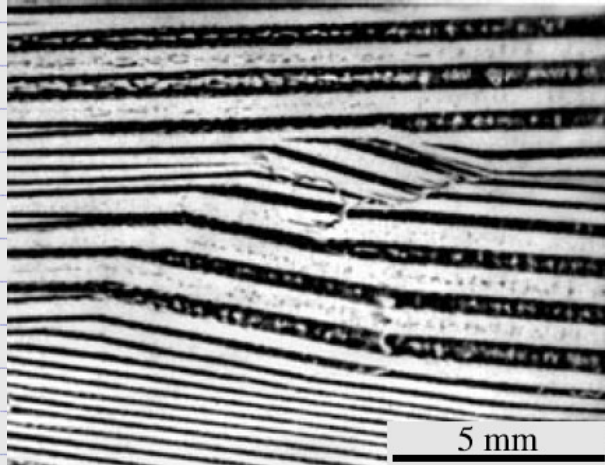


Hard magnetic materials



Bulk material

Numerous and complex magnetic domains

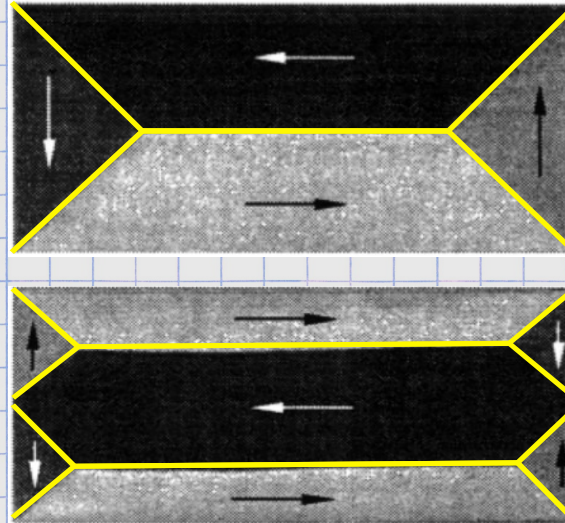


FeSi soft sheet

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

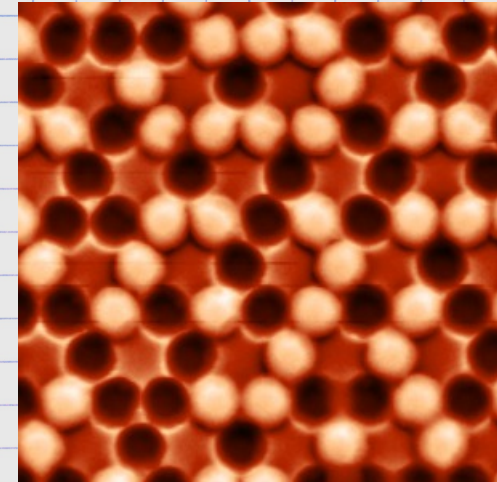


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain



Nanofabricated dots
MFM

I. A. Chioar, PRB90, 064411 (2014)

↪ Nanomagnetism ~ mesoscopic magnetism

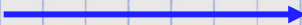


Magnetization

Magnetization vector **M** 

May vary over time and space

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

Modulus is constant 
(hypothesis in micromagnetism)

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



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

Exchange interaction

Atomistic view :

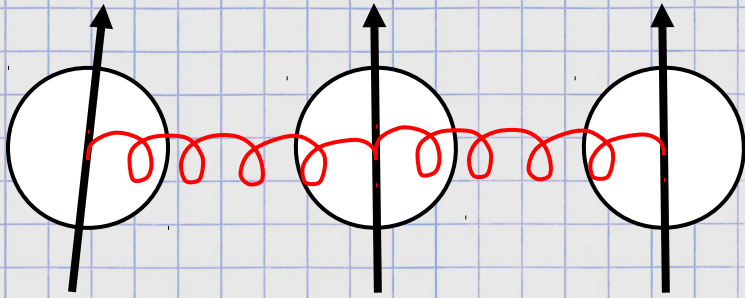
$$\mathcal{E} = -2 \sum_{i>j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \quad (\text{total energy})$$

Micromagnetic view :

$$\mathbf{S}_i \cdot \mathbf{S}_j = S^2 \cos \theta_{ij} \approx S^2 (1 - \theta_{ij}^2 / 2)$$

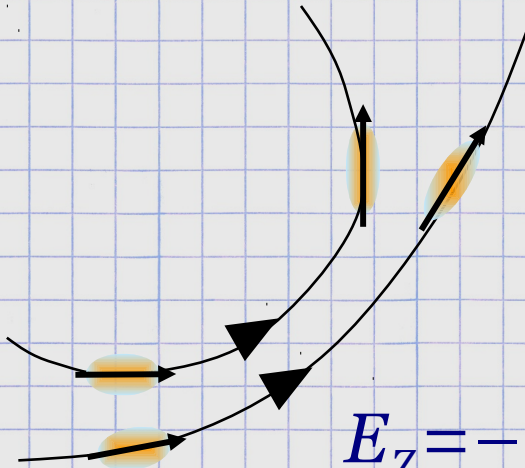
$$E = A (\nabla \cdot \mathbf{m})^2 \quad (\text{energy per unit volume})$$

Exchange energy



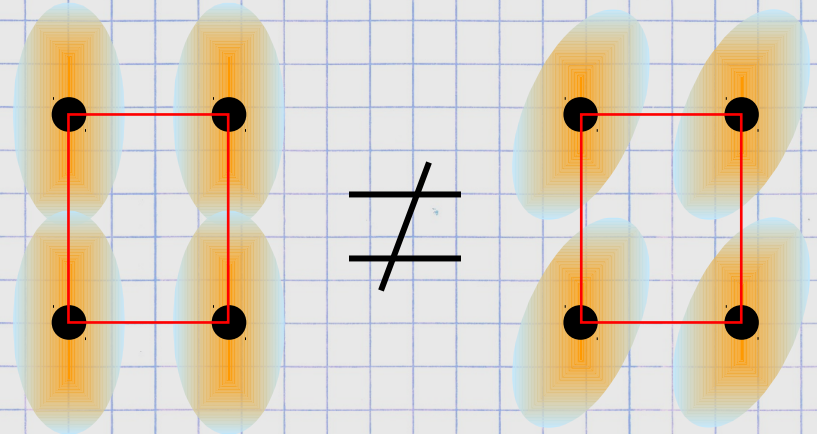
$$E_{\text{ex}} = A (\nabla \cdot \mathbf{m})^2 = A \sum_{i,j} \left(\frac{\partial m_i}{\partial x_j} \right)^2$$

Zeeman energy



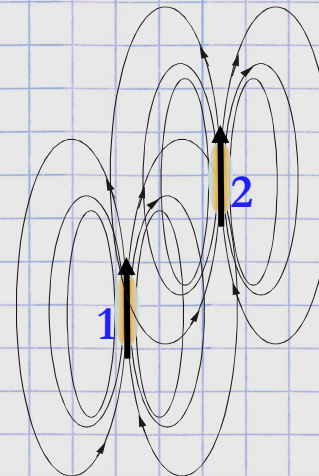
$$E_Z = -\mu_0 \mathbf{M} \cdot \mathbf{H}$$

Magnetocrystalline anisotropy energy

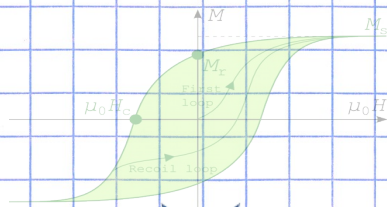


$$E_{\text{mc}} = A f(\theta, \varphi)$$

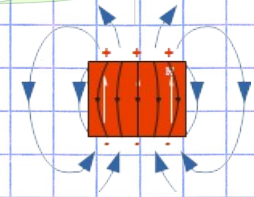
Dipolar energy



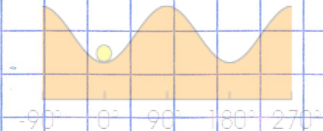
$$E_d = -\frac{1}{2} \mu_0 \mathbf{M} \cdot \mathbf{H}_d$$



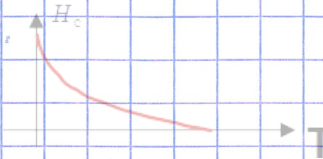
⇒ Motivation for understanding magnetization switching



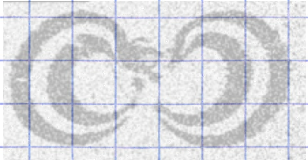
⇒ Magnetostatics



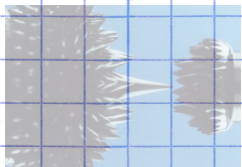
⇒ Stoner-Wohlfarth model



⇒ Thermal activation



⇒ Precessional switching



⇒ Applications of macrospins (nanoparticles)



Analogy with electrostatics (synonym : magnetostatic energy) Usefull expressions

Maxwell equation $\rightarrow \text{div}(\mathbf{H}_d) = -\text{div}(\mathbf{M})$

$$\Rightarrow \mathbf{H}_d(\mathbf{r}) = -M_s \iiint_{\text{Space}} \frac{\text{div}[\mathbf{m}(\mathbf{r}')] \cdot (\mathbf{r} - \mathbf{r}')}{4\pi \|\mathbf{r} - \mathbf{r}'\|^3} dV'$$

To lift the singularity that may arise at boundaries, a volume integration around the boundaries yields:

$$\mathbf{H}_d(\mathbf{r}) = \iiint \frac{\rho(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}{4\pi \|\mathbf{r} - \mathbf{r}'\|^3} dV' + \iint \frac{\sigma(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}{4\pi \|\mathbf{r} - \mathbf{r}'\|^3} dS'$$

$$\mathcal{E}_d = -\frac{1}{2} \mu_0 \iiint_{\text{Sample}} \mathbf{M} \cdot \mathbf{H}_d dV$$

$$\mathcal{E}_d = \frac{1}{2} \mu_0 \iiint_{\text{Space}} \mathbf{H}_d^2 dV$$

$\Rightarrow$ Dipolar energy is always positive

$\Rightarrow$ Zero energy means a minimum

Magnetic charges

$\rho(\mathbf{r}) = -M_s \text{div}[\mathbf{m}(\mathbf{r})] \rightarrow$ volume density of magnetic charges

$\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) \rightarrow$ surface density of magnetic charges

Notice

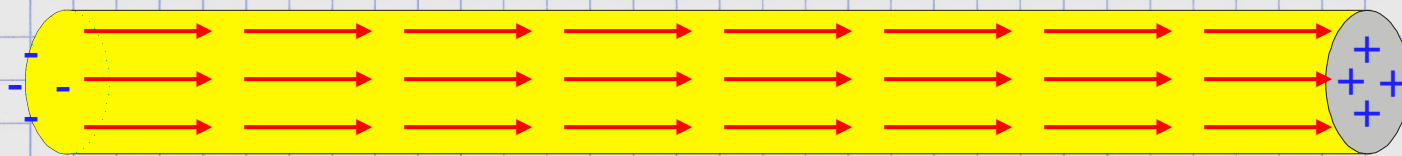
$\Rightarrow H_d$ depends on sample shape, not size

$\Rightarrow$ Synonym : dipolar $\leftrightarrow$ magnetostatic

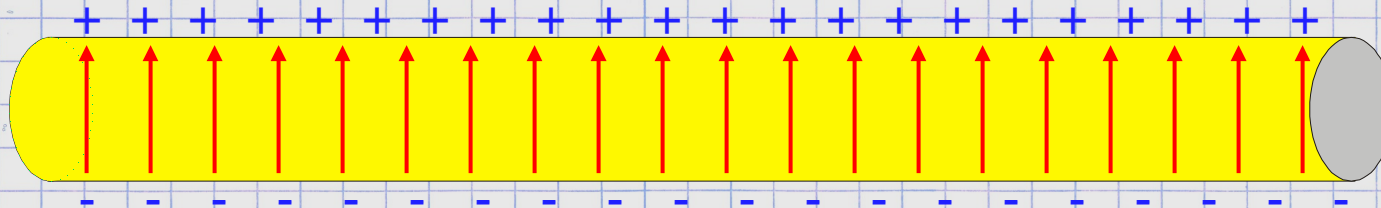
$$\rho(\mathbf{r}) = -M_s \operatorname{div}[\mathbf{m}(\mathbf{r})] \rightarrow \text{volume density of charges}$$

Examples of magnetic charges

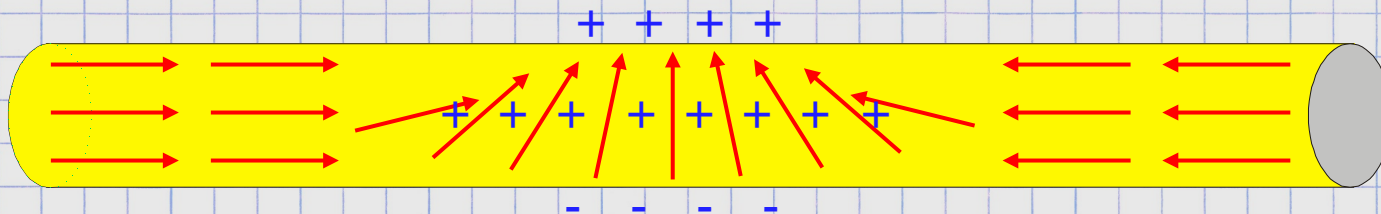
$$\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r}) \rightarrow \text{surface density of charges}$$



Notice: no charges and $\mathcal{E}=0$ for infinite cylinder



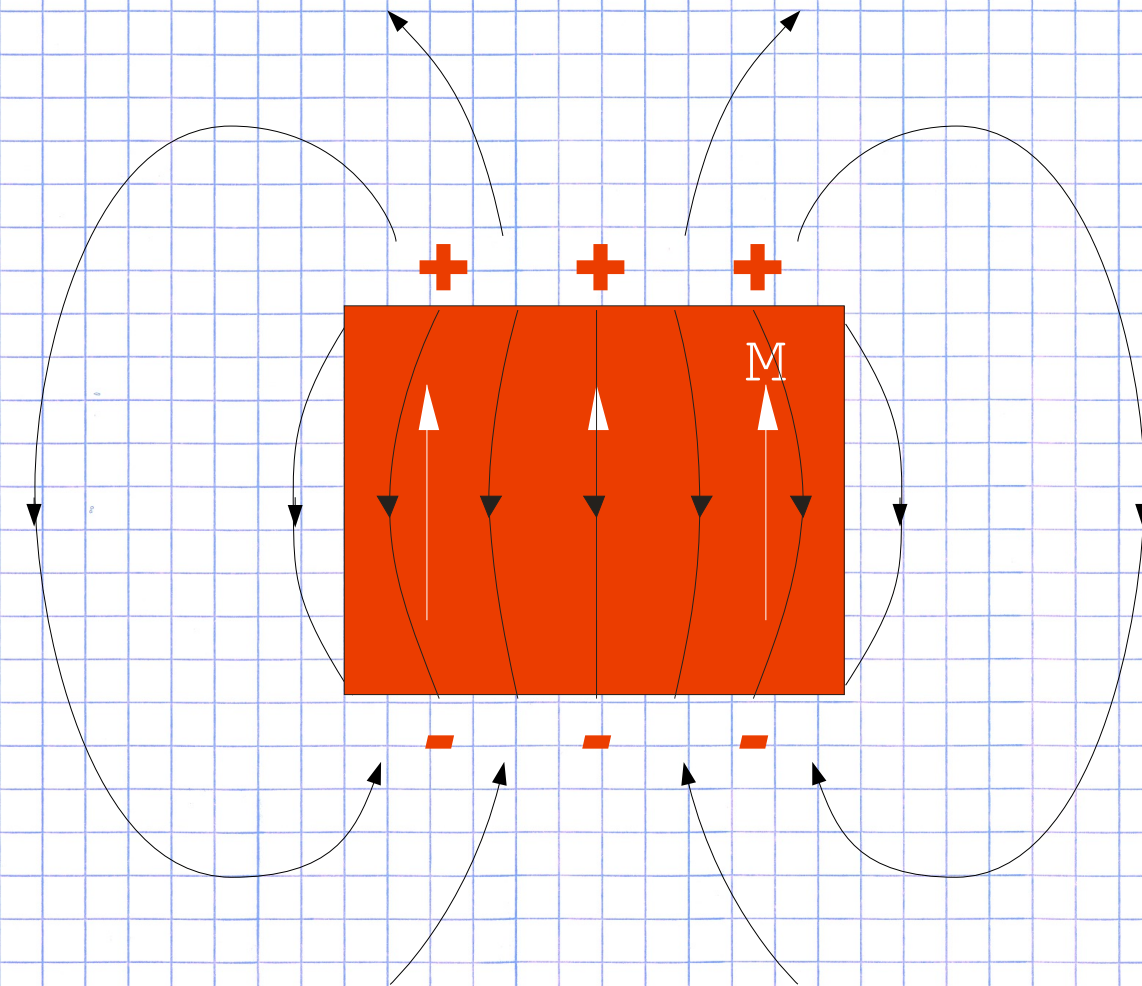
Charges on surfaces



Surface and volume charges

Take-away message

↪ Dipolar energy favors alignment of magnetization with longest direction of sample



Names

⇒ Generic names

Magnetostatic field

Dipolar field

⇒ Within sample

Demagnetizing field

⇒ Outside sample

Stray field



Principle

Goal : evaluate strength of demagnetizing field and energy

Assume uniform magnetization $\mathbf{M}(\mathbf{r}) = \mathbf{M} = M_s(m_x \mathbf{u}_x + m_y \mathbf{u}_y + m_z \mathbf{u}_z) = M_s m_i \mathbf{u}_i$

Demagnetizing coefficients (Easy to prove, however not done here)

$$\langle \mathbf{H}_d(\mathbf{r}) \rangle = -M_s \bar{\mathbf{N}} \cdot \mathbf{m} = -N_i M_s m_i$$

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

Dipolar constant (J/m³)

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

$$\bar{\mathbf{N}}$$

Demagnetizing tensor

➡ Along all three main directions : $H_i = -N_i M_s m_i$ and $\mathcal{E}_d = K_d V N_i m_i^2$

Notice: Valid for any shape

$$N_x + N_y + N_z = 1$$



$$\begin{aligned} \langle \mathbf{H}_d \rangle_{\text{cgs}} &= -4\pi \bar{\mathbf{N}} \cdot \mathbf{M} \\ \bar{\mathbf{D}} &= 4\pi \bar{\mathbf{N}} \end{aligned}$$

Model cases : slabs, cylinders and ellipsoids (Not easy to prove, mathematics...)

H_d is uniform for surfaces of polynomial boundary with order ≤ 2 $\mathbf{H}_d = -M_s \bar{\mathbf{N}} \cdot \mathbf{m}$

J. C. Maxwell, Clarendon 2, 66-73 (1872)

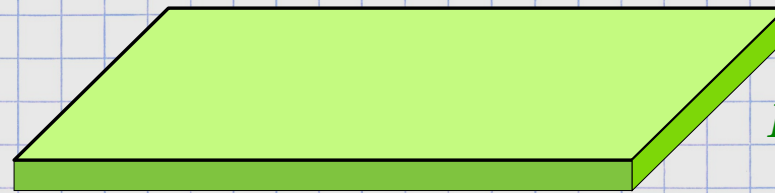
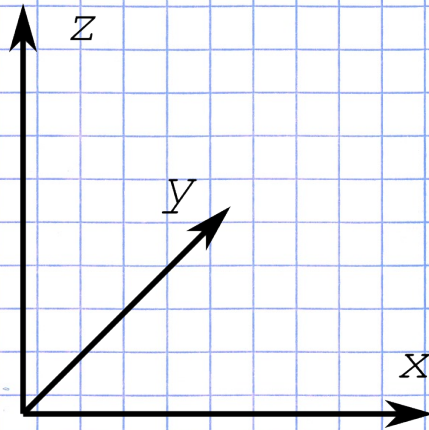
➡ Dipolar energy contributes to magnetic anisotropy with second-order term

Example :

$$\mathcal{E}_d = V K_d (N_x m_x^2 + N_y m_y^2) = V K_d (N_x - N_y) \cos^2 \theta$$



Slabs (infinite thin films)

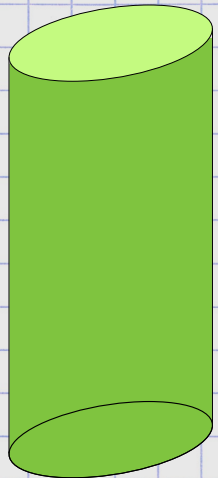


$$L_x = L_y = \infty$$

$$N_x = N_y = 0$$

$$N_z = 1$$

Cylinders (infinite)



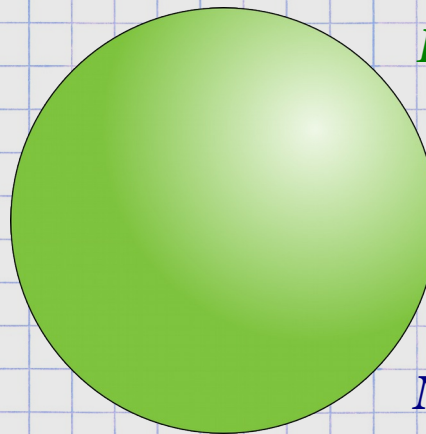
$$L_x = L_y = D$$

$$L_z = \infty$$

$$N_x = N_y = \frac{1}{2}$$

$$N_z = 0$$

Spheres



$$L_x = L_y = L_z = D$$

$$N_x = N_y = N_z = \frac{1}{3}$$



Ellipsoids

$$N_x = \frac{1}{2} abc \int_0^\infty \left[(a^2 + \eta) \sqrt{(a^2 + \eta)(b^2 + \eta)(c^2 + \eta)} \right]^{-1} d\eta \quad \text{General ellipsoid: main axes (a,b,c)}$$

$$N_x = \frac{\alpha^2}{1 - \alpha^2} \left[\frac{1}{\sqrt{1 - \alpha^2}} \operatorname{arsinh} \left(\frac{\sqrt{1 - \alpha^2}}{\alpha} \right) - 1 \right]$$

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

For prolate revolution ellipsoid:
(a,c,c) with $\alpha = c/a < 1$

For oblate revolution ellipsoid:
(a,c,c) with $\alpha = c/a > 1$

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

Cylinders

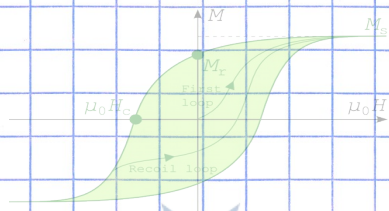
$$N_x = 0 \quad N_y = \frac{c}{b+c} \quad N_z = \frac{b}{b+c}$$

For a cylinder with axis along x

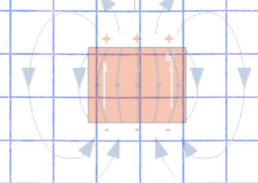
J. A. Osborn, Phys. Rev. 67, 351 (1945).

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

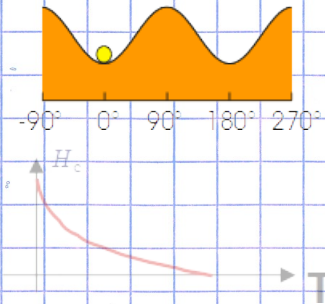
More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**



⇒ Motivation for understanding magnetization switching

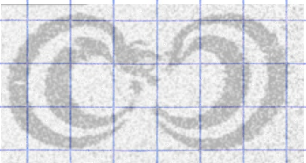


⇒ Magnetostatics

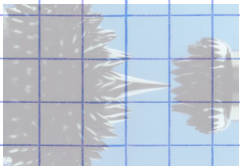


⇒ Stoner-Wohlfarth model

⇒ Thermal activation



⇒ Precessional switching



⇒ Applications of macrospins (nanoparticles)

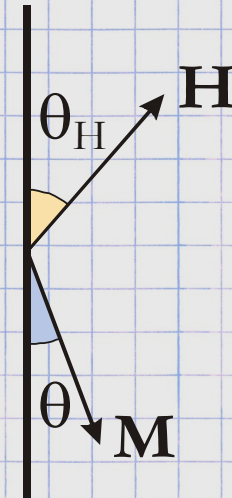


Framework

Approximation: $\partial_r \mathbf{m} = \mathbf{0}$ (uniform magnetization)
(strong!)

$$\mathcal{E} = EV = V [K_{\text{eff}} \sin^2 \theta - \mu_0 M_s H \cos(\theta - \theta_H)]$$

$$K_{\text{eff}} = K_{\text{mc}} + (\Delta N) K_d$$



Dimensionless units:

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

$$e = \mathcal{E} / KV$$

$$h = H / H_a$$

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

L. Néel, *Compte rendu Acad. Sciences* 224, 1550 (1947)

E. C. Stoner and E. P. Wohlfarth, *Phil. Trans. Royal. Soc. London* A240, 599 (1948)

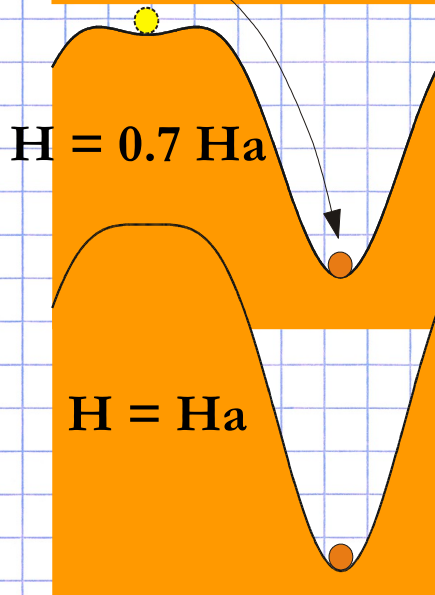
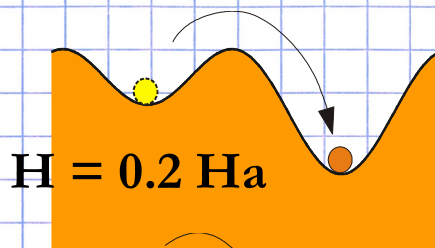
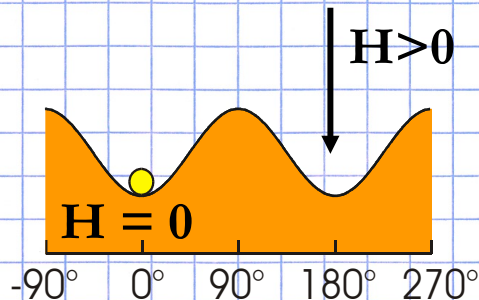
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

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



Example for $\theta_H = 180^\circ \longrightarrow e = \sin^2 \theta + 2h \cos \theta$



Equilibrium states

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

$$\partial_\theta e = 0 \implies$$

$$\cos \theta_m = h$$

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

Stability

$$\partial_{\theta\theta} e = 2 \cos 2\theta - 2h \cos \theta$$

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

$$\partial_{\theta\theta} e(0) = 2(1-h)$$

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

$$\partial_{\theta\theta} e(\pi) = 2(1+h)$$

Energy barrier

$$\Delta e = e(\theta_{\max}) - e(0)$$

$$= 1 - h^2 + 2h^2 - 2h$$

$$= (1-h)^2$$



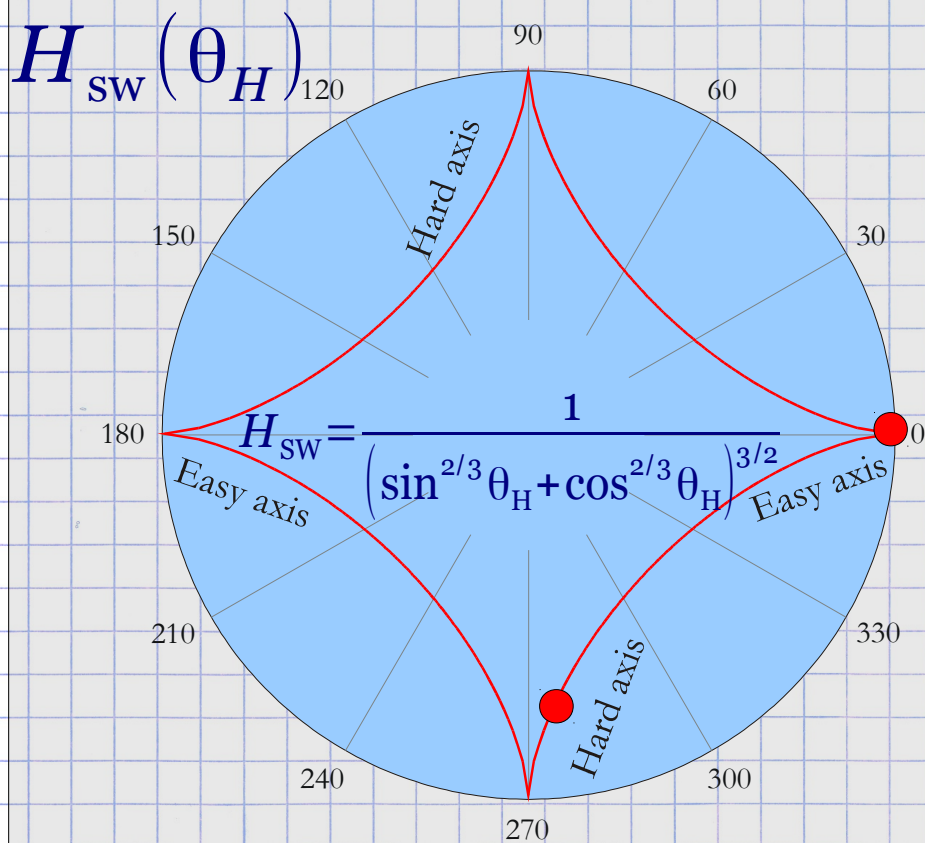
Switching

$$h = 1$$

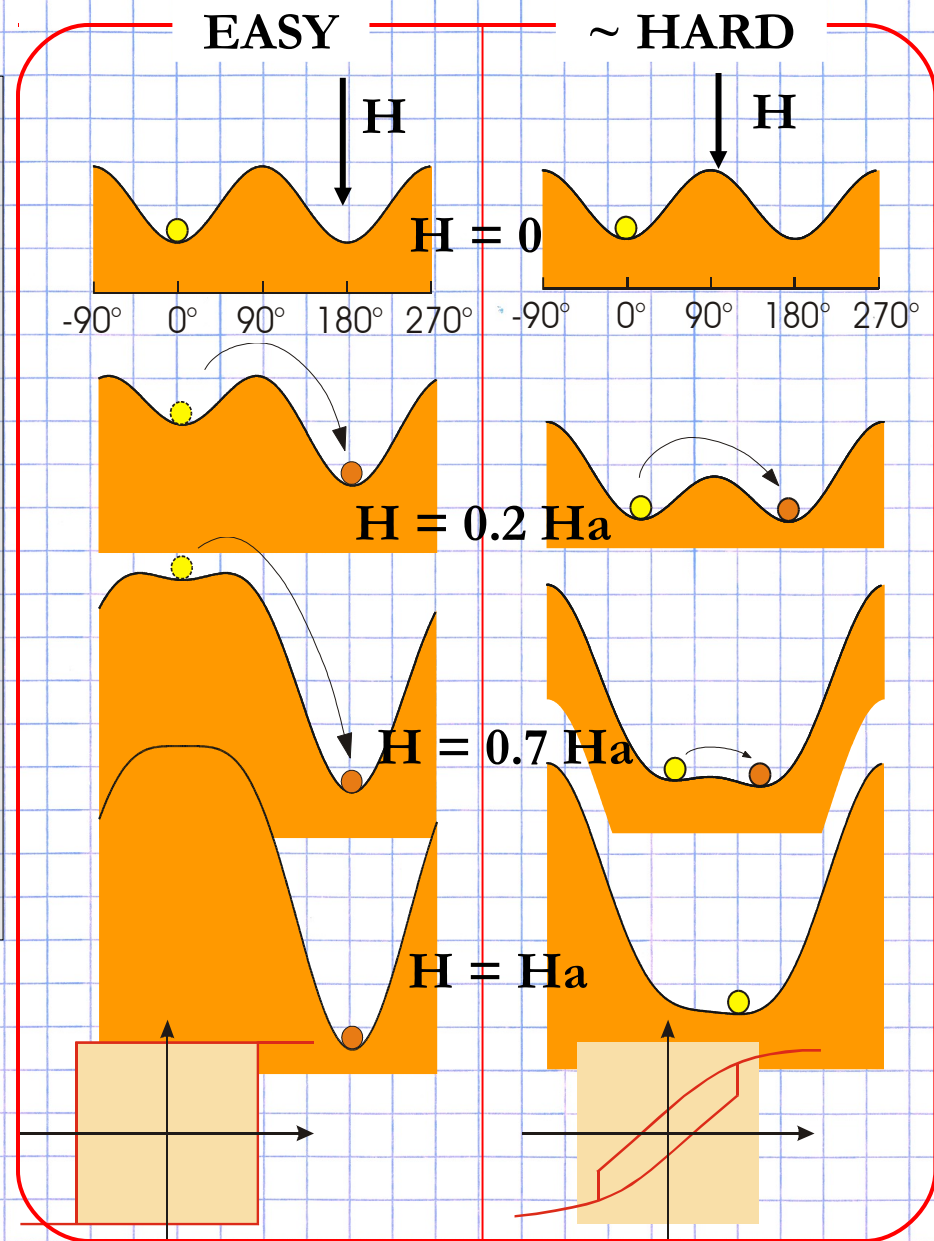
$$H = H_a = 2K / \mu_0 M_s$$

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

'Astroid' curve



➤ $H_{sw}(\theta)$ is only one signature of reversal modes



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

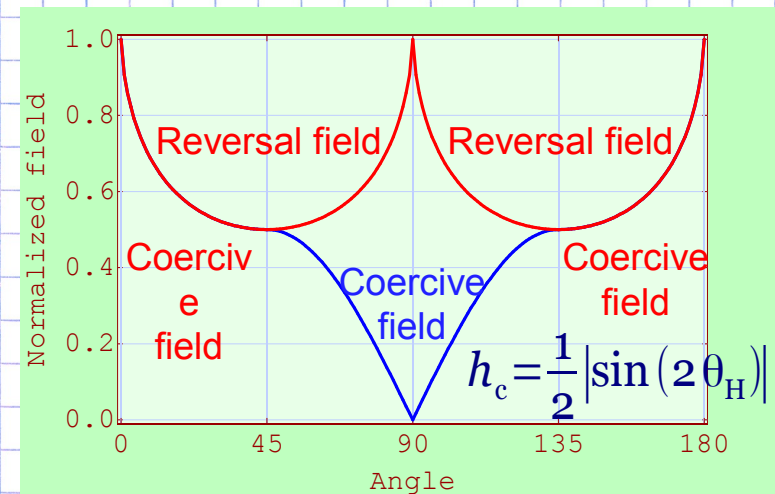
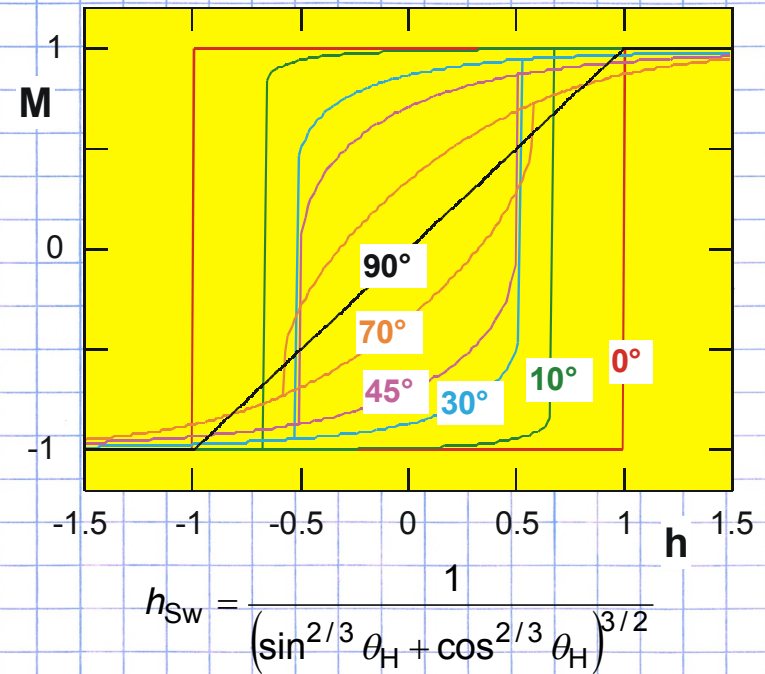
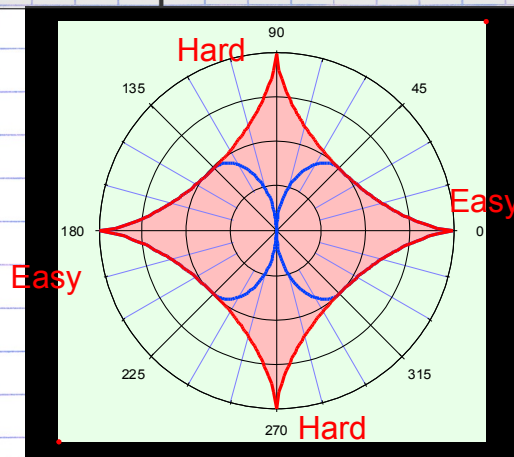


Switching field = Reversal field

A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.
Can be measured only in single particles.

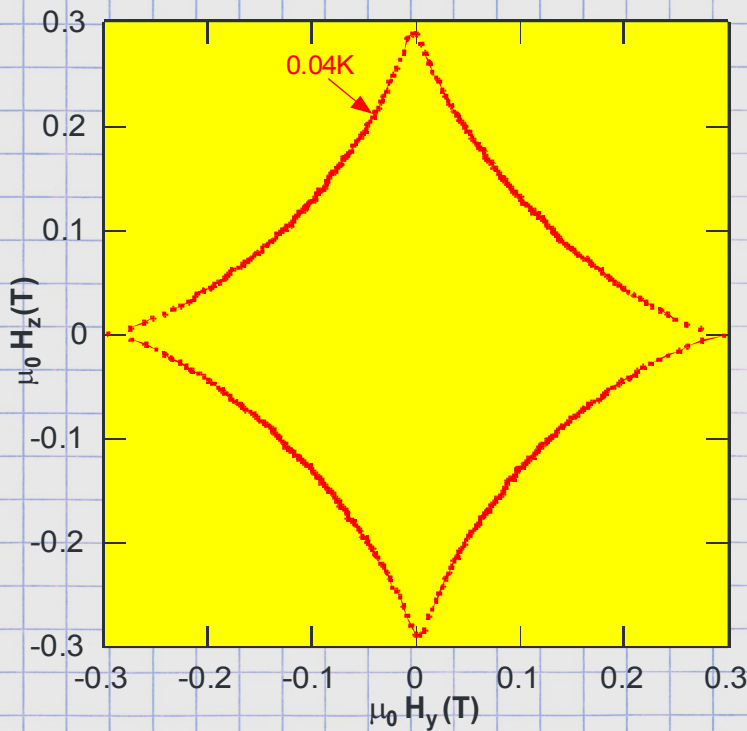
Coercive field

The value of field at which $\mathbf{M} \cdot \mathbf{H} = 0$ ($\theta = \theta_H \pm \pi/2$)
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

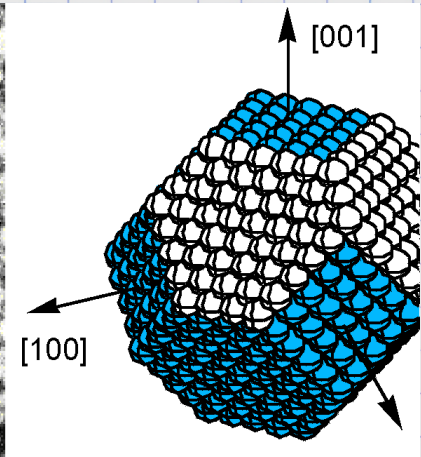
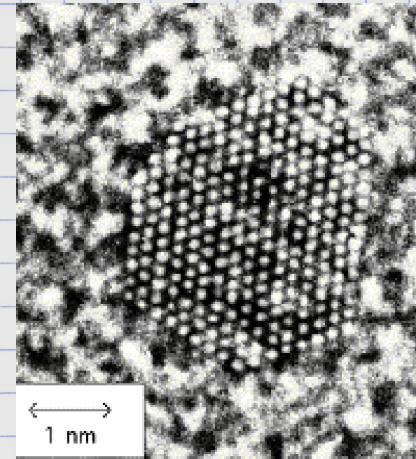




Experimental evidence



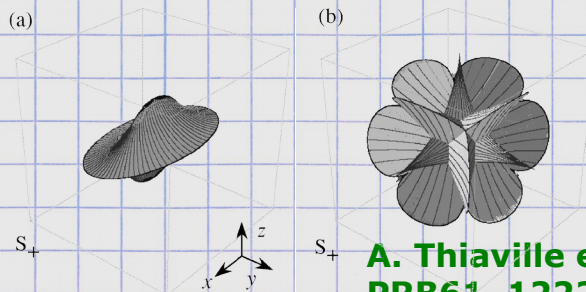
First evidence: W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)



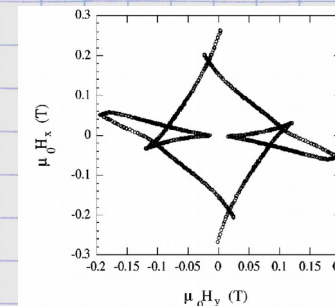
Co cluster

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

Extensions: 3D, arbitrary anisotropy etc.



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

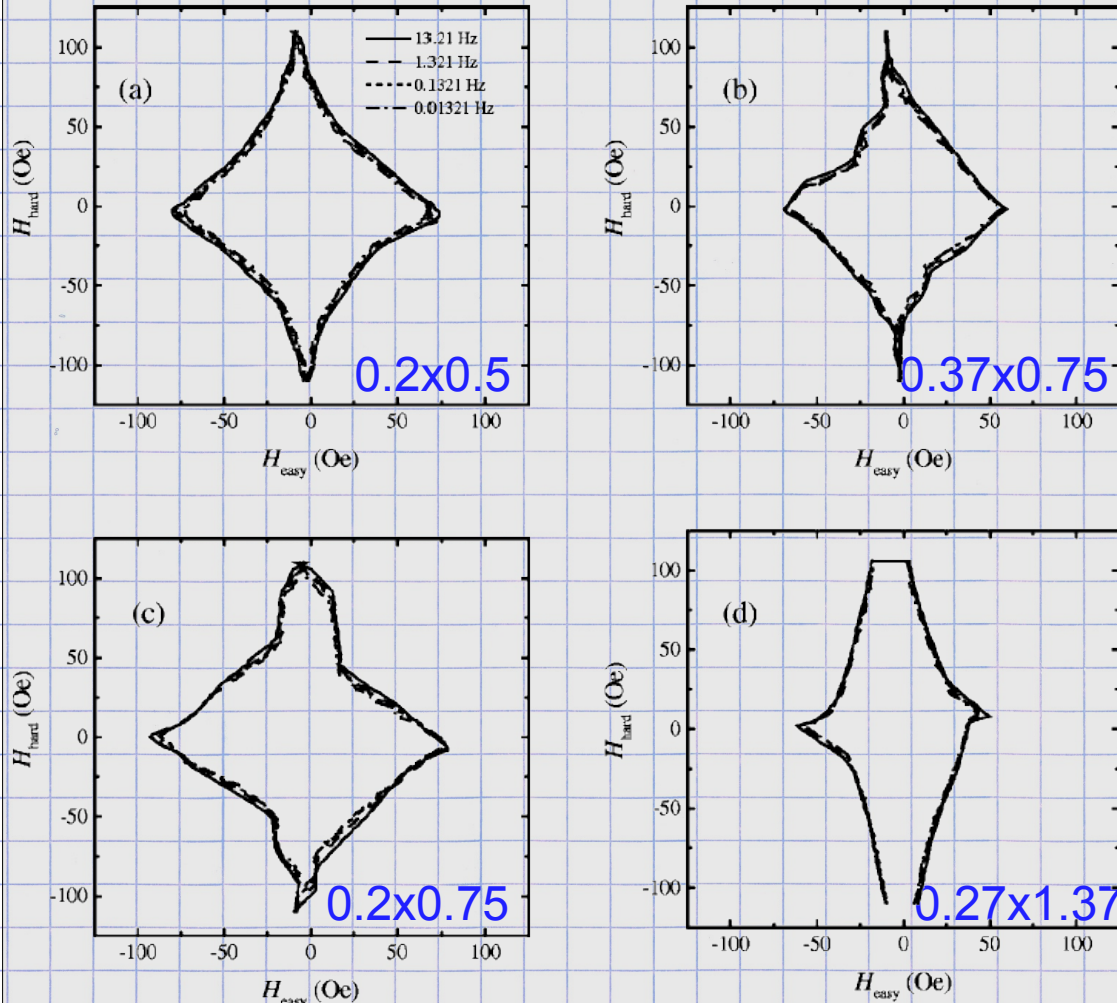


M. Jamet et al., PRB69, 024401 (2004)

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)

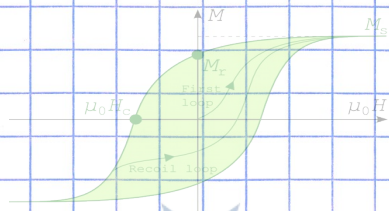
Conclusion over coherent rotation

↪ The simplest model

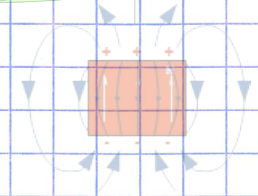
↪ Fails for most systems because they are too large: **apply model with great care!..**

↪ $H_c \ll H_a$ for most large systems (thin films, bulk): **do not use H_c to estimate K!**

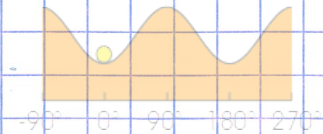
Early known as **Brown's paradox**



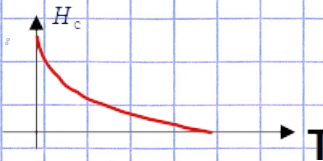
⇒ Motivation for understanding magnetization switching



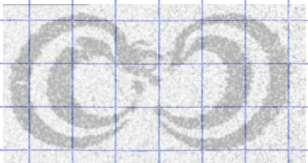
⇒ Magnetostatics



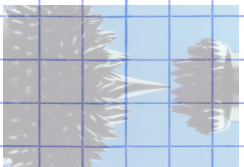
⇒ Stoner-Wohlfarth model



⇒ Thermal activation



⇒ Precessional switching



⇒ Applications of macrospins (nanoparticles)

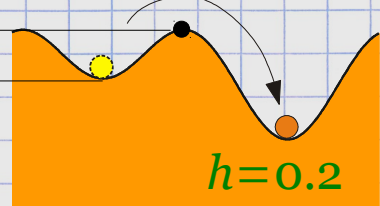


Barrier height

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

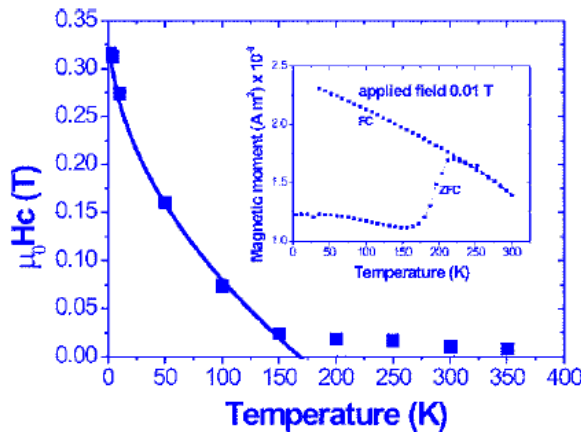
Δe

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



$h=0.2$

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



Thermal activation

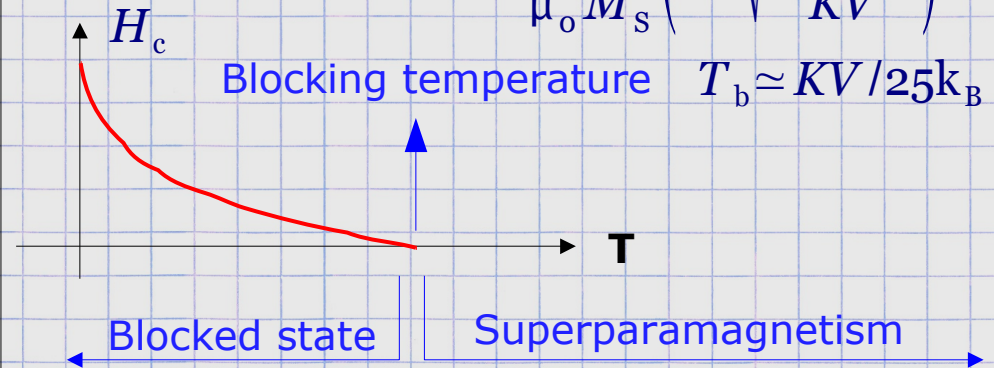
Brown, Phys.Rev.130, 1677 (1963)

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

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

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

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



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



Formalism

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

Energy

$$\mathcal{E} = KV f(\theta, \varphi) - \mu_0 \mu H$$

Partition function

$$Z = \sum \exp(-\beta \mathcal{E})$$

Average moment

$$\langle \mu \rangle = \frac{1}{\beta \mu_0 Z} \frac{\partial Z}{\partial H}$$

Isotropic case

$$Z = \int_{-\mathcal{N}}^{\mathcal{N}} \exp(\beta \mu_0 \mu H) d\mu$$

Note: equivalent to integration over solid angle

$$\langle \mu \rangle = \mathcal{N} \left[\coth\left(x - \frac{1}{x}\right) \right]$$

Langevin function

Note:

Use the moment $\mathcal{N}$ of the particule, not spin $\frac{1}{2}$.

$$x = \beta \mu_0 \mathcal{N} H$$

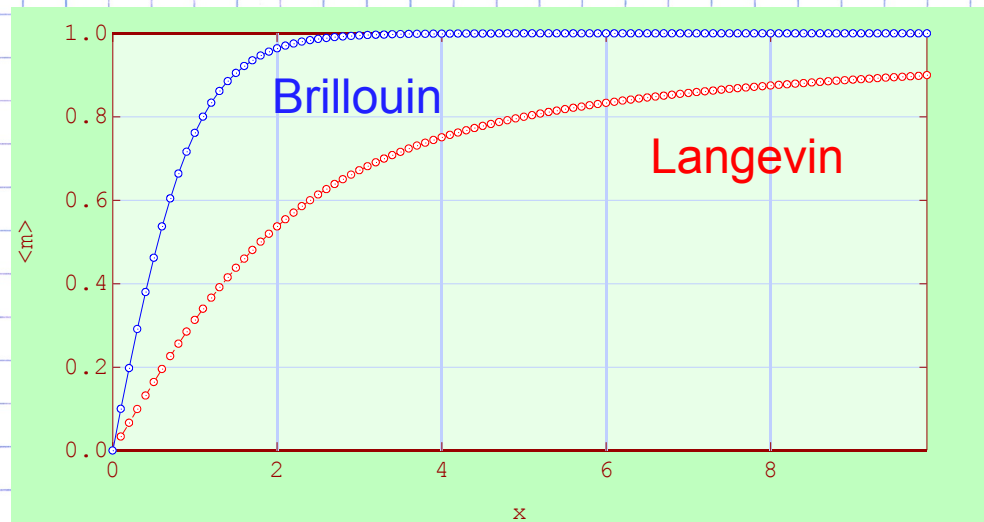


Infinite anisotropy

$$Z = \exp(\beta \mu_0 \mathcal{N} H) + \exp(-\beta \mu_0 \mathcal{N} H)$$

$$\langle \mu \rangle = \mathcal{N} \tanh(x)$$

Brillouin $\frac{1}{2}$ function



REVIEW : S. Bedanta & W. Kleemann, Supermagnetism, J. Phys. D: Appl. Phys., 013001 (2009)



Properties (including thermal) of usual magnetic materials

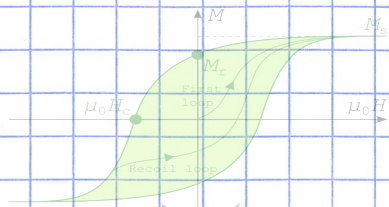
Material	T_C (K)	M_s (kA/m)	$\mu_0 M_s$ (T)	K (kJ/m ³)	D_{300K} (nm)
Fe	1043	1730	2.174	48	16
Co	1394	1420	1.784	530	7.2
Ni	631	490	0.616	-4.5	35
Fe ₂₀ Ni ₈₀ (Permalloy)	850	835	1.050	≈ 0	—
Fe ₃ O ₄	858	480	0.603	-13	25
BaFe ₁₂ O ₁₉	723	382	0.480	250	9.2
Nd ₂ Fe ₁₄ B	585	1280	1.608	4900	3.4
SmCo ₅	995	907	1.140	17000	2.3
Sm ₂ Co ₁₇	1190	995	1.250	3300	3.9
FePt L ₁₀	750	1140	1.433	6600	3.1
CoPt L ₁₀	840	796	1.000	4900	3.4
Co ₃ Pt	1100	1100	1.382	2000	4.6

T_c Curie ordering temperature

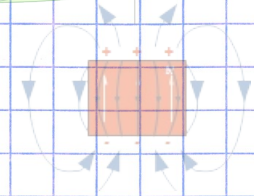
M_s Spontaneous magnetization at 300K

K First magnetocrystalline anisotropy coefficient at 300K

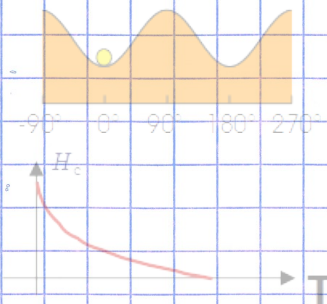
D_{300K} Diameter for superparamagnetic limit at 300K and time constant 1s



⇒ Motivation for understanding magnetization switching

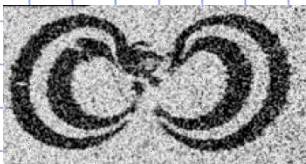


⇒ Magnetostatics

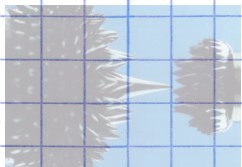


⇒ Stoner-Wohlfarth model

⇒ Thermal activation



⇒ Precessional switching



⇒ Applications of macrospins (nanoparticles)

Basics of precessional switching

Demonstration: 1999

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0| \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

γ_0 Gyromagnetic factor

$$\gamma_0 = \mu_0 \gamma \quad \gamma = -g_J \frac{|e|}{2m_e} < 0$$

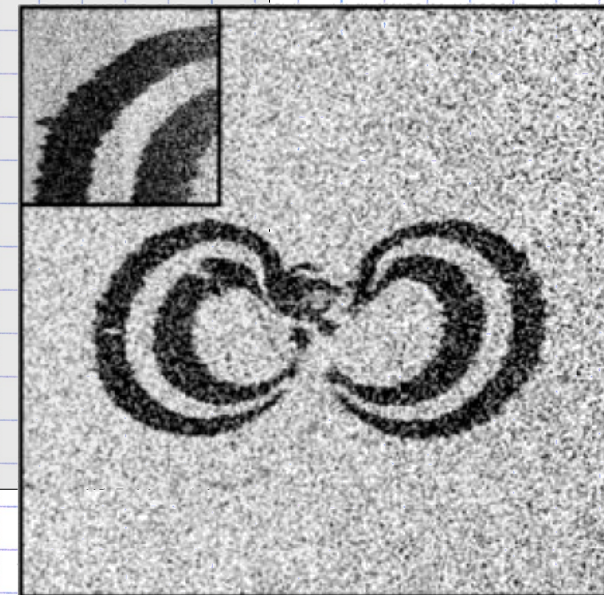
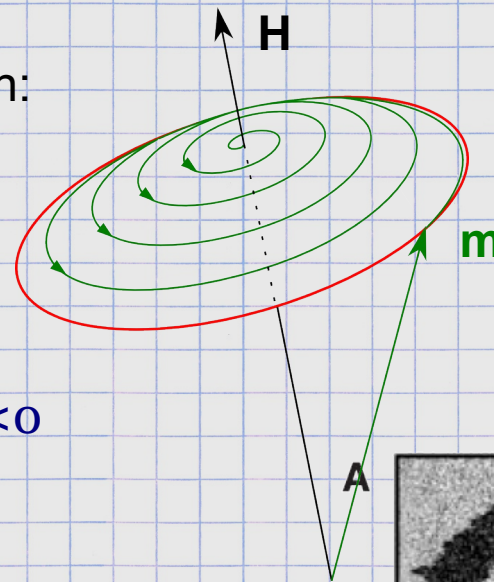
$$|\gamma_0|/2\pi \approx 28 \text{ GHz/T}$$

H_{eff} Effective field
(including applied)

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

α Damping coefficient

$$\alpha = 10^{-1} - 10^{-3}$$

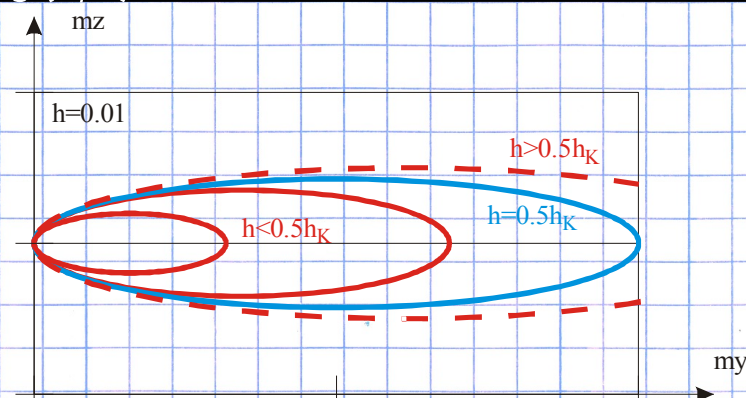
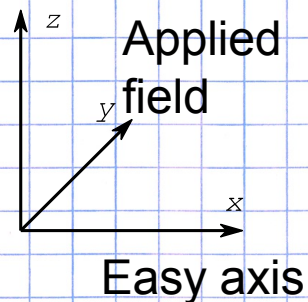


150 μm

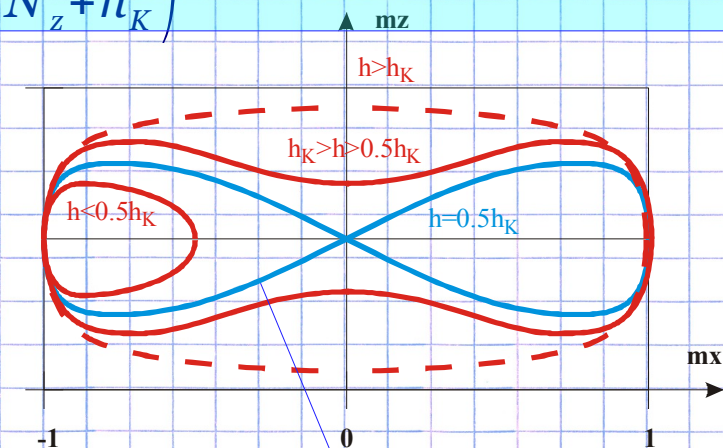
C. Back et al., Science 285, 864 (1999)



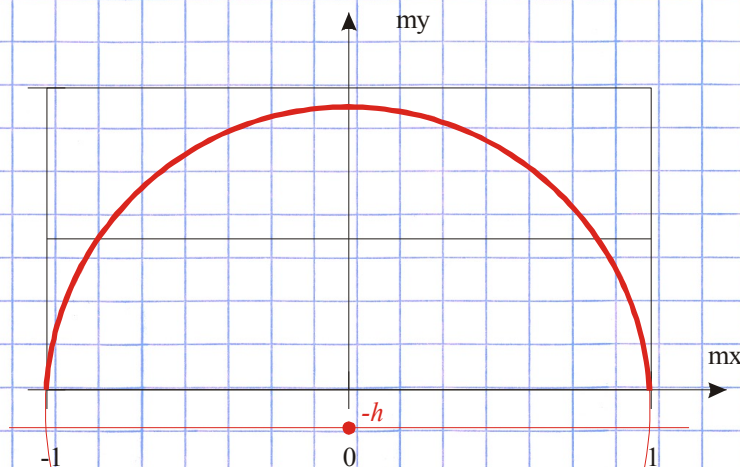
Magnetization trajectories



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



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

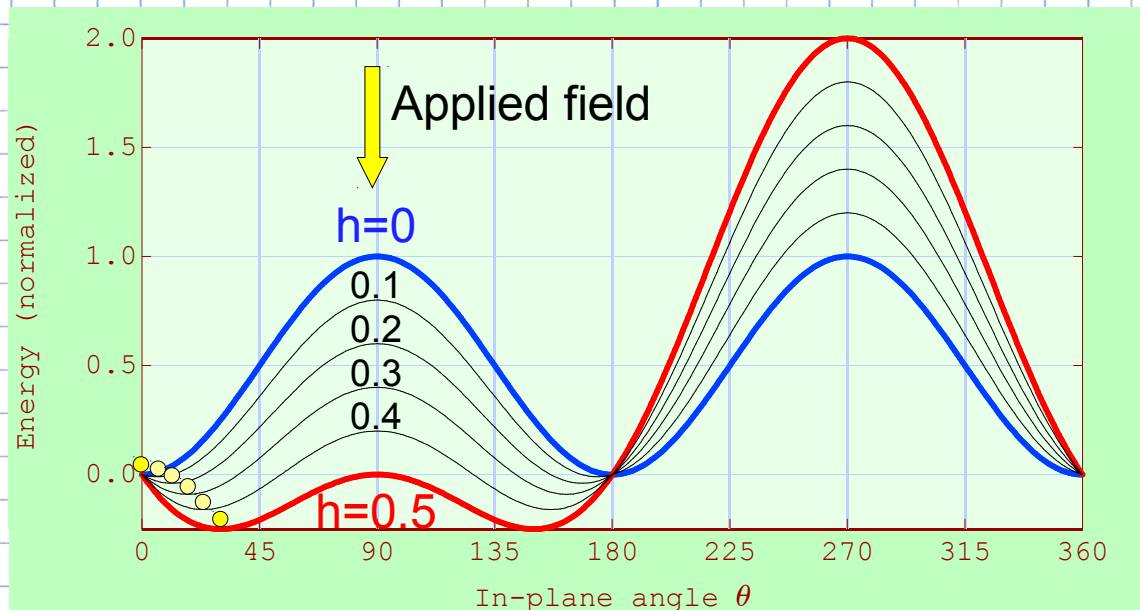


$$m_x^2 + \frac{(m_y + h/N_z)^2}{1 + h_K/N_z} = 1 + \frac{h^2}{N_z(N_z + h_K)}$$

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

$$2\pi/|\gamma| = 35 \text{ ps} \cdot \text{T}$$

➡ 25-500 ps

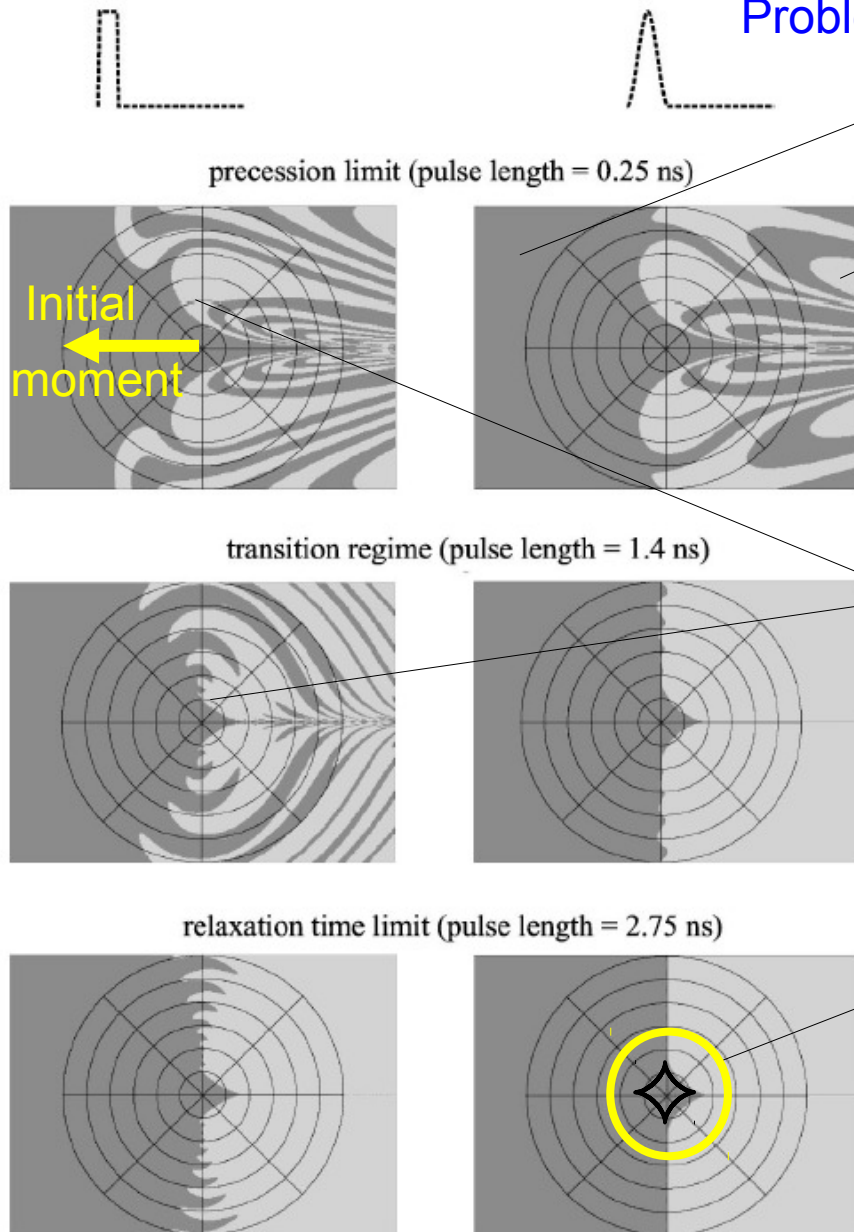
Precession damping

$$1/(2\pi\alpha) \text{ per period}$$

$$\alpha = 0.01 - 0.5$$

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

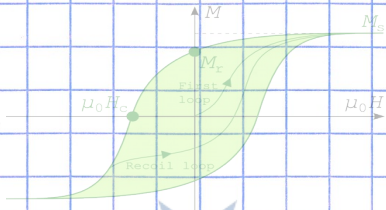
Problems : multiple switching and ringing



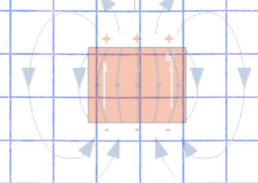
Reversal below the quasistatic value $h=1$ for h_y , and even for $m \cdot h > 0$!

Stoner-Wohlfarth astroid (quasistatic limit)

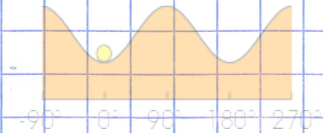
M. Bauer et al., PRB61, 3410 (2000)



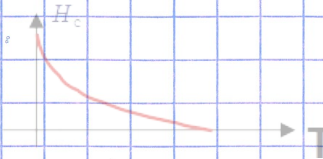
⇒ Motivation for understanding magnetization switching



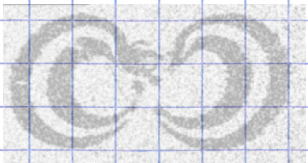
⇒ Magnetostatics



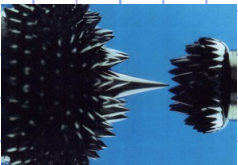
⇒ Stoner-Wohlfarth model



⇒ Thermal activation



⇒ Precessional switching



⇒ Applications of macrospins (nanoparticles)



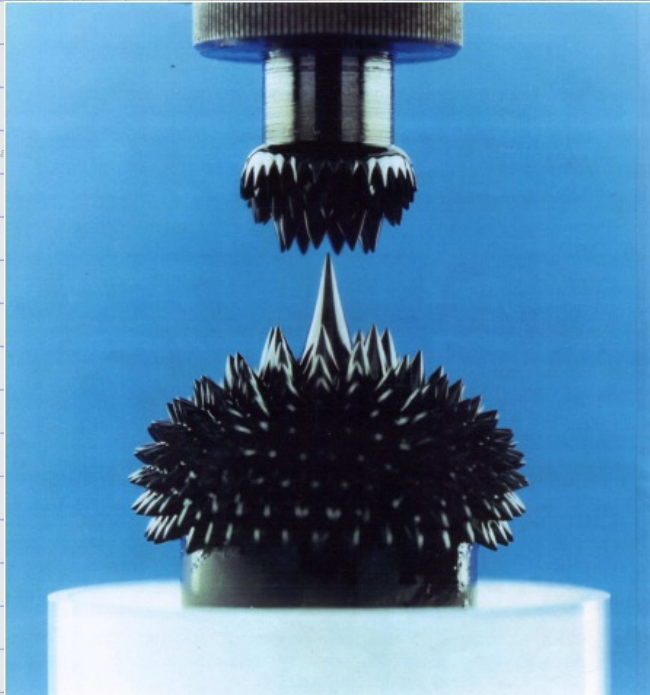
Ferrofluids

⇒ Principle

Surfactant-coated nanoparticles,
preferably superparamagnetic

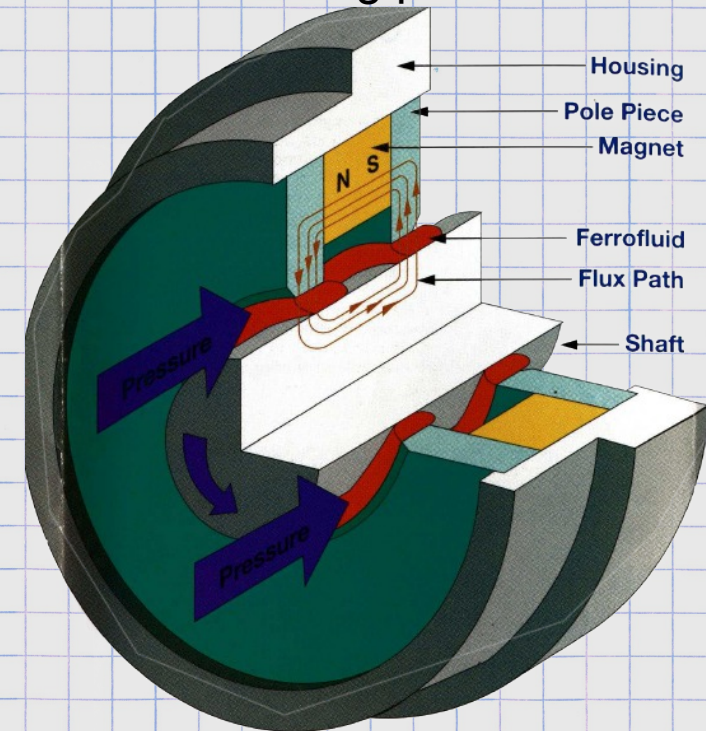
→ Avoid agglomeration of the particles

→ Fluid and polarizable



⇒ Example of use

Seals for rotating parts



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

<http://magnetism.eu/esm/2007-cluj/slides/vekas-slides.pdf>

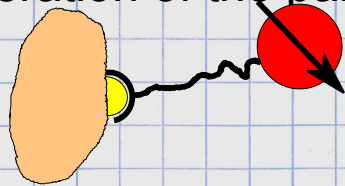
Health and biology

Beads = coated nanoparticles,
preferably superparamagnetic

→ Avoid agglomeration of the particles

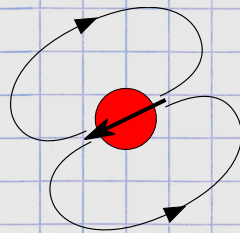
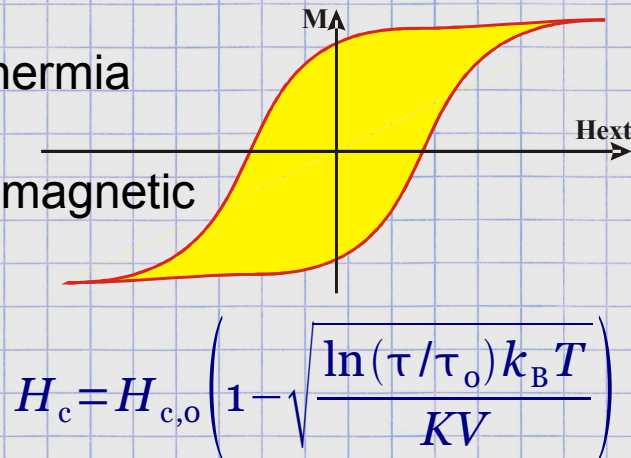
⇒ Cell sorting

$$\mathbf{F} = \nabla \mu \cdot \mathbf{B}$$



⇒ Hyperthermia

Use ac magnetic
field



RAM (radar absorbing materials)

⇒ Principle

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

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

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

