Nanomagnetism
Part 4 – Learn from loops

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Manipulation of magnetic materials:

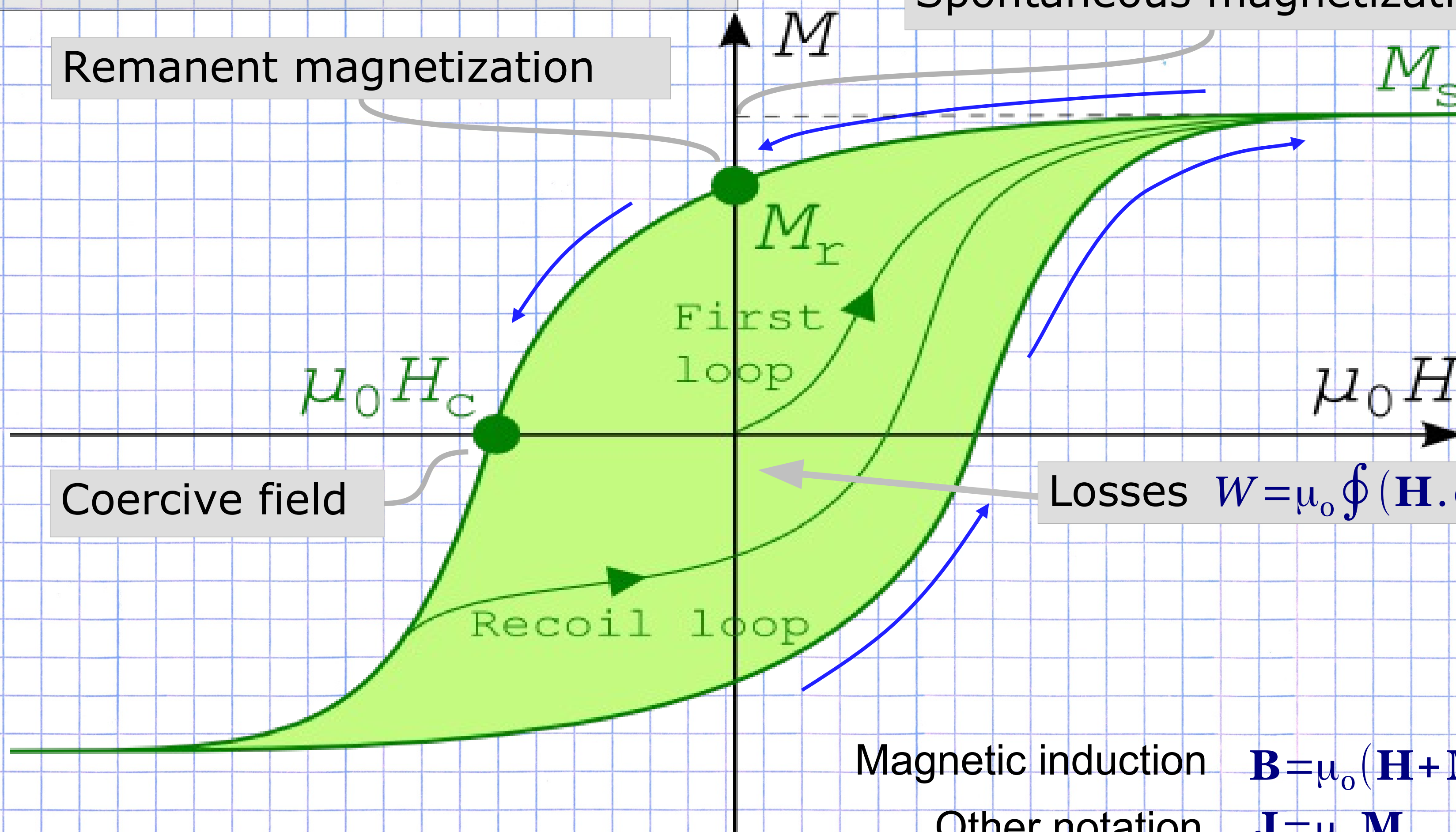
↳ Application of a magnetic field

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

Spontaneous ≠ **S**aturation

Spontaneous magnetization

Remanent magnetization



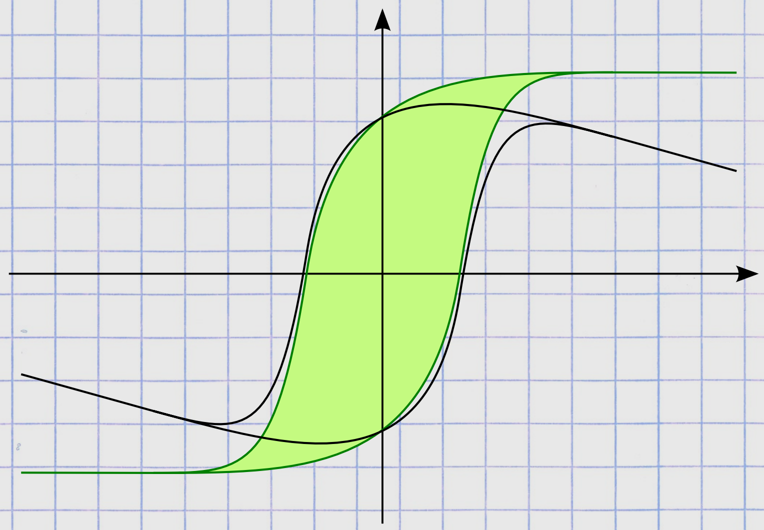
Coercive field

Losses $W = \mu_0 \oint (\mathbf{H}.\mathrm{d}\mathbf{M})$

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

Other notation $\mathbf{J} = \mu_0 \mathbf{M}$

Diamagnetic substrate / holder

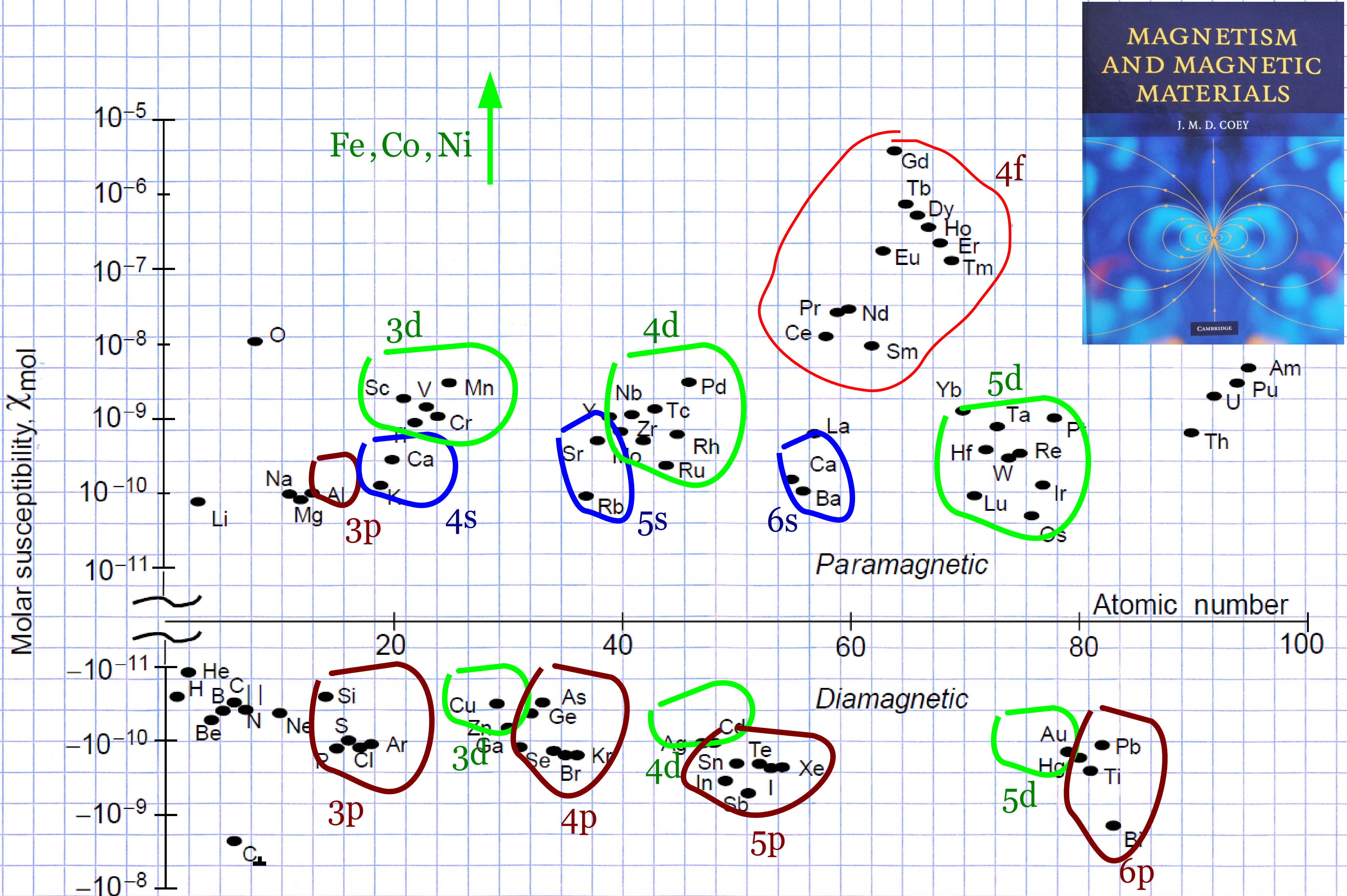


$$M(H) \leftarrow M(H) - \chi H$$

Problems :

⇨ Quantitative compensation a priori difficult

⇨ Approach to saturation difficult to investigate


Fe, Co, Ni
Molar susceptibility, χ_{mol}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
-10^{-11}
-10^{-10}
-10^{-9}
-10^{-8}
Atomic number
20
40
60
80
100
Paramagnetic
Diamagnetic
3d
4d
5d
4f
3p
4s
5s
6s
4p
5p
6p
Li
O
Na
Mg
Al
Sc
V
Mn
Cr
Ca
K
Sr
Rb
Nb
Pd
Tc
Zr
Rh
Ru
Pr
Nd
Ce
Sm
Gd
Tb
Dy
Ho
Er
Eu
Tm
La
Ca
Ba
Yb
Ta
Hf
Re
W
Ir
Lu
Am
Pu
U
Th
He
H
B
C
Be
N
Ne
Si
S
Ar
Cl
Cu
Ga
As
Ge
Se
Br
Te
Sn
Xe
In
I
Sb
Au
Pb
Ti
Bi
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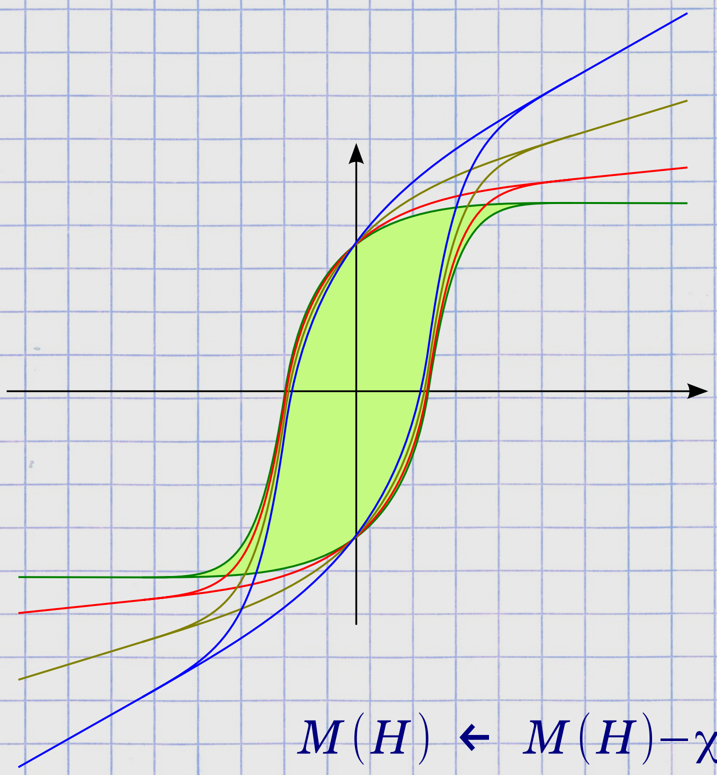
Paramagnetic substrate / holder



$$M(H) \leftarrow M(H) - \chi(T)H$$

- Example : ions impurities in metals, and oxides
- Problem : temperature dependent, non-linear

Example:

- 1nm ferro layer
- 1ppm in 1mm support

Paramagnetic substrate / holder

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Journal of Magnetism and Magnetic Materials 301 (2006) 50–66

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Magnetism of cigarette ashes

Neli Jordanova[a,*], Diana Jordanova[a], Bernard Henry[b], Maxime Le Goff[b], Dimo Dimov[c], Tsenka Tsacheva[d]

⇨ Be careful with : cleaness, tweezers, holders, ink, etc.

Artifacts in various techniques

⇨ X-ray Magnetic Circular Dichroism (XMCD)

⇨ Magneto-Optical Kerr Effect (MOKE)

⇨ Lorentz microscopy

⇨ Etc.

Case of a bulk soft magnetic material

Hypotheses:

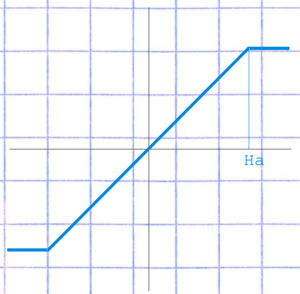
1. Use an ellipsoid, cylinder or slab along a main direction so that the demagnetizing field may be homogeneous.

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

Density of energy: $E_{tot} = E_d + E_Z$

$$E_{tot} = \frac{1}{2}\mu_o N M_{eff}^2 - \mu_o M_{eff} H_{ext}$$

Minimization: $$\frac{\partial E_{tot}}{\partial M_{eff}} = \mu_o N M_{eff} - \mu_o H_{ext}$$ ⇒ $$M_{eff} = \frac{1}{N} H_{ext}$$

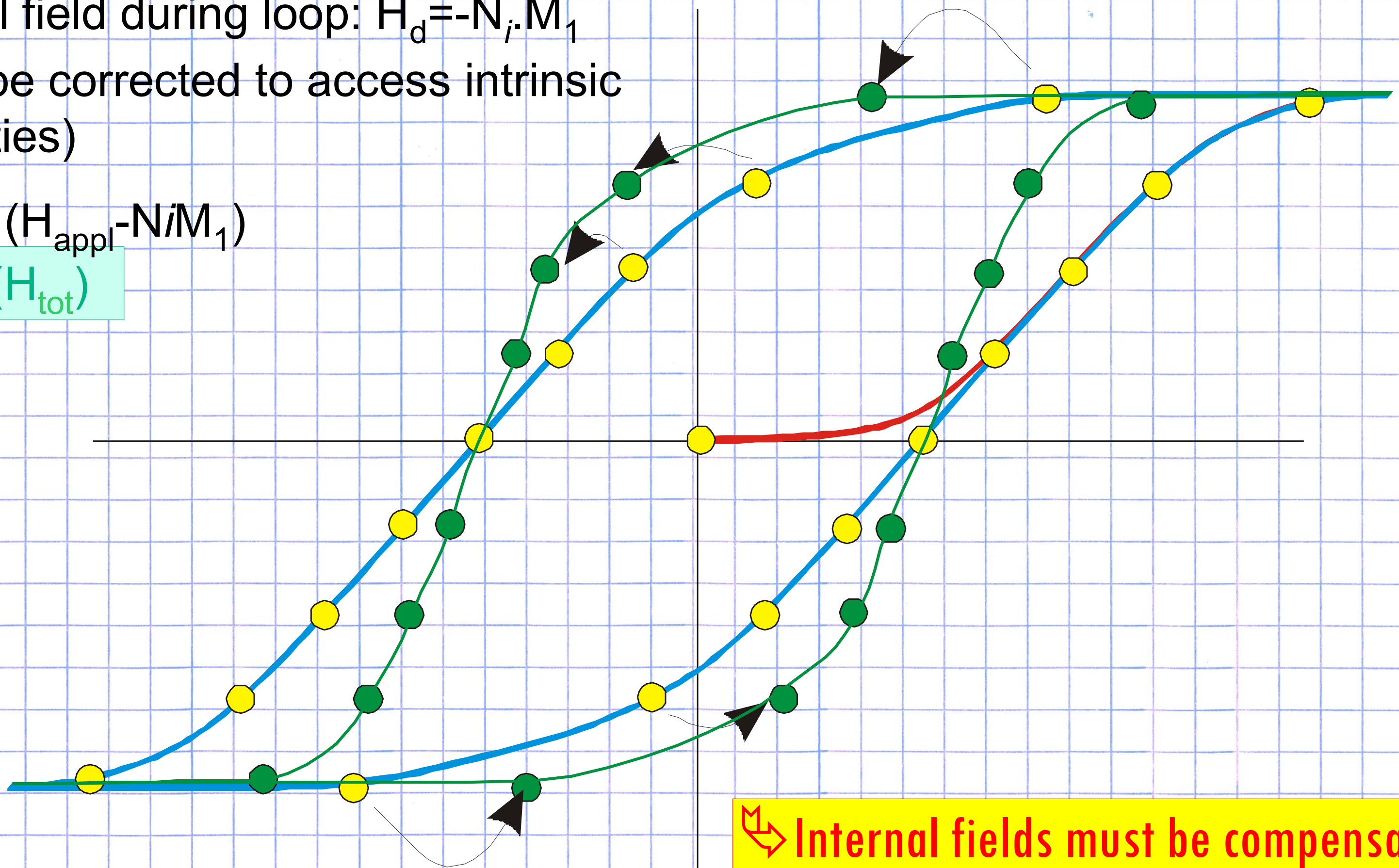


Conclusion for soft magnetic materials

Susceptibility is constant and equal to 1/N

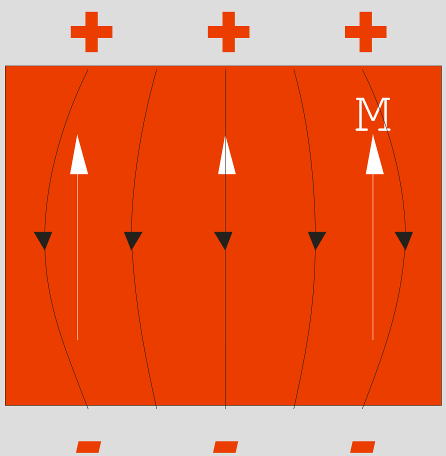
Case of an arbitrary material

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 $M_1(H_{appl}-N_iM_1)$
   ➡ $M_2(H_{tot})$

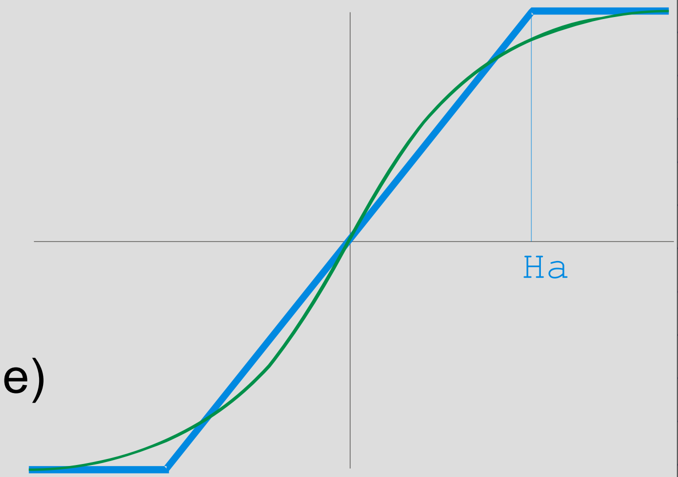


Internal fields must be compensated

Specific aspects to systems with non-ellipsoidal shapes



In a non-ellipsoidal (or cylindrical, slab) system the demagnetizing field is not homogeneous in magnitude nor direction



1. Initial slope higher than 1/N (demag field smaller than average)

2. Late slope smaller than 1/N (demag field larger than average)

Demagnetizing energy (thus area above loop) is identical $E_\mathrm{d} = \int_0^{M_\mathrm{s}} \mu_0 H_\mathrm{ext} \mathrm{d}M = \frac{1}{2}\mu_0 N M_\mathrm{s}^2$

In a non-ellipsoidal sample (or cylinder, slab) the loop is overcompensated at low magnetization and undercompensated at high field, even for soft magnetic materials.

This effect adds up to the previous effect of grain shape

P. O. Jubert, O. Fruchart et al., Europhys. Lett. 63, 102-108 (2003)

Magnetization loop of a macrospin along a hard axis

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

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

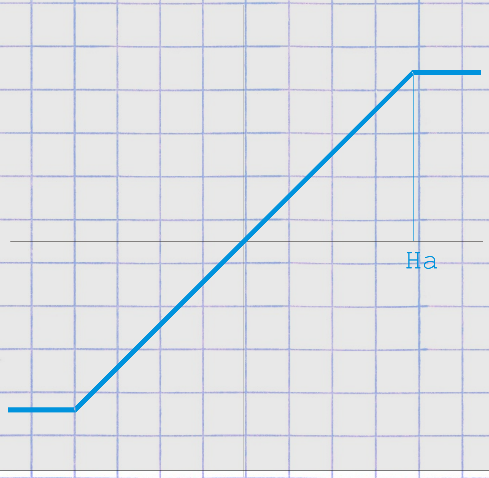
Hard axis: $\theta_H = \pi / 2$

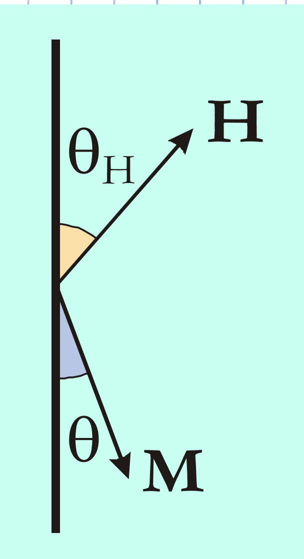
$$e = \sin^2(\theta) - 2h\sin(\theta)$$

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

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

Equilibrium position

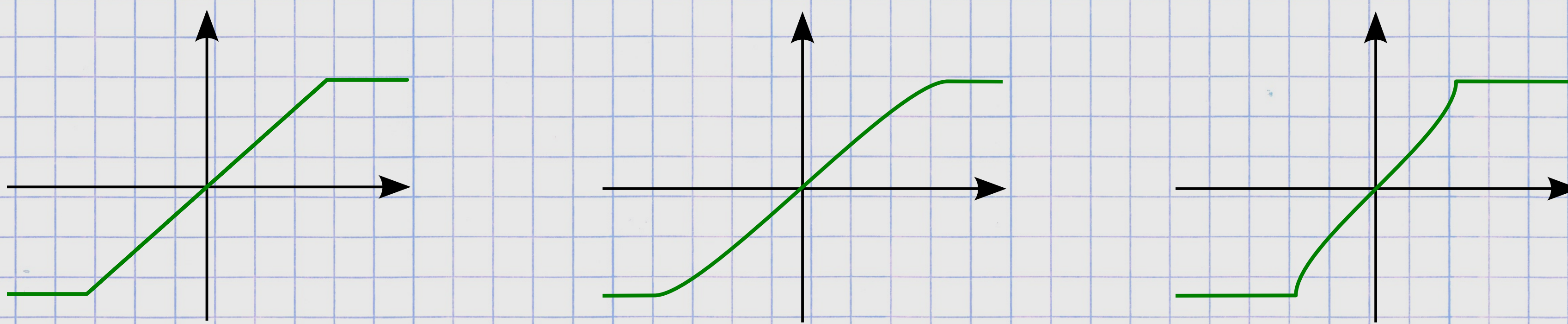




Loops

$$E_{mc} = K_1 \sin^2\theta + K_2 \sin^4\theta + \ldots$$

$$K_1 > 0$$

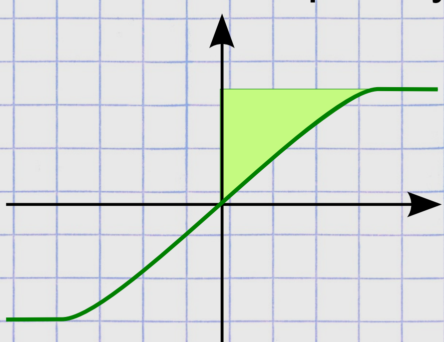


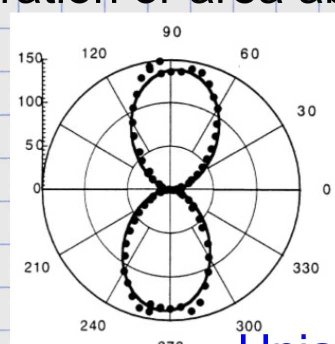
$K_2 = 0$ $\qquad$ $K_2 > 0$ $\qquad$ $K_2 < 0$

Means of analysis

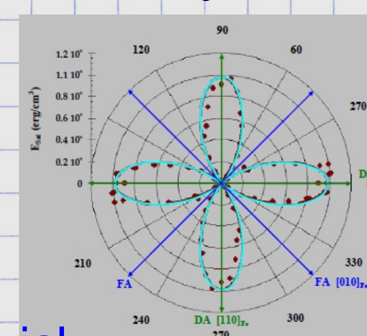
⇨ Fit curve $H(M)$ (is analytical)

⇨ Initial susceptibility + saturation or area above curve as $E_{sat} - E_0 = \mu_0 \oint (\mathbf{H} . \mathrm{d}\mathbf{M})$





Uniaxial



Biaxial

Distribution

- Use area above curve
- Singular point detection for saturation field

G. Asti et al., J. Appl. Phys. 45, 3600 (1974)

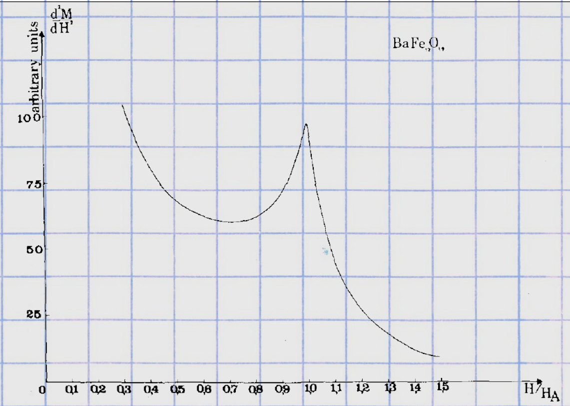
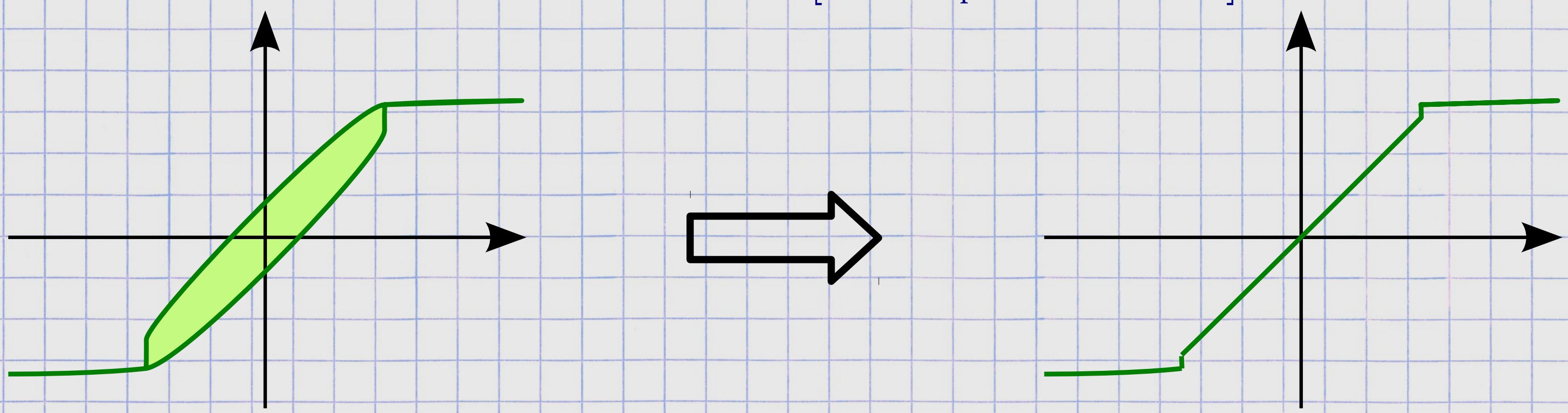


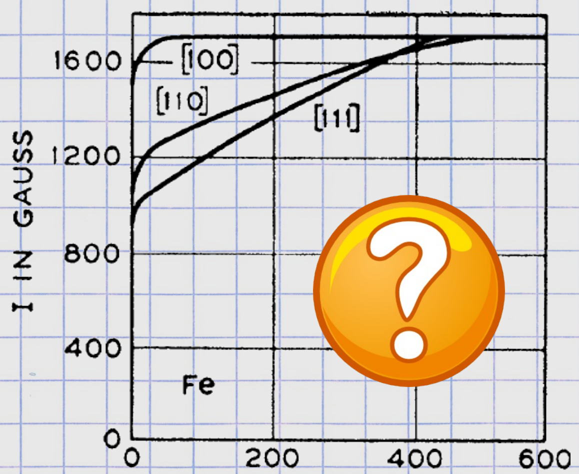
FIG. 5. Experimental plot of d^2M/dH^2 vs $H = H_{ext} - NM$ for an isotropic polycrystalline sample of $BaFe_{12}O_{19}$. H_{ext} is the applied field, and N denotes the demagnetizing factor of the sample.

Residual hysteresis

- Compute anhysteretic curve $M(H) \rightarrow [M(H_{up}) + M(H_{down})]/2$



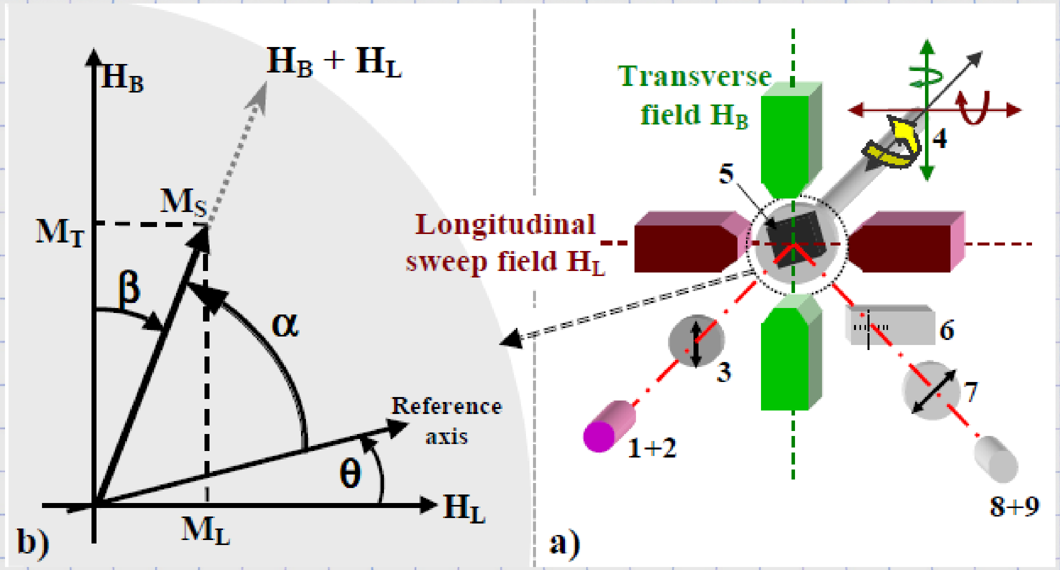
Issue



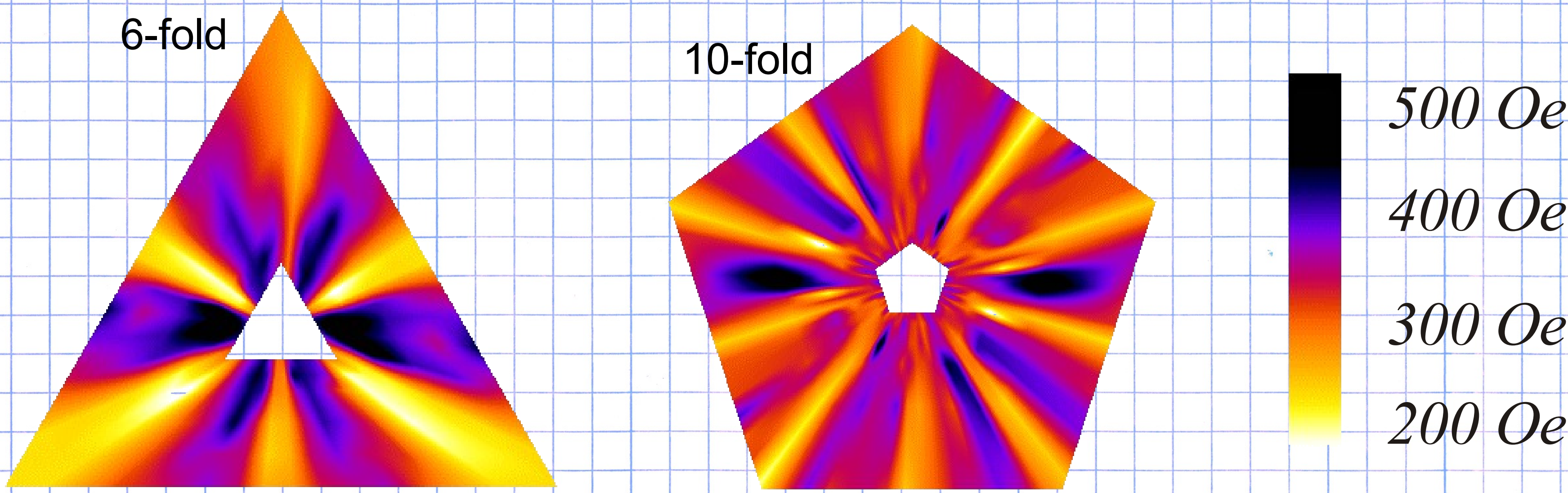
- High remanence in all directions
- Fit over small part of loop → sensitive to imperfections
- Solution : loop under transverse bias field

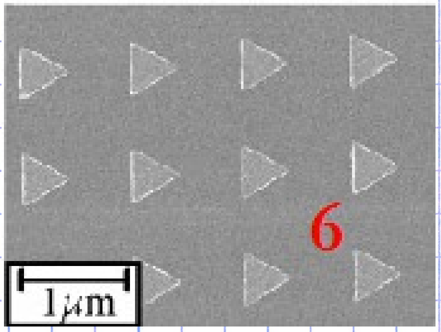
Solution

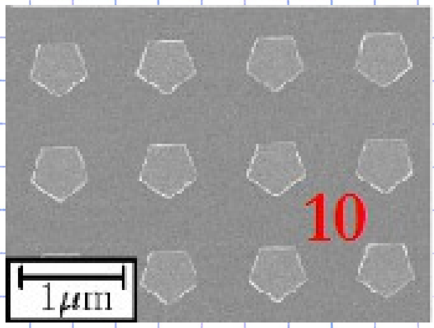
TBIIST: Transverse Bias Initial Inverse Susceptibility and Torque



D. Berling, J. Magn. Magn. Mater. 297, 118 (2006)



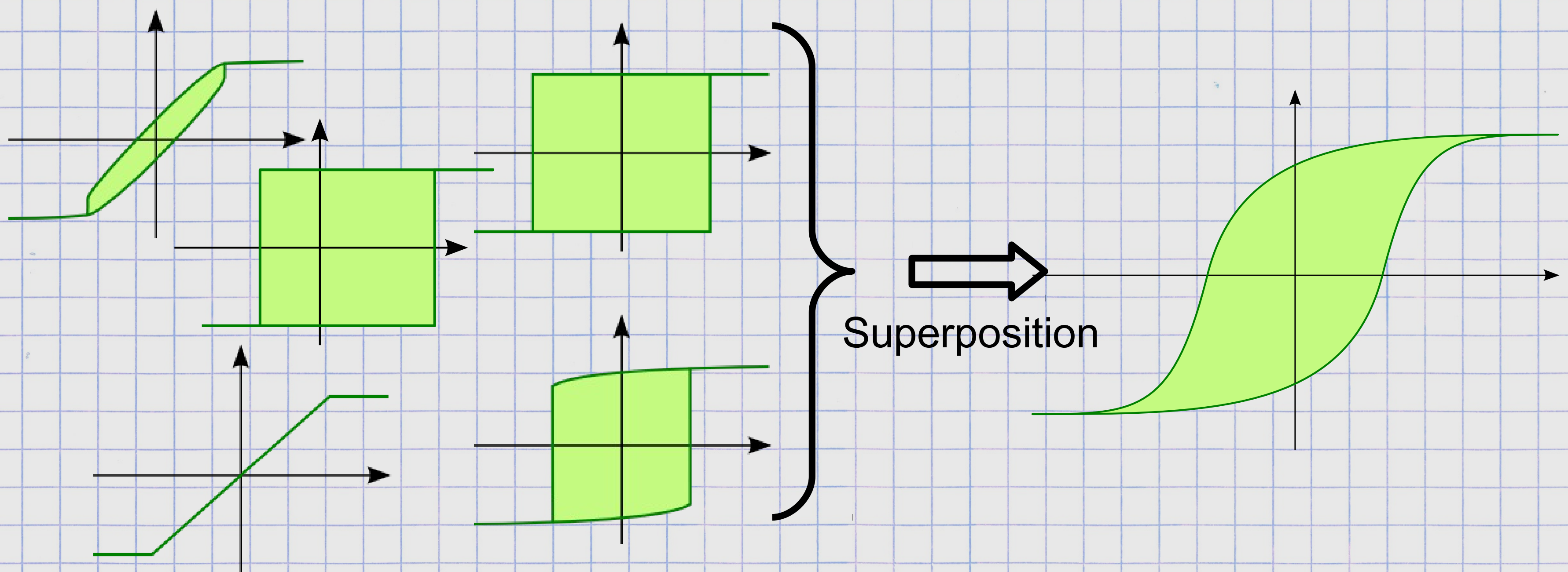




R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Physics : coercivity determined dual grains

⇨ Different loops with distribution



Possible effects that may arise

- Distribution of coercive fields
- (Dipolar) interactions
- The loops of the macrospins are slanted

Textbook case

- Uniaxial anisotropy, second order : $E_{\mathrm{mc}} = K \sin^2\theta$
- Fully remanent grains

3D distribution

- Remanence : $m_{\mathrm{r}}^{\mathrm{3D}} = 1/2$
- Measured anisotropy : $\langle K^{\mathrm{3D}} \rangle = 2\mathrm{K}/3$

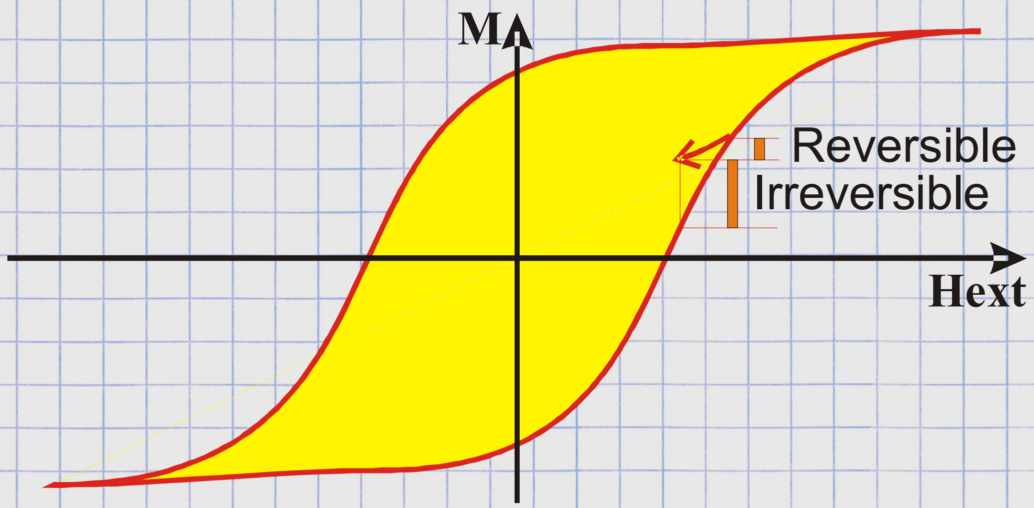
2D distribution

- Remanence : $m_{\mathrm{r}}^{\mathrm{3D}} = 2/\pi$
- Measured anisotropy : $\langle K^{\mathrm{3D}} \rangle = K/2$

Use

- Distribution : estimate K
- Interactions : impact on increased or decreased remanence

Distribution of properties



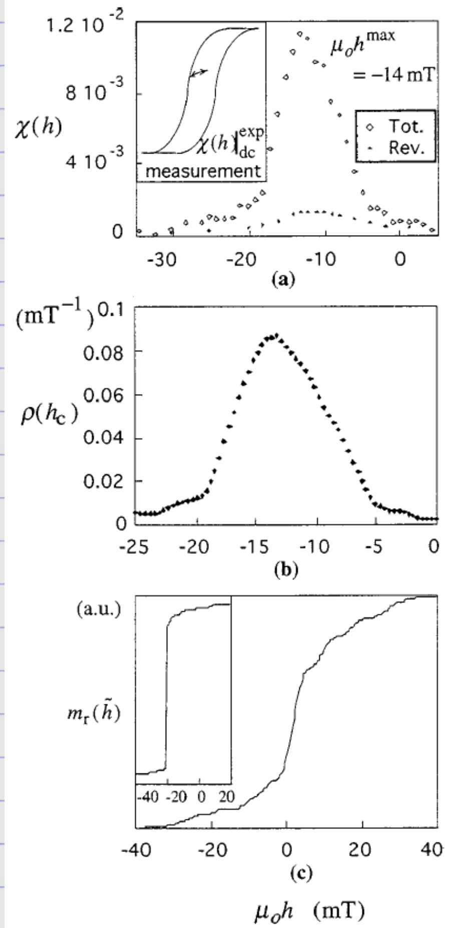
$$\rho(H_r) = \left.\frac{dm}{dH}\right|_{\mathrm{irreversible}}$$

Hc(T) for a given population of the distribution can be studied at a given stage of the reversal (10%, 20% etc.)

Effect of distributions and dipolar interactions are sometimes difficult to disentangle

Reconstruct average single hysteresis loop

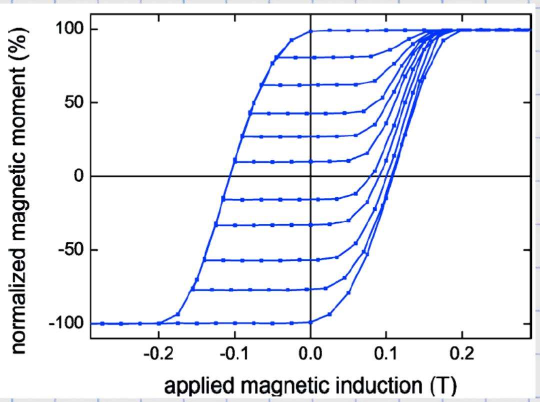
Ultrathin Fe(110) dots



O. Fruchart et al.,
Phys. Rev. B 57, 2596 (1998)

Susceptibility or distribution ?

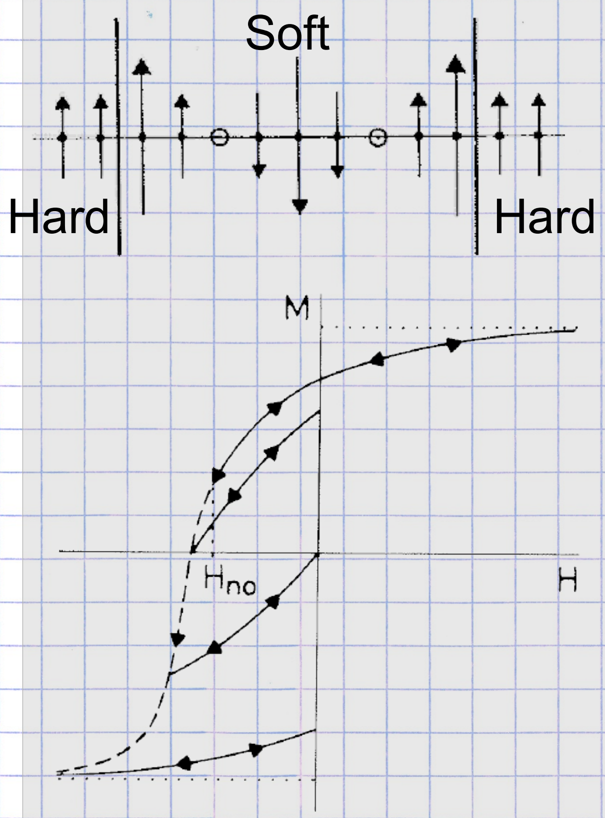
Arrays of electroplated parallel Ni nanowires



S. Da-Col et al.,
Appl. Phys. Lett. 98, 112501 (2011)

Scrutinize multiphased materials

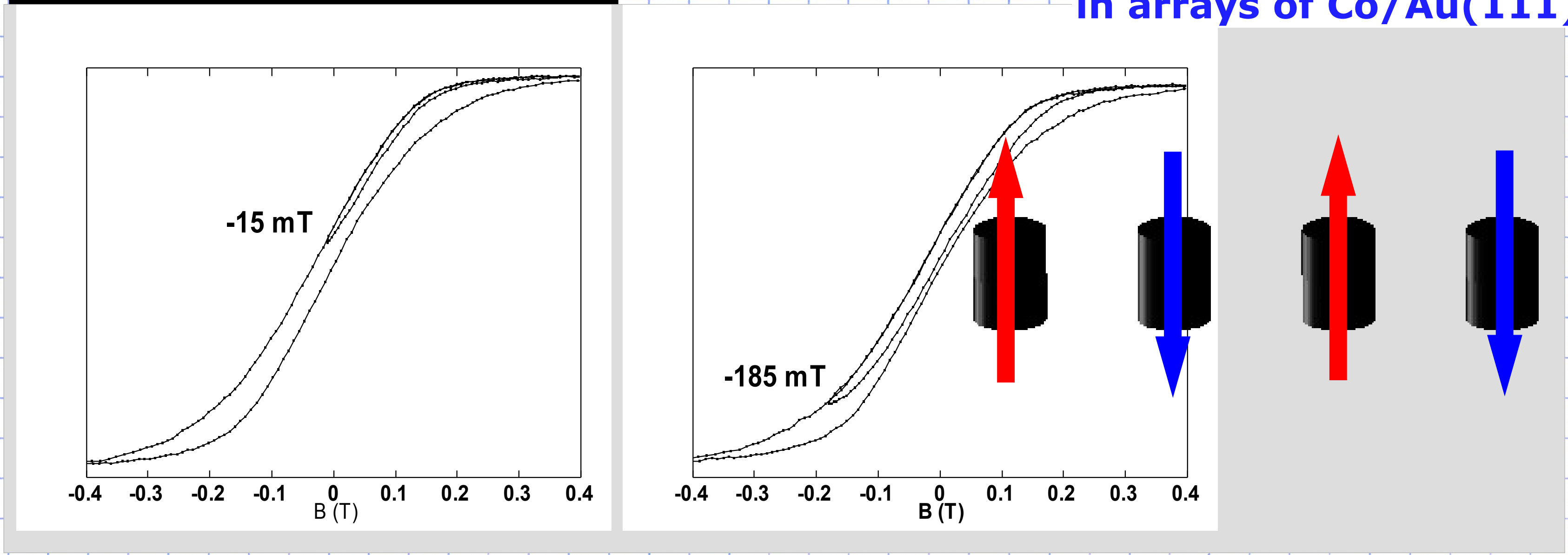
Exchange-spring magnets



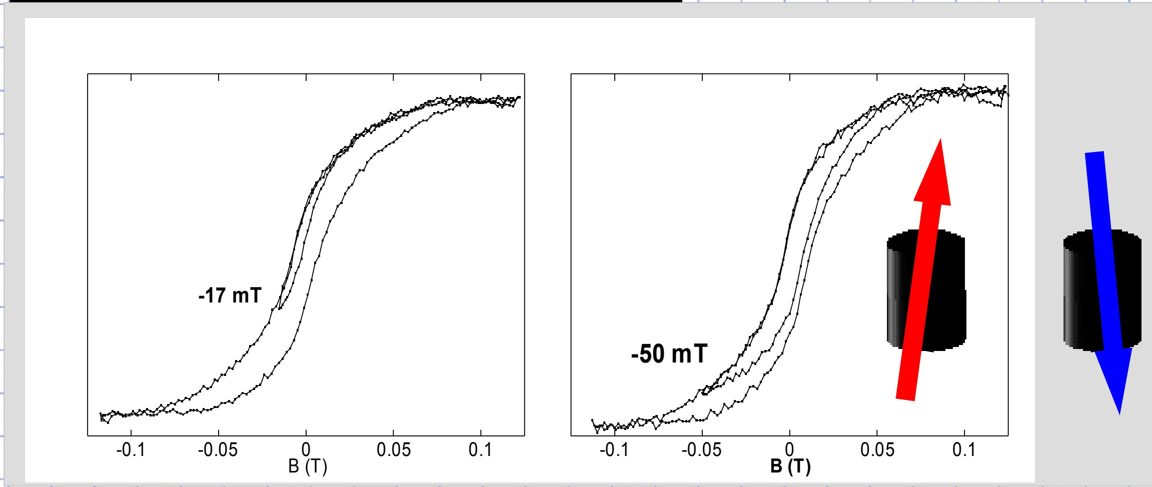
E. Kneller et al.,
IEEE Trans. Magn. 27, 3588 (1991)

Minor loops: negative interactions

Example: dipolar interactions in arrays of Co/Au(111) pillars



Minor loops: negligible interactions



- Faster than Henkel and Preisach
- Other applications: characterization of exchange bias

O. Fruchart et al., unpublished

Henkel plots

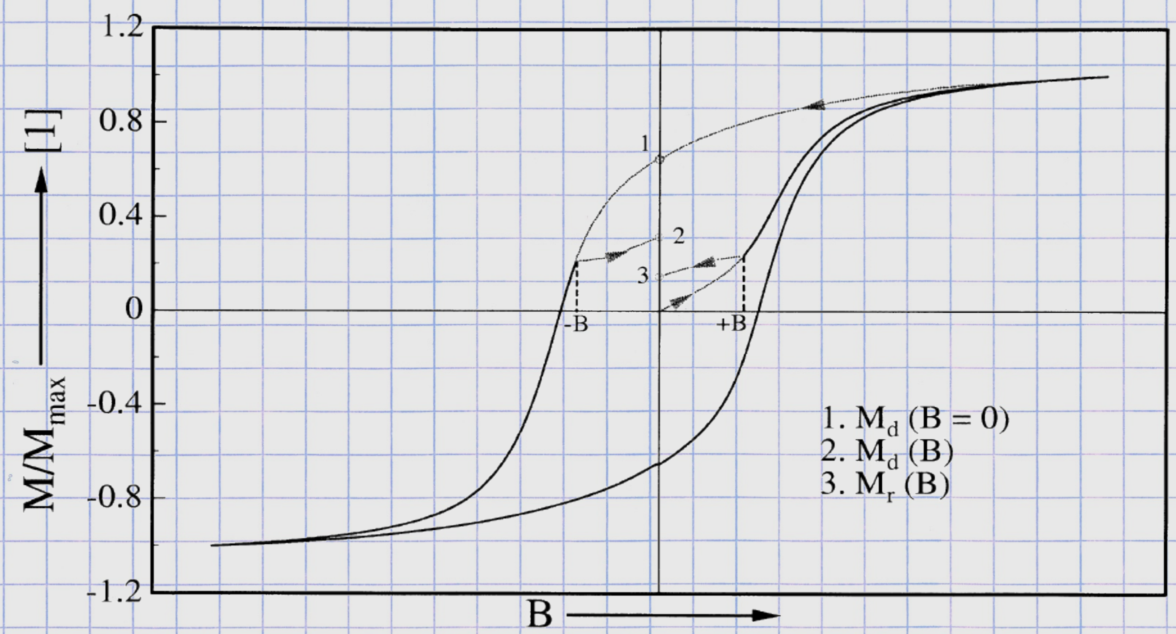


Fig. 1. Explanation of how to measure the two different remanent magnetisations M_r and M_d.

O. Henkel, Phys. Stat. Sol. 7, 919 (1964)
S. Thamm et al., JMMM184, 245 (1998)

Measure of dipolar interactions

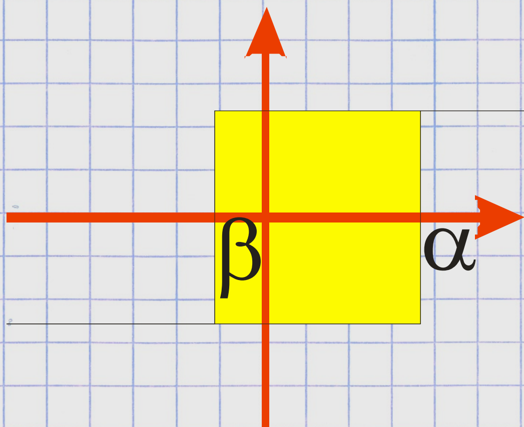
$$\Delta M_H(x) = M_d(x) - [1 - 2M_r(x)]$$

- The analysis of interactions on qualitative
- Long experiments (ac demagnetization)

Preisach model

G. Biorci et al., Il Nuov. Cim. VII, 829 (1958)

I. D. Mayergoyz, Mathematical models of hysteresis, Springer (1991)

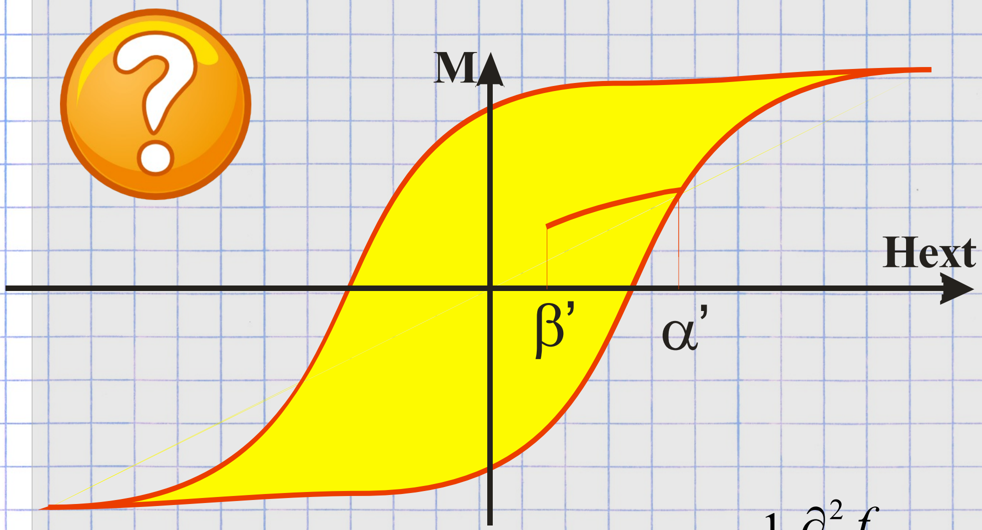


⇨ Distribution function

$\mu(\alpha,\beta)$ with $\alpha > \beta$

⇨ No true link between real particles and μ

Solving



$$\mu(\alpha',\beta') = \frac{1}{2}\frac{\partial^2 f_{\alpha',\beta'}}{\partial\alpha'\partial\beta'}$$

- Long experiments (1D set of hysteresis curves)
- Better suited to bulk materials with strong interactions

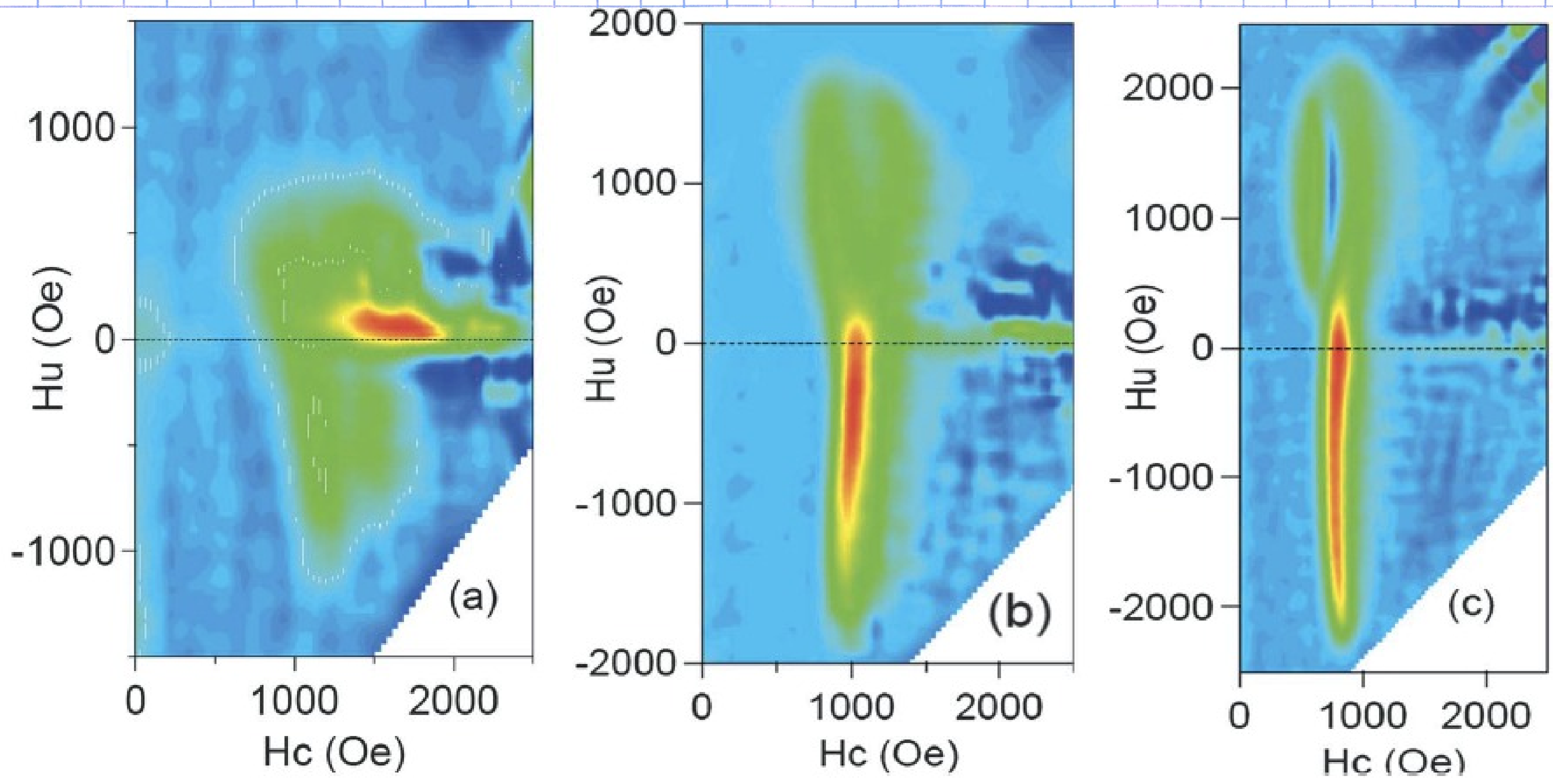
Recent 'rediscovery' or 're-interpretation : the FORc diagrams:

First-Order Reversal Curves

→ Outline distribution of switching field and bias field

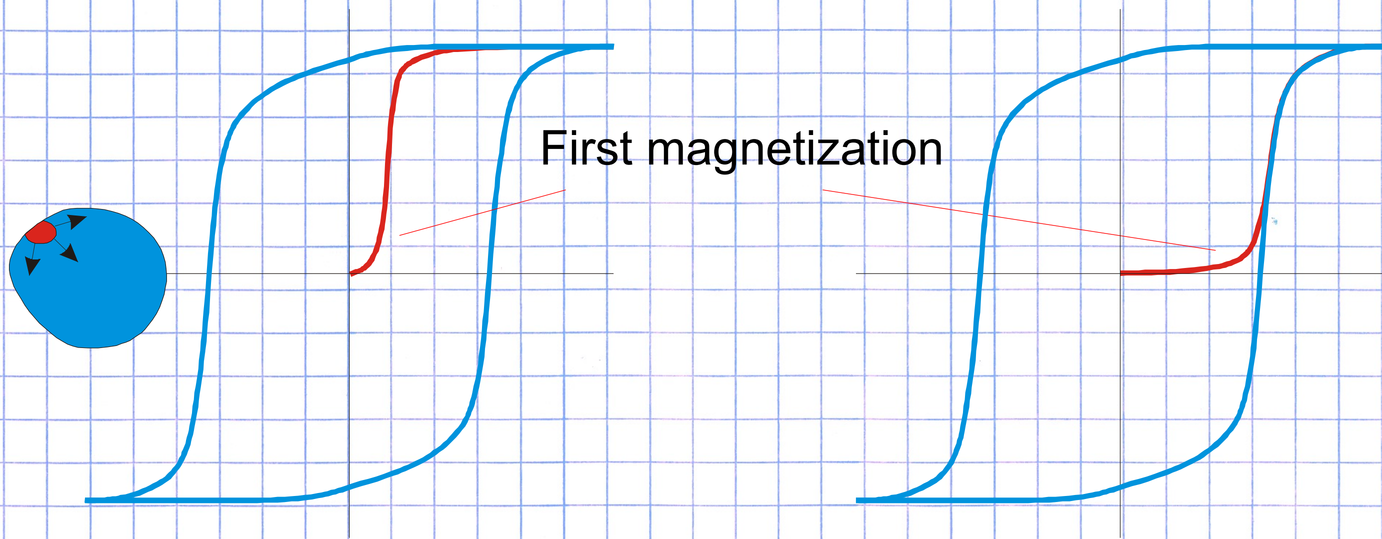
C. Pike et al., J. Appl. Phys. 85, 6668 (1999)

Ex : arrays of parallel permalloy nanowires wire increasing diameter



M. S. Salem et al., J. Mater. Chem. 22, 8549 (2012)

Use first-magnetization curves to determine the type of coercivity

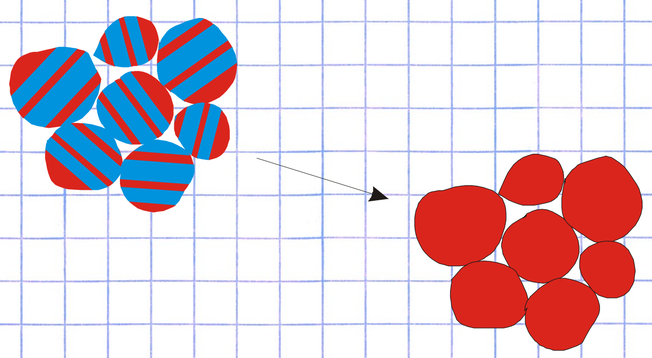


Nucleation-limited

Ex: Sm_2Co_{17}

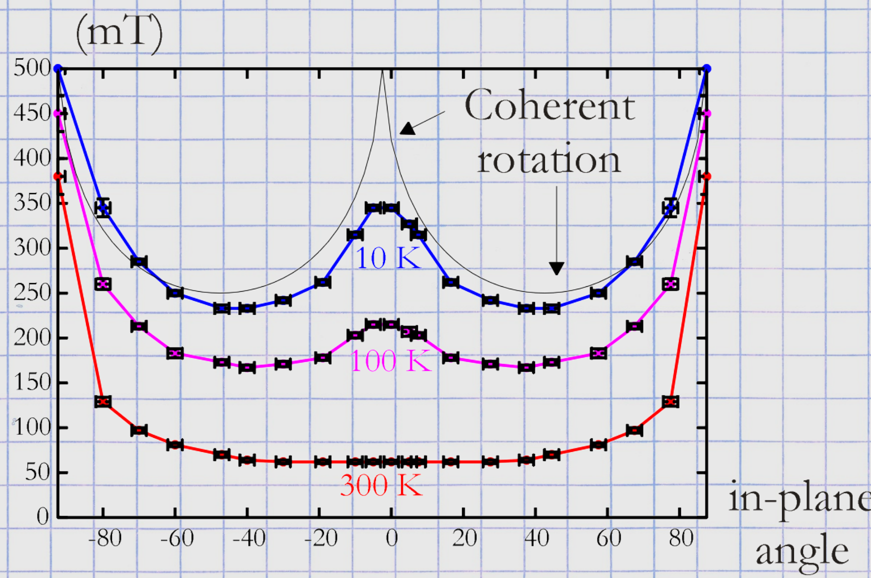
Propagation-limited

Ex: $SmCo_5$



Max(Hc) for easy axis → nucleation

Ultrathin uniaxial Fe(110) dots

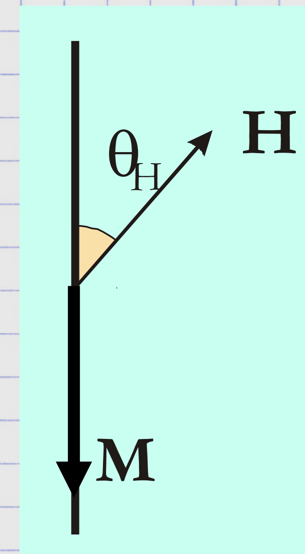


O. Fruchart et al., Phys. Rev. Lett. 82, 1305-1308 (1999)

$1/\cos\theta_H$ law → propagation

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

Hypothesis:

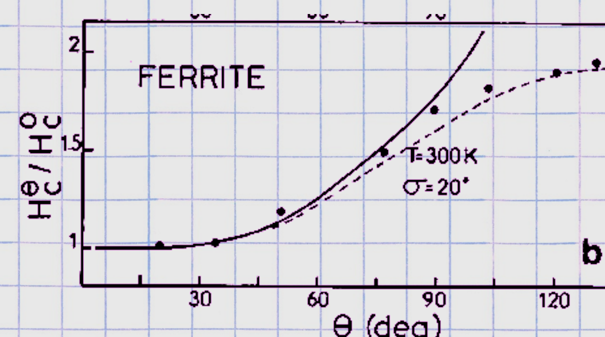


⇨ Based on nucleation volume

⇨ Hc<<Ha

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

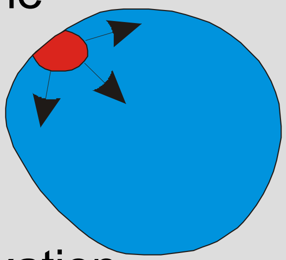
$$E_0 = -\mu_0 M_s v_a H \cos(\theta_H) + 25 k_B T$$



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

Activation volume

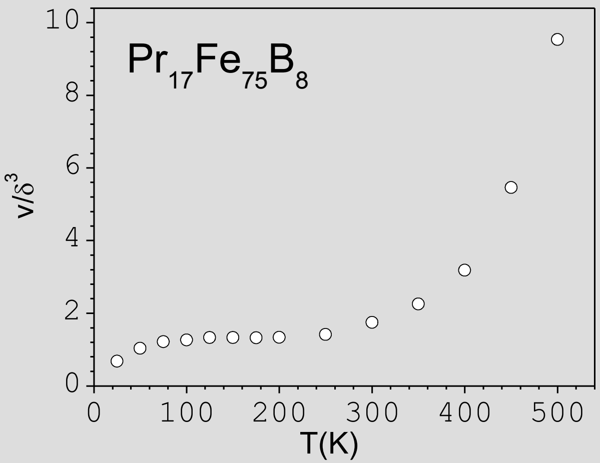
Also called: nucleation volume



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:

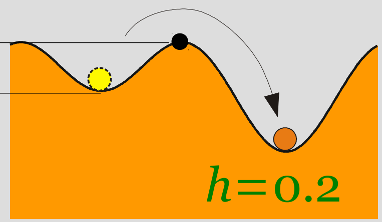
D. Givord et al., JMMM258, 1 (2003)

Barrier height

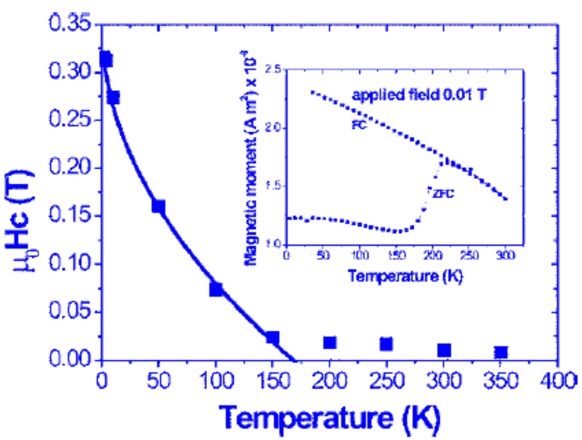
$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$

Δe

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



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



Thermal activation

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

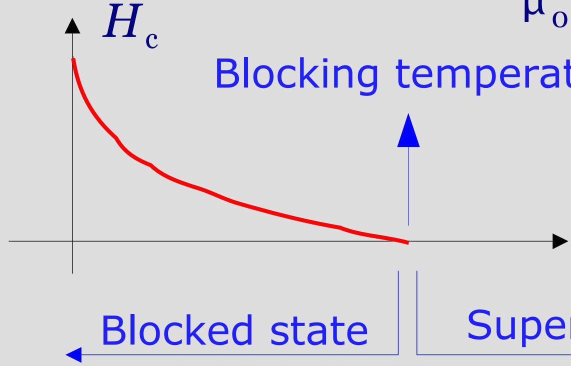
$$\tau = \tau_0 \exp\left(\frac{\Delta \mathscr{E}}{k_B T}\right) \Rightarrow \Delta \mathscr{E} = k_B T \ln(\tau/\tau_0)$$

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

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

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

Blocking temperature $T_b \simeq KV / 25 k_B$



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

Formalism

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

Energy

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

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

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

Langevin function

Infinite anisotropy

$$Z = \exp(\beta \mu_0 M H) + \exp(-\beta \mu_0 M H)$$

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

Brillouin ½ function

Note:

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

$$x = \beta \mu_0 M H$$