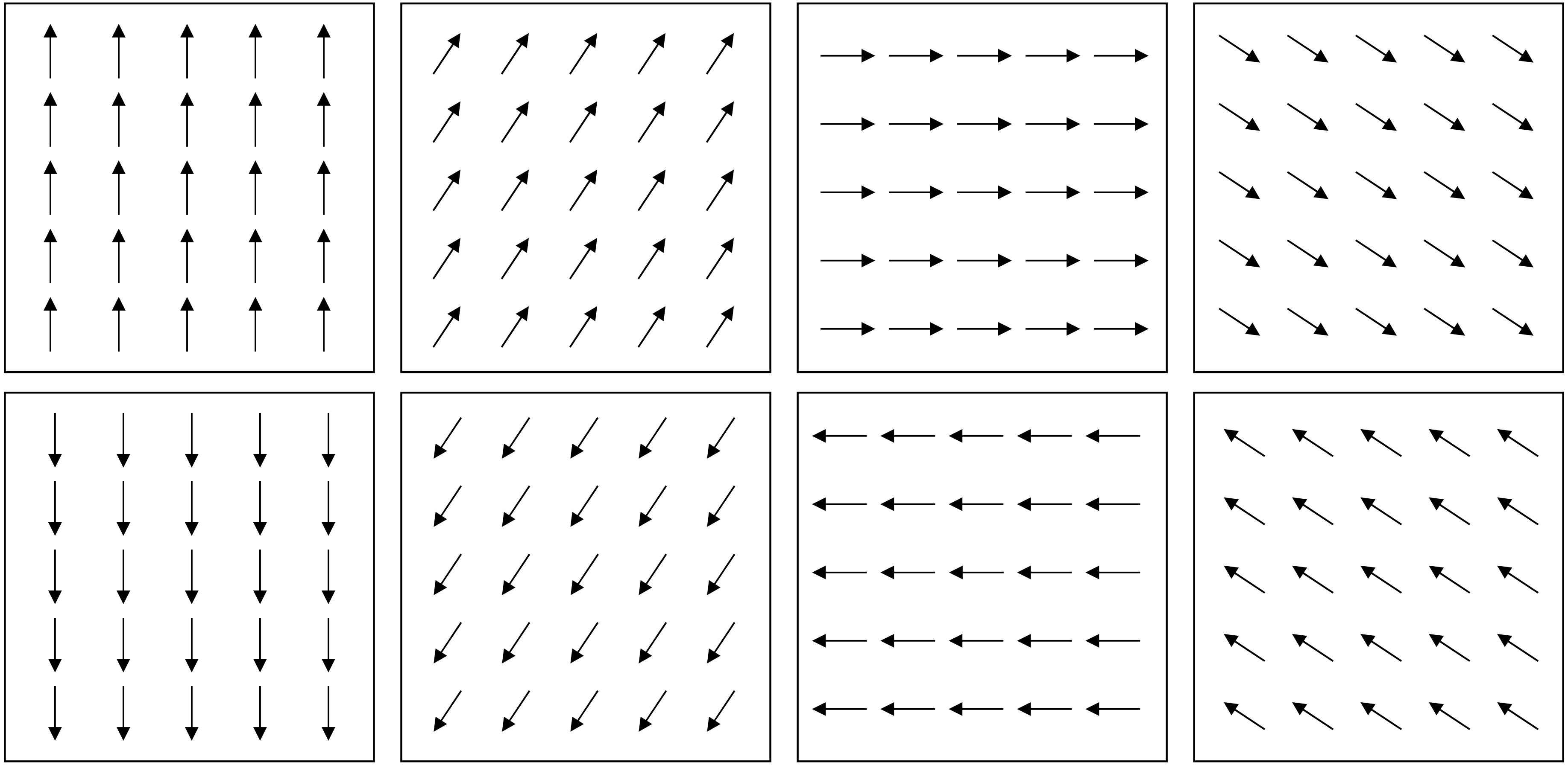
Anisotropía magnetocristalina

Sólo intercambio
(ausencia de anisotropía)

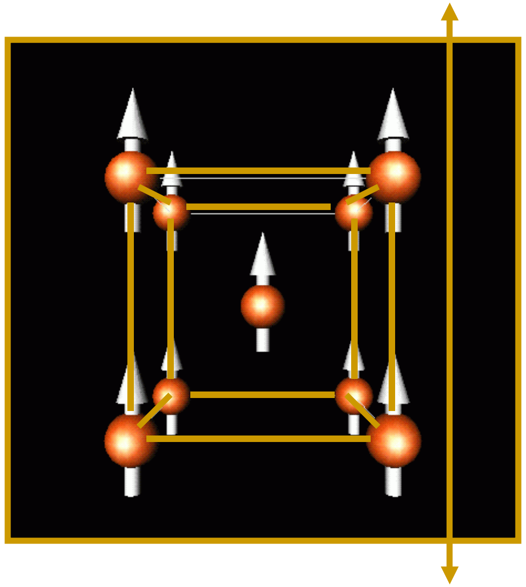
Dirección aleatoria de **M** en 4π => estado continuamente degenerado

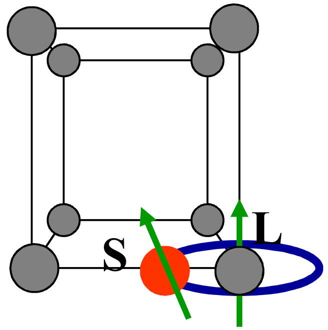


Siempre estaríamos en presencia de un superparamagneto

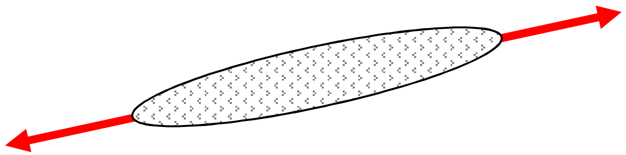
Anisotropía

Fe

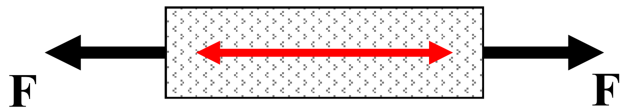




Estructura cristalina → Int. elect - Campo cristalino + interacción Spin – órbita = Anisotropía magneto-cristalina

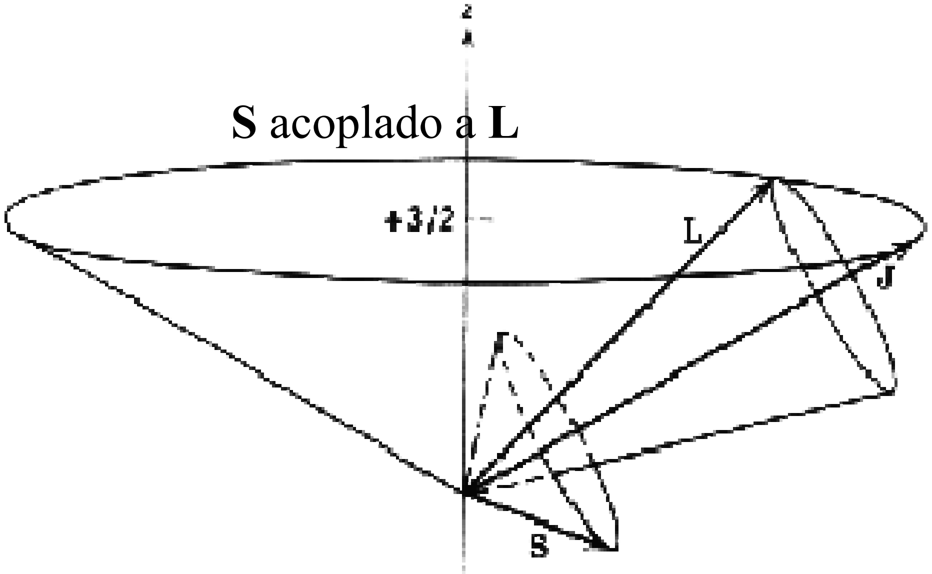


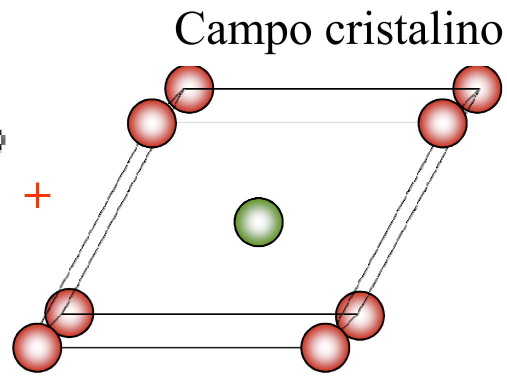
Forma: anisotropía magnetostática



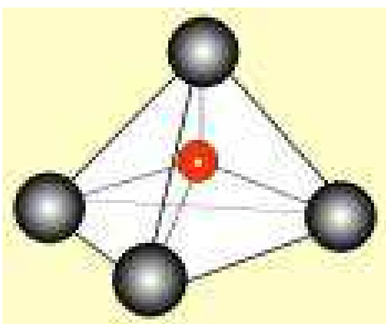
Esfuerzo: anisotropía magnetoelástica

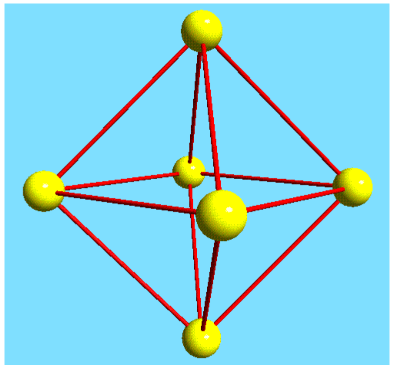
spin – órbita + campo cristalino

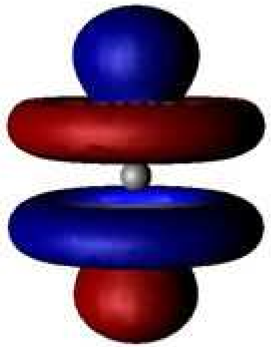




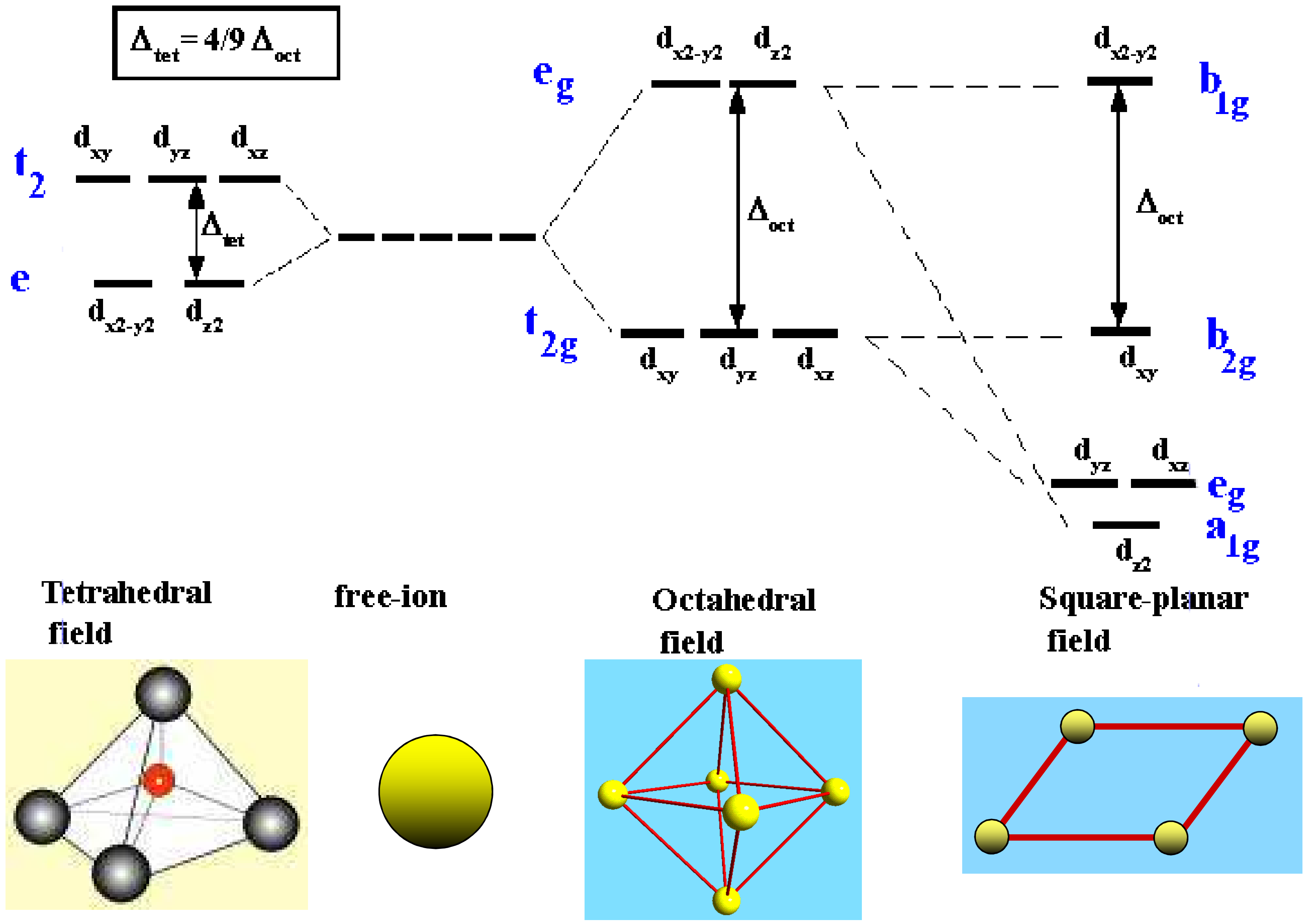
$$= \begin{cases} \textit{anisotropía} \\ \textit{sobre} \\ \vec{L}, \vec{S} \ y \ \vec{J} \end{cases}$$





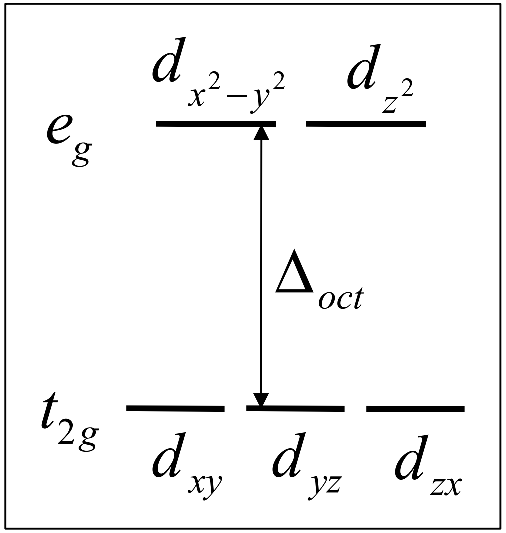


Diagramas de desdoblamiento de orbitales d por el campo cristalino



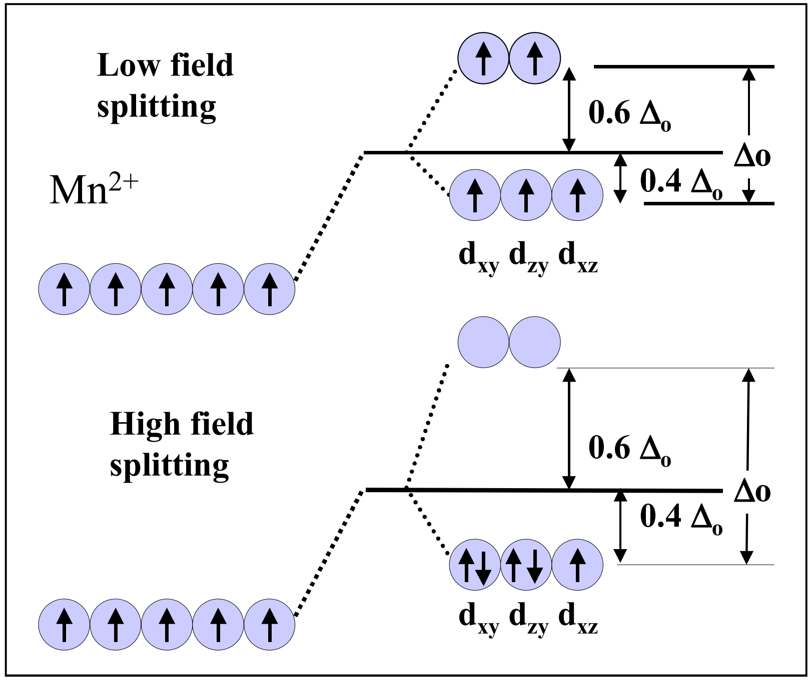
spin – órbita + campo cristalino

Ejemplo 1



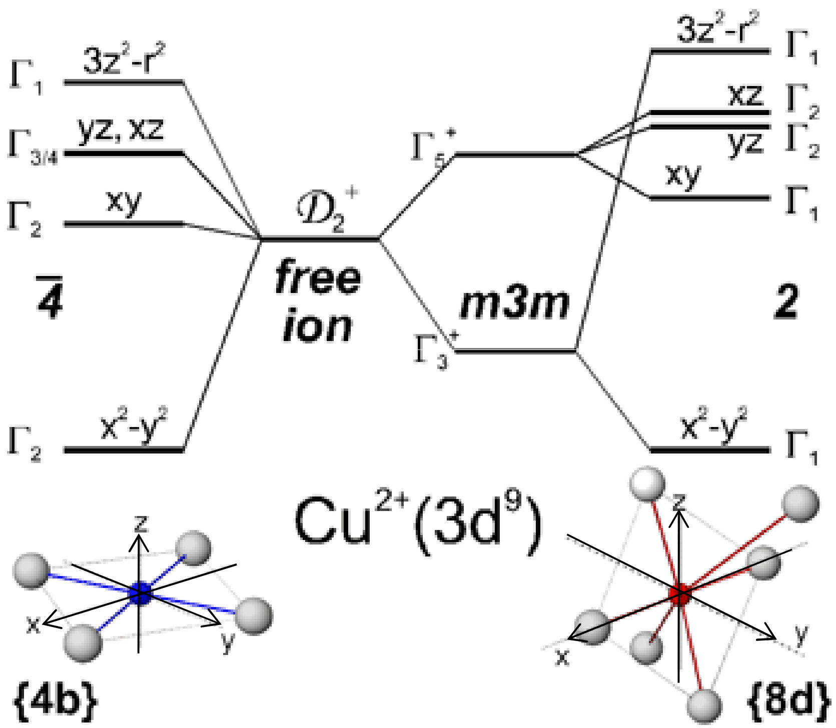
$[Mn^{2+}]=[Ar].3d^5$

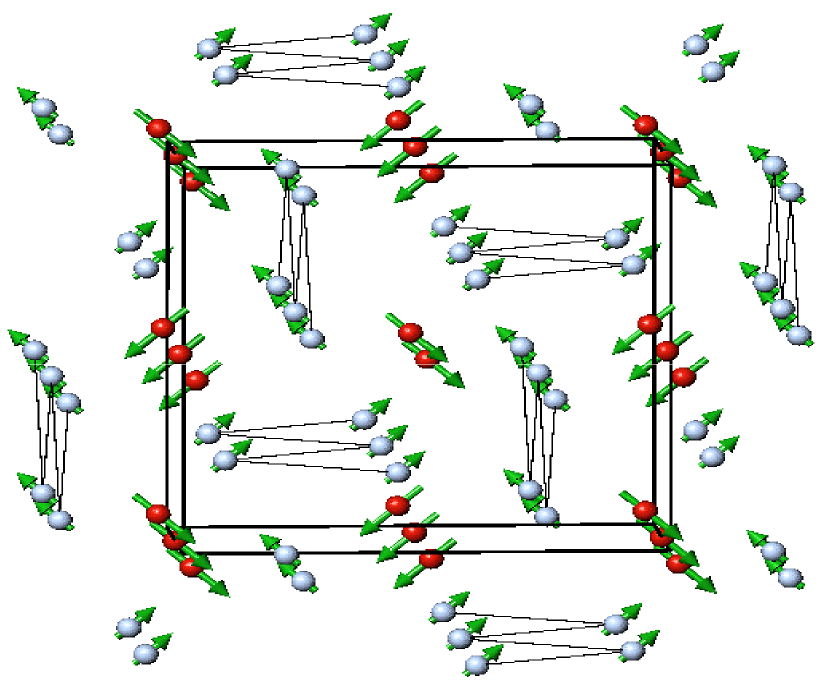
Desdoblamientos bajo campos cristalinos altos y bajos



voh.chem.ucla.edu

Ejemplo Ordenamiento Magnético del CuB_2O_4





Estados electrónicos, simetría local y cordinación de iones Cu^{2+} en sitios 4b y 8d de CuB_2O_4.

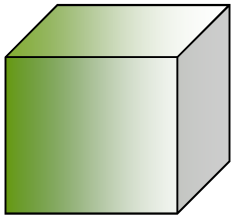
Manfred Fiebig, September 2004 mbi-berlin.de

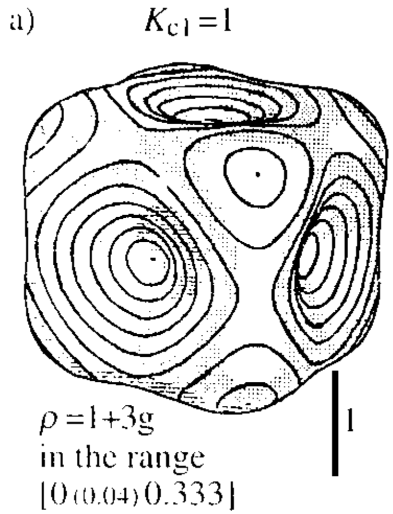
B.Roessli , J.Schefer , G.Petrakovskii, B.Ouladdiaf , M.Böhm , U.Staub, A. Vorotinov and L.Bezmaternikh. Phys. Rev. Letter, (2001).

Energía de anisotropía Magnetocristalina

Definiciones

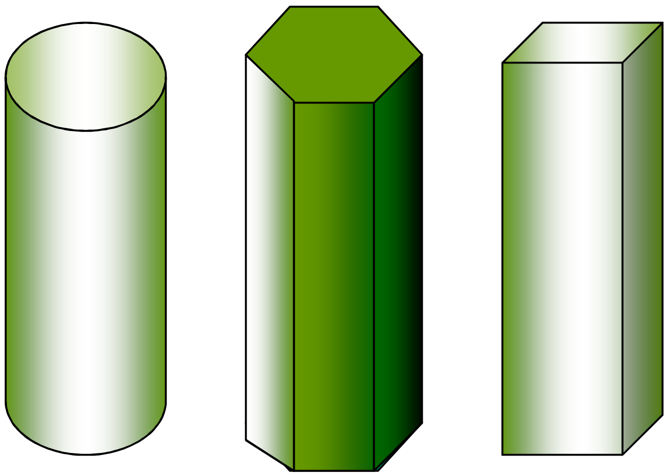
Geometría cúbica

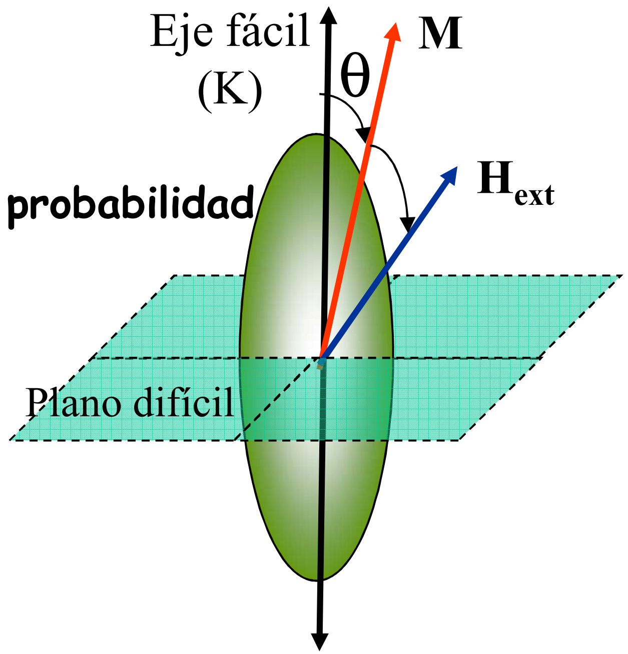




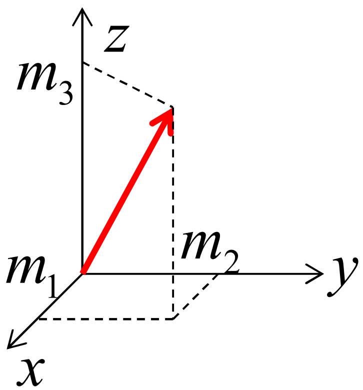
Curvas de **energía** constante

Geometría cilíndrica, tetragonal, exagonal





Anisotropía – descripción fenomenológica



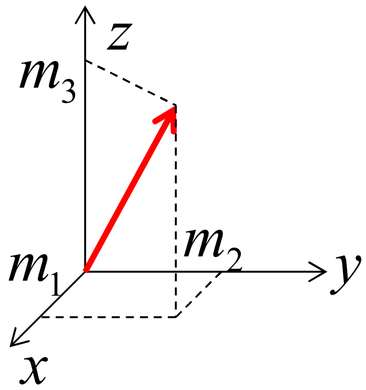
m_i cosenos directores de la magnetización

$$m_{1,2,3} = \frac{M_{x,y,z}}{M} \ldots$$

e_K energía de anisotropía por unidad de volumen

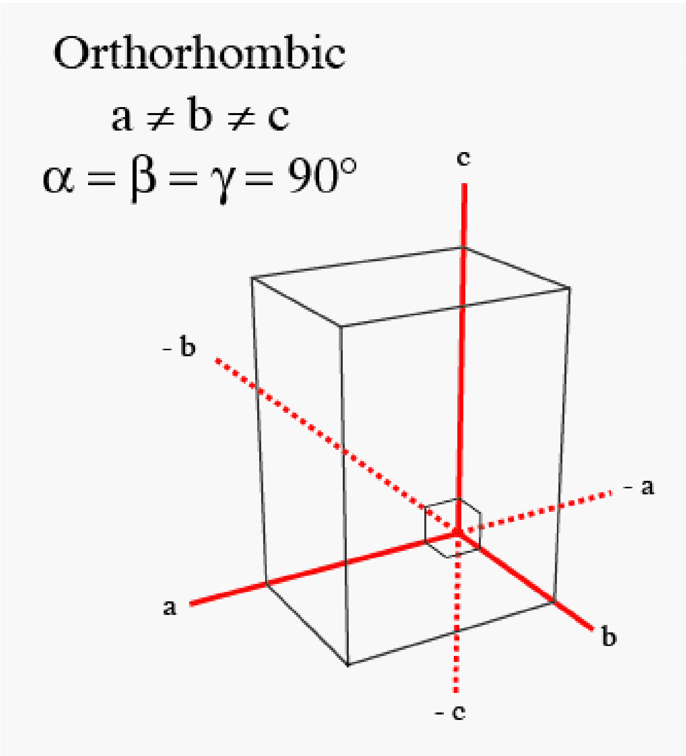
$$e_K = \sum_i K_i m_i^2 + \sum_{ij} K_{ij} m_i^2 m_j^2 + K_{123} m_1^2 m_2^2 m_3^2 + \sum_i K_i m_i^4 + \cdots$$

E_K energía de anisotropía $\quad E_K = \int e_K dV$



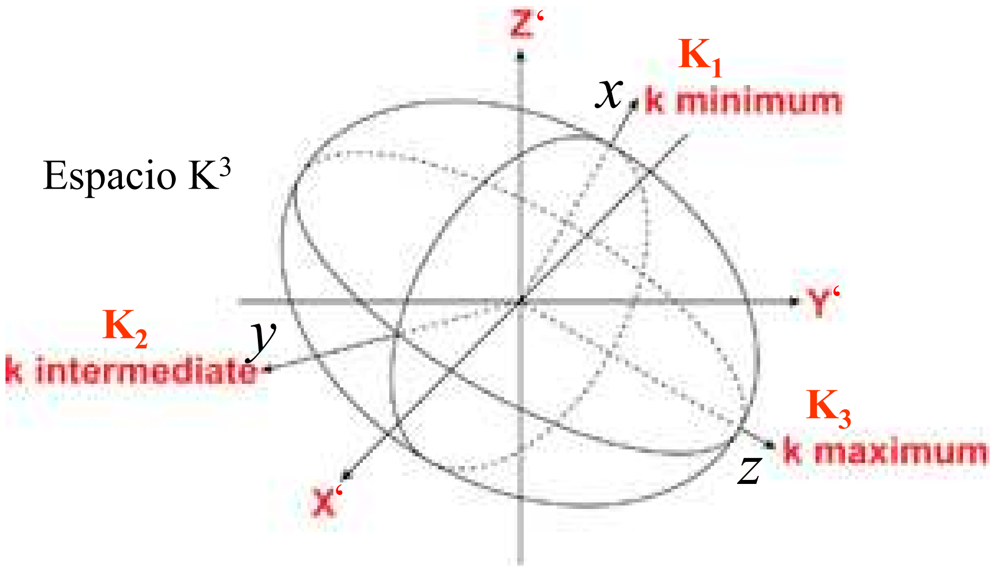
$$e_K = \sum_i K_i m_i^2 + \sum_{ij} K_{ij} m_i^2 m_j^2 + K_{123} m_1^2 m_2^2 m_3^2 + \sum_i K_i m_i^4 + \cdots$$

Ejemplo: sistema ortorrómbico

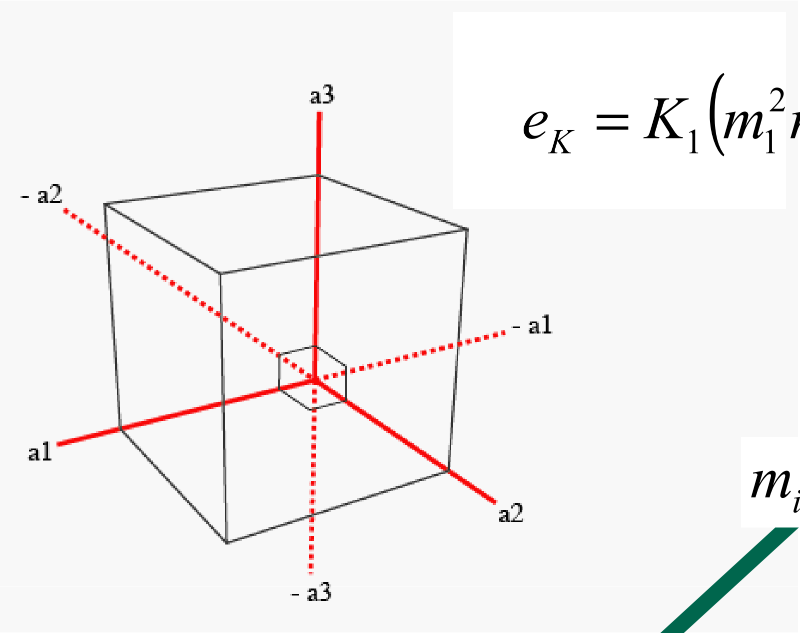


$$e_K \approx K_1 m_1^2 + K_2 m_2^2 + K_3 m_3^2$$

Espacio K^3



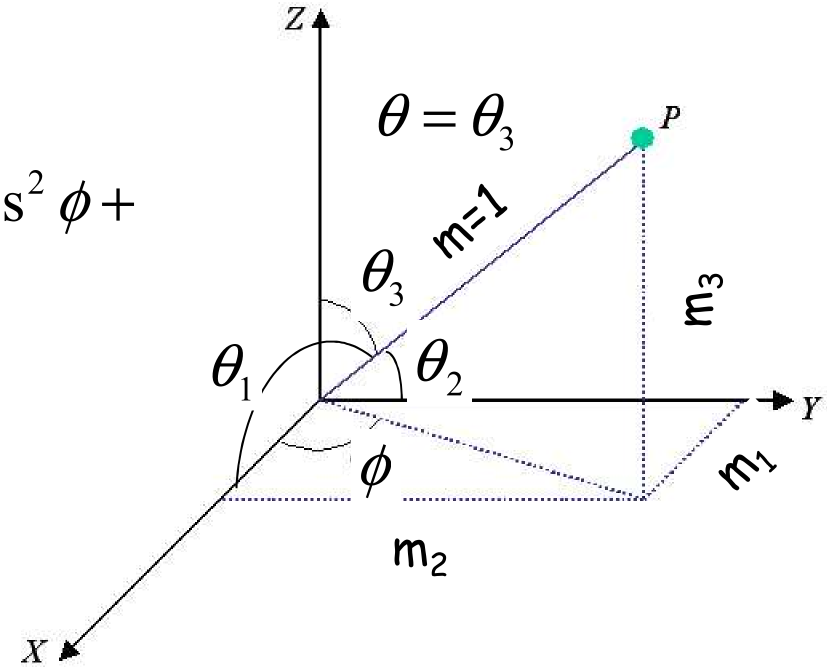
sistema cúbico



$$e_K = K_1\left(m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2\right) + K_2 m_1^2 m_2^2 m_3^2$$

$$m_i = \cos\theta_i$$

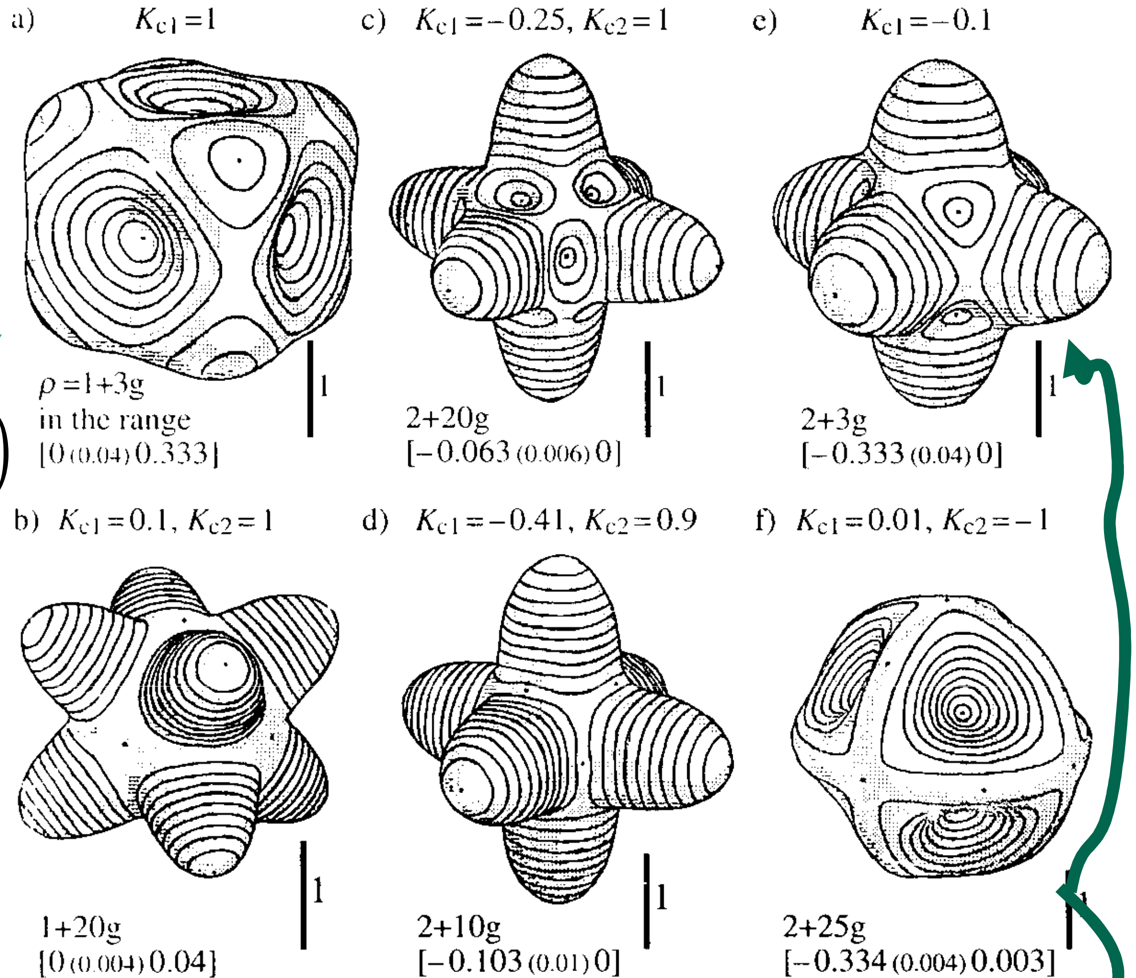
$$e_K = \left(K_1 + K_2\cos^2\theta\right)\sin^4\theta\sin^2\phi\cos^2\phi + $$
$$+ K_1\sin^2\theta\cos^2\theta$$



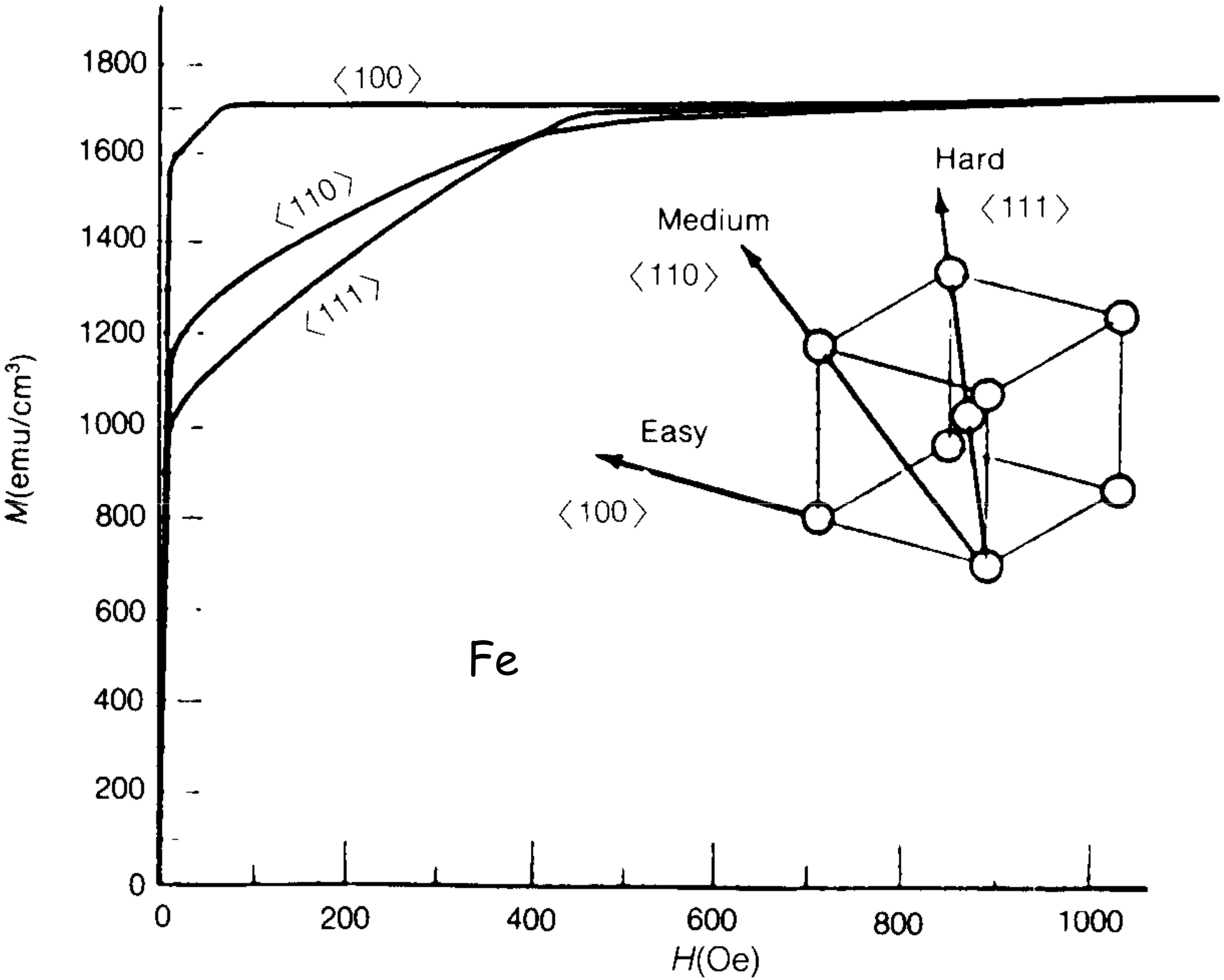
sistema cúbico

Curvas de energía constante

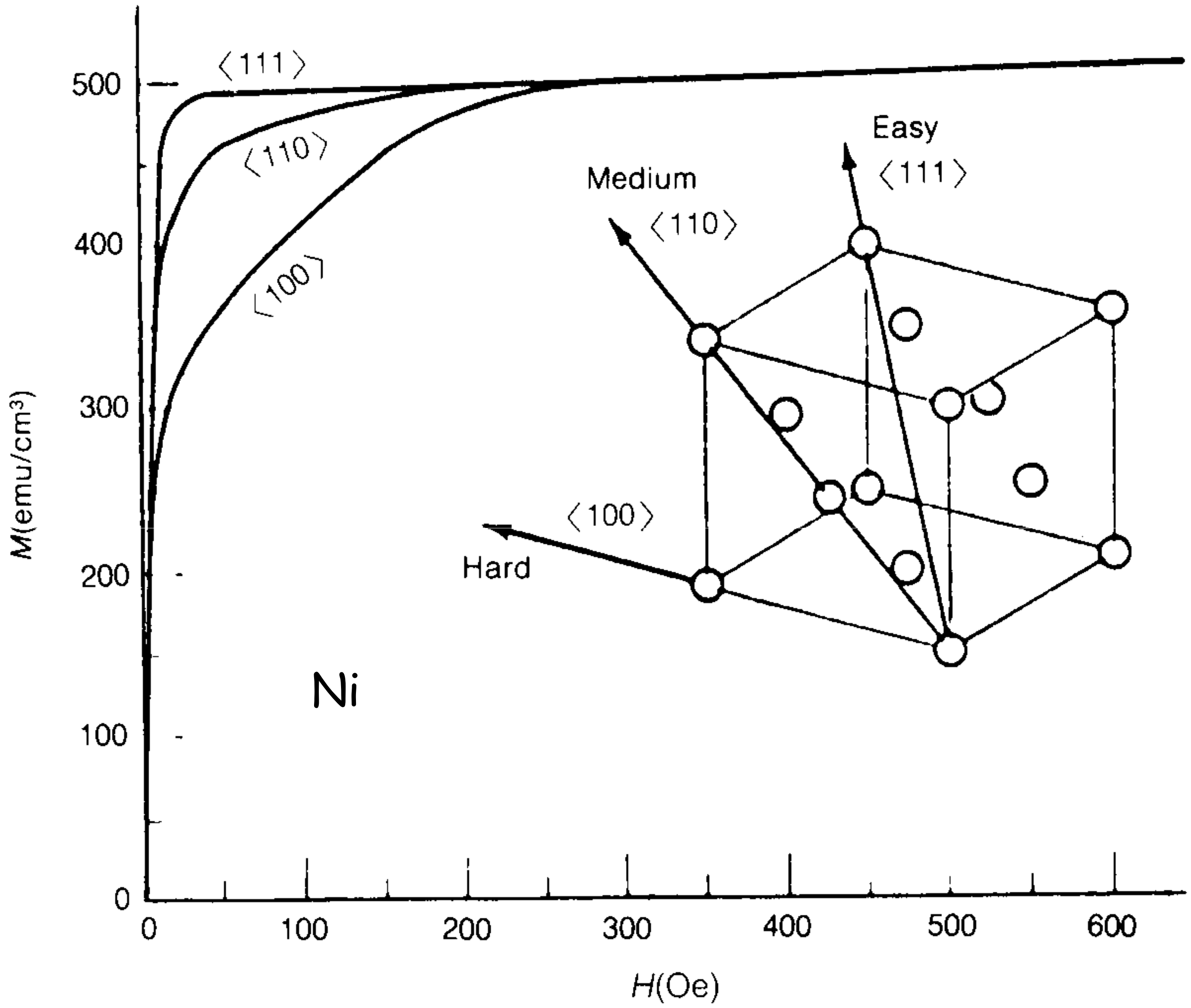
$$e_K = K_1\left(m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2\right) + K_2 m_1^2 m_2^2 m_3^2$$



Material	K_1 (10^5 J/m^3)	K_2 (10^5 J/m^3)	Eje fácil
Fe	0.480	0.05	(100)
Ni	-0.045	-0.023	(111)

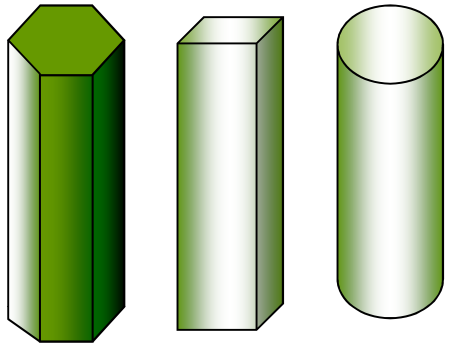


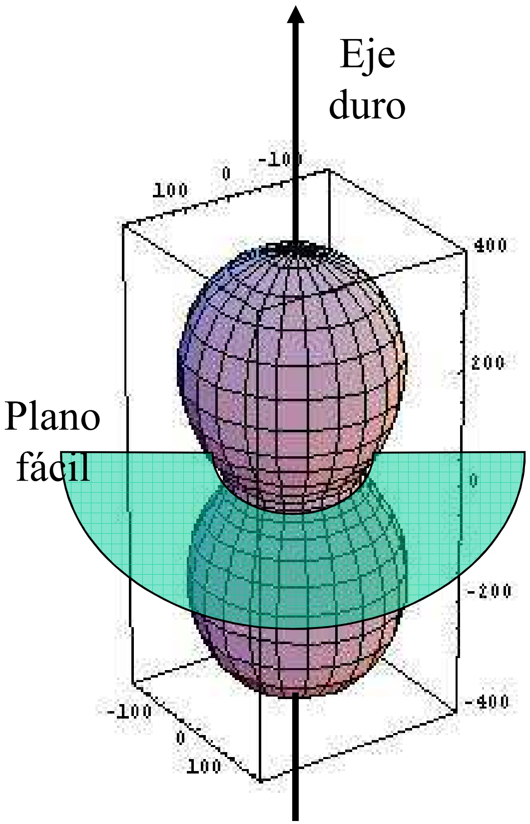
1800
1600
1400
1200
1000
800
600
400
200
0
M(emu/cm³)
⟨100⟩
⟨110⟩
⟨111⟩
Hard
⟨111⟩
Medium
⟨110⟩
Easy
⟨100⟩
Fe
0
200
400
600
800
1000
H(Oe)



⟨111⟩
⟨110⟩
⟨100⟩
Easy
⟨111⟩
Medium
⟨110⟩
⟨100⟩
Hard
Ni
M(emu/cm³)
500
400
300
200
100
0
0
100
200
300
400
500
600
H(Oe)

Sistemas hexagonal y tetragonal

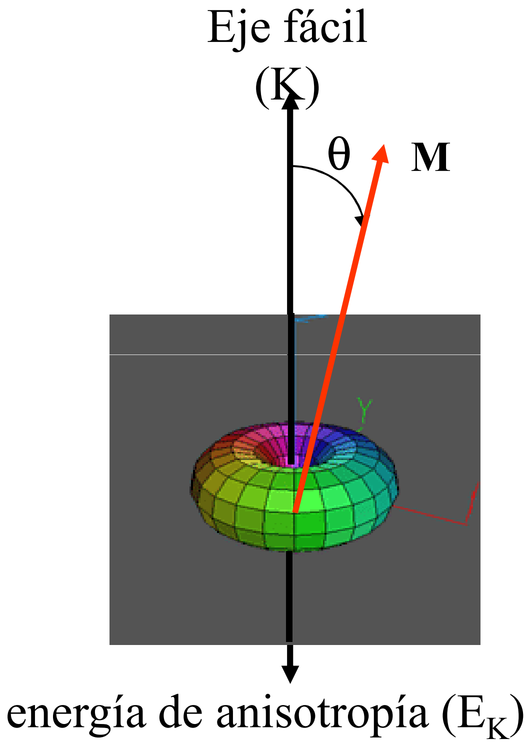


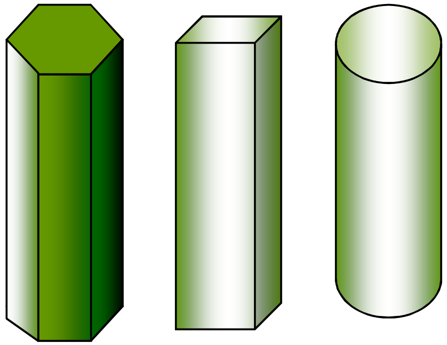


$$e_K = K_1 \cos^2\theta + K_2 \cos^4\theta$$

$$\Downarrow$$

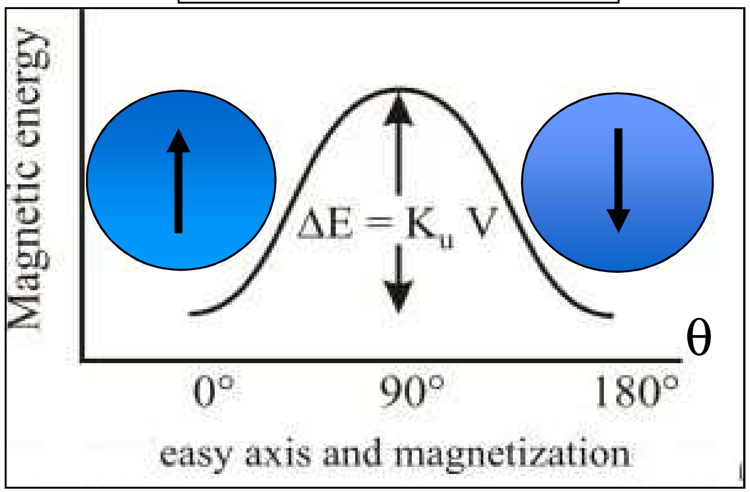
$$e_K = K_1' \sin^2\theta + K_2' \sin^4\theta$$





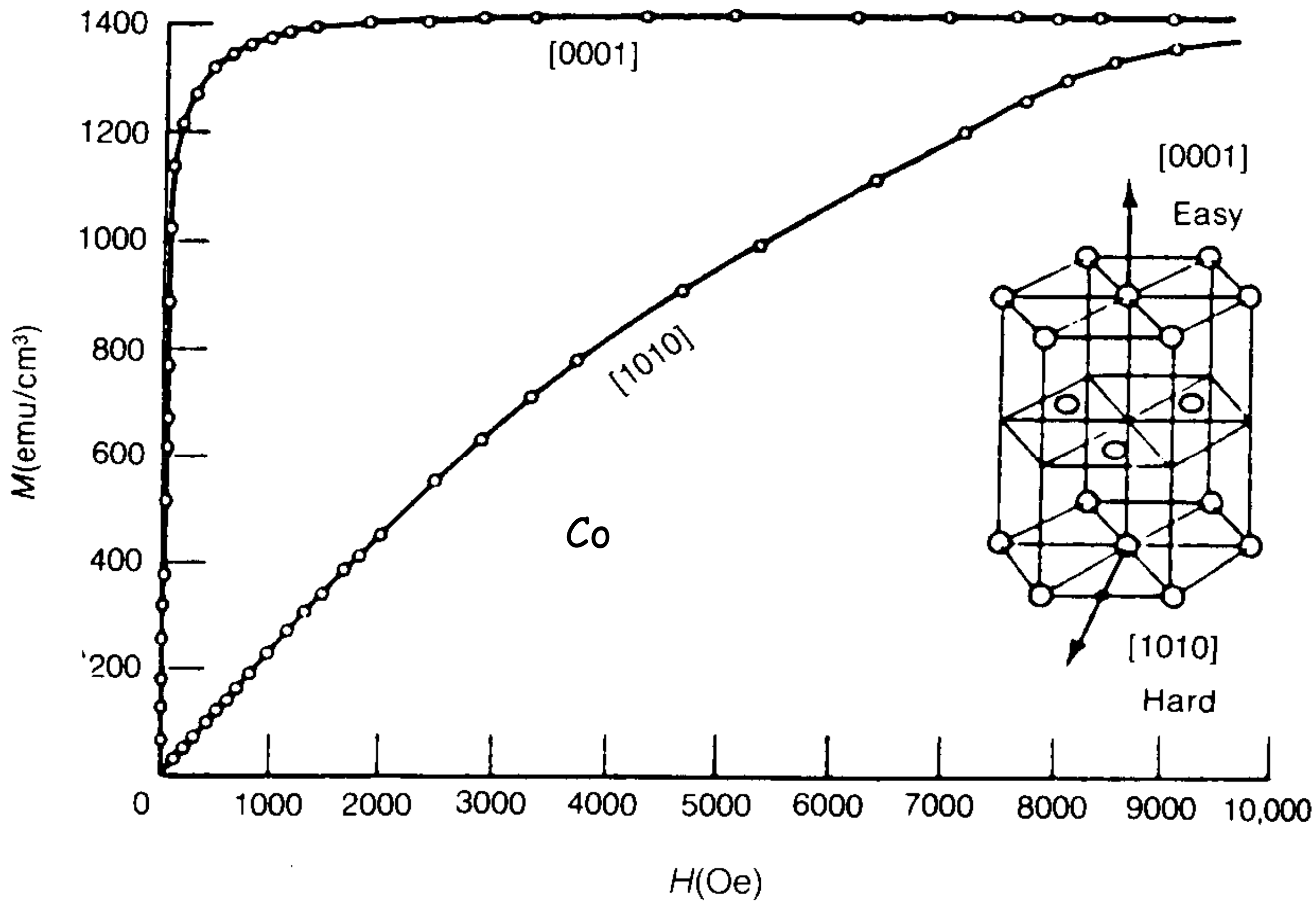
$$e_K = K_1 \sin^2\theta + K_2 \sin^4\theta \xrightarrow[\text{caso uniaxial}]{\text{descripción simple}} e_K = K \sin^2\theta$$

$$E_K = KV \sin^2\theta$$



$$e_K = K_1 \sin^2 \theta + K_2 \sin^4 \theta$$

Material	K_1 (10^5 J/m^3)	K_1 (10^5 J/m^3)	Eje fácil
Co	4.1	1.0	hexagonal
$SmCo_5$	1100	-	hexagonal



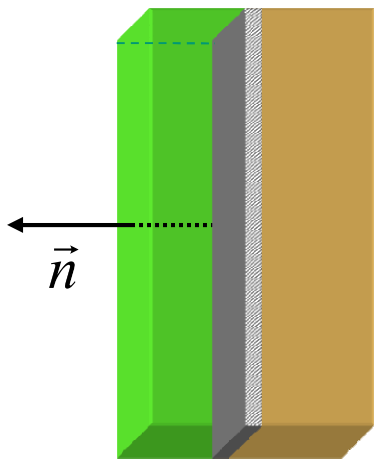
1400
1200
1000
800
600
400
200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
M(emu/cm³)
H(Oe)
[0001]
[1010]
Co
[0001]
Easy
[1010]
Hard

Anisotropía de Interfaz

Anisotropía de Intercambio

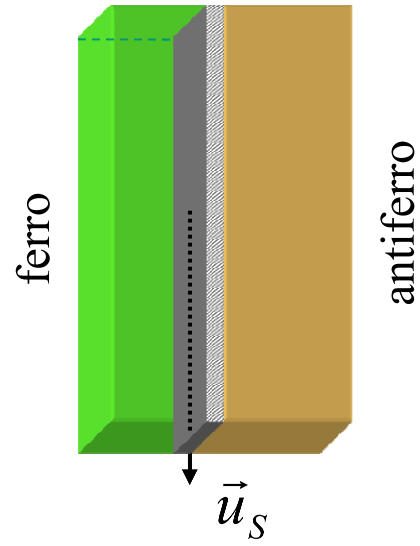
superficies e interfaces

Anisotropía de interfaz



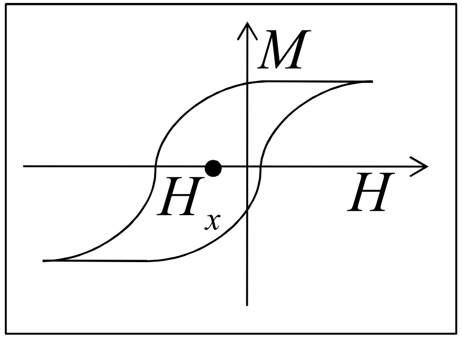
$$e_K = K_S\left[1-(\vec{m}\cdot\vec{n})^2\right] \begin{cases} K_S > 0 \Rightarrow \vec{m} \,//\, \text{sup} \\ K_S < 0 \Rightarrow \vec{m} \perp \text{sup} \end{cases}$$

Anisotropía de intercambio*



$$e_K = K_S \vec{m}\cdot\vec{u}_S = \frac{H_x}{2}\vec{m}\cdot\vec{u}_S$$

$$e_K = \frac{H_x}{2} m\cos\varphi$$

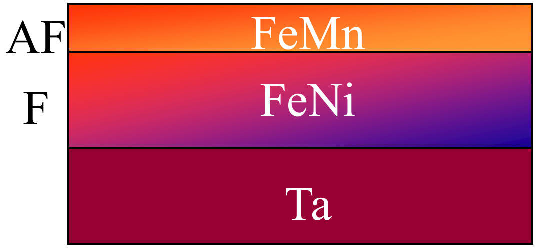


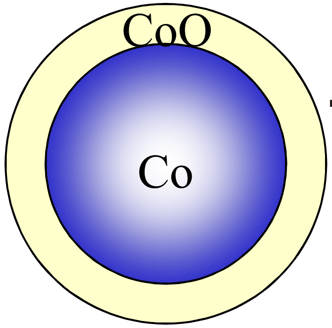
Exchange bias field

*también llamada unidireccional

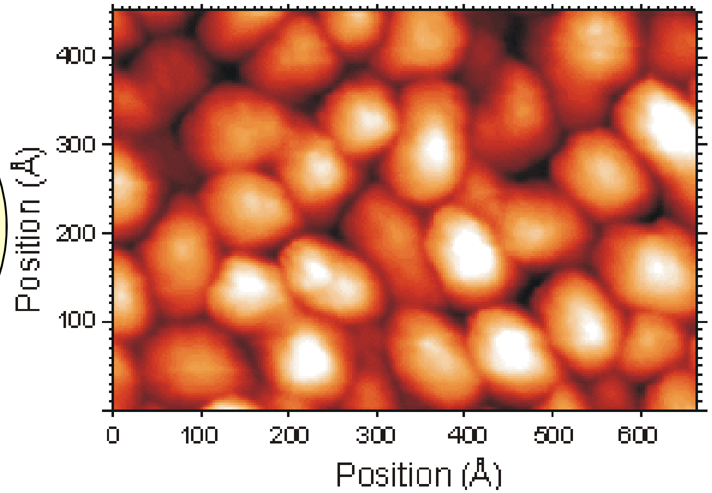
Observación del exchange bias

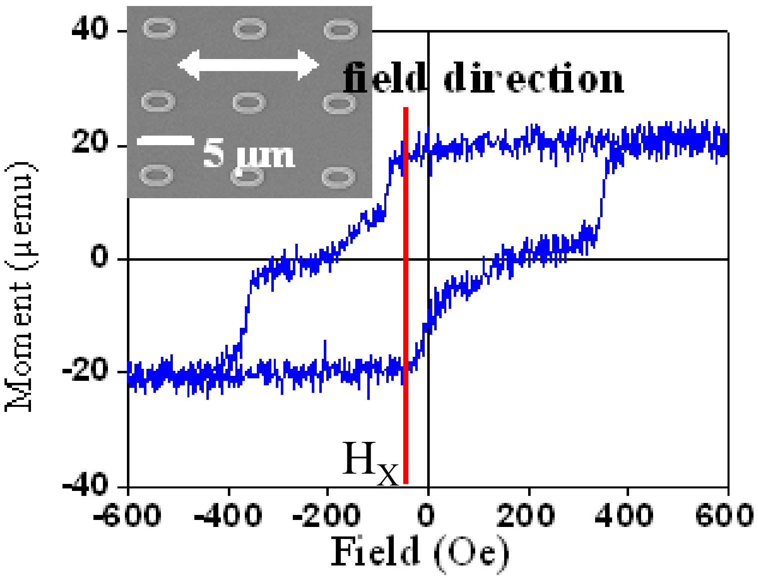
$$e_K = K_S \vec{m} \cdot \vec{u}_S = \frac{H_x}{2} \vec{m} \cdot \vec{u}_S$$



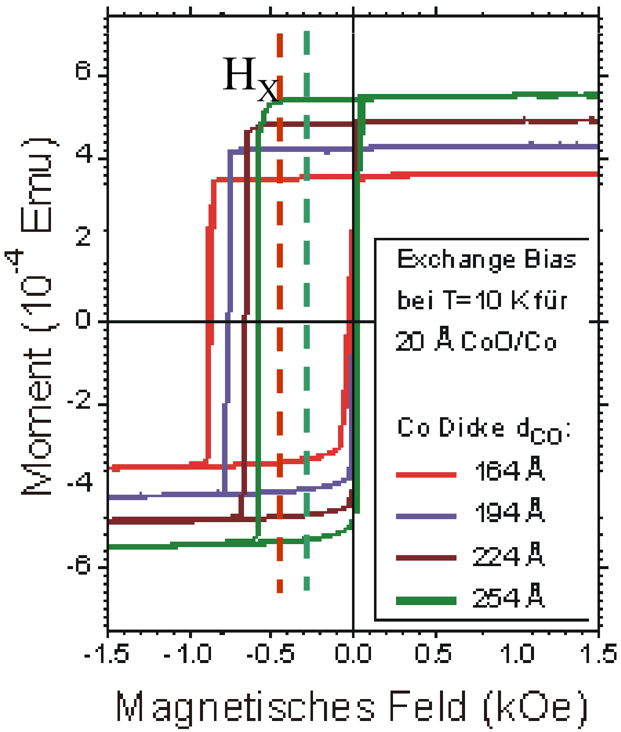


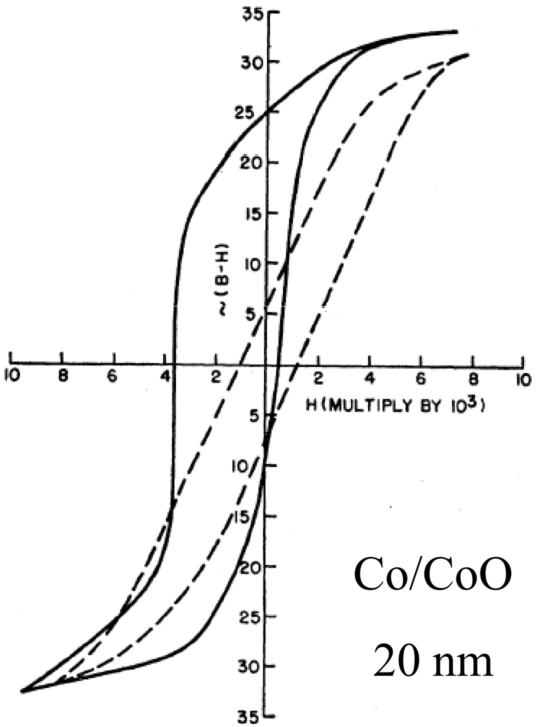
CoO/Co





Ta 20nm / NiFe 20nm/ FeMn 10 nm film



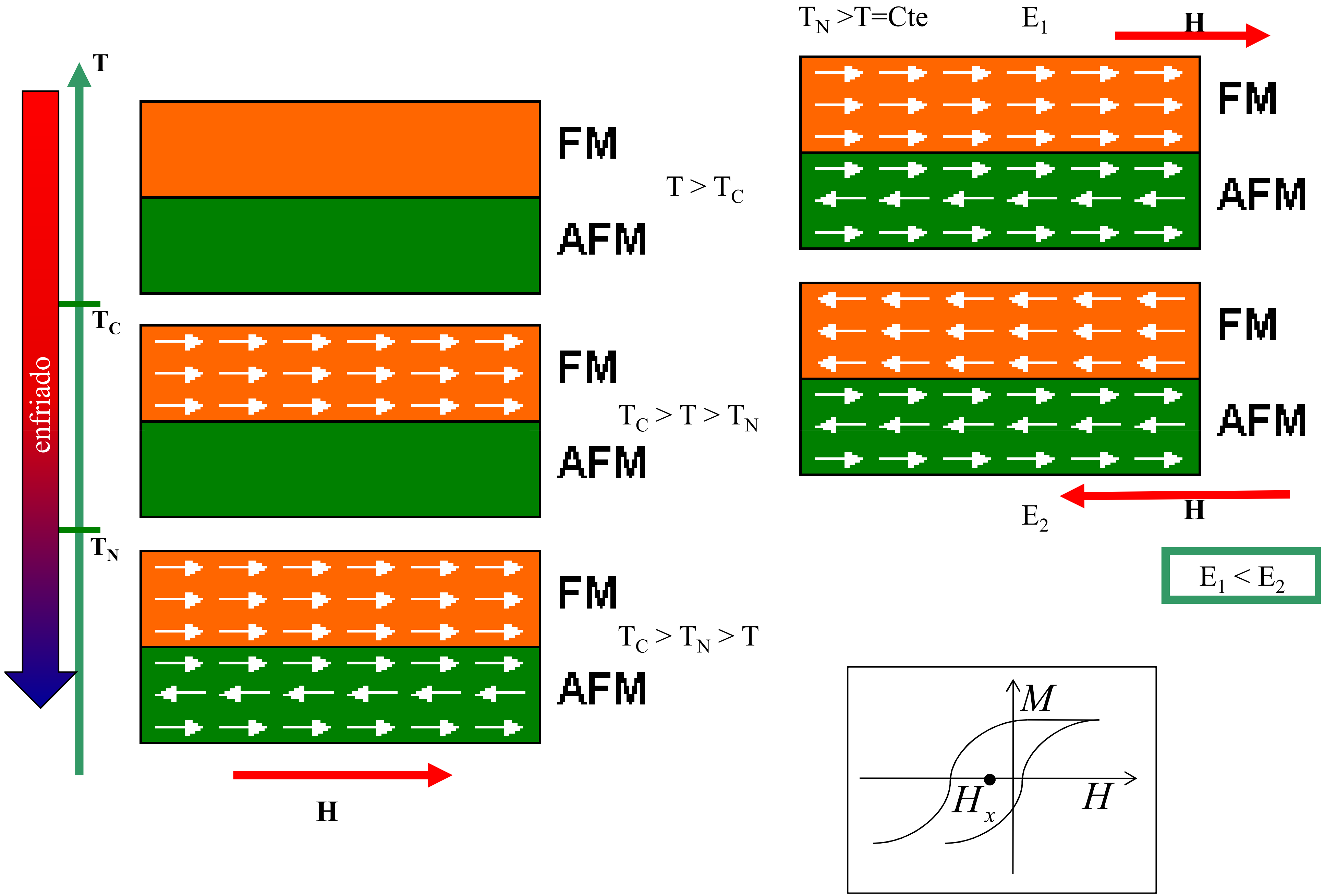


Letters to the Editor

New Magnetic Anisotropy

W. H. Meiklejohn and C. P. Bean
General Electric Research Laboratory, Schenectady, New York

(Received March 7, 1956)
PHYSICAL REVIEW
VOLUME 102, NUMBER 5
JUNE 1, 1956


T
T_C
T_N
enfriado
FM
AFM
$T > T_C$
FM
AFM
$T_C > T > T_N$
FM
AFM
$T_C > T_N > T$
H
$T_N > T = Cte$
E_1
H
FM
AFM
FM
AFM
H
E_2
$E_1 < E_2$
M
H_x
H

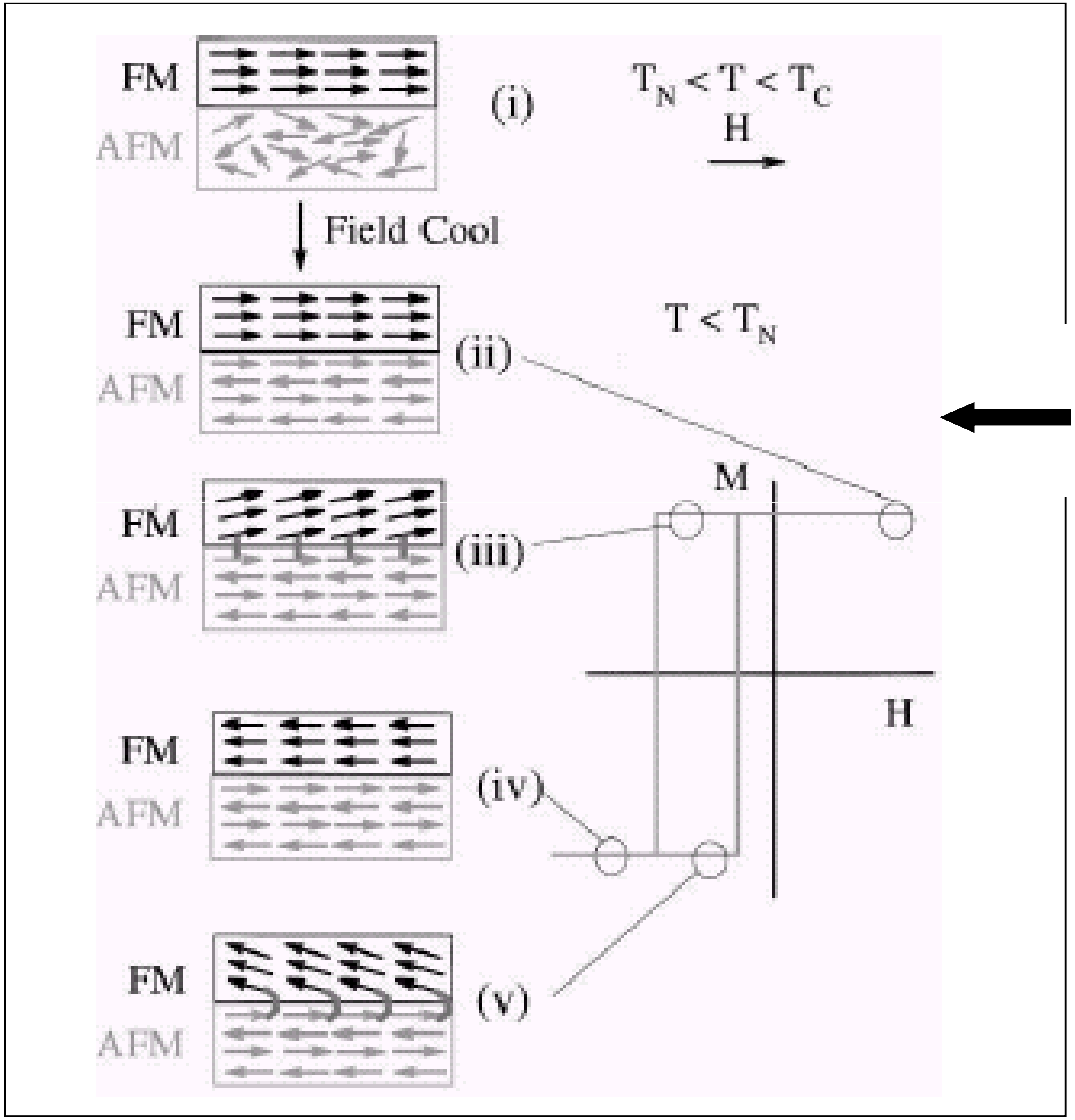
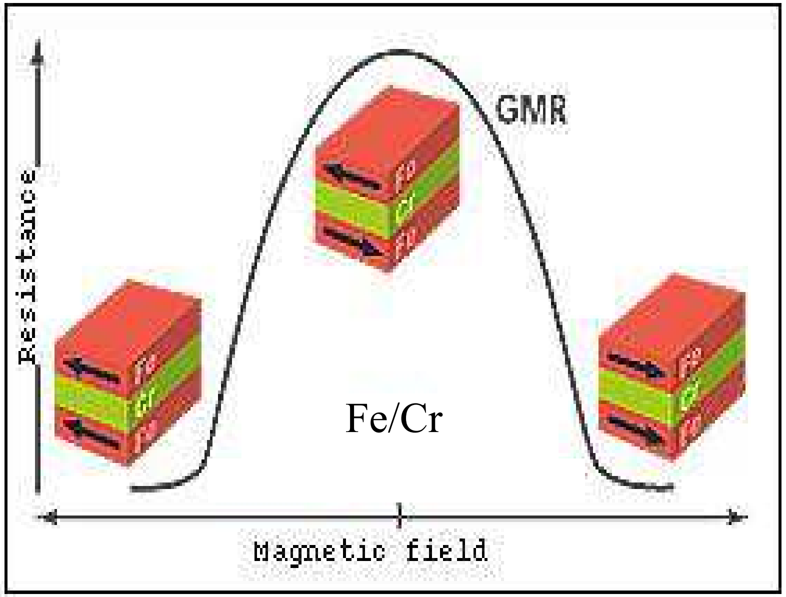


Diagrama esquemático de una configuración de spin FM /AFM.

Anisotropía de intercambio – válvula de spin

Magnetoresistencia gigante



Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France

(Received 24 August 1988)

PHYSICAL REVIEW LETTERS

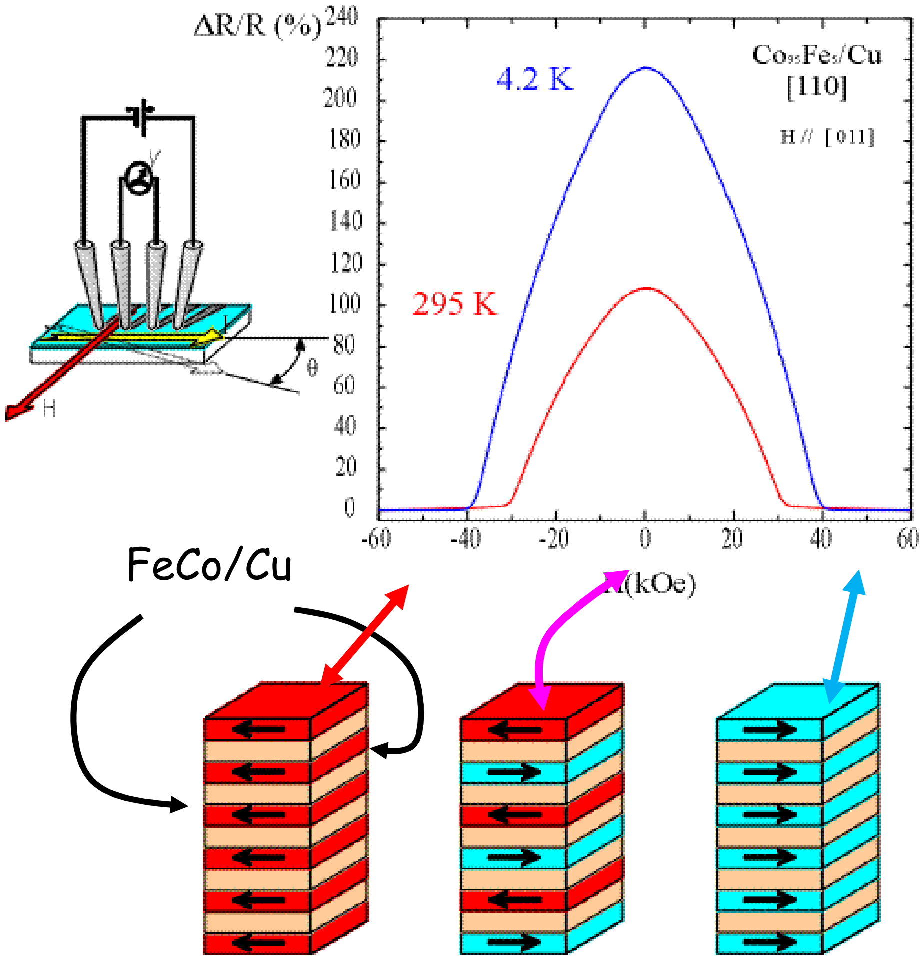
VOLUME 61, NUMBER 21

21 NOVEMBER 1988

Albert Fert, Nobel Prize in Physics 2007

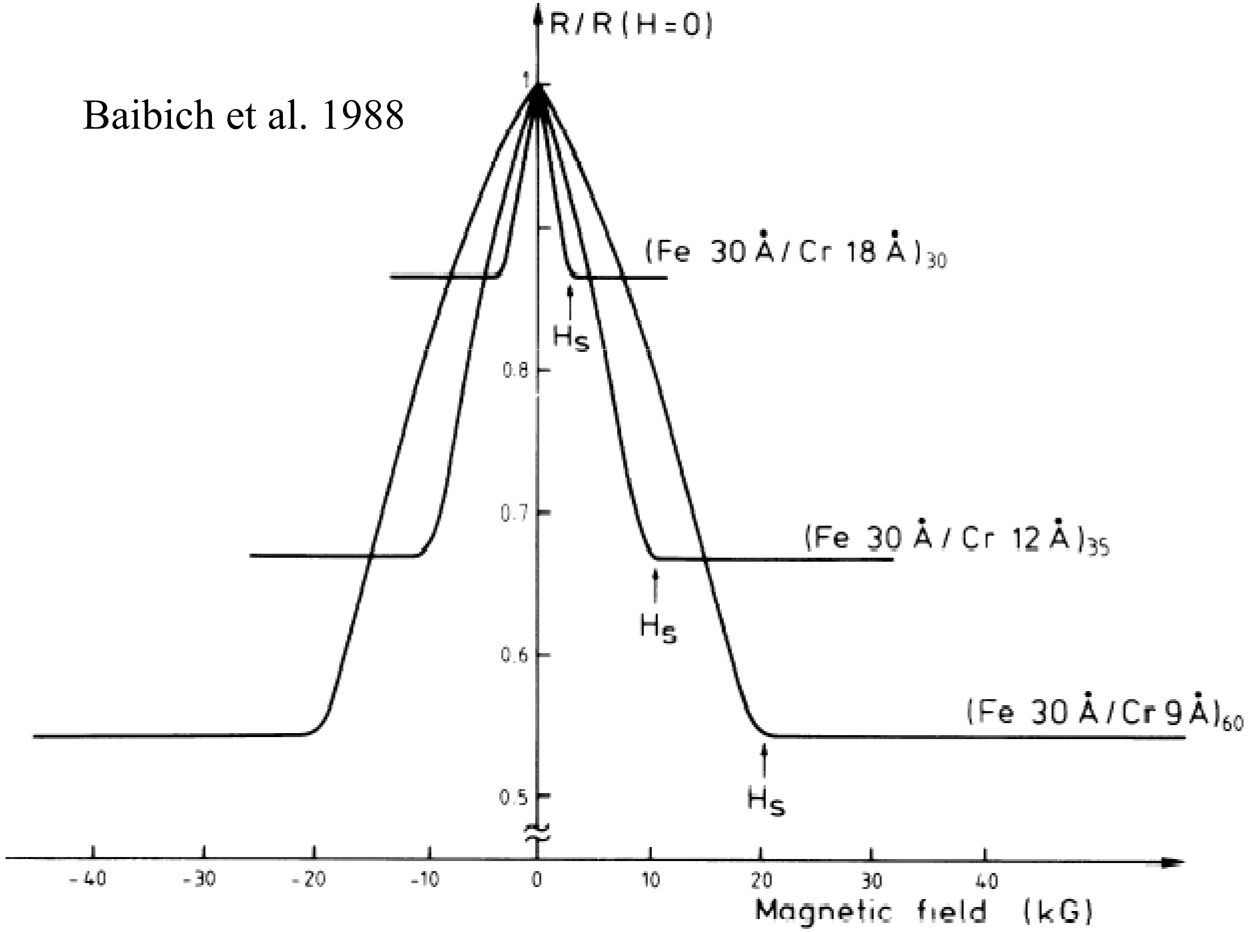
Peter Grünberg, Nobel Prize in Physics 2007

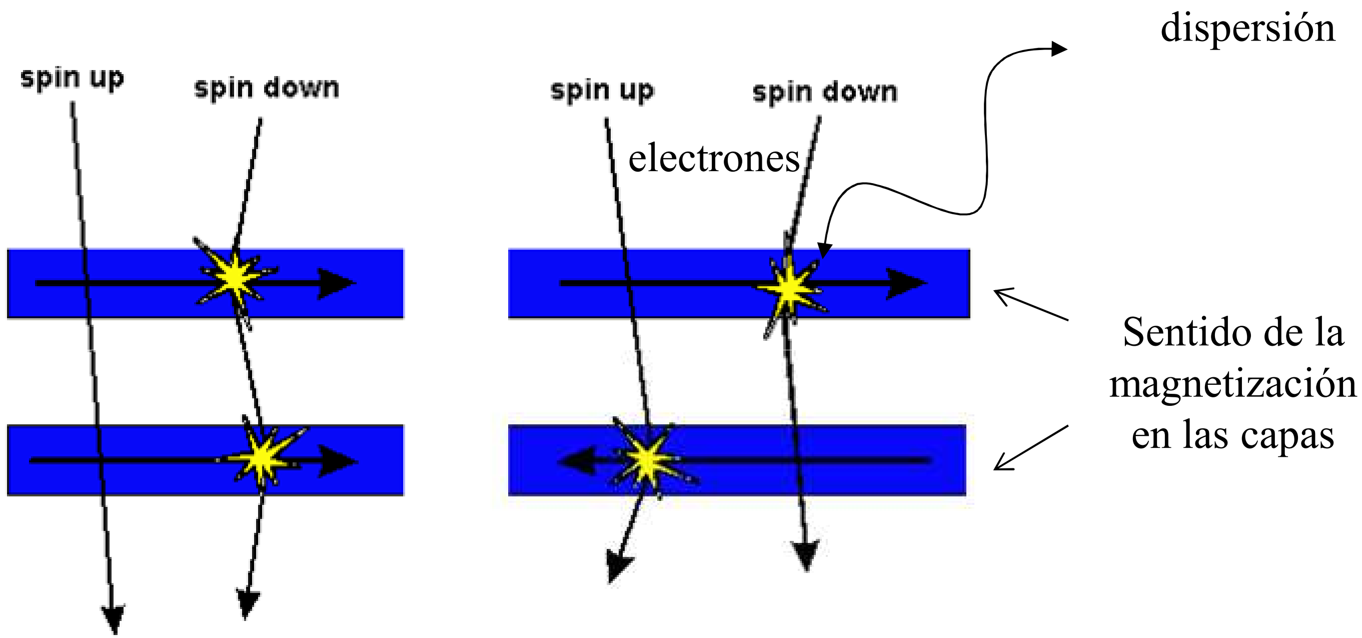
Giant Magnetoresistance



Resultados experimentales

Baibich et al. 1988





Acoplamiento ferro

Baja resistencia

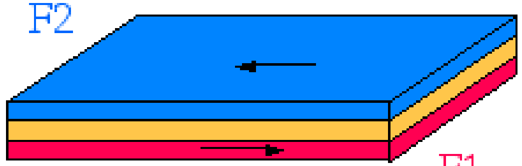
Acoplamiento antiferro

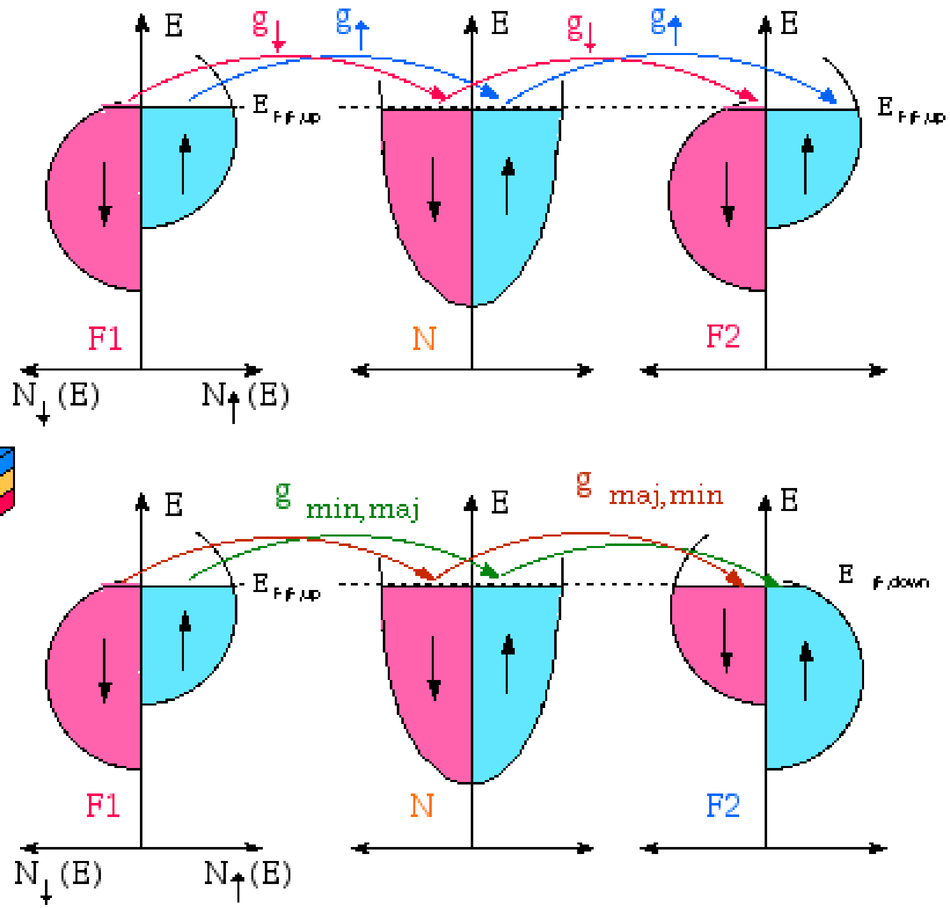
Alta resistencia

Magnetoresistance - spin valve

$g \propto N(E_F)$

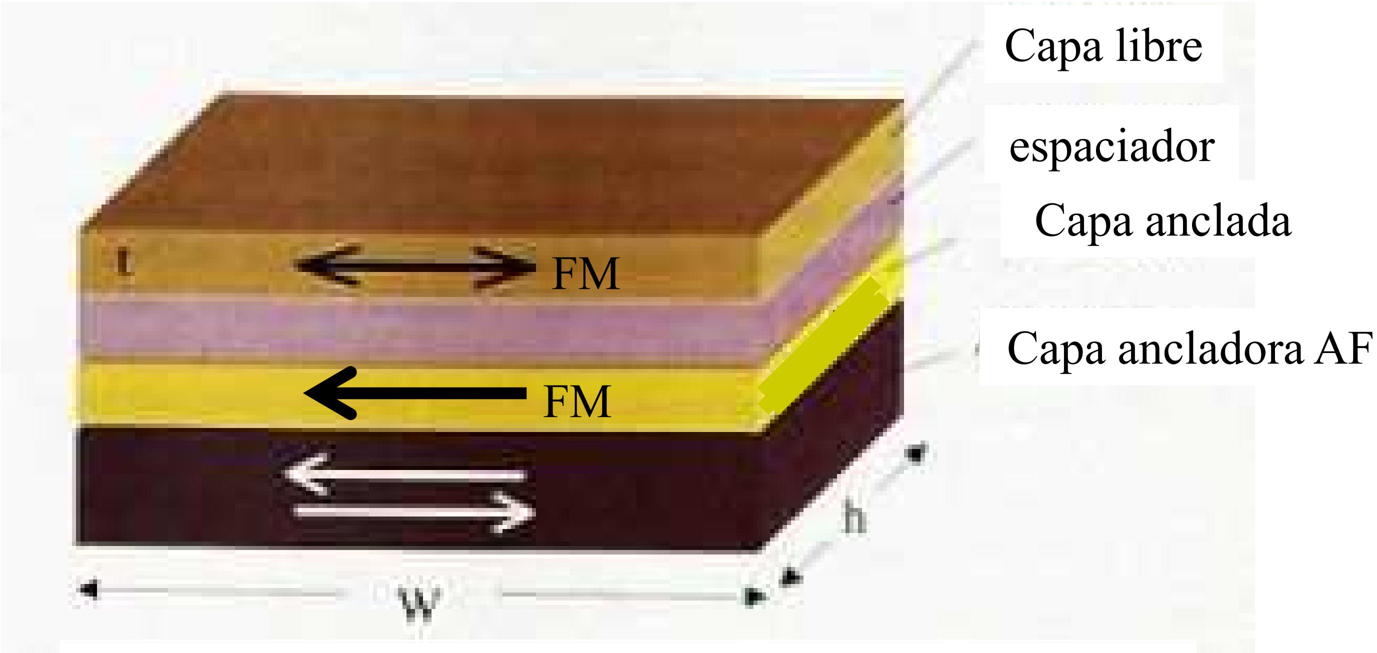
F1 and F2 parallel:
$g_\uparrow > g_\downarrow$
$g_\uparrow$ dominates
Low R state



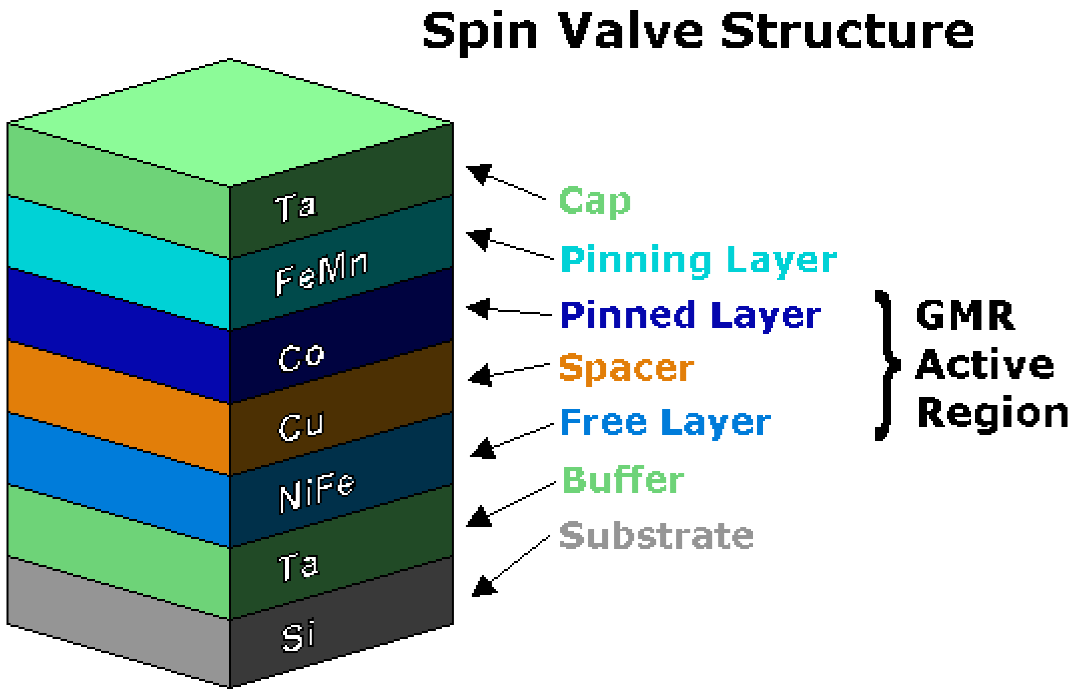


F1 and F2 antiparallel:
$g_{min,maj} = g_{maj,min} < g_\uparrow$
High R state

Grunberg PRB (89), Fe/Cr spin valve MR=1.5%
Baibich et al., PRL (88), Fe/Cr multilayer

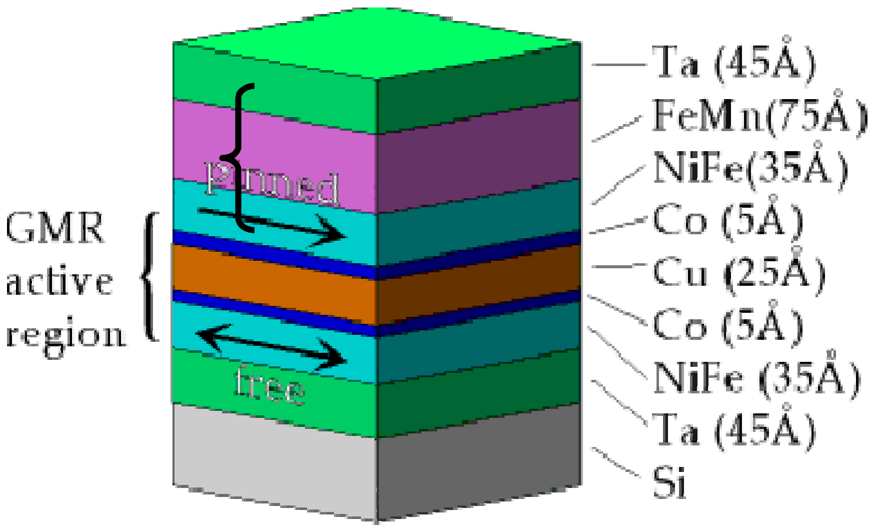


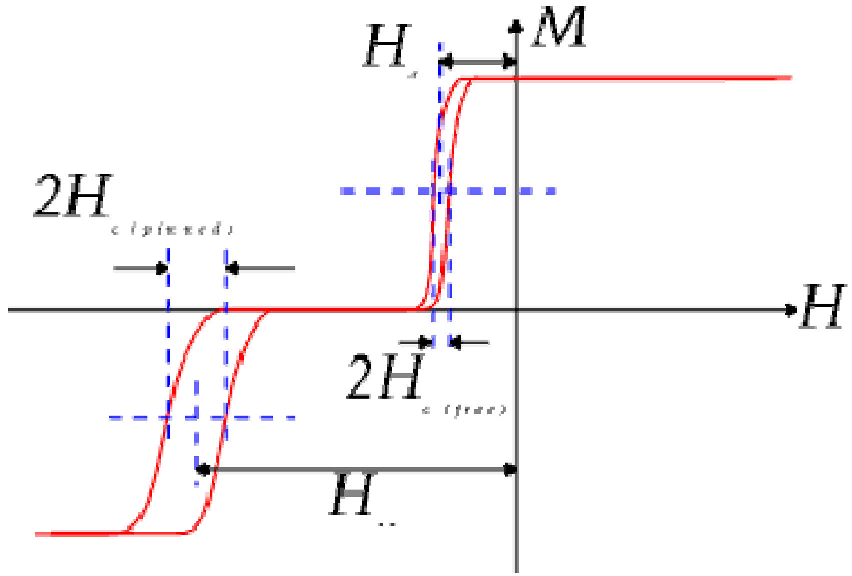
Capa libre
espaciador
Capa anclada
Capa ancladora AF
FM
FM
t
h
W

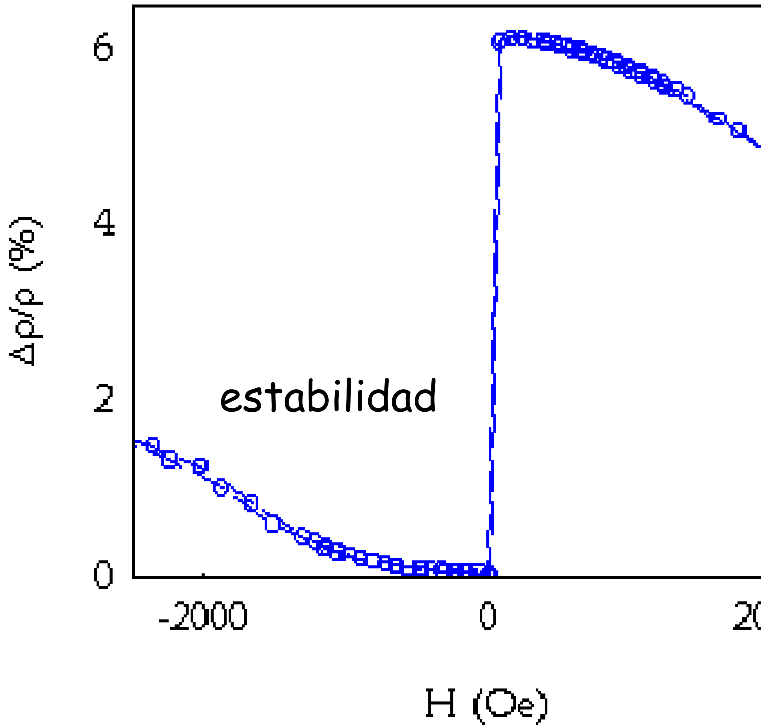


Spin Valve Structure
Ta
FeMn
Co
Cu
NiFe
Ta
Si
Cap
Pinning Layer
Pinned Layer
Spacer
Free Layer
Buffer
Substrate
GMR Active Region

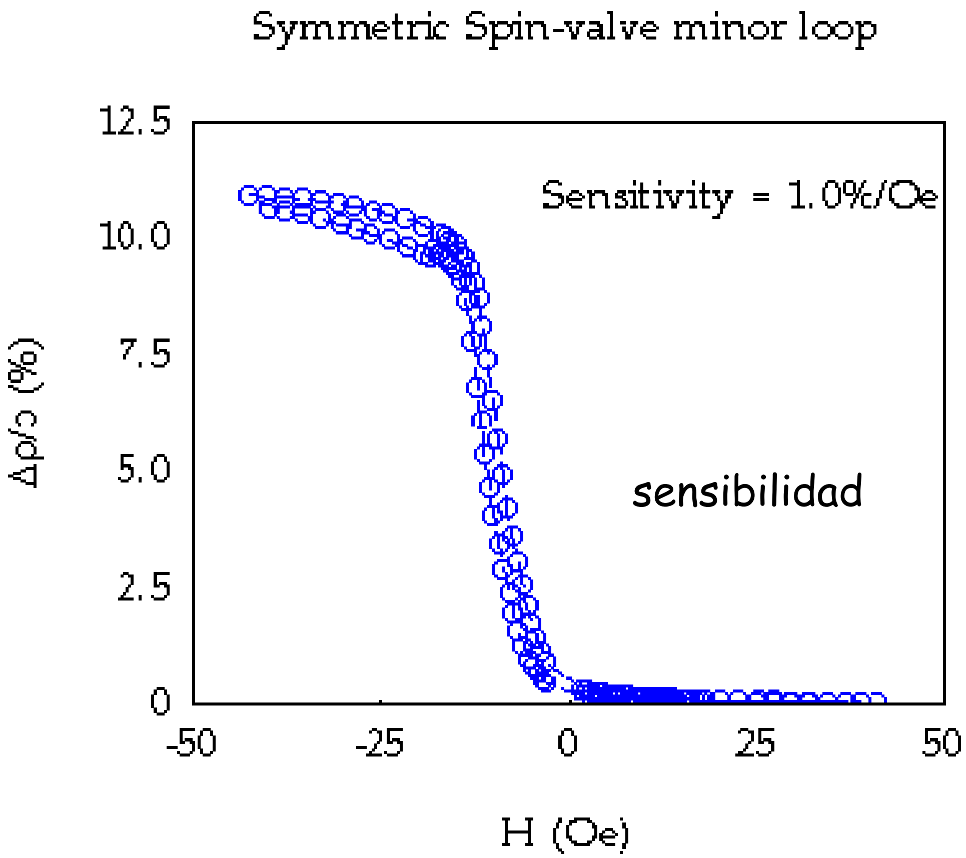
Válvula de spin







6
4
2
0
Δρ/ρ (%)
estabilidad
-2000
0
2(
H (Oe)

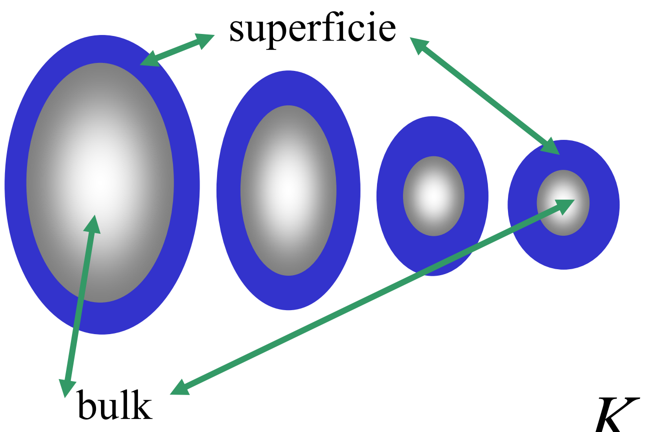


Symmetric Spin-valve minor loop
12.5
10.0
7.5
5.0
2.5
0
Δρ/ρ (%)
Sensitivity = 1.0%/Oe
sensibilidad
-50
-25
0
25
50
H (Oe)

animación

Anisotropía en nanopartículas magnéticas y fluctuaciones térmicas

anisotropía de superficie en nanopartículas



$$K_{ef} = K_B + K_{V_S}^{ef}$$

$K_S = 10^{-4}$-10^{-3} J/m^2, energía de anisotropía por unidad de área superficial

$$K_{V_S}^{ef} \approx \frac{SK_S}{V} \approx \frac{4\pi r^2}{\frac{4}{3}\pi r^3} K_S = \frac{3}{r} K_S = \frac{6}{d} K_S$$

Partícula esférica

$$K_{ef} = K_B + \frac{6K_s}{d}$$

$$K_{ef} = K_B + \gamma \frac{K_s}{\bar{d}}$$

Bødker et. Al (1994)

superficies/interfaces:

- discontinuidad composicional y configuracional
- mayor efecto anisotrópico

Anisotropía de superficie - ejemplo

$$K_B\left(Co_{fcc}\right)\approx 1\times 10^5\, J/m^3$$

Alúmina

$$K_S\left(Co/Al_2O_3\right)\approx 3.3x10^{-4}\, J/m^2$$

$$K_{ef}=K_B+\gamma\frac{K_s}{\bar{d}}$$

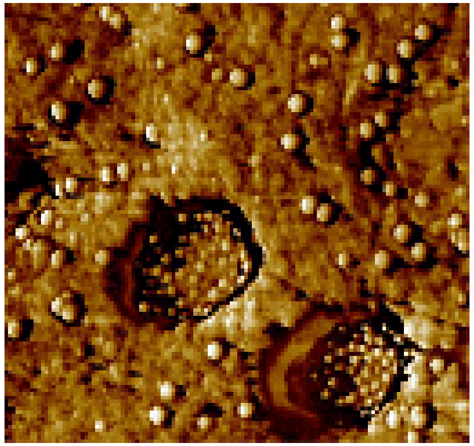


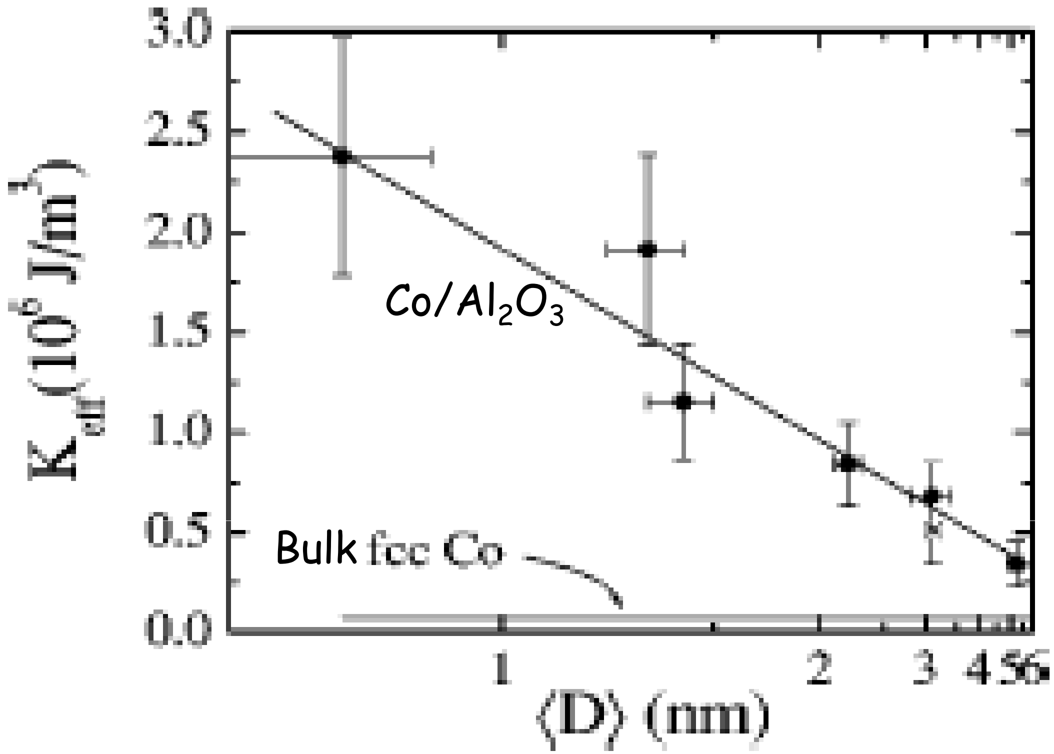
imagen MFA de nanopartículas de Co fcc en una matriz de alúmina. Las partículas son de aprox 11 nm (diámetro).

$$K_{ef}\left(Co/Al_2O_3\right)\approx\left[1\times 10^5+6\frac{3.3\times 10^{-4}}{11\times 10^{-9}}\right]J/m^3\approx 2.8\times 10^5\, J/m^3$$

Si d ~ 3 nm = $3x10^{-9}$m ⇒ $K_{ef}\left(Co/Al_2O_3\right)\approx 10^6\, J/m^3$

$$\tau=\tau_0 e^{\frac{K_{ef}V}{kT}}$$

Mayores tiempos de relajación



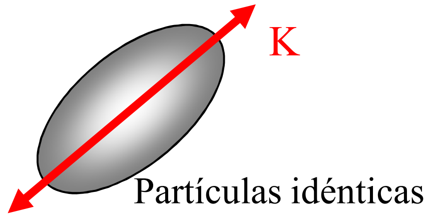
F. Luis, J.M. Torres, L.M. Gracía, J. Bartolomé, J. Stankiewicz, F. Petroff, F. Fettar, J. L. Maurice and A. Vaurés. Phys. Rev B, **65** (2002) 094409

Modelo de Stoner - Wohlfarth

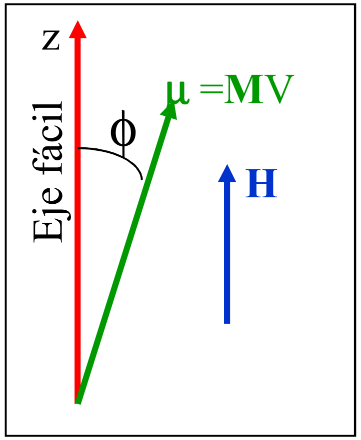
monodominio

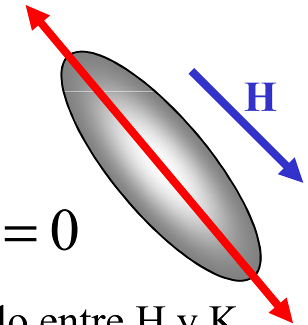
Anisotropía uniaxial

no interactuantes



Campo paralelo al eje fácil





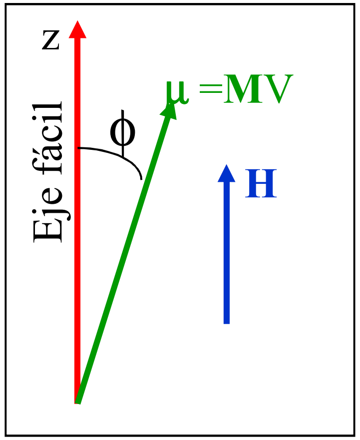
$$\theta = 0$$

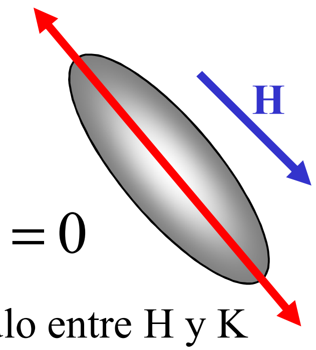
ángulo entre H y K

$$E_K = e_K V = KV \sin^2 \phi$$

$$E_H = -\vec{\mu} \cdot \vec{B} = -\mu_0 \vec{\mu} \cdot \vec{H} = -\mu_0 V M_z H = -\mu_0 V M_S H \cos\phi$$

$$E = E_K + E_H = KV \sin^2 \phi - \mu_0 V M_S H \cos\phi$$





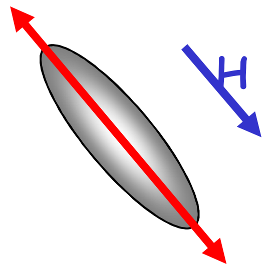
$$E = E_K + E_H = KV\sin^2\phi - \mu_0 V M_S H\cos\phi$$

llamamos Campo de anisotropía

$$H_K = \frac{2K}{\mu_0 M_S}$$

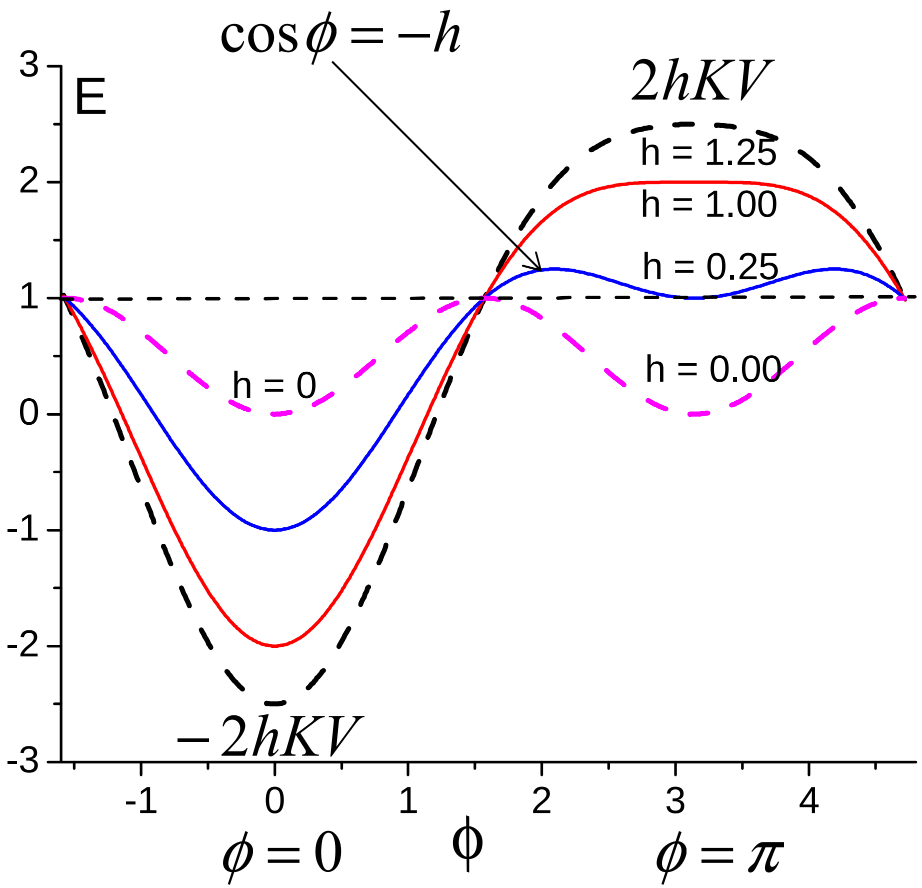
$$h = \frac{H}{H_K} = \frac{\mu_0 M_S H}{2K}$$

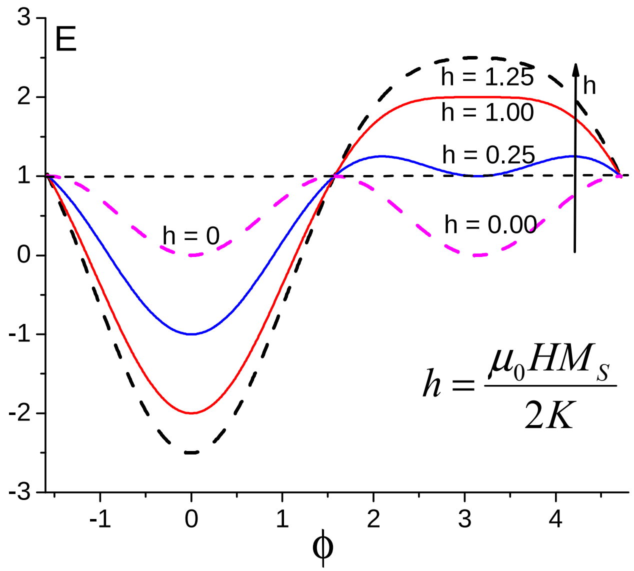
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$



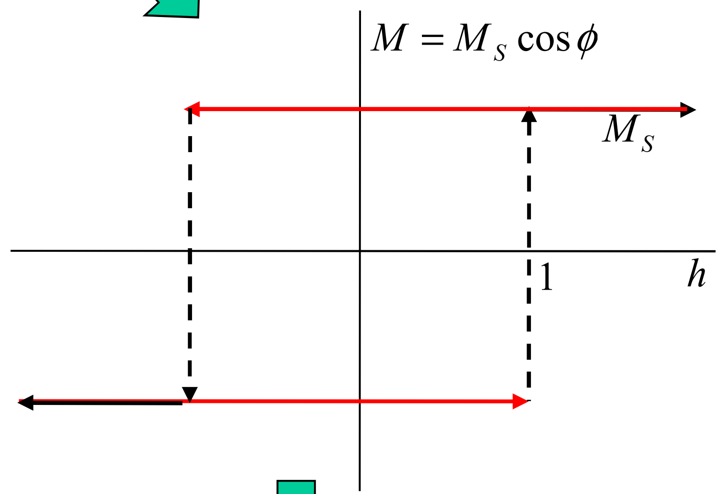
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

$$h = \frac{H}{H_K} \quad H_K = \frac{2K}{\mu_0 M_S}$$



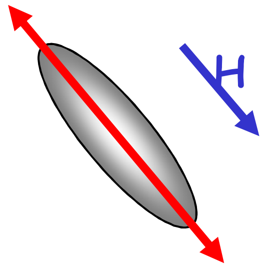


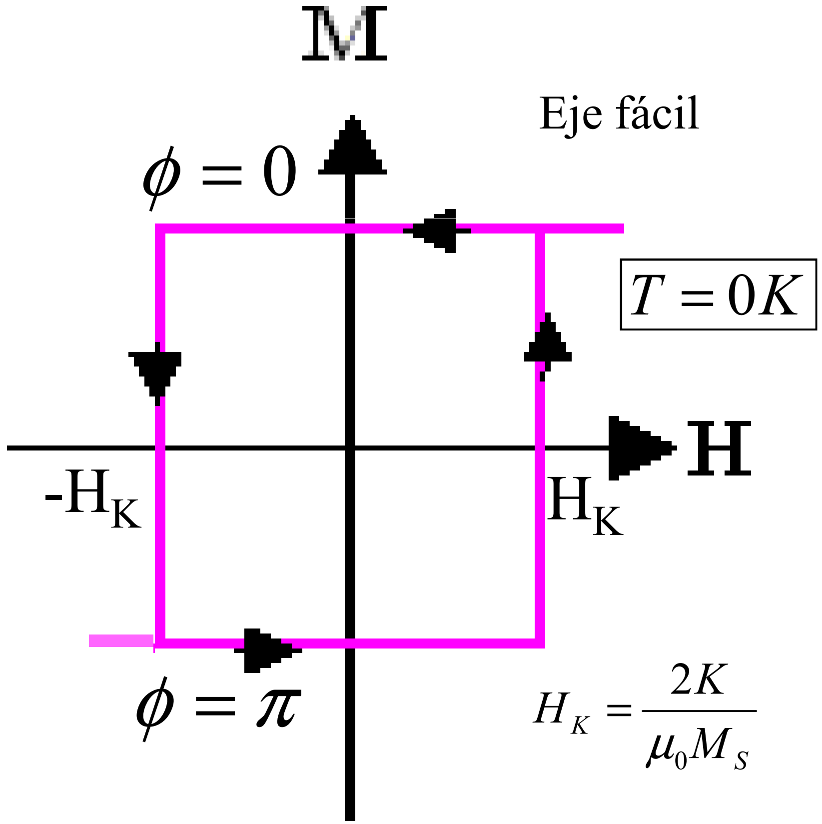
E
h = 1.25
h = 1.00
h = 0.25
h = 0.00
h = 0
h
$h = \frac{\mu_0 H M_S}{2K}$
ϕ
3
2
1
0
-1
-2
-3
-1
0
1
2
3
4



$M = M_S \cos\phi$
M_S
1
h

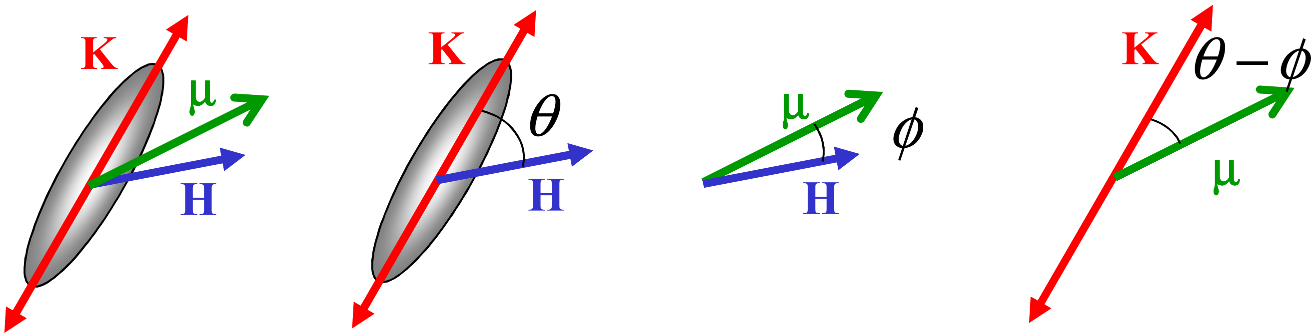
$$M_z = M_s \cos\theta$$



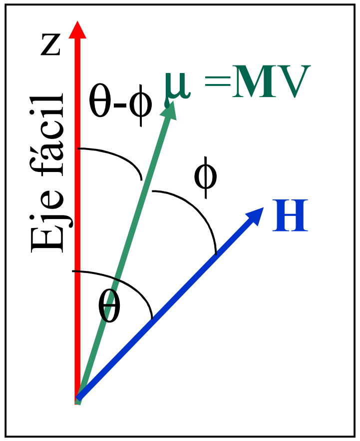


Campo en dirección arbitraria

$$\theta \neq 0$$

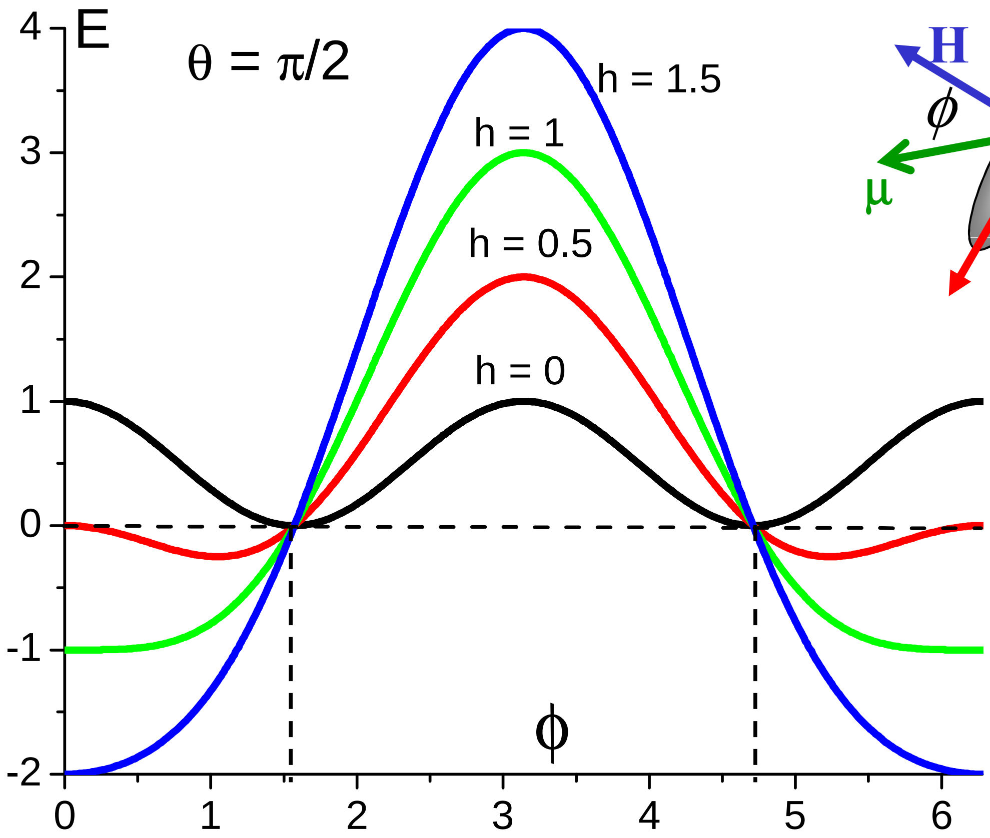


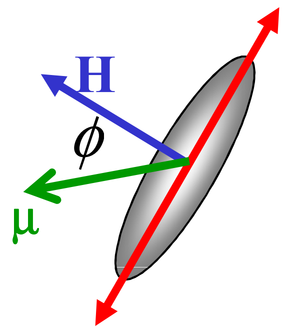
$$E = E_K + E_H = KV\left[\sin^2(\phi - \theta) - 2h\cos\phi\right]$$

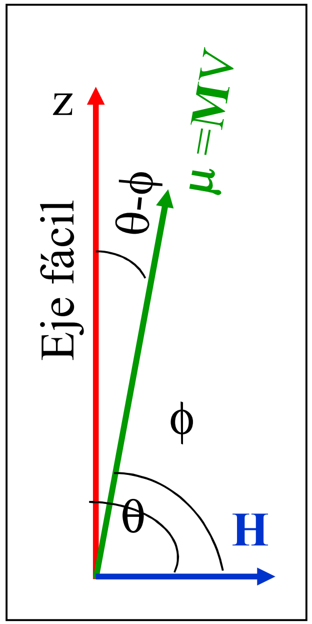


$\theta = \pi / 2$

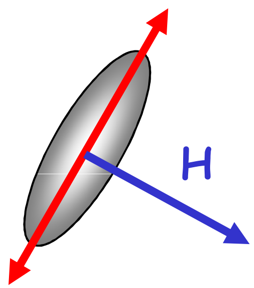
$$E = E_K + E_H = KV\cos\phi\left(\cos(\phi) - 2h\right)$$

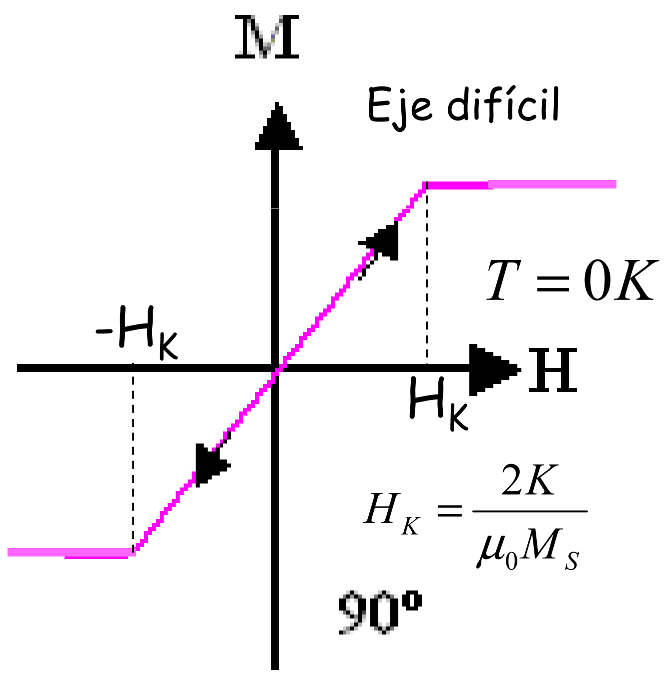






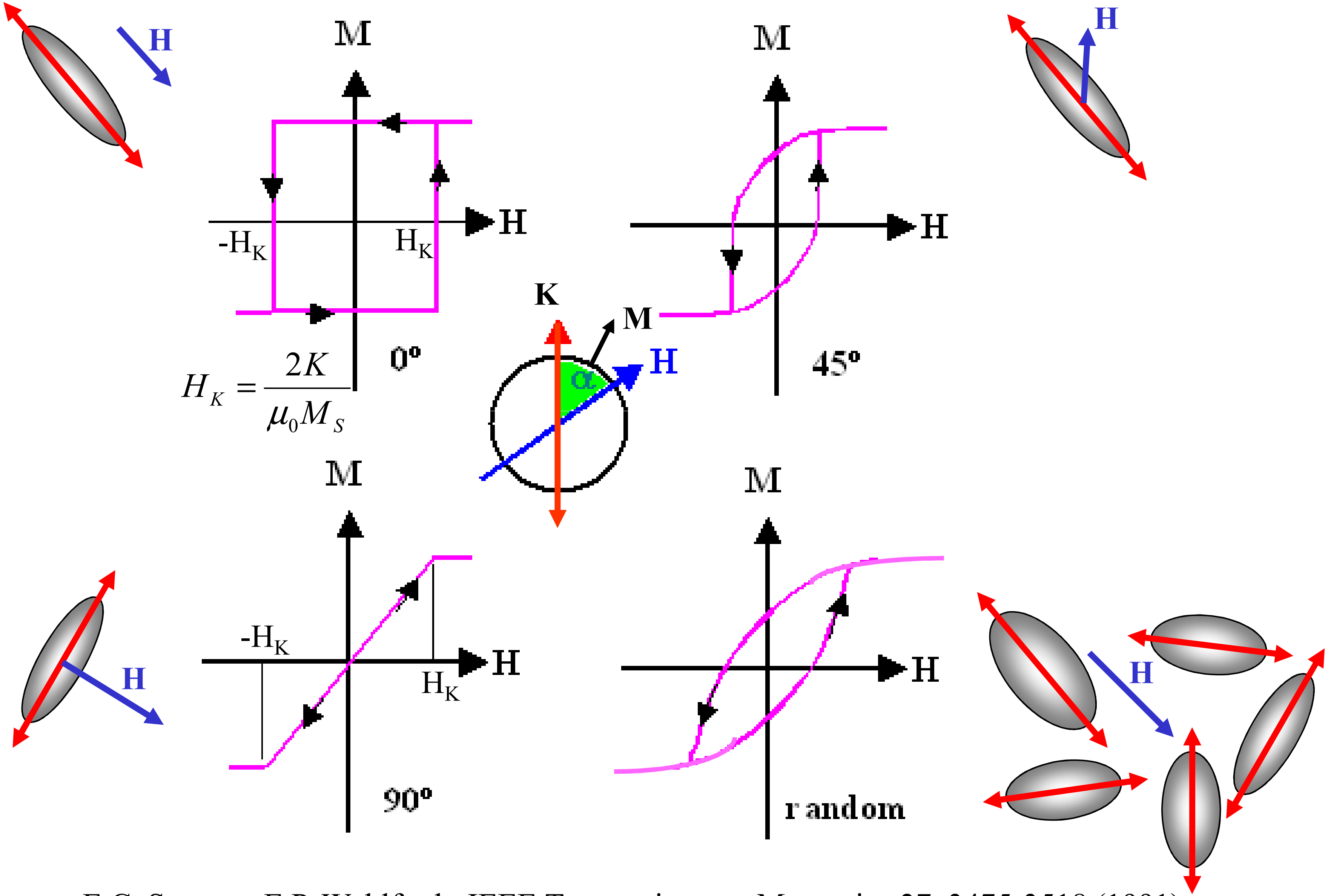
$$M_z = \frac{M_S}{H_K} H; \qquad |h| < 1$$





Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

régimen bloqueado → T = 0



E.C. Stoner y E.P. Wohlfarth, IEEE Transactions on Magnetics **27**, 3475-3518 (1991)

A MECHANISM OF MAGNETIC HYSTERESIS IN HETEROGENEOUS ALLOYS

By E. C. STONER, F.R.S. and E. P. WOHLFARTH
Physics Department, University of Leeds

(*Received* 24 *July* 1947)

Vol. 240. A. 826 (Price 10*s*.) 74 [Published 4 May 1948

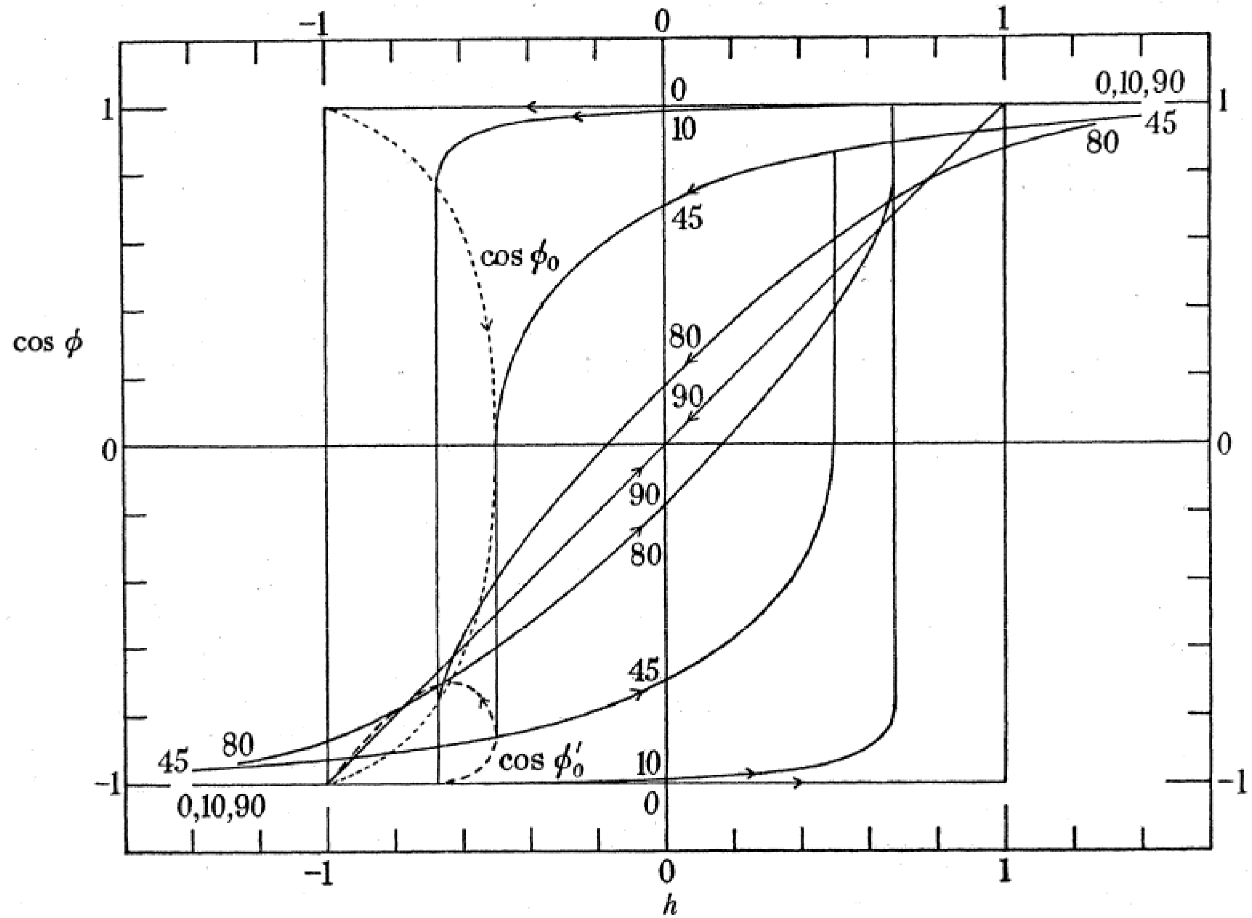


FIGURE 6. Magnetization curves for prolate spheroids. The resolved magnetization in the positive field direction is given by $I_0 \cos \phi$, where I_0 is the saturation magnetization. The field, H, is given by $H = (N_b - N_a)\, I_0 h$, where N_a and N_b are the demagnetization coefficients along the polar and equatorial axes. The angle, θ, between the polar axis and the direction of the field, is shown, in degrees, by the numbers on the curves. The dotted curves give $\cos \phi_0$ and $\cos \phi_0'$, where ϕ_0 and ϕ_0' are the angles made with the positive field direction by the magnetization vector at the beginning and end of the discontinuous change at the critical value, h_0, of the field.

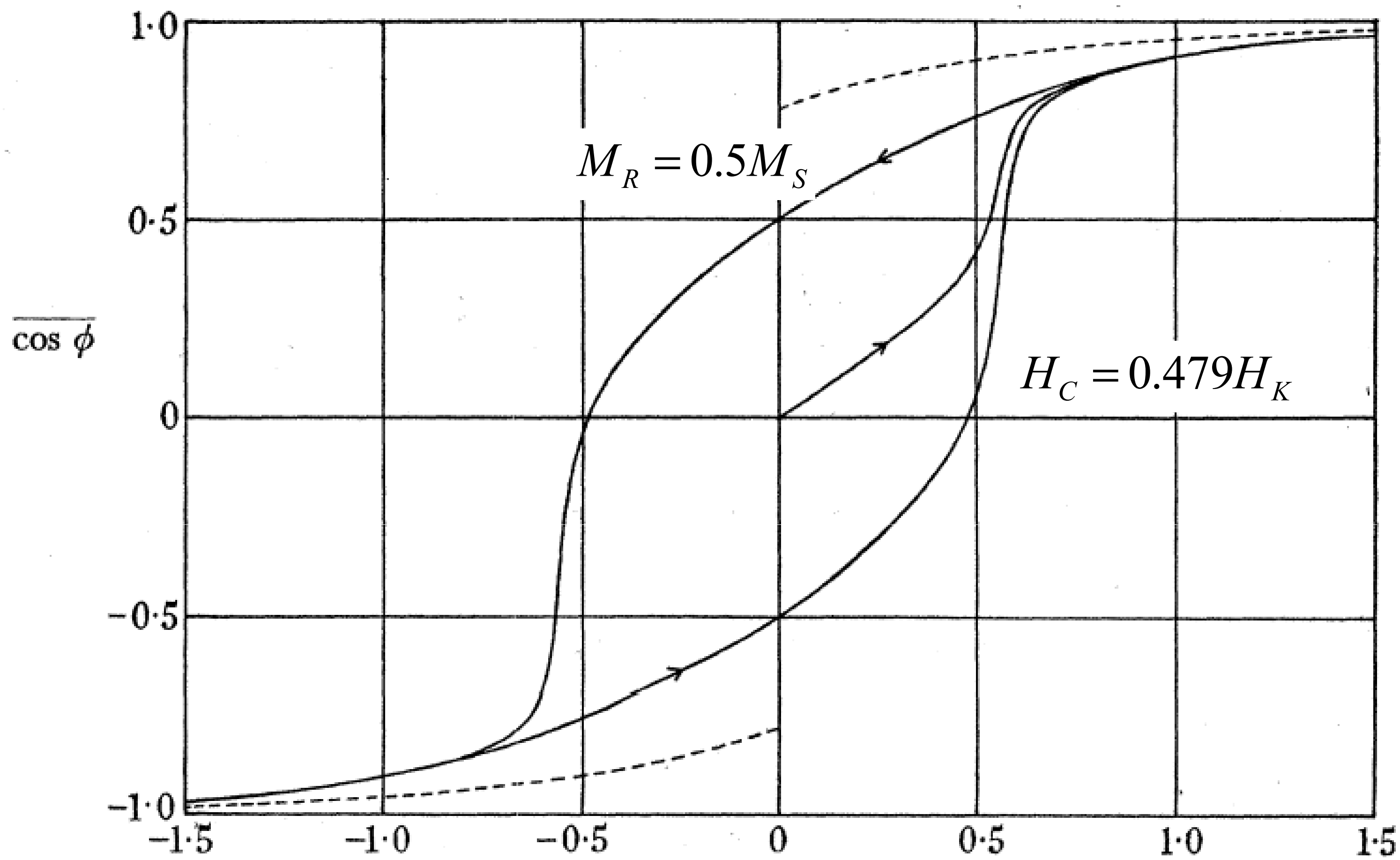


FIGURE 7. Magnetization curves for prolate (full curves) and oblate (broken curves) spheroids orientated at random. The curves refer to similar prolate (or oblate) spheroids orientated at random. $\overline{\cos\phi}$ is proportional to the mean resolved magnetization per spheroid in the positive field direction, or to the resultant magnetization in this direction of the assembly. $H = (|N_a - N_b|)\, I_0 h$.

IBM Journal of Research and Development
Spintronics Volume 50, Number 1, 2006

Rapid-turnaround characterization methods for MRAM development

by D. W. Abraham,
P. L. Trouilloud,
and D. C. Worledge

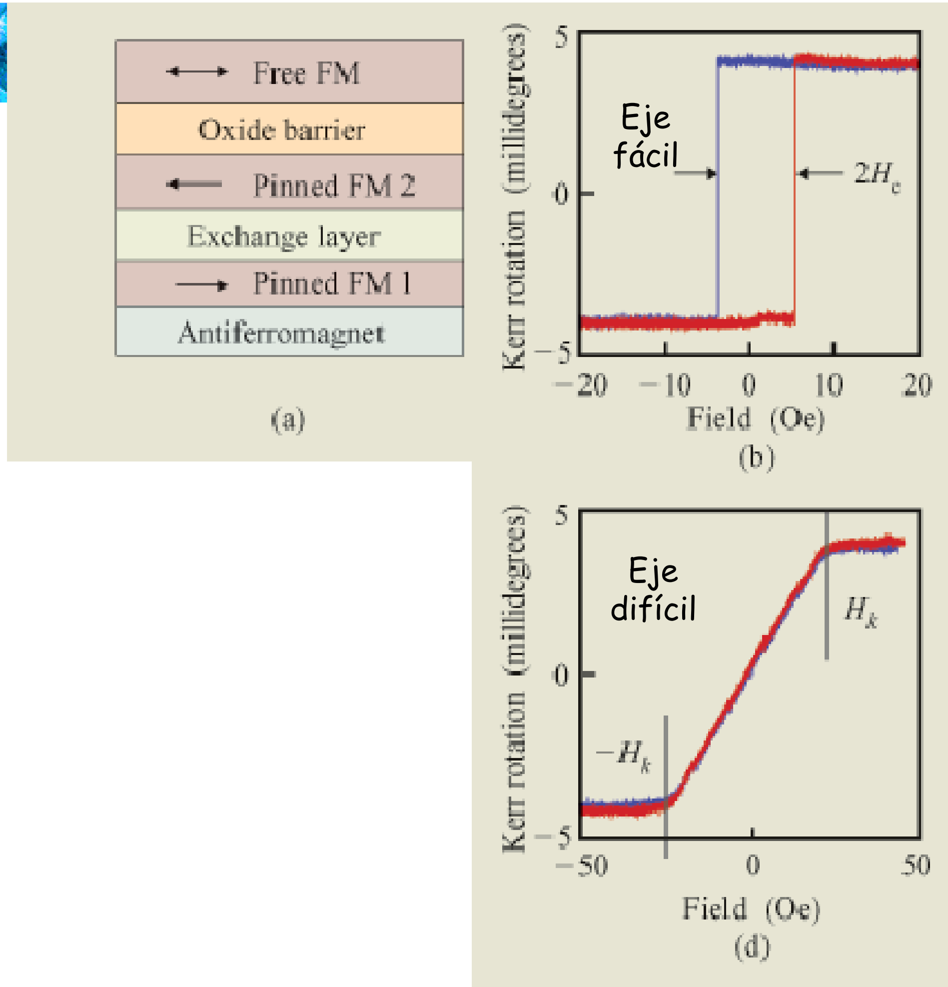
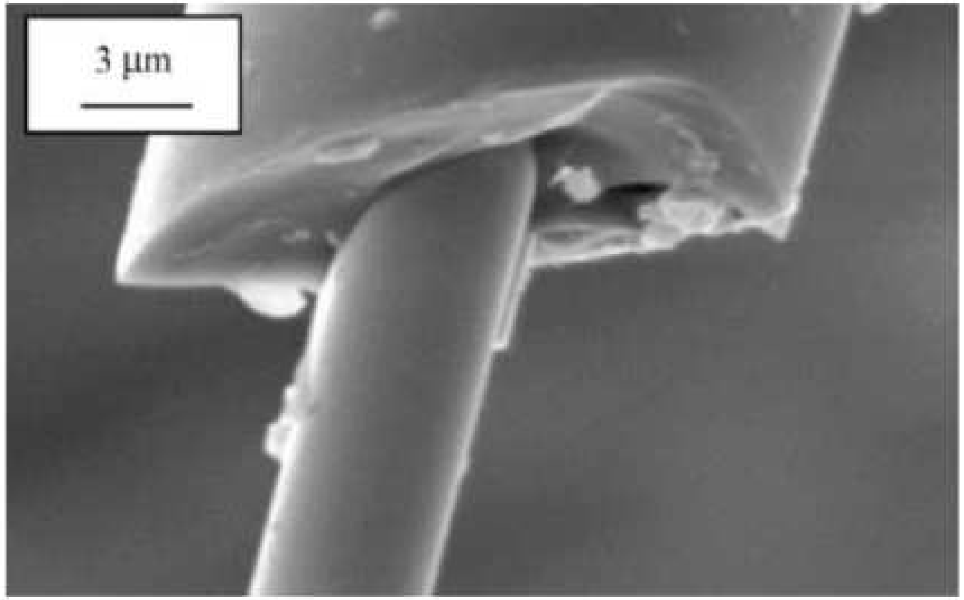
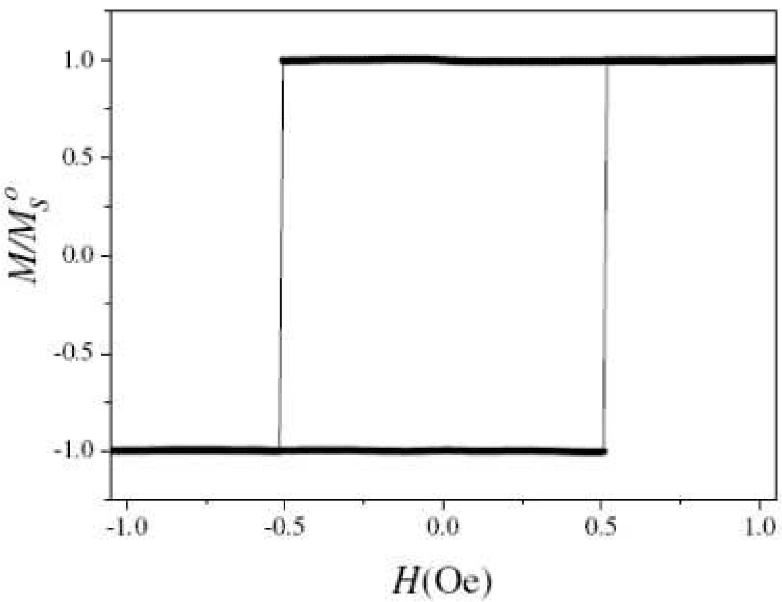


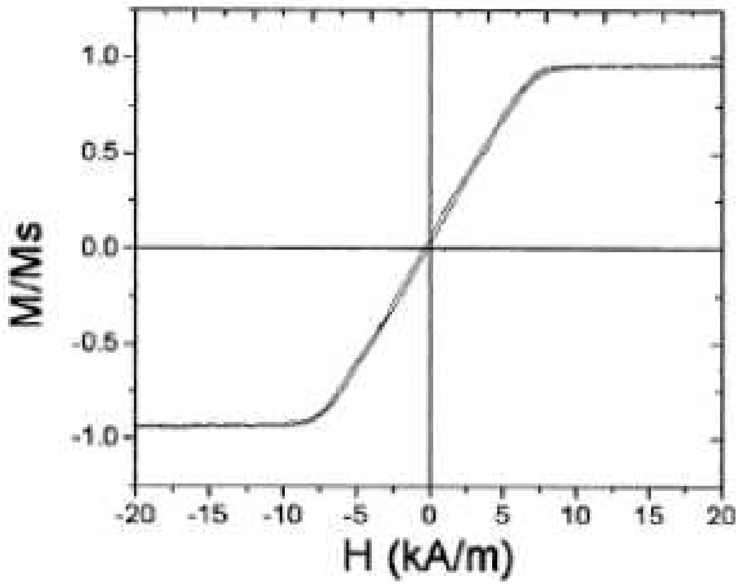
Figure 4

(a) Typical data for a Stoner–Wohlfarth stack. (a) Kerr easy-axis (EA) data taken at low field, showing the excellent low Néel offset and sharp hysteresis loop. (c) High-field EA Kerr magnetometry data showing the relative motion of the magnetization in the two ferromagnetic films, permitting direct measurement of pinning and interlayer coupling. (d) Hard-axis data revealing the film anisotropy.

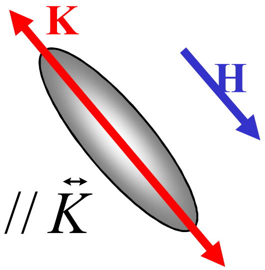
Microhilos, *P. Mendoza Zéliz et al, 2007*







Efectos Dinámicos ($T \neq 0$)

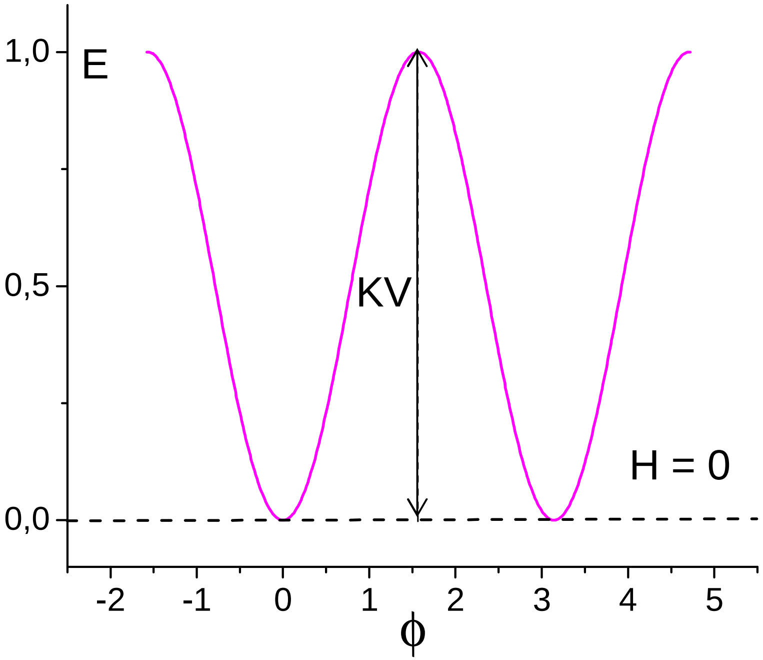


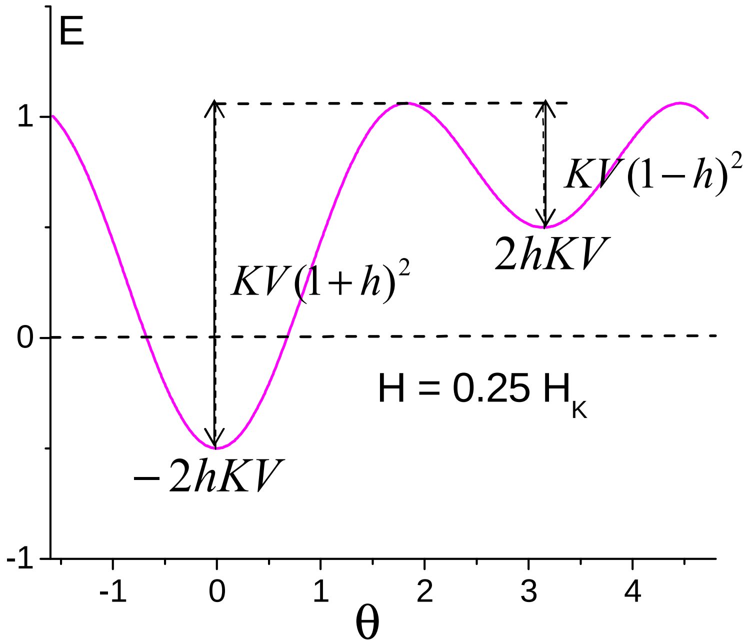
$$\vec{H} // \overleftrightarrow{K}$$

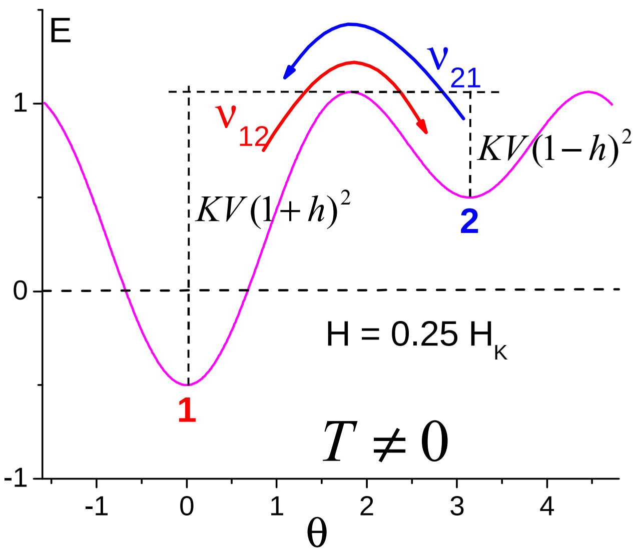
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

$$h = \frac{H}{H_K}$$

$$H_K = \frac{2K}{\mu_0 M_S}$$







$$\Delta E_{ij} = KV(1+h)^2$$

$$\nu_{ij} = c_0 e^{-\frac{\Delta E_{ij}}{kT}}$$

Frecuencia de saltos

$$\xrightarrow[T=0]{} \nu_{ij} = 0$$

$$\xrightarrow[T=\infty]{} \nu_{ij} = c_0$$

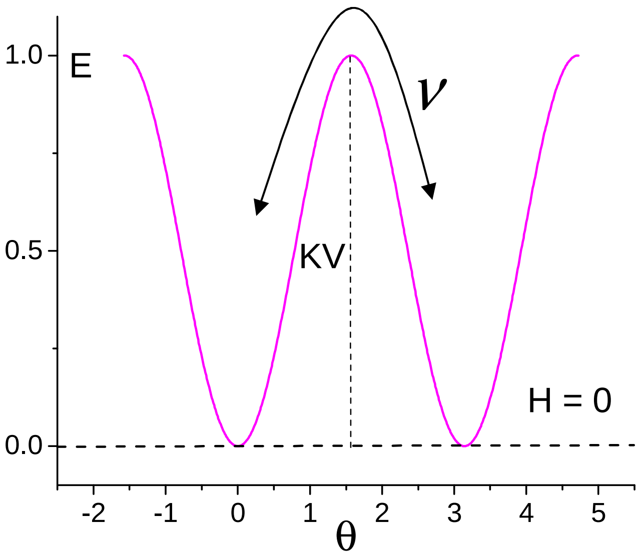
Frecuencia de intentos

$$\tau_{ij} = c_0^{-1} e^{\frac{\Delta E_{ij}}{kT}}$$

Tiempo de relajación

$$\tau_{ij} = c_0^{-1} e^{\frac{\Delta E_{ij}}{kT}}$$

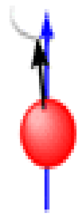
Tiempo de relajación



Para H = 0

$$\nu_{12} = \nu_{21} = \nu$$

$$\nu = \nu_0 e^{-\frac{KV}{kT}}$$



$$\tau = \tau_0 e^{\frac{KV}{kT}}$$

$$10^{-12} s \leq \tau_0 \leq 10^{-9} s$$

$$\tau = \tau_0 e^{\frac{KV}{kT}}$$

$$\tau_0 \approx cte$$

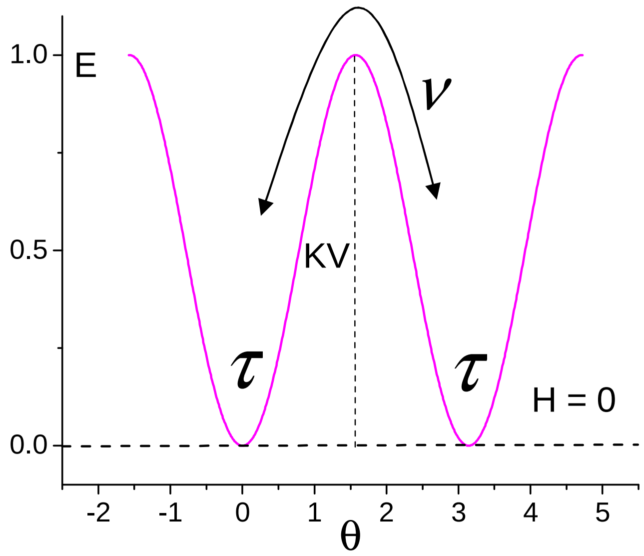
Ejemplo, usando $\tau_0 = 10^{-9}$ s

material	$K(J/m^3)$	R(nm)	τ(s)
Co	3.9×10^5	4.4	6×10^5
		3.6	0.1
Fe	4.7×10^4	14.0	1.5×10^5
		11.5	0.07

Comportamiento superparamagnético

$$\tau = \tau_0 e^{\frac{KV}{kT}}$$

Tiempo Experimental vs Tiempo de Relajación

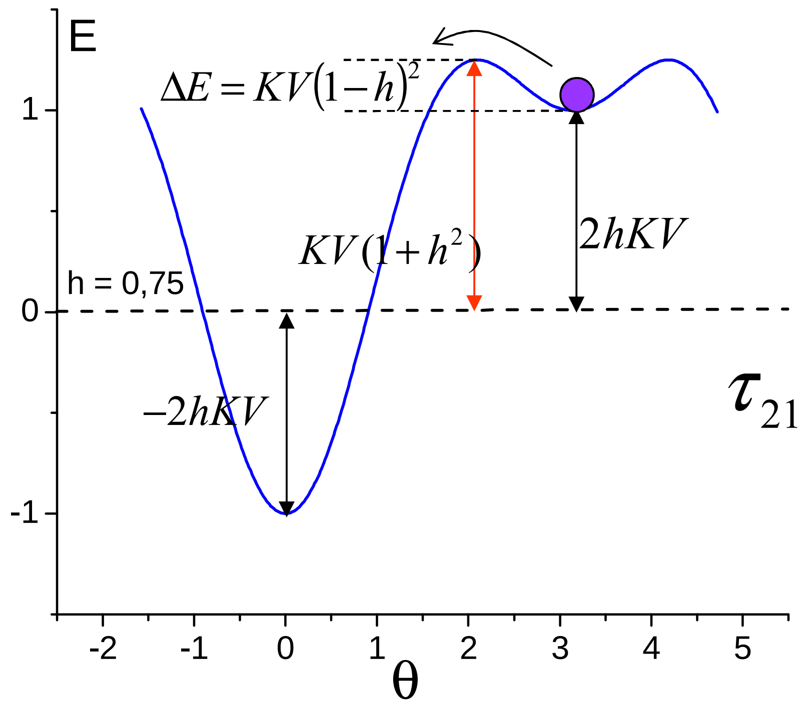


Técnica	τ_{exp}
Mössbauer ^{57}Fe, ^{119m}Sn	$\approx 10^{-8}$s
Susceptibilidad *ac*	$10^{-4} – 1$ s
Susceptibilidad *ac hf*	desde 10^{-6} s
Magnetización *dc*	0.1 –100 s

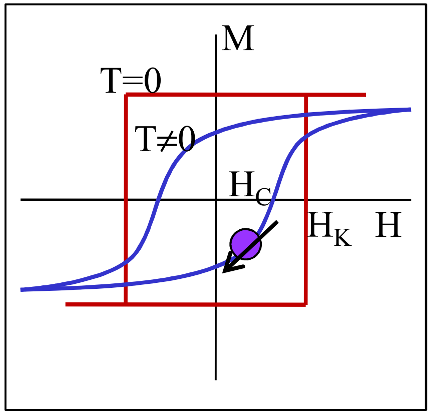
$\tau_{exp} < \tau \Leftrightarrow T < T_B$	Sistema bloqueado	Patrón estático	Histéresis, desdoblamiento Zeeman (EM)
$\tau_{exp} > \tau \Leftrightarrow T > T_B$	Sistema desbloqueado	Patrón dinámico	Equilibrio, patrón super-paramagnético (EM)

Dependencia del campo coercitivo con la temperatura

$$h = H / H_K = \frac{\mu_0 M_S H}{2K}$$



$$H_C = H_K = \frac{2K}{\mu_0 M_S}$$



$$\tau_{21} = \tau_0 e^{\frac{KV(1-h)^2}{kT}}$$

a T ≠ 0 K la inversión de M se producirá cuando $\tau_{21} \approx \tau_{exp}$

Dependencia del campo coercitivo con la temperatura

$$KV(1-h)^2 = kT\ln(\tau_{\exp}/\tau_0)$$

$\tau_{\exp} = 10^2 s$ *SQUID*

$\tau_{\exp} = 10^{-8} s$ *Möss*

$$\ln(\tau_{\exp}/\tau_0) \approx \begin{cases} 27.6\, kT & SQUID \\ 4.6\, kT & Möss \end{cases}$$

$$KV(1-h)^2 \approx 27.6\, kT \qquad \xrightarrow[h<<1]{} \qquad KV \approx 27.6\, kT \quad SQUID$$

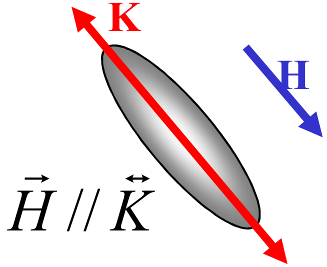
$$KV(1-h)^2 \approx 4.6\, kT \qquad \xrightarrow[h<<1]{} \qquad KV \approx 4.6\, kT \quad Möss$$

Dependencia del campo coercitivo con la temperatura

$$KV(1-h)^2 \approx kT\ln(\tau_{exp}/\tau_0)$$

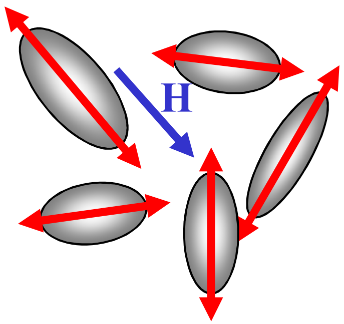
$$h \approx 1-\sqrt{\frac{kT}{KV}\ln(\tau_{exp}/\tau_0)}$$

$$H_C(T) \approx H_K\left(1-\sqrt{\frac{kT}{KV}\ln(\tau_{exp}/\tau_0)}\right)$$

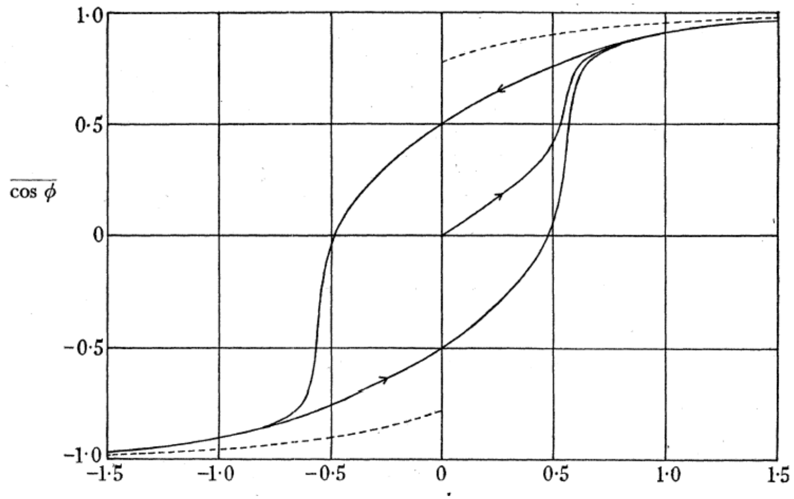


orientación aleatoria

$$H_C(T) \approx 0.48H_K\left(1-\sqrt{\frac{kT}{KV}\ln(\tau_{exp}/\tau_0)}\right)$$



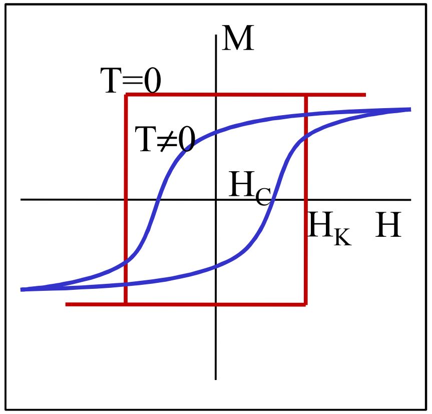
$$H_C(0) = 0.479H_K$$



Temperature Dependent Magnetic Properties of Barium-Ferrite Thin-Film Recording Media

Yingjian Chen, *Member, IEEE,* and Mark H. Kryder, *Fellow, IEEE*

IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 3, MAY 1998



$$H_c(t') = H_k\left\{1 - \left[\frac{k_B T}{K_u V_{sw}} \ln\left(\frac{At'}{0.693}\right)\right]^n\right\}$$

the easy axis orientation. In a system with uniaxially aligned easy axes, n is 1/2 [29], and in a system with random easy axis orientations n is 2/3 [30]. The fitting parameters V_{sw}

[29] M. P. Sharrock and J. T. McKinney, *IEEE Trans. Magn.*, vol. MAG-17, p. 3020, 1981.
[30] R. H. Victora, "Predicted time dependence of the switching field for magnetic materials," *Phys. Rev. Lett.*, vol. 63, pp. 457–460, 1989.

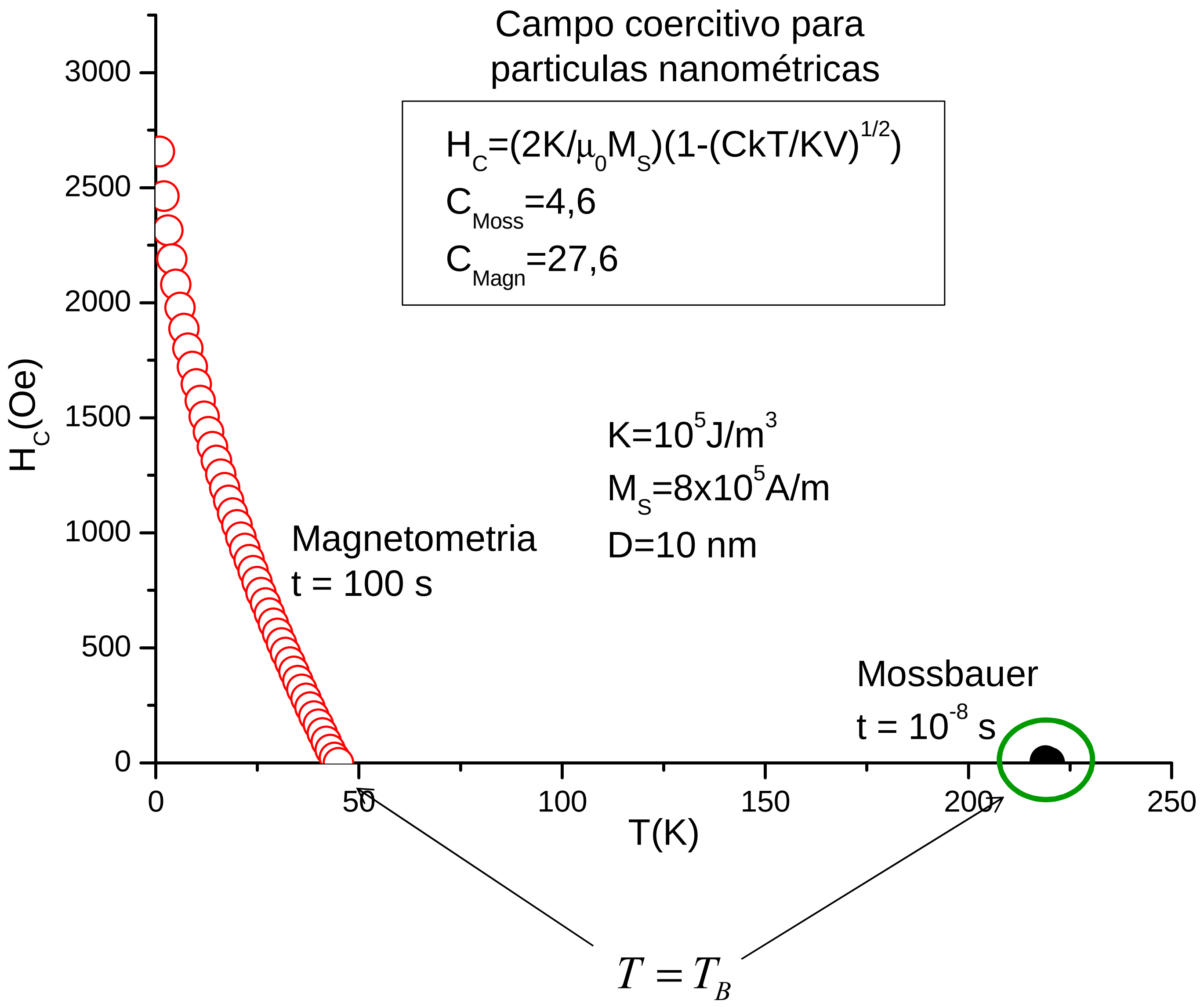
Uso extendido de la expresión

$$H_C = \alpha \frac{2K}{M_S}\left[1 - \left(\frac{T}{T_B}\right)^{1/2}\right]$$

Interacciones magnéticas en nanotubos ferromagnéticos de LaCaMnO y LaSrMnO,

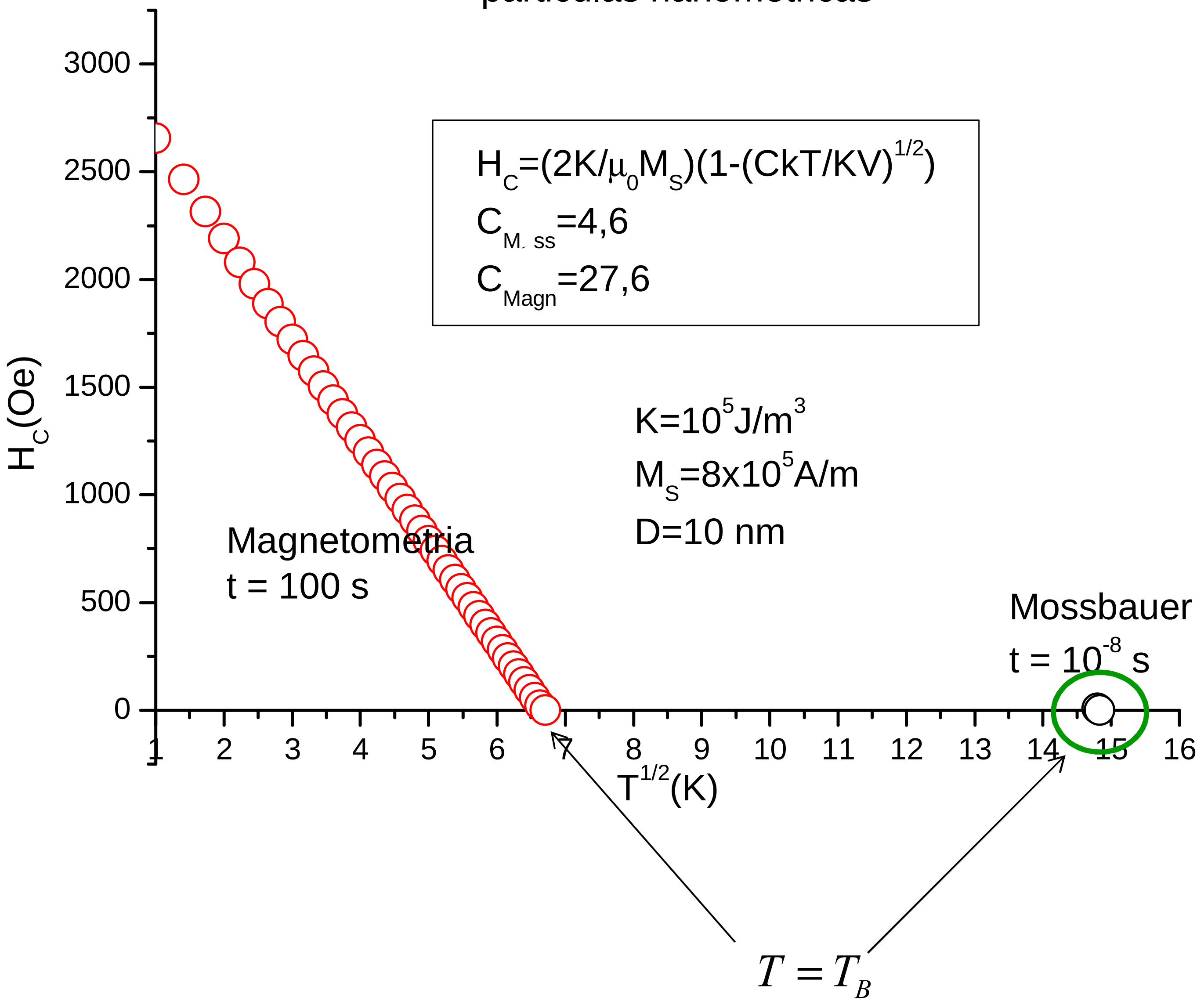
J.Curiale et al., AFA 2006

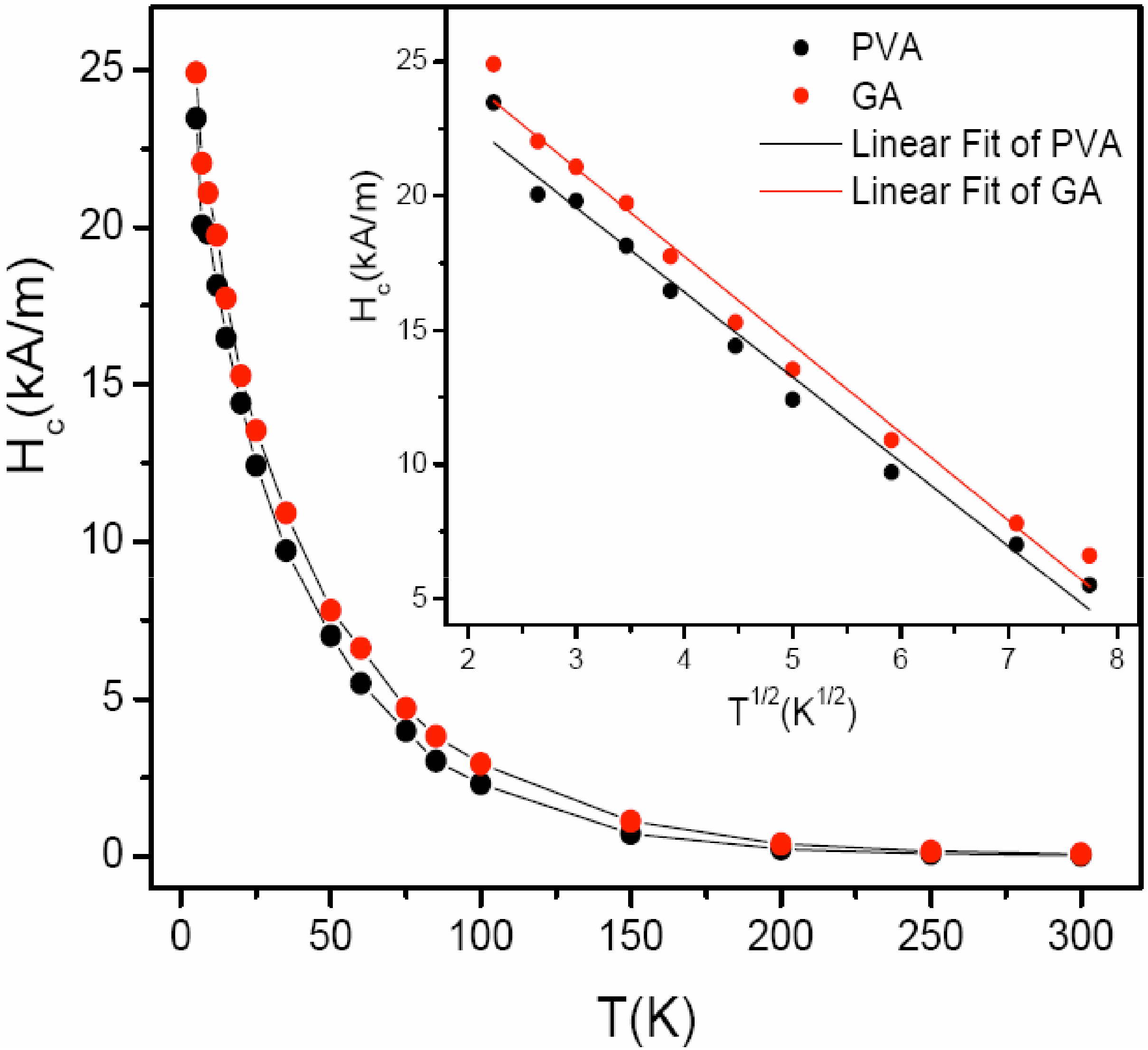
Marina Tortarola, Tesis, IB, 2008



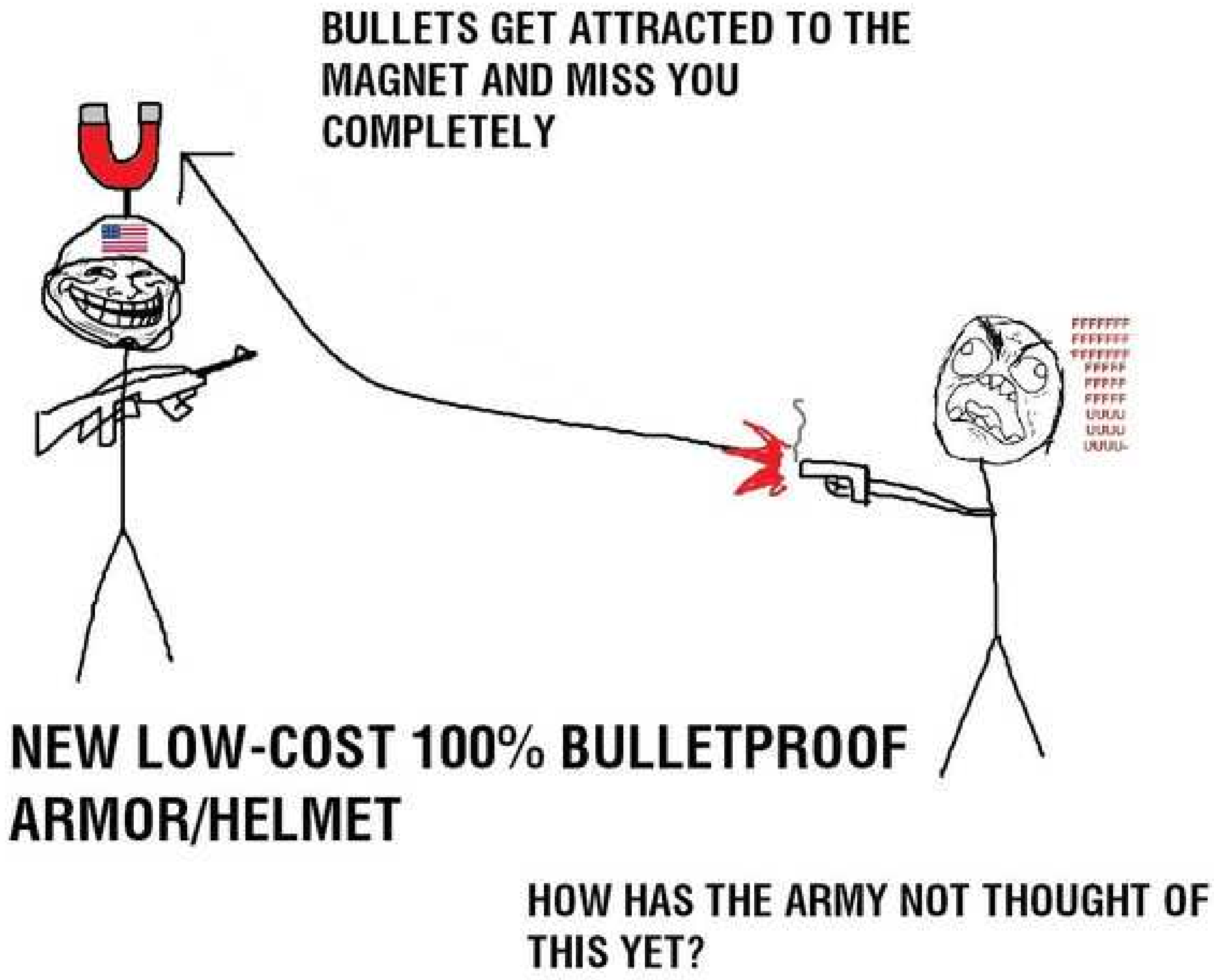
Campo coercitivo para
particulas nanométricas
$H_C=(2K/\mu_0 M_S)(1-(CkT/KV)^{1/2})$
$C_{Moss}=4,6$
$C_{Magn}=27,6$
$K=10^5 J/m^3$
$M_S=8x10^5 A/m$
D=10 nm
Magnetometria
t = 100 s
Mossbauer
$t = 10^{-8}$ s
H_C(Oe)
T(K)
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
$T = T_B$

Campo coercitivo para particulas nanométricas





Ferrogel de NP de magnetita (8 nm) en hidrogel de PVA, Mendoza
Zélis et al, enviado


BULLETS GET ATTRACTED TO THE MAGNET AND MISS YOU COMPLETELY
NEW LOW-COST 100% BULLETPROOF ARMOR/HELMET
HOW HAS THE ARMY NOT THOUGHT OF THIS YET?

Fin módulo