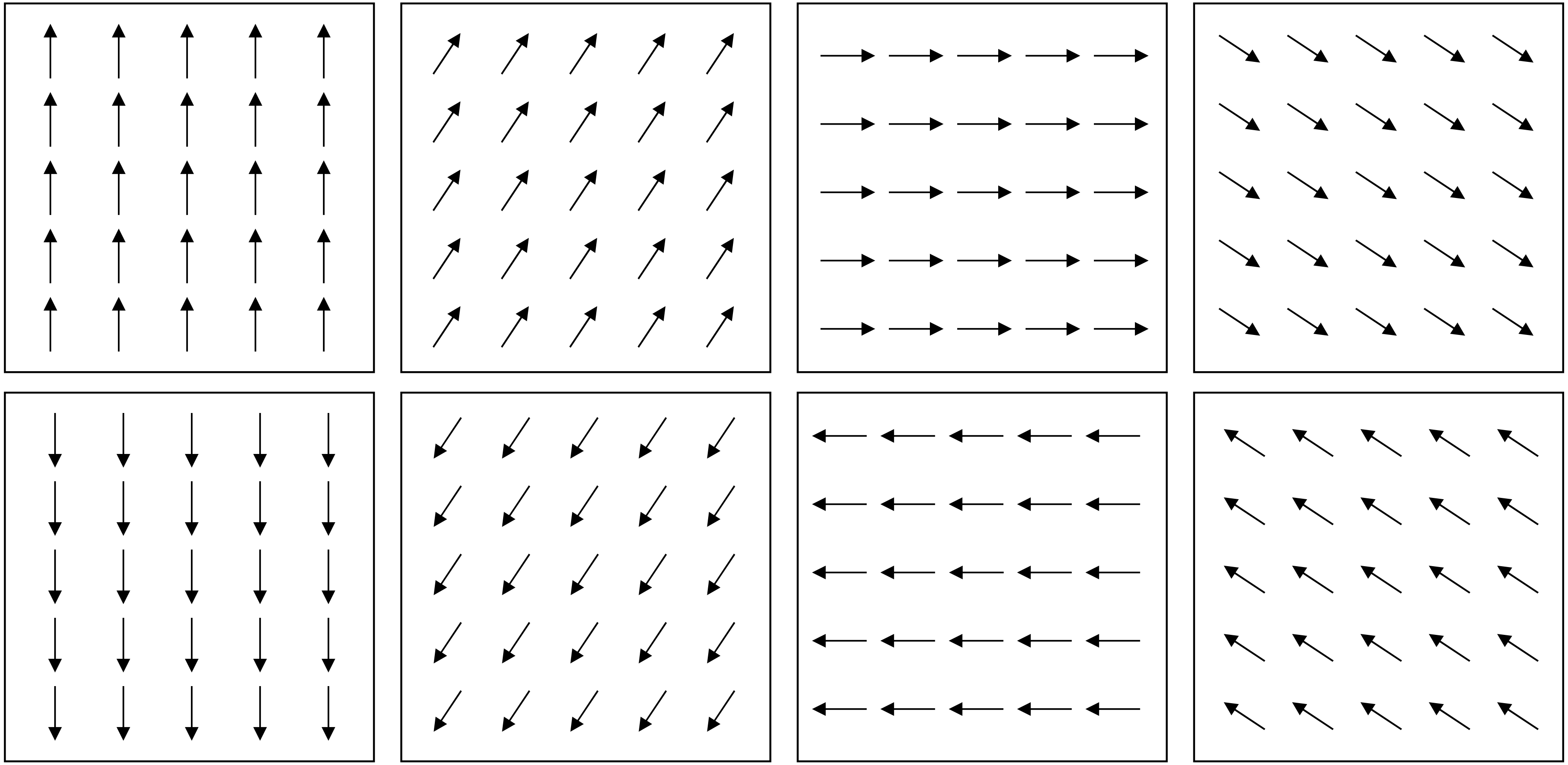
Anisotropía magnetocristalina

Sólo intercambio
(ausencia de anisotropía)

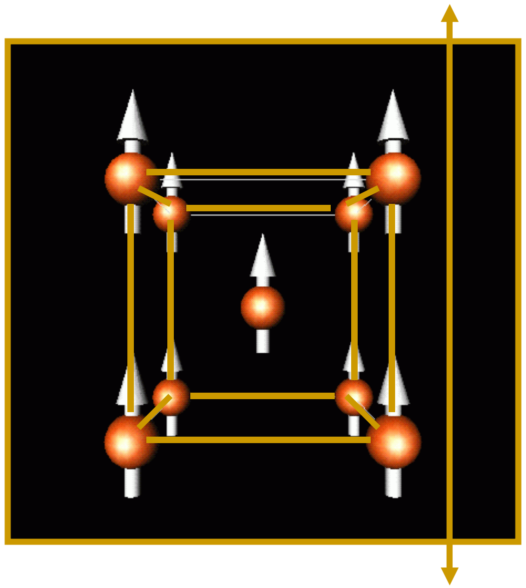
Dirección aleatoria de **M** en 4π => estado continuamente degenerado

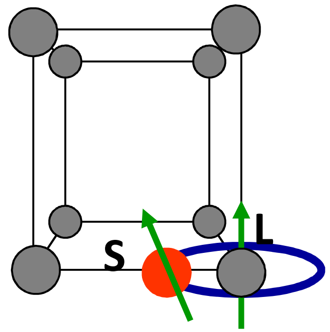


Siempre estaríamos en presencia de un superparamagneto

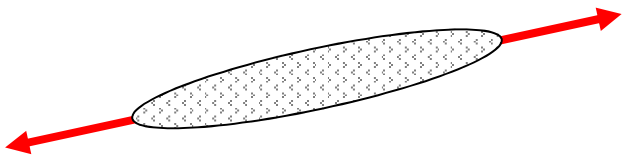
Anisotropía

Fe

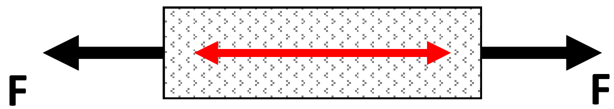




Estructura cristalina → Int. elect - Campo cristalino + interacción Spin – órbita = Anisotropía magneto-cristalina

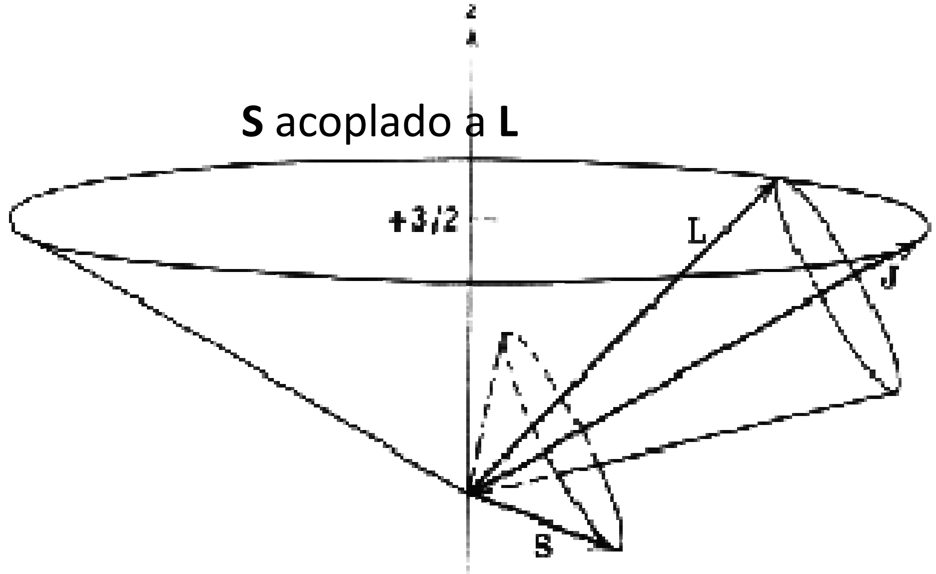


Forma: anisotropía magnetostática



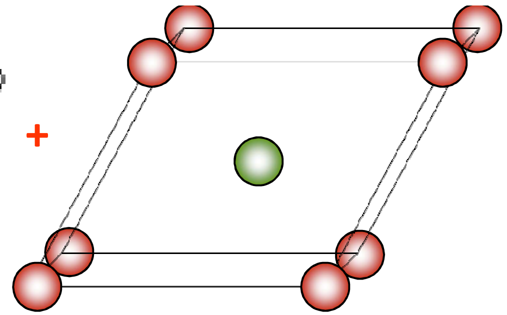
Esfuerzo: anisotropía magnetoelástica

spin – órbita + campo cristalino

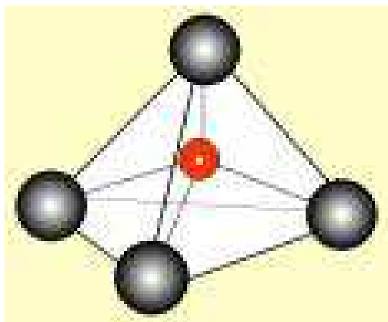


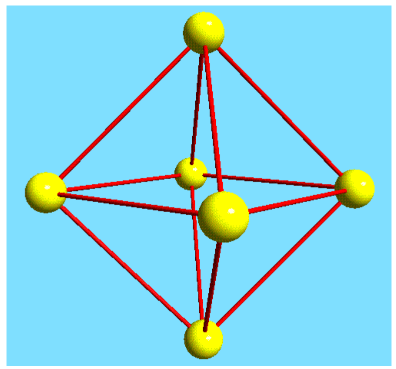
+

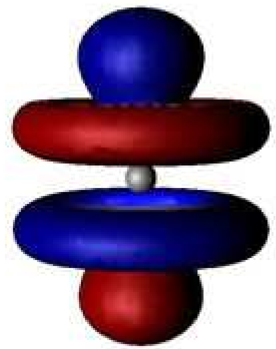
Campo cristalino



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

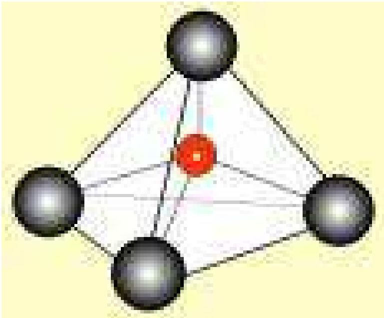


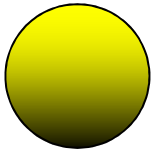


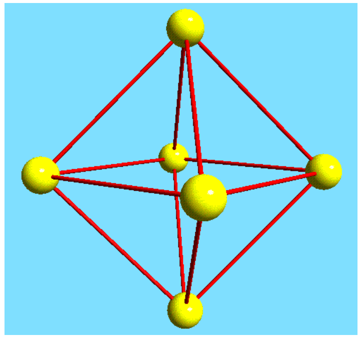


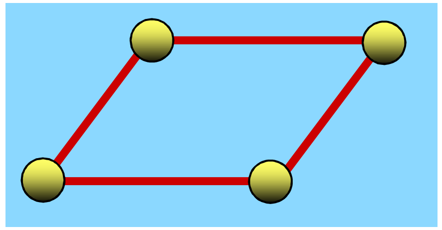
Diagramas de desdoblamiento de orbitales d por el campo cristalino

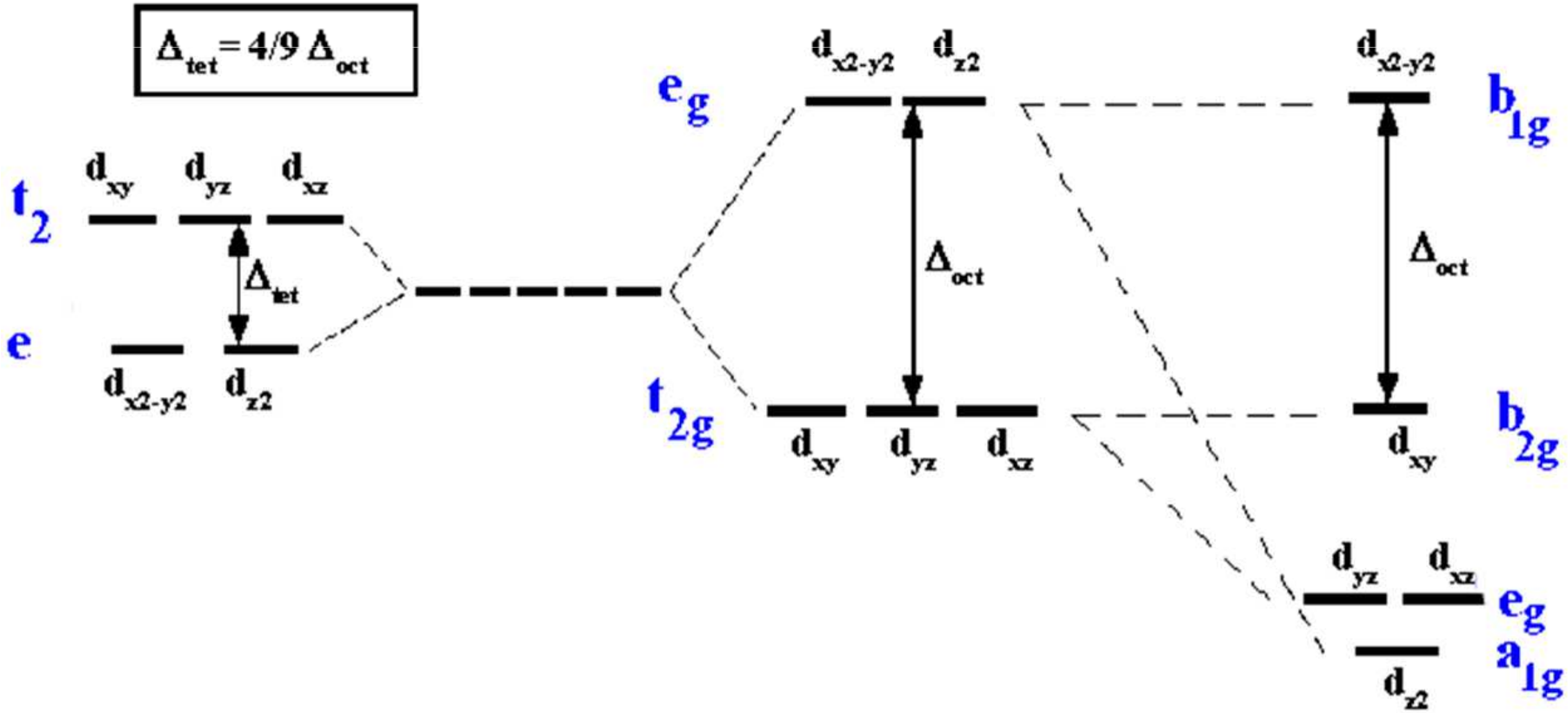
Campo tetraédrico   ión libre   campo octaédrico   campo planar cuadrado







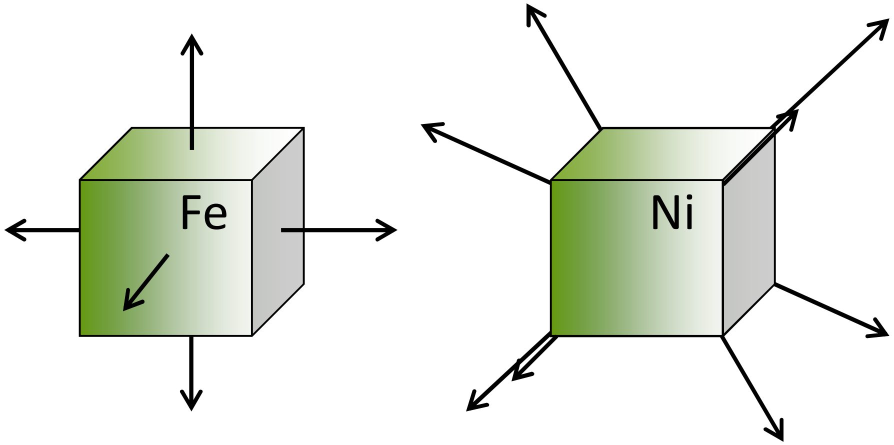


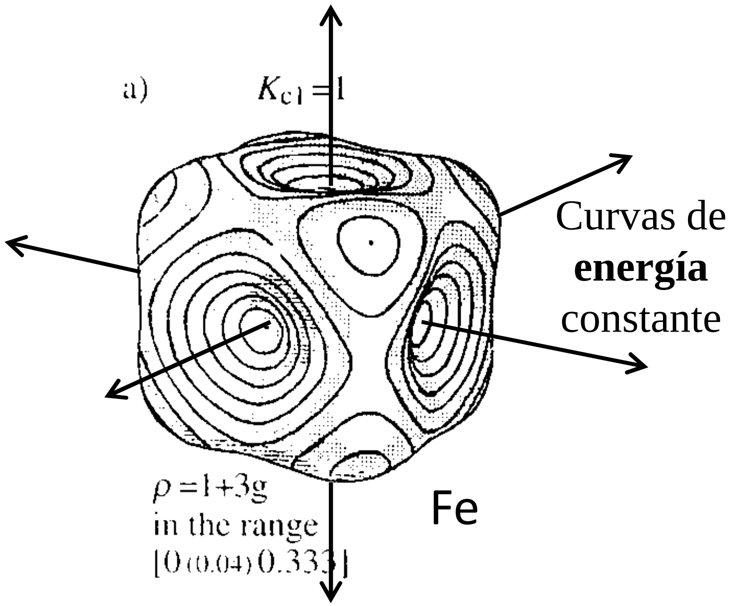


Energía de anisotropía Magnetocristalina

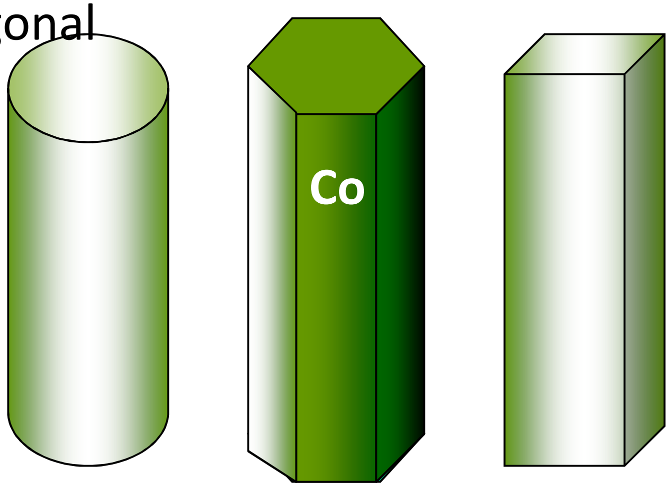
Definiciones

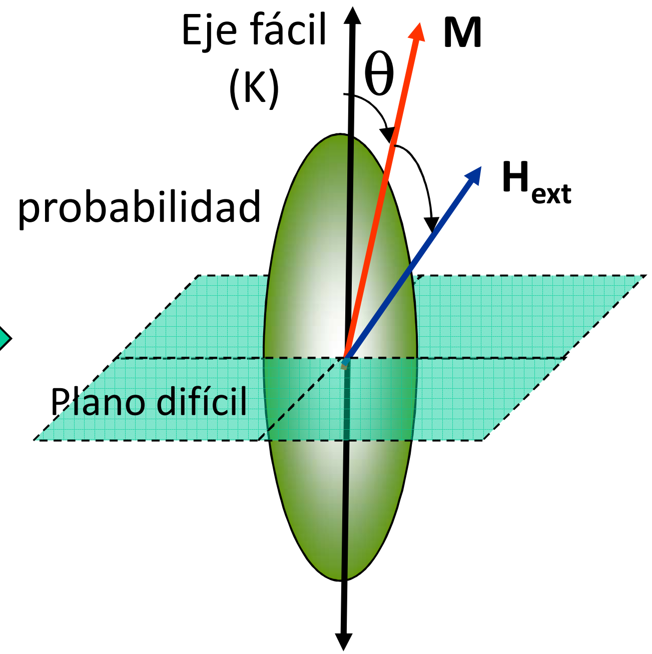
Geometría cúbica



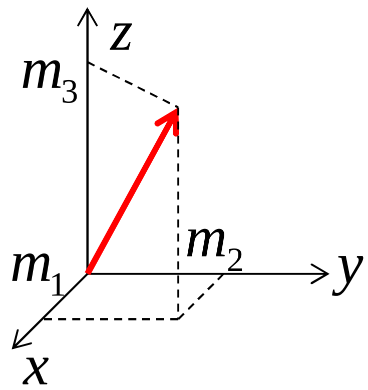


Geometría cilíndrica, tetragonal, hexagonal





Anisotropía – descripción fenomenológica



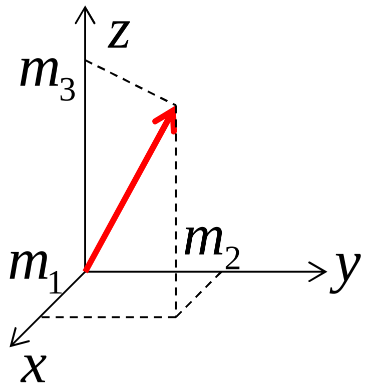
m_i cosenos directores de la magnetización

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

e_K energía de anisotropía por unidad de volumen

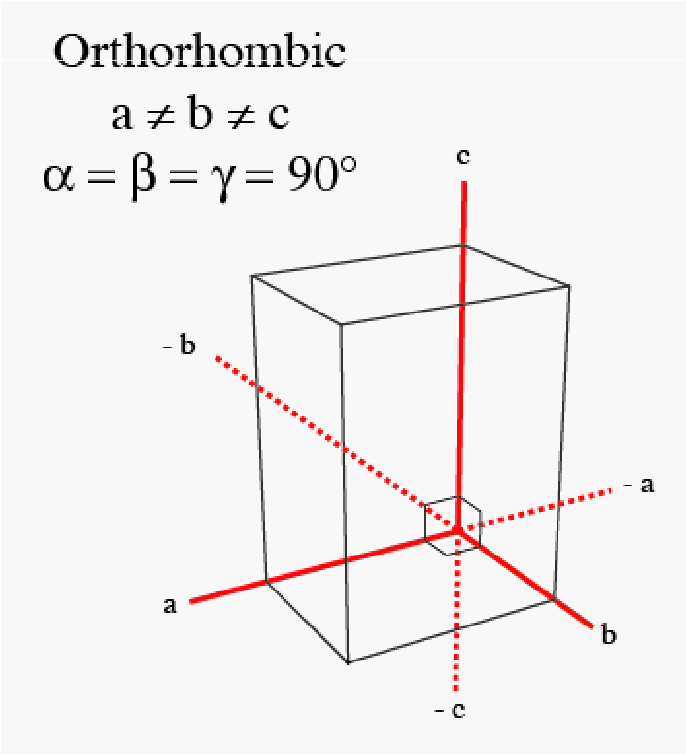
$$e_K = \sum_i K_i m_i^2 + \sum_{ij} K_{ij} m_i^2 m_j^2 + K_{123} m_1^2 m_2^2 m_3^2 + \sum_{ij} K'_{ij} m_i^4 m_j^4 + \cdots$$

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

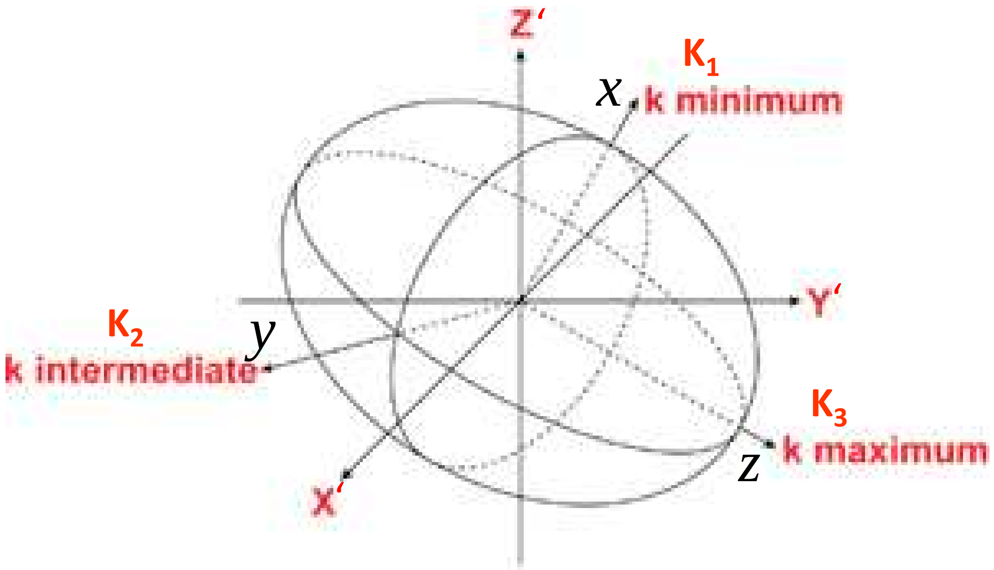


$$e_K = \sum_i K_i m_i^2 + \sum_{ij} K_{ij} m_i^2 m_j^2 + K_{123} m_1^2 m_2^2 m_3^2 + \sum_{ij} K'_{ij} m_i^4 m_j^4 + \cdots$$

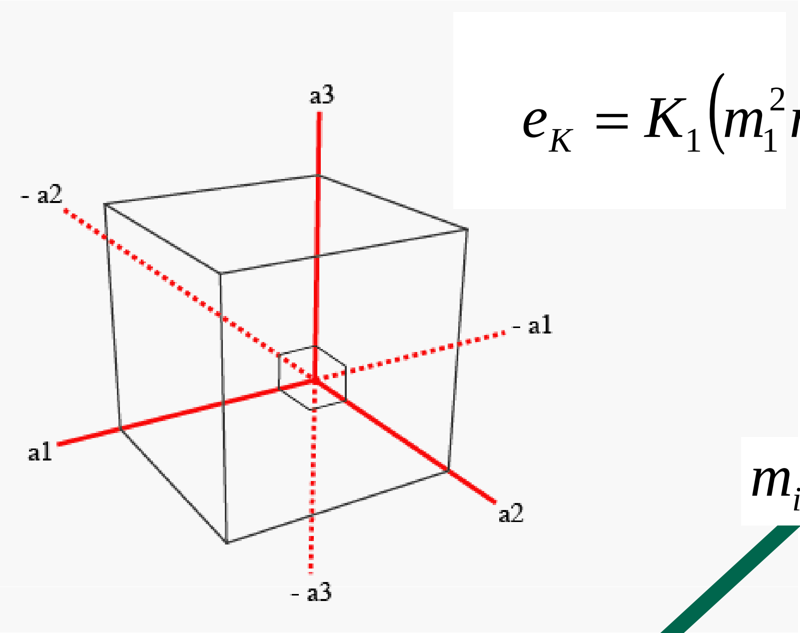
Ejemplo: sistema ortorrómbico



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

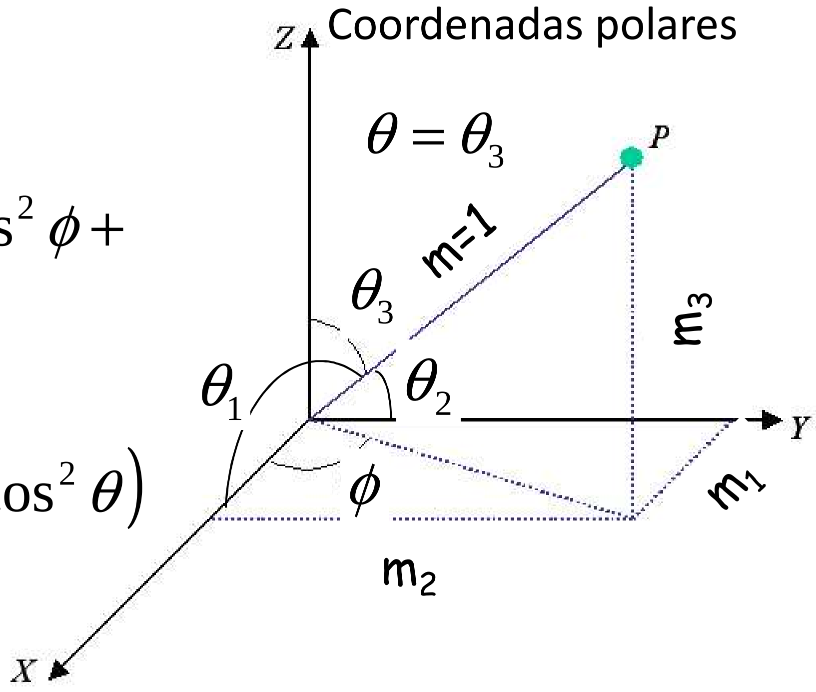


sistema cúbico



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

$$m_i = \cos\theta_i$$



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

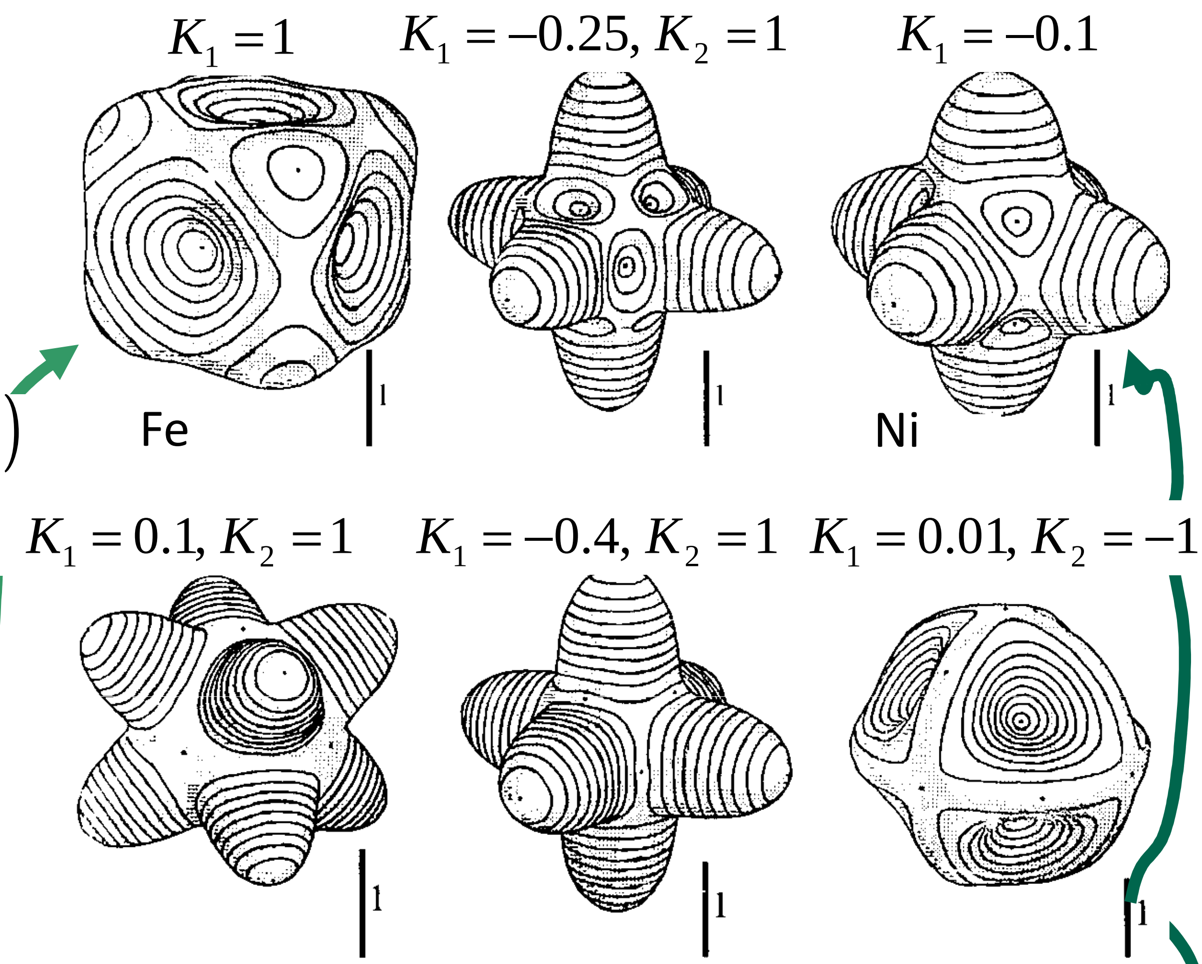
$$e_{K_1} = K_1\sin^2\theta\left(\sin^2\theta\sin^2\phi\cos^2\phi + \cos^2\theta\right)$$

$$e_{K_2} = K_2\cos^2\theta\sin^4\theta\sin^2\phi\cos^2\phi$$

sistema cúbico

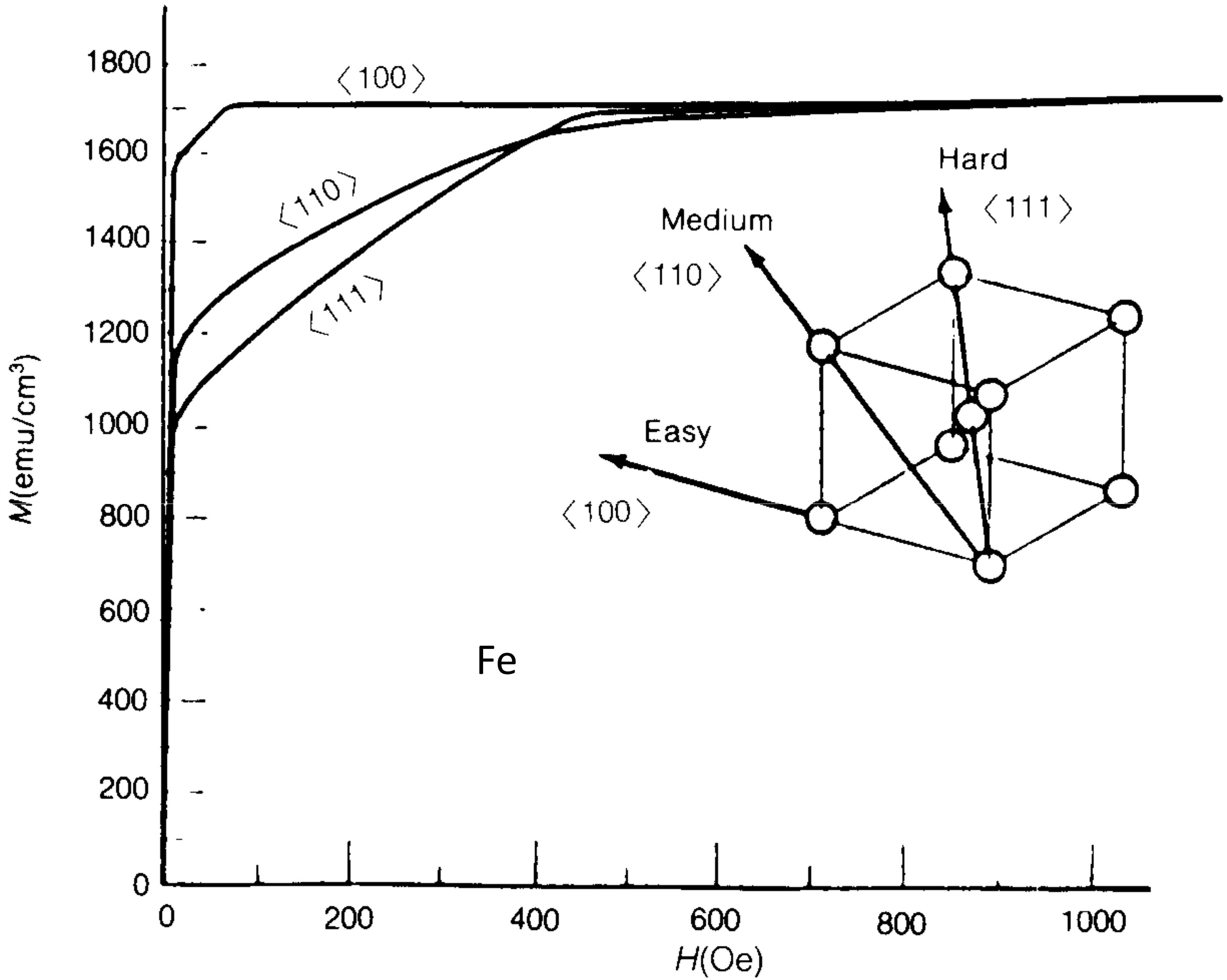
Curvas de energía constante

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

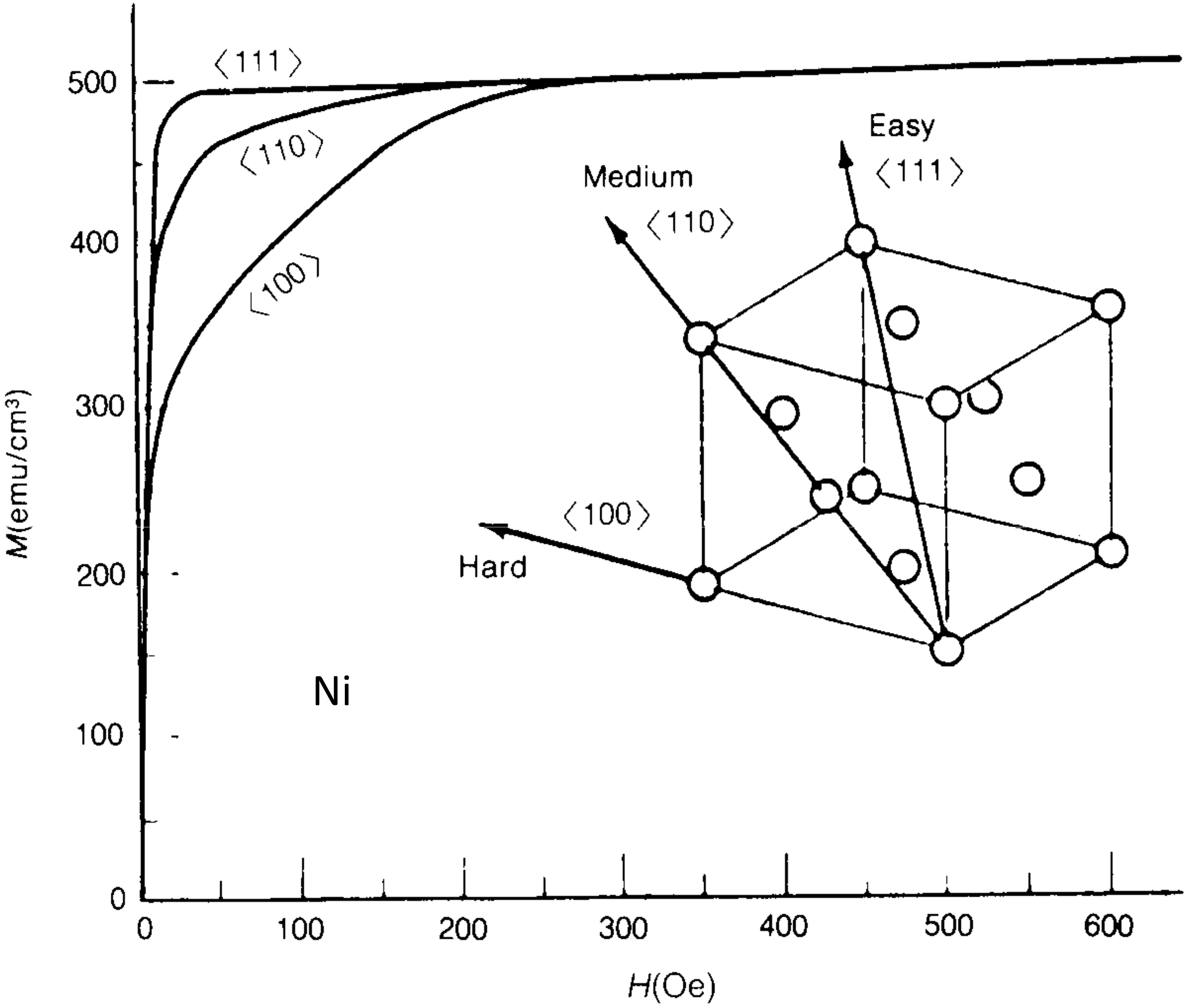


Material	K_1 (10^5 J/m^3)	K_2 (10^5 J/m^3)	Eje fácil
Fe	0.480	0.05	(100)
Ni	-0.045	-0.023	(111)

sistema cúbico

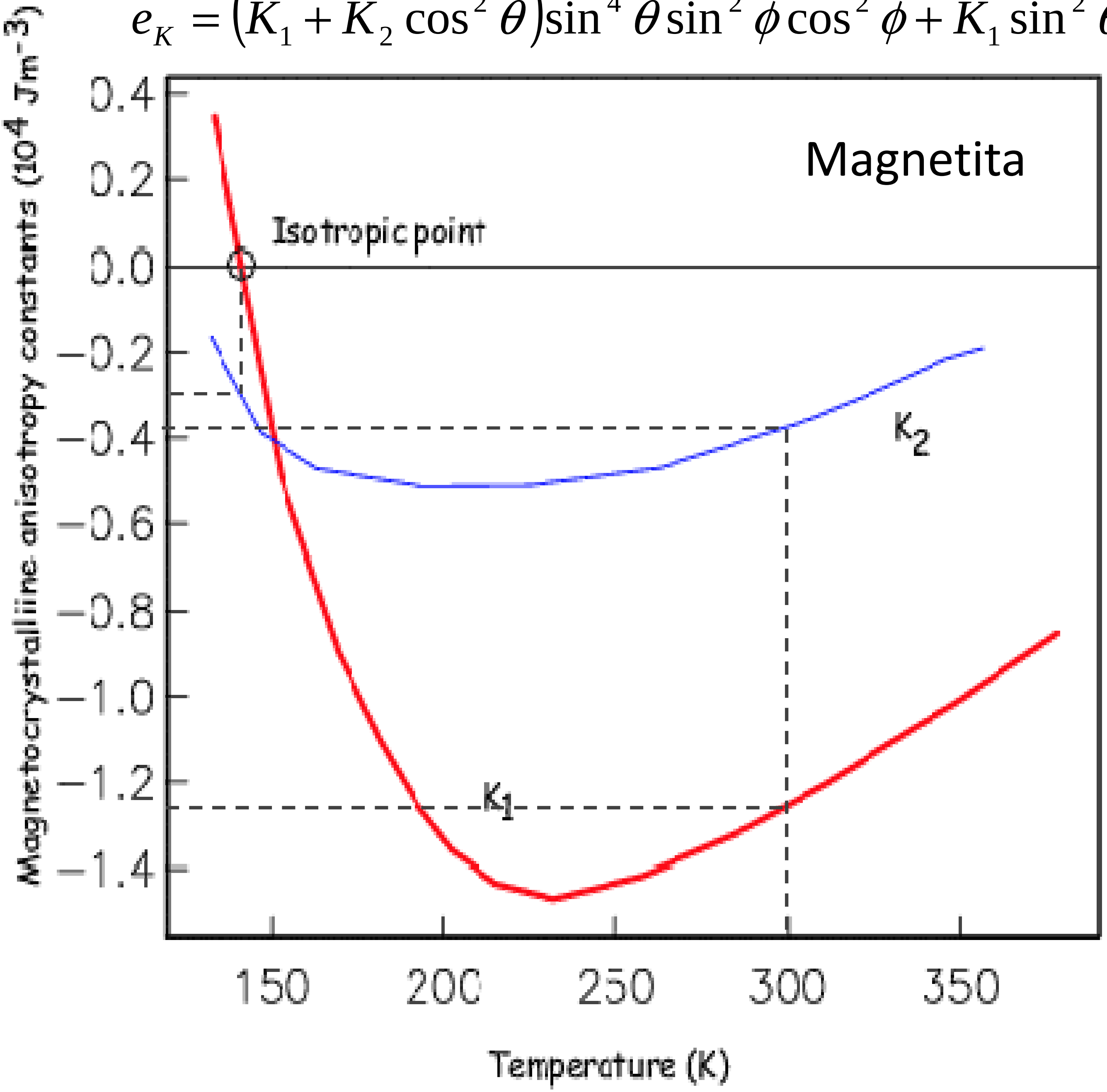


sistema cúbico

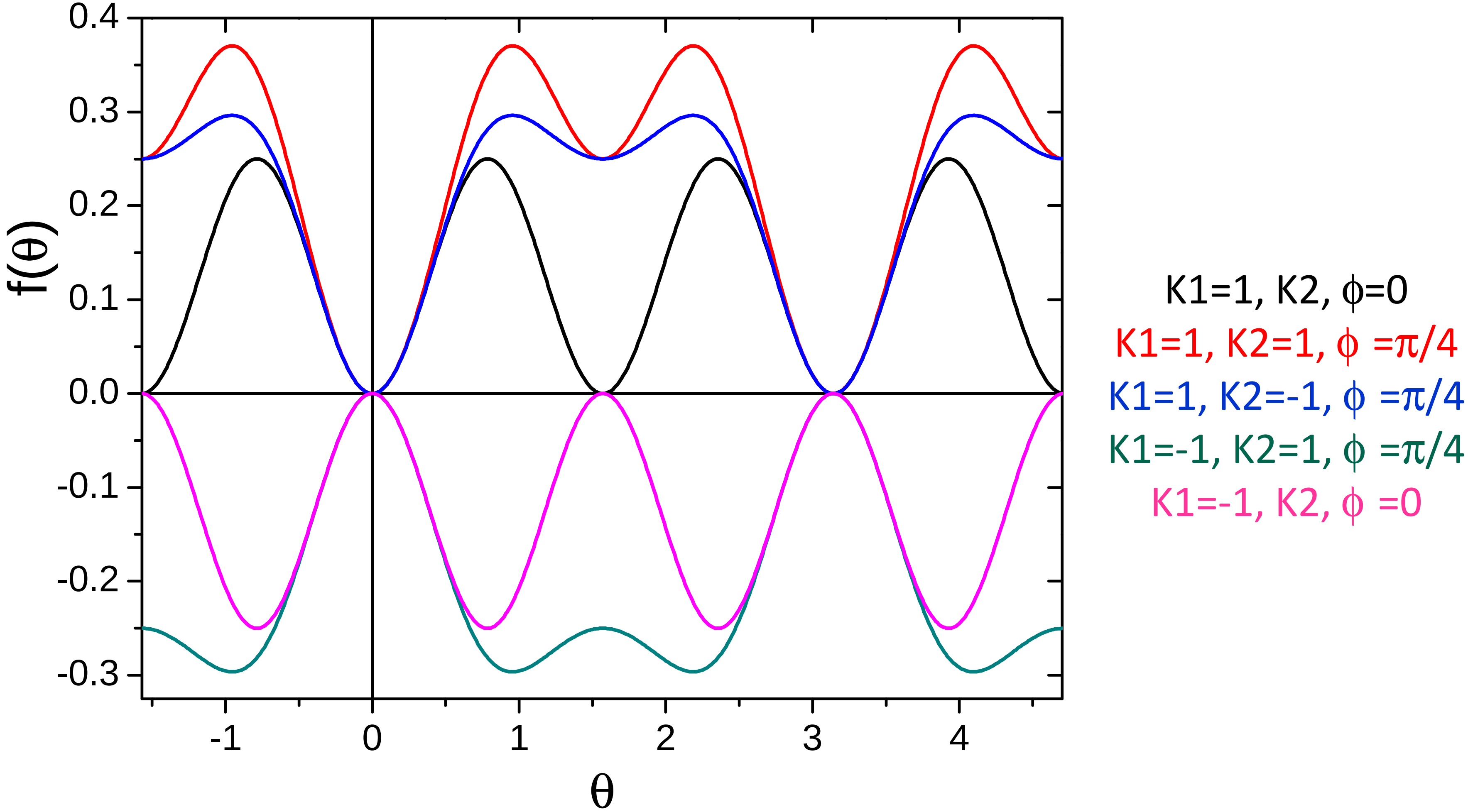


sistema cúbico

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

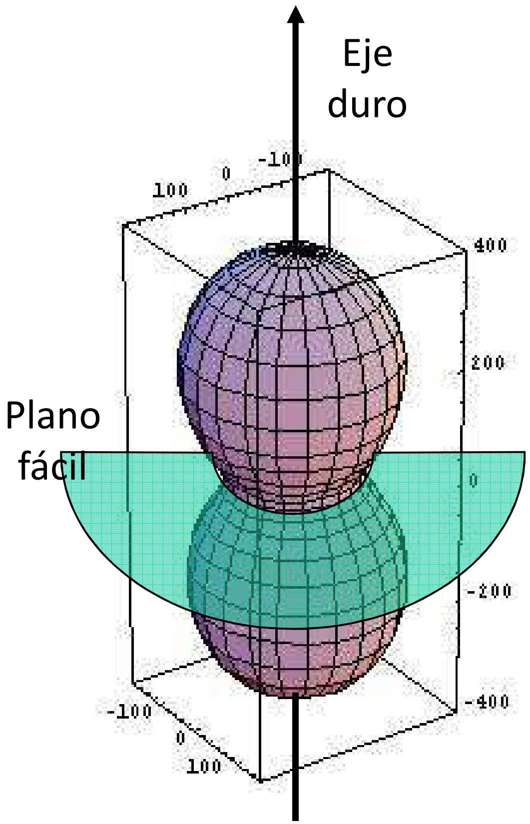


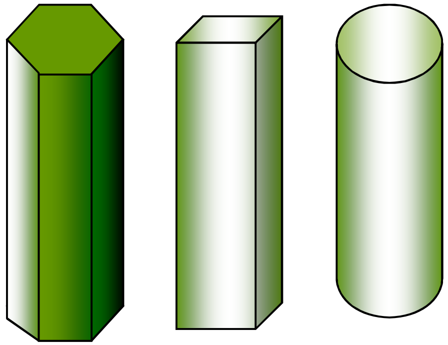
sistema cúbico



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

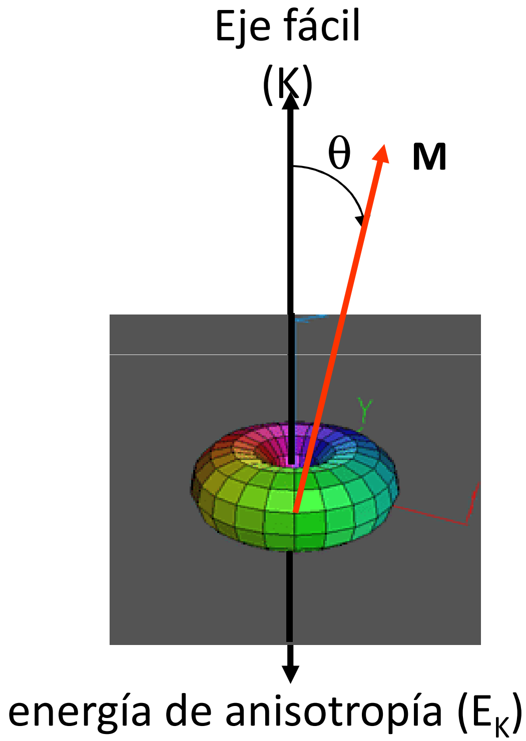
Sistemas hexagonal y tetragonal



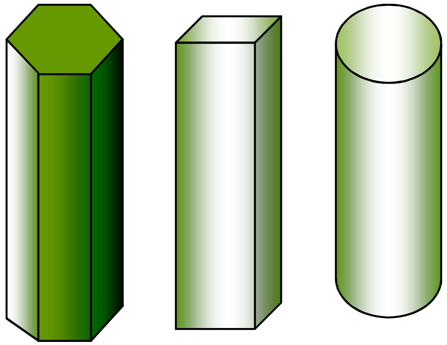


$$e_K = K_1 \cos^2\theta + K_2 \cos^4\theta$$

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



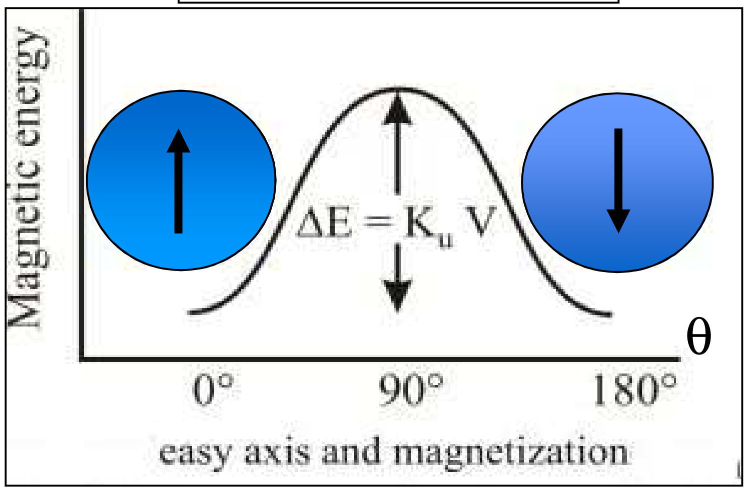
Anisotropía uniaxial



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

Siempre que pueda simplificarse

$E_K = KV \sin^2 \theta$



Anisotropía uniaxial

ejemplos

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

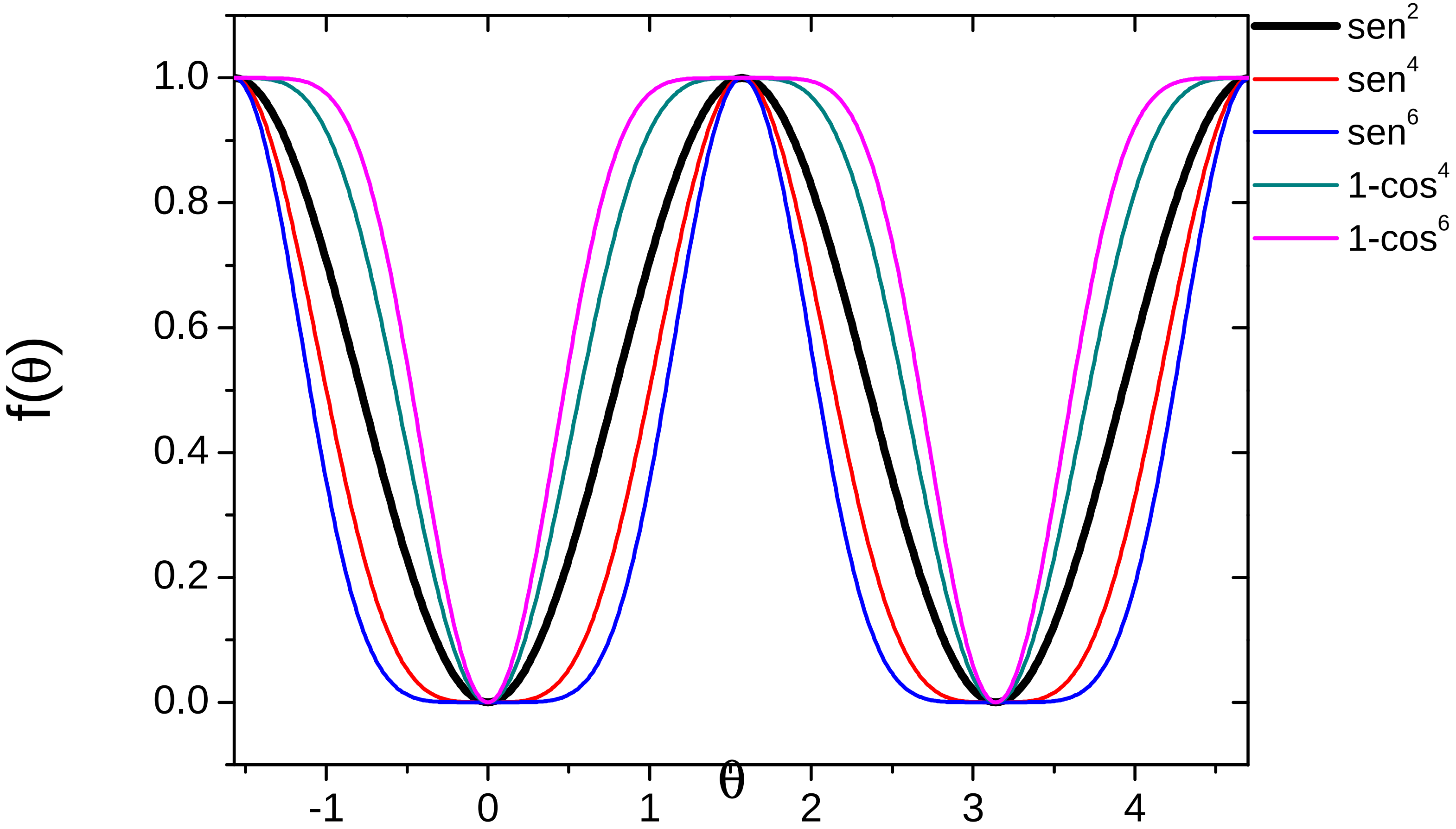
Material	K_1 (10^5 J/m^3)	K_2 (10^5 J/m^3)	Eje fácil
Co	4.1	1.0	hexagonal
$SmCo_5$	1100	-	hexagonal

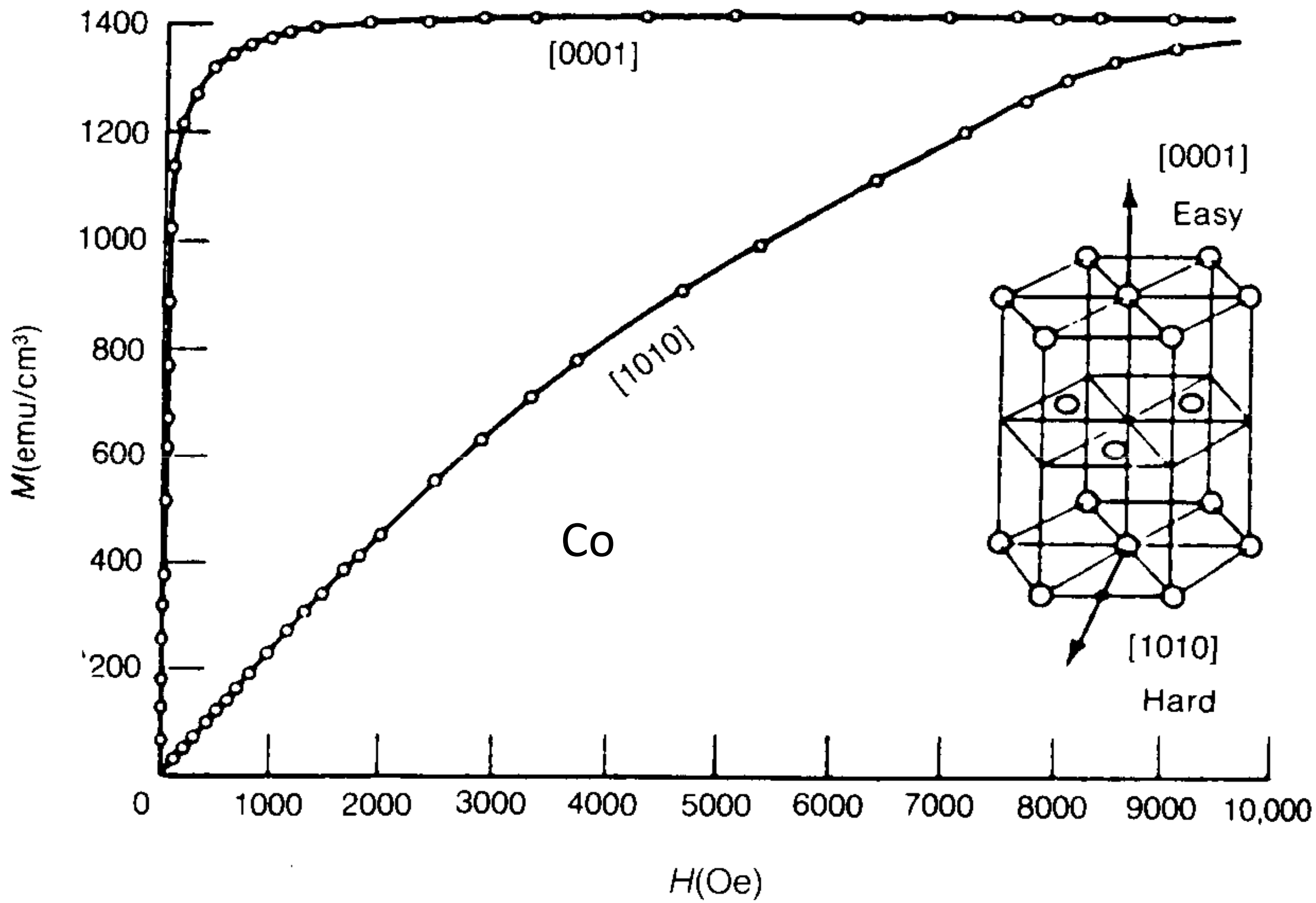
Anisotropía uniaxial

Efecto de las potencias de seno y coseno

$$e_K = K \sin^n \theta$$

$$e_K = K\left(1 - \cos^n \theta\right)$$





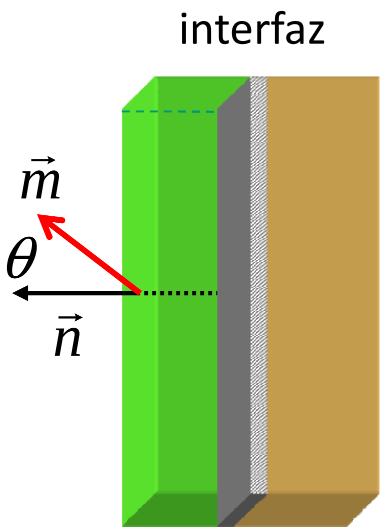
1400
1200
1000
800
600
400
200
M(emu/cm³)
[0001]
[1010]
Co
[0001]
Easy
[1010]
Hard
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
H(Oe)

Anisotropía de Interfaz

Anisotropía de Intercambio

superficies e interfaces

Anisotropía de interfaz

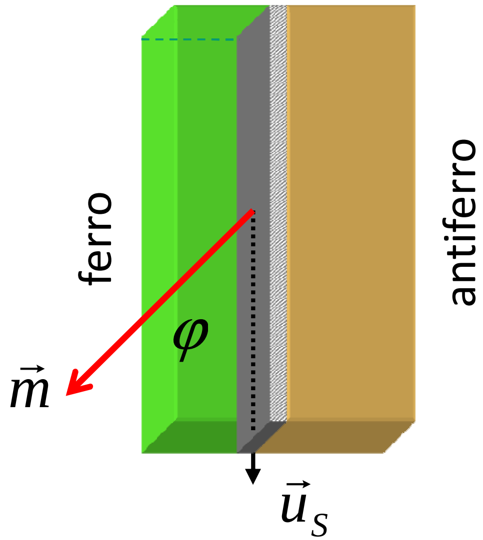


$$\vec{m} = \vec{M} / M$$

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

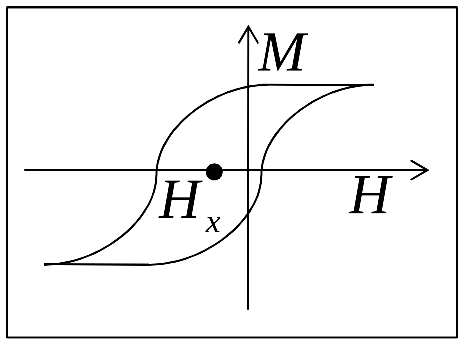
$$\left(e_K = K_S\left[1-(\cos\theta)^2\right]\right)$$

Anisotropía de intercambio*



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

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



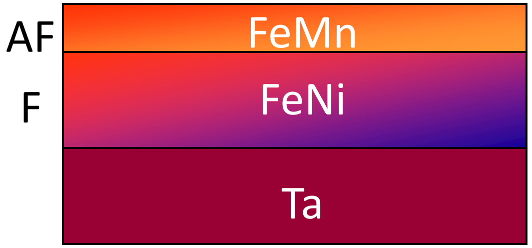
Exchange bias field

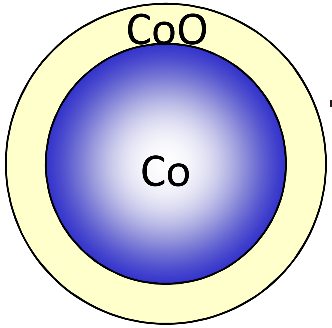
*también llamada unidireccional

Anisotropía de intercambio

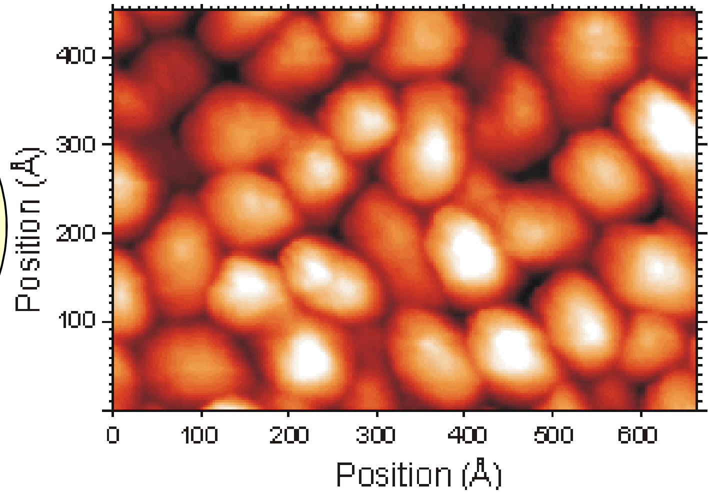
Observación del exchange bias

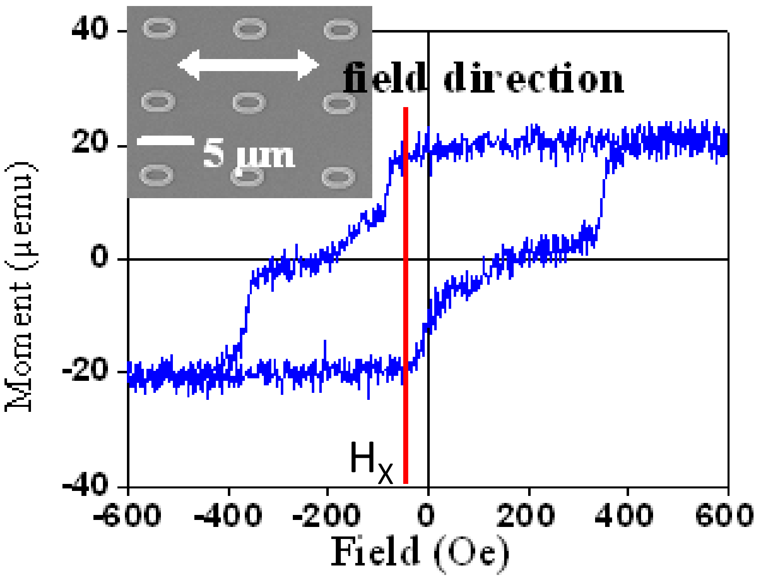
$$e_K = K_S \vec{m} \cdot \vec{u}_S = \frac{H_x}{2} \vec{m} \cdot \vec{u}_S$$

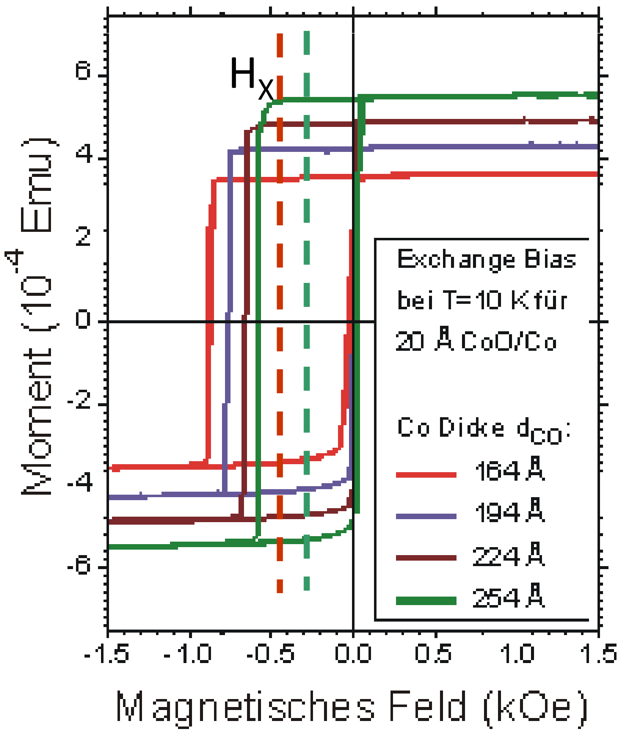




CoO/Co

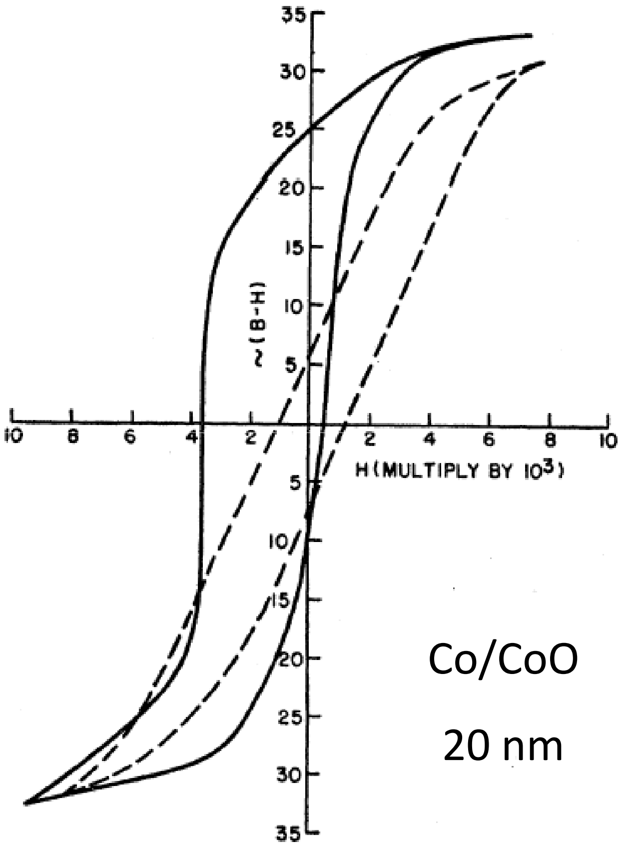






Ta 20nm / NiFe 20nm/ FeMn 10 nm film

In the news...



Letters to the Editor

New Magnetic Anisotropy

W. H. Meiklejohn and C. P. Bean

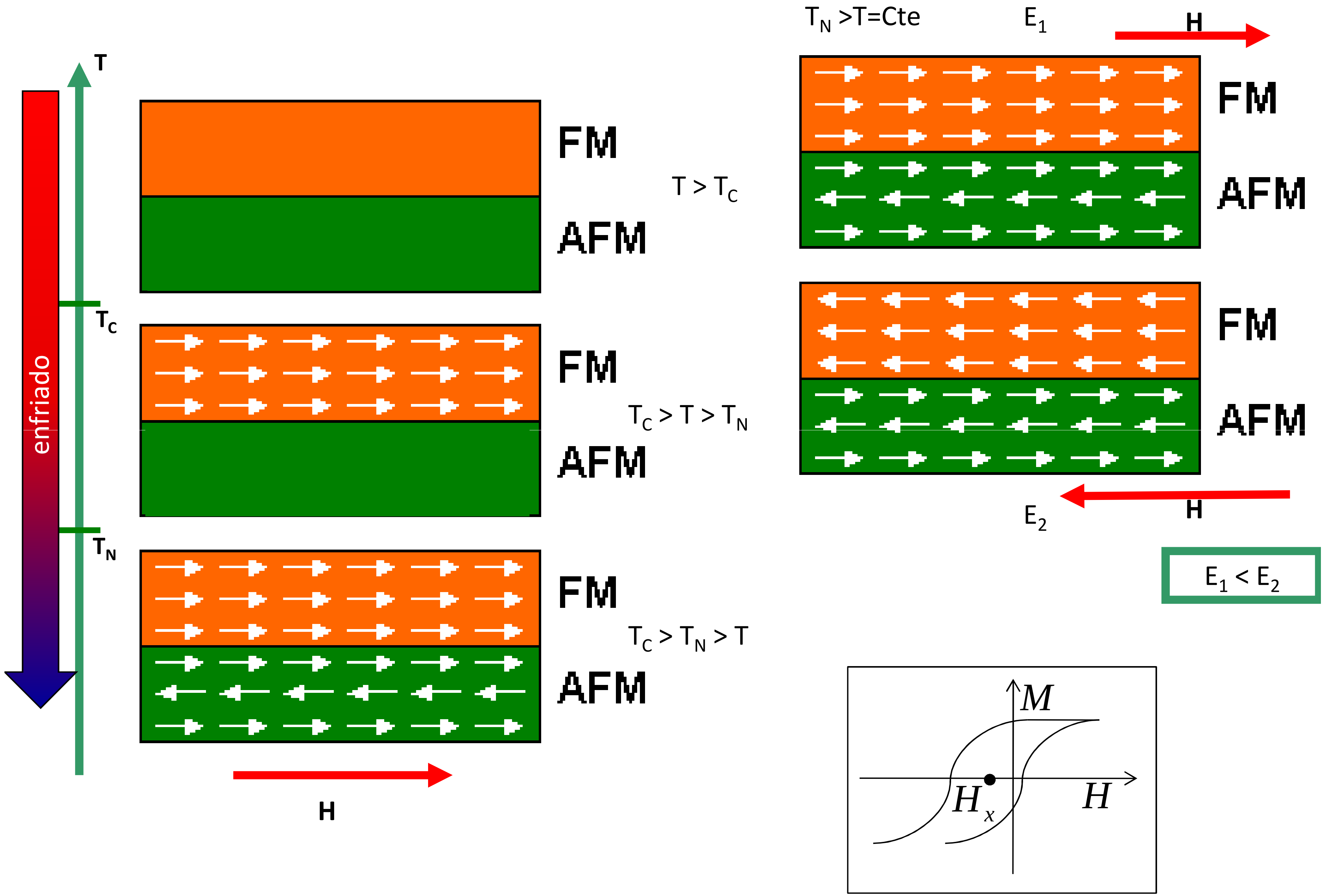
General Electric Research Laboratory, Schenectady, New York

(Received March 7, 1956)

PHYSICAL REVIEW

VOLUME 102, NUMBER 5

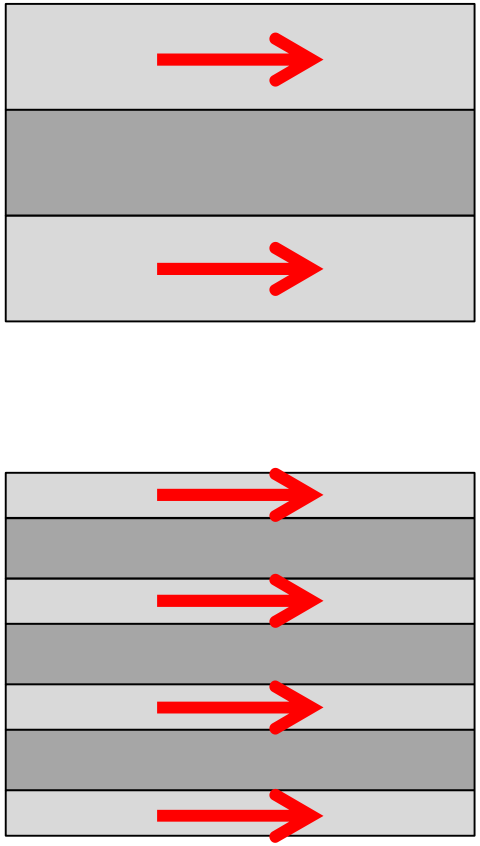
JUNE 1, 1956



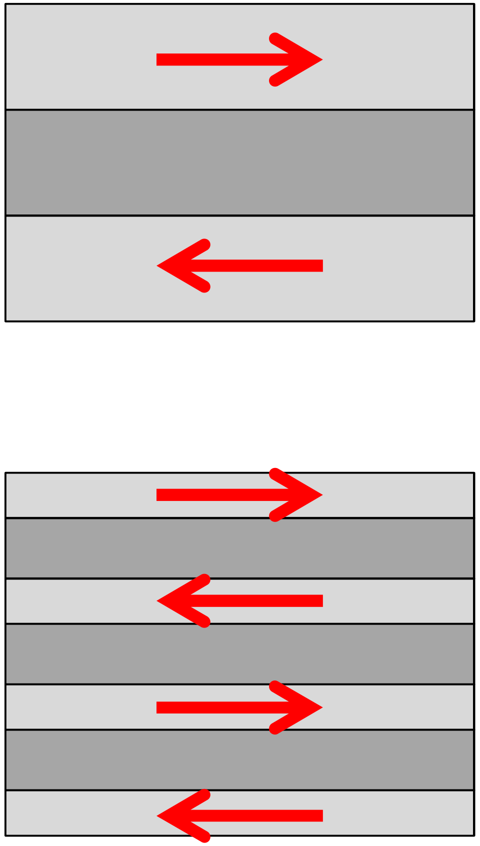
T
T_C
T_N
enfriado
FM
AFM
$T > T_C$
FM
AFM
$T_C > T > T_N$
FM
AFM
$T_C > T_N > T$
H
$T_N > T = Cte$
E_1
H
FM
AFM
FM
AFM
E_2
H
$E_1 < E_2$
M
H_x
H

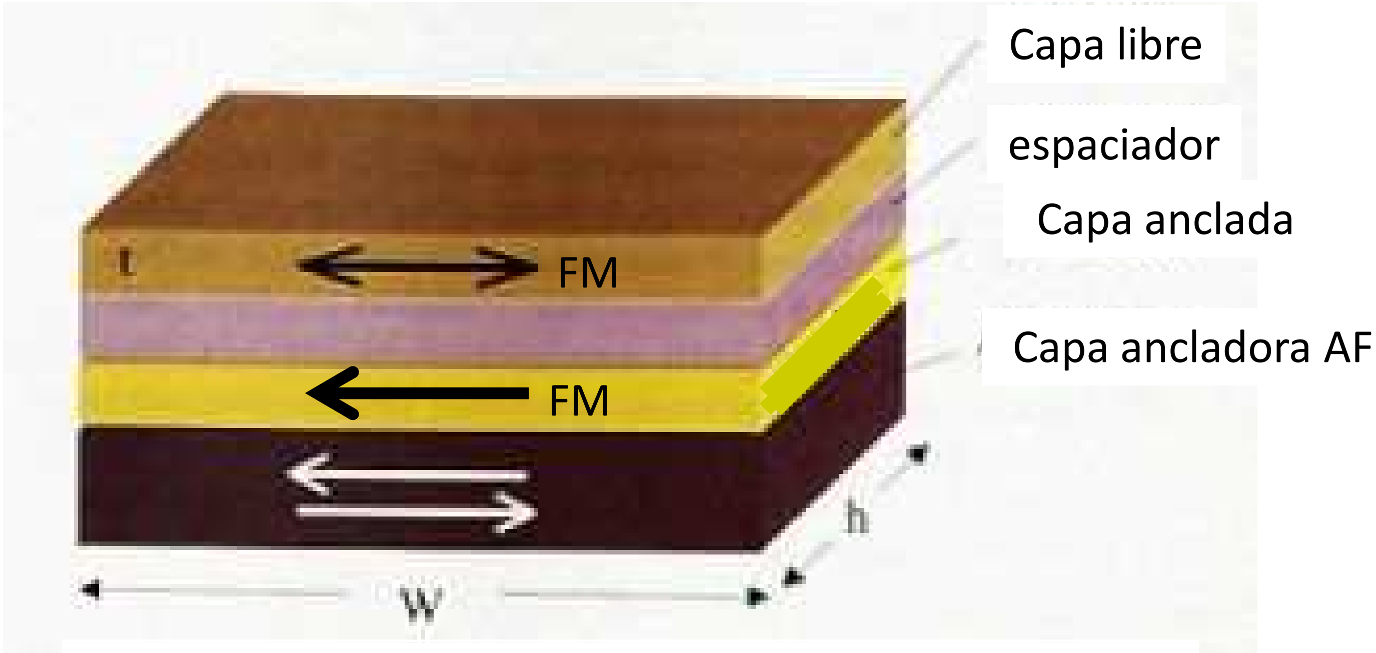
Magnetoresistencia

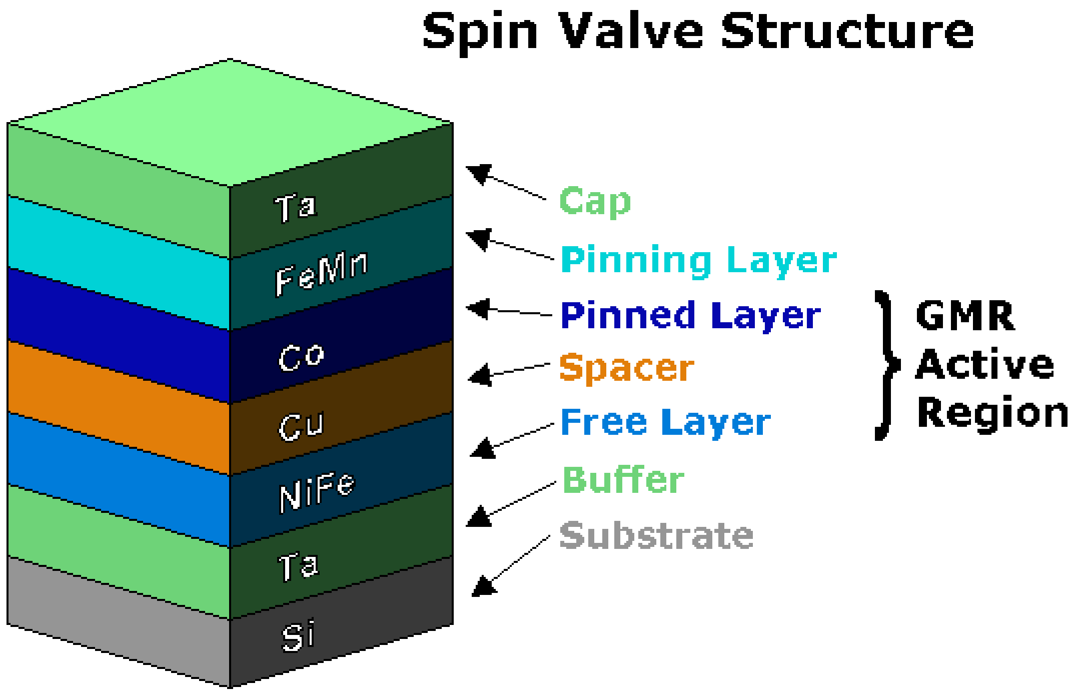
baja resistencia



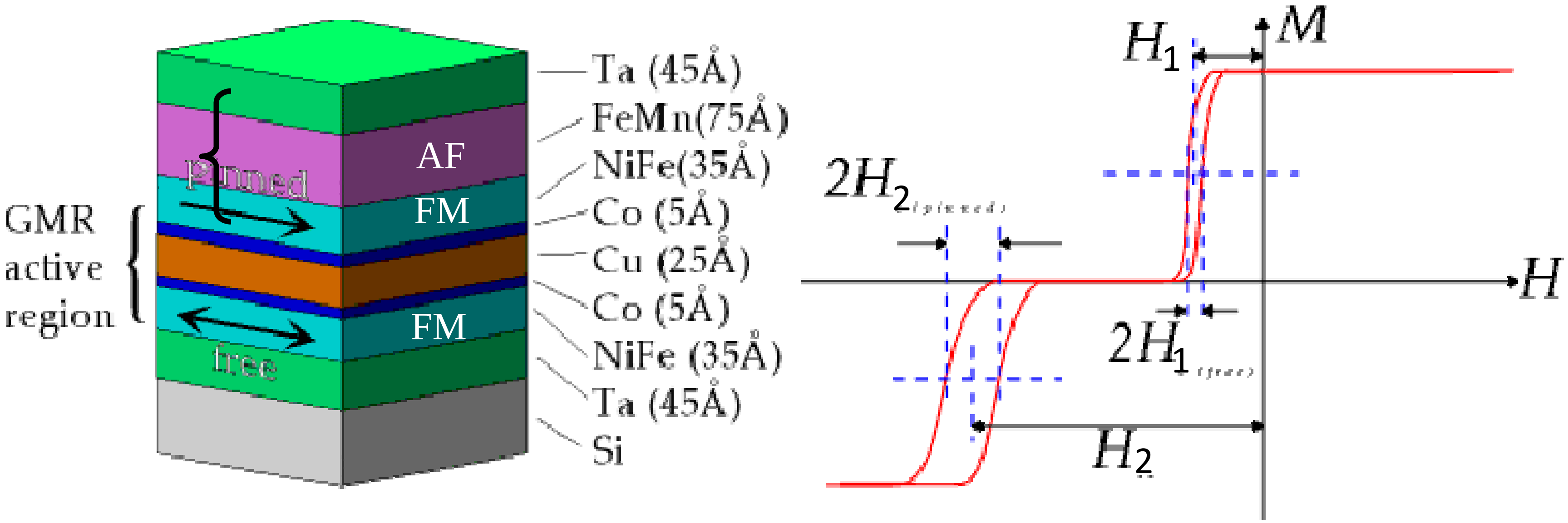
alta resistencia




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

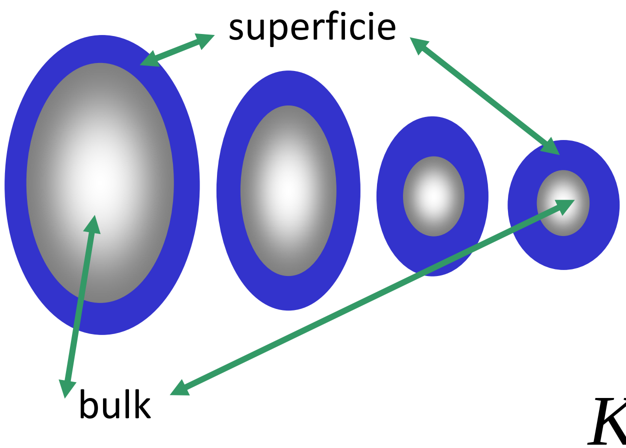

Spin Valve Structure
Ta
FeMn
Co
Cu
NiFe
Ta
Si
Cap
Pinning Layer
Pinned Layer
Spacer
Free Layer
Buffer
Substrate
GMR Active Region

Válvula de spin



Anisotropía en nanopartículas magnéticas

anisotropía de superficie en nanopartículas



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

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

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

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

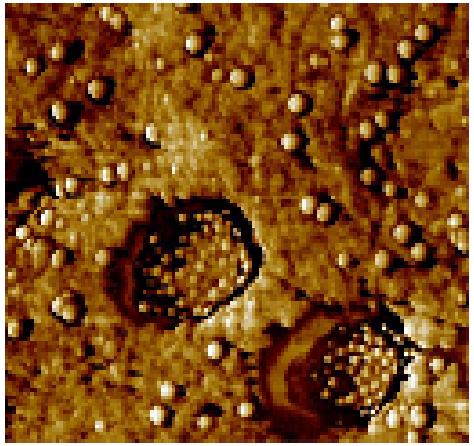


imagen MFA de nanopartículas de Co fcc en una matriz de alúmina. Las partículas son de aprox 11 nm (diámetro).

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

Alúmina

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

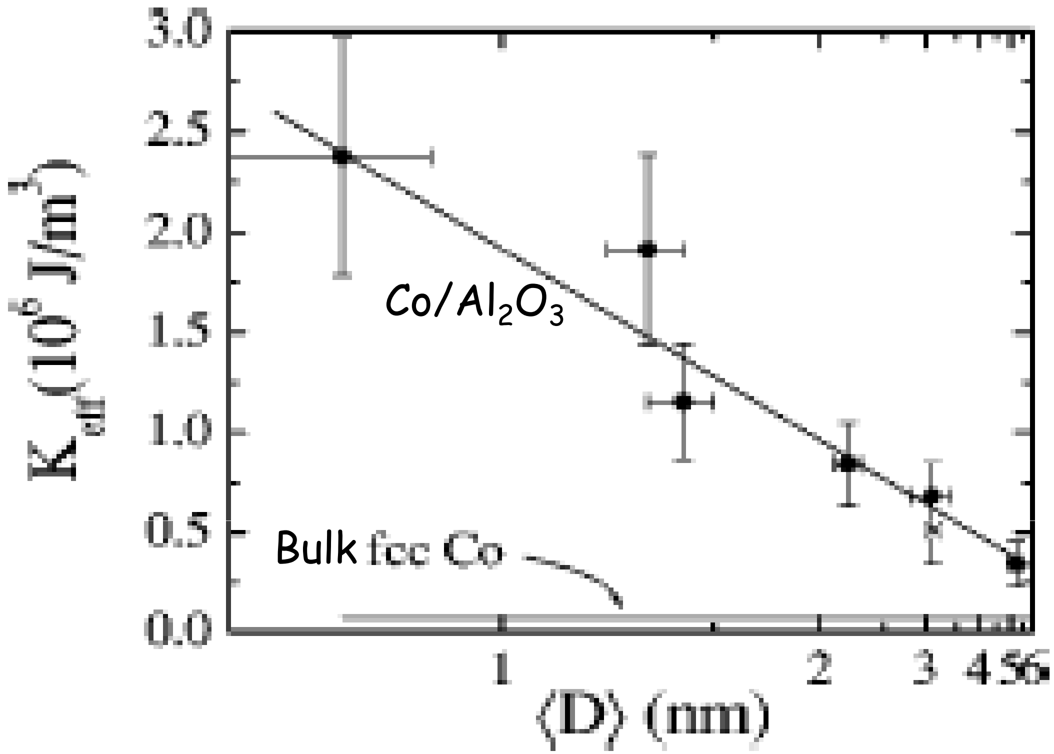
$$K_{ef} = K_B + \gamma \frac{K_s}{\bar{d}}$$

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

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

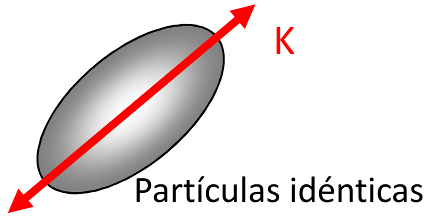
Modelo de Stoner - Wohlfarth

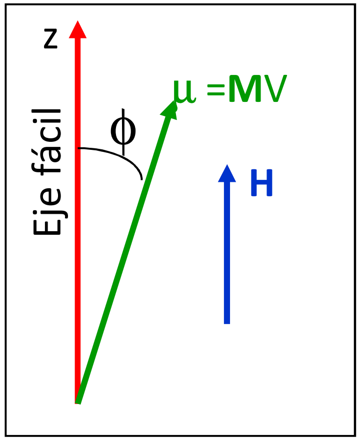
$$\boxed{T = 0K}$$

monodominio

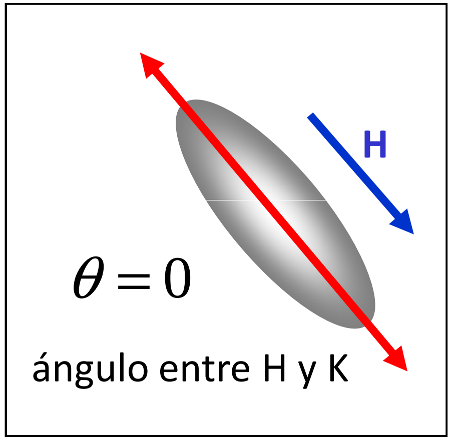
Anisotropía uniaxial

no interactuantes





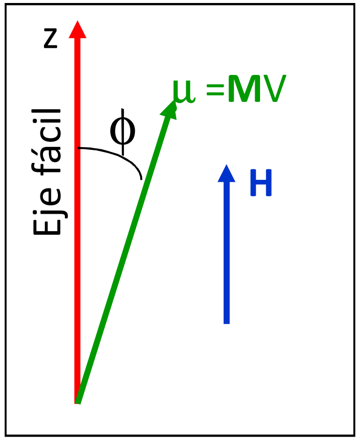
Campo paralelo al eje fácil

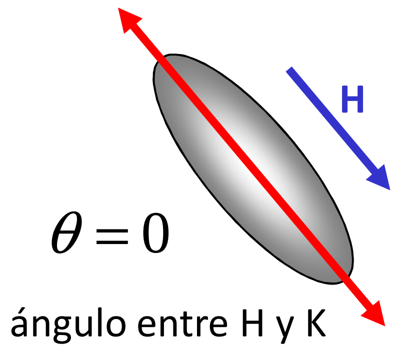


$$E_K = e_K V = KV \sin^2\phi$$

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

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





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

llamamos Campo de anisotropía

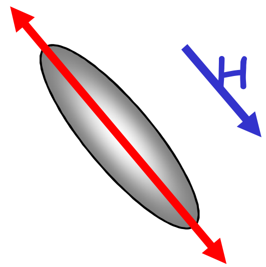
$$H_K = \frac{2K}{\mu_0 M_S}$$

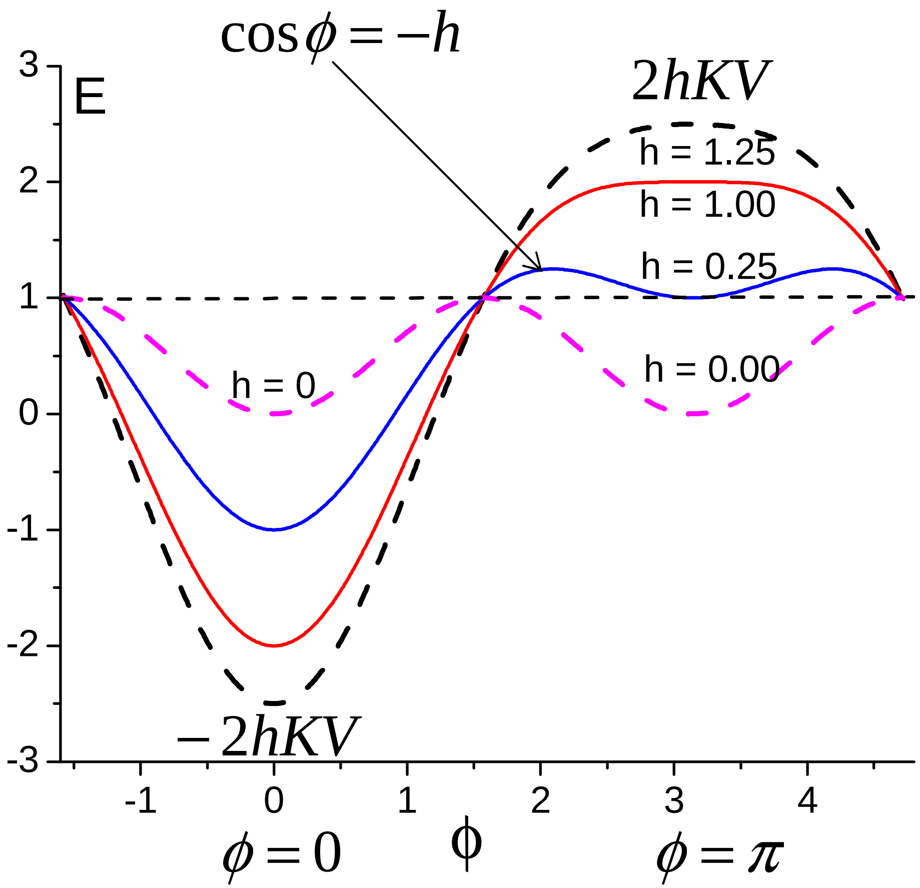
$$h = \frac{H}{H_K} = \frac{\mu_0 M_S H}{2K}$$

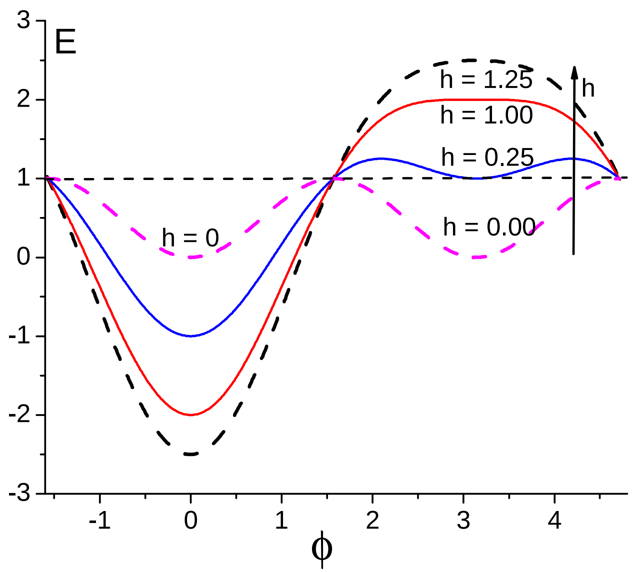
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

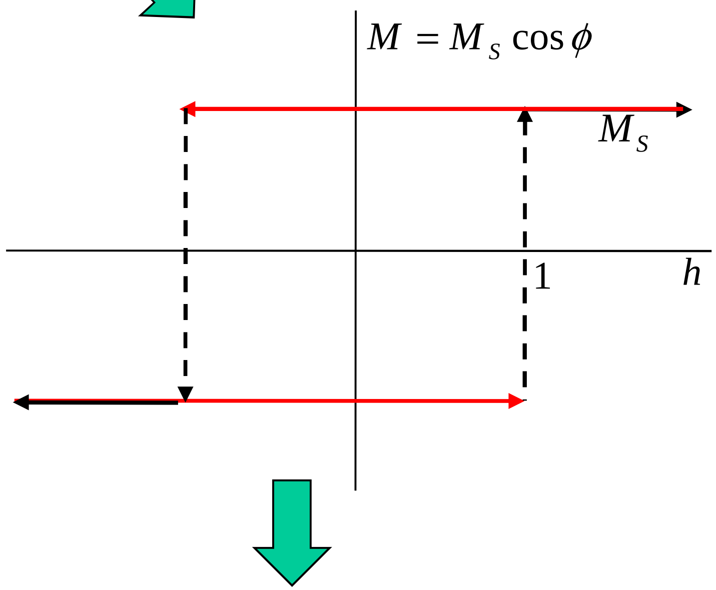
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

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

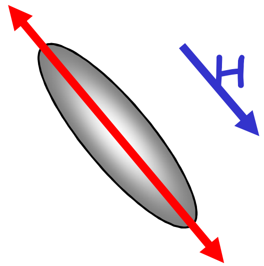


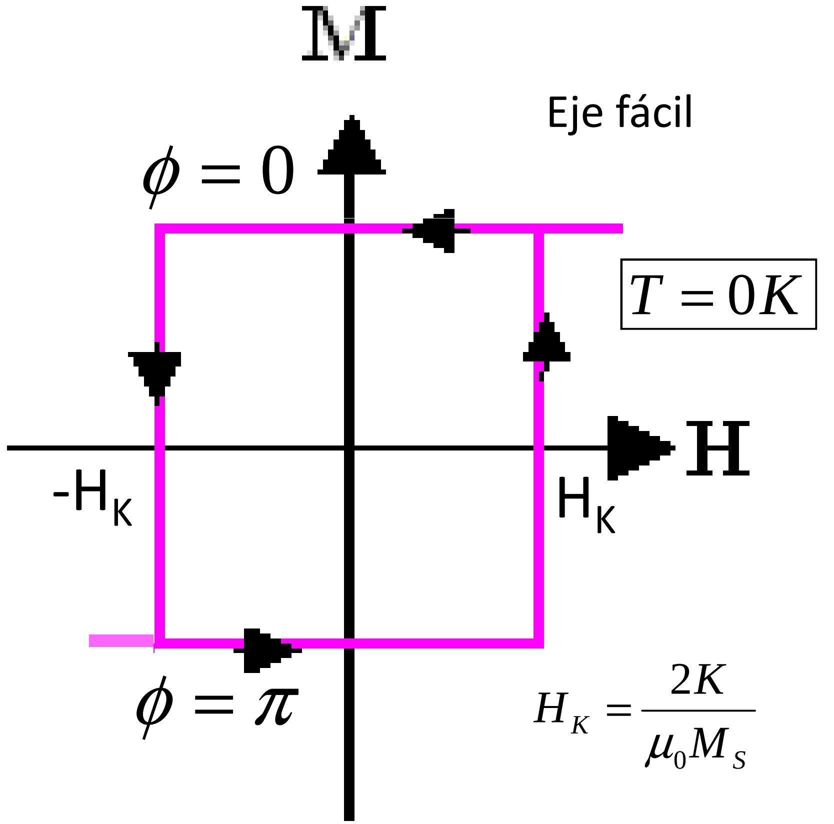



E
h = 1.25
h = 1.00
h = 0.25
h = 0.00
h = 0
h
3
2
1
0
-1
-2
-3
-1
0
1
2
3
4
ϕ


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

$$M_z = M_s \cos\theta$$

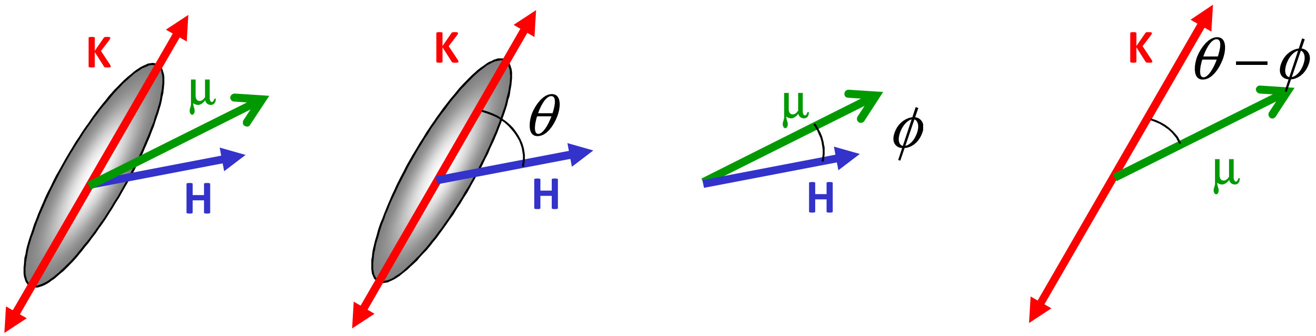




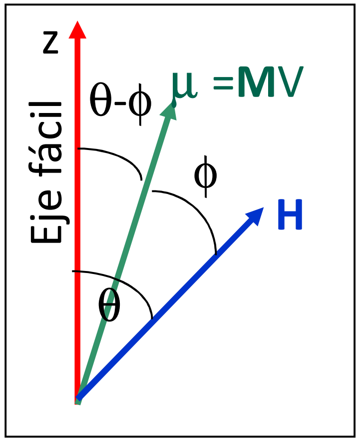
$$H_K = \frac{2K}{\mu_0 M_S}$$

Campo en dirección arbitraria

$$\theta \neq 0$$

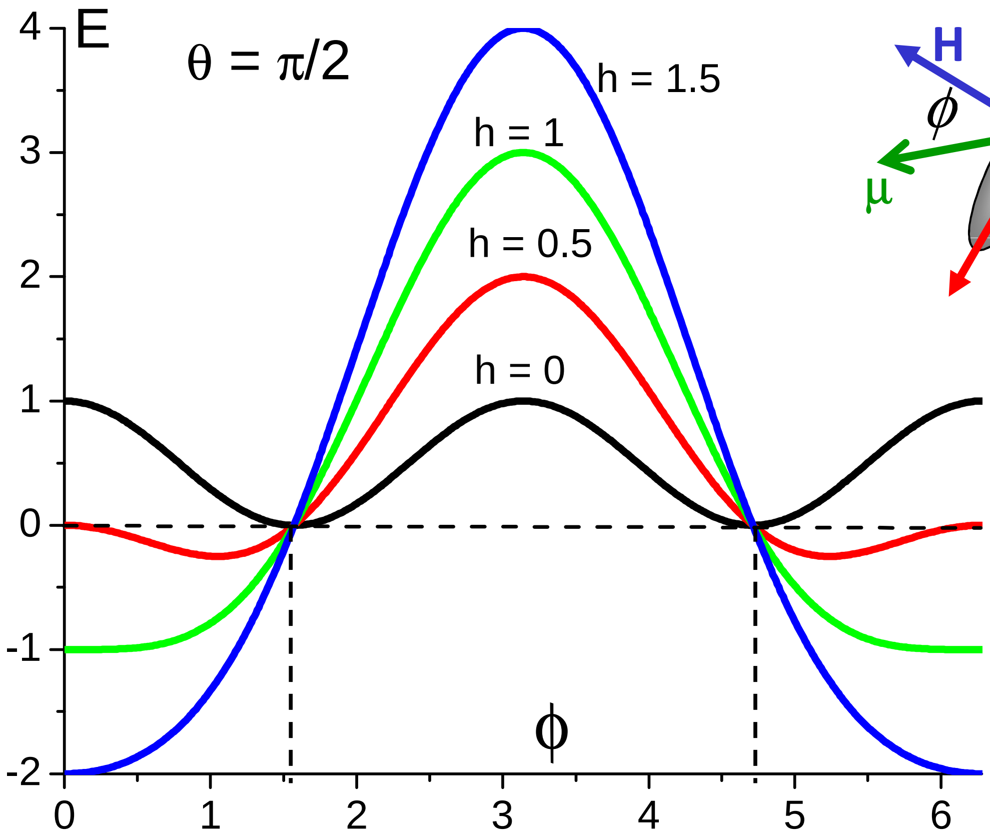


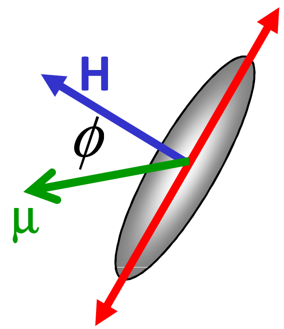
$$E = E_K + E_H = KV\left[\sin^2(\phi - \theta) - 2h\cos\phi\right]$$

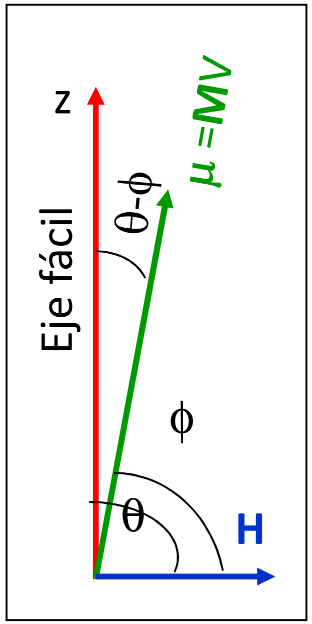


$$\theta = \pi / 2$$

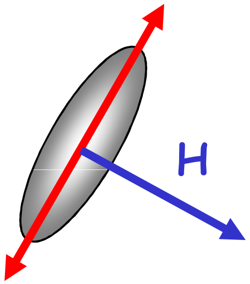
$$E = E_K + E_H = KV \cos\phi\left(\cos(\phi) - 2h\right)$$

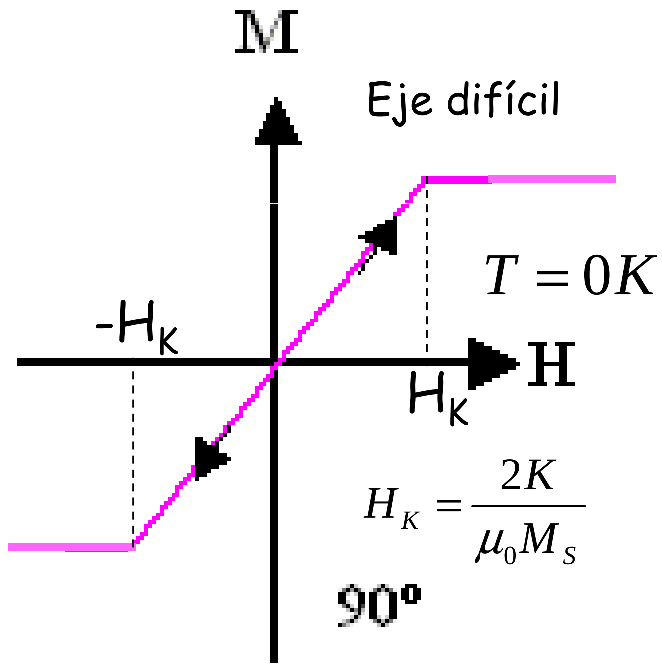






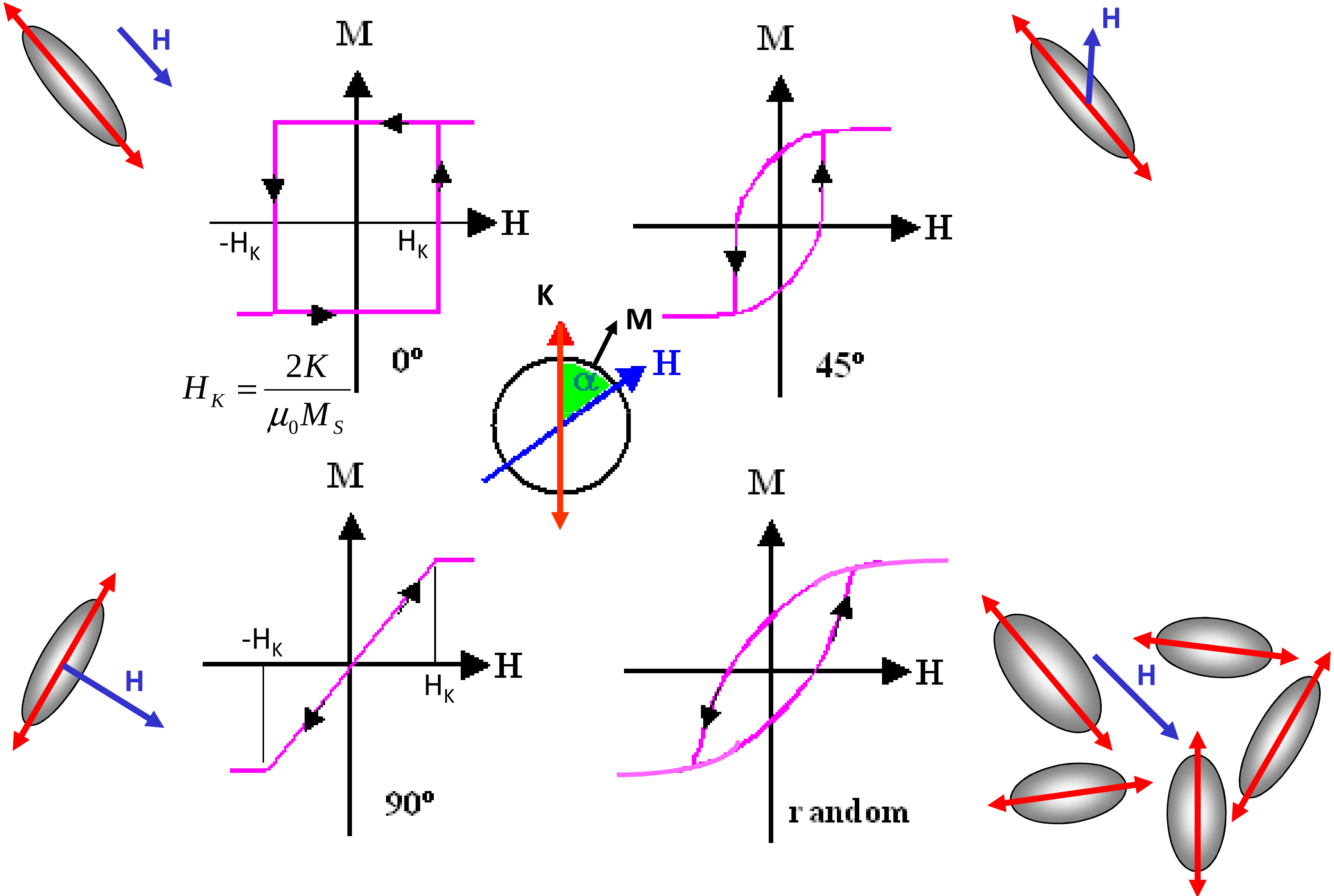
$$M_z = \frac{M_S}{H_K} H; \qquad |h| < 1$$





Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

régimen bloqueado $\rightarrow$ T = 0 K



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

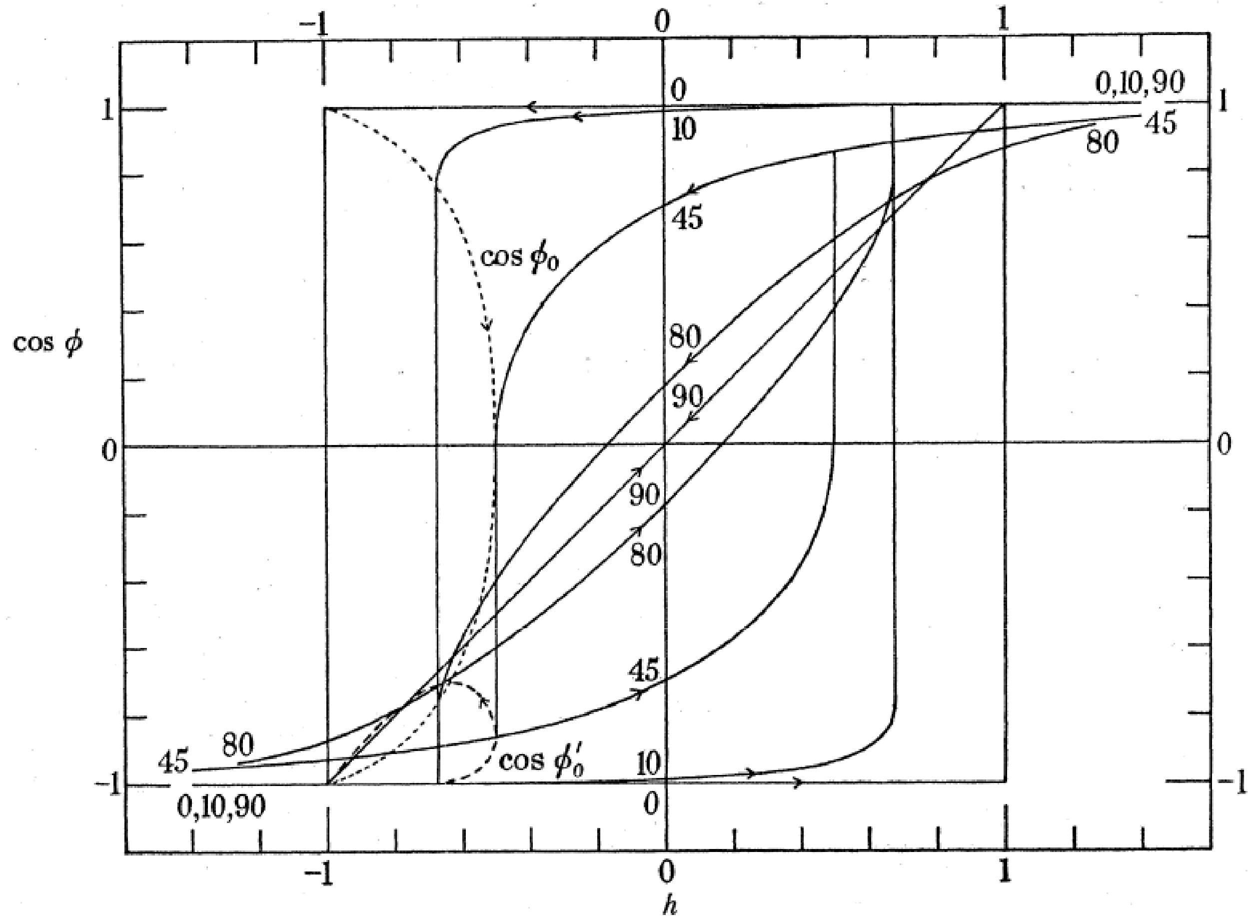


FIGURE 6. Magnetization curves for prolate spheroids. The resolved magnetization in the positive field direction is given by $I_0 \cos \phi$, where I_0 is the saturation magnetization. The field, H, is given by $H = (N_b - N_a)\, I_0 h$, where N_a and N_b are the demagnetization coefficients along the 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.

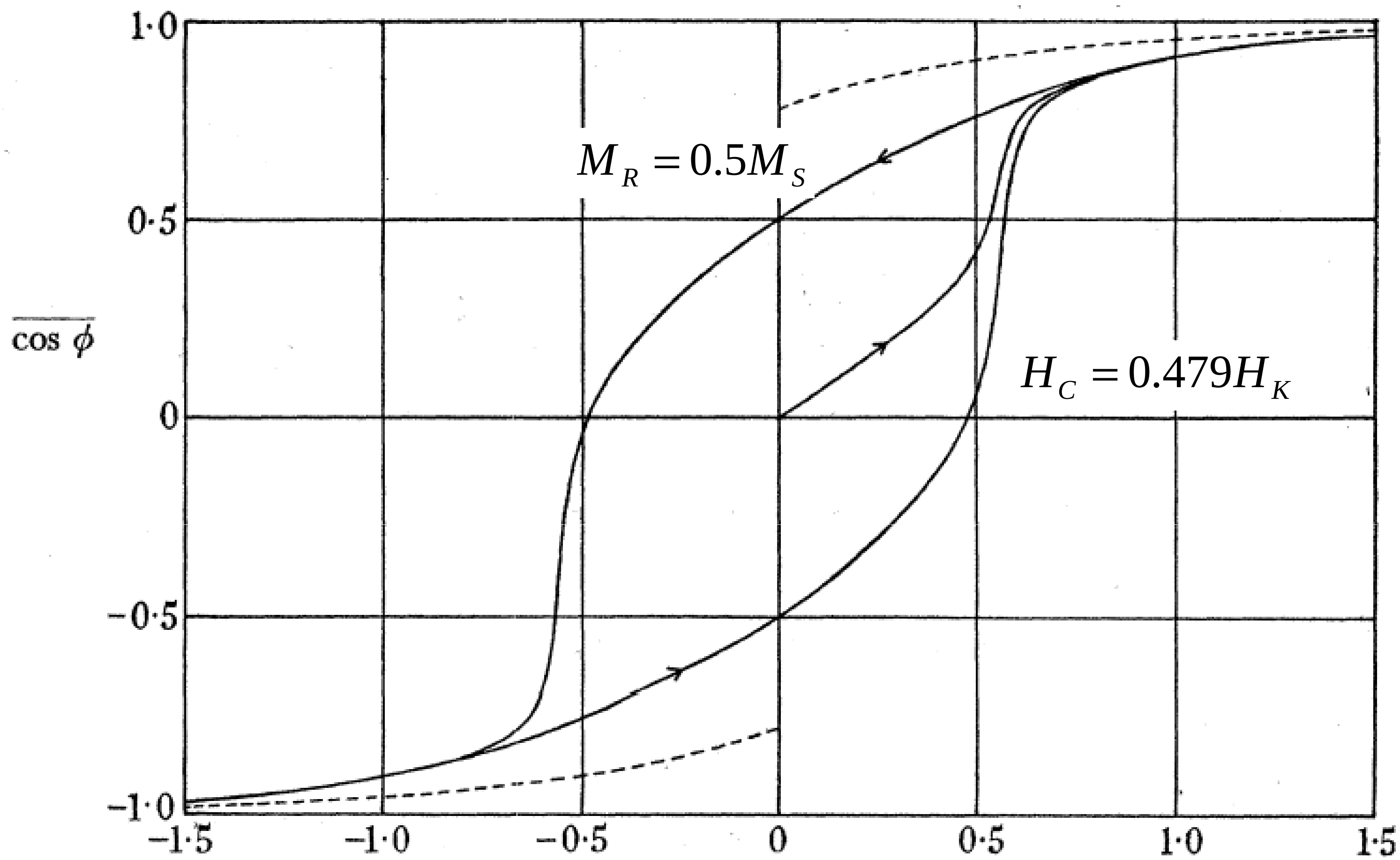


FIGURE 7. Magnetization curves for prolate (full curves) and oblate (broken curves) spheroids orientated at random. The curves refer to similar prolate (or oblate) spheroids orientated at random. $\overline{\cos\phi}$ is proportional to the mean resolved magnetization per spheroid in the positive field 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

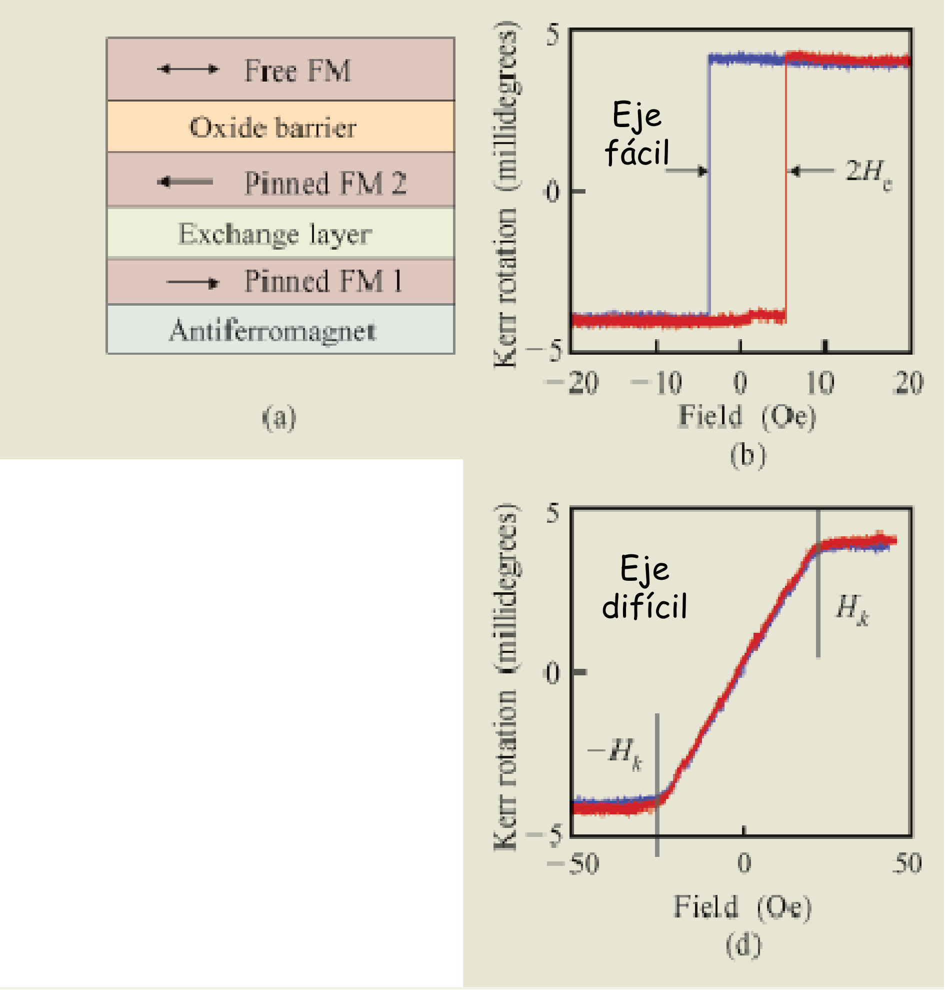
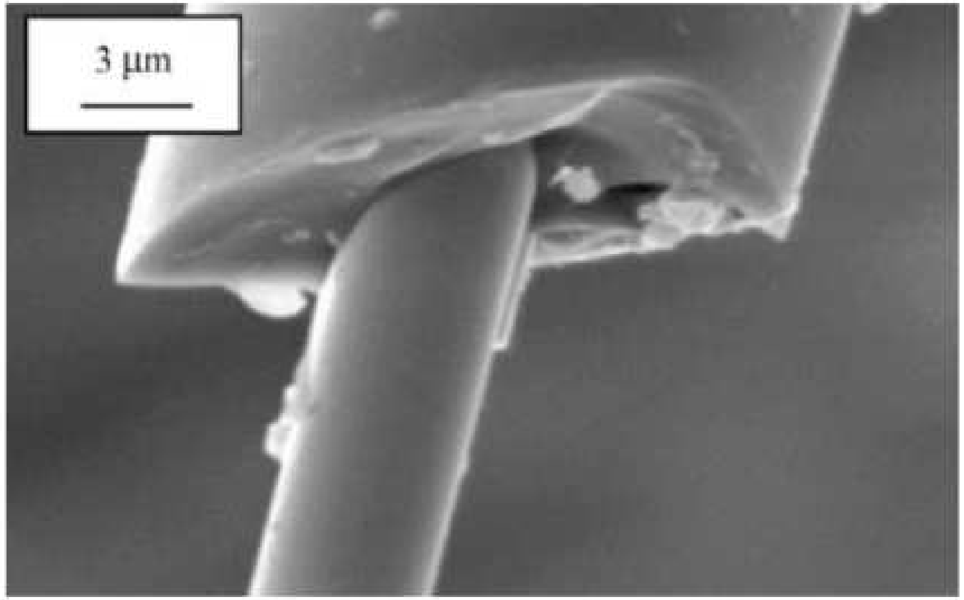
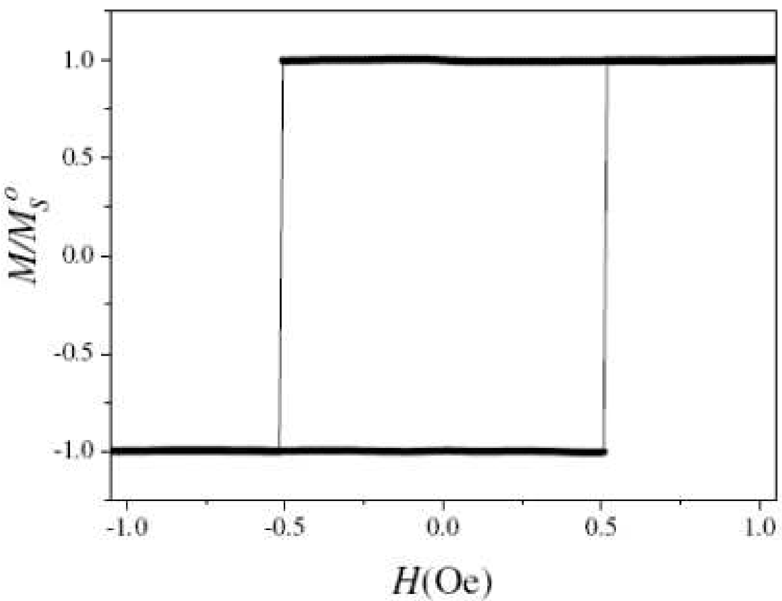


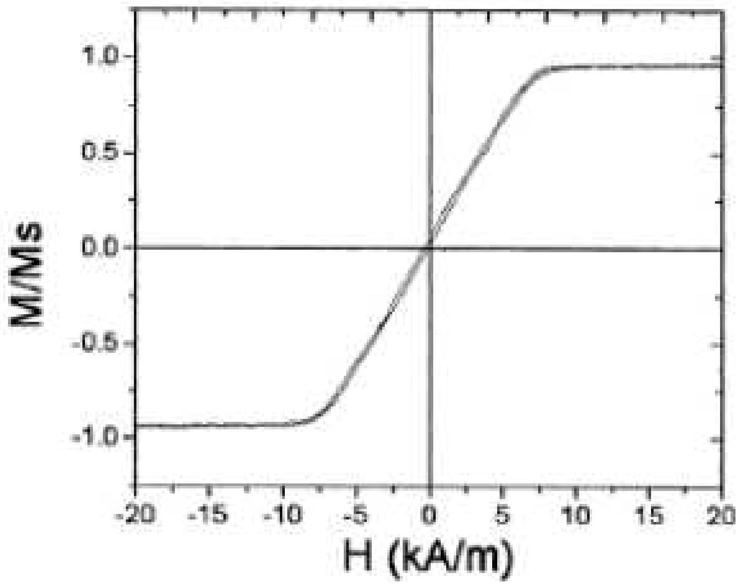
Figure 4

(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.

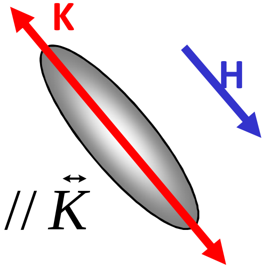
Microhilos, *P. Mendoza Zéliz et al, 2007*







Efectos Dinámicos ($T \neq 0$)

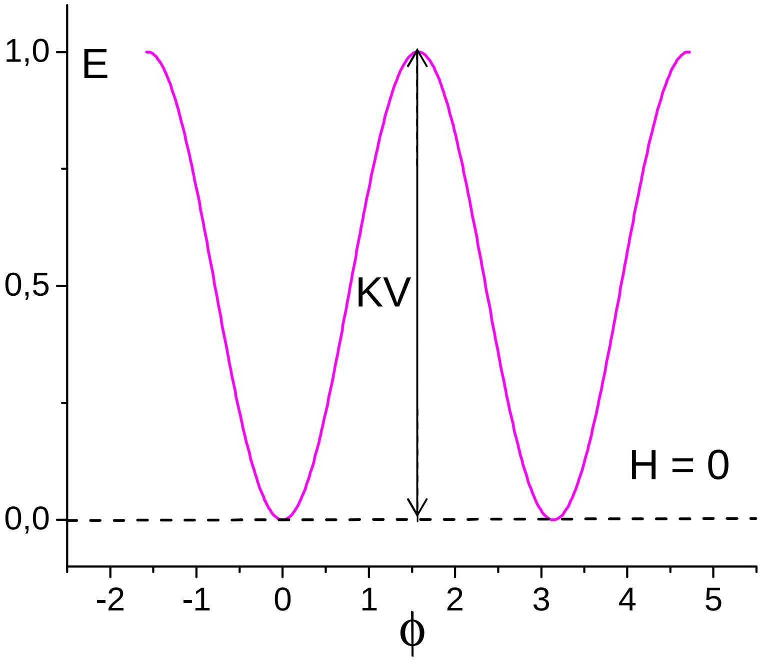


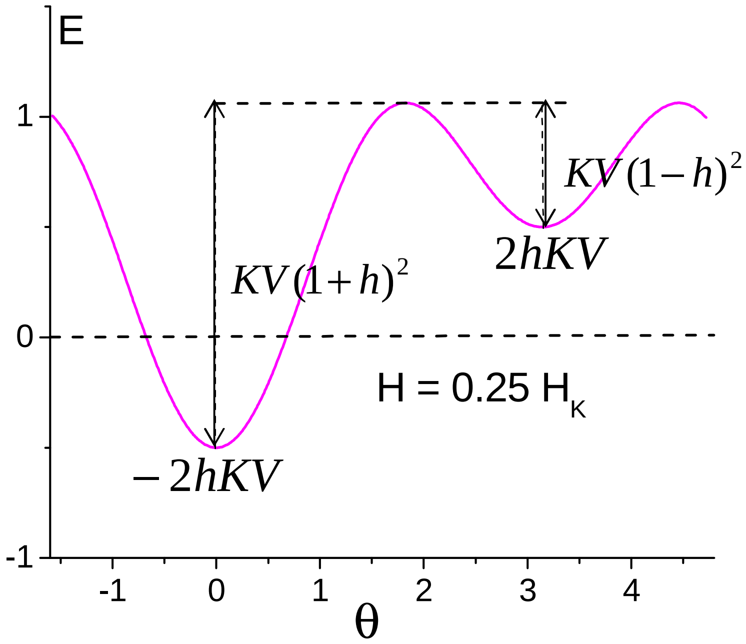
$$\vec{H} \,//\, \overleftrightarrow{K}$$

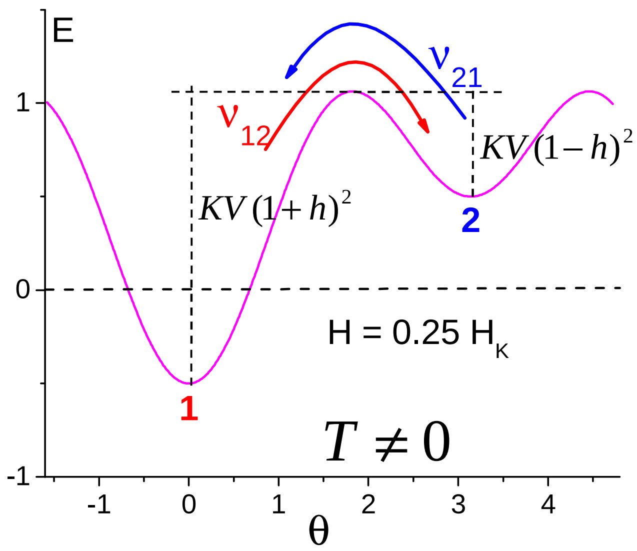
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

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

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







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

$$\nu_{ij} = c_0 e^{-\frac{\Delta E_{ij}}{kT}} \quad \xrightarrow[T=0]{} \nu_{ij} = 0$$

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

Frecuencia de saltos

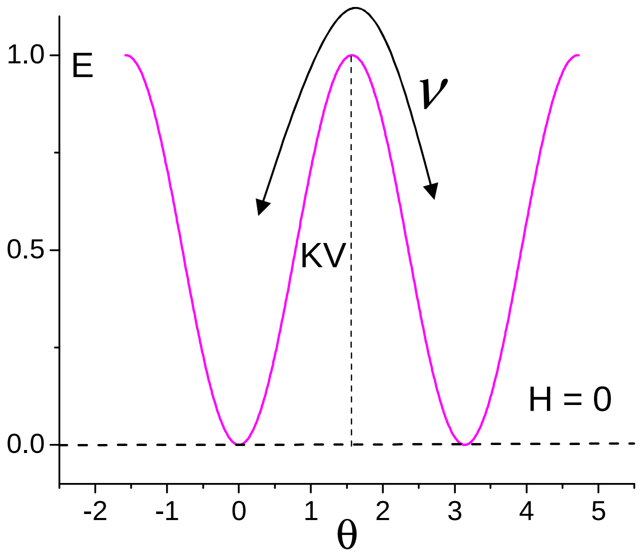
Frecuencia de intentos

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

Tiempo de relajación

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

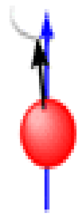
Tiempo de relajación



Para H = 0

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

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



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

$$\tau_0 = c_0^{-1}$$

$$10^{-12}\, s \leq \tau_0 \leq 10^{-8}\, s$$

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

$$\tau_0 \approx cte$$

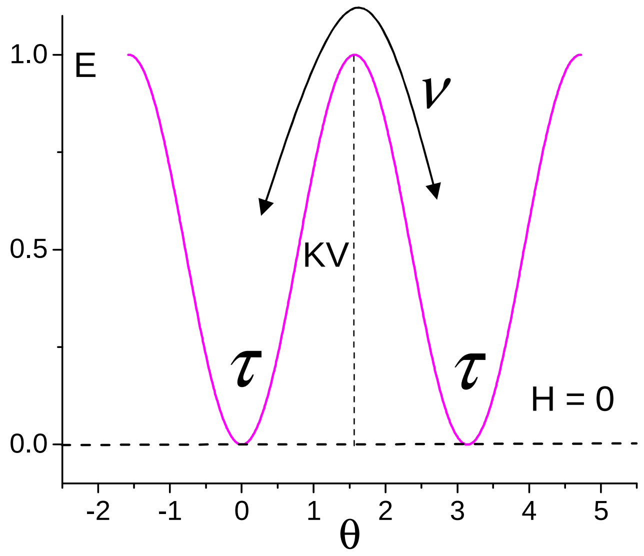
Ejemplo, usando $\tau_0 = 10^{-9}$ s

material	K(J/m³)	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

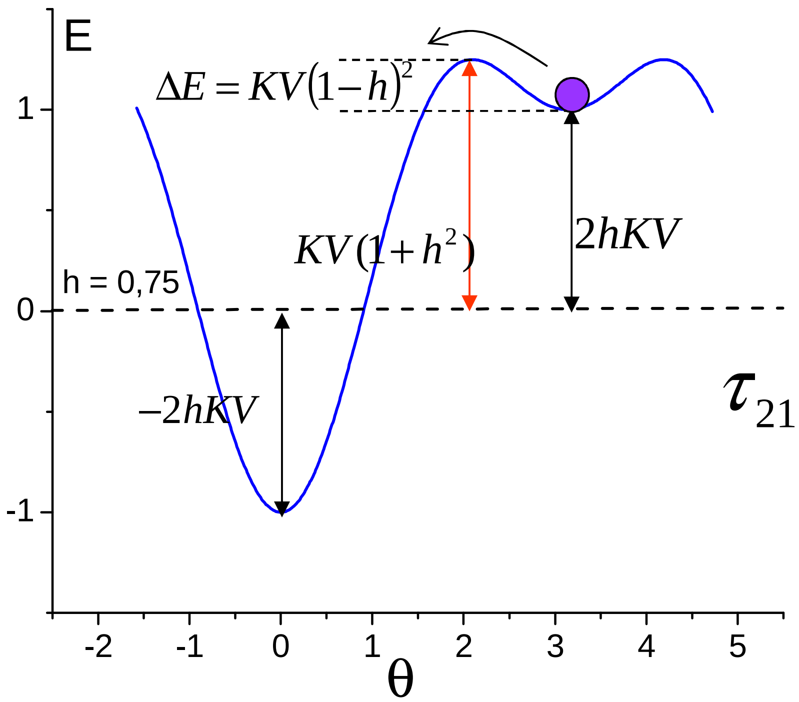


Técnica	τ_{exp}
Mössbauer ^{57}Fe, ^{119m}Sn	$\approx 10^{-8}$s
Susceptibilidad *ac*	10^{-4}–1 s
Susceptibilidad *ac hf*	desde 10^{-6} s
Magnetización *dc*	0.1 –100 s

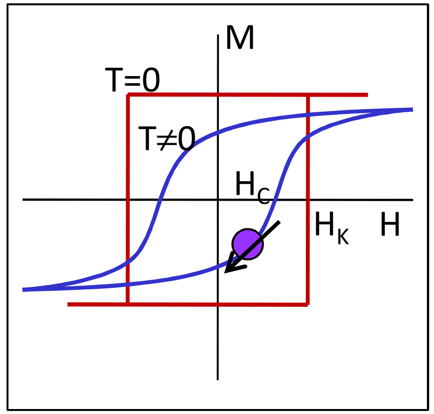
$\tau_{exp} < \tau \Leftrightarrow T < T_B$	Sistema bloqueado	Patrón estático	Histéresis, desdoblamiento Zeeman (EM)
$\tau_{exp} > \tau \Leftrightarrow T > T_B$	Sistema desbloqueado	Patrón dinámico	Equilibrio, patrón super-paramagnético (EM)

Dependencia del campo coercitivo con la temperatura

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



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

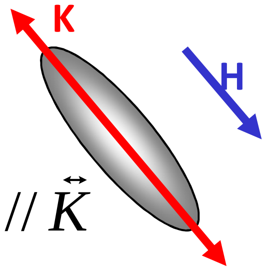


$$\tau_{21} = \tau_0 e^{\frac{KV(1-h)^2}{kT}}$$

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

Dependencia del campo coercitivo con la temperatura

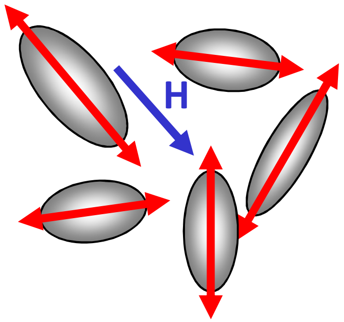
$$H_C(T) \approx H_K\left(1-\sqrt{\frac{kT}{KV}\ln\left(\tau_{\exp}/\tau_0\right)}\right)$$



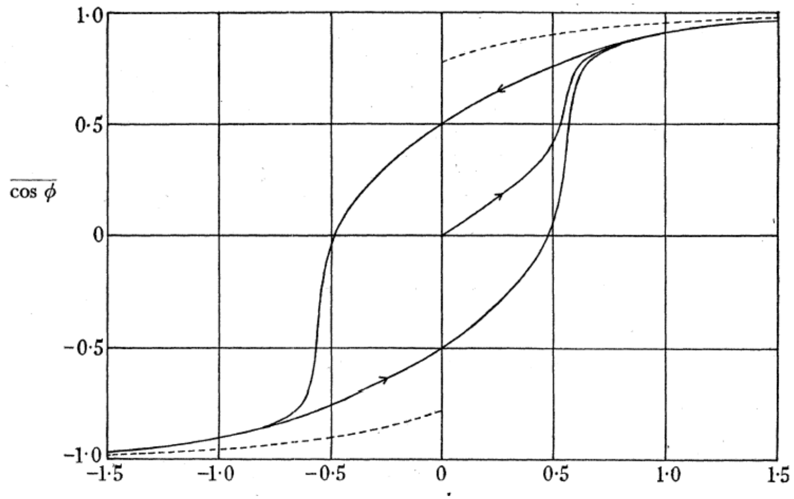
$\vec{H} // \overleftrightarrow{K}$

orientación aleatoria

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



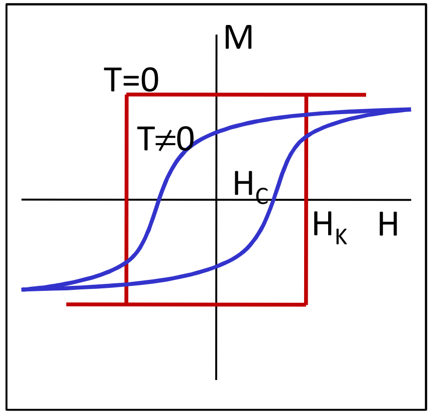
$H_C(0) = 0.479 H_K$



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



$$H_C(T) \approx cH_K\left(1-\left[\frac{kT}{KV}\ln\left(\tau_{\exp}/\tau_0\right)\right]^n\right)$$

$c=1$

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.

$c=0.48$

introduciendo

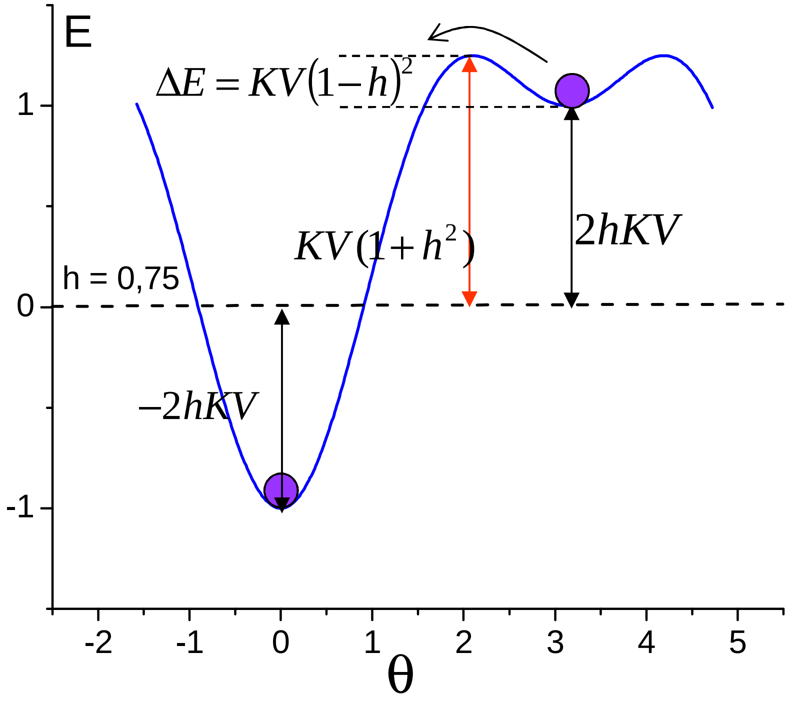
$$T_B=\frac{KV}{k\ln\left(\tau_{\exp}/\tau_0\right)}$$

$$H_C=c\frac{2K}{\mu_0 M_S}\left[1-\left(\frac{T}{T_B}\right)^{1/2}\right]$$

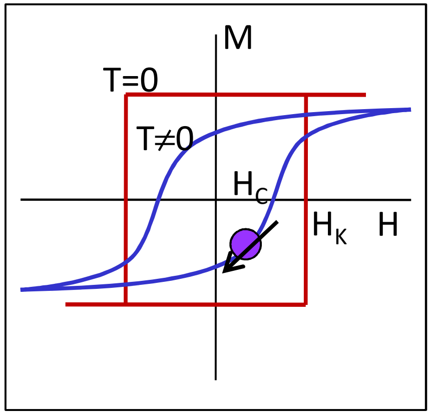
expresión de uso extendido

Dependencia del campo coercitivo con la temperatura 2

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



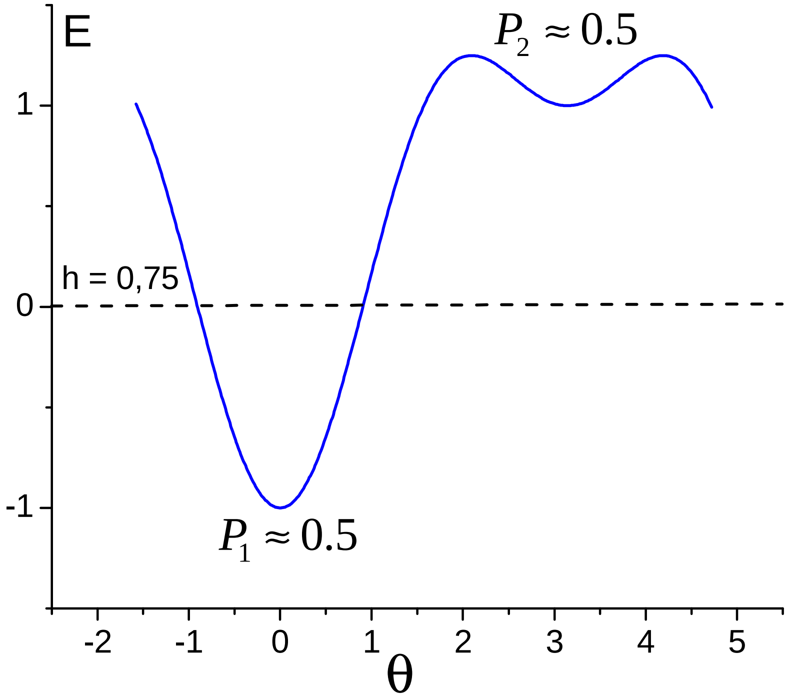
$$H_C = H_K = \frac{2K}{\mu_0 M_S}$$



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

$$\tau_{12} = \tau_0 e^{\frac{KV(1+h)^2}{kT}} \qquad f_{12} = \nu_0 e^{-\frac{KV(1+h)^2}{kT}}$$

$$\tau_{21} = \tau_0 e^{\frac{KV(1-h)^2}{kT}} \qquad f_{21} = \nu_0 e^{-\frac{KV(1-h)^2}{kT}}$$



Población de los estados orientacionales

$$P_1 + P_2 = 1$$

$$M \approx 0 \rightarrow P_1 \approx P_2 \approx 0.5$$

Evolución temporal
Por el principio del balance detallado

$$\frac{dP_1}{dt}_2 = P_2 f_{21} - P_1 f_{12}$$

$$\frac{dP_1}{dt}_2 \approx 0.5\left(f_{21} - f_{12}\right)$$

$$M = M_S\left(P_1 - P_2\right) = M_S\left(2P_1 - 1\right)$$

$$\frac{dM}{dt} = 2M_S \frac{dP_1}{dt} \approx M_S\left(f_{21} - f_{12}\right)$$

$$\frac{1}{\nu_0 M_S}\frac{dM}{dt} \approx e^{-\frac{KV(1-h)^2}{kT}} - e^{-\frac{KV(1+h)^2}{kT}}$$

$$\frac{1}{\nu_0 M_S}\frac{dM}{dt} \approx e^{-\frac{KV(1-h)^2}{kT}} - e^{-\frac{KV(1+h)^2}{kT}} \approx e^{-\frac{KV(1-h)^2}{kT}}$$

$$\frac{1}{\nu_0 M_S}\frac{dM}{dt} \approx e^{-\frac{KV(1-h)^2}{kT}} - e^{-\frac{KV(1+h)^2}{kT}} \approx e^{-\frac{KV(1-h)^2}{kT}}$$

$$\frac{dM}{dt} = \frac{dM}{dH}\frac{dH}{dt}$$

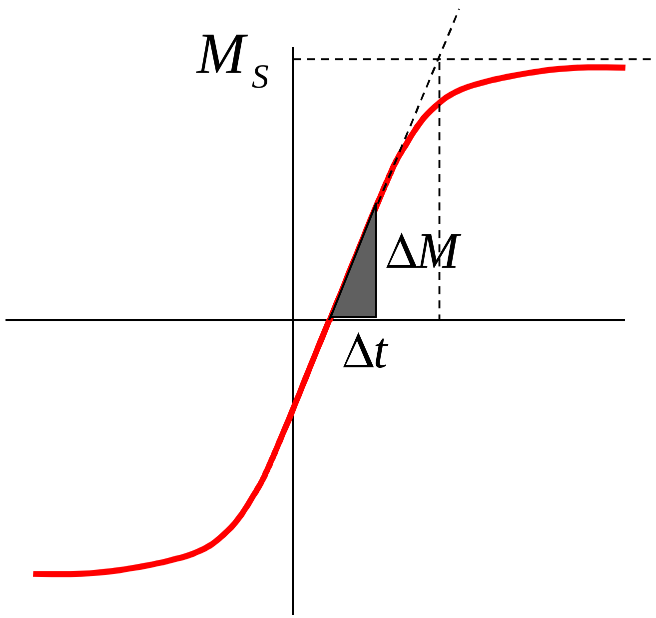
cuando $H \approx H_C \rightarrow \frac{dM}{dH} = \chi \approx cte$

$$\frac{1}{\nu_0 M_S}\chi\frac{dH}{dt}\bigg|_{H_C} \approx e^{-\frac{KV(1-h_C)^2}{kT}}$$

$$H_C \approx H_K\left\{1-\sqrt{\frac{kT}{KV}\ln\left[\frac{M_S}{\chi(dH/dt)_{H_C}}\frac{1}{\tau_0}\right]}\right\} \qquad \tau_0 = 1/c_0$$

escribiendo $\chi \approx \Delta M / \Delta H, \quad dH/dt \approx \Delta H / \Delta t$

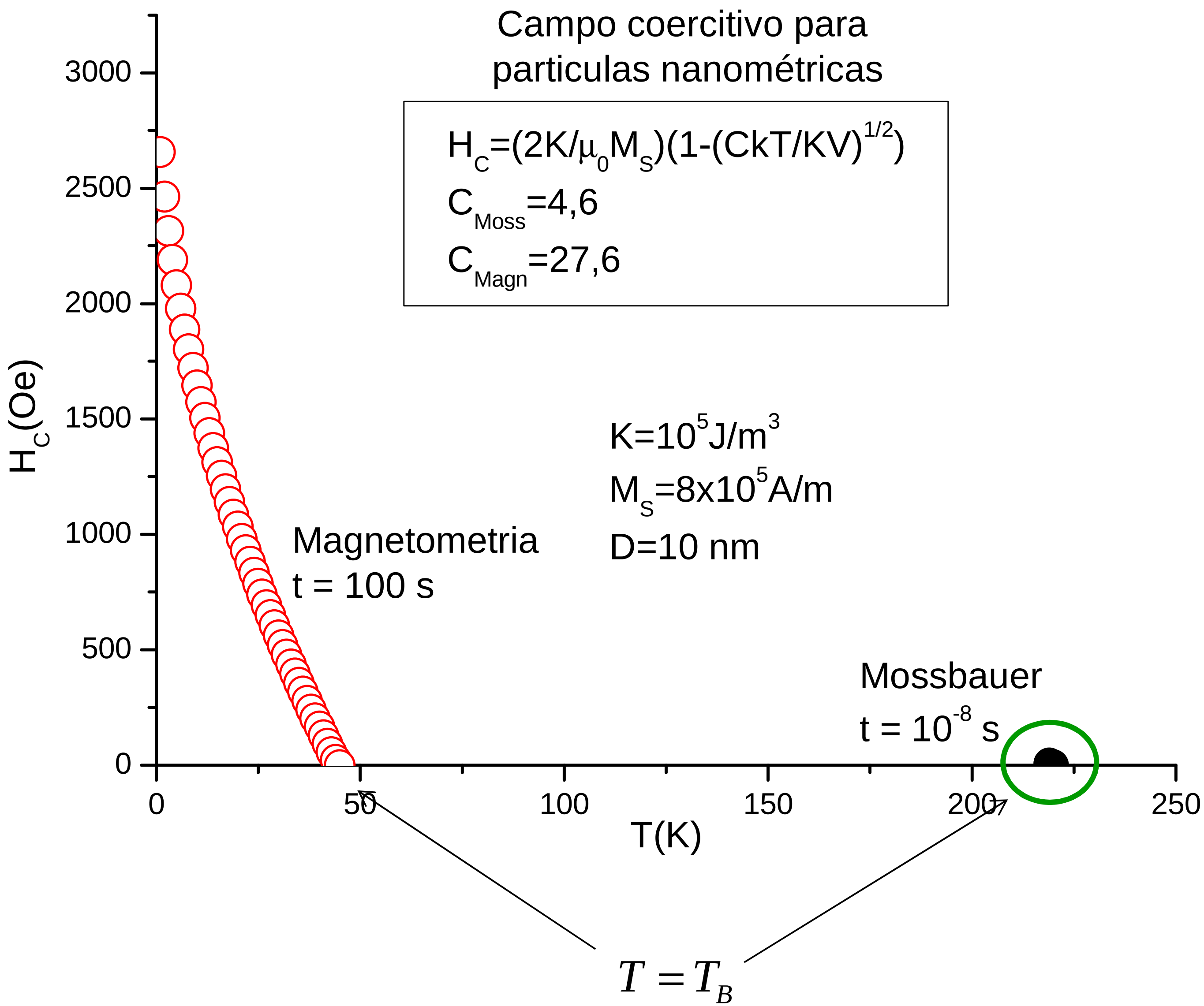
$$H_C \approx H_K \left\{ 1 - \sqrt{\frac{kT}{KV} \ln\left[\frac{(M_S / \Delta M)\Delta t}{\tau_0} \right]} \right\}$$



llamando $\quad n = M_S / \Delta M \quad \tau_{\exp} = n\Delta t$

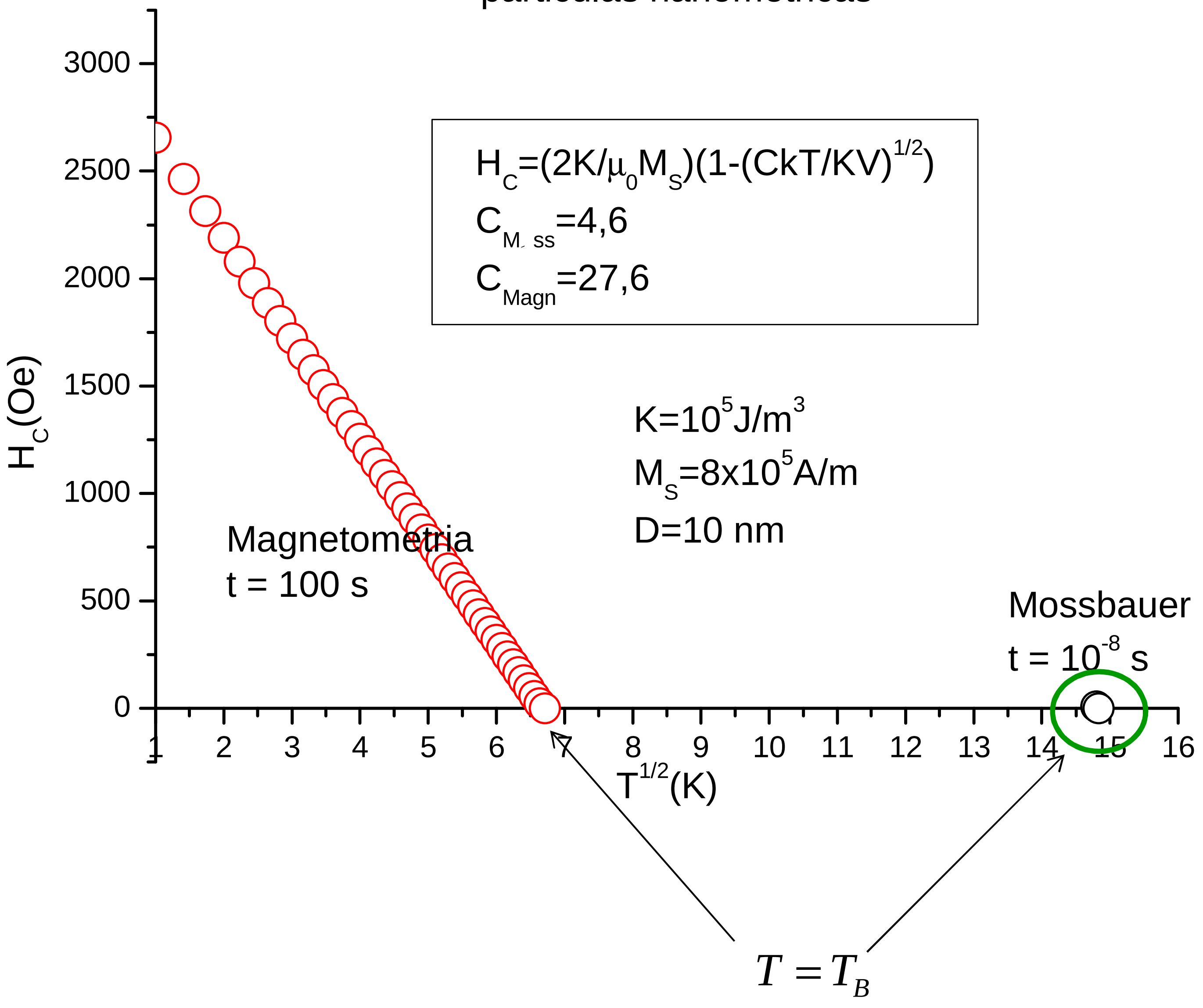
$$H_C \approx H_K \left\{ 1 - \sqrt{\frac{kT}{KV} \ln\left(\frac{\tau_{\exp}}{\tau_0} \right)} \right\}$$

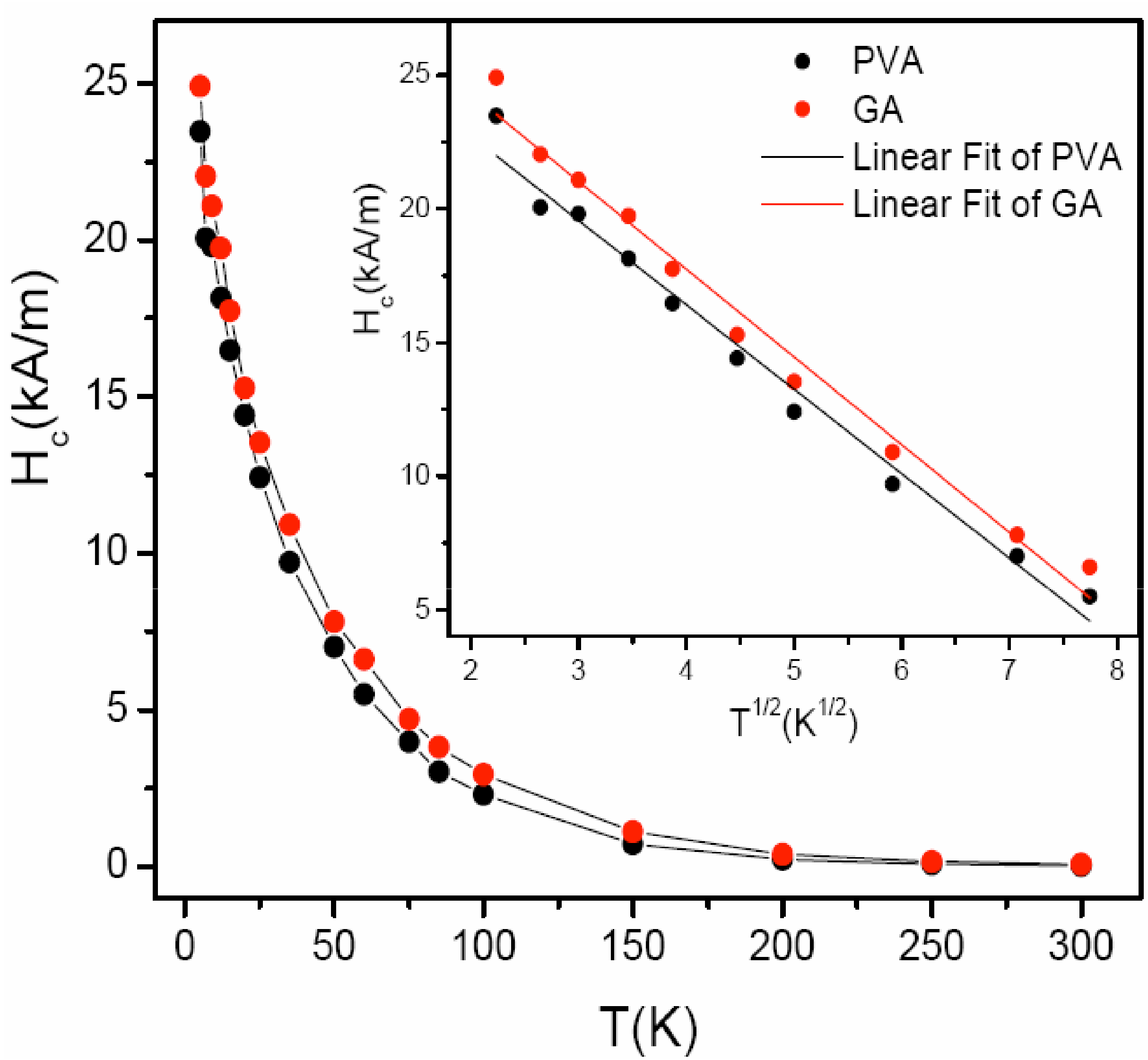
Donde $\tau_{\exp}$ sería el tiempo aproximado requerido para alcanzar la saturación desde $M = 0$



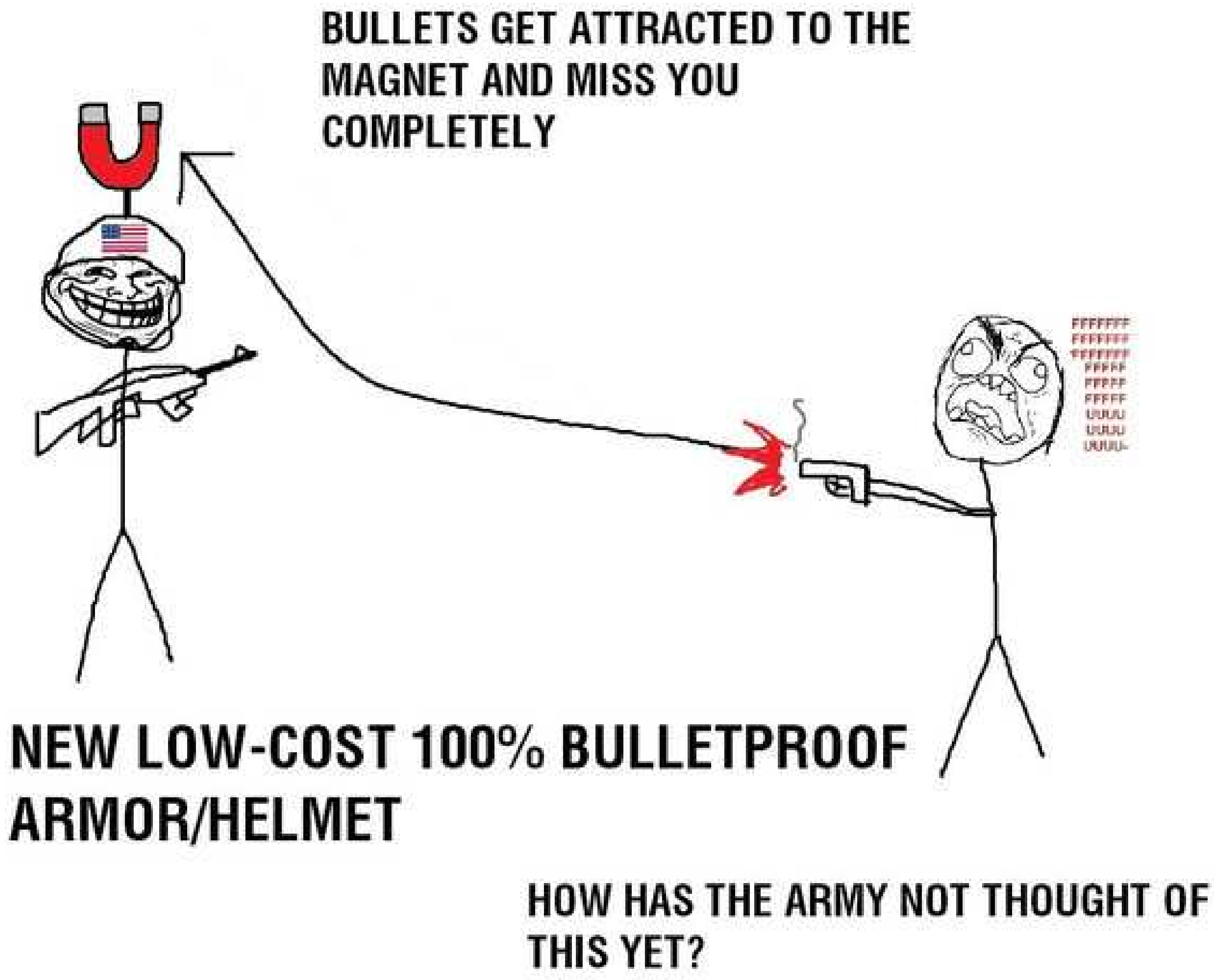
Campo coercitivo para
particulas nanométricas
$H_C=(2K/\mu_0 M_S)(1-(CkT/KV)^{1/2})$
$C_{Moss}=4,6$
$C_{Magn}=27,6$
$K=10^5 J/m^3$
$M_S=8x10^5 A/m$
D=10 nm
Magnetometria
t = 100 s
Mossbauer
$t = 10^{-8}$ s
H_C(Oe)
T(K)
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
$T = T_B$

Campo coercitivo para
particulas nanométricas





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