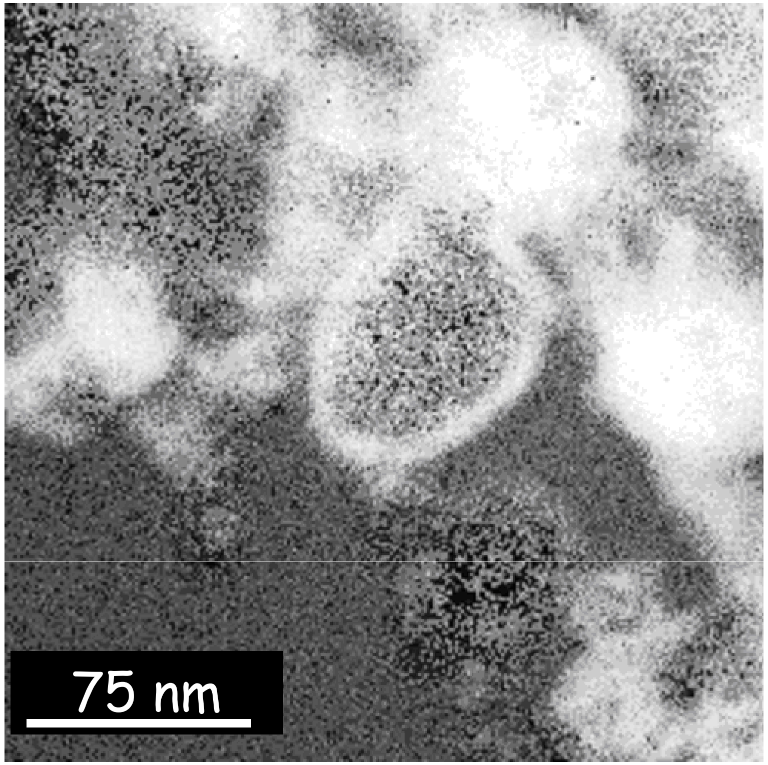
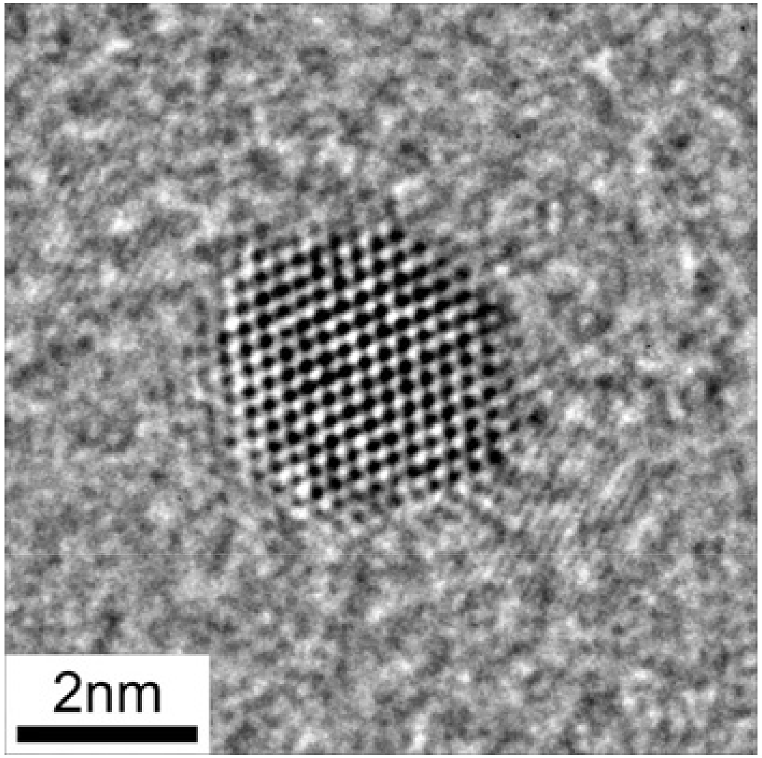
8b Anisotropía en nanopartículas ferromagnéticas

Partículas ferromagnéticas pequeñas



Elemental map of the spatial distribution of C in a Sm-Co-C magnetic nanoparticle materials

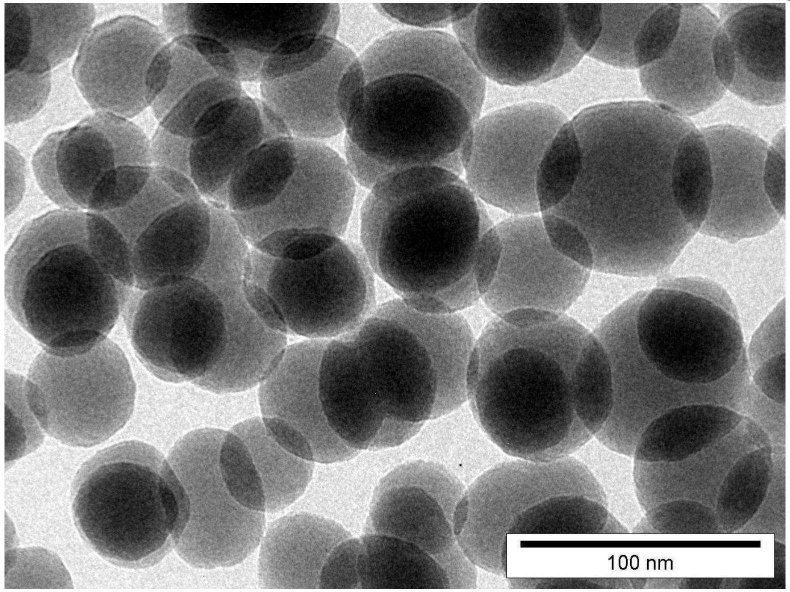


High resolution TEM micrograph of an individual FePt nanoparticle. The image is contrast enhanced by means of Fourier filtering

Bernd Rellinghaus, IFW Dresden,

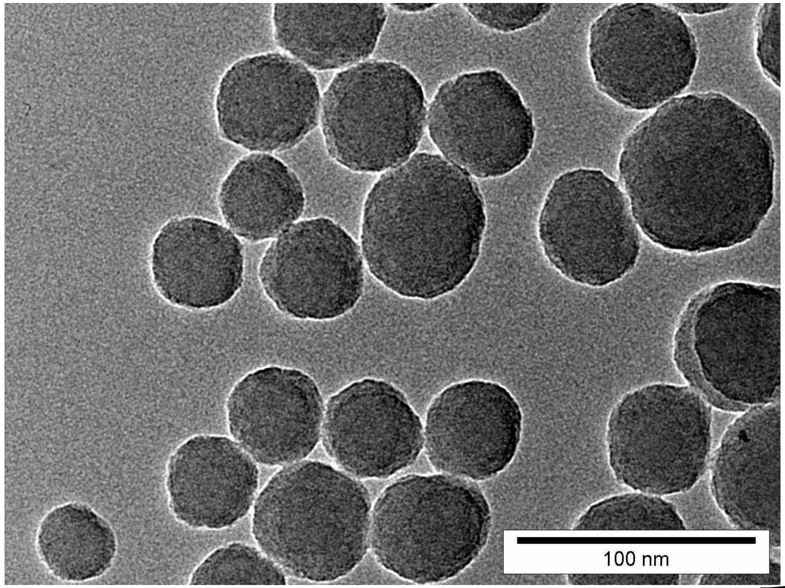
http://www.ifw-dresden.de/imw/25/nanoparticles_engl.html

Partículas ferromagnéticas pequeñas

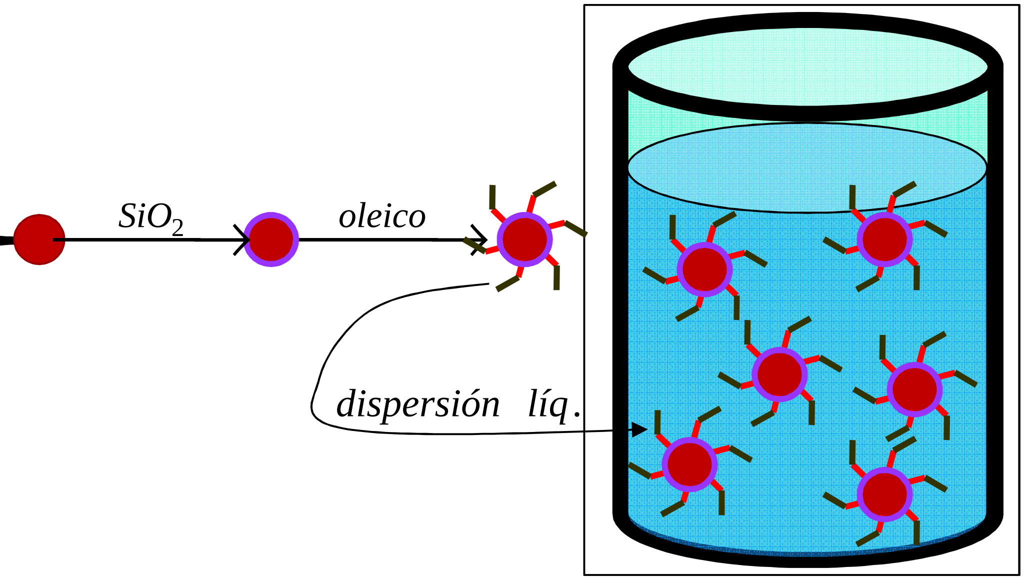


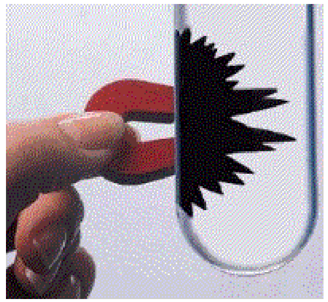
manganitas

$La_{2/3}Sr_{1/3}MnO_4$

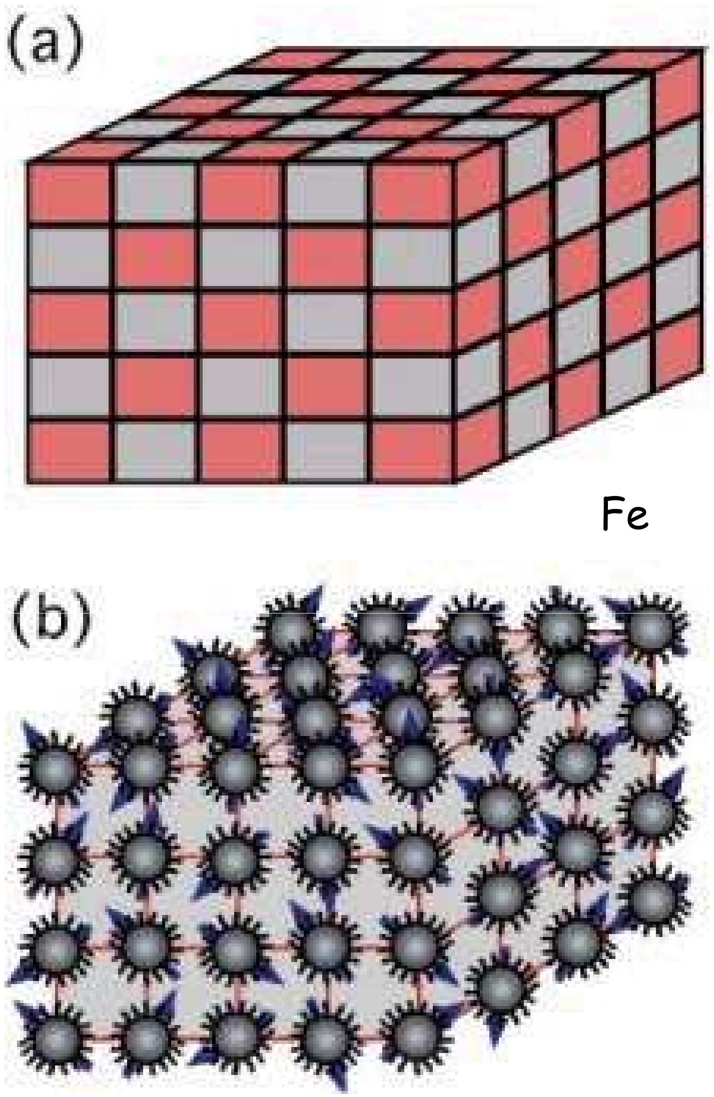


ferrofluidos





Partículas ferromagnéticas pequeñas



Surfactants are used to coat the particle surface to prevent effectively the irreversible aggregation of the particles.

A large effort has been devoted to the synthesis of highly monodisperse nanoparticles, and this can be achieved by precise control of the nucleation and growth process, which involves rapid nucleation and prevention of particle coalescence.

The self-ordering process is carried out by placing a droplet of a suspension of the particles on a substrate followed by slow evaporation of the solvent.

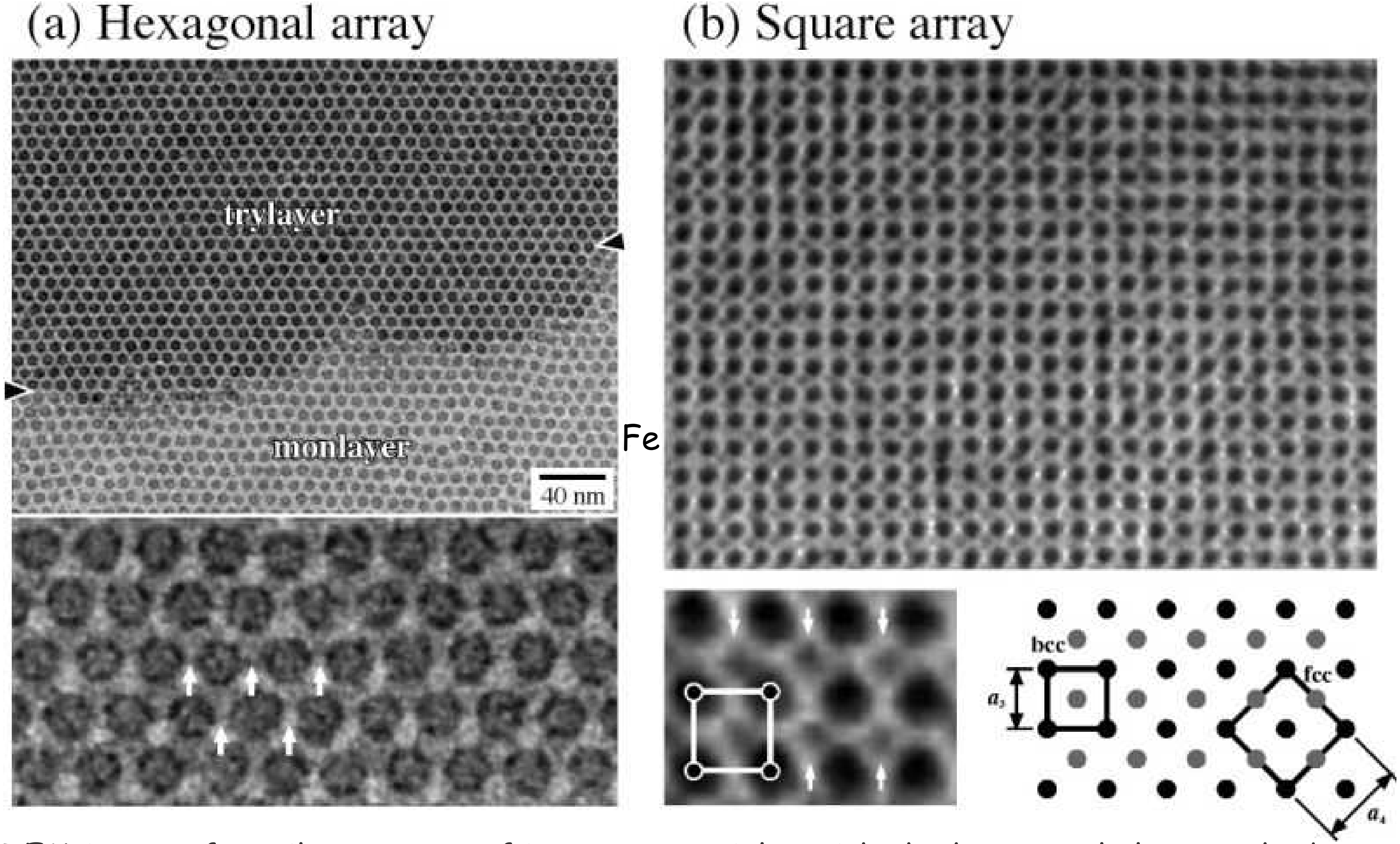
Saeki YAMAMURO

Department of Materials Science and Engineering, Nagoya Institute of Technology

Schematics of (a) a three-dimensional superlattice crystal, and (b) a magnetic superlattice of a nanoparticle self-assembly.

http://www.nanonet.go.jp/english/mailmag/2004/030b.html

Partículas ferromagnéticas pequeñas



A TEM image of a trilayer array of iron nanoparticles with the hexagonal close-packed stacking sequence and its enlarged image and (b) a TEM image of a multilayer array of iron-platinum nanoparticles with the body-centered cubic structure and its enlarged image

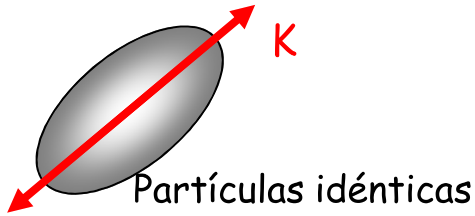
http://www.nanonet.go.jp/english/mailmag/2004/030b.html

Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

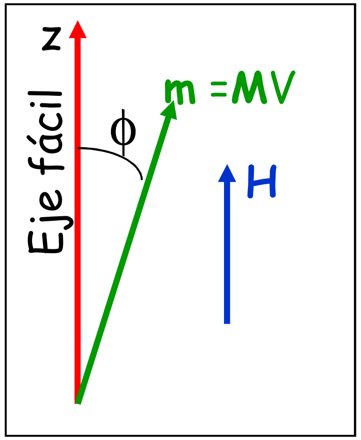
monodominio

Anisotropía uniaxial

no interactuantes



Campo paralelo al eje fácil



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

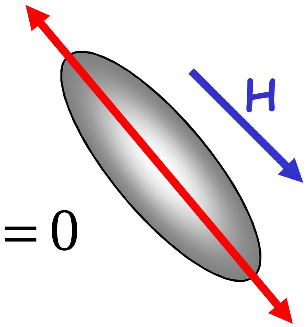
$$E_H = -\vec{m}\cdot\vec{B} = -\mu_0\vec{m}\cdot\vec{H} = -\mu_0 VM_z H = -\mu_0 VM_S H\cos\phi$$

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

llamamos Campo de anisotropía

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

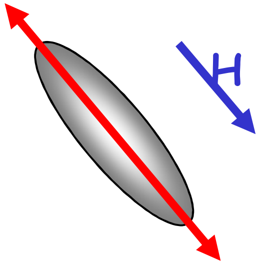
$$h = \frac{H}{H_K} = \frac{\mu_0 M_S H}{2K}$$



$\theta = 0$

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

Partículas ferromagnéticas pequeñas – modelo de Stoner – Wohlfarth – régimen bloquedo



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

extremo $\quad \dfrac{\partial E}{\partial \phi} = 0 \Rightarrow \sin\phi\left(\cos\phi + h\right) = 0 \quad \begin{cases} \phi = \begin{cases} 0 \\ \pi \end{cases} \\ \cos\phi = -h \end{cases}$

mínimo $\quad \dfrac{\partial^2 E}{\partial \phi^2} = 2KV\left[\cos\phi\left(\cos\phi + h\right) - \sin^2\phi\right] > 0$

Valores de la función

$$E(\phi = 0) = -2hKV$$

$$E(\phi = \pi) = 2hKV$$

$$E(\cos\phi = -h) = KV(1 + h^2)$$

Condición de mínimo

$$\frac{\partial^2 E}{\partial \phi^2}(\phi = 0) = 2KV(1 + h) > 0$$

$$\frac{\partial^2 E}{\partial \phi^2}(\phi = \pi) = 2KV(1 - h) > 0$$

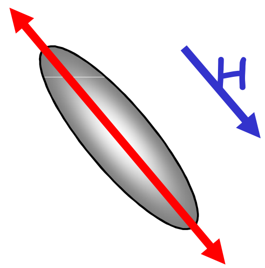
$$\frac{\partial^2 E}{\partial \phi^2}(\cos\phi = -h) = 2KV(h^2 - 1) > 0$$

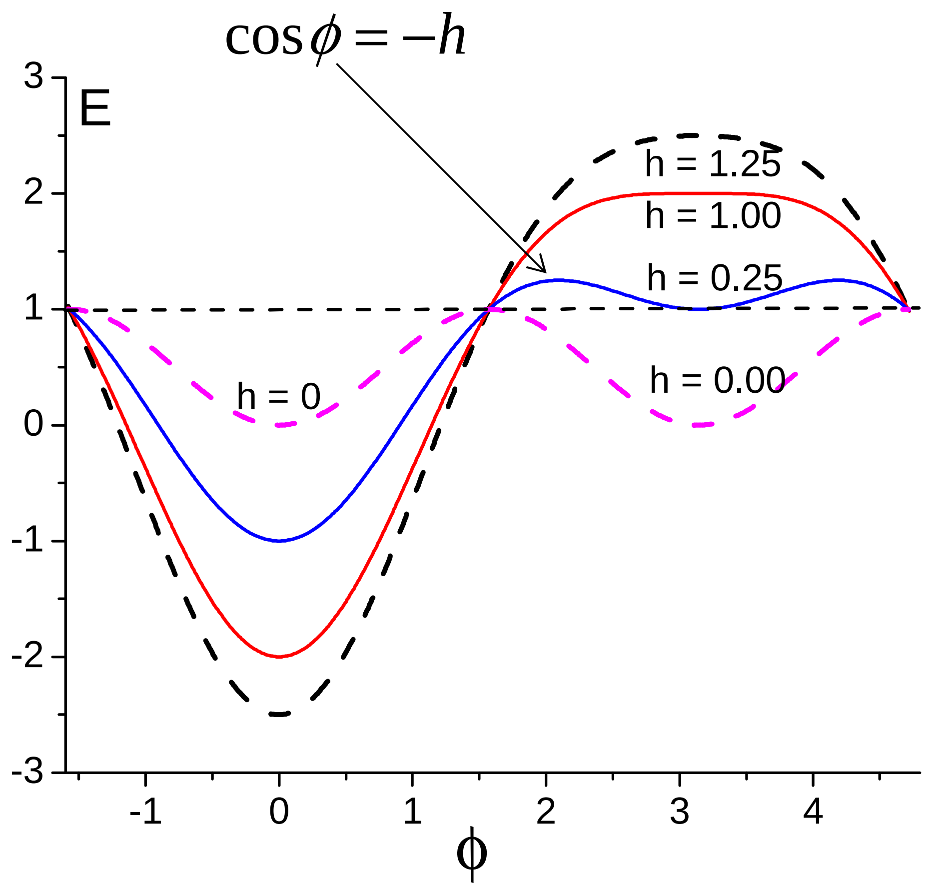
siempre que $h < 1 \Rightarrow$ *máximo*

Partículas ferromagnéticas pequeñas – modelo de Stoner – Wohlfarth – régimen bloqueado

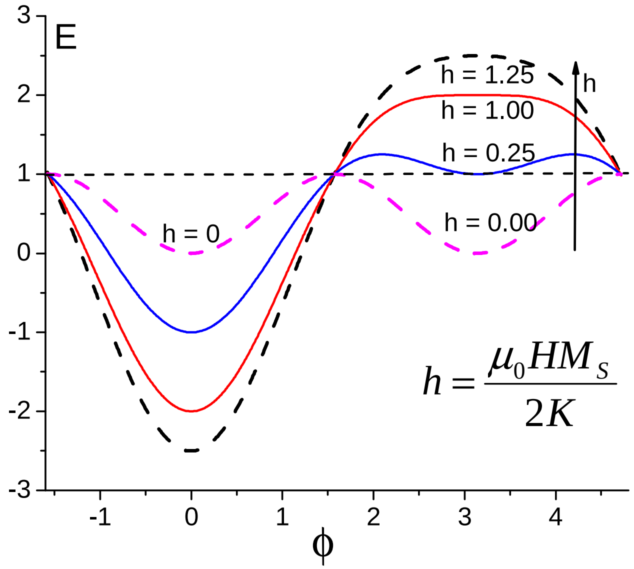
$$E = KV\left(\sin^2\phi - 2h\cos\phi\right)$$

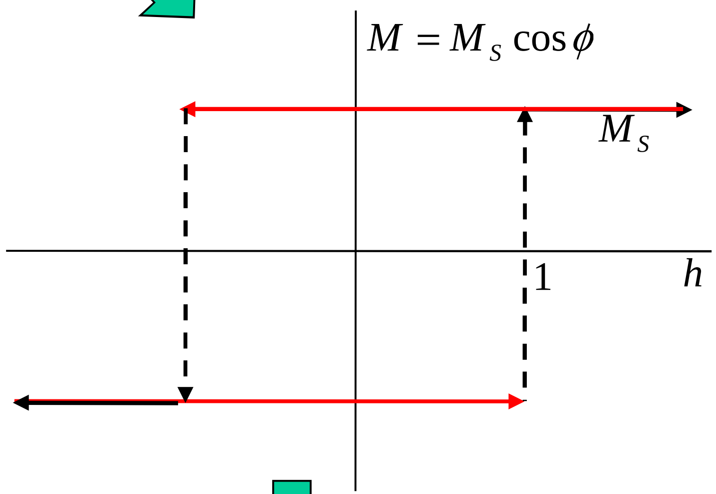
$$h = \frac{H}{H_K} \quad H_K = \frac{2K}{\mu_0 M_S}$$





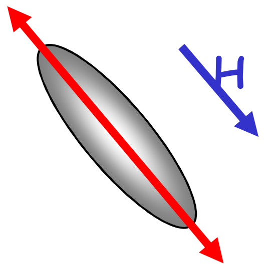
Partículas ferromagnéticas pequeñas – modelo de Stoner – Wohlfarth – régimen bloqueado

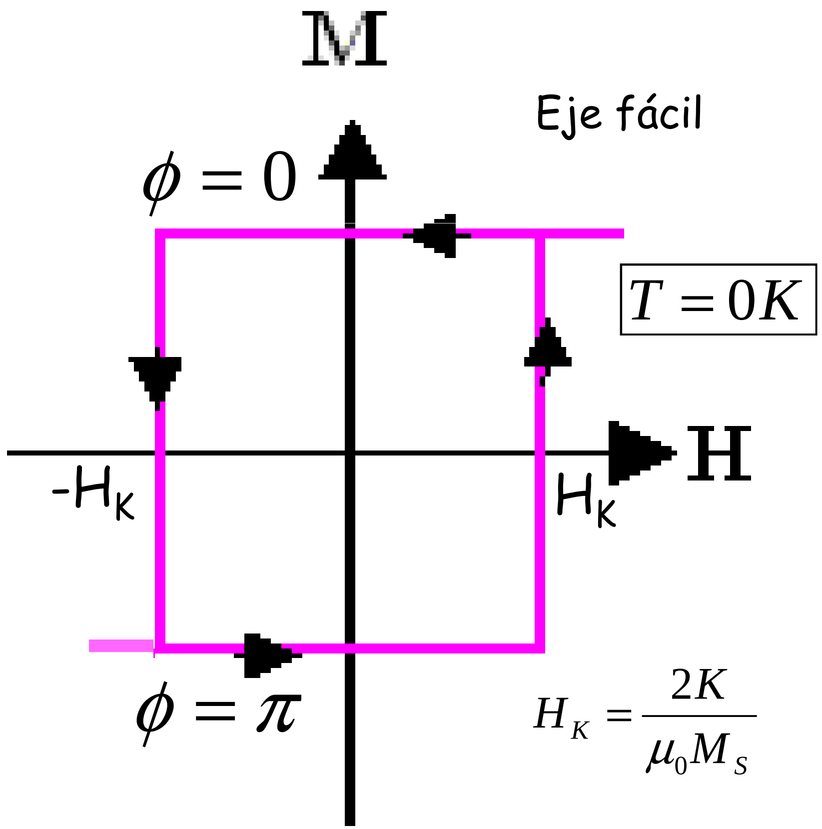




Partículas ferromagnéticas pequeñas – modelo de Stoner – Wohlfarth – régimen bloquedo

$$M_z = M_s \cos\theta$$

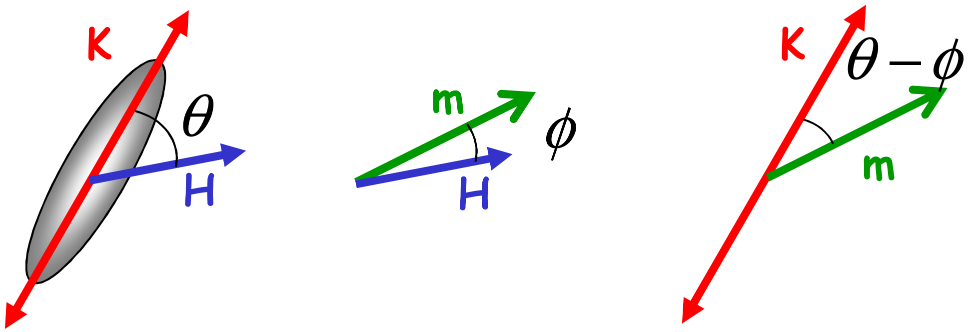




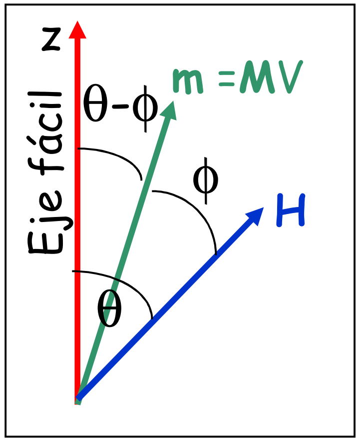
Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

Campo en dirección arbitraria

$$\theta \neq 0$$



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

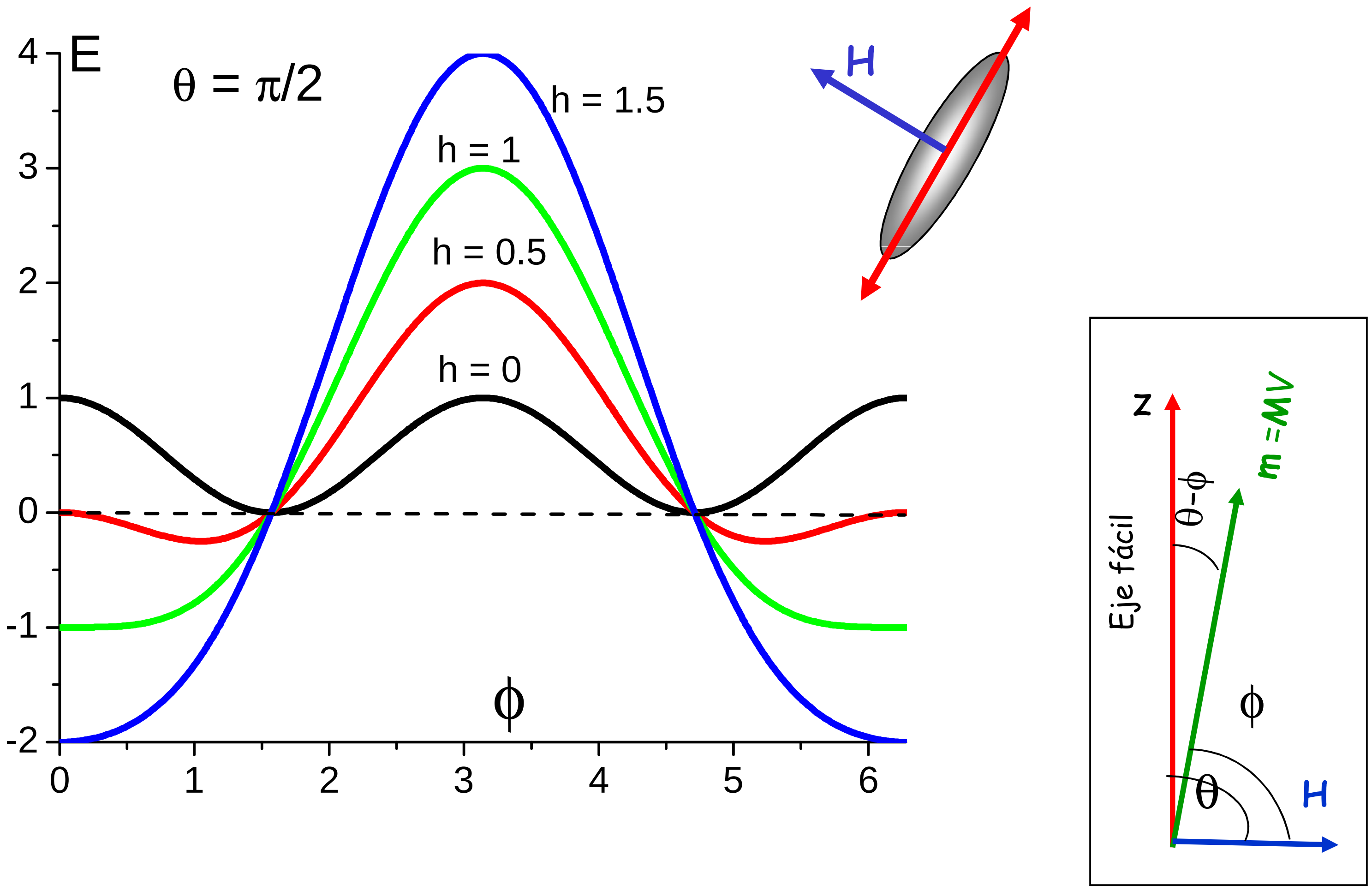


Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

$$\theta = \pi / 2$$

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

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

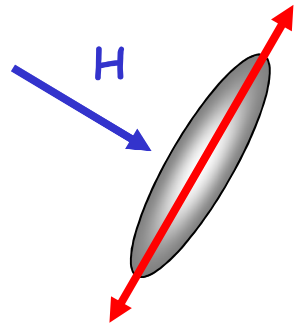


Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

Solución analítica sólo para $\theta = 0$ (ó π) y $\theta = \pm \pi/2$

Caso $\theta = \pi/2$

$$E = KV\cos\phi(\cos\phi - 2h)$$



extremo → $\begin{cases} \sin\phi = 0 \rightarrow \phi = \begin{cases} 0 \\ \pi \end{cases} \\ \cos\phi = h; |h| < 1 \end{cases}$

mínimo → $-\cos(2\phi) + h\cos\phi > 0$

$\phi = 0$ → $-1 + h > 0$ → $h > 1$ → $H > H_K$

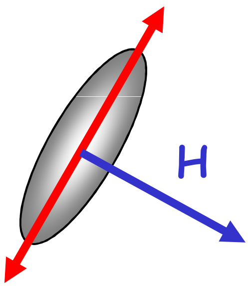
$\phi = \pi$ → $-1 - h > 0$ → $h < -1$ → $H < -H_K$

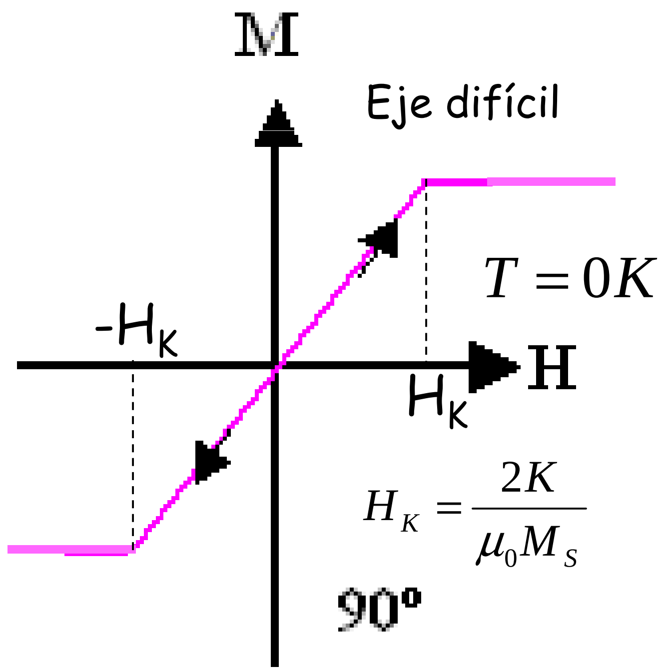
$\cos\phi = h$ → $1 - h^2 > 0$ → $-1 < h < 1$ → $-H_K < H < H_K$

Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

Caso $\theta = \pi/2$

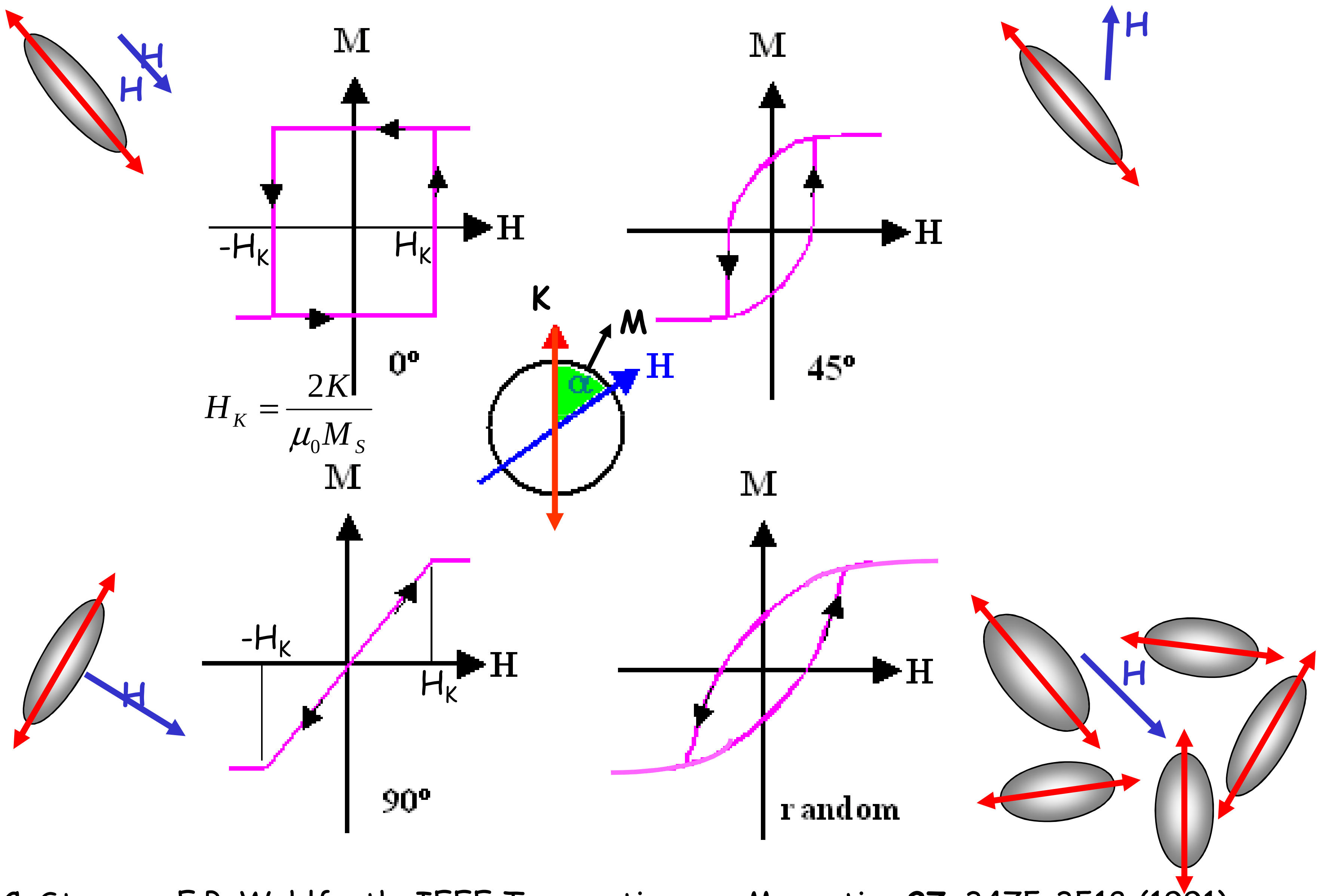
$$M_z = M_s \cos\phi$$





Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

régimen bloqueado → T = 0 K



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

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

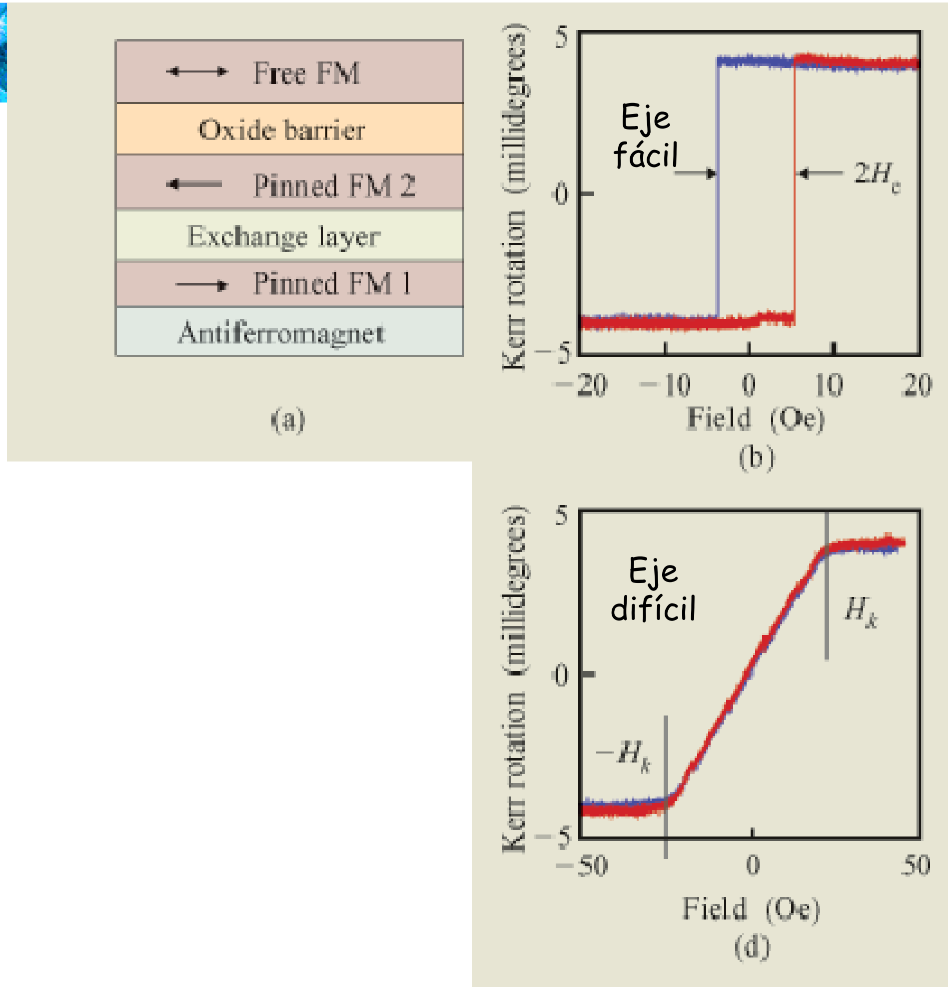


Figure 4

(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.

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

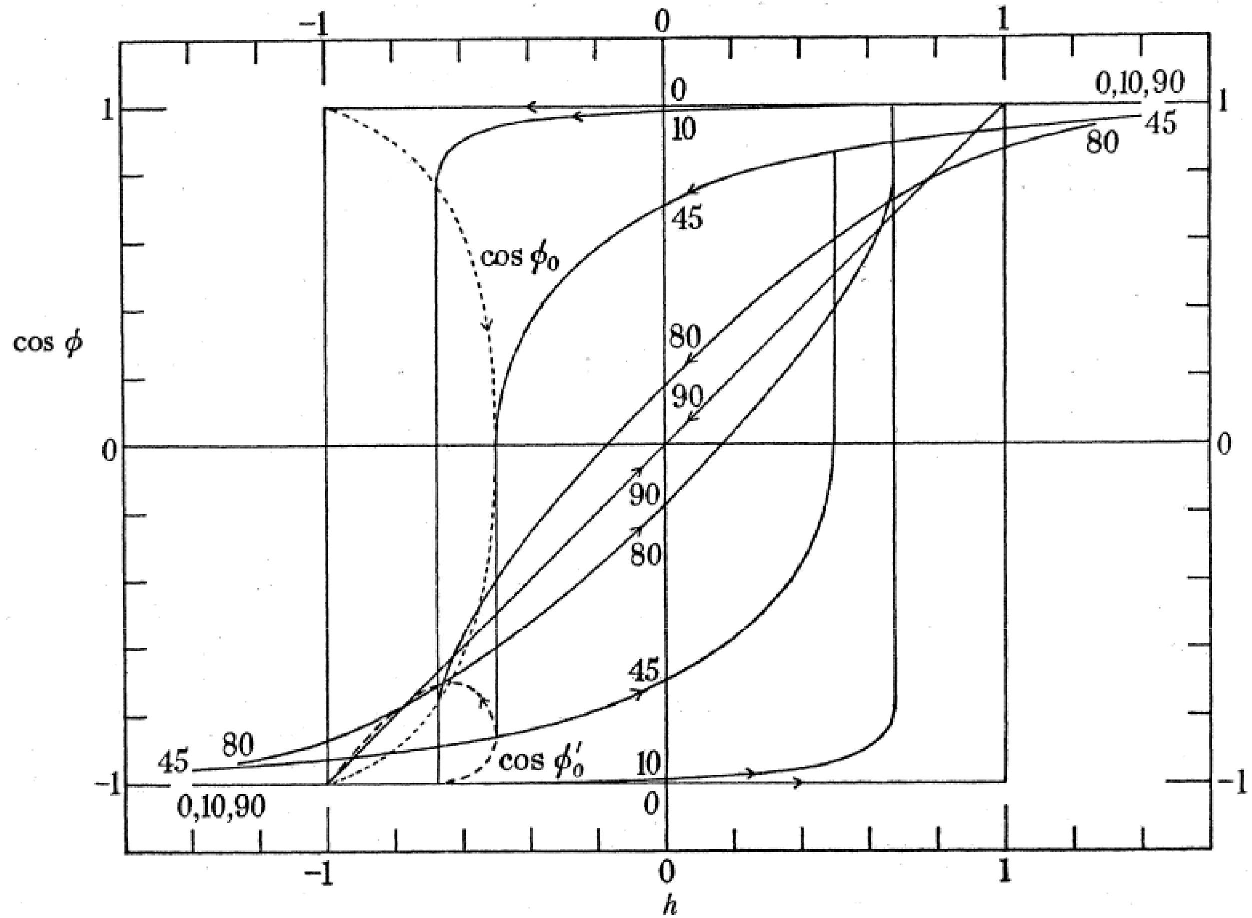


FIGURE 6. Magnetization curves for prolate spheroids. The resolved magnetization in the positive field direction is given by $I_0 \cos\phi$, where I_0 is the saturation magnetization. The field, H, is given by $H = (N_b - N_a)\, I_0 h$, where N_a and N_b are the demagnetization coefficients along the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

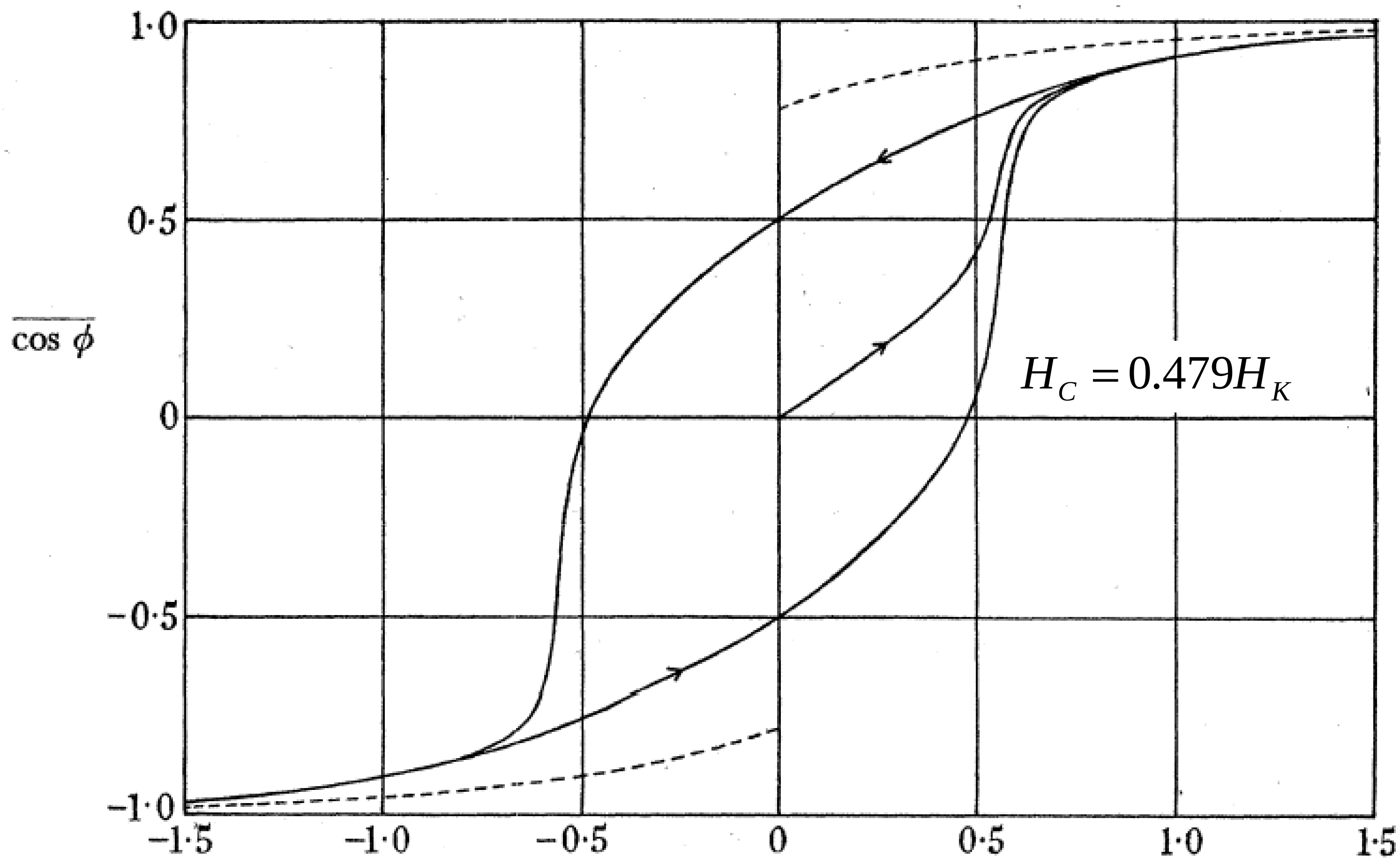


FIGURE 7. Magnetization curves for prolate (full curves) and oblate (broken curves) spheroids orientated at random. The curves refer to similar prolate (or oblate) spheroids orientated at random. $\overline{\cos\phi}$ is proportional to the mean resolved magnetization per spheroid in the positive field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

Partículas ferromagnéticas pequeñas – modelo de Stoner - Wohlfarth

Referencias adicionales

G. Zimmerman, J. Appl. Phys. **77**, 2097-2101 (1995)

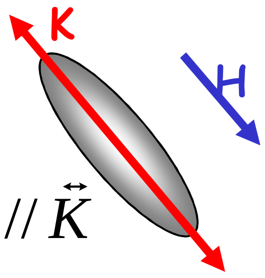
M.J. Vos et al., IEEE Trans. Magnetics **29**, 3652-3657 (1995)

Efectos Dinámicos ($T \neq 0$)

Partículas ferromagnéticas pequeñas - efectos dinámicos - T ≠ 0 K

Partículas no interactuantes

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

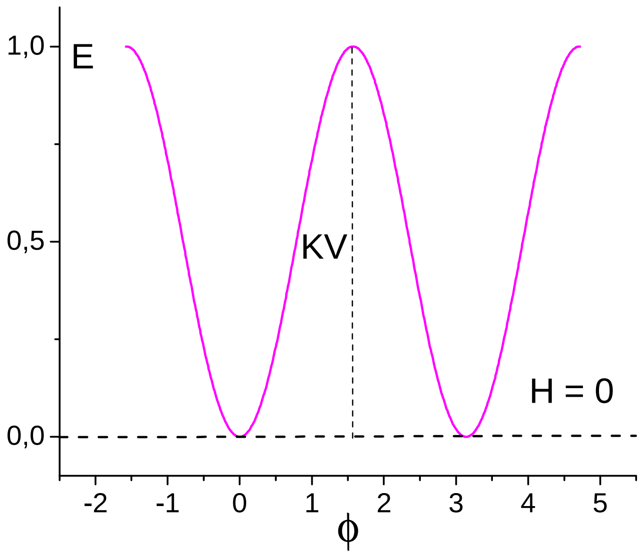


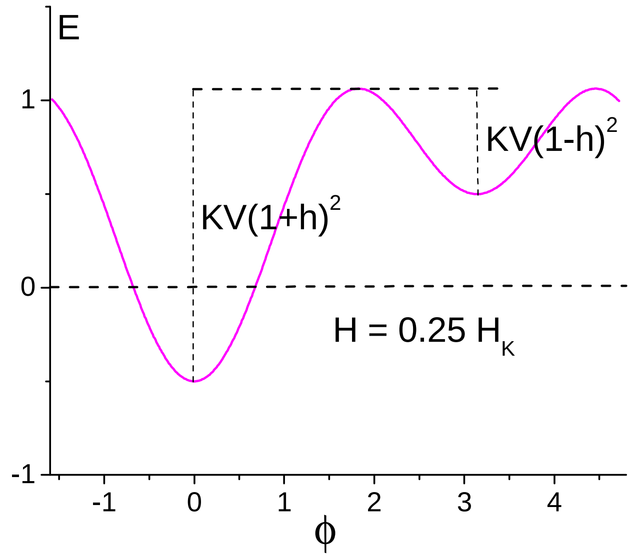
$\vec{H} \,//\, \overleftrightarrow{K}$

Valores de la función	
$E(\phi=0) = -2hKV$	mín
$E(\phi=\pi) = 2hKV$	mín
$E(\cos\phi=-h) = KV(1+h^2)$	máximo o inflexión

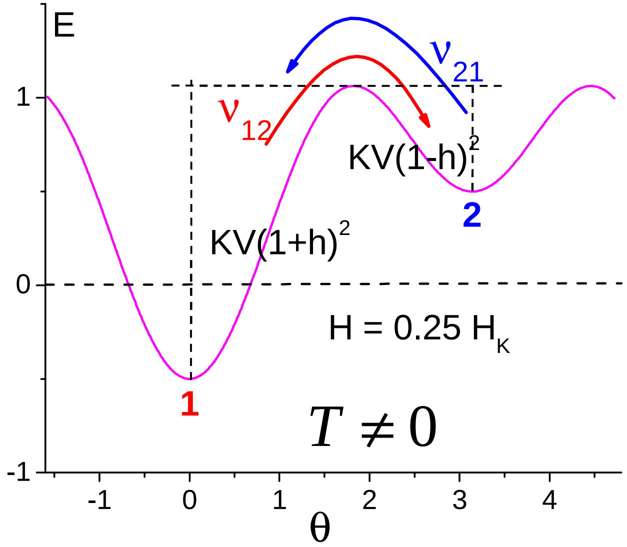
$$h = \frac{H}{H_K}$$

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





Partículas ferromagnéticas pequeñas – efectos dinámicos



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

Frecuencia de saltos

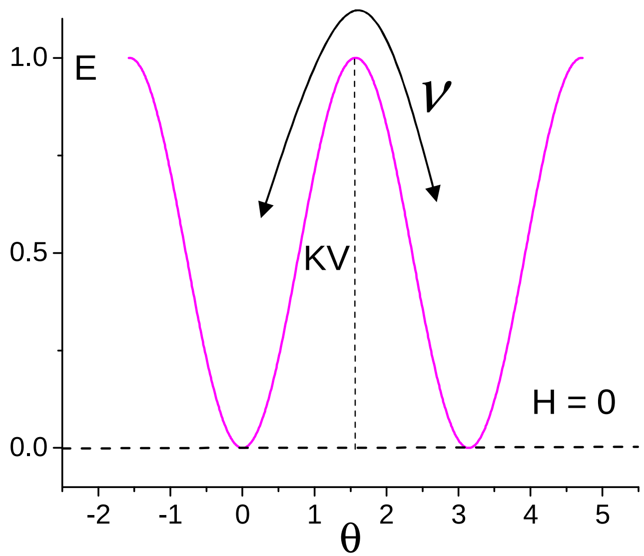
$$\xrightarrow[T=0]{} \nu_{ij} = 0$$

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

Frecuencia de intentos

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

Tiempo de relajación

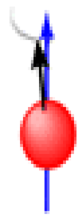


Para H = 0

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

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

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



$$10^{-12}\,s \le \tau_0 \le 10^{-9}\,s$$

Partículas ferromagnéticas pequeñas – efectos dinámicos

Estructura de τ_0

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

$$\tau_0 \approx cte$$

Modelo de Brown

$$\tau_0 \approx \frac{m}{2KV\gamma_0}\sqrt{\frac{\pi}{\alpha}} \qquad \alpha \approx \frac{KV}{kT}$$

$$M_S(T)$$

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

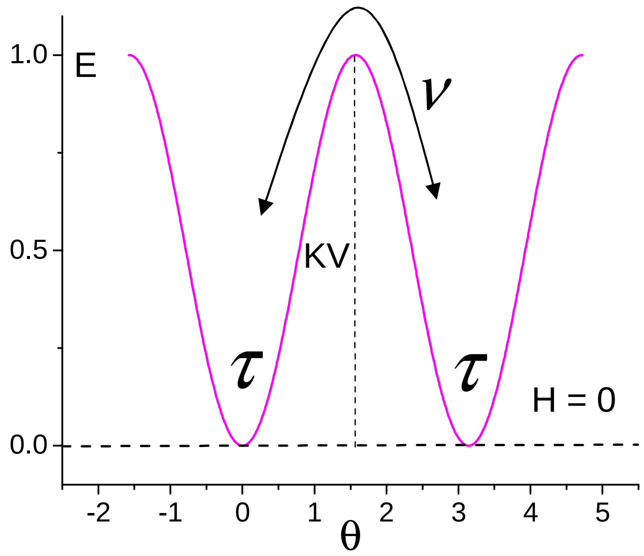
material	$K(J/m^3)$	R(nm)	τ(s)
Co	3.9×10^5	4.4	6×10^5
		3.6	0.1
Fe	4.7×10^4	14.0	1.5×10^5
		11.5	0.07

Partículas ferromagnéticas pequeñas – efectos dinámicos

Comportamiento superparamagnético

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

Tiempo Experimental vs Tiempo de Relajación



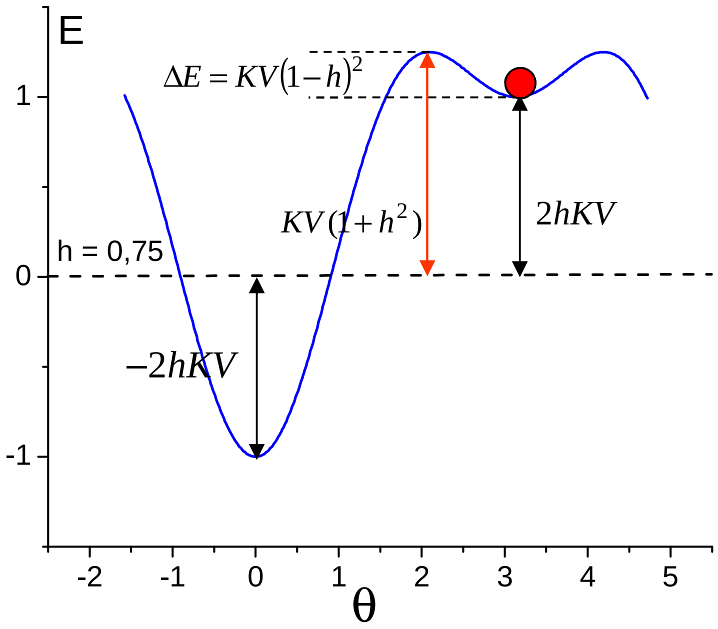
Técnica	τ_{exp}
Mössbauer ^{57}Fe, ^{119m}Sn	$\approx 10^{-8}$s
Susceptibilidad *ac*	10^{-4} -1 s
Susceptibilidad *ac hf*	desde 10^{-6} s
Magnetización *dc*	0.1 -100 s

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

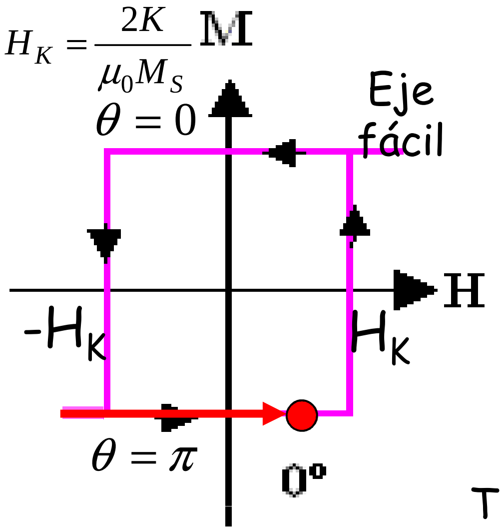
Partículas ferromagnéticas pequeñas – efectos dinámicos

Dependencia del campo coercitivo con la temperatura

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

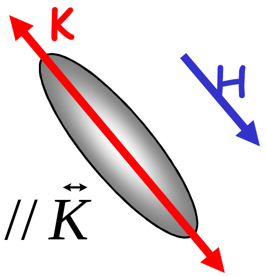


$$H_C = H_K = \frac{2K}{\mu_0 M_S}$$



T = 0 K

$$\Delta E = KV(1-h)^2$$



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

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

$$\tau_{21} = \tau_0 e^{\frac{\Delta E}{kT}}$$

$$\Delta E = kT \ln(\tau_{21} / \tau_0)$$

$\tau_{exp} = 10^2 s$	$\Delta E = 27.6\, kT$	*VSM*
$\tau_{exp} = 10^{-8} s$	$\Delta E = 4.6\, kT$	*Möss*

$$\Delta E = C\, kT$$

$$C = \ln(\tau_{21} / \tau_0)$$

Partículas ferromagnéticas pequeñas – efectos dinámicos

Dependencia del campo coercitivo con la temperatura

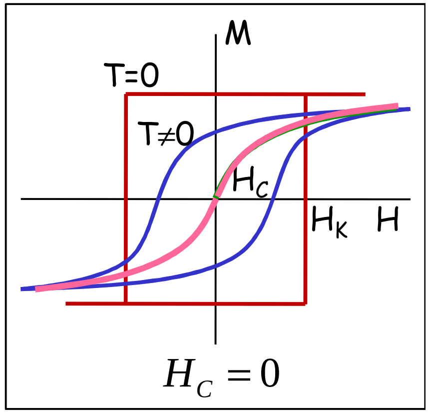
$$\Delta E = KV(1-h)^2 \qquad \Delta E = CkT$$

$$\Rightarrow h = 1-\left(\frac{CkT}{KV}\right)^{1/2}$$

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

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

$$H_C = H_K\left[1-\left(\frac{CkT}{KV}\right)^{1/2}\right]$$



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

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

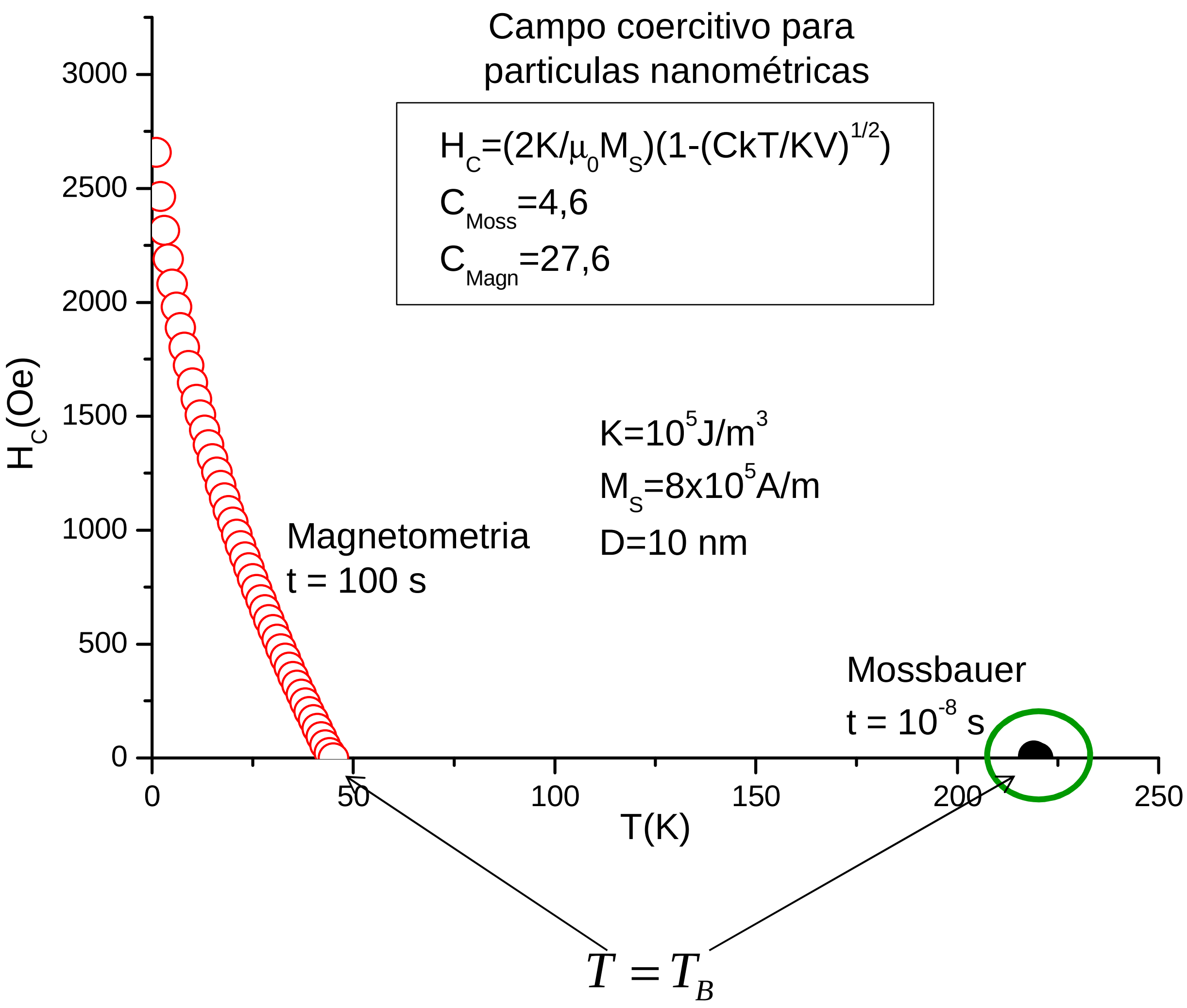
Interacciones magnéticas en nanotubos ferromagnéticos de LaCaMnO y LaSrMnO,

J.Curiale et al., AFA 2006

Marina Tortarola, Tesis, IB, 2008

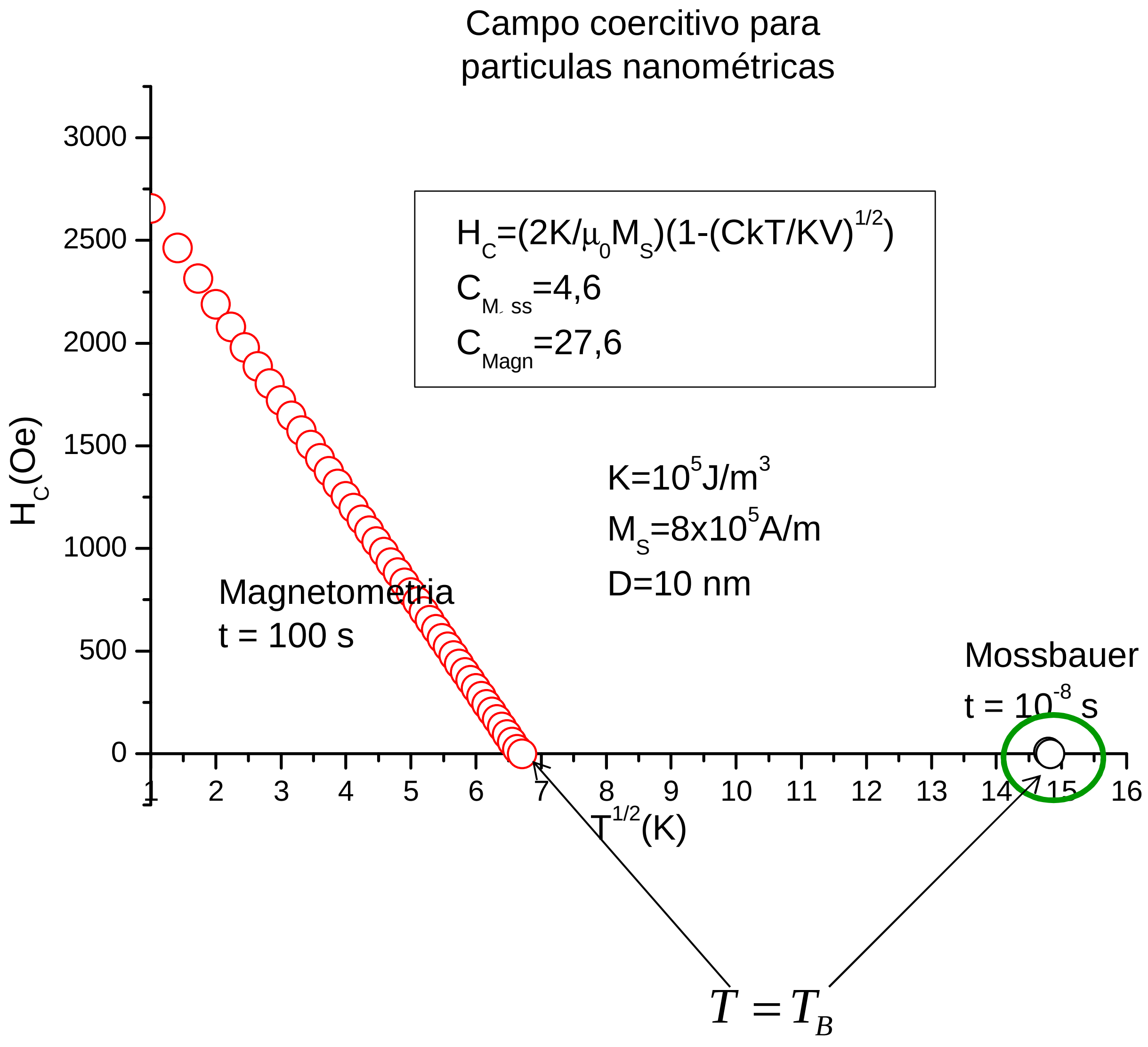
Partículas ferromagnéticas pequeñas – efectos dinámicos

Dependencia del campo coercitivo con la temperatura



Partículas ferromagnéticas pequeñas – efectos dinámicos

Dependencia del campo coercitivo con la temperatura



Partículas ferromagnéticas pequeñas – efectos dinámicos

Regimen Superparamagnético

Brillouin

$$B_S(x) = \frac{2S+1}{2S}\coth\left(\frac{2S+1}{2S}x\right) - \frac{1}{2S}\coth\left(\frac{x}{2S}\right) \qquad x = \mu_0 g \mu_B SH / kT$$

Para $S \to \infty$

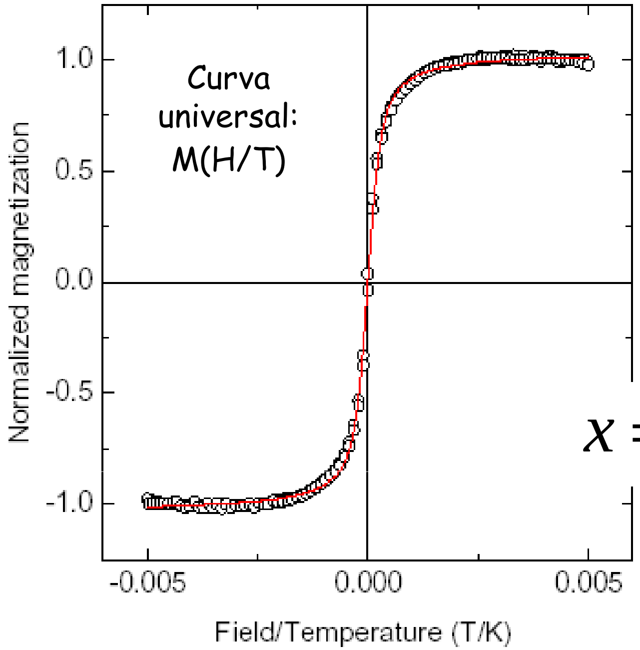
$$B_S(x) \to L(x) = \coth(x) - \frac{1}{x}$$

Langevin

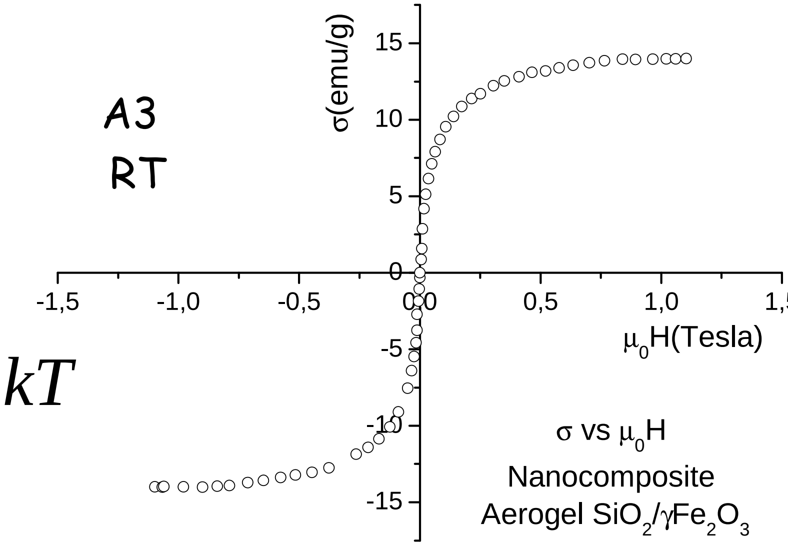
$$\left.\begin{matrix} B_S \\ L \end{matrix}\right\} = F(H/T) \quad \Rightarrow \quad M = F(H/T)$$

Partículas ferromagnéticas pequeñas – efectos dinámicos

Comportamiento superparamagnético de partículas de maghemita - γ-Fe_2O_3 dispersas en una superficie o incluidas en nanoporos de aerogel de SiO_2



$$x = \mu_0 g \mu_B SH / kT$$



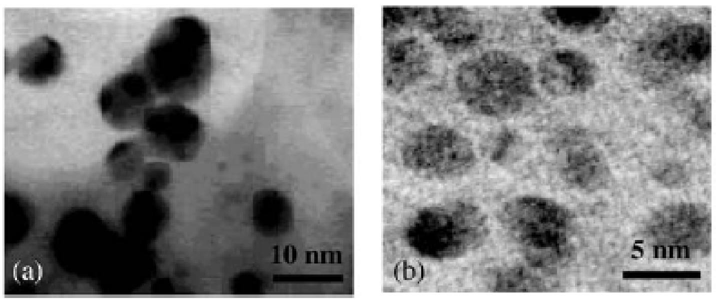
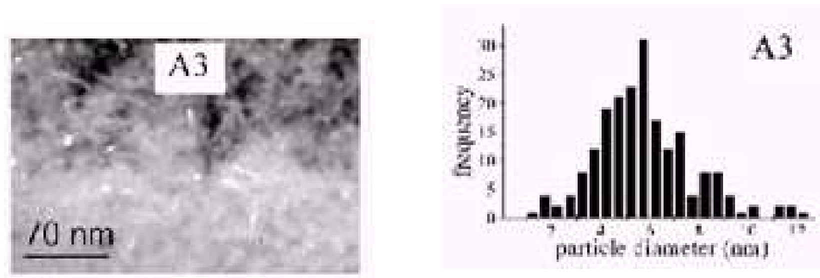


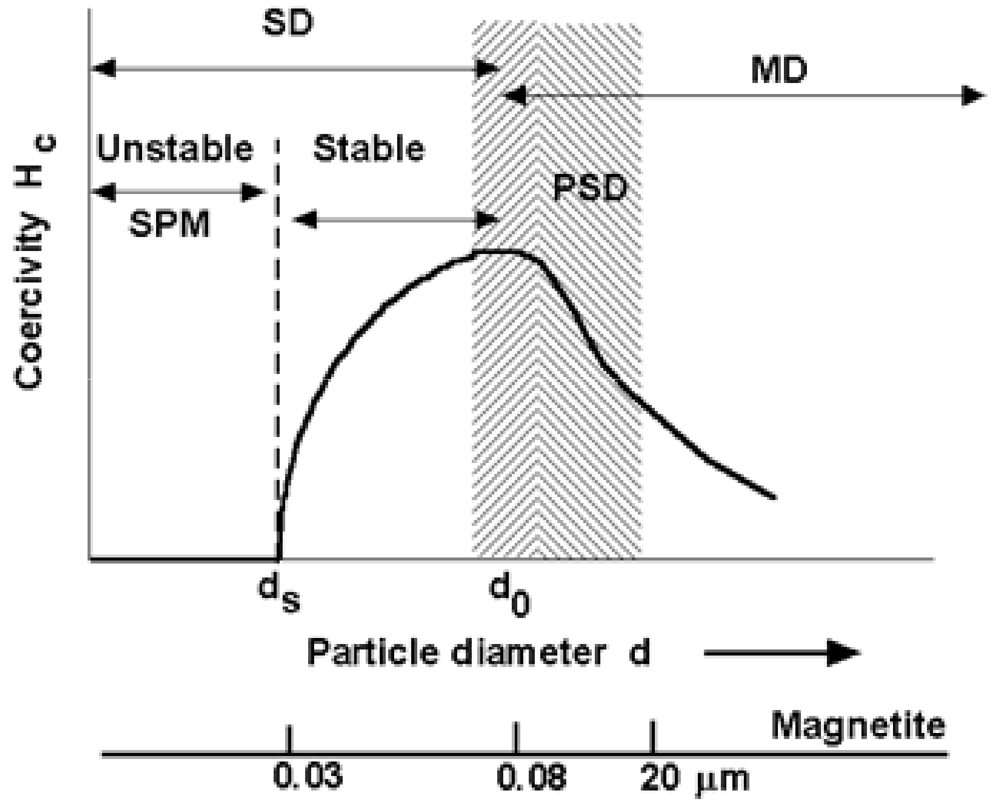
Fig. 3. TEM image of maghemite (γ-Fe_2O_3) nanoparticles: (a) the pipette drop method; (b) piezoelectric nozzle method.



M B Fernández van Raap[1], F H Sánchez[1], C E Rodríguez Torres[1], Ll Casas[2], A Roig[2] and E Molins[2]
J. Phys.: Condens. Matter **17** (2005) 6519–6531

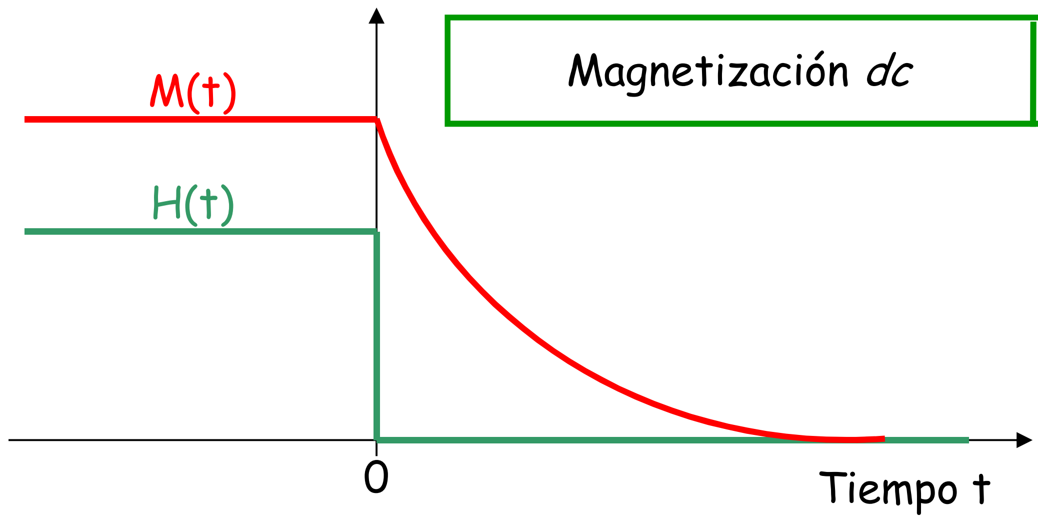
S.-J. Lee et al. / Journal of Magnetism and Magnetic Materials 282 (2004) 147–150

De multidominio a monodominio



Partículas ferromagnéticas pequeñas – efectos dinámicos

Viscosidad magnética



Magnetización *dc*	0.1 -100 s

Tiempo de relajación único → $M(t) = M(0)e^{-t/\tau}$

Partículas no interactuantes

Distribución de tamaños → Distribución de tiempos de relajación

$$P(\tau)d\tau$$

$$M(t) = M(0)\int_0^{\infty} e^{-t/\tau} P(\tau)d\tau$$

Partículas ferromagnéticas pequeñas – efectos dinámicos

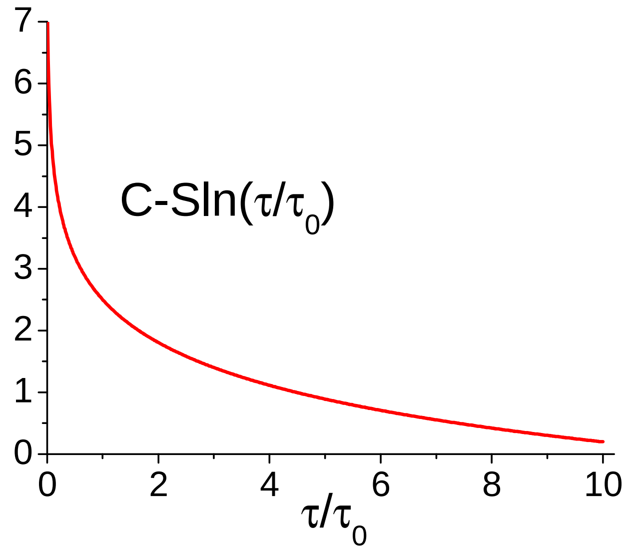
Viscosidad magnética

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

empírica ← $\mathcal{P}(V)dV$ ↔ $P(\tau)d\tau$ → $M(t)$

Partículas no interactuantes

$\mathcal{P}(V)dV$ → normal, lognormal, ¿?



Desconocimiento de P(V)

Falta de expresión analítica para

$$M(t) = M(0)\int_0^{\infty} e^{-t/\tau} P(\tau)d\tau$$

Expresión empírica $M(t) = C - S\ln(t/\tau_0)$

¿Significado físico de C, S, τ_0?

t $\rightarrow$0, diverge!

t $\rightarrow\infty$, diverge!

Partículas ferromagnéticas pequeñas – efectos dinámicos

Viscosidad magnética

Propuesta (A. Aharoni)

$$p = 2,3,\ldots$$

Distribución Gamma

$$P(\tau) = \frac{1}{\tau_0 \Gamma(p)} \left(\frac{\tau}{\tau_0} \right)^{p-1} e^{-\frac{\tau}{\tau_0}}$$

función Gamma

$$\begin{cases} \langle \tau \rangle = p\tau_0 \\ \sigma_\tau^2 = p\tau_0^2 \end{cases}$$

integrable

$$M(t) = M(0) \int_0^\infty e^{-t/\tau} P(\tau)\, d\tau$$

$$\frac{M(t)}{M(0)} = \frac{2}{\Gamma(p)} \left(\frac{t}{\tau_0} \right)^{p/2} K_p\left(2\sqrt{t/\tau_0} \right)$$

Expresión analítica

función de Bessel