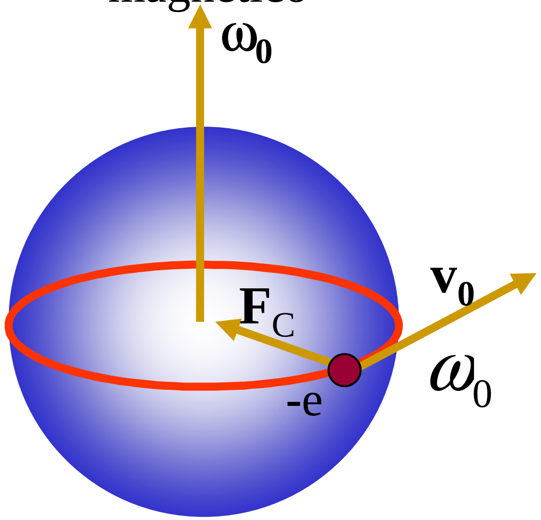
Diamagnetismo y paramagnetismo

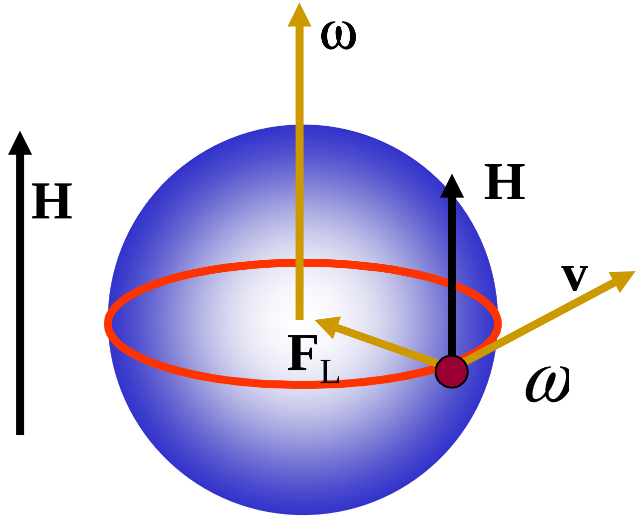
Diamagnetismo

En ausencia de campo magnético



$$F_C = F_e = eE(r)$$

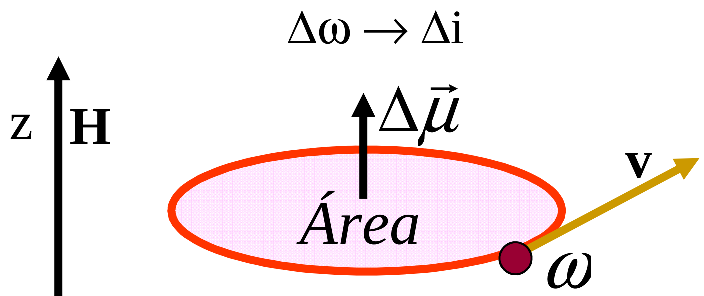
En presencia de campo magnético



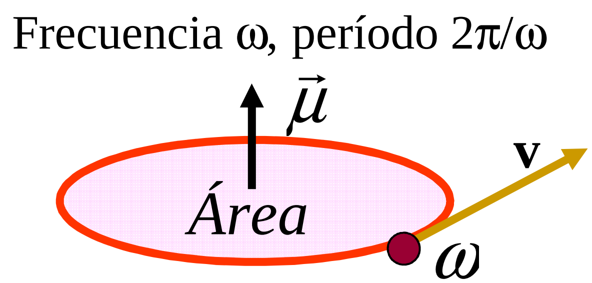
$$\vec{F}_L = -e\vec{v} \times \vec{B} \Rightarrow F_L = -\mu_0 evH$$

$$\vec{F}_C = \vec{F}_e + \vec{F}_L$$

Diamagnetismo



$$\Delta\mu = Area \cdot \Delta i$$



$$\mu = i \times Area$$

$$\Delta\chi = \frac{\Delta M}{H} = N\,\frac{\Delta\mu}{H}$$

Para un ión con Z electrones

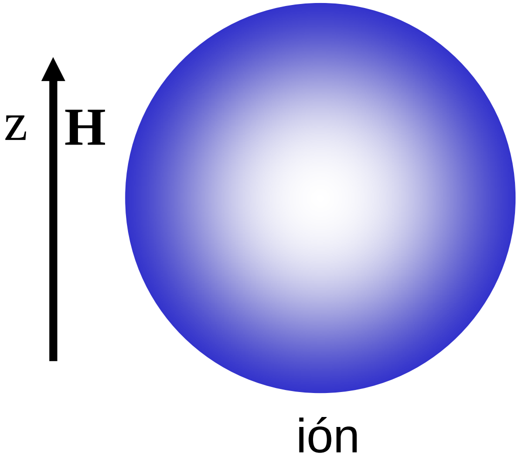
$$\chi_{dia} = -\frac{N\mu_0 e^2}{6m}\sum_{i=1}^{z}\overline{r_i^2}$$

Diamagnetismo de Langevin

Susceptibilidades magnéticas de algunos materiales

Material	**T (K)**	**P(atm)**	χ_m **(m³/kg)**	χ_V
agua	293	1	$-9.05 x 10^{-9}$	$-9.04 x 10^{-6}$
bismuto	293	1	$-1.70 x 10^{-8}$	$-1.66 x 10^{-4}$
diamante	RT	1	$-6.2 x 10^{-9}$	$-2.2 x 10^{-5}$
aire	293	1		$3.6 x 10^{-7}$
N_2	293	0.78	-5.56×10^{-9}	-5.06×10^{-9}
O_2	293	0.21	1.34×10^{-6}	3.73×10^{-7}

Diamagnetismo y Paramagnetismo



momento angular

$$\chi = -\frac{e\hbar}{2m} N g \, \partial\langle J_z \rangle / \partial H - \frac{\mu_0 e^2 N}{6m} \sum_{i=1}^{Z} \langle r^2 \rangle_i$$

paramagnetismo

diamagnetismo

Poco dependiente de T

Magnetón
de Bohr

$$\mu_B = -\frac{e\hbar}{2m} \quad \Longrightarrow \quad \chi_{para} = -N g \mu_B \frac{\partial \langle \vec{J}_z \rangle}{\partial H}$$

Paramagnetismo

Momento permanente

$$\langle \mu_z \rangle = -\mu_B g \sum_{i=1}^{Z} \langle j_z \rangle = -\mu_B g \langle J_z \rangle \quad \Longrightarrow \quad \vec{\mu} = -\mu_B g \vec{J}$$

$$\vec{\mu} = -g\mu_B \vec{J}$$

Factor de Landé

$$\vec{J} = \vec{L} \Rightarrow g = 1$$

$$\vec{J} = \vec{S} \Rightarrow g = 2$$

$$\vec{J} = \vec{L} + \vec{S} \Leftrightarrow g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

Paramagnetismo

$$\vec{\mu} = -g\mu_B \vec{J}$$

$$\mu^2 \Leftrightarrow J^2$$

$$|\vec{\mu}| = g\left[\left\langle J^2 \right\rangle\right]^{1/2} \mu_B$$

Medidas de susceptibilidad

$$|\vec{\mu}| = g\left[J(J+1)\right]^{1/2} \mu_B$$

$$\mu_z \Leftrightarrow J_z$$

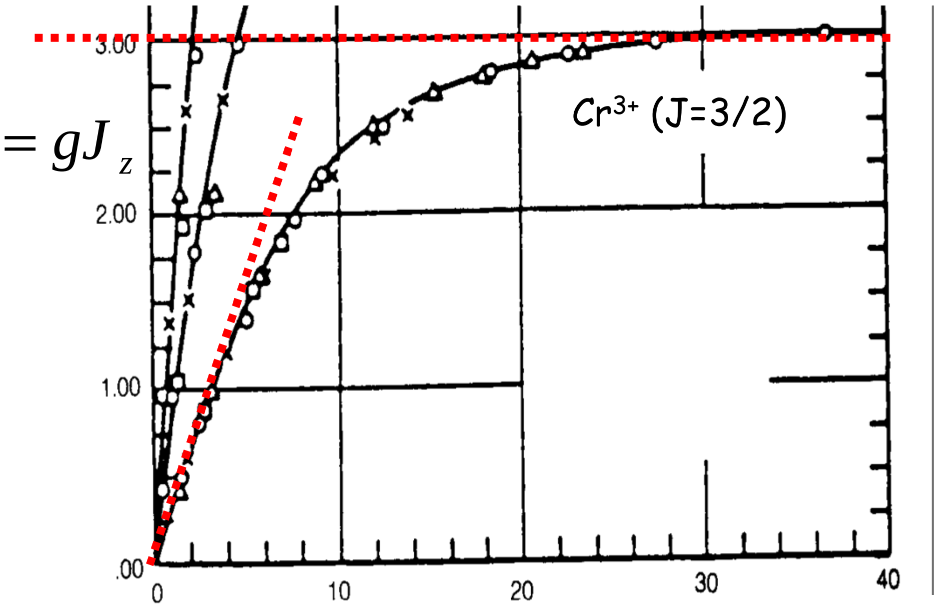
Medidas de magnetización de saturación

$$\mu_z = gJ_z\mu_B$$

$$\mu_z^{máx} = gJ\mu_B = \mu$$

$$|\mu| = \left\langle \mu^2 \right\rangle^{1/2}$$

$$\frac{\mu_z}{\mu_B} = gJ_z$$



$$H/T\left(A/mK\right)$$

Paramagnetismo

"Quenching" del momento angular en iones 3d

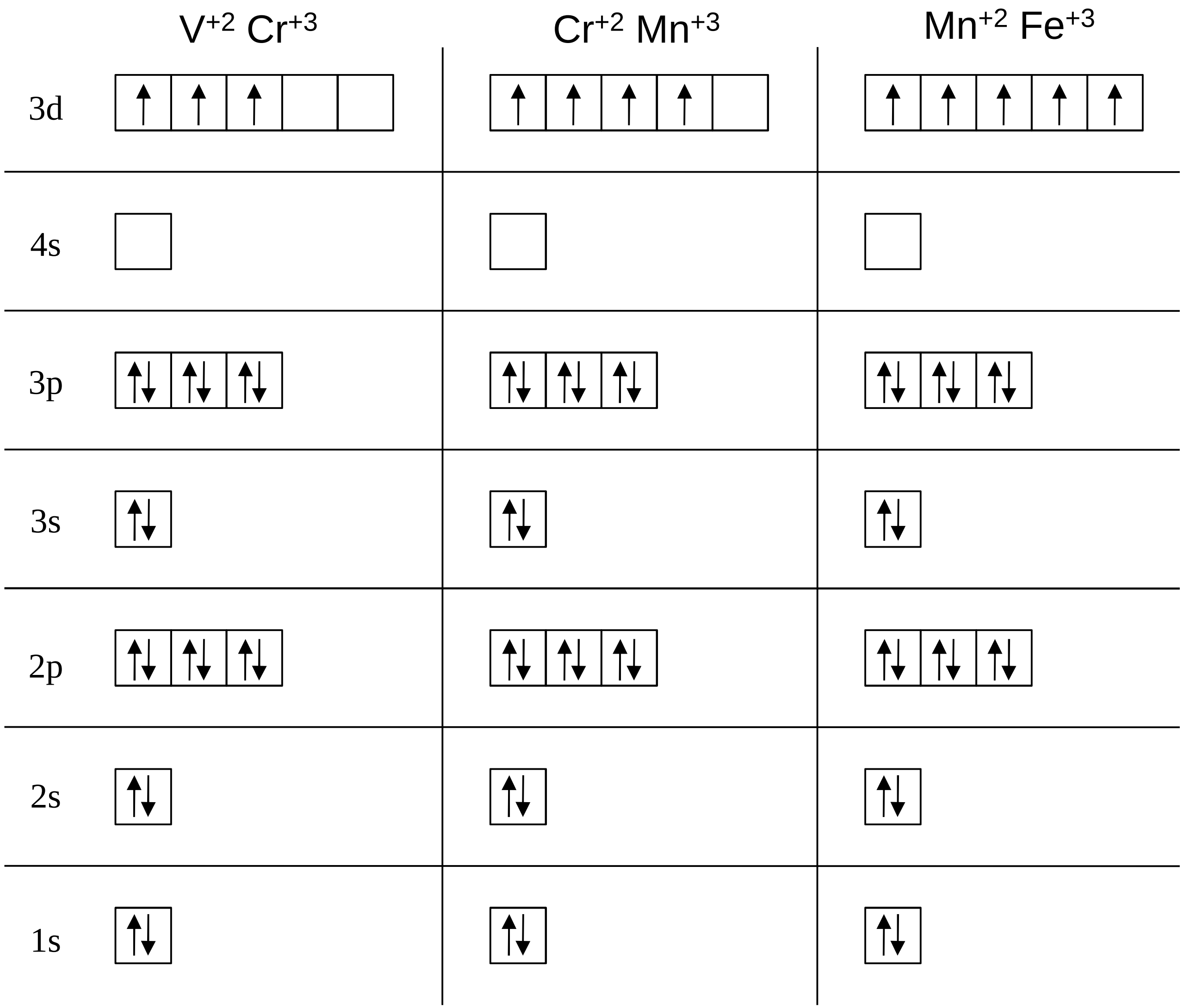
$$\vec{J} = \vec{L} + \vec{S} \approx \vec{S}$$

$\vec{L}$ no es una constante del movimiento, no conmuta con el Hamiltoniando.

Su valor medio promedia a cero

$$\langle \vec{L} \rangle \approx 0$$

Paramagnetismo en iones 3d



$1s^2 2s^2 2p^6 3s^2 3p^6 4s^0 3d^n$

Mn^{+2} Fe^{+3}

$$|\vec{\mu}| = g\left[J(J+1)\right]^{1/2} \mu_B$$

$$J \approx S = 2.5$$

$$\mu = \mu_z^{máx} = gJ\mu_B$$

$$J \approx 2.5$$

$$g \approx 2$$

$$|\vec{\mu}| \approx 2 \times (2.5 \times 3.5)^{1/2} \mu_B$$

$$|\vec{\mu}| \approx 5.92 \mu_B$$

$$\mu_z \approx 2 \times 2.5 \mu_B$$

$$\mu_z \approx 5 \mu_B$$

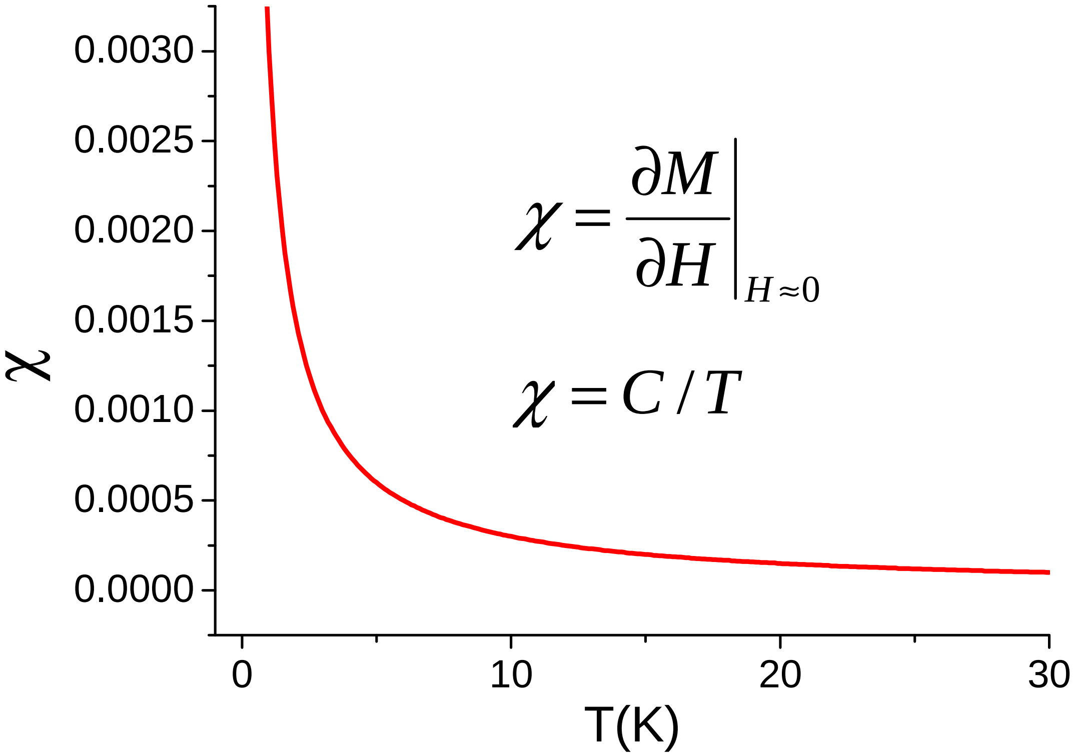
Paramagnetismo en iones 3d

Momento magnético en magnetones de Bohr

ión	Configuración	$g[j(j+1)]^{0.5}$ Calc.	$g[s(s+1)]^{0.5}$ Calc.	medido
Ti^{3+}, V^{4+}	$3d^1$	1.55	**1.73**	1.8
V^{3+}	$3d^2$	1.63	**2.83**	2.8
Cr^{3+}, V^{3+}	$3d^3$	0.77	**3.87**	3.8
Mn^{3+}, Cr^{3+}	$3d^4$	0	**4.90**	4.9
Fe^{3+}, Mn^{2+}	$3d^5$	5.92	**5.92**	5.9
Fe^{2+}	$3d^6$	6.70	4.90	5.4
Co^{2+}	$3d^7$	6.63	3.87	4.8
Ni^{2+}	$3d^8$	5.59	2.83	3.2
Cu^{2+}	$3d^9$	3.55	1.73	1.9

Paramagnetismo: **experimentos**

Dependencia de **M** con T y con **H**



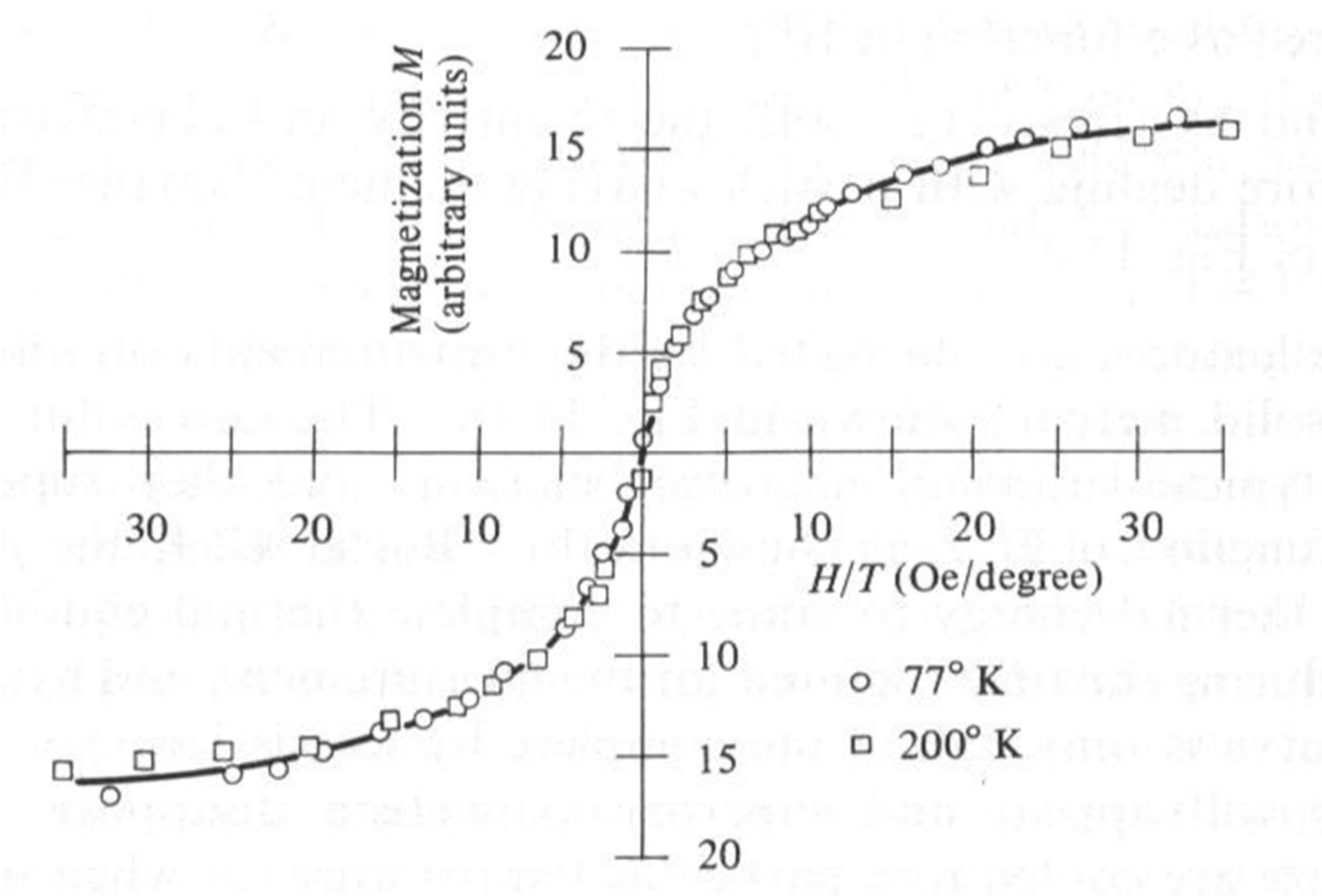
$$\chi = \left.\frac{\partial M}{\partial H}\right|_{H\approx 0}$$

$$\chi = C / T$$

Susceptibilidad de un paramagneto bajo pequeños campos (H = cte)

Paramagnetismo: experimentos

Dependencia de **M** con **H** y con T



Función universal de H/T

Dependencia de **M** con **H** y con T. Modelo estadístico

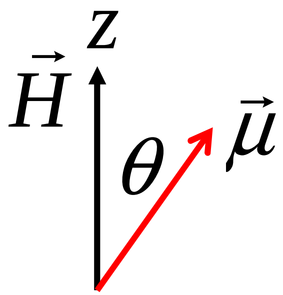
Paramagneto (Curie):

Ausencia de interacciones entre espines

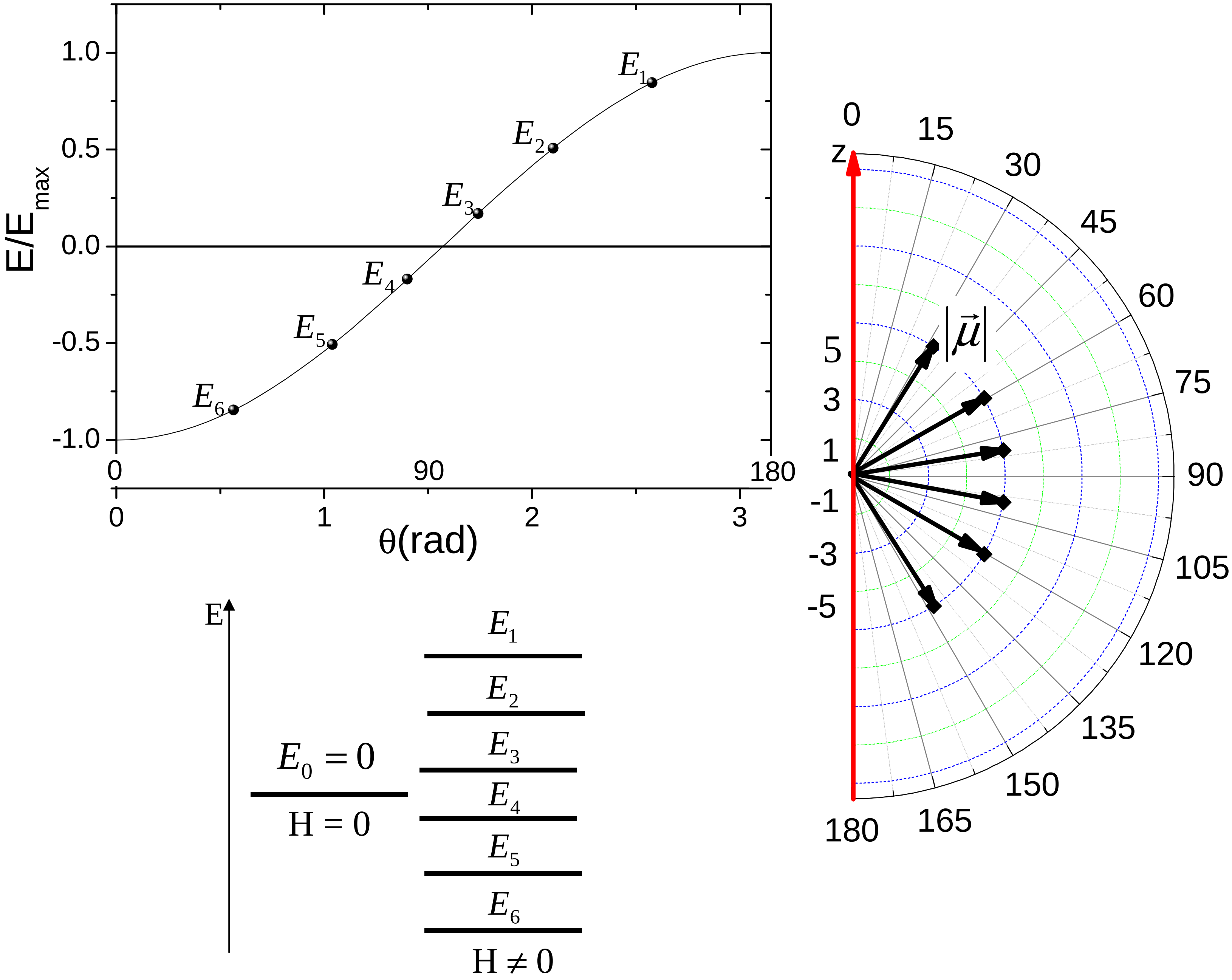
Momento permanente localizado

Ejemplo: $J = 3/2$

$$\vec{\mu} = -g\mu_B \vec{J}$$



$$\mathcal{E}_Z = -\vec{\mu}\cdot\vec{B} = -\mu_0\vec{\mu}\cdot\vec{H} = -\mu_0\mu_z H = -\mu_0|\vec{\mu}|H\cos\theta$$

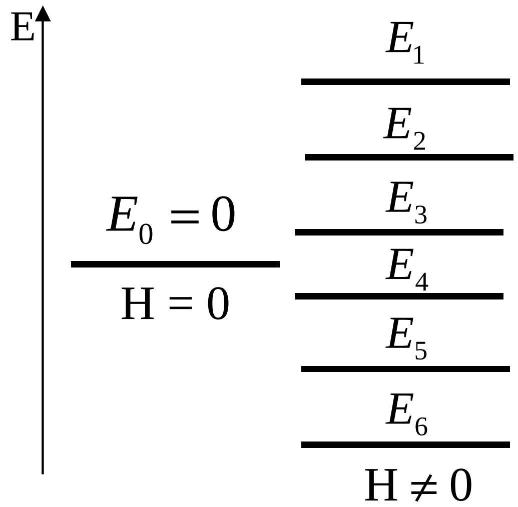


E/E_max
1.0
0.5
0.0
-0.5
-1.0
E_1
E_2
E_3
E_4
E_5
E_6
0
90
180
0
1
2
3
θ(rad)
E
E_0 = 0
H = 0
H ≠ 0
z
|μ|
0
15
30
45
60
75
90
105
120
135
150
165
180
5
3
1
-1
-3
-5

En equilibrio la probabilidad de ocupación
de los subniveles de energía es proporcional
a los factores de Boltzmann:

$$e^{-E_z/kT} = e^{\mu_0 \mu_z H/kT} = e^{x} \qquad x = \mu_0 \mu H / kT$$

probabilidad $$p(\mu_z) = \frac{e^{\mu_0 \mu_z H/kT}}{\sum e^{\mu_0 \mu_z H/kT}}$$



Se promedia μ_z usando las probabilidades $p(\mu_z)$

solución

$$\frac{\langle \mu_z \rangle}{\mu} = B_J(x) \qquad x = \mu_0 \mu H / kT$$

Función de Brillouin

$$B_J(x) = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J}\coth\left(\frac{x}{2J}\right)$$

$$M = N\langle \mu_z \rangle = N\mu B_J(x) \qquad \leftarrow \qquad M = M(H/T)$$

Número de momentos por unidad de volumen

$$J = 1/2$$

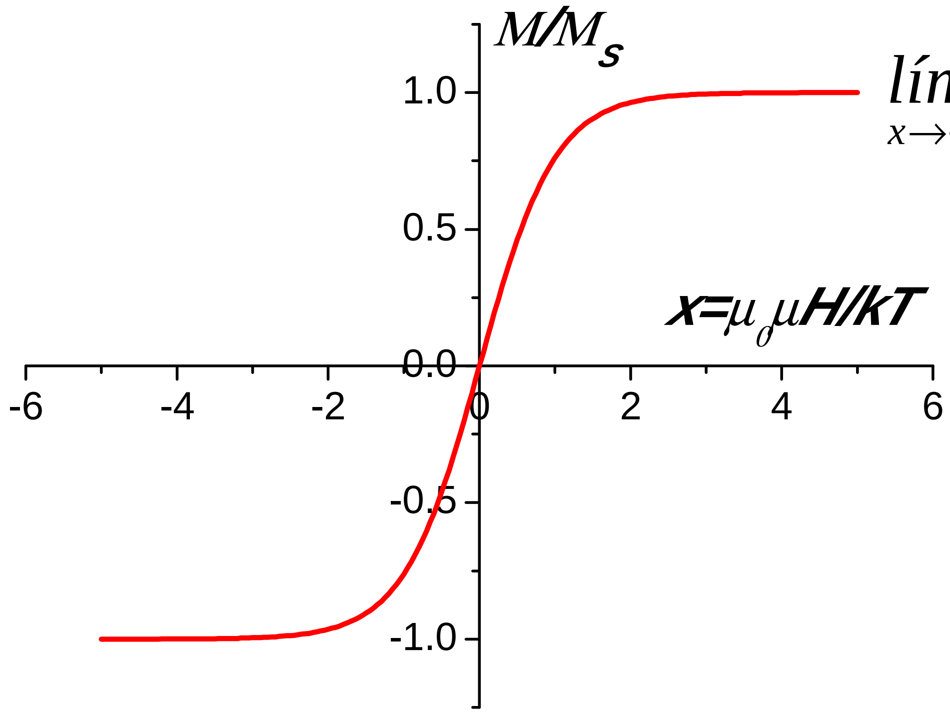
$$g = 2$$

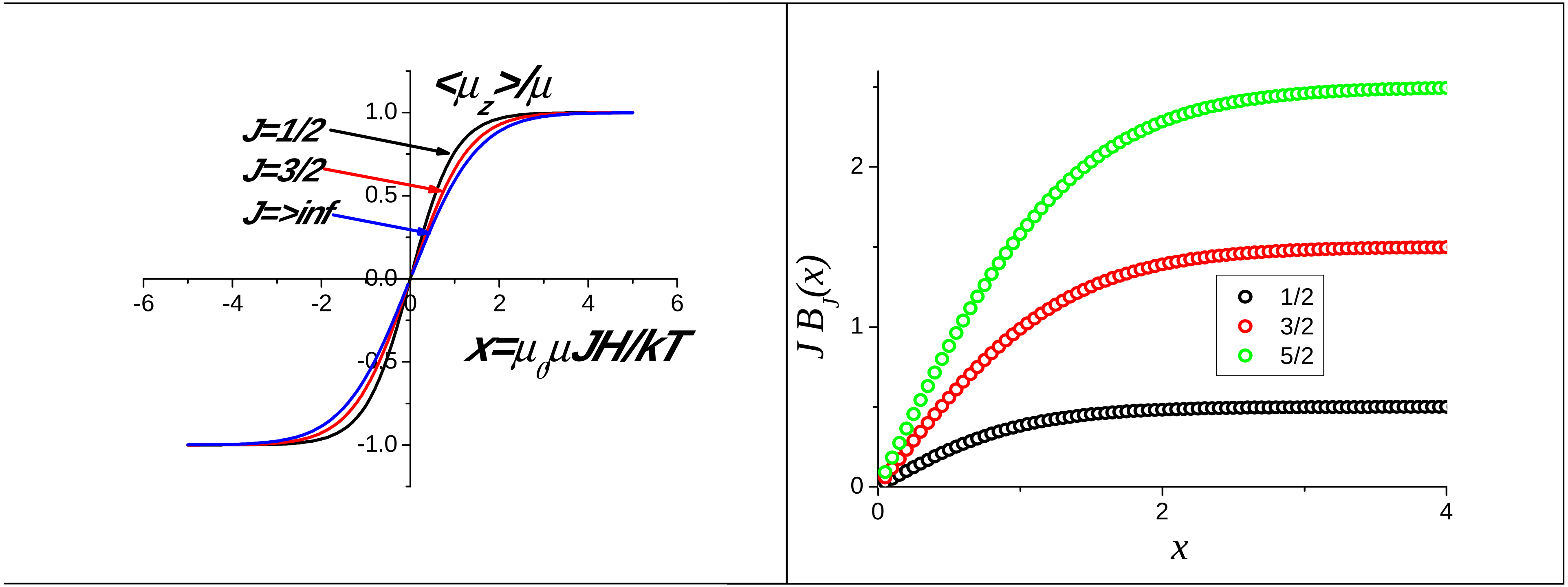
$$B_J(x) = \tanh x$$

$$M(x) = N\mu \tanh x = N\mu_B \tanh x$$

$$M_S(x) = N\mu$$

$$\lim_{x\to\infty} \tanh x = 1$$

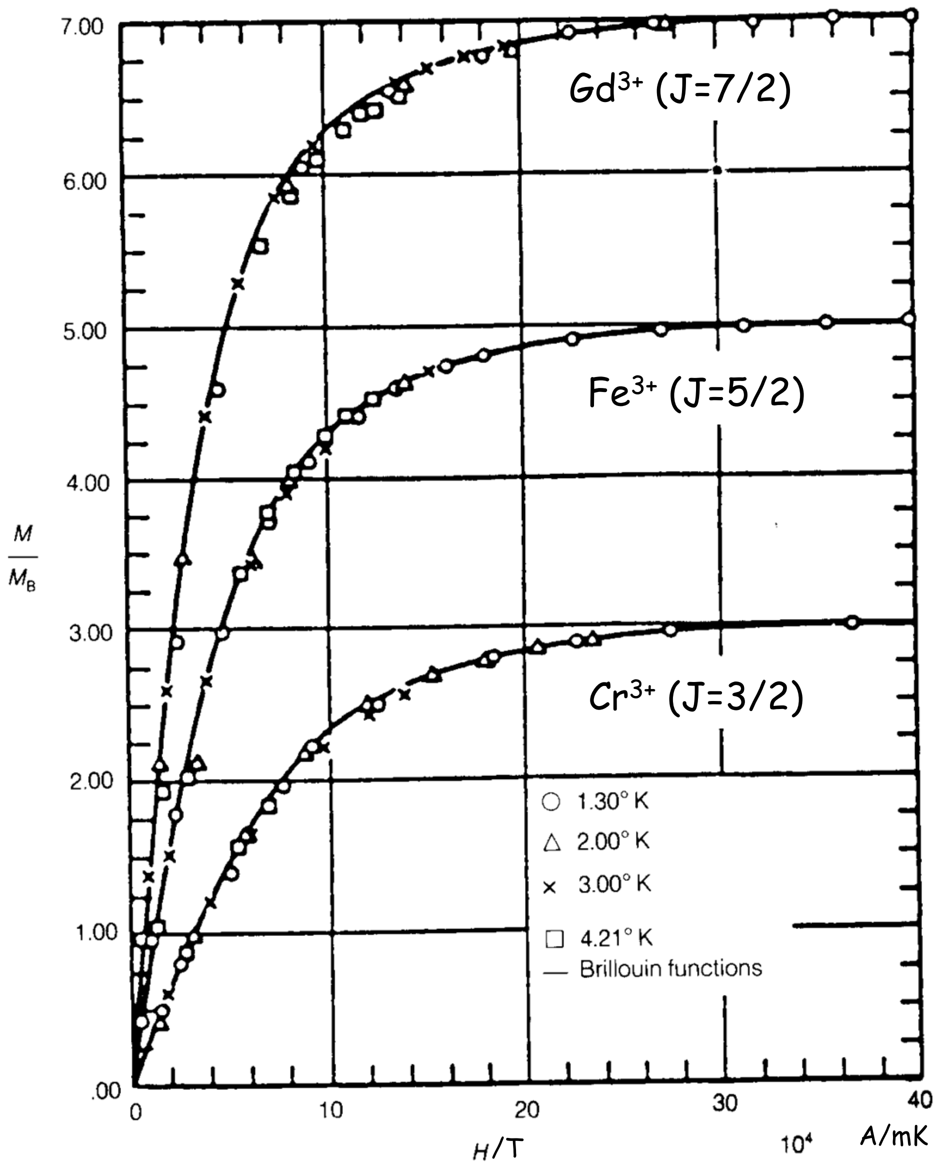




La función "satura" para $x \geq 4$

Sales paramagnéticas de:

Cr^{3+} (J=3/2) Fe^{3+} (J=5/2) Gd^{3+} (J=7/2)



Buen acuerdo de la teoría con los resultados experimentales

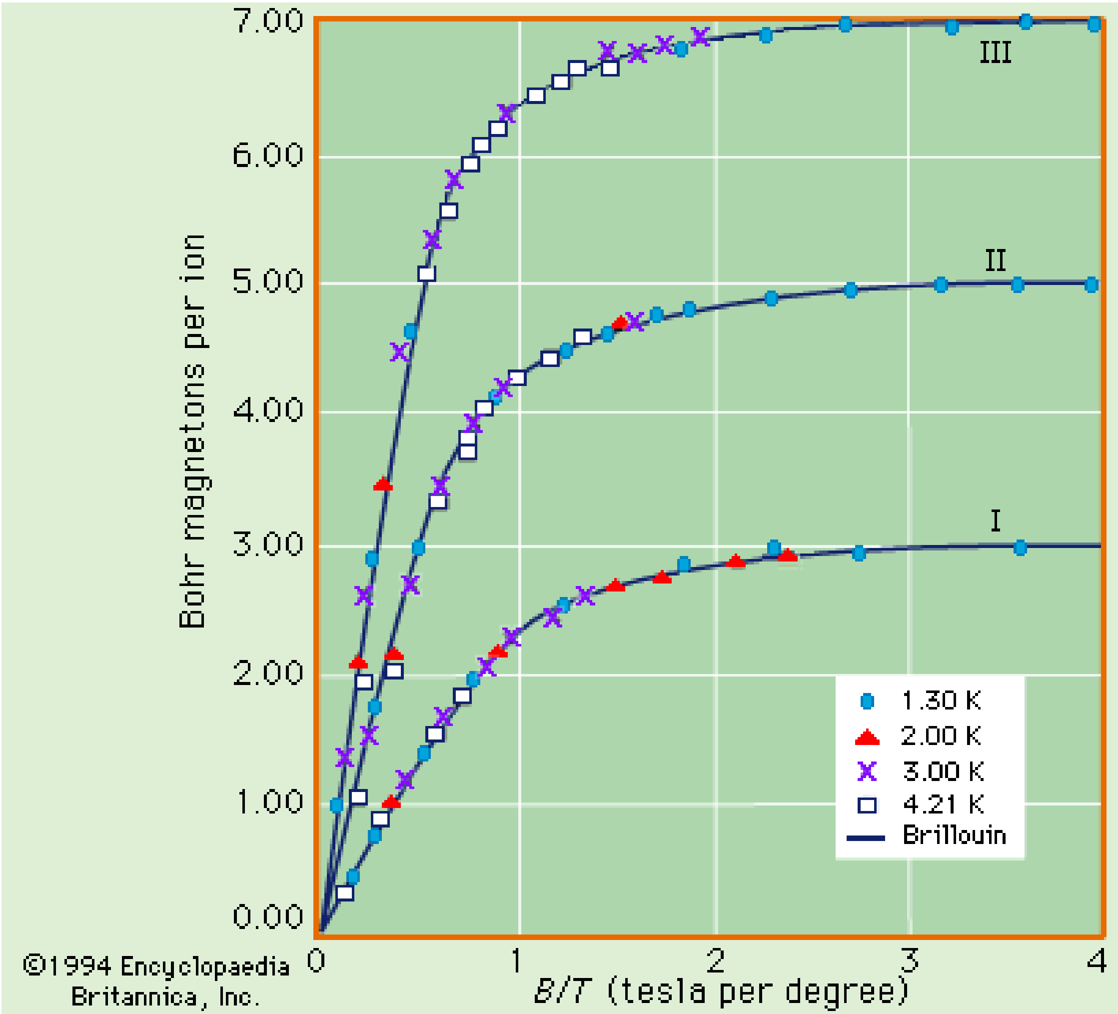
Comportamientos límites

Saturación

x → ∞ $$B_J(x) \rightarrow 1$$

$$M = M_S = N\mu$$

De la medida de M_S se obtiene el valor de la proyección máxima del momento en la dirección del campo



Campo necesario para saturar un conjunto de iones paramagnéticos de un metal de transición con J = 1/2

$$x = \frac{\mu_0 \mu H}{kT} \qquad \mu = g\mu_B J$$

$$\left.\begin{array}{l} \mu_0 = 4\pi x 10^{-7}(SI) \\ \mu_B = 9.27x10^{-24}(SI) \\ k = 1.38x10^{-23}(SI) \\ g = 2; J = 1/2 \end{array}\right\} x = 8.44x10^{-6}\frac{H(A/m)}{T(K)}$$

x = 5

$$T = 1K \Rightarrow H_S \geq 5.92x10^5 A/m \Rightarrow B_S \geq 0.74T$$

$$T = 300K \Rightarrow H_S \geq 1.78x10^8 A/m \Rightarrow B_S \geq 222T$$!!!!

Comportamientos límite

Medidas de susceptibilidad y magnetización inicial

$x \to 0\ (x << 1)$

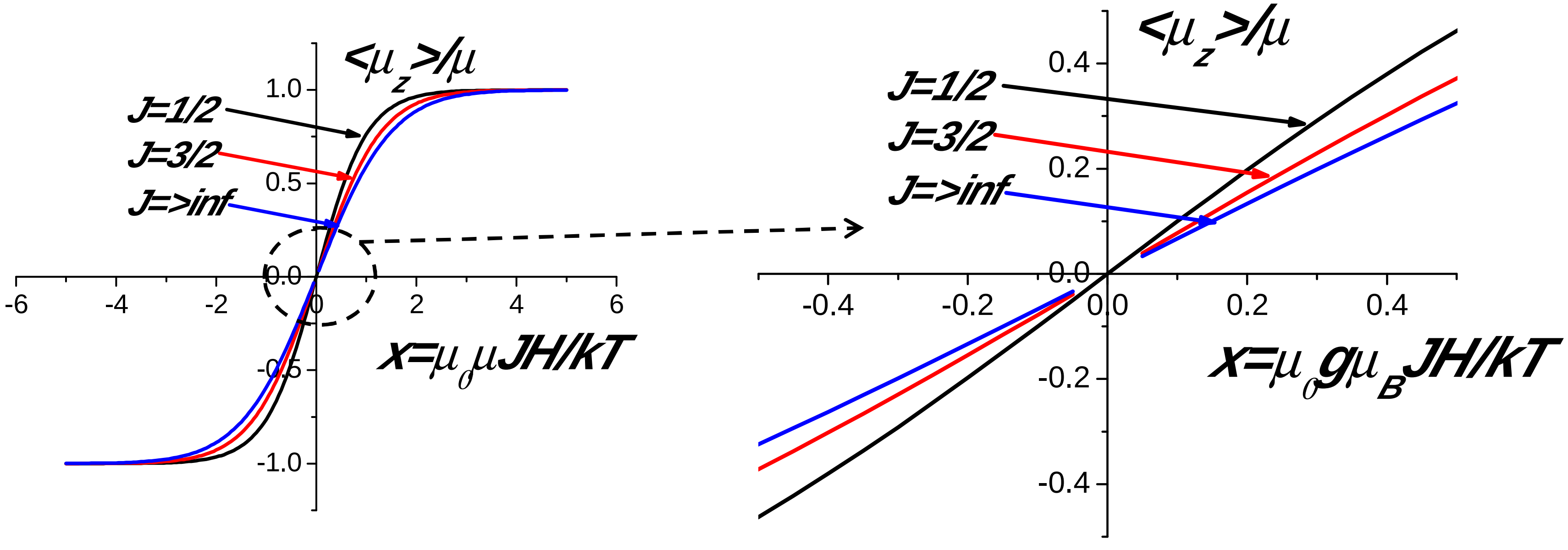
$$B_J(x) \approx \frac{J+1}{3J}x + O(x^3)$$

$$x = \frac{\mu_0 \mu H}{kT}$$

$$\langle \mu_z \rangle = \mu B_J(x) \approx \mu \frac{(J+1)}{3J} x$$

$$\langle \mu_z \rangle \approx (g\mu_B J)\frac{(J+1)}{3J}\left(\frac{\mu_0 g \mu_B J H}{kT}\right) = \frac{\mu_0 \mu^2 H}{3kT}$$

$$M = N\langle \mu_z \rangle = \frac{N\mu_0 |\mu|^2 H}{3kT}; \quad |\mu|^2 = \langle \mu^2 \rangle$$



Dependencia lineal con H,

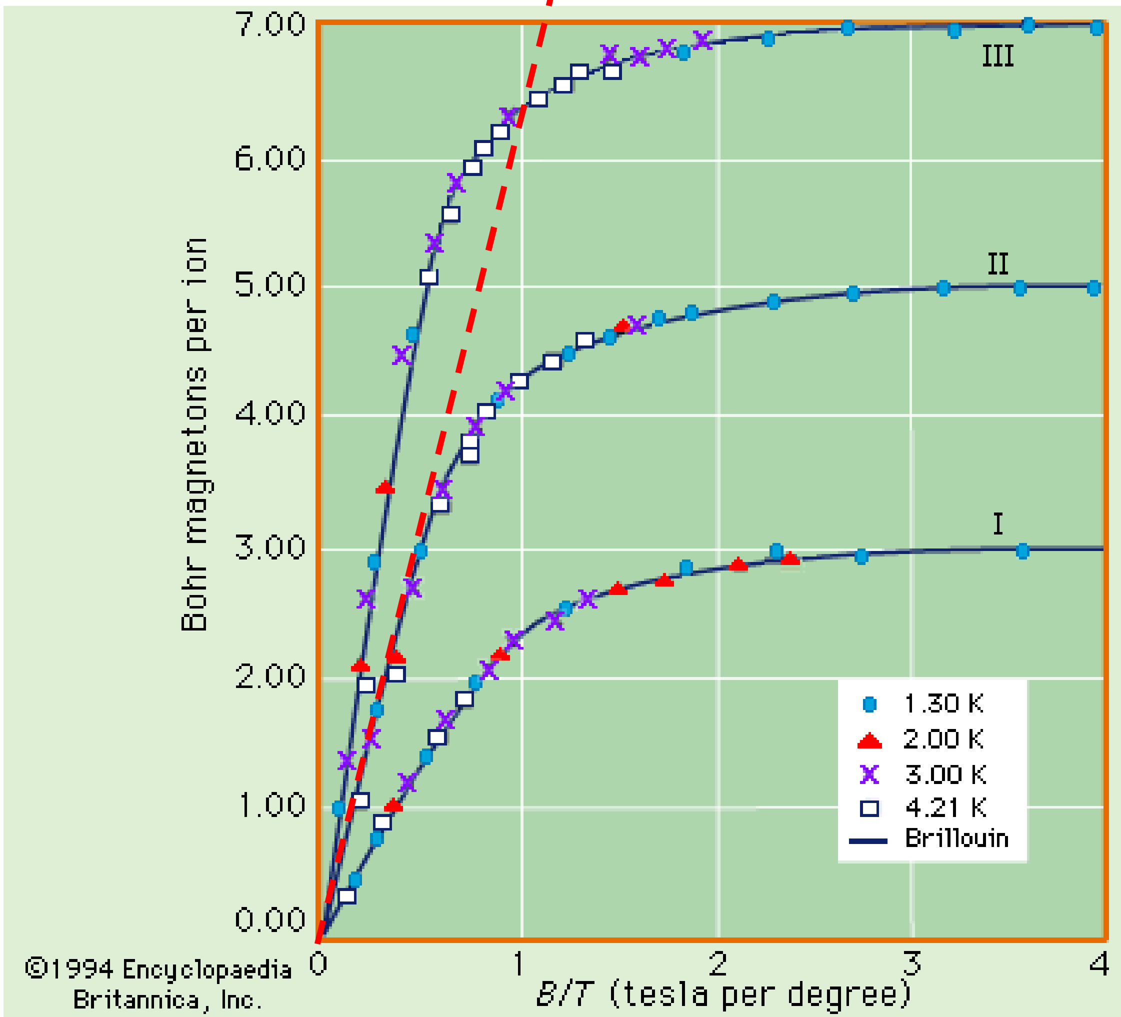
x ≤ 0.2

T = 300 K

$$H_i \leq 2.4\times10^4\ A/m \approx 300 Oe \Rightarrow B_i \leq 30\, mT$$

$$\chi_{inic} = \frac{M_{inic}}{H} \approx \frac{N\mu_0\langle\mu^2\rangle}{3kT}$$

Información sobre
N, μ, g, J, T



$$\mu^2 = g^2 \mu_B^2 J(J+1)$$

Susceptibilidad inicial

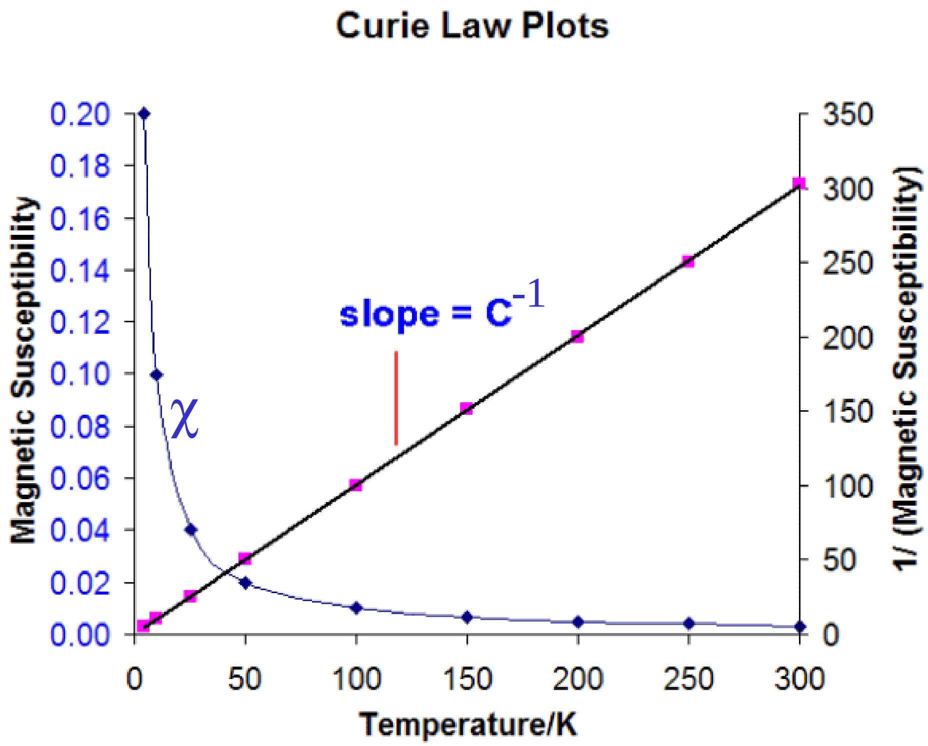
$$\chi = \frac{M}{H} \approx \frac{N\mu_0 \mu^2}{3kT} = \frac{C}{T}$$

Constante de Curie

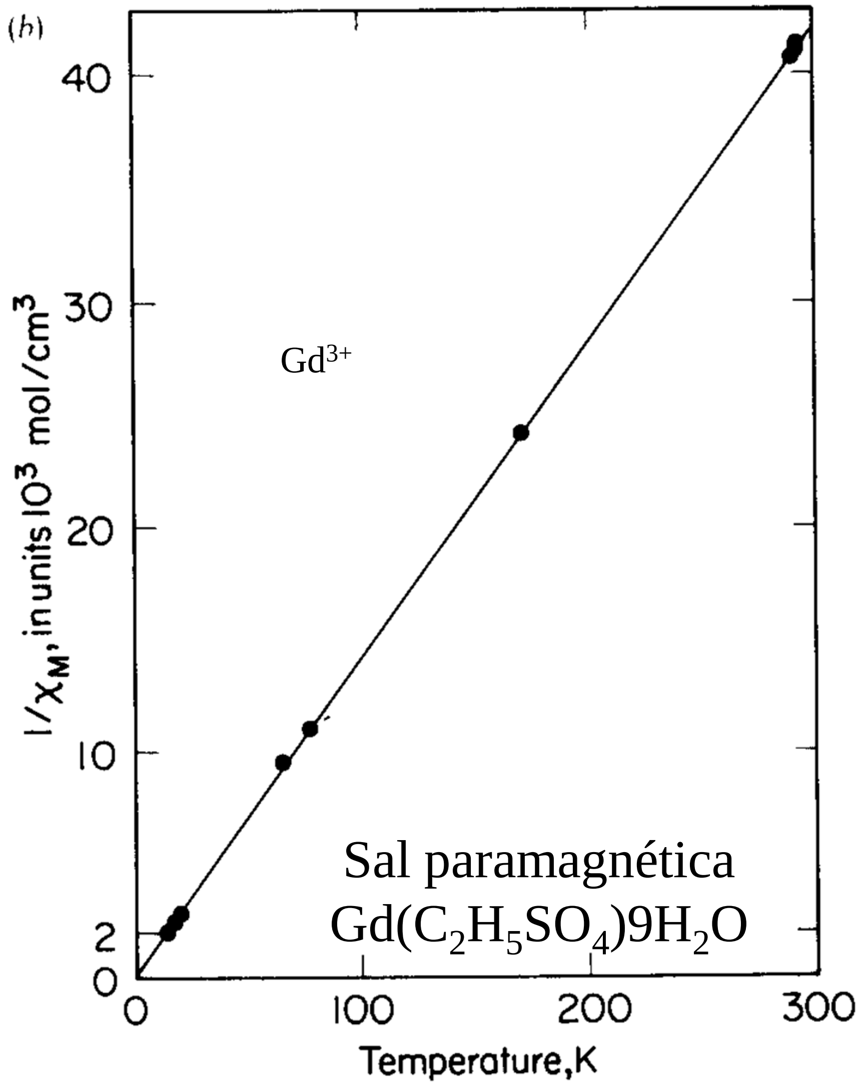
$$\chi^{-1} = \frac{T}{C}$$

Ley de Curie

Pierre Curie (1859-1906)



Susceptibilidad inicial



Límite clásico ($J \to \infty$)

$$B_J(x) = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J}\coth\left(\frac{x}{2J}\right)$$

Función de Brillouin

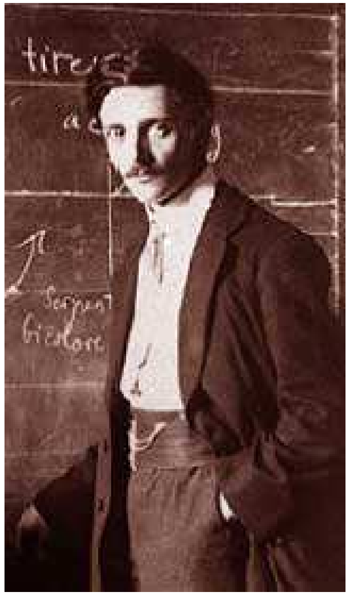
Cuando $J \to \infty$

$(2J+1)/2J \to 1$

$\coth(x/2J) \to 2J/x$

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

Función de Langevin



Léon Brillouin
(1889-1969)

Paul Langevin
(1872-1946)

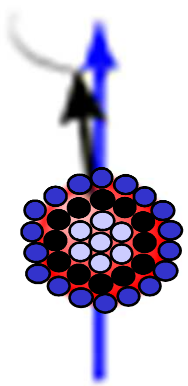
Límite clásico ($J \to \infty$)

$\mu \to \infty$

"muchos" iones/NP

- nanopartículas
- superparamagneto

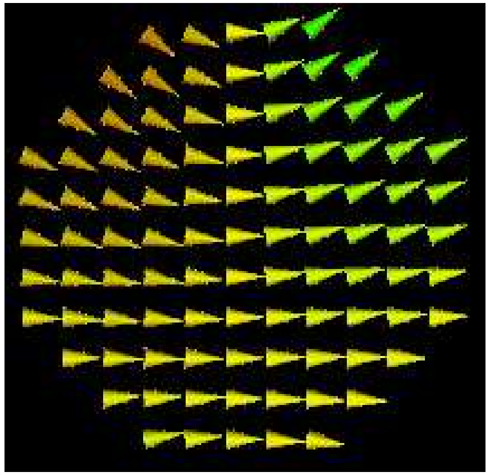
$$\mu >> \mu_{át} \approx \mu_B$$



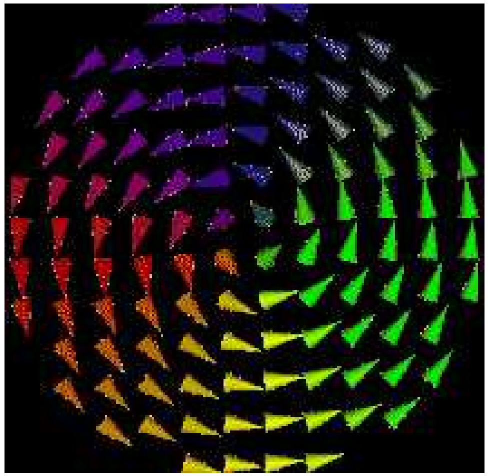
$$\tau < \tau_{obs}$$

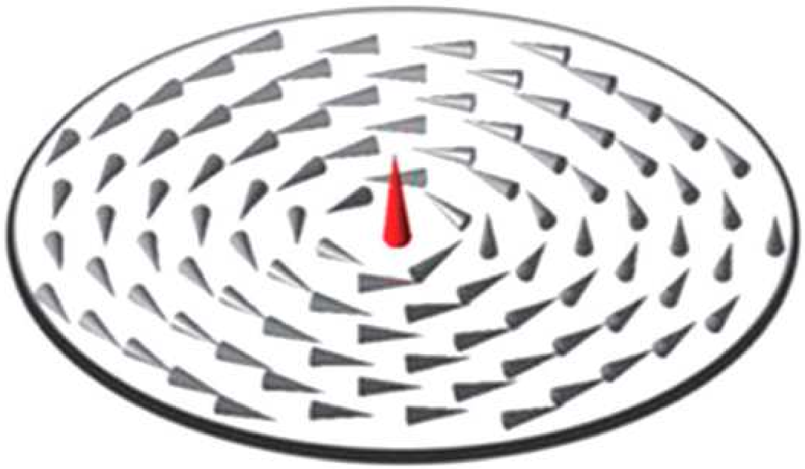
De NPs monodominio a NPs multidominio

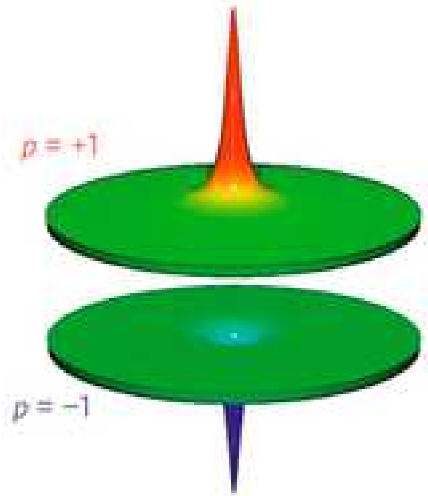
monodominio



vórtice







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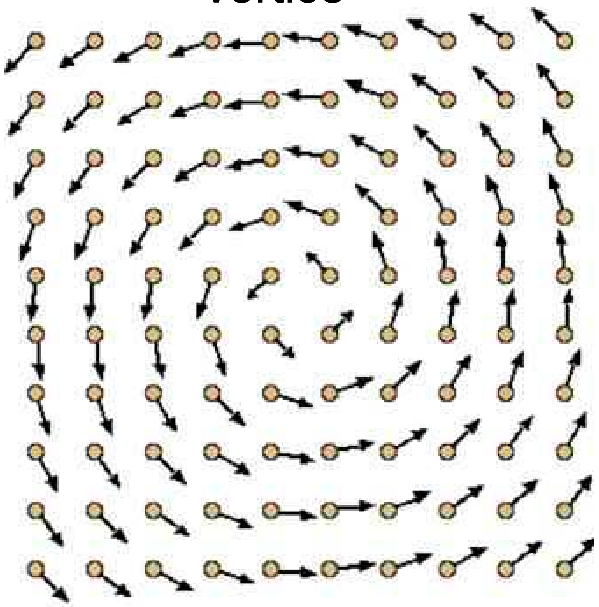
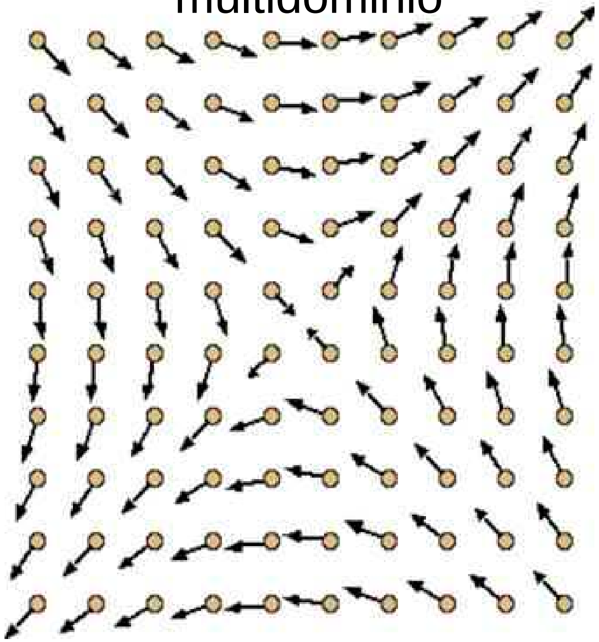
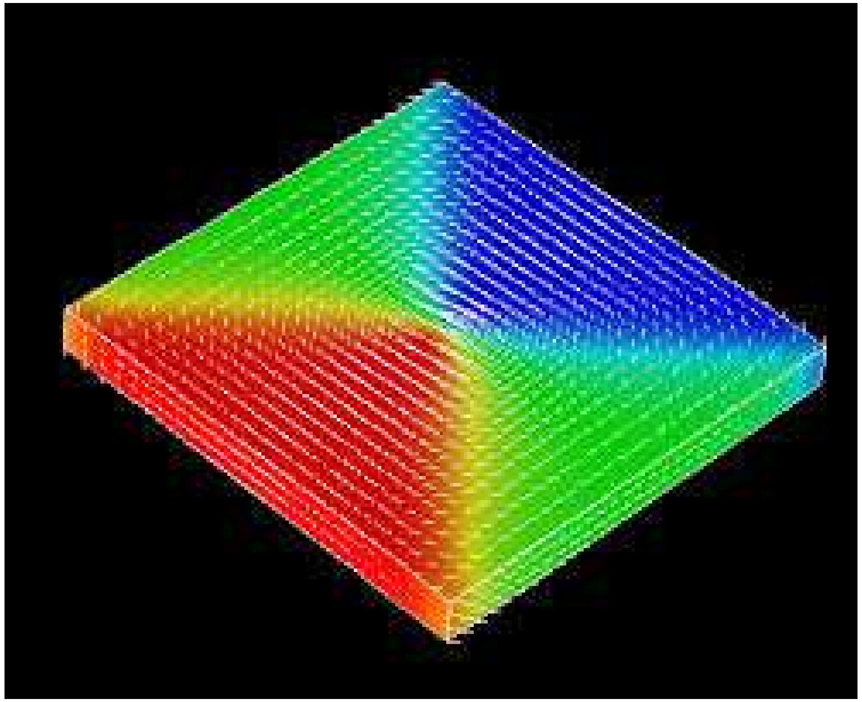


multidominio



multidominio



Estimación del tamaño límite para NPs monodominio

JOURNAL OF APPLIED PHYSICS **108**, 123920 (2010)

A collective dynamics description of dipolar interactions and the coercive field of magnetic nanoparticles

R. K. Das,[1] S. Rawal,[2] D. Norton,[2] and A. F. Hebard[1,a)]
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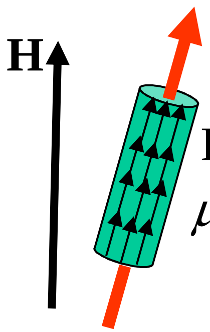
[2]*Department of Material Science and Engineering, University of Florida, Gainesville, Florida 32611, USA*

Tamaño monodominio máximo: $d_c = 72\sqrt{AK}/\mu_0 M_s^2$

[9]C. Kittel, Rev. Mod. Phys. **21**, 541 (1949).
[10]R. Skomski, J. Phys.: Condens. Matter **15**, R841 (2003).

NPs monodominio, superparamagnetismo



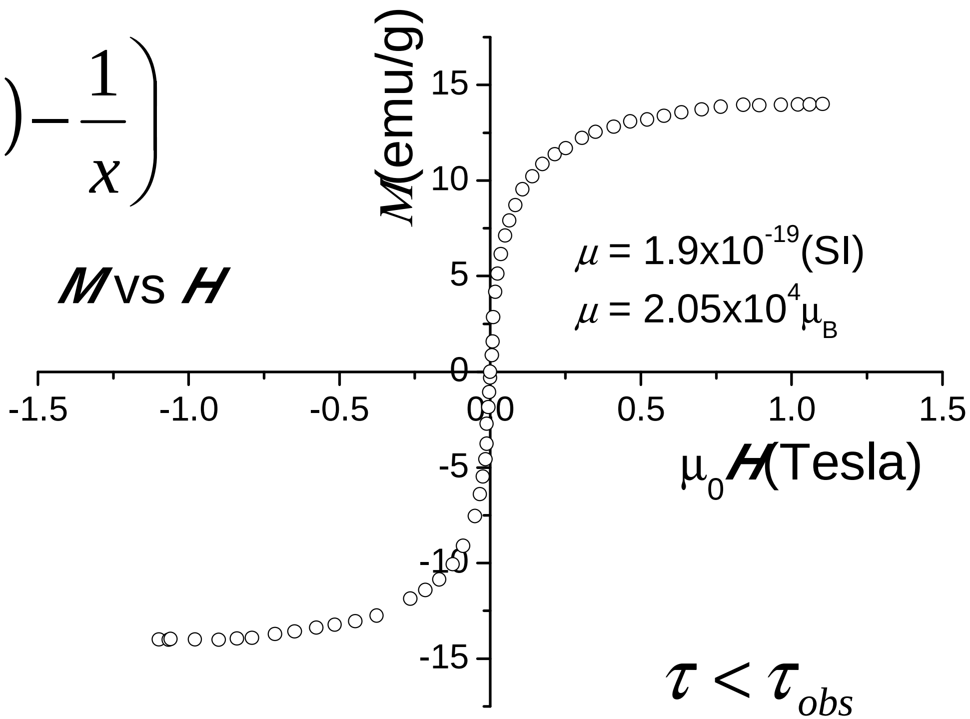
Aerogel de sílica con partículas de maghemita (~5x20 nm)

$$\langle \mu \rangle_H = \mu L(x) = \mu\left(\coth(x) - \frac{1}{x}\right)$$

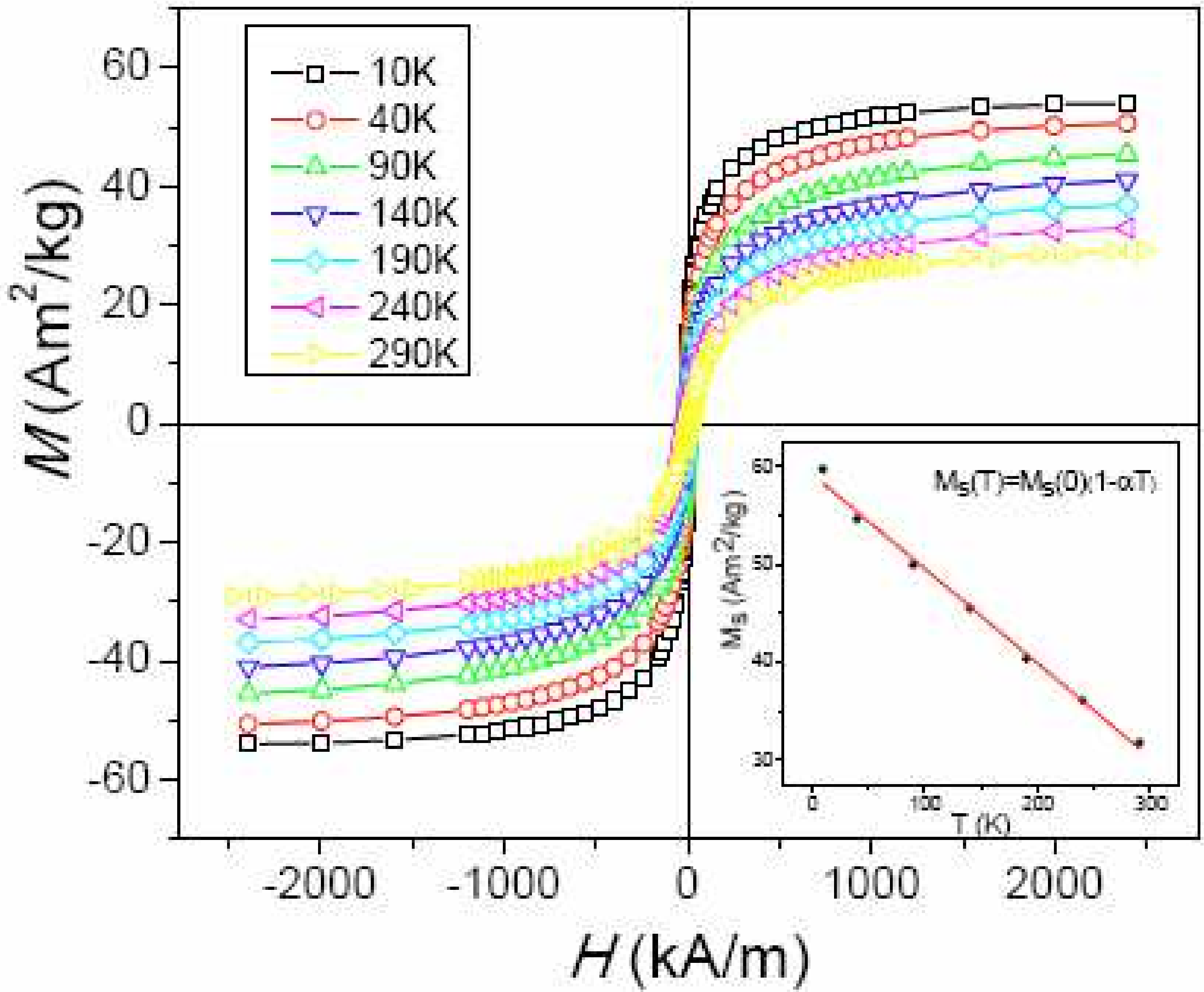
$$x = \frac{\mu_0 \mu H}{kT}$$

M vs *H*

RT

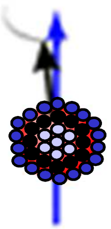


$$\tau < \tau_{obs}$$



$\tau < \tau_{obs}$

Comportamiento superparamagnético de NP de magnetita (4 nm) dispersas en un hidrogel de PVA (ferrogel).



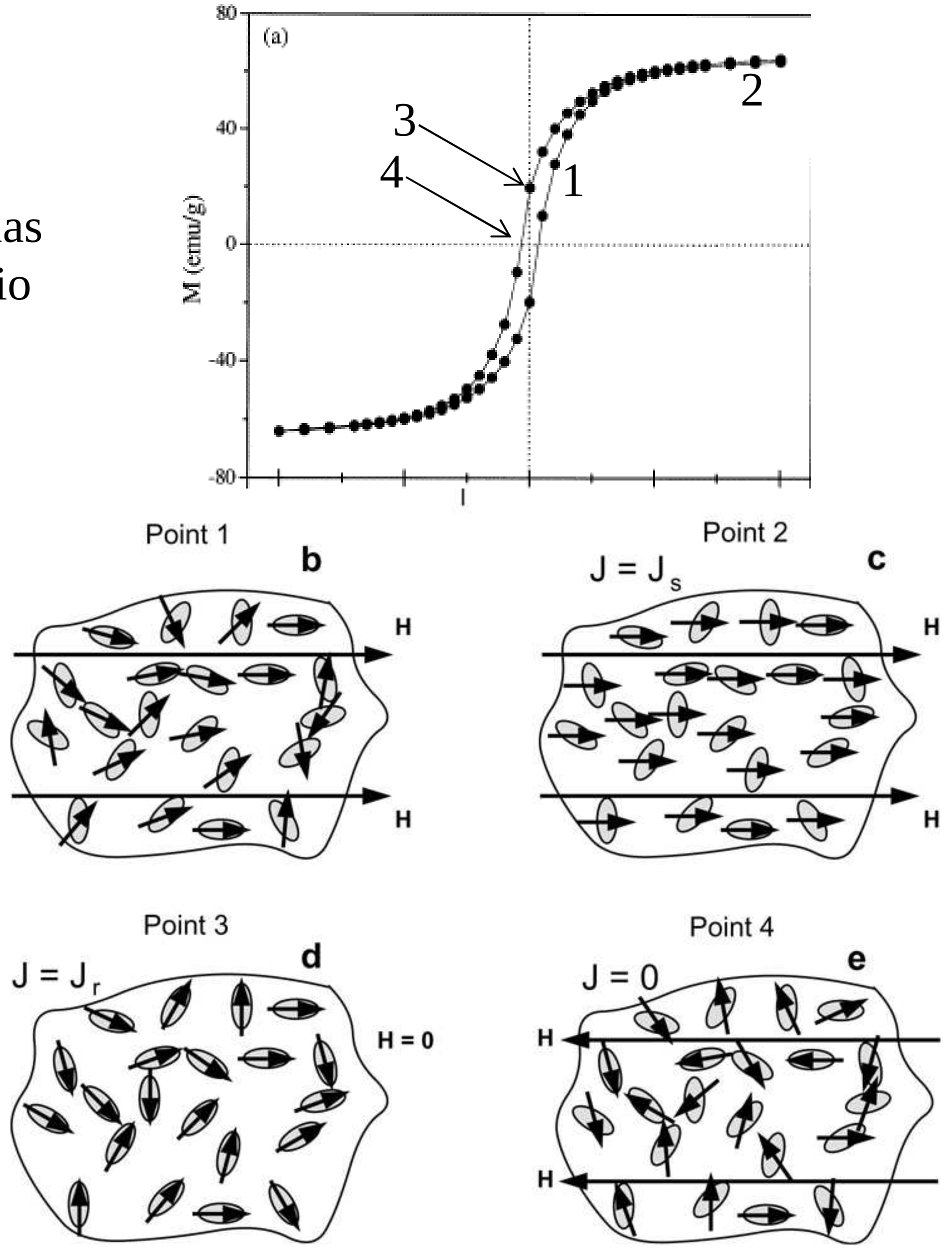
NPs monodominio,
superparamagnetismo?

$$\tau < \tau_{obs}$$

Cuando consideramos estabilidad de coloides y aplicaciones biomédicas, qué es τ_{obs}?

Regimen bloqueado

Nanopartículas monodominio



$$\tau > \tau_{obs}$$

Fin módulo