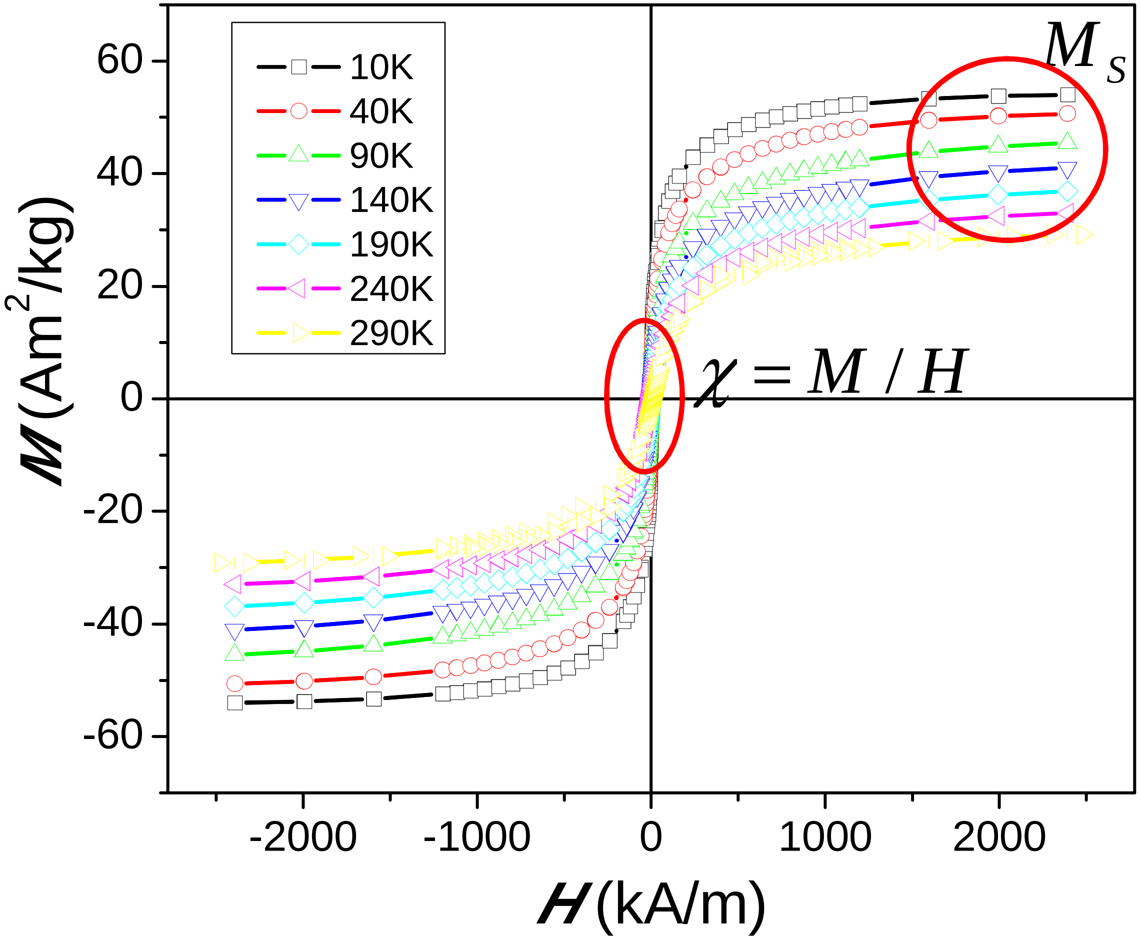
Magnetización
Susceptibilidad

Susceptibilidad en equilibrio
Susceptibilidad fuera del equilibrio
Protocolos dc: FC, ZFC
Susceptibilidad ac

Magnetización y susceptibilidad en equilibrio

Si no hay distribución de tamaños:

$$M(H,T) = N\mu L(x), \qquad x = \frac{\mu_0 \mu H}{kT}$$




$$M_S = N\mu$$

$$\chi = \frac{N\mu_0\mu^2}{3kT}$$

$$N = 1/V_{pp}$$

$$\mu = M_S V_{pp}$$

$$M_S$$

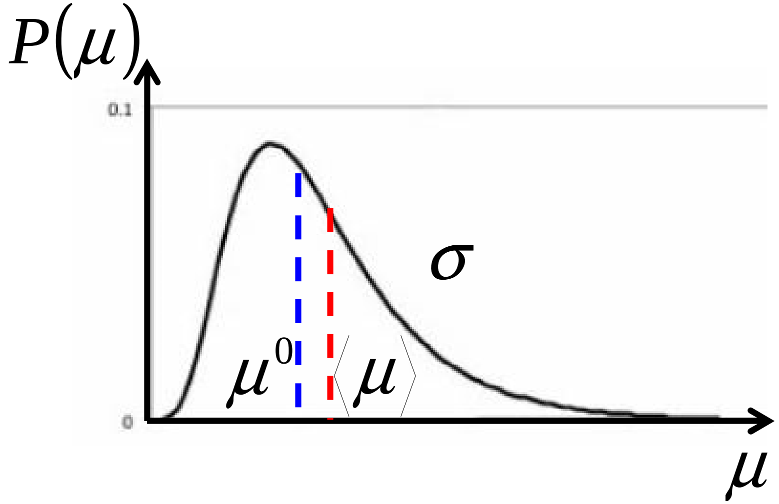
$$\chi = \frac{\mu_0 M_S^2 V_{pp}}{3kT}$$

Magnetización en equilibrio

Si hay distribución de tamaños:

$$M(H,T) = N\int \mu L(x) f(\mu) d\mu, \qquad x = \frac{\mu_0 \mu H}{kT}$$

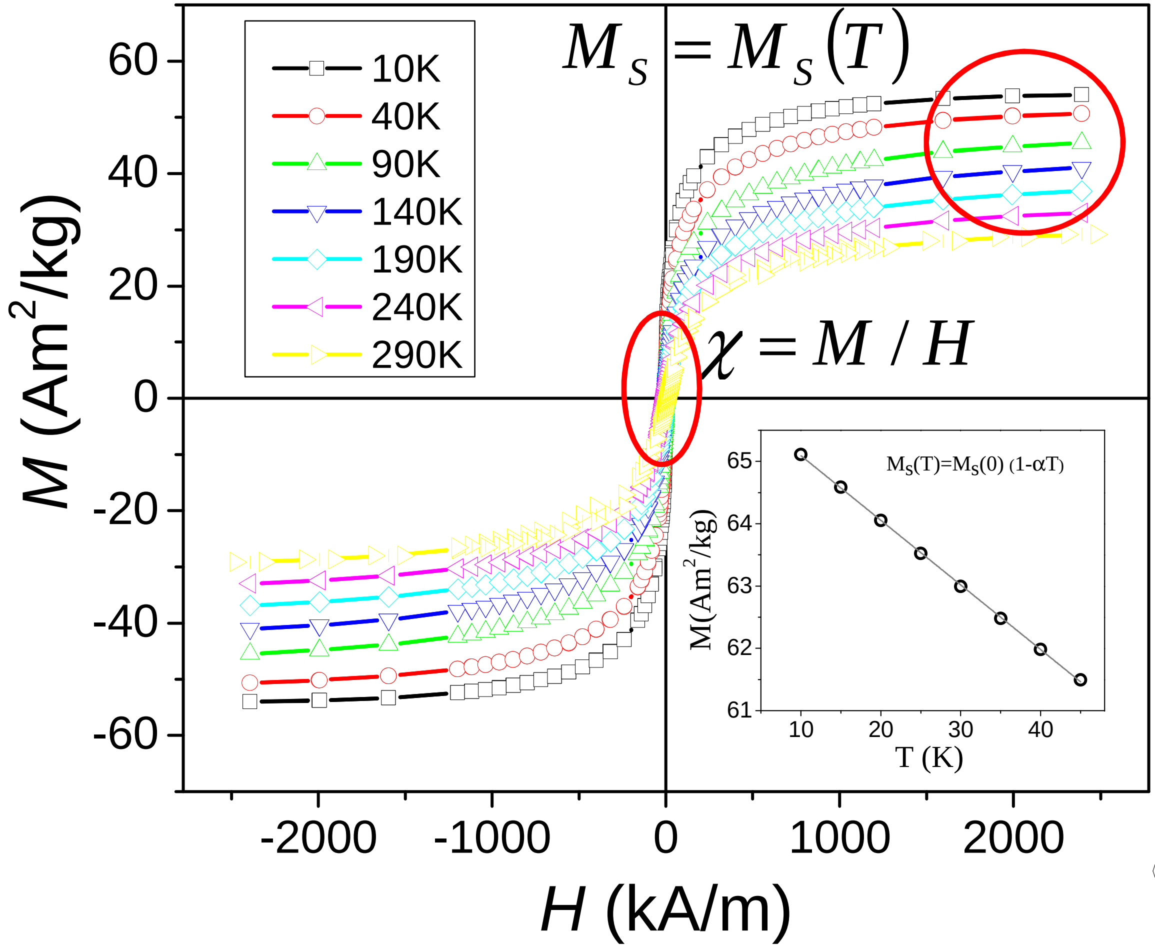
$$f(\mu) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\ln(\mu/\mu^0)^2/2\sigma^2}$$




$$\langle\mu\rangle = \mu^0 e^{\sigma^2/2}$$

$$SD = \langle\mu\rangle\sqrt{e^{\sigma^2} - 1}$$

$$M_S = N\langle \mu \rangle$$




$$\chi = \frac{N\mu_0 \langle \mu^2 \rangle}{3kT}$$

$$SD_\mu = \sqrt{\langle \mu^2 \rangle - \langle \mu \rangle^2}$$

$$\langle \mu^2 \rangle = \langle \mu \rangle^2 \left(1 + SD_\mu^2 / \langle \mu \rangle^2\right)$$

$$\chi = \frac{N\mu_0 \langle \mu \rangle^2 \left(1 + SD_\mu^2 / \langle \mu \rangle^2\right)}{3kT}$$

# Susceptibilidad en equilibrio

N = nro nps por unidad de volumen
μ = momento de la np

$$N = 1/\langle V_{pp} \rangle$$

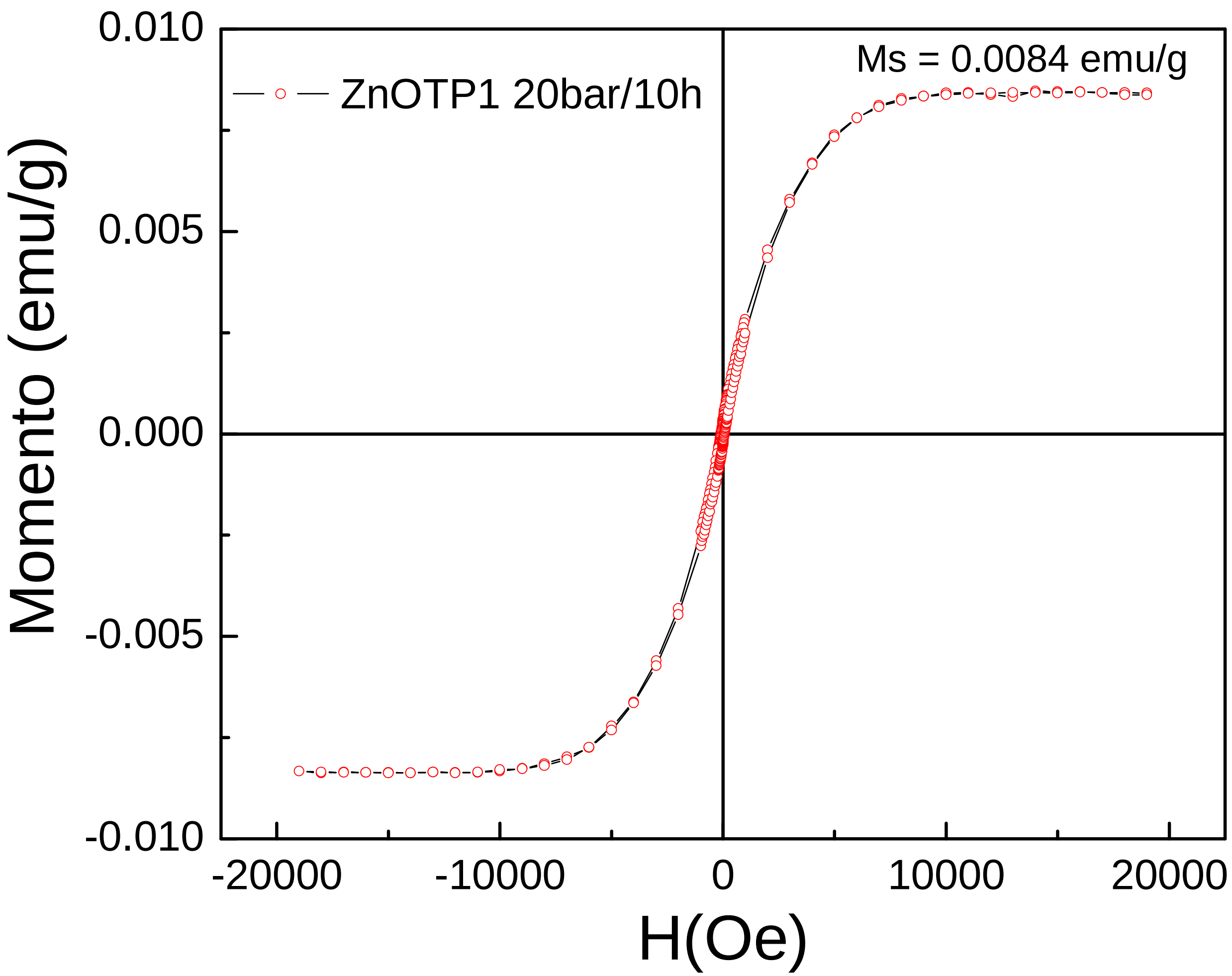
$$\chi(H,T) = \frac{N\mu_0 \langle \mu^2 \rangle}{3kT} = \frac{N\mu_0 \langle \mu \rangle^2 \left(1 + SD_\mu^2 / \langle \mu \rangle^2\right)}{3kT}$$

$$SD_V / \langle V_{pp} \rangle = SD_\mu / \langle \mu \rangle$$

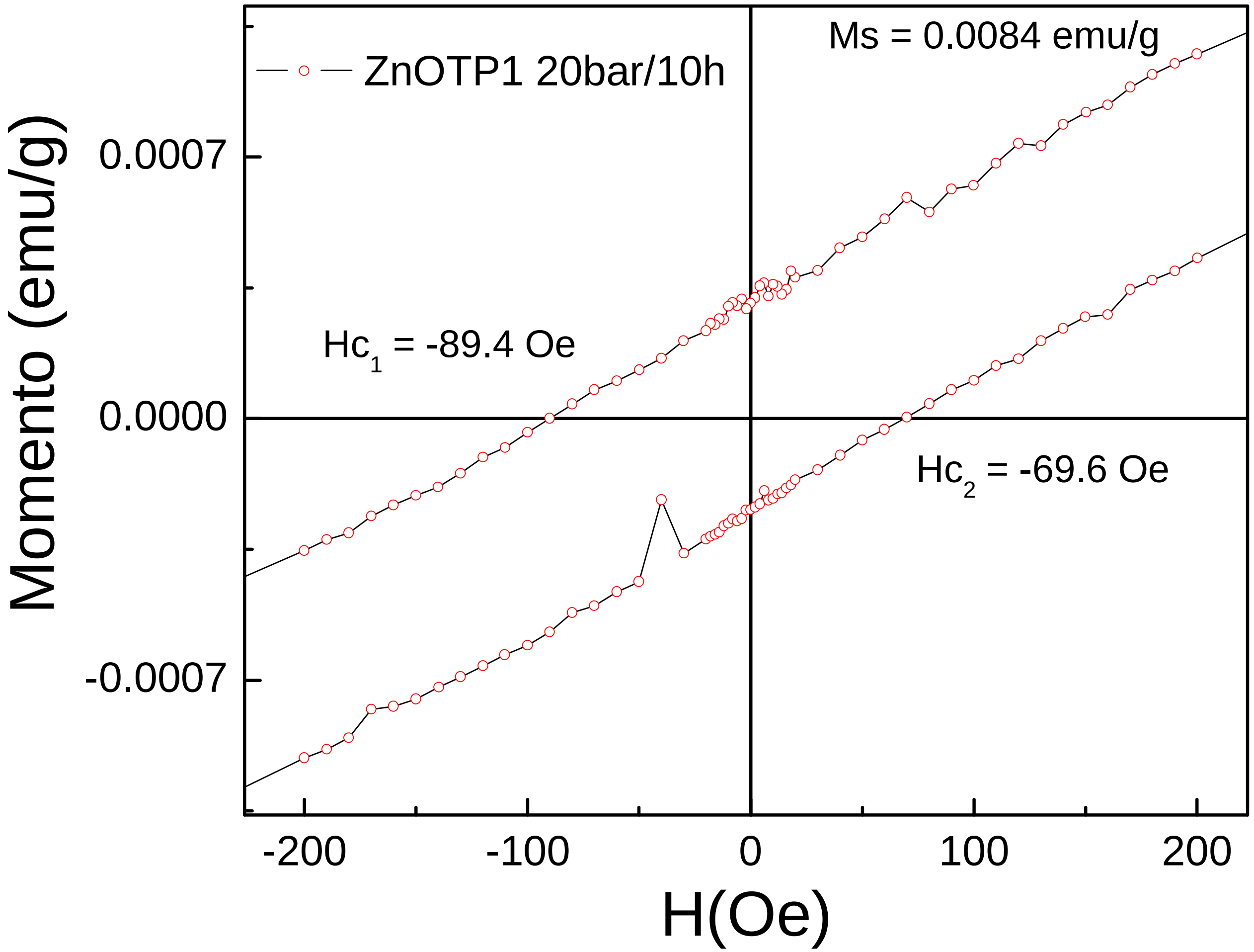
$M_S$

$$\chi(H,T) = \frac{\mu_0 \langle V_{pp} \rangle \left(1 + SD_V^2 / \langle V_{pp} \rangle^2\right) M_S^2}{3kT}$$

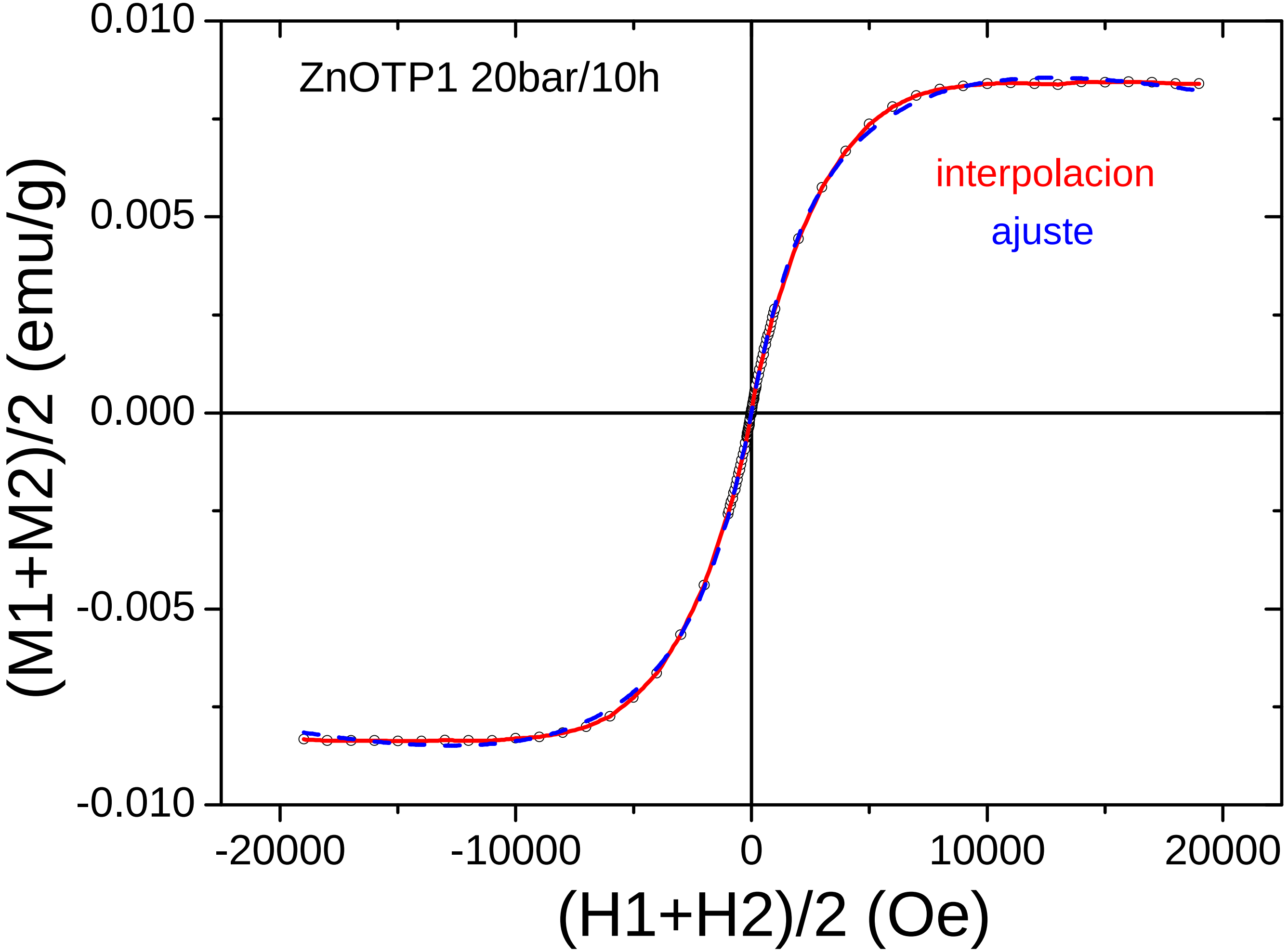
# Problema-ejemplo



# Problema-ejemplo



Problema-ejemplo, ajuste



# Datos del ajuste

$$M(H,T)) = N\int \mu L(x) f(\mu) d\mu + C_{par} H + Cte, \qquad x = \frac{\mu_0 \mu H}{kT}$$

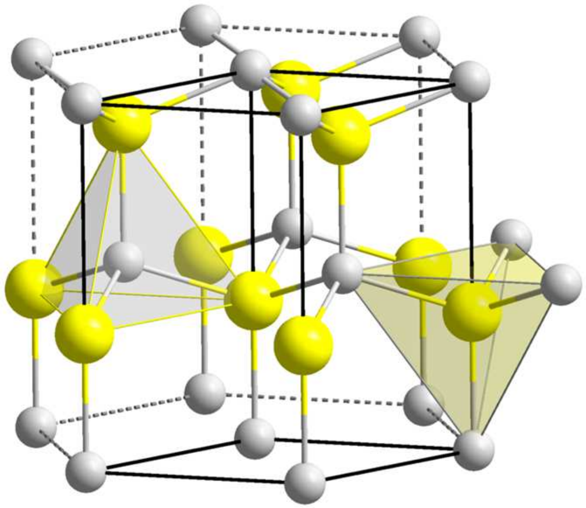
$$f(\mu) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\ln(\mu/\mu^0)^2/2\sigma^2}$$

| | valor | incerteza |
|---|---|---|
| σ | 0.844 | 0.001 |
| $\mu^0$ ($\mu_B$) | 1102.0 | 0.6 |
| N (1/g) | 9.37e14 | - |
| $C_{par}$ (emu/gOe) | -1.86e-7 | 1e-9 |
| Cte (emu/g) | 3.14e-5 | 6e-7 |

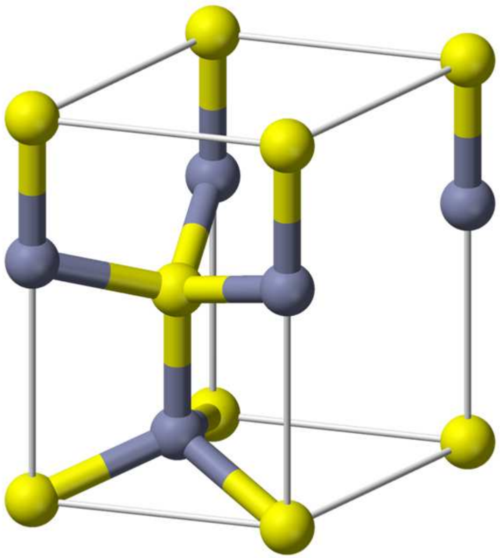
$$\langle \mu \rangle = \mu^0 e^{\sigma^2/2} = 1574\, \mu_B$$

$$SD = \langle \mu \rangle \sqrt{e^{\sigma^2} - 1} = 1605\, \mu_B$$

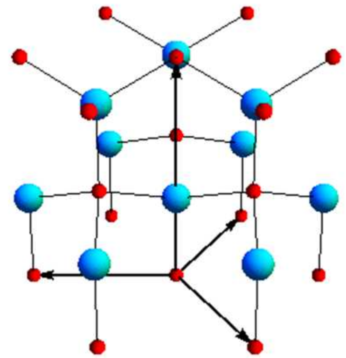
Datos del ZnO



masa molar=81.38 g/mol
densidad=5.606 g/cm3
hexagonal, a = 3.25 Å, c = 5.2 Å
2Zn, 2O por celda
volumen celda Vc=0.0476 nm^3



si $\mu_{at}(Zn) = 1\ \mu_B$
entonces,
Vp=1574*Vc/2=37.4 nm^3
y Dp=4.2 nm



# Susceptibilidad en equilibrio

llamando

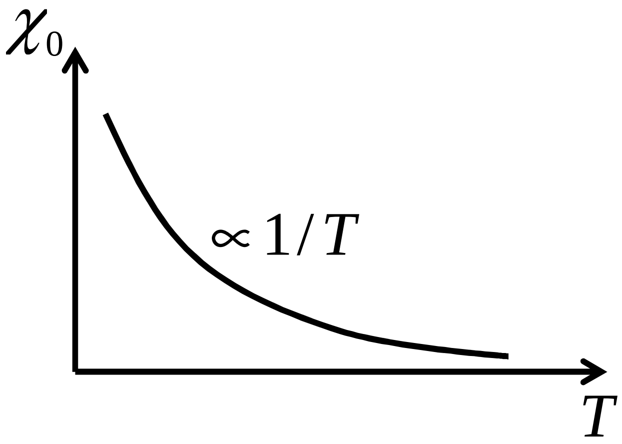
$$\rho = \langle \mu^2 \rangle / \langle \mu \rangle^2 \qquad \text{(Allia et al.)}$$

La expresión de la susceptibilidad queda:

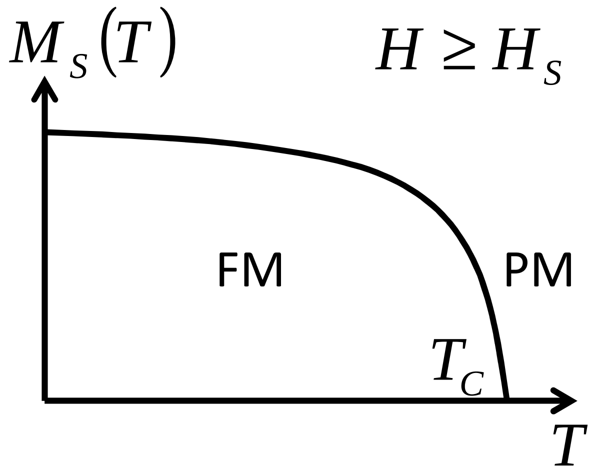
$$\chi(H,T) = \frac{N\mu_0 \rho \langle \mu \rangle^2}{3kT}$$

$$\chi(H,T) = \frac{\mu_0 \langle V_{pp} \rangle \rho M_S^2}{3kT}$$

Medidas de M o Susceptibilidad en función de T



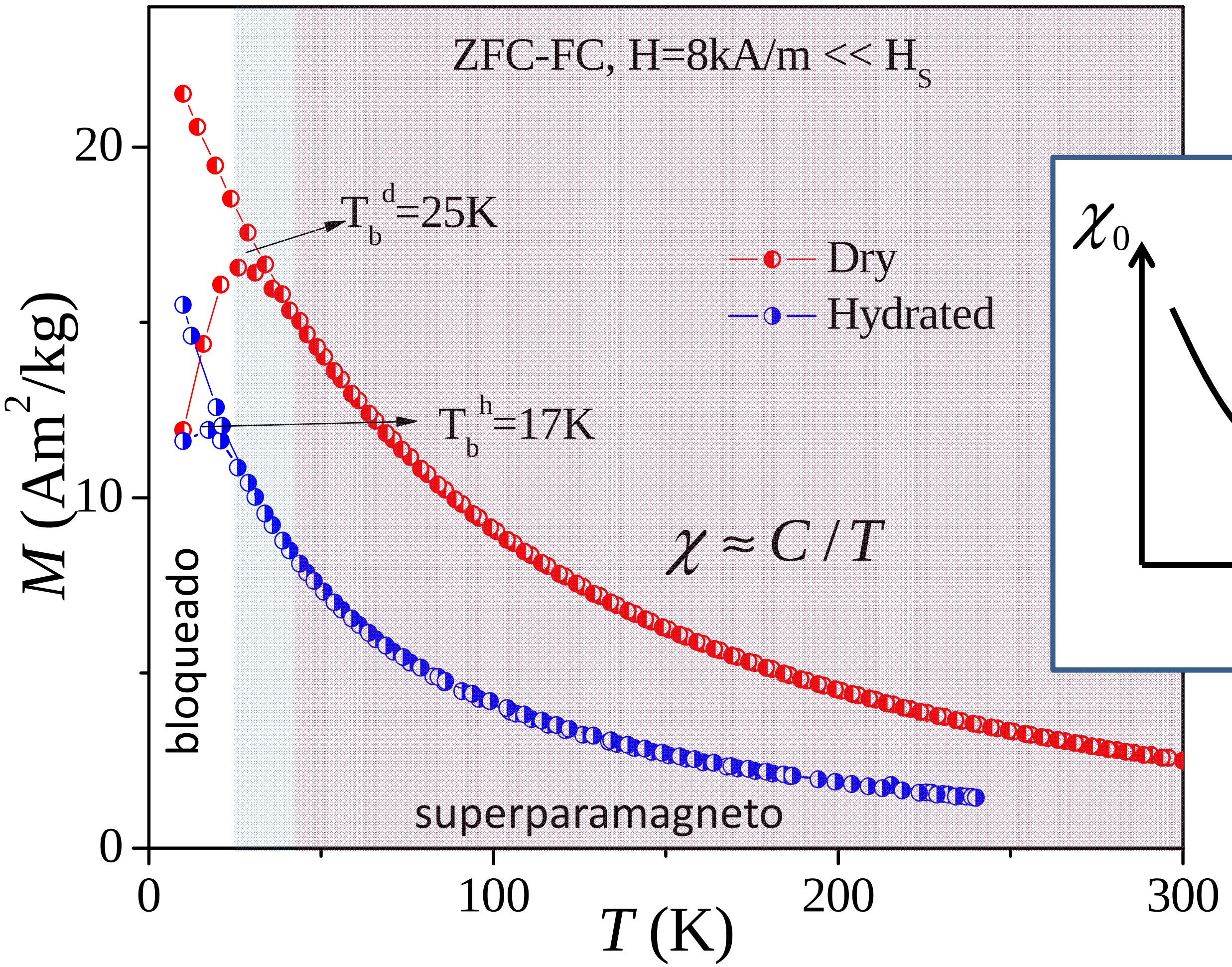

paramagneto

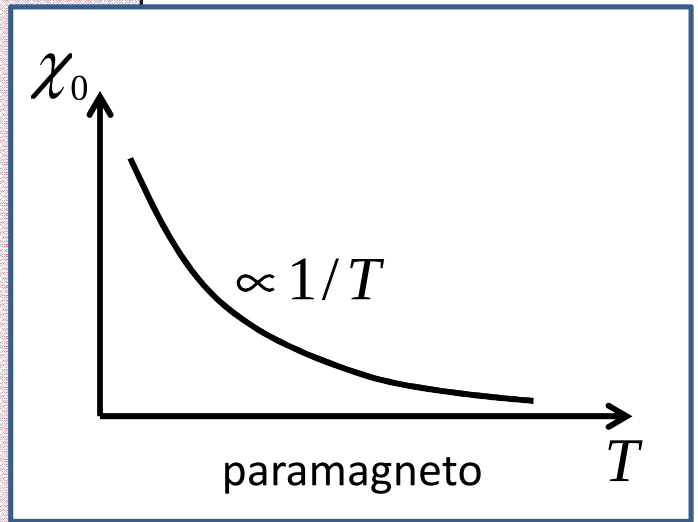



ferromagneto

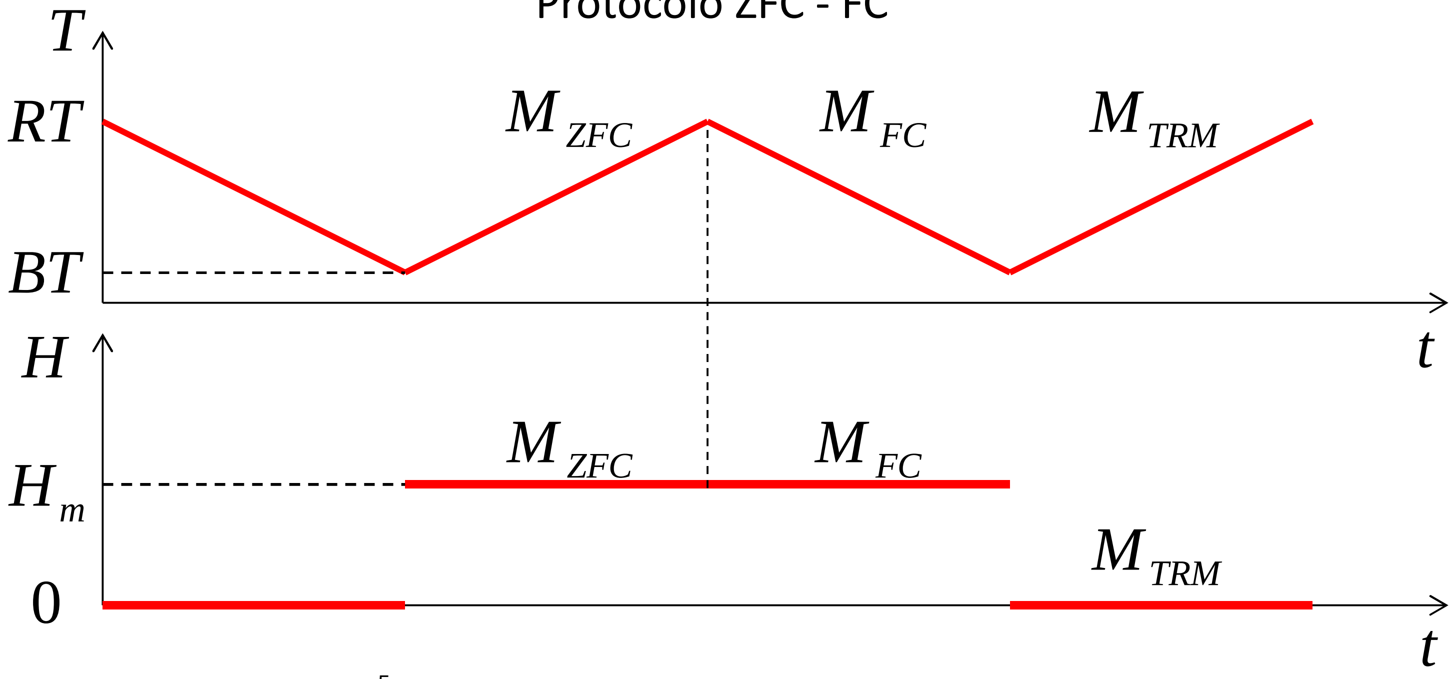
Medidas de susceptibilidad en función de T

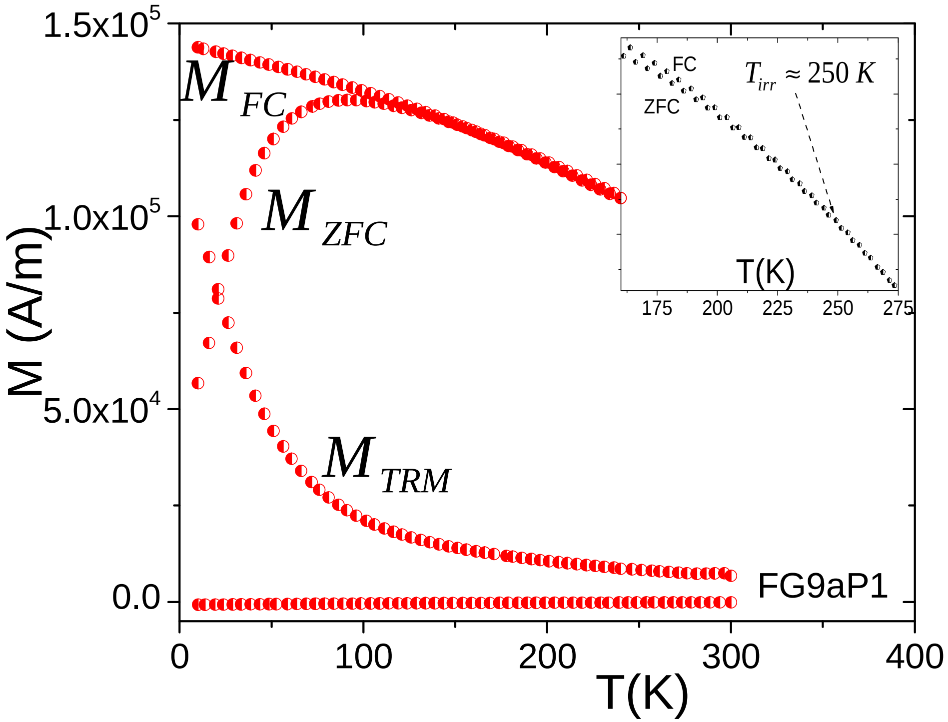
NPs monodominio



Protocolo ZFC - FC

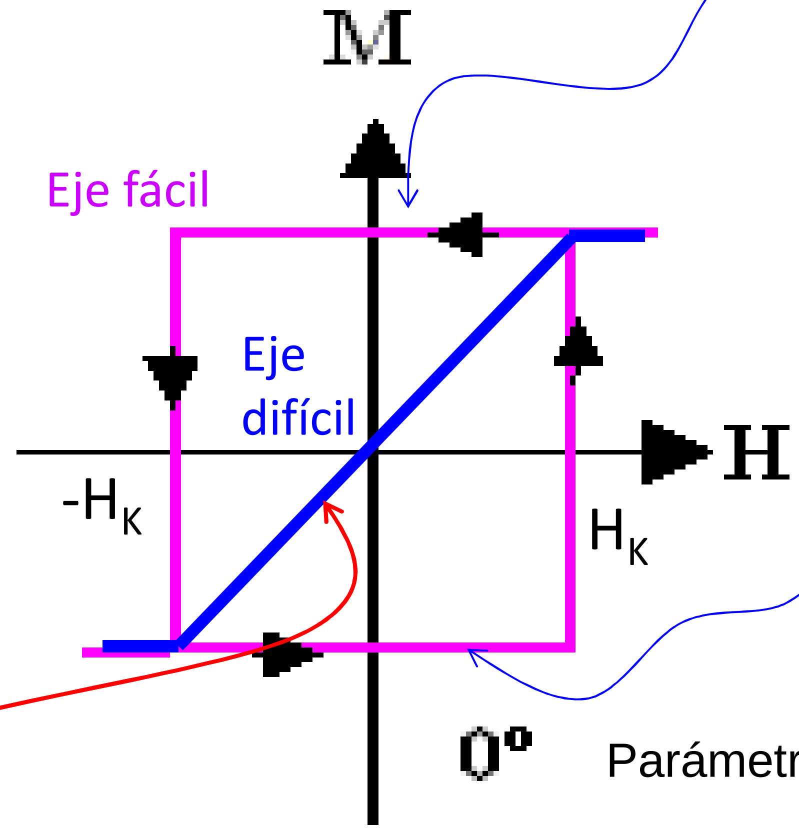


## Susceptibilidad fuera del equilibrio (régimen bloqueado) a T = 0 K

$$\chi_{//} = \frac{\Delta M}{\Delta H} = 0$$

$$T = 0K$$




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

$$H_K \geq 1000 Oe$$

Parámetro de orden //: $0 \leq S \leq 1$

perpendicular

paralelo

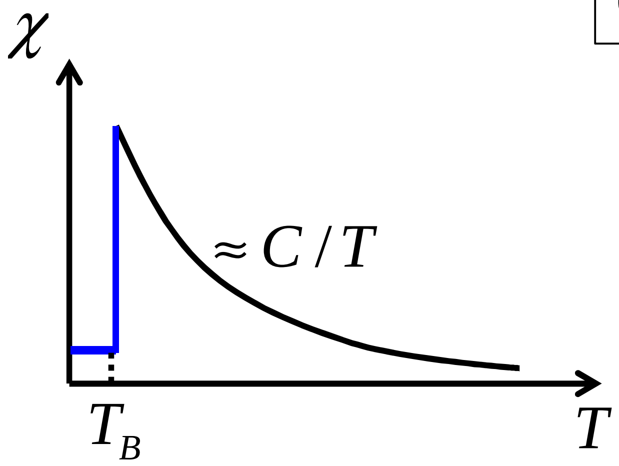
$$\chi_{\perp} = \frac{\Delta M}{\Delta H} = \frac{M_S}{H_K} = \frac{\mu_0 M_S^2}{2K}$$

$$\chi = (1 - S)\chi_{\perp} = (1 - S)\frac{\mu_0 M_S^2}{2K}$$

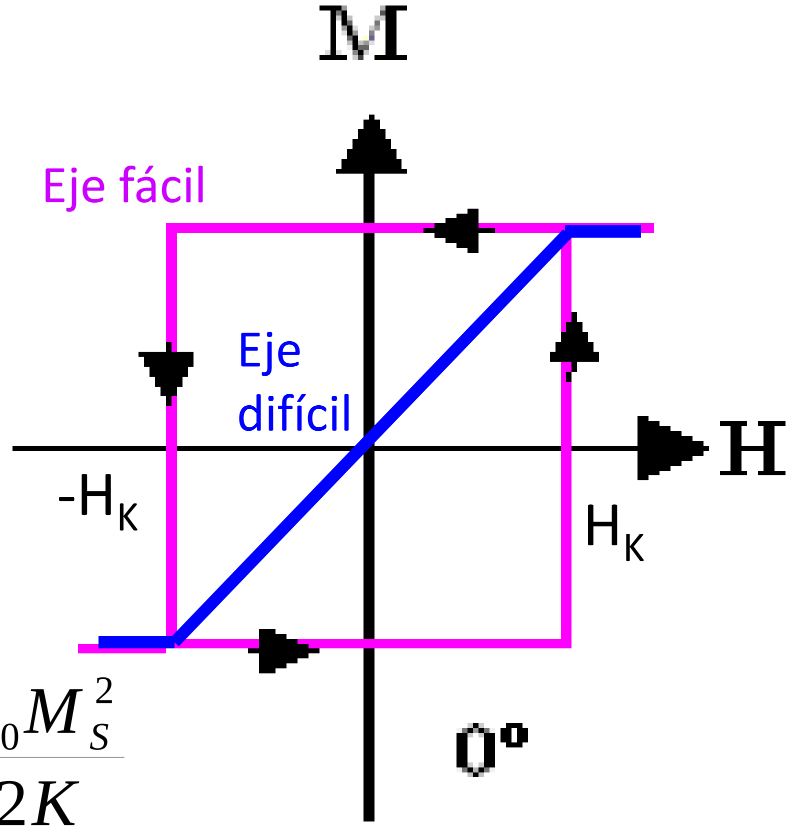
$$\chi_0 = \frac{\mu_0 N V^2 M_S^2}{3kT} \quad \tau << \tau_{exp} \quad \tau / \tau_{exp} \rightarrow 0$$

$$\chi_\infty ? \quad \tau >> \tau_{exp} \quad \tau / \tau_{exp} \rightarrow \infty$$

Caso ZFC




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

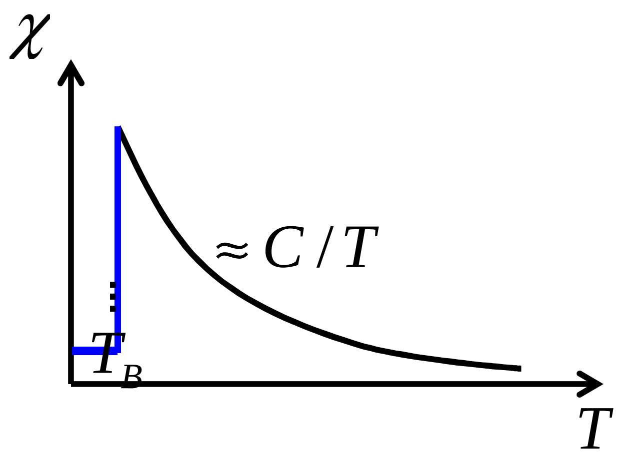



$$\chi_\infty^{ZFC} = (1 - S)\frac{\mu_0 M_S^2}{2K}$$

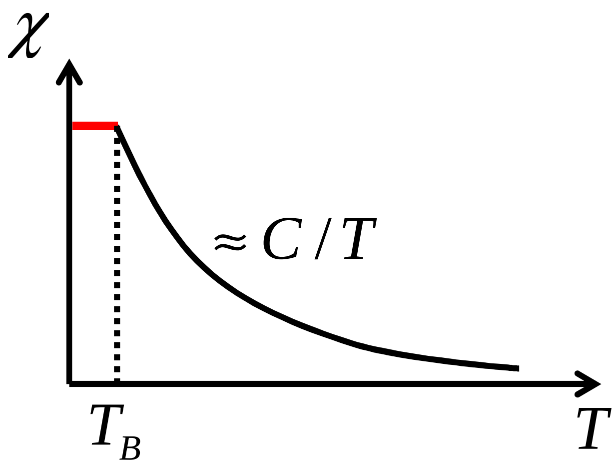
$$\text{random} \rightarrow \text{S} = 1/3; \quad \chi_\infty^{ZFC} = \frac{\mu_0 M_S^2}{3K}$$

Caso ZFC

$$\chi_{ZFC} = \chi_\infty^{ZFC} + \left(\chi_0 - \chi_\infty^{ZFC}\right)\frac{1}{1+\left(\tau/\tau_{\exp}\right)^2}$$



# Caso FC



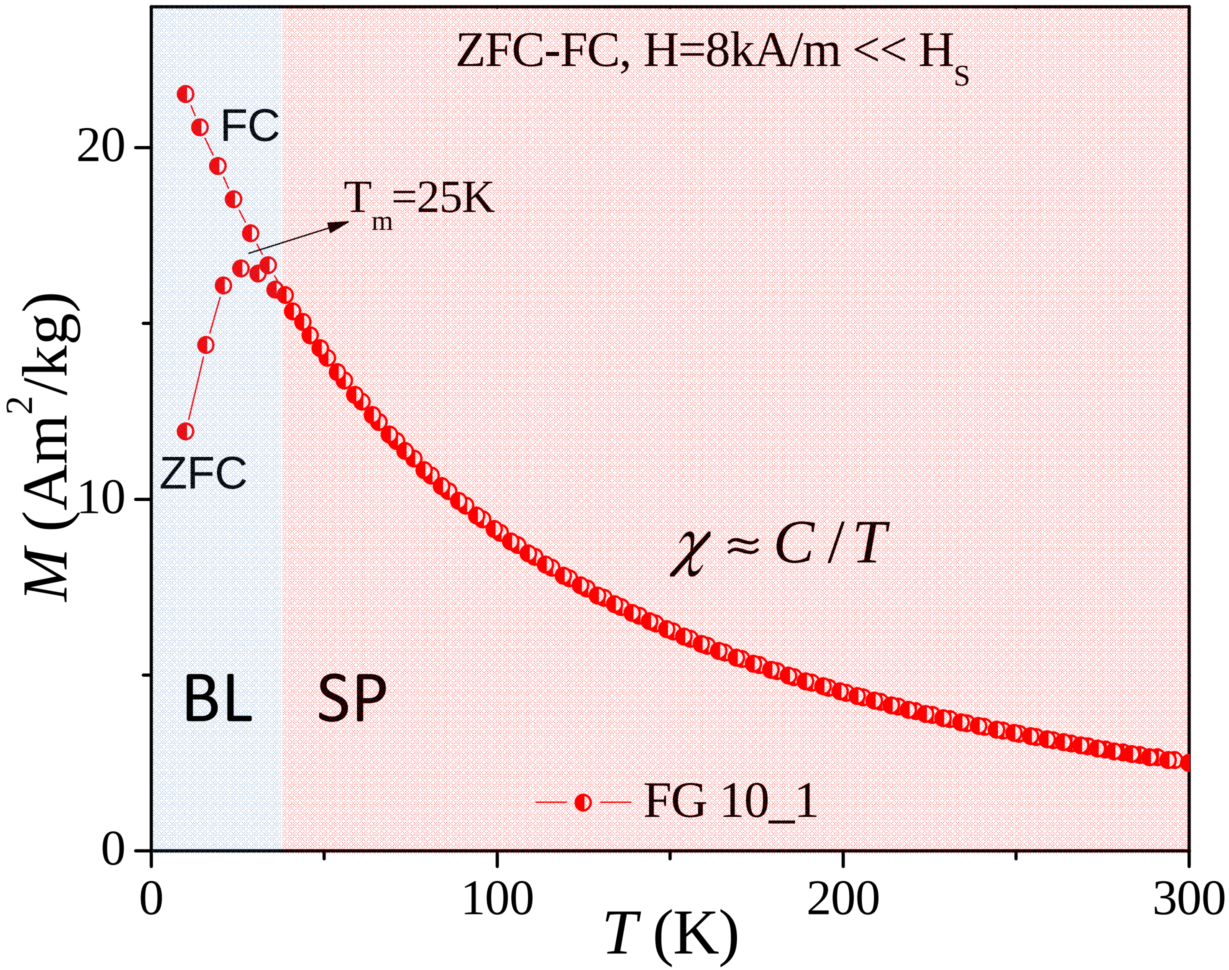

$$\chi_0 = \frac{\mu_0 N V^2 M_S^2}{3kT} \quad \tau << \tau_{\exp} \quad \tau / \tau_{\exp} \to 0$$

$$\chi_\infty ? \quad \tau >> \tau_{\exp} \quad \tau / \tau_{\exp} \to \infty$$

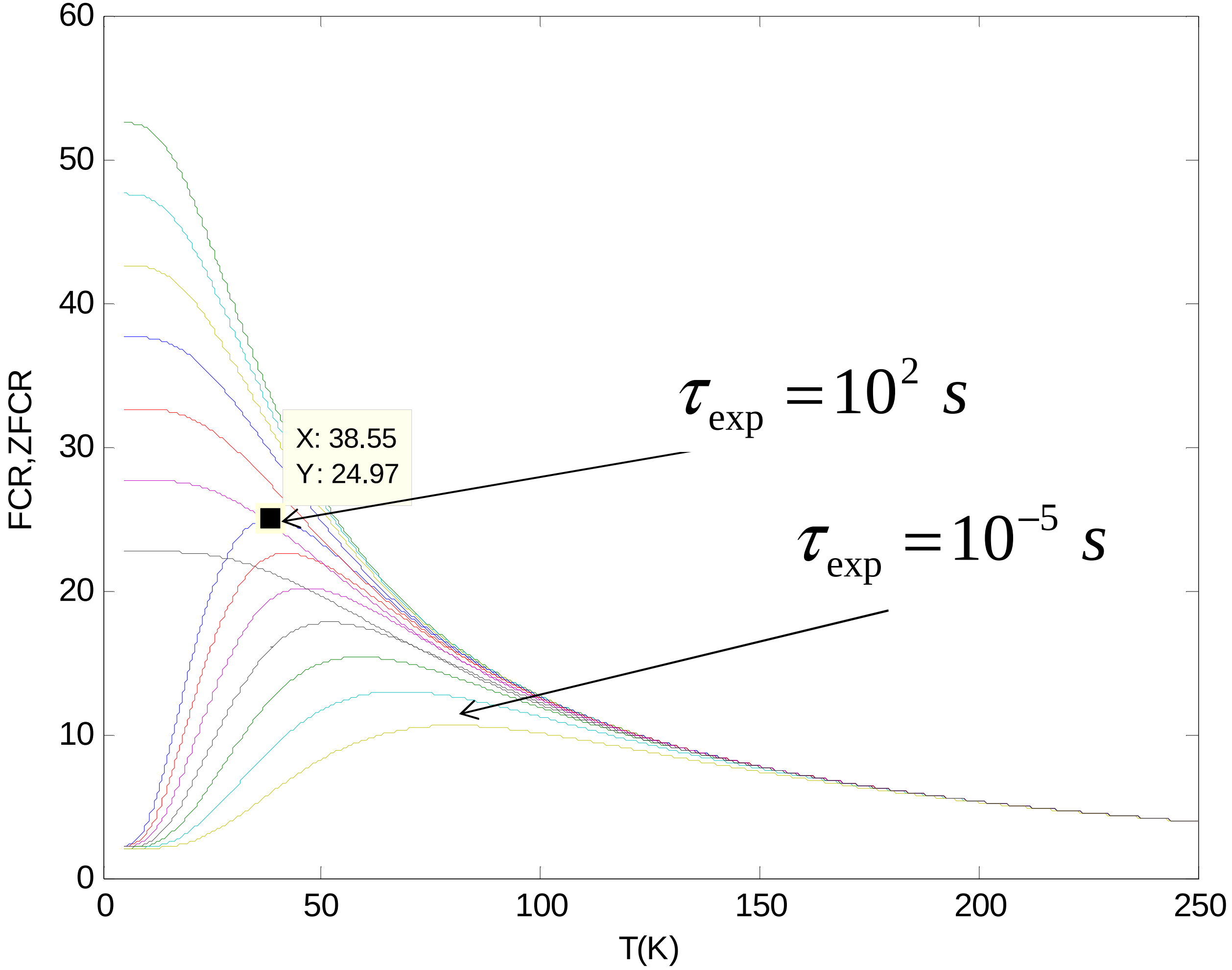
$$\chi_\infty^{FC} = (1 - S)\frac{\mu_0 M_S^2}{2K} + \frac{\mu_0 N V^2 M_S^2}{3kT_B}$$ medida dc

$$\chi_{FC} = \chi_\infty^{FC} + \left(\chi_0 - \chi_\infty^{FC}\right)\frac{1}{1 + \left(\tau / \tau_{\exp}\right)^2}$$

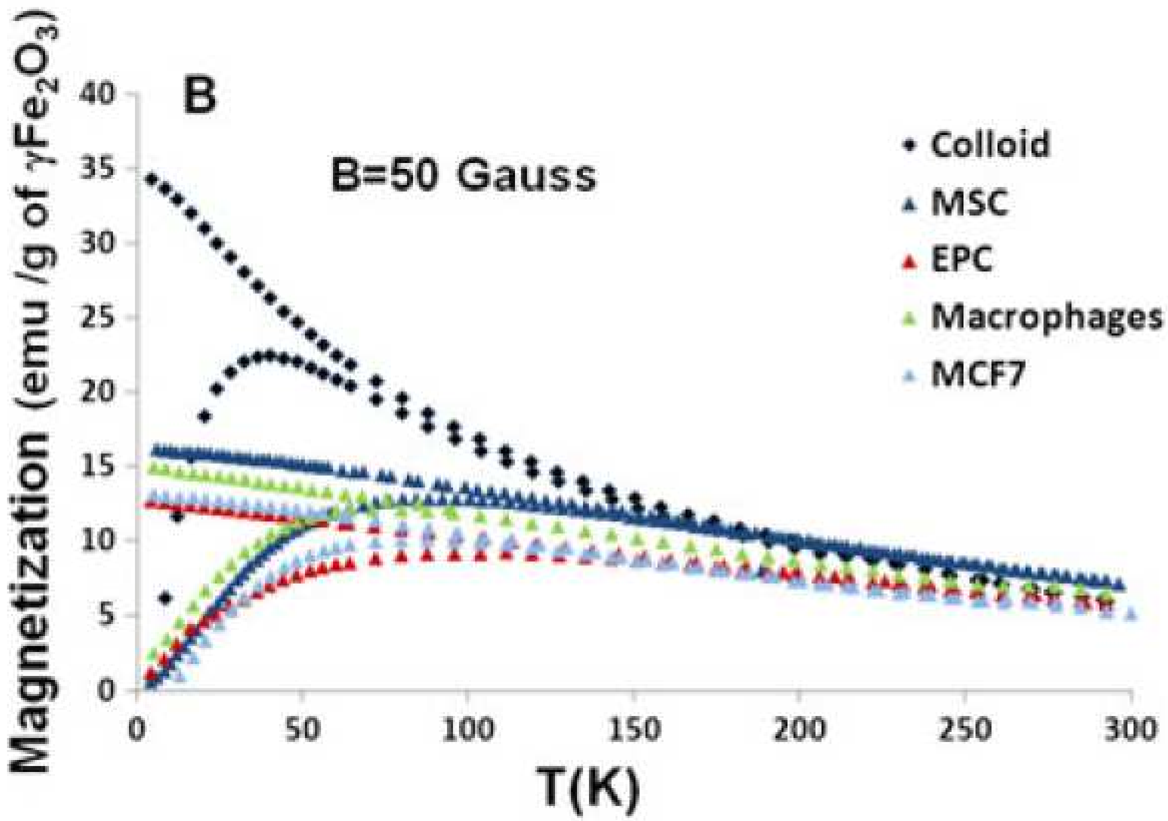
# Medidas ZFC - FC



# Simulación numérica

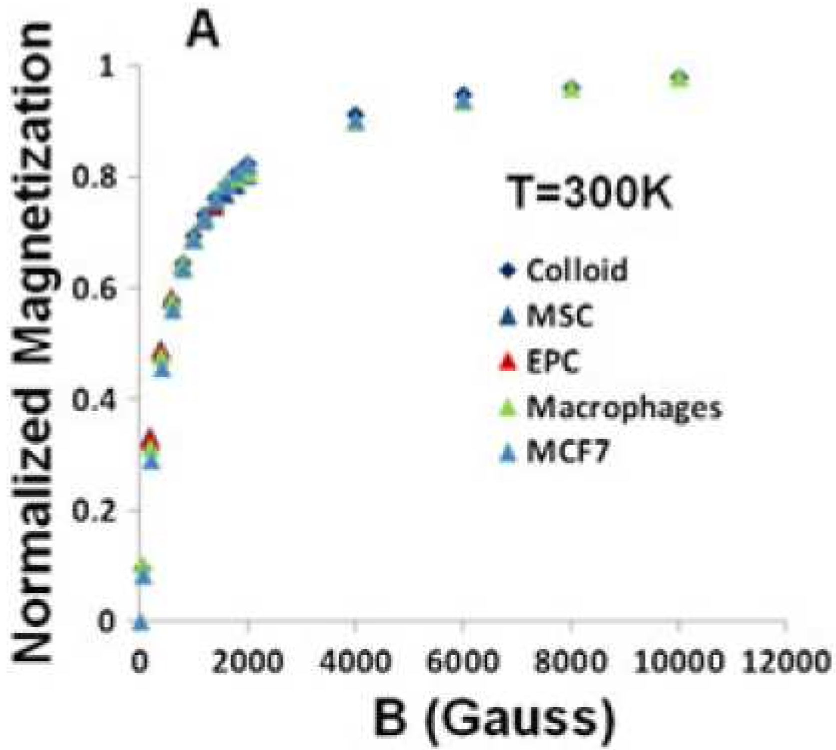



$$\tau_{\exp} = 100, 10, 1, 0.1, 0.01, 0.001, 0.0001, 0.00001\ s$$




Magnetic and NMR characterization of nanoparticles (NPs) internalized in EPC (13.8 pg iron per cell), MSC (30.5 pg per cell), macrophages (13.1 pg per cell), MCF7 (3.2 pg per cell) or PC3 (2.7 pg per cell) in comparison with the corresponding colloid.

M. Levy et al., Contrast Media Mol. Imaging 2012, 7 373–383

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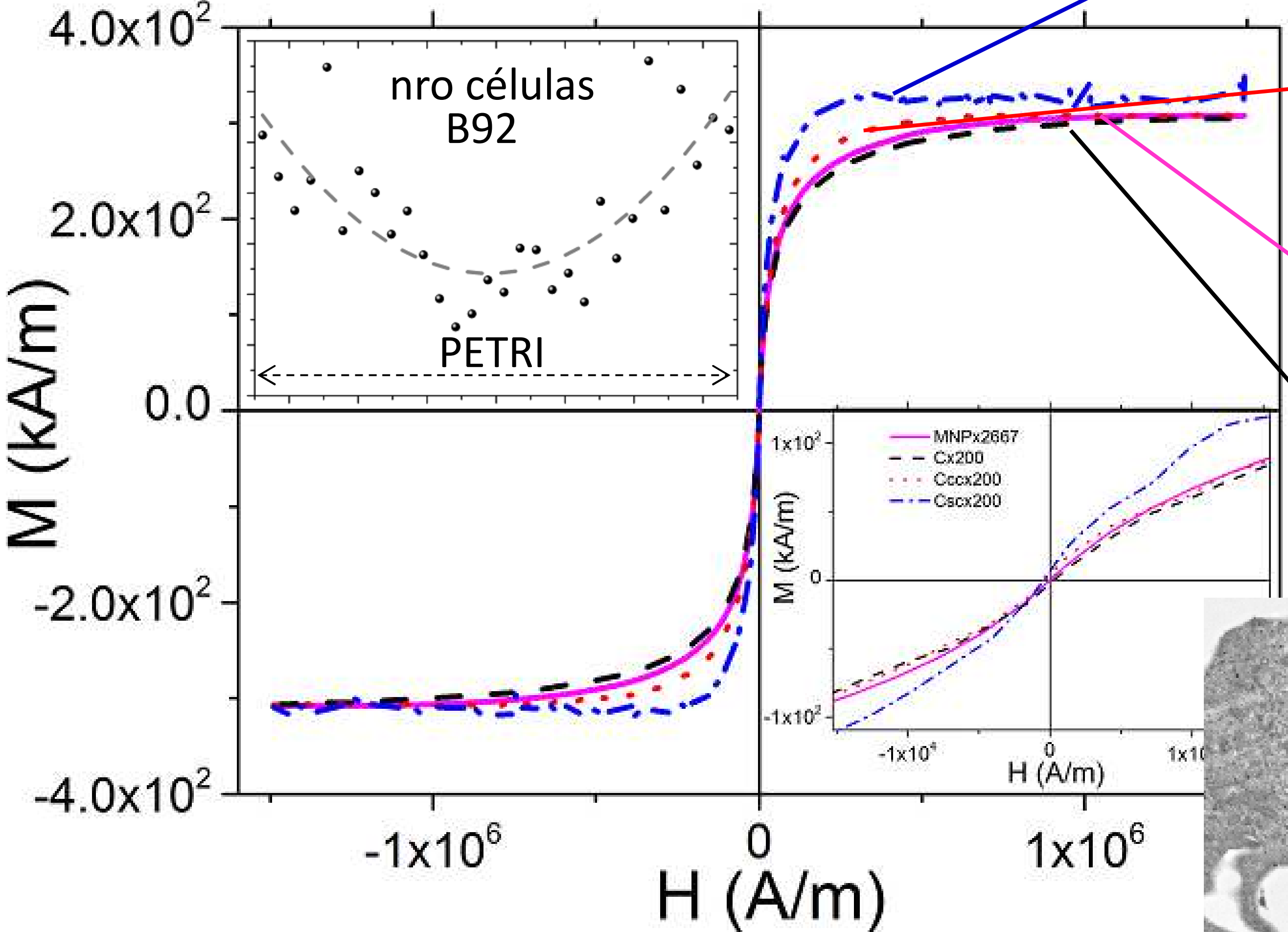
# Caracterización magnética de NPs y complejos



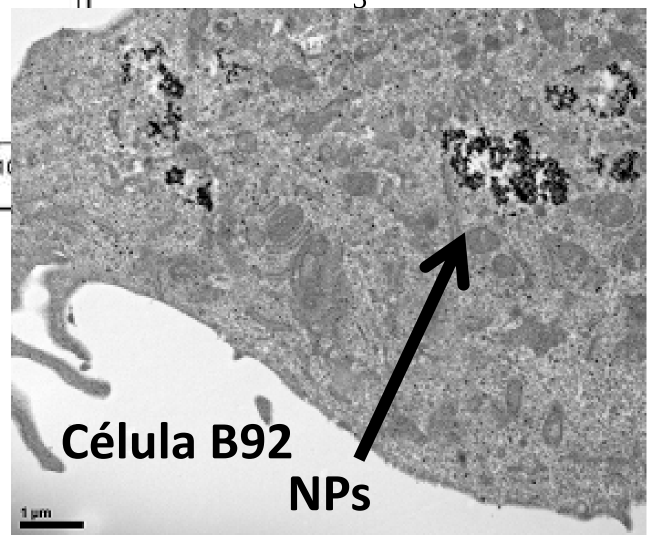

B92

Cx intern. sin campo
$D \approx 9_3\ nm$
3.7x10$^2$ NP/cell
1 PVP/cell

Cx intern. con campo
$D \approx 7_3\ nm$
3.7x10$^3$ NP/cell
5 PVP/cell

Cx
$D \approx 5_3\ nm$

MNPs
$D \approx 5_3\ nm$



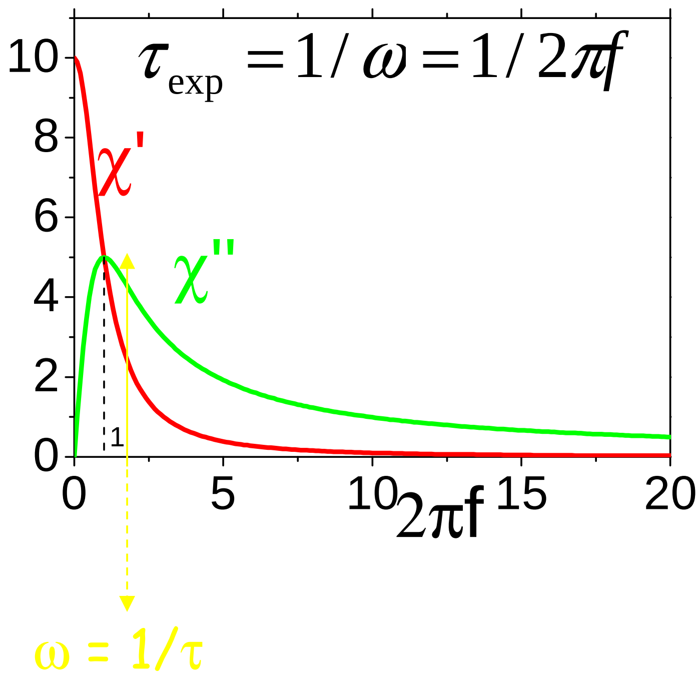

M.L. Arciniegas et al., en preparación.

Medidas ac - Desfasaje – Caso ZFC

$$H = H_0 \cos(\omega t) \qquad \tau_{\exp} = 1/\omega = 1/2\pi f$$

$$\chi'_{ZFC}(T) = \chi_\infty^{ZFC} + \left(\chi_0(T) - \chi_\infty^{ZFC}\right)\frac{1}{1+(\omega\tau(T))^2}$$

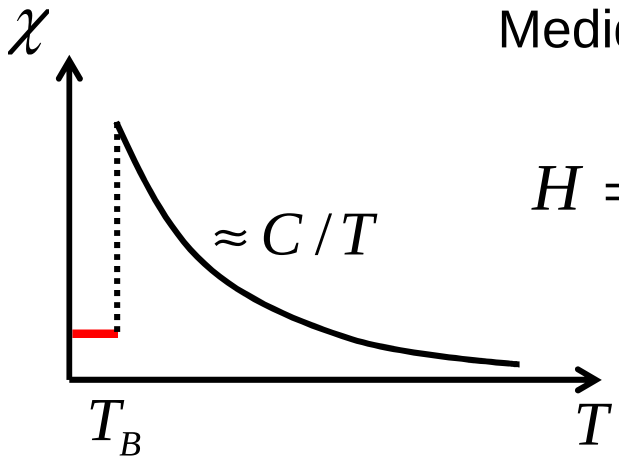
$$\chi''_{ZFC}(T) = \chi_0(T)\frac{\omega\tau(T)}{1+(\omega\tau(T))^2}$$




$$\tau(T) = \tau_0 e^{K_{ef}V(1+H/H_K)^2/kT} \qquad H_K = \frac{2K}{\mu_0 M_S}$$

$$\chi_\infty^{ZFC} = (1-S)\frac{\mu_0 M_S^2}{2K}$$

# Medidas ac - Desfasaje - Caso FC




$$H = H_0 \cos(\omega t) + H_{dc} \qquad \tau_{\exp} = 1/\omega = 1/2\pi f$$

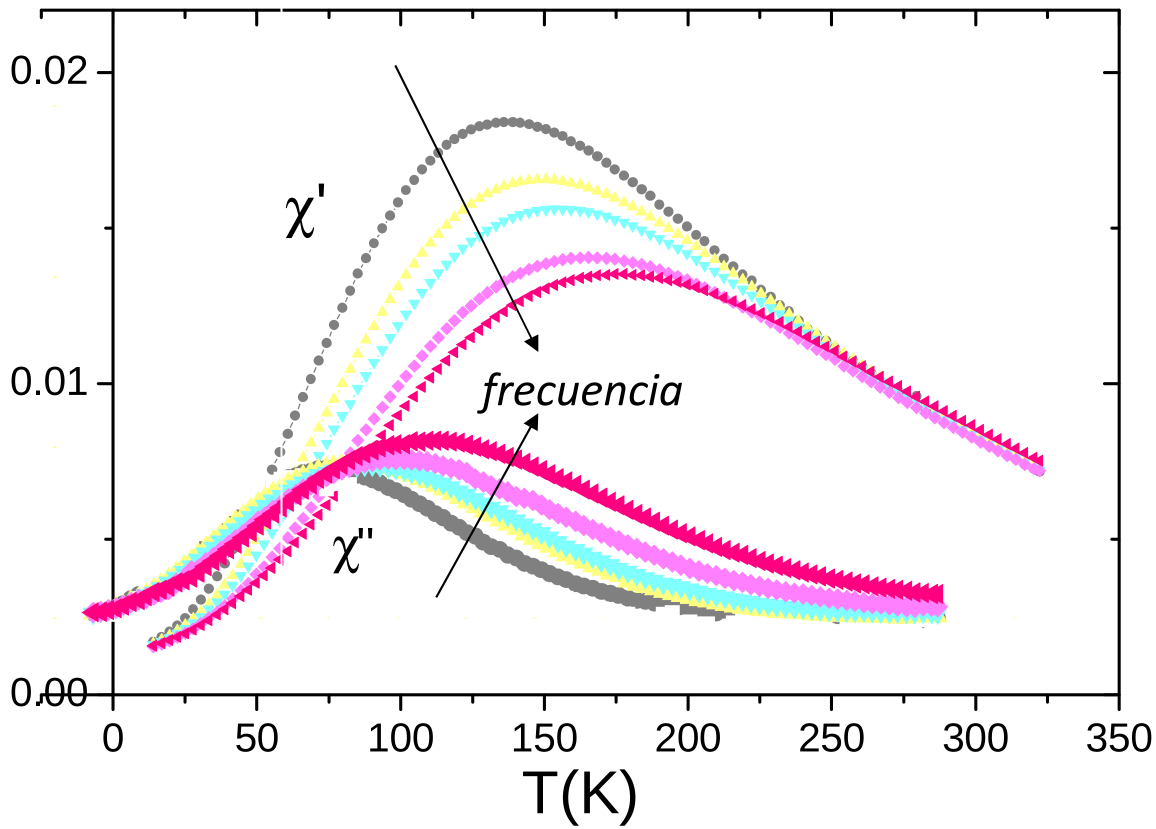
$$\chi_\infty^{FC} = (1-S)\frac{\mu_0 M_S^2}{2K}$$

$$\chi'_{FC}(T) = \chi_\infty^{FC} + \left(\chi_0(T) - \chi_\infty^{ZFC}\right)\frac{1}{1+(\omega\tau(T))^2}$$

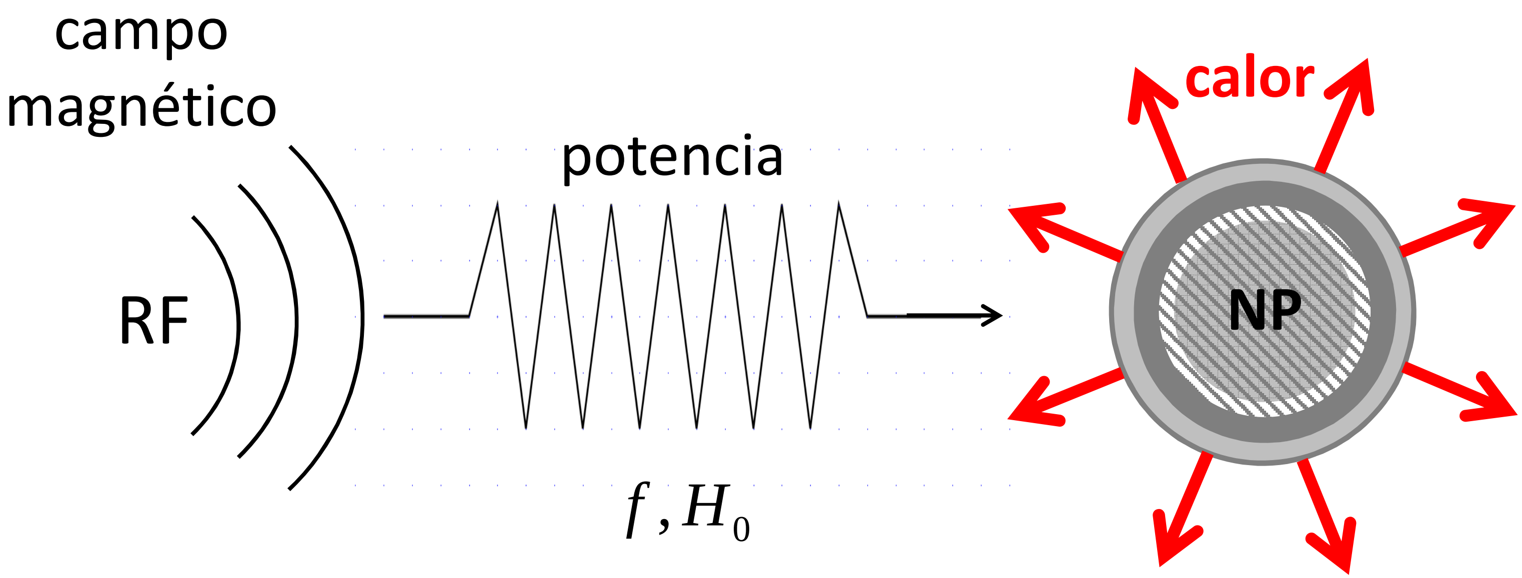
$$\chi''_{FC}(T) = \chi_0(T)\frac{\omega\tau(T)}{1+(\omega\tau(T))^2}$$

$$\tau(T) = \tau_0 e^{K_{ef}V(1+H/H_K)^2/kT} \qquad H_K = \frac{2K}{\mu_0 M_S}$$

Medidas ac - Desfasaje – Caso ZFC



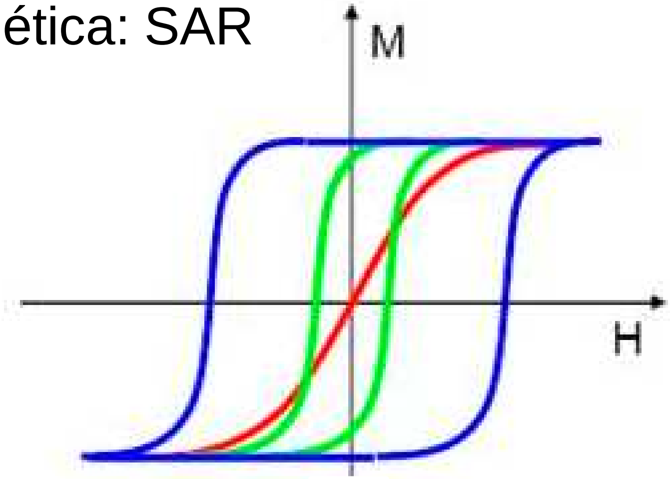
# Hipertermia Magnética




$$SAR \propto \langle V \rangle M_S^2 f H_0^2 \cdot \frac{2\pi f \tau}{1+(2\pi f \tau)^2}$$

Specific Absorption Rate

# Hipertermia Magnética: SAR




$$P = \mu_0 \pi \chi'' f H_0^2$$

$$\chi''(T) = \chi_0(T) \frac{\omega\tau(T)}{1 + (\omega\tau(T))^2} \qquad \chi_0 = \frac{\mu_0 N V^2 M_S^2}{3kT}$$

Se define el SAR normalizando la potencia P por la masa de NPs en lugar del volumen, de modo que

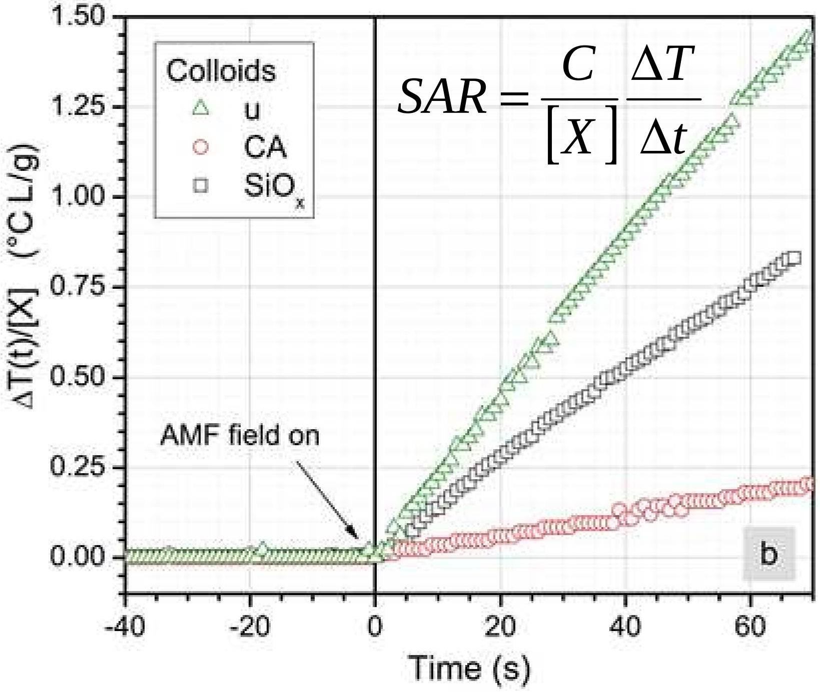
$$SAR = \frac{\pi \mu_0^2 V M_S^2 f H_0^2}{3\delta kT} \frac{\omega\tau(T)}{1 + (\omega\tau(T))^2}$$

Donde $\delta$ es la densidad de las NPs

R.E. Rosensweig, Heating magnetic fluid with alternating magnetic field, Journal of Magnetism and Magnetic Materials 252 (2002) 370–374

# Hipertermia Magnética

## coloides




$$SAR = \frac{C}{[X]}\frac{\Delta T}{\Delta t}$$


128 kHz, 20.3 kA/m

$$10\,W / g \leq SAR \leq 400\,W / g$$

M. Elisa de Sousa et al., J. Phys. Chem. C 2016, 120, 7339−7348

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