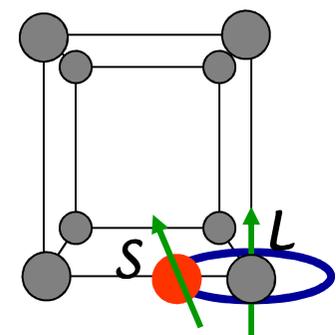
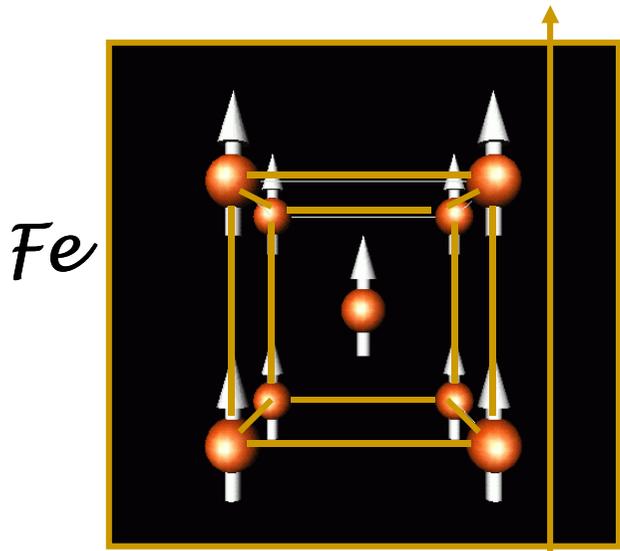


Anisotropía magnetocrystalina

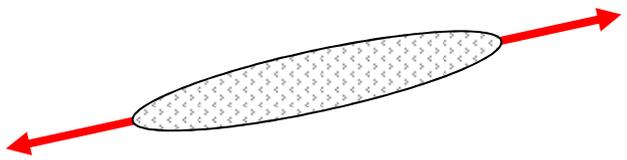
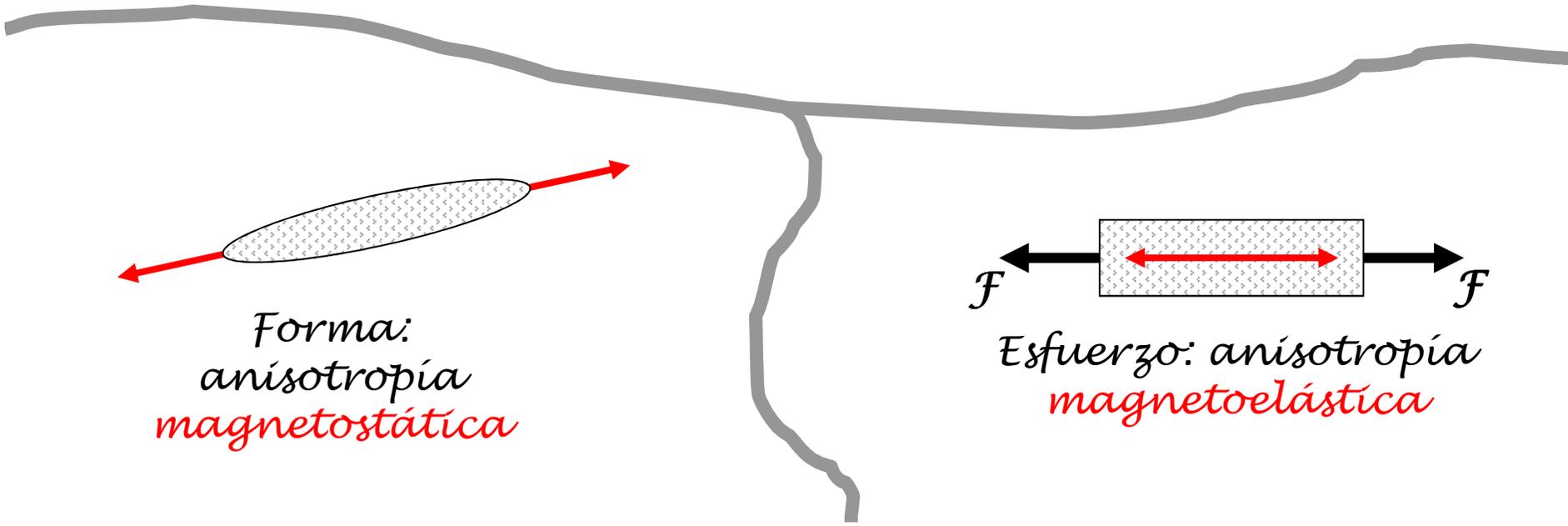
Anisotropía



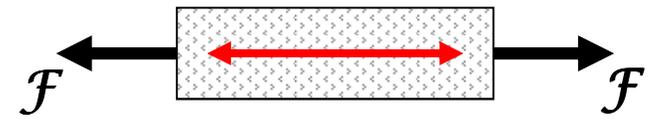
Estructura cristalina → Int. elect - Campo cristalino

+ interacción Spín - órbita

= Anisotropía magneto-cristalina



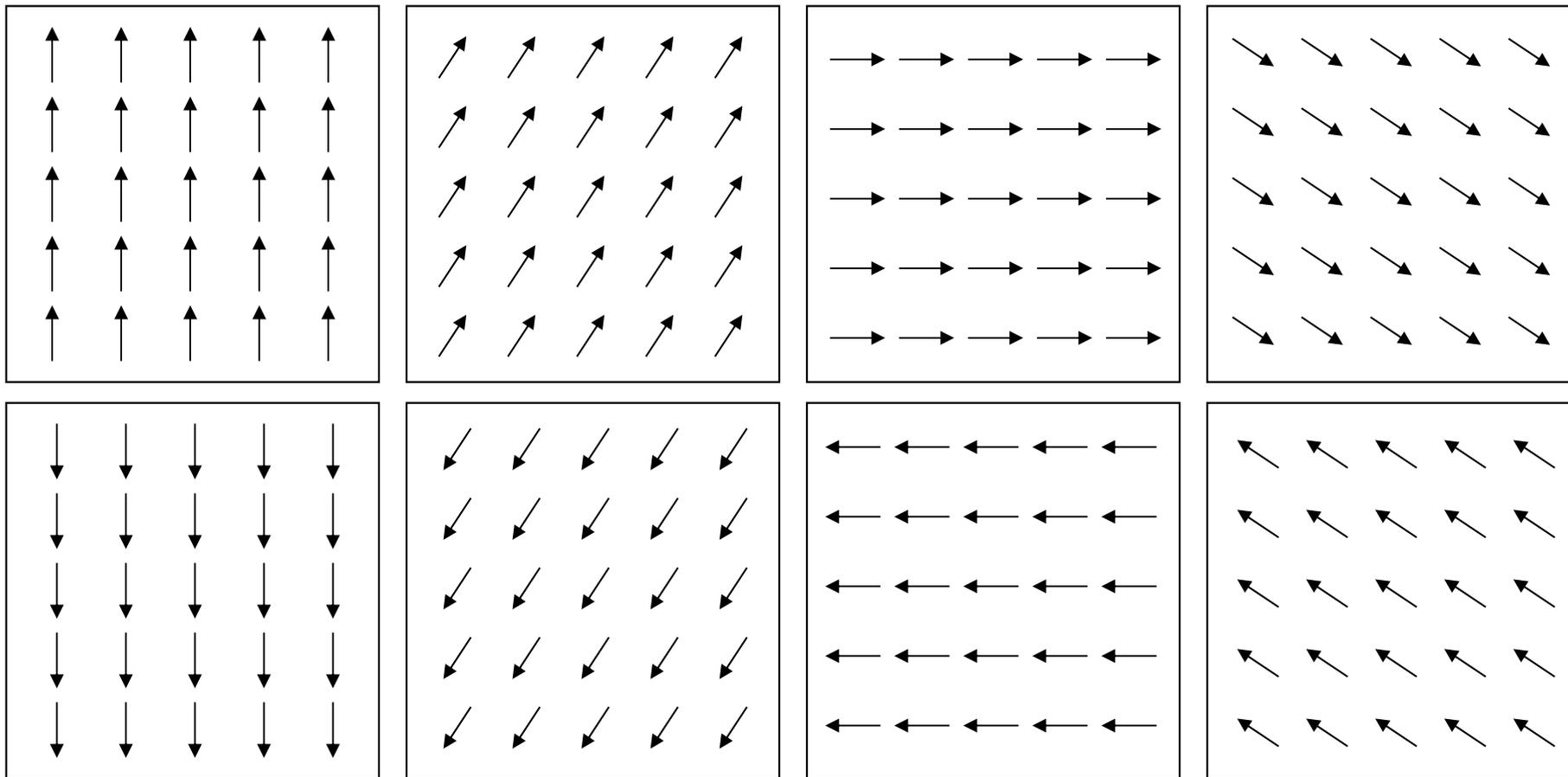
Forma: anisotropía magnetostática



Esfuerzo: anisotropía magnetoelástica

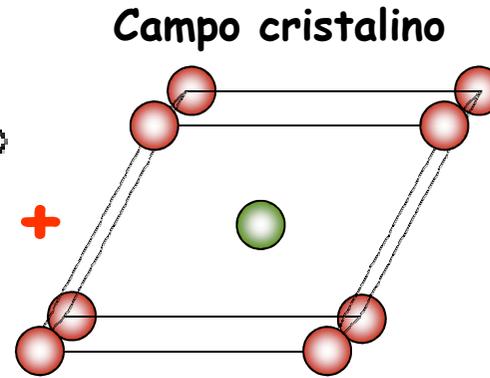
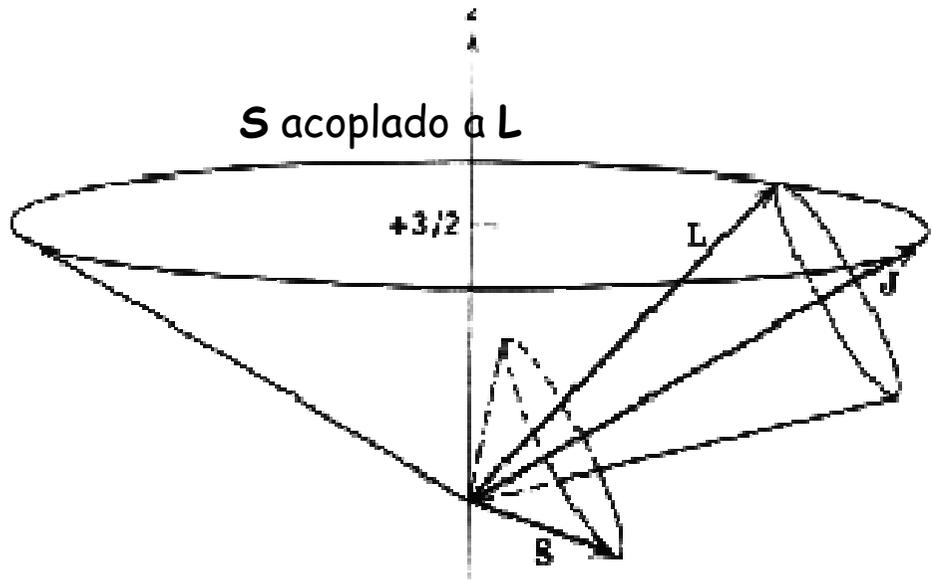
Sólo intercambio
(ausencia de anisotropía)

Dirección aleatoria de \mathbf{M} en $4\pi \Rightarrow$ estado continuamente degenerado

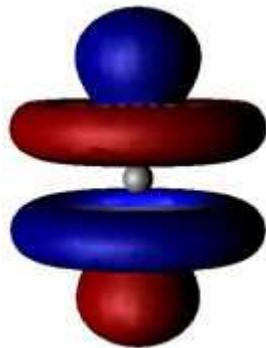
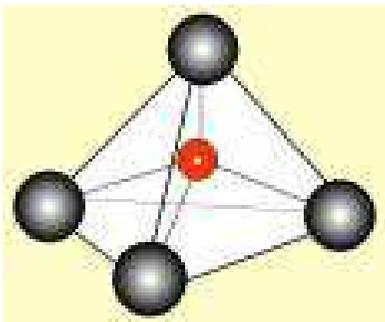
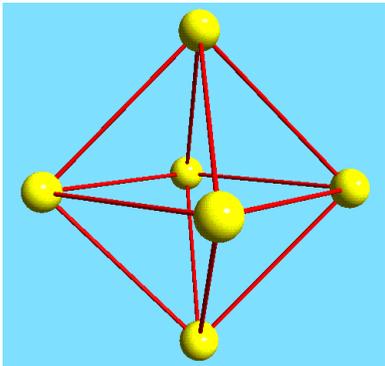


Siempre estaríamos en presencia de un superparamagneto

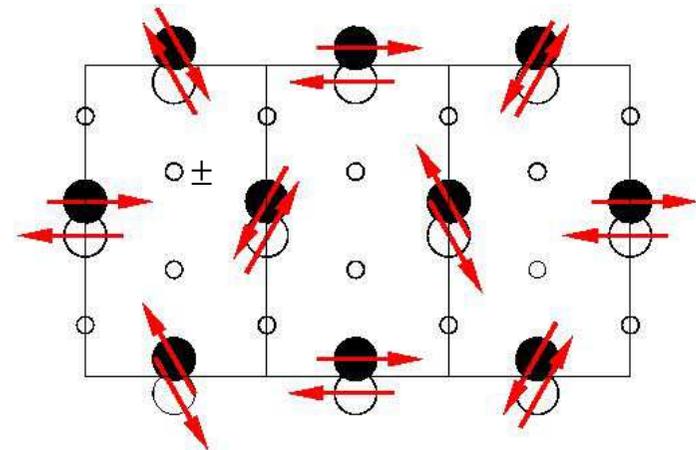
spin - órbita + campo cristalino



= $\left\{ \begin{array}{l} \textit{anisotropía} \\ \textit{sobre} \\ \vec{L}, \vec{S} \textit{ y } \vec{J} \end{array} \right.$

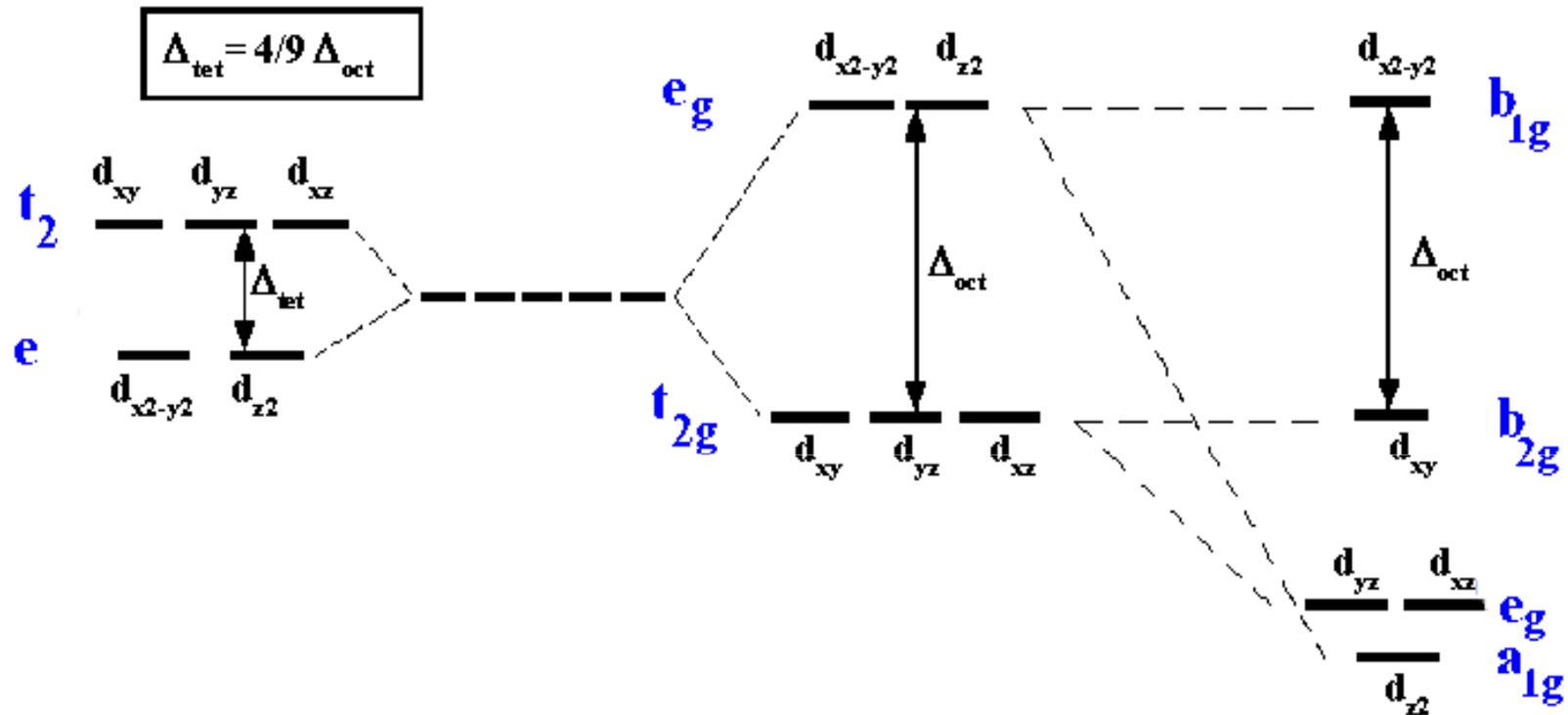


Estructura magnética del $GdCu_2$

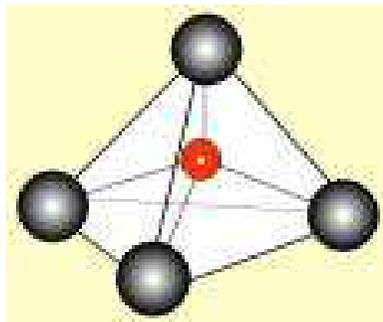


spin - órbita + campo cristalino

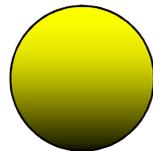
Diagramas de desdoblamiento de orbitales d por el campo cristalino



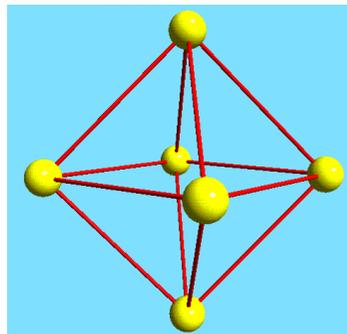
Tetrahedral field



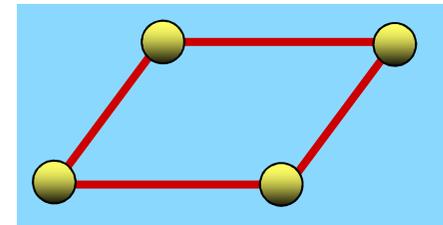
free-ion



Octahedral field

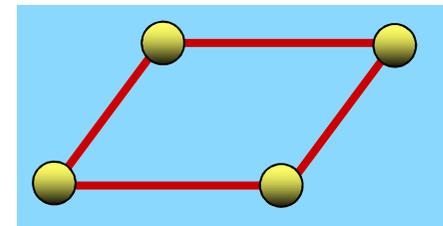
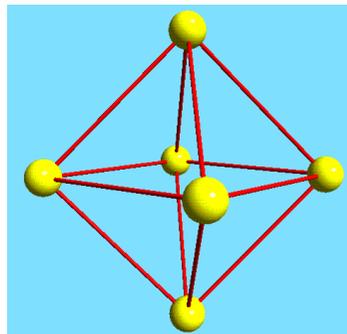
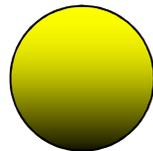
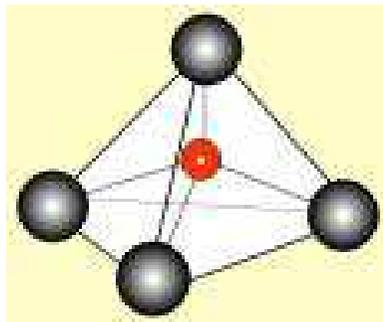
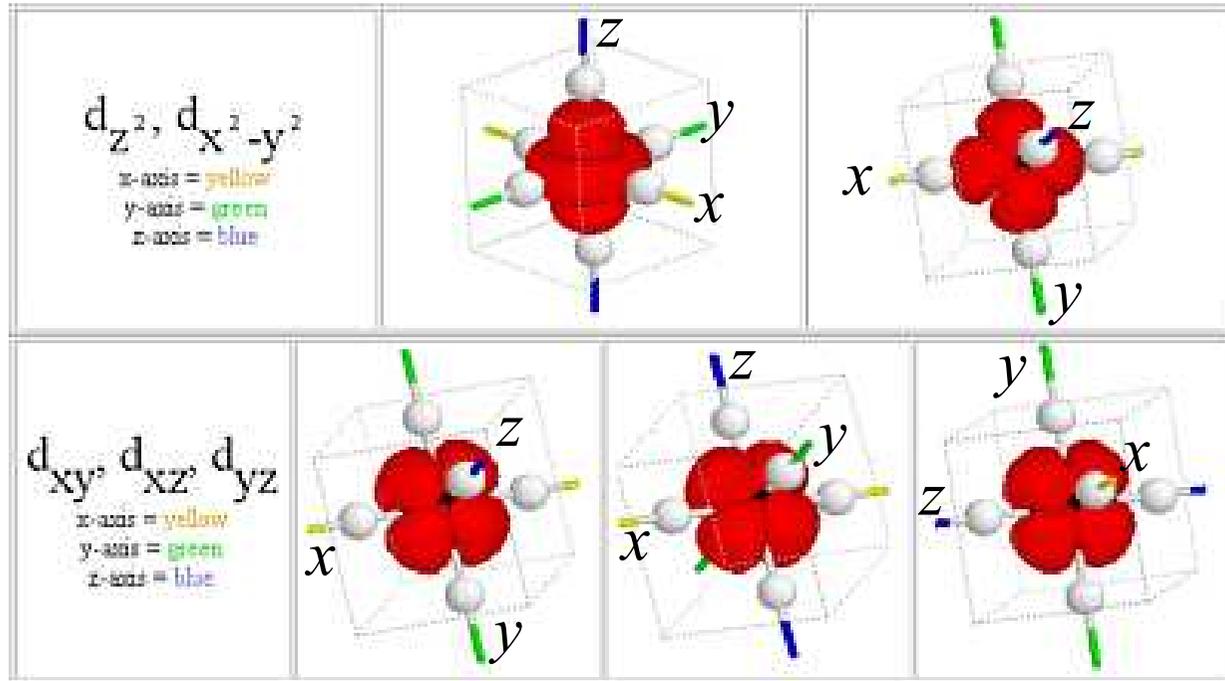


Square-planar field



spin - órbita + campo cristalino

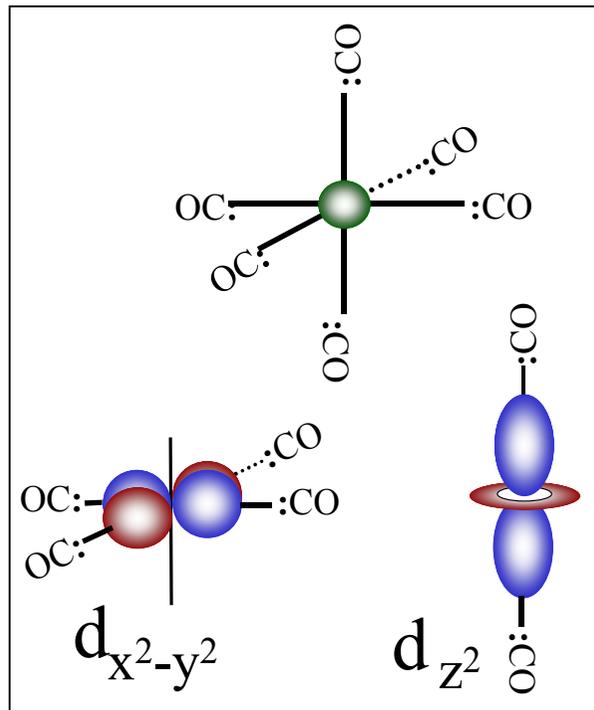
Efecto del campo cristalino sobre orbitales d



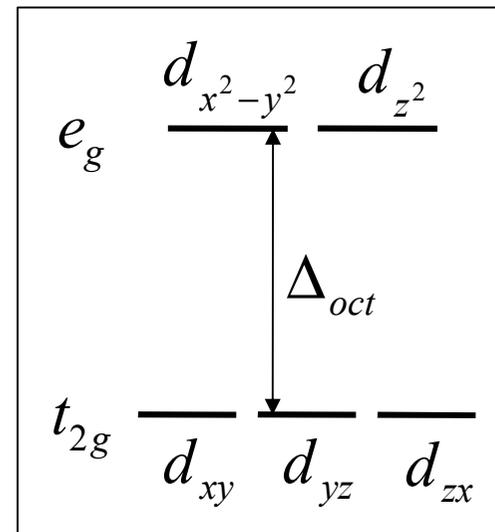
spin - órbita + campo
cristalino

Ejemplo 1

$\text{Cr}(\text{CO})_6$. Cr rodeado de 6 grupos carbonilo en simetría octaédrica. Los grupos carbonilo apuntan hacia dos orbitales d.

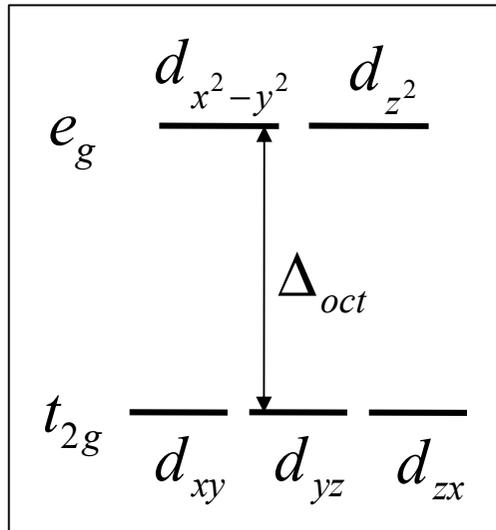


Hexacarbonilo de Cr

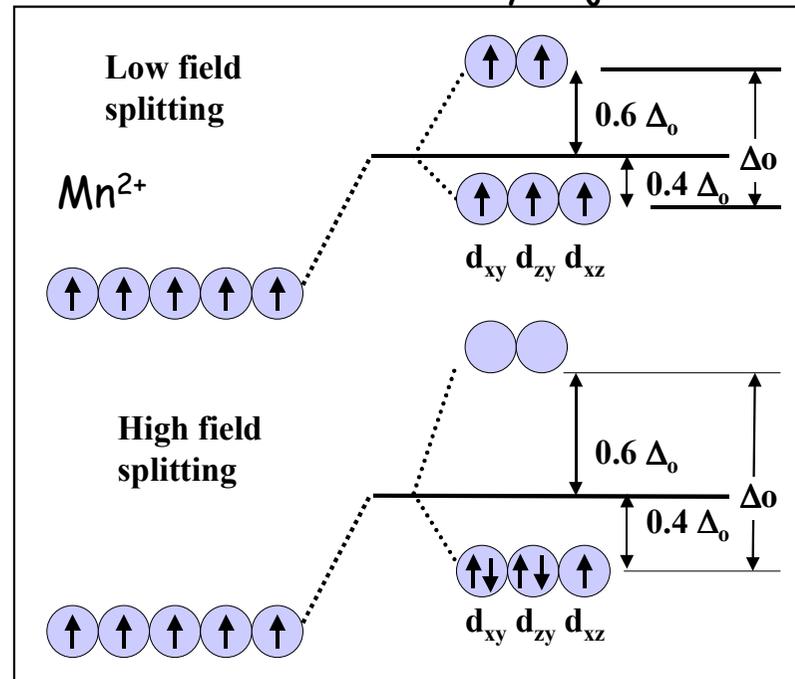


spin - órbita + campo
cristalino

Ejemplo 2



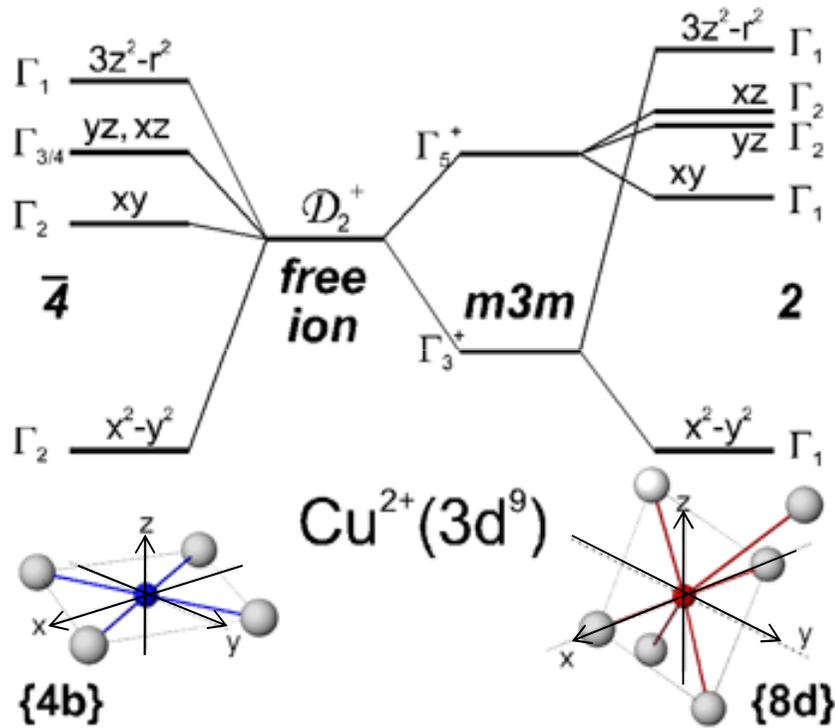
Desdoblamiento bajo campos
cristalinos altos y bajos



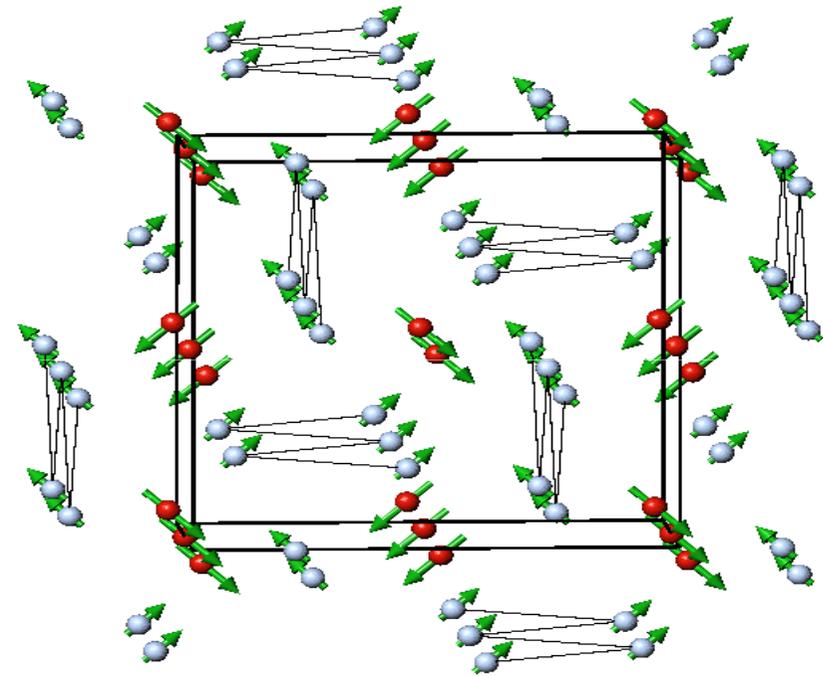
spin - órbita + campo
cristalino

Ejemplo 3

Ordenamiento Magnético del CuB_2O_4



Manfred Fiebig, September 2004 mbi-berlin.de



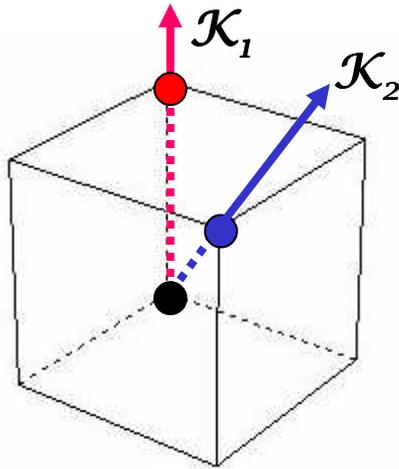
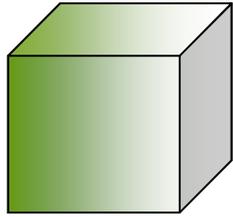
B.Roessli, J.Schefer, G.Petrakovskii, B.Ouladdiaf, M.Böhm, U.Staub, A. Vorotinov and L.Bezmaternikh. Phys. Rev. Letter, (2001).

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

Energía de anisotropía **Magnetocristalina**

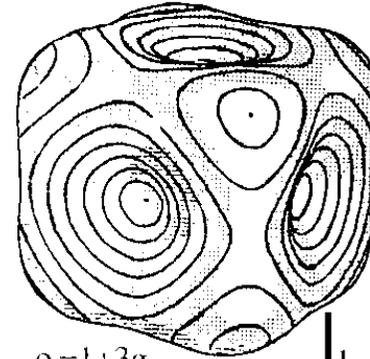
Definiciones

Geometría cúbica



a)

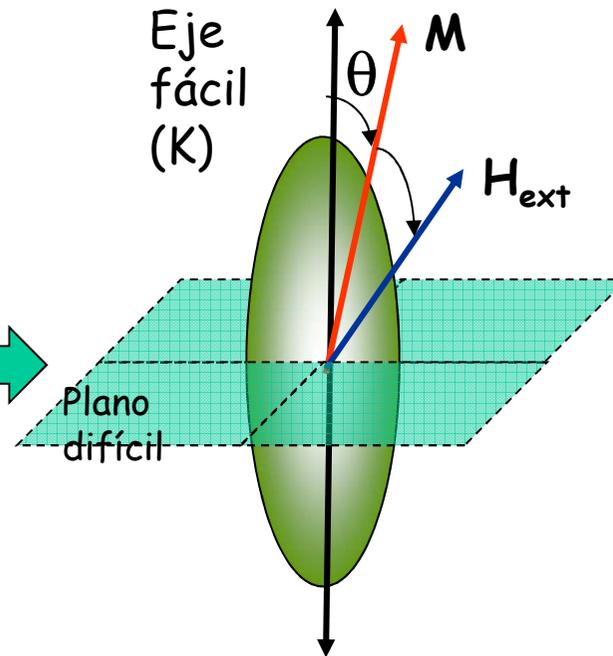
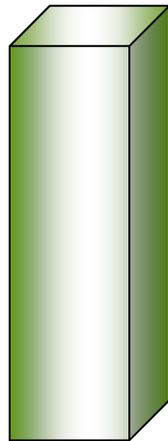
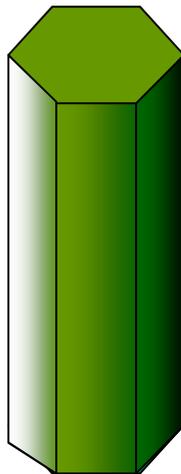
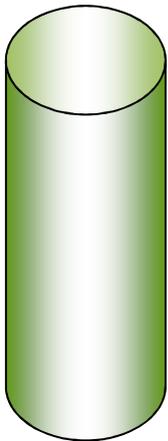
$K_{c1}=1$

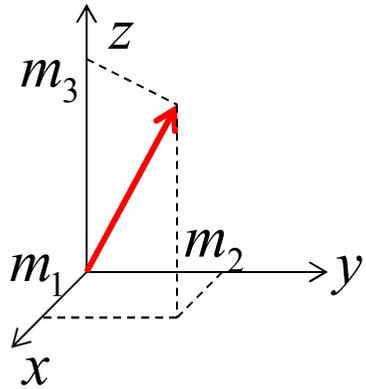


Curvas de energía constante

$\rho = 1 + 3g$
in the range
[0 (0.04) 0.333]

Geometría cilíndrica, tetragonal, exagonal





m_i cosenos directores de la magnetización

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

Anisotropía - descripción fenomenológica

E_K energía de anisotropía

e_K energía de anisotropía por unidad de volumen

$$E_K = \int e_K dV$$

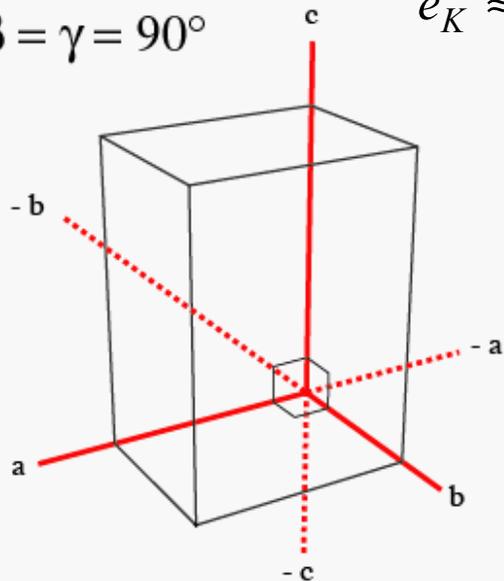
$$e_K = \sum_i K_i m_i^2 + \sum_{ij} K_{ij} m_i^2 m_j^2 + K_{123} m_1^2 m_2^2 m_3^2 + \sum_i K_i m_i^4 + \dots$$

Ejemplo: sistema ortorrómbico

Orthorhombic

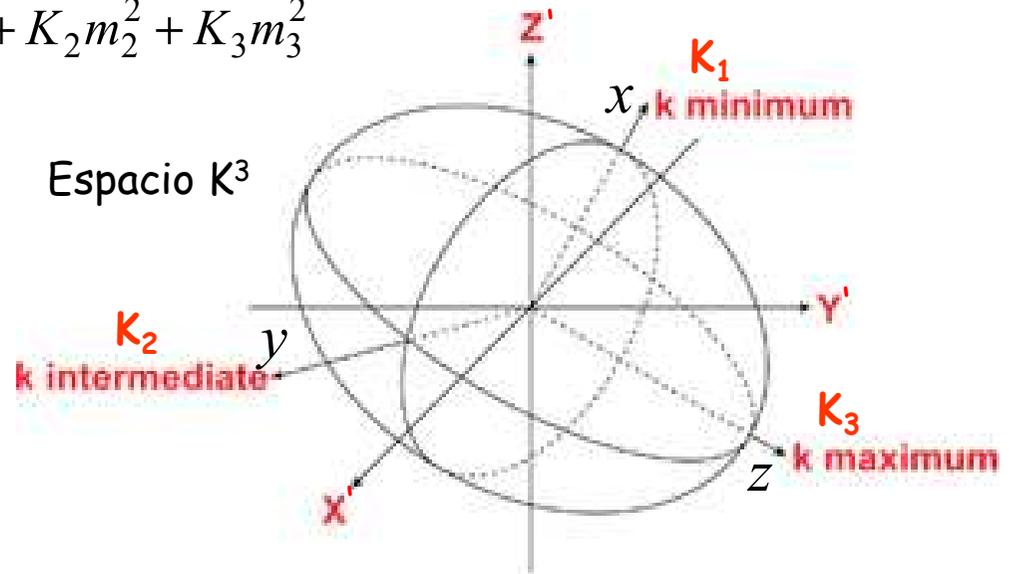
$$a \neq b \neq c$$

$$\alpha = \beta = \gamma = 90^\circ$$



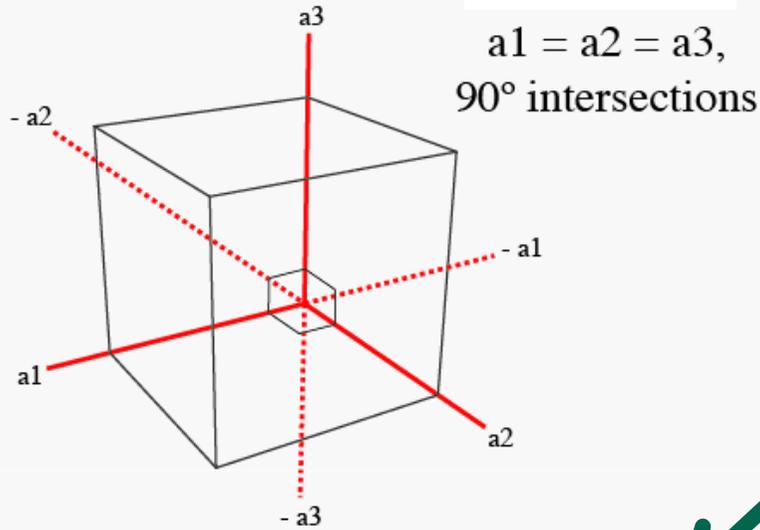
$$e_K \approx K_1 m_1^2 + K_2 m_2^2 + K_3 m_3^2$$

Espacio K^3



Anisotropía - descripción fenomenológica

sistema cúbico



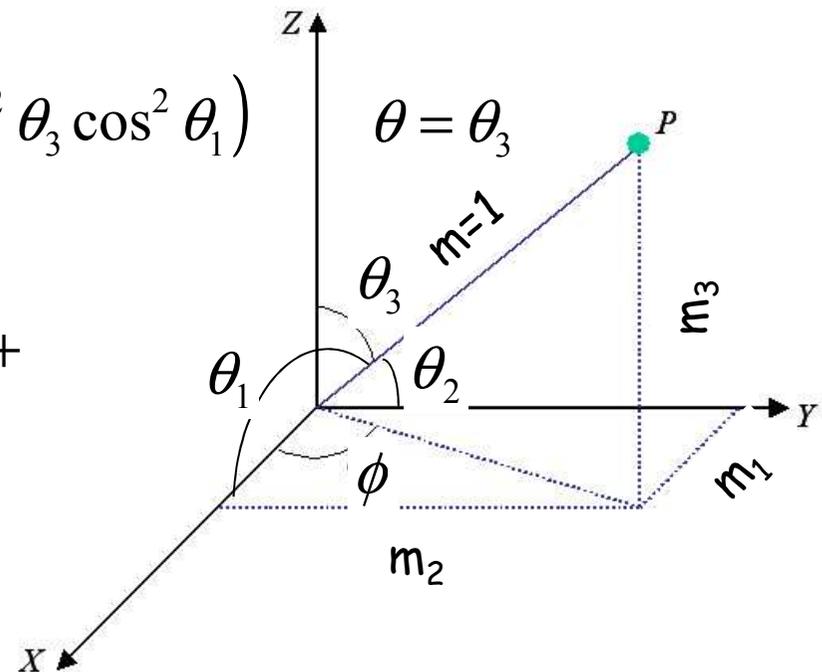
~~$$e_K \approx K_0 m_1^2 + K_0 m_2^2 + K_0 m_3^2 - K_0 (m_1^2 + m_2^2 + m_3^2) = K_0 ?$$~~

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

$$m_i = \cos \theta_i$$

$$e_K = K_1 (\cos^2 \theta_1 \cos^2 \theta_2 + \cos^2 \theta_2 \cos^2 \theta_3 + \cos^2 \theta_3 \cos^2 \theta_1) + K_2 \cos^2 \theta_1 \cos^2 \theta_2 \cos^2 \theta_3$$

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

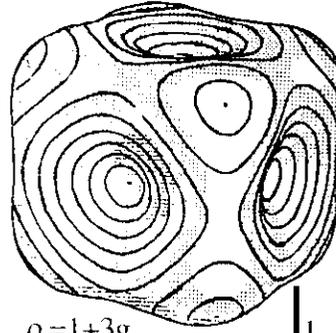


sistema cúbico

Curvas de energía constante

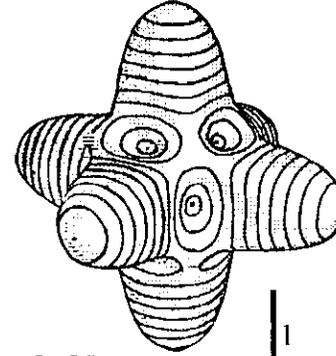
$$e_K = K_1 (m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2) + K_2 m_1^2 m_2^2 m_3^2$$

a) $K_{c1}=1$



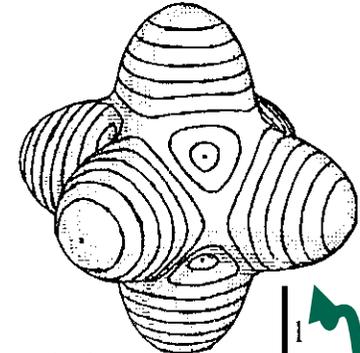
$\rho=1+3g$
in the range
[0(0.04)0.333]

c) $K_{c1}=-0.25, K_{c2}=1$



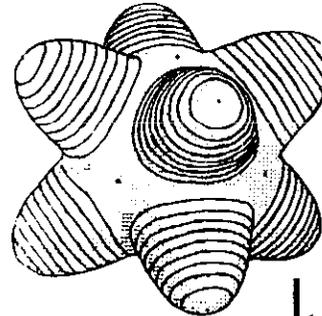
$2+20g$
[-0.063(0.006)0]

e) $K_{c1}=-0.1$



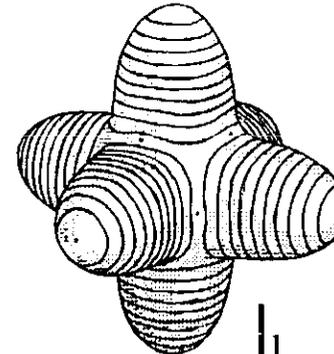
$2+3g$
[-0.333(0.04)0]

b) $K_{c1}=0.1, K_{c2}=1$



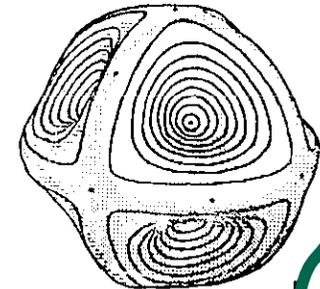
$1+20g$
[0(0.004)0.04]

d) $K_{c1}=-0.41, K_{c2}=0.9$



$2+10g$
[-0.103(0.01)0]

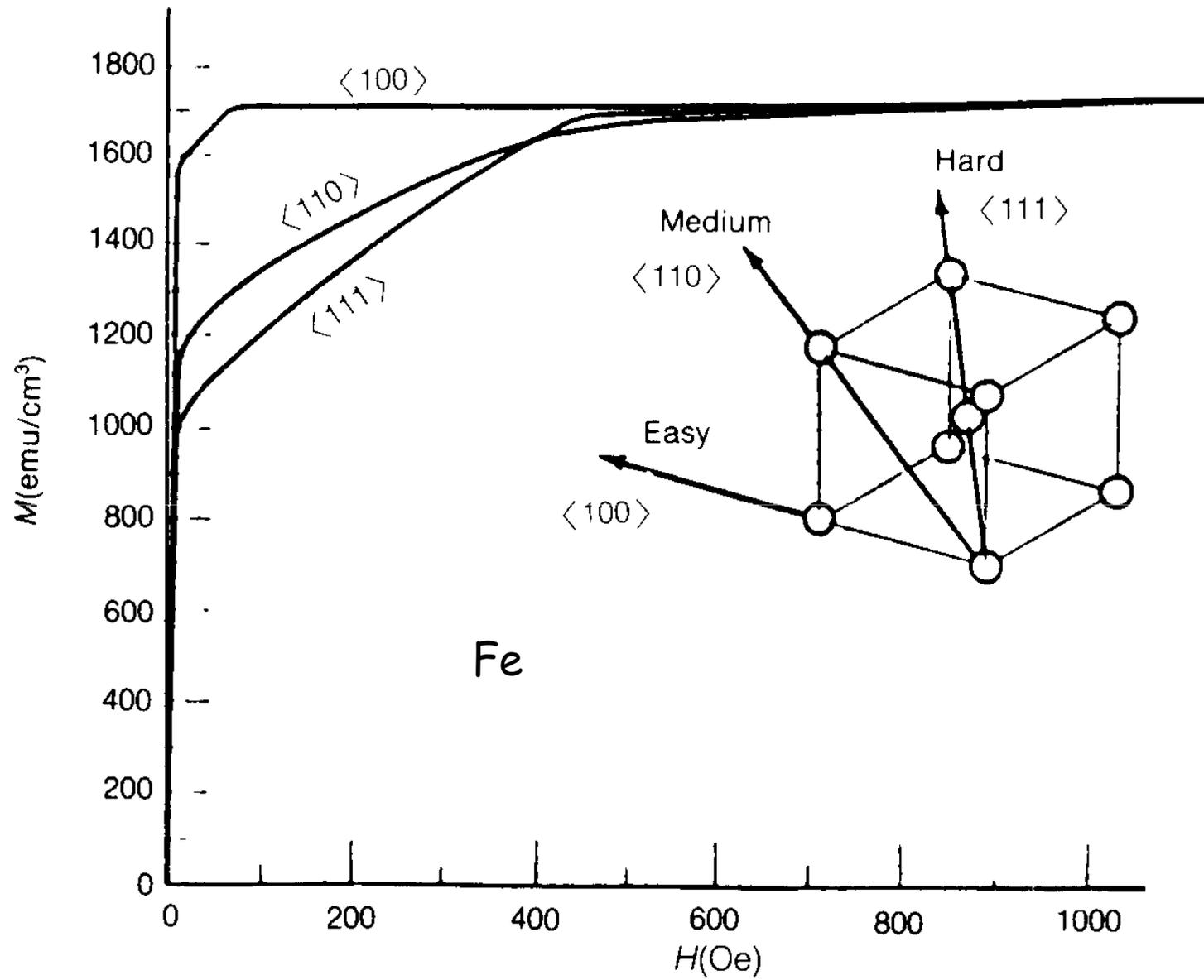
f) $K_{c1}=0.01, K_{c2}=-1$



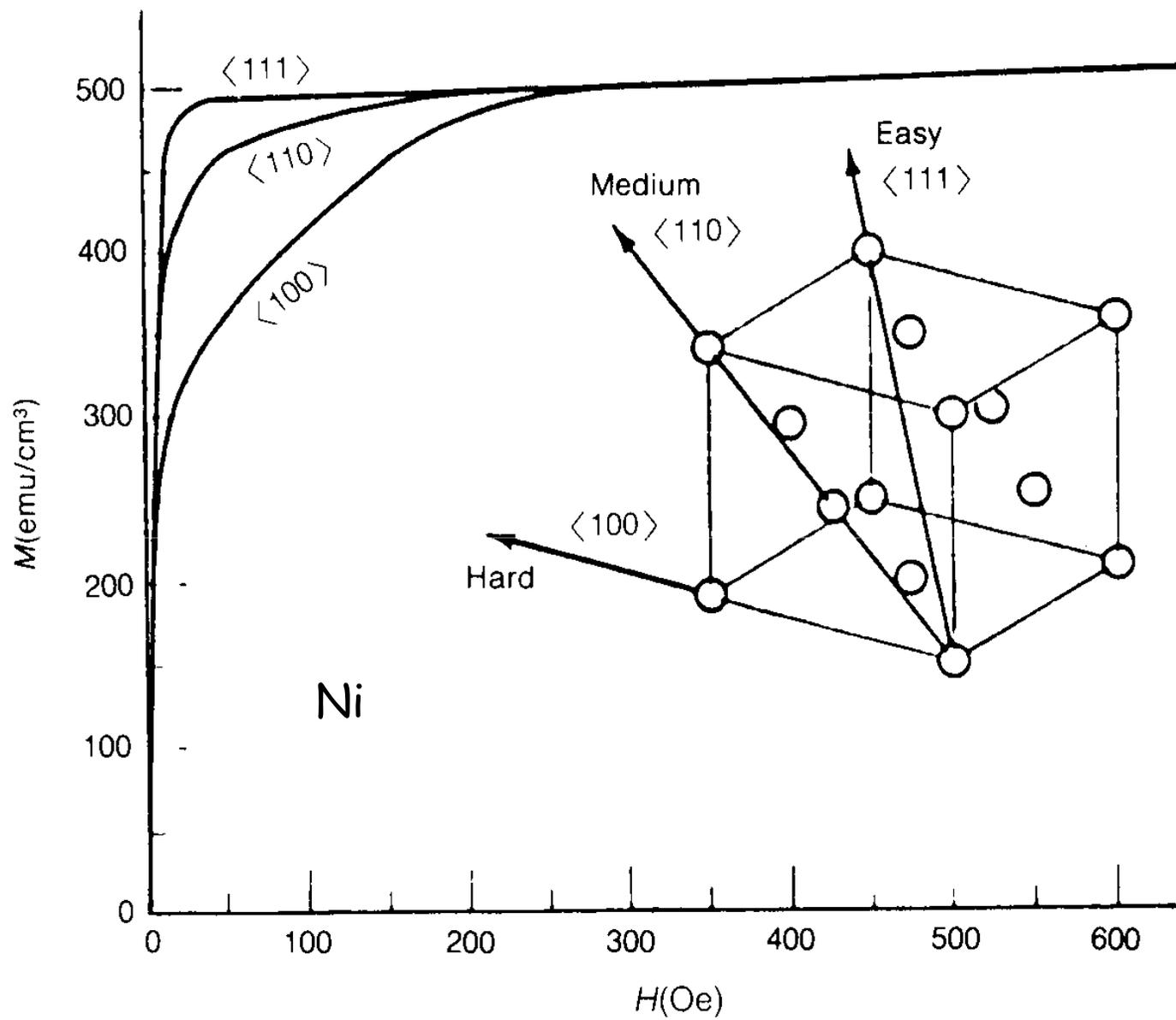
$2+25g$
[-0.334(0.004)0.003]

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

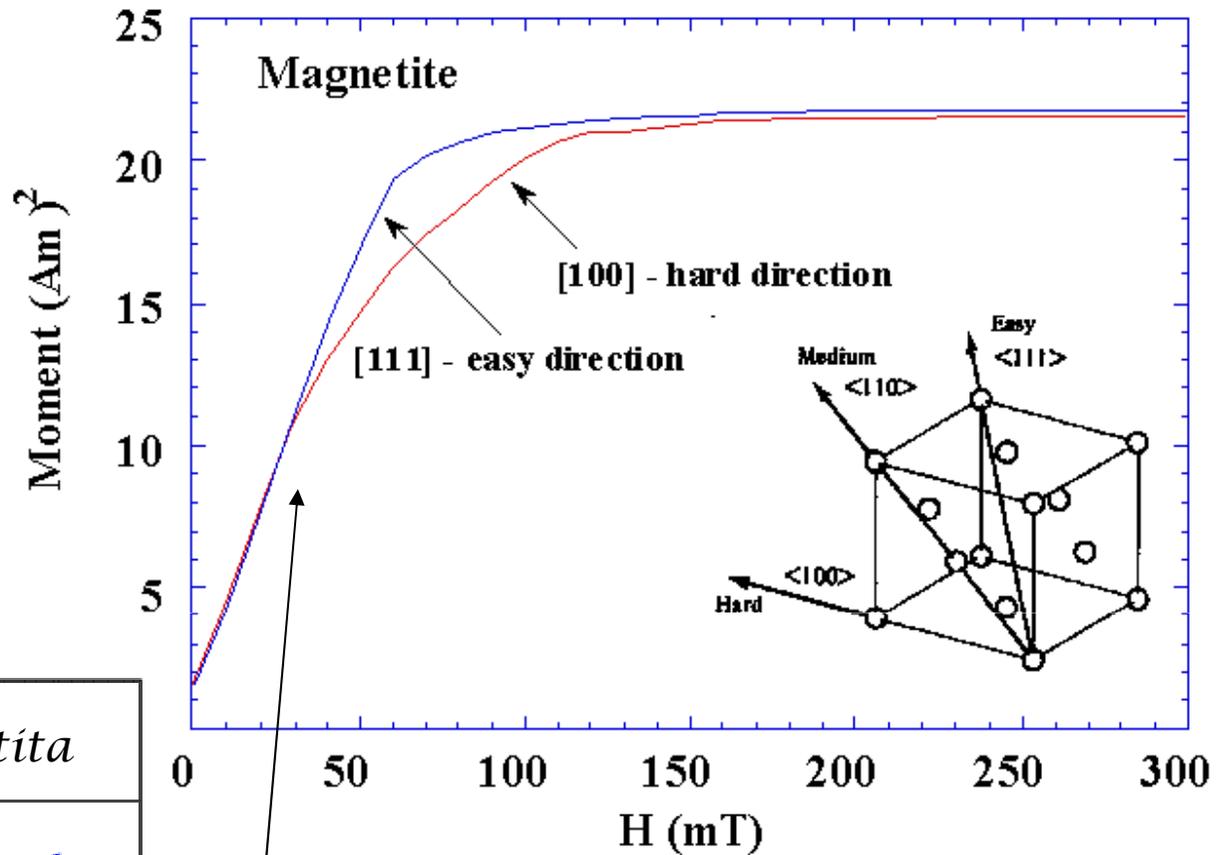
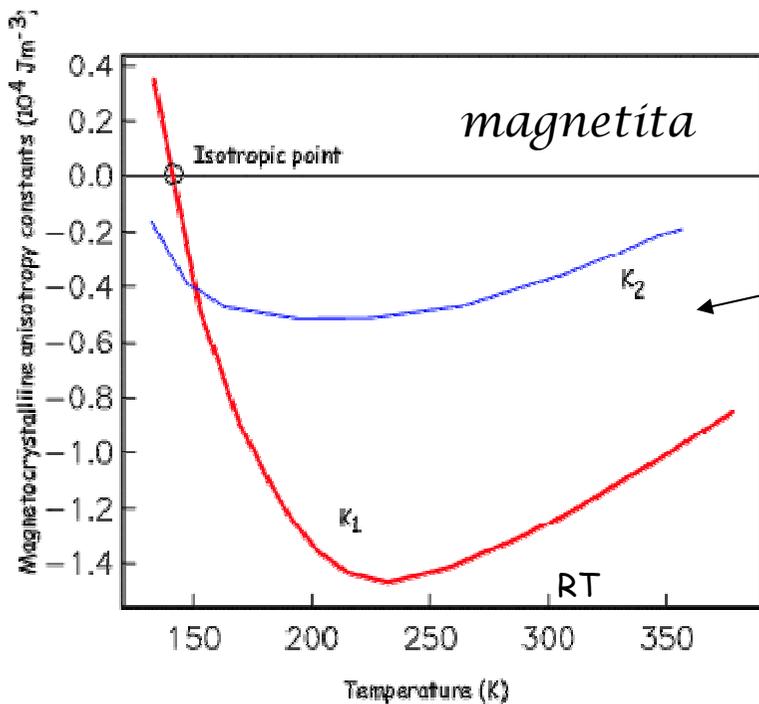


sistema cúbico



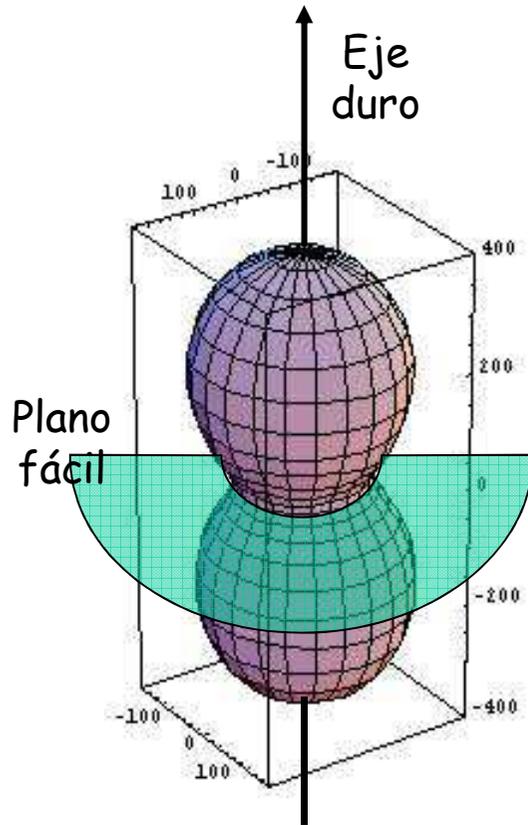
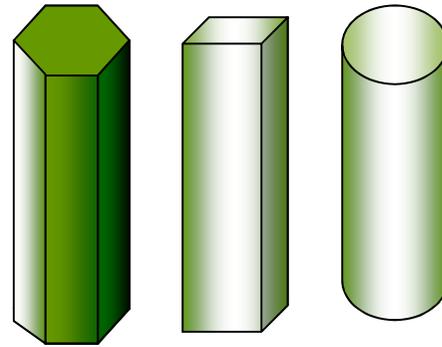
sistema cúbico

Dependencia de la anisotropía con la temperatura en la Magnetita



Ojo!! colores invertidos

Sistemas hexagonal y tetragonal



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

usando $\cos^2 \theta = 1 - \sin^2 \theta$

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

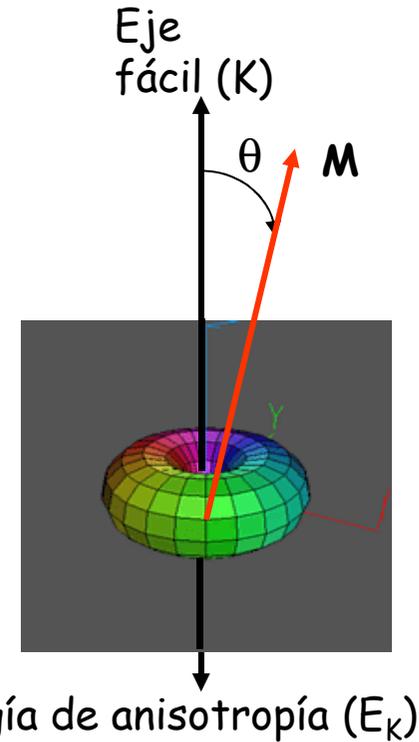
llamando

$$K_1' = -(K_1 + 2K_2)$$

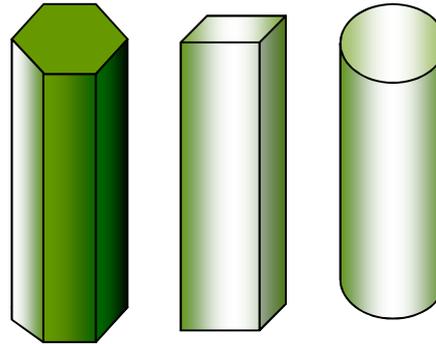
$$K_2' = K_2$$

y corriendo el cero de la energía

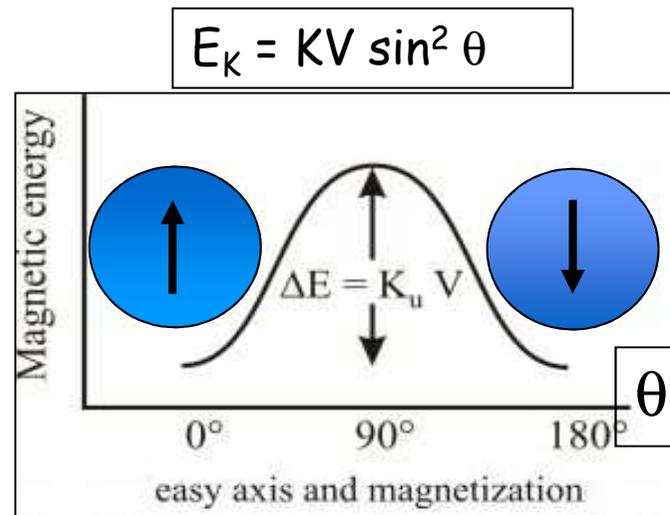
$$e_K = K_1' \sin^2 \theta + K_2' \sin^4 \theta$$



Sistemas hexagonal y tetragonal



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



Sistemas hexagonal y tetragonal

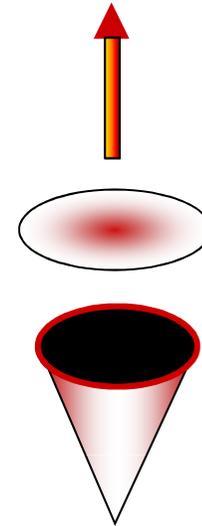
Anisotropía uniaxial (hexagonal y tetragonal)

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

$K_1 > 0$ y $K_1 \gg |K_2| \Rightarrow$ eje fácil $\theta = 0$
anisotropía uniaxial

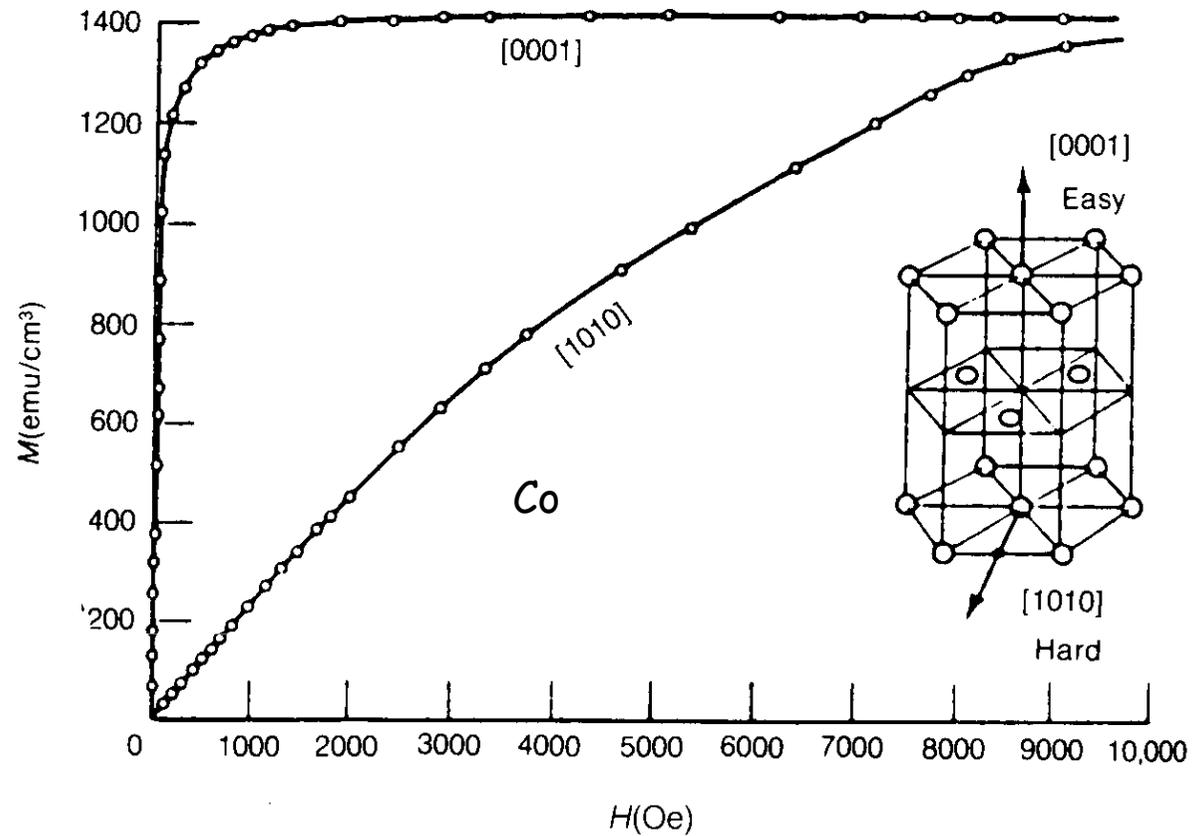
$K_1 < 0$ y $|K_1| \gg |K_2| \Rightarrow$ plano fácil $\theta = \pi/2$
anisotropía planar

$-2 < K_1 / K_2 < 0 \Rightarrow 0 < \sin^2 \theta < 1$
anisotropía cónica



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

Sistemas hexagonal y tetragonal



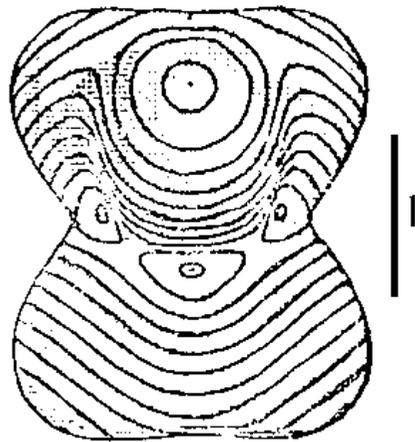
Material	K_{u1} (10^5 J/m ³)	K_{u1} (10^5 J/m ³)	Eje fácil
Co	4.1	1.0	hexagonal
SmCo ₅	1100	-	hexagonal

situaciones con anisotropías más complejas:

$$e_K = \underbrace{K_{u1} \sin^2 \theta + K_{u2} \sin^4 \theta}_{\text{uniaxial}} + \underbrace{K_{c1} \sin^2 \theta (\sin^2 \theta \sin^2 \phi \cos^2 \phi + \cos^2 \theta)}_{\text{cúbica}}$$

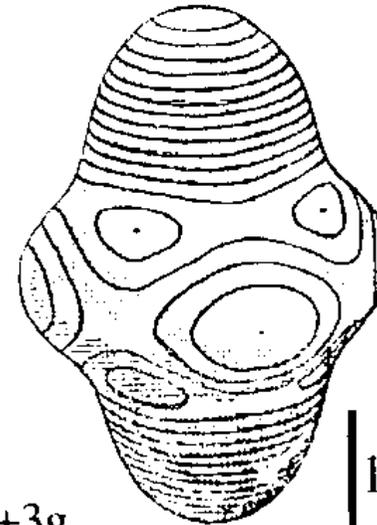
ejemplos

g) $K_{c1} = -0.4,$
 $K_{u1} = -0.15 [111]$



$2+5g$
 $[-0.272 (0.018) -0.086]$

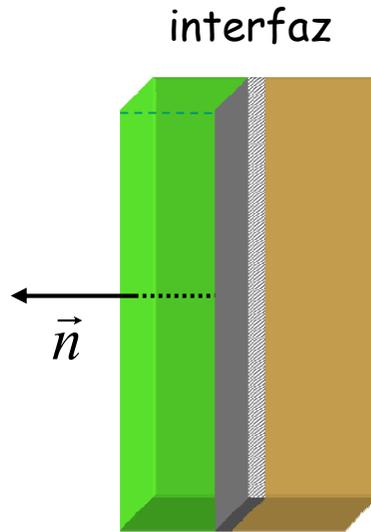
h) $K_{c1} = 0.1, K_{u1} = -1$
 $K_{u2} = 0.75 [111]$



$2+3g$
 $[-0.291 (0.02) 0]$

superficies e interfaces

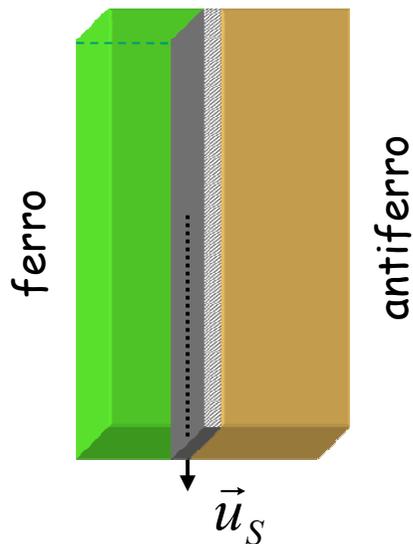
Anisotropía de interfaz



$$e_K = K_S [1 - (\vec{m} \cdot \vec{n})^2]$$

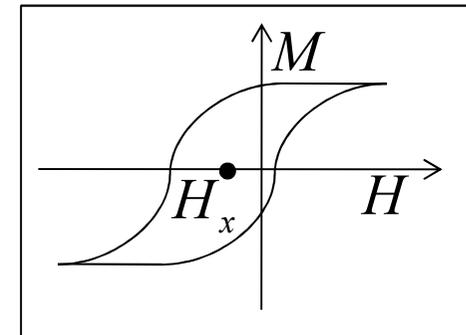
$K_S > 0 \Rightarrow \vec{m} // \text{sup}$
 $K_S < 0 \Rightarrow \vec{m} \perp \text{sup}$

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

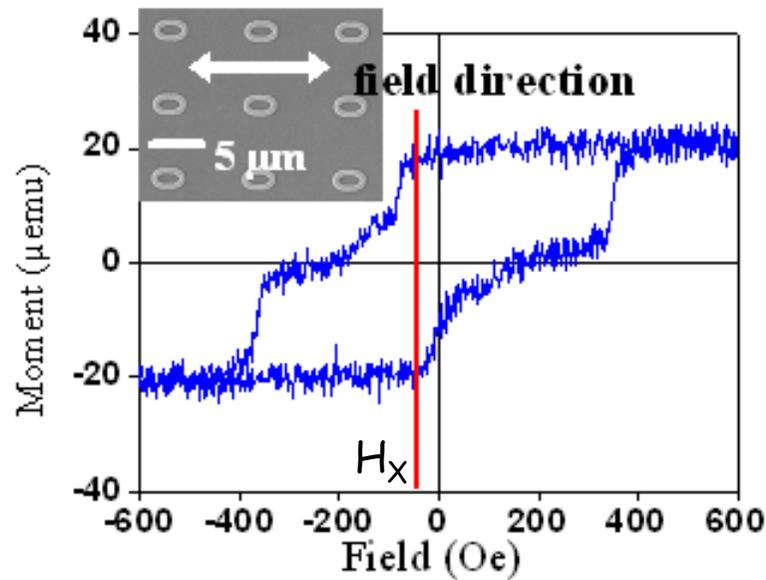
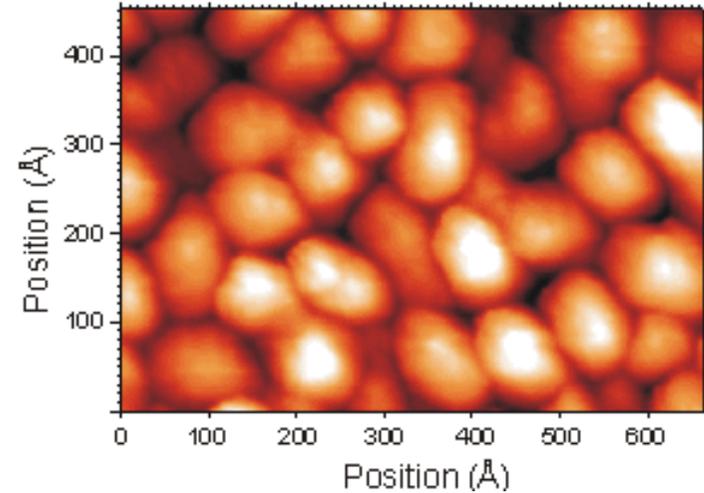
Otros usos: superficies e interfaces

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

