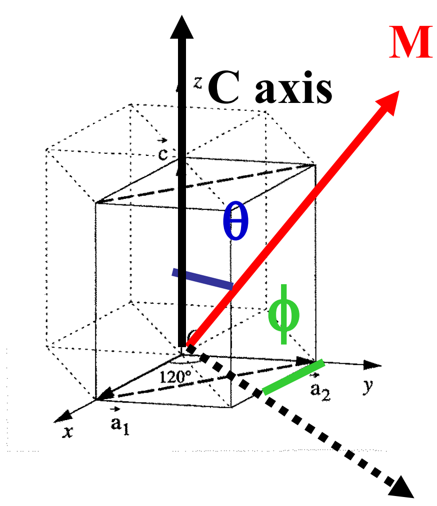
Magnetic anisotropy or better Magnetocrystalline anisotropy

- The magneocrystalline anisotropy energy is expressed by the formula :

$$E_a(\theta,\phi) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} K_n^m P_n^m(\cos\theta)\cos m\phi$$

- where P_n^m represents the Legendre polynoms,
- K_n^m anisotropy constants,

∀ θ and ϕ are the polar and azimutal angles (sphéric coordinates) of magnetization direction.

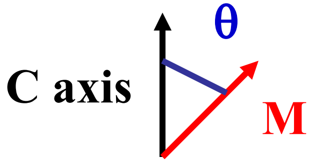


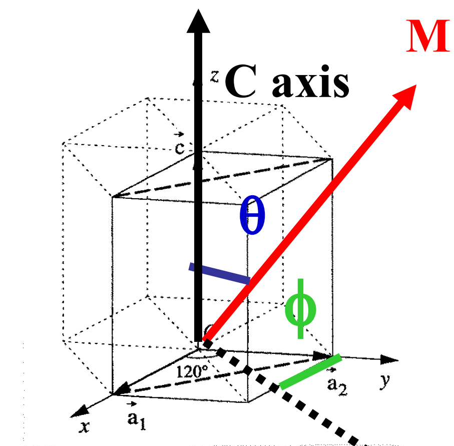
•K.H.J. Buschow and F.R. de Boer (2003) "Physics of Magnetism and materials" Kluver Academic/Plenum publisher

Magnetic anisotropy or better Magnetocrystalline anisotropy

uniaxial symmetry

$$E_a(\theta,\phi) = K_1 \sin^2\theta + K_2 \sin^4\theta + \cdots$$





Hexagonal symmetry

$$E_a(\theta,\phi) = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_4 \sin^4\theta\cos(6\phi) + \ldots$$

a

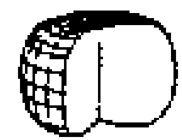
E is an important parameter for soft and hard magnetic materials

Crystal electric field

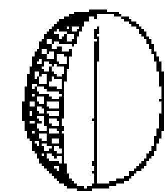
$$V(\vec{r}) = \sum_{l} \sum_{m=-l}^{+l} A_l^m r^l Y_l^m(\vec{r})$$

A_l^m Crystal electric field coefficients

Y_l^m Spherical harmonics



Nd

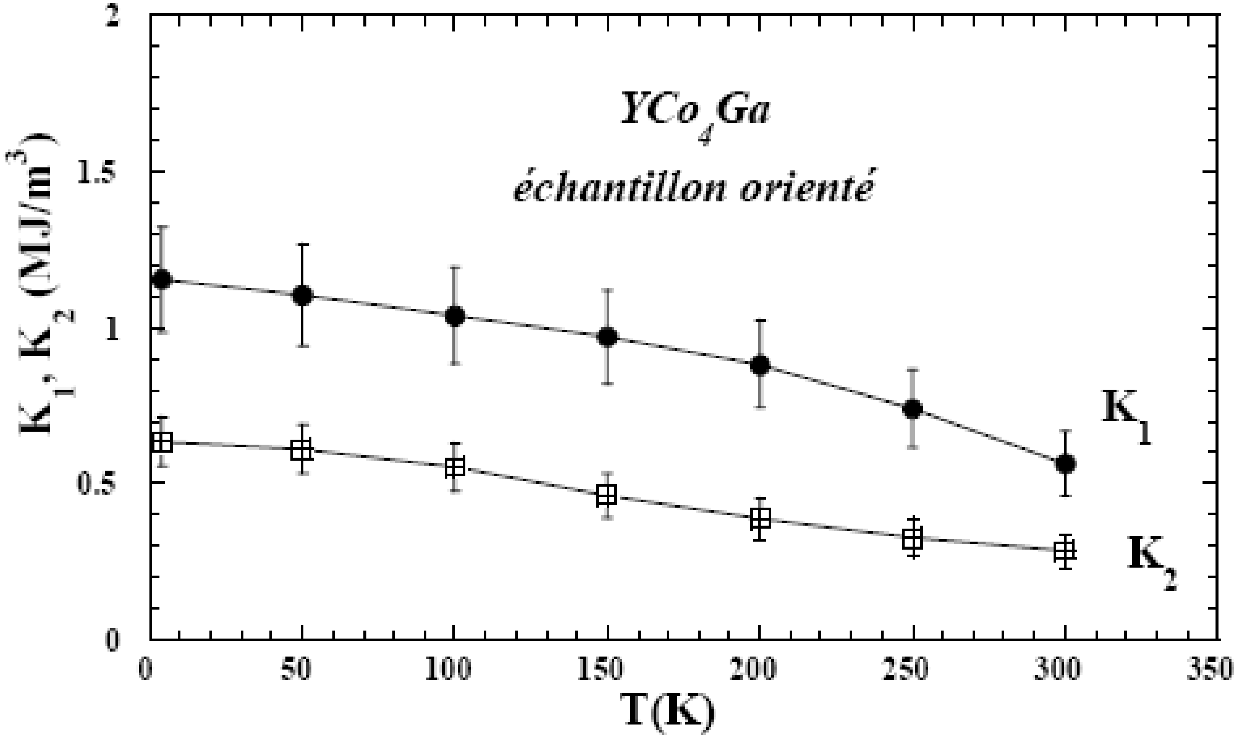


Sm

- Coupling with the 4f electronic shell
- Favors the orientation of the shell in the electric field gradient

- Hutchings, M. T. (1964) *Solid state phys., 16,* 227.
- Stevens coefficients

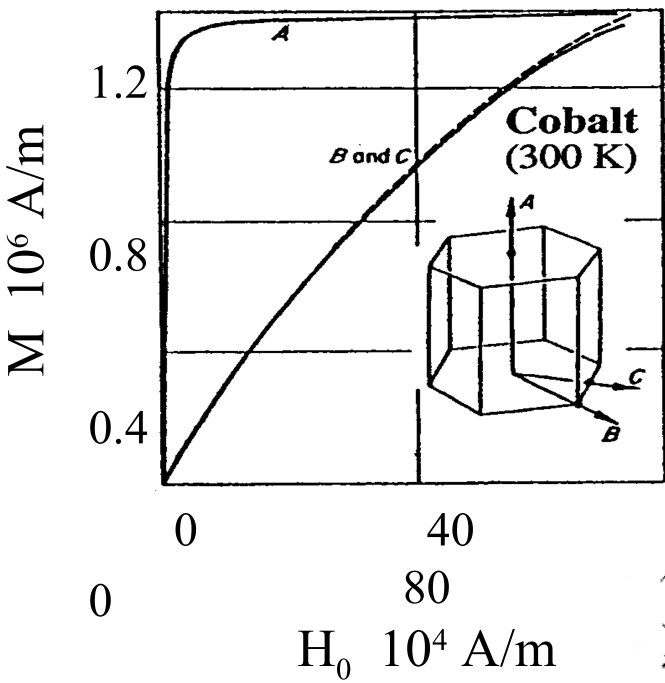
Anisotropy constant may vary with T !



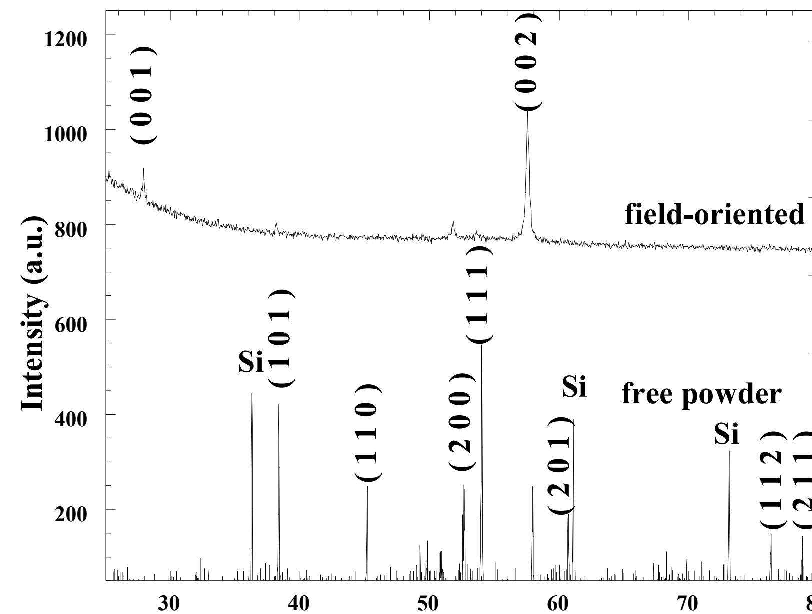
May even change of sign

How to identify the Easy Magnetization Direction

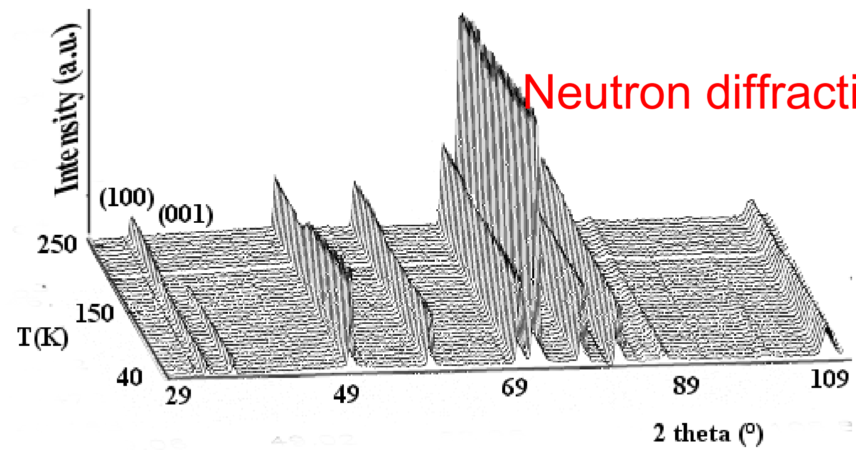
Magnetization curves



X-ray diffraction

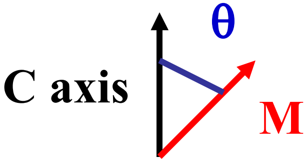


Neutron diffraction experiments

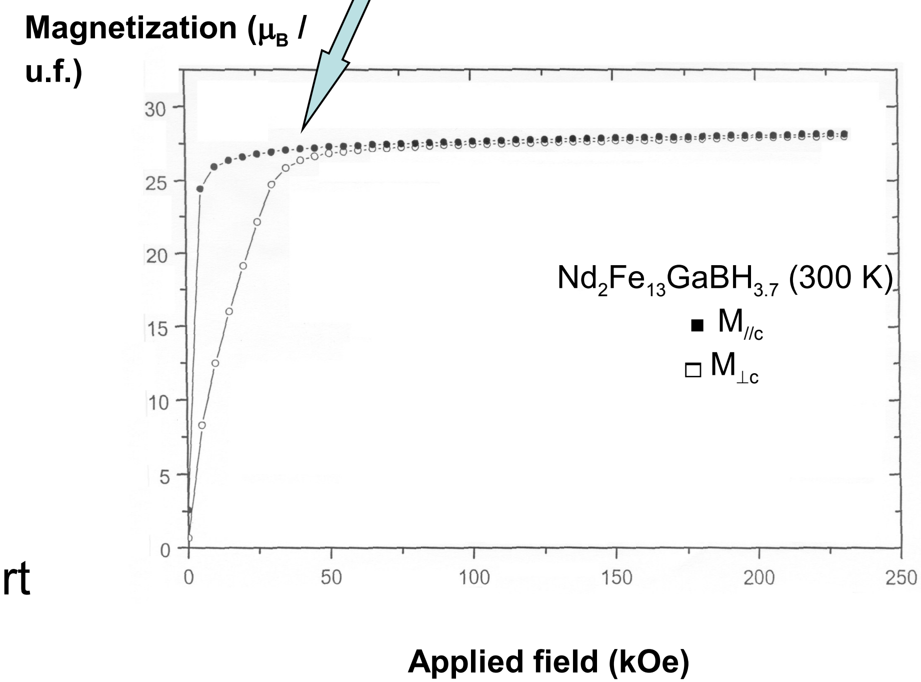


Anisotropy field

$H_a = 2\,K_1 / \;\mu_0 M_s + \ldots$



$H_a = 2\,K_1 / \mu_0 M_s$



c a

See talk O. Fruchart

H < H

Higher order :

$$\mu_0 H_a = (2K_1 + 4K_2) / M_S.$$

Rare earth contribution to magnetocrystalline anisotropy

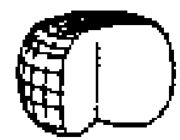
$$K_1(T=0) = -\frac{3}{2}\alpha_J \langle r^2 \rangle^{4f} (3J_z - J(J+1))A_2^0$$

Purely Atomic parameter

α_J second order Stevens coefficient (α_J) for R^{3+}

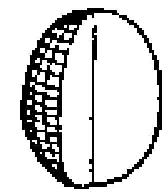
$$(3J_z - J(J+1))$$

$\langle r^2 \rangle^{4f}$ 4f shell



Nd

$\alpha_J < 0$



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$\alpha_J > 0$

Atomic environment electric charges

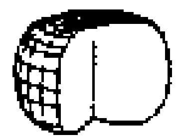
A_2^0 **Crystal electric field gradient**

Remark : $\alpha_J \langle r^2 \rangle^{4f} (3J_z - J(J+1))$ **Quadrupolar moment**

2 order Stevens coefficient

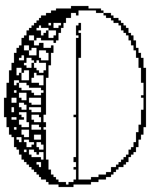
Ion	Ce^{3+}	Pr^{3+}	Nd^{3+}	Sm^{3+}	Tb^{3+}	Dy^{3+}	Ho^{3+}	Er^{3+}	Tm^{3+}	Yb^{3+}
$\alpha_J\ 10^2$	-5,71	-2,10	-0,64	+4,13	-1,01	-0,63	-0,22	+0,25	+1,01	+3,17

Similar equation for K_2; K_3 and so on



Nd

$\alpha J < 0$



Sm

$\alpha J > 0$

- **References**

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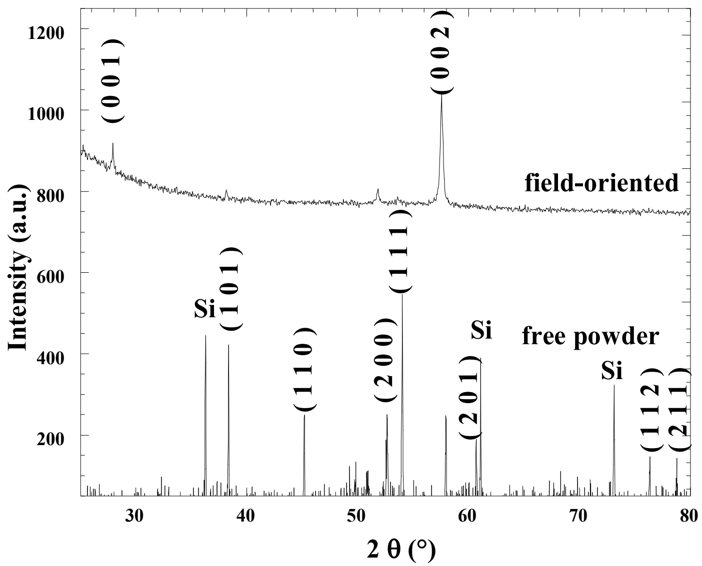
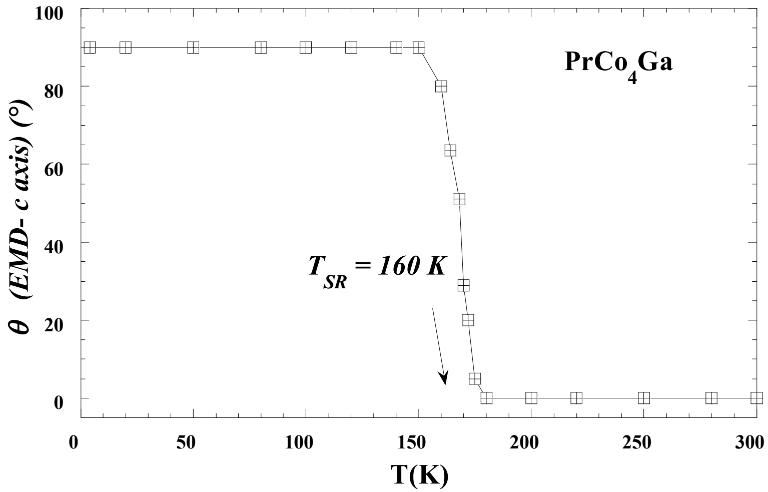
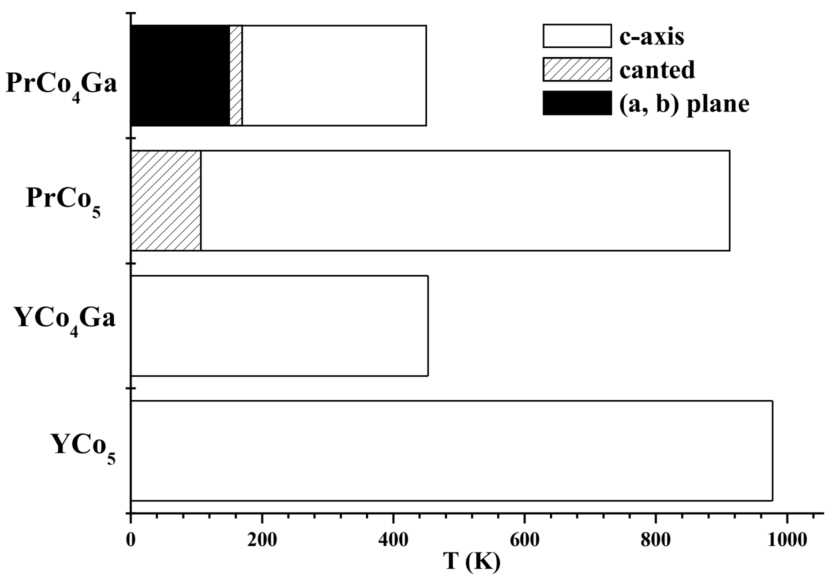
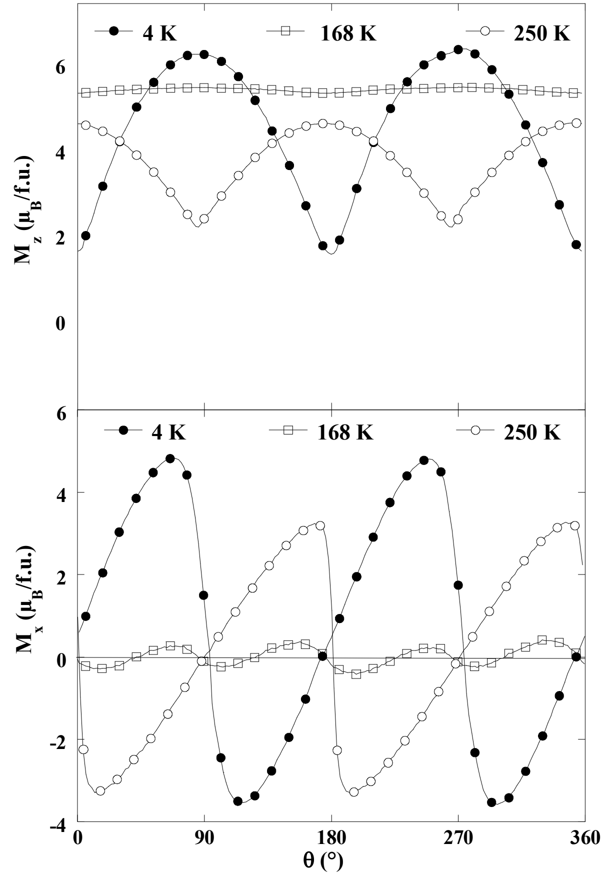
- K.W.H. Stevens, Proc. Phys. Soc., 65, (1951), p. 209.
- K.H.J. Buschow and F.R. de Boer (2003) “Physics of Magnetism and materials” Kluver Academic/Plenum publisher
- K.H.J. Buschow, Magnetism and Processing of Permanent Magnet Materials, Handbook of Magnetic Materials Volume 10, édited by K.H.J. Buschow, Elsevier Science B.V., Amsterdam (1997), Ch. 4, p. 463. ISBN 0 444 853138.

More complex behaviour :

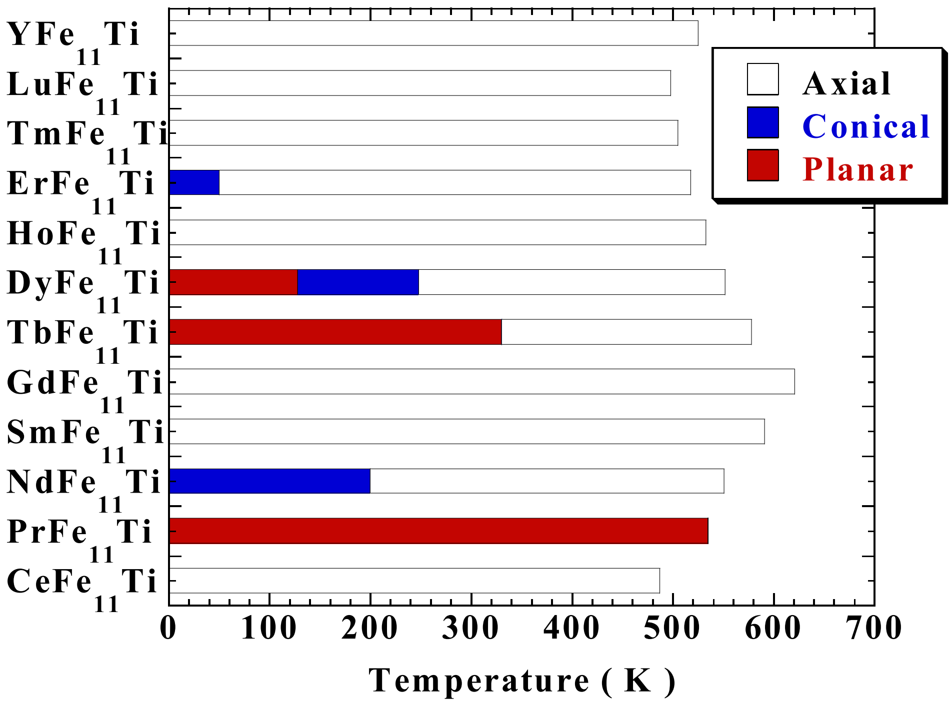








Complex behaviour



Magnetic phase diagram

K_1	$K_1 > 0$	$K_1 > 0$	$K_1 < 0$	$K_1 < 0$
K_2	$\infty > K_2 > -K_1$	$-K_1 > K_2 > -\infty$	$-K_1/2 > K_2 > -\infty$	$\infty > K_2 > -K_1/2$
EMD	$\theta = 0$; axe c	$\theta = 90$; plan de base		$\theta = \arcsin(-K_1/2K_2)^{1/2}$; cône