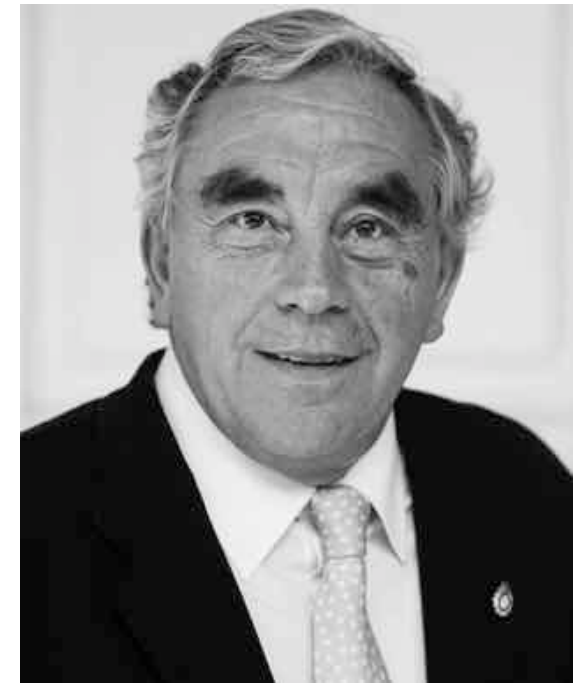


# CEMAG

Club Español de Magnetismo

## Premio Salvador Velayos

Girona 12 Noviembre 2021



colores de  
**almodóvar**

**¿QUÉ HE  
HECHO YO PARA  
MERECE  
ESTO?**




# 50 años a vueltas con la Magnetostricción (1972-2022) y unos pocos de neutrones

Manu Barandiaran



Universidad  
del País Vasco

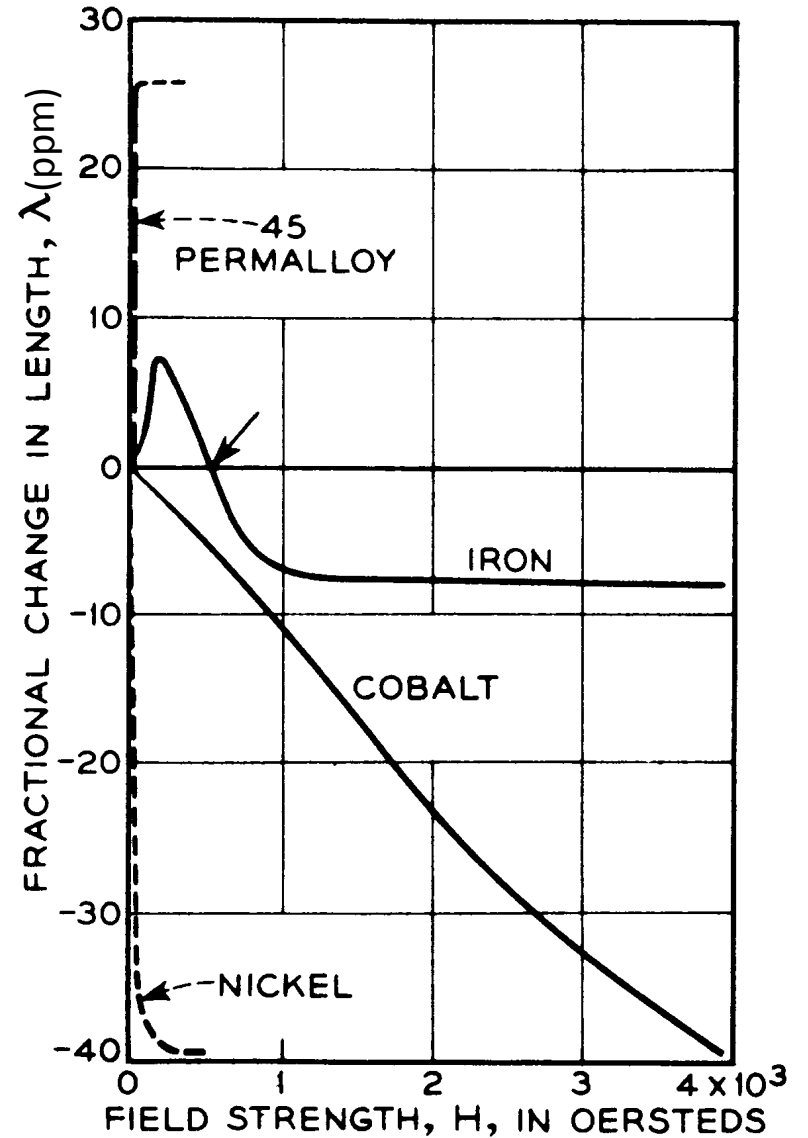
Euskal Herriko  
Unibertsitatea

Grupo de   
Magnetismo y Materiales Magnéticos

# Magnetostricción (JP Joule, 1848)

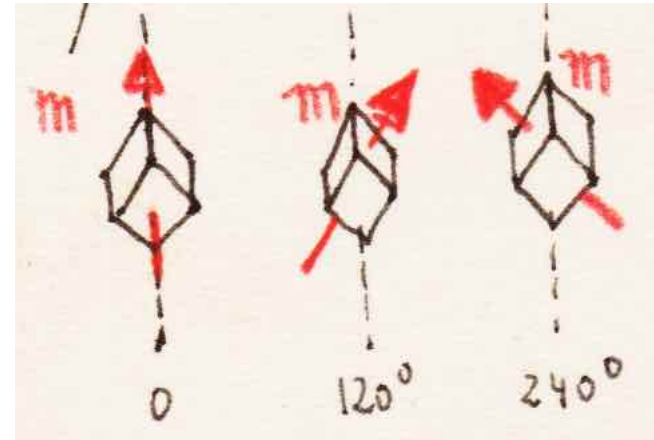
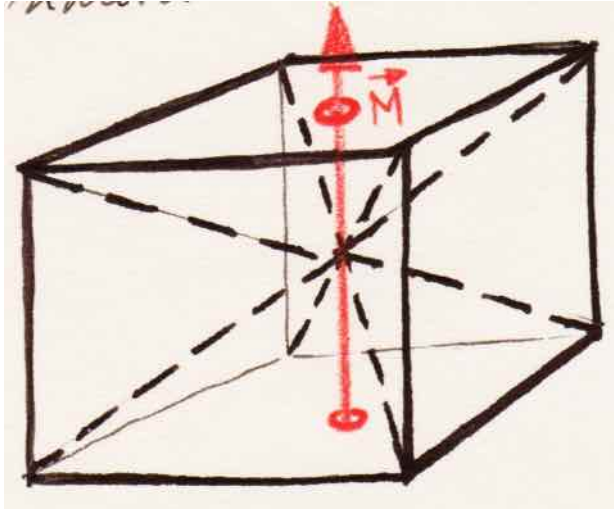


Magnetostricción  $10^{-7} \leq \lambda_s \leq 10^{-3}$   
Expansión térmica  $10^{-6} \text{ K}^{-1} \leq \alpha \leq 10^{-4} \text{ K}^{-1}$

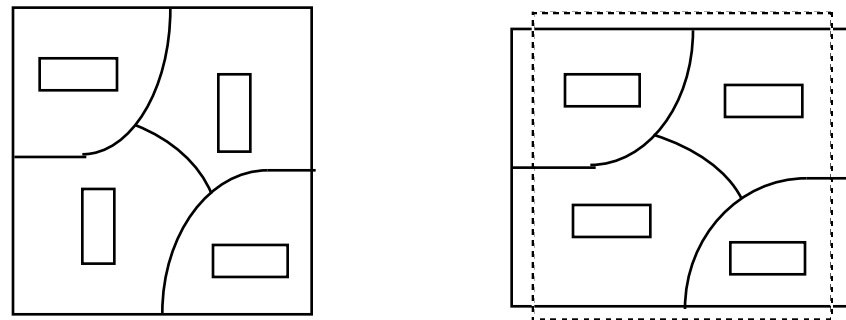


# 1972 trabajo para “Magnetismo” de 5º (Don Salvador)

## Magnetostricción (argumento de simetría)



Un cristal cúbico, imanado, pierde sus ejes ternarios  $\rightarrow$  cristal tetragonal  
¡Tiene que existir una deformación ligada a la imanación!



magnetostricción macroscópica

# **Théorie du magnétisme**

André Herpin; Louis Néel, Presses Universitaires de France (PUF), Paris 1968.

# **Ferromagnetismus**

R. Becker and W. Döring, J. Springer, Berlin, 1939

# **Magnetostriction, Forced Magnetostriction, and Anomalous Thermal Expansion in Ferromagnets**

Earl Cullen and Herbert B. Cullen, Phys. Rev. 139, A455 (1965)

# **Magnetostriction: Theory and Applications of Magnetoelasticity**

Étienne du Trémolet de Lacheisserie, CRC-Press, Boca Raton, 1993

# **Handbook of magnetostriction and magnetostrictive materials. (2 Vols.)**

Agustín del Moral, Del Moral Publ., University of Zaragoza, 2008

# Magnetostricción

Deformación por imanación

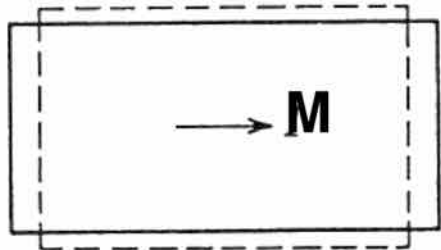
$$K_u = (3/2) \lambda_s \sigma$$

$\lambda_s > 0$



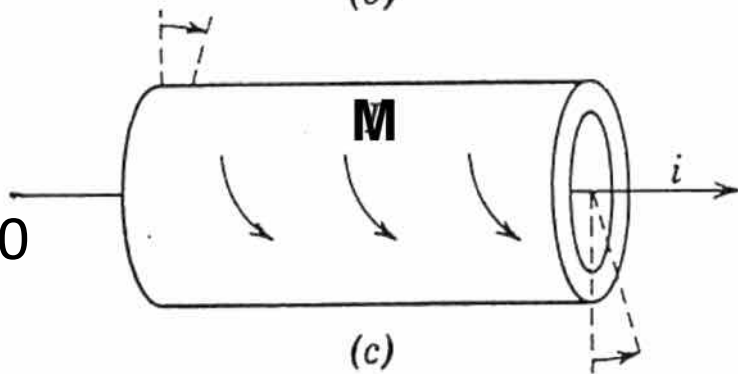
(a)

$\lambda_s < 0$



(b)

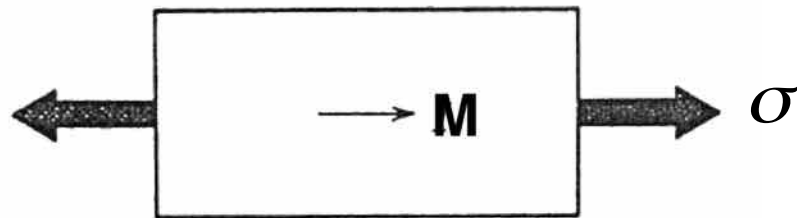
$\lambda_s > 0$



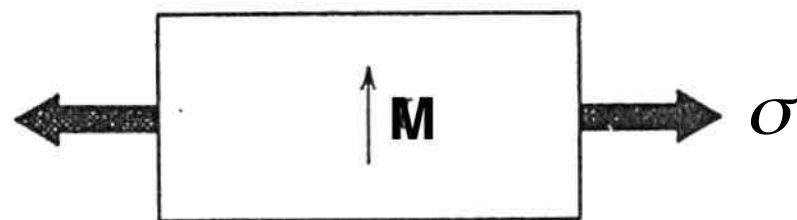
(c)

# Magnetoelasticidad

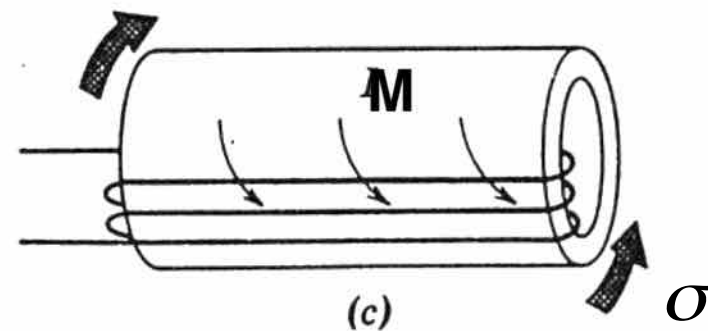
Imanación por esfuerzo o tensión



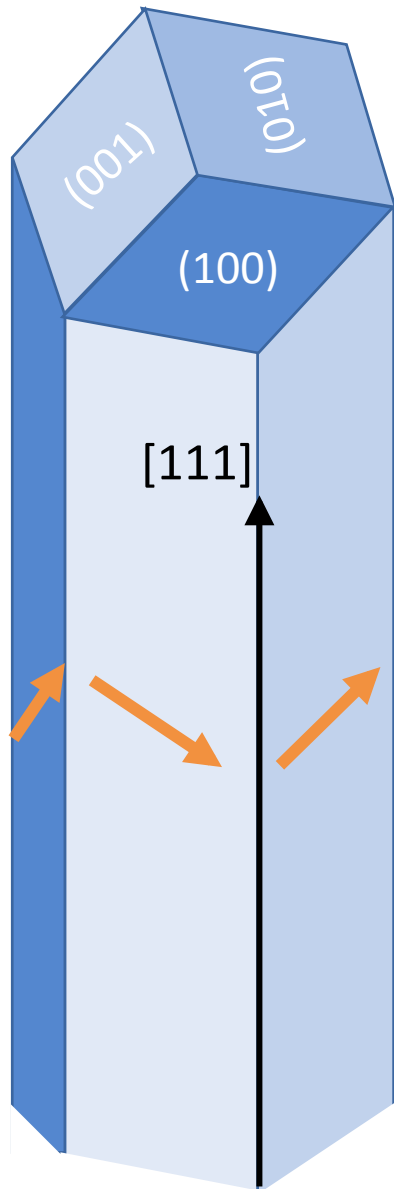
(a)



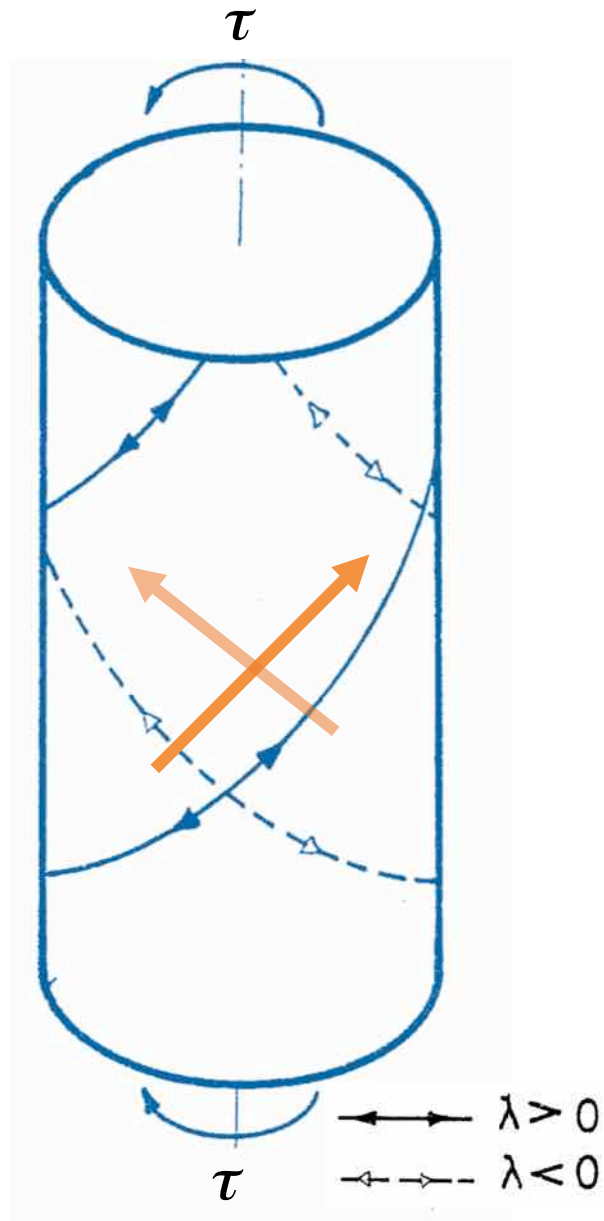
(b)



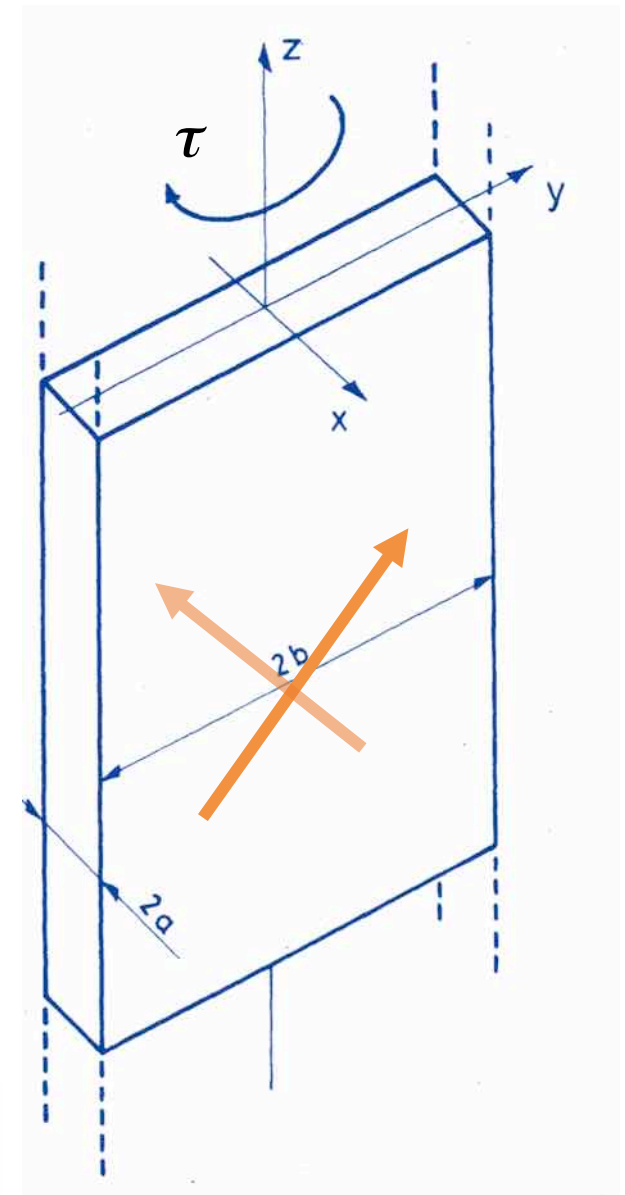
(c)



Whisker [111]



Hilo policristalino



Cinta amorfa



**Micromagnetics of twisted amorphous ribbons**

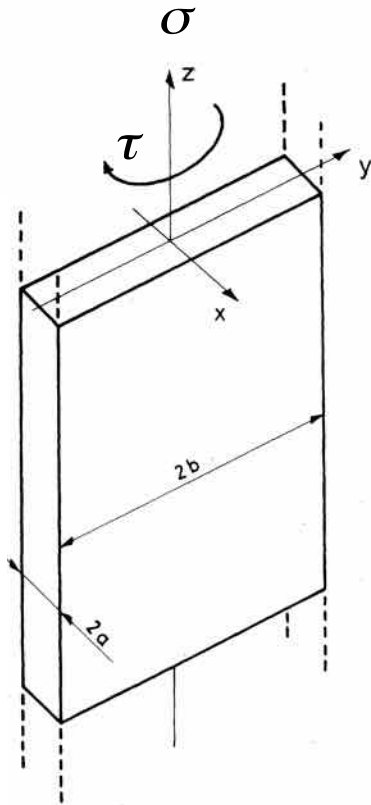
A. Hernando

*Laboratory of Magnetism, University Complutense, Madrid, Spain*

J. M. Barandiarán\*

*Laboratory of Magnetism, University of Navarra, San Sebastián, Spain*

(Received 7 November 1978)



$$t = T/S = 2\tau/\sigma$$

$$M_r = \left[ \frac{M_s}{\sqrt{2}t} \right] \left( [1 + t^2 - (1 + t^2)^{1/2}]^{1/2} - \frac{1}{2} \ln \{ 2(1 + t^2)^{1/2} - 2[1 + t^2 - (1 + t^2)^{1/2}]^{1/2} - 1 \} \right)$$

$$M_s \int_0^1 \sin \theta dx = \left[ \frac{M_s}{\sqrt{2}t} \right] \left( [1 + t^2 + (1 + t^2)^{1/2}]^{1/2} - \ln \{ [1 + (1 + t^2)^{1/2}]^{1/2} + (1 + t^2)^{1/4} \} - 0.533 \right)$$

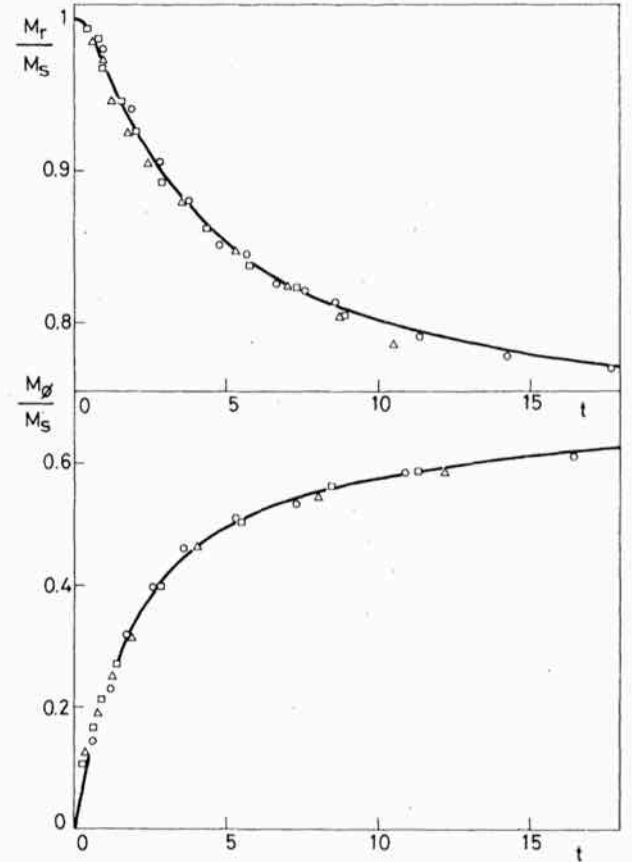


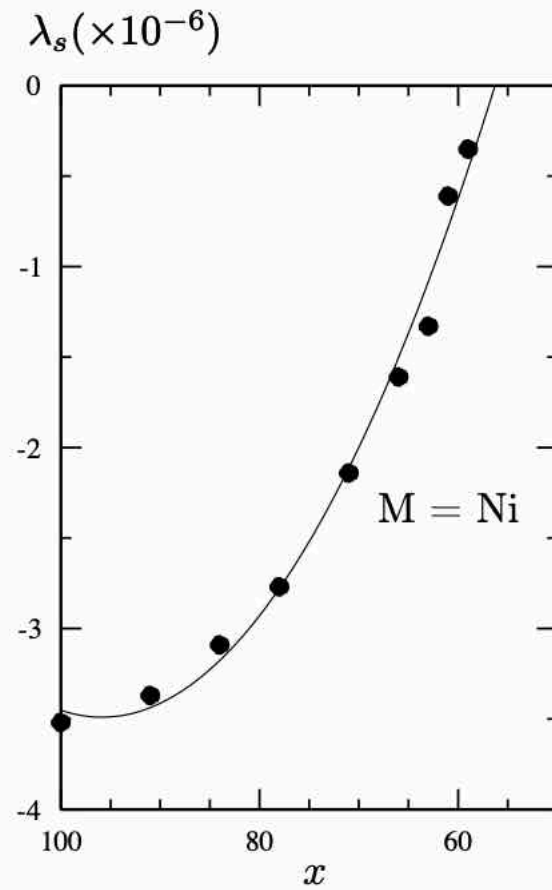
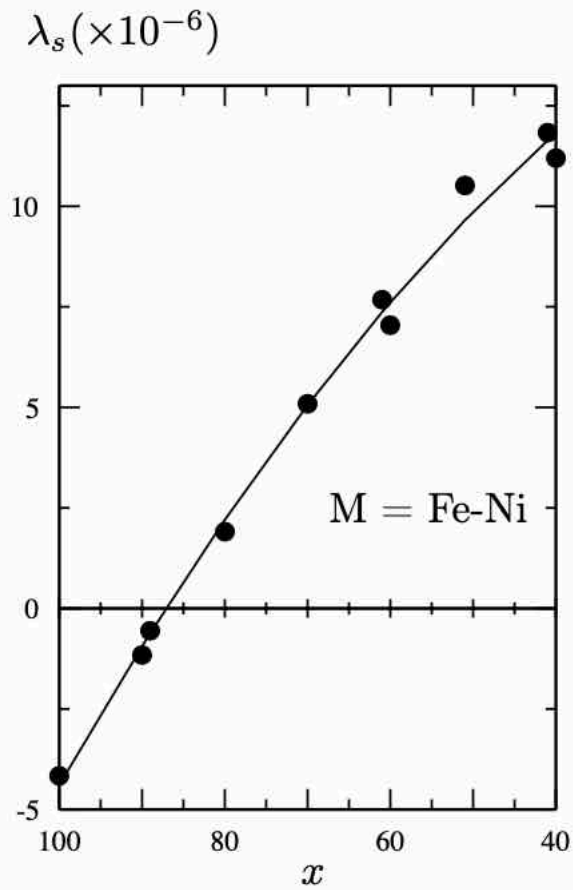
FIG. 5. Remanence of the longitudinal magnetization (upper), and Matteucci effect (lower) as a function of the applied torsion, for different values of the tension stress. (O) 8, ( $\Delta$ ) 16, ( $\square$ ) 24 N mm<sup>-2</sup>. Full lines are given by expressions (15) and (16).

Lyngby, Dinamarca, 1984 (DTH)

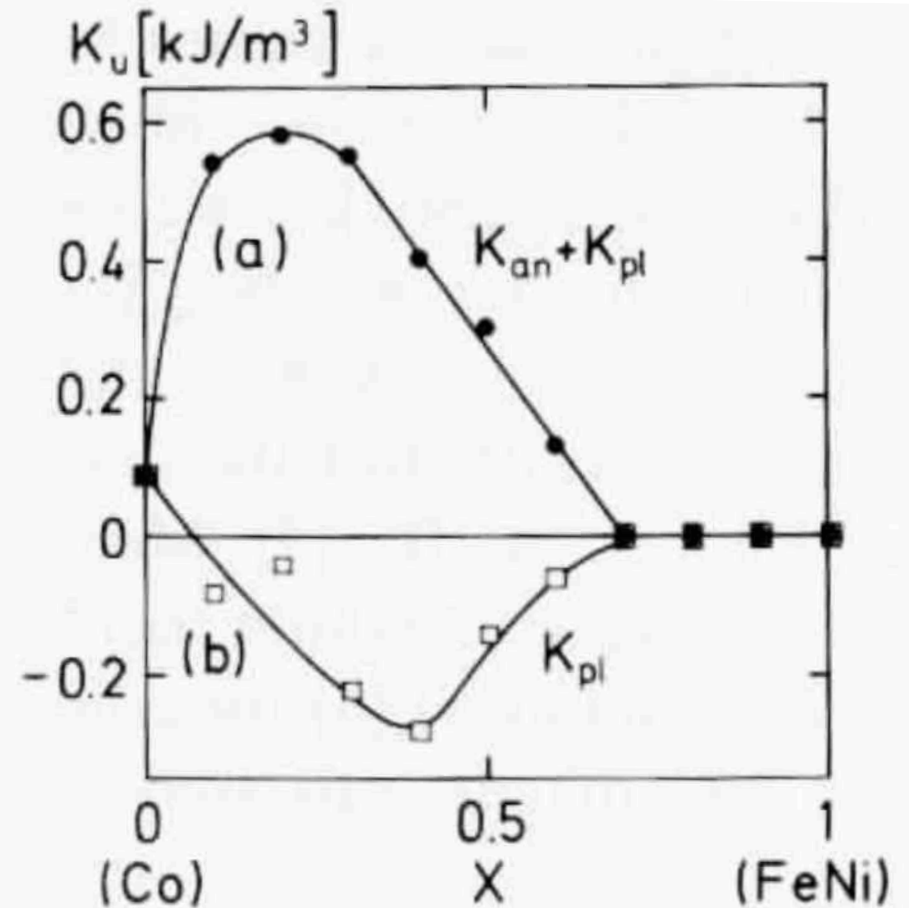
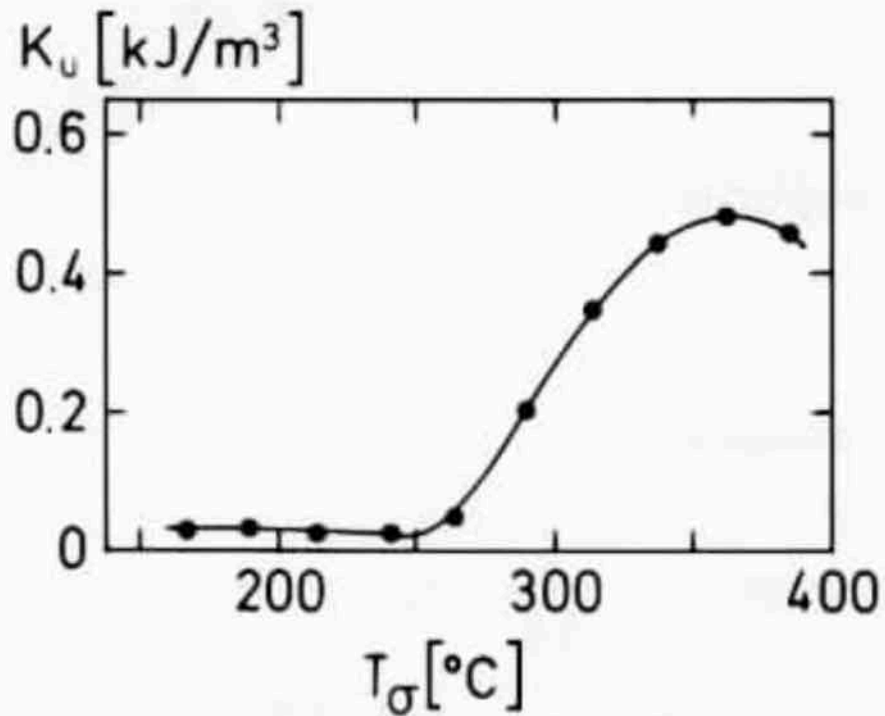
OV Nielsen



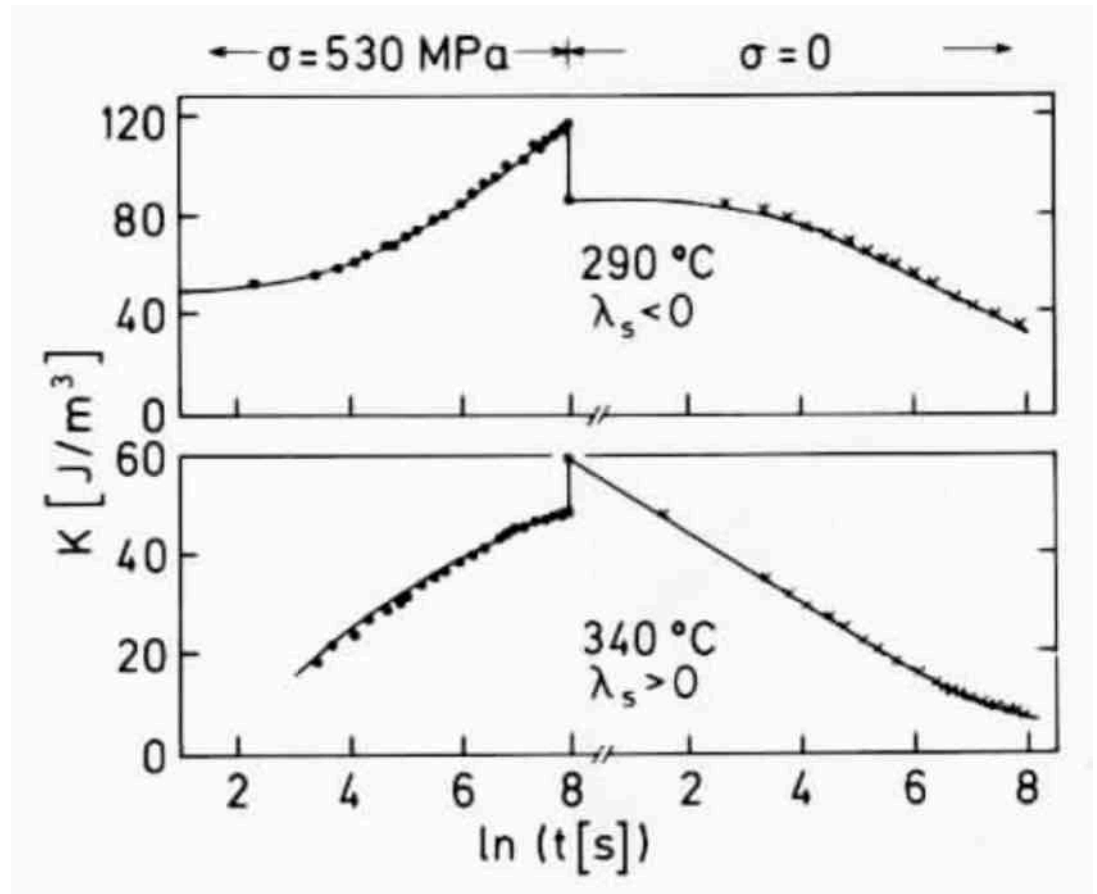
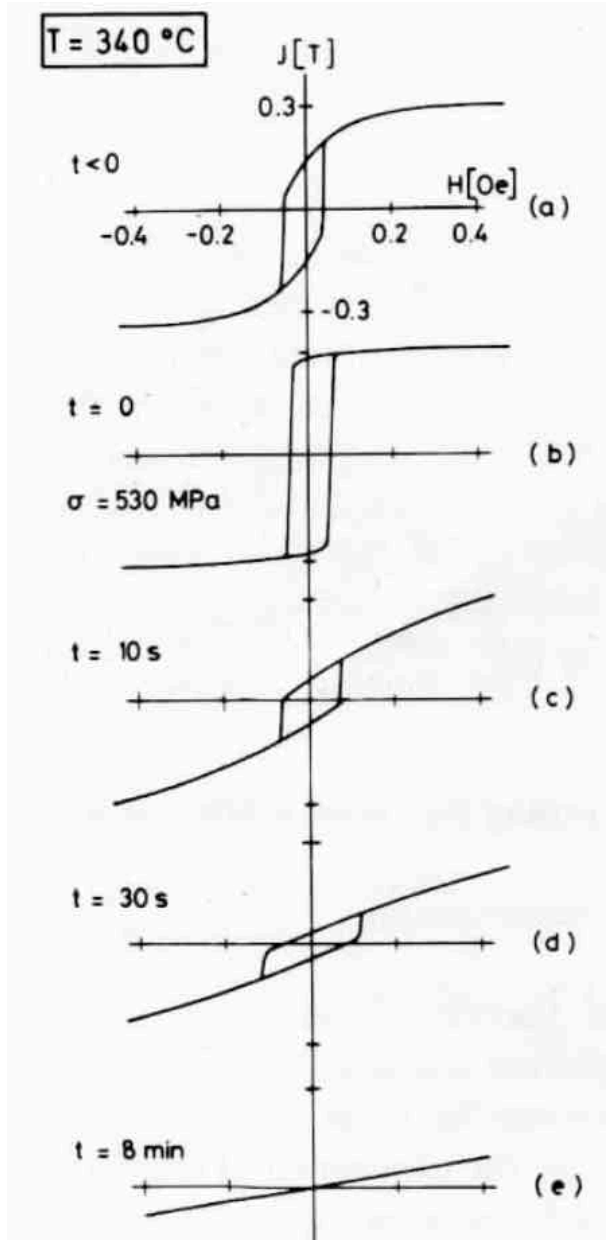
# Magnetostricción de aleaciones amorfas $(\text{Co}_{100-x}\text{M}_x)_{75}\text{Si}_{15}\text{B}_{10}$



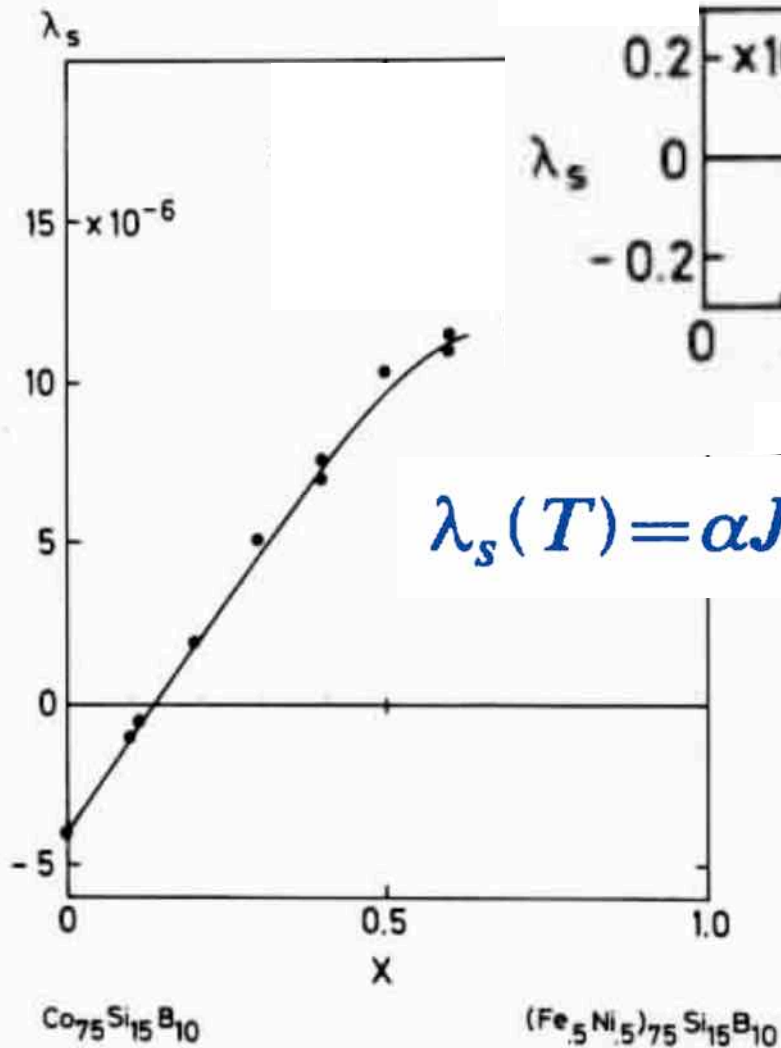
# Anisotropía inducida por tensión en aleaciones amorfas



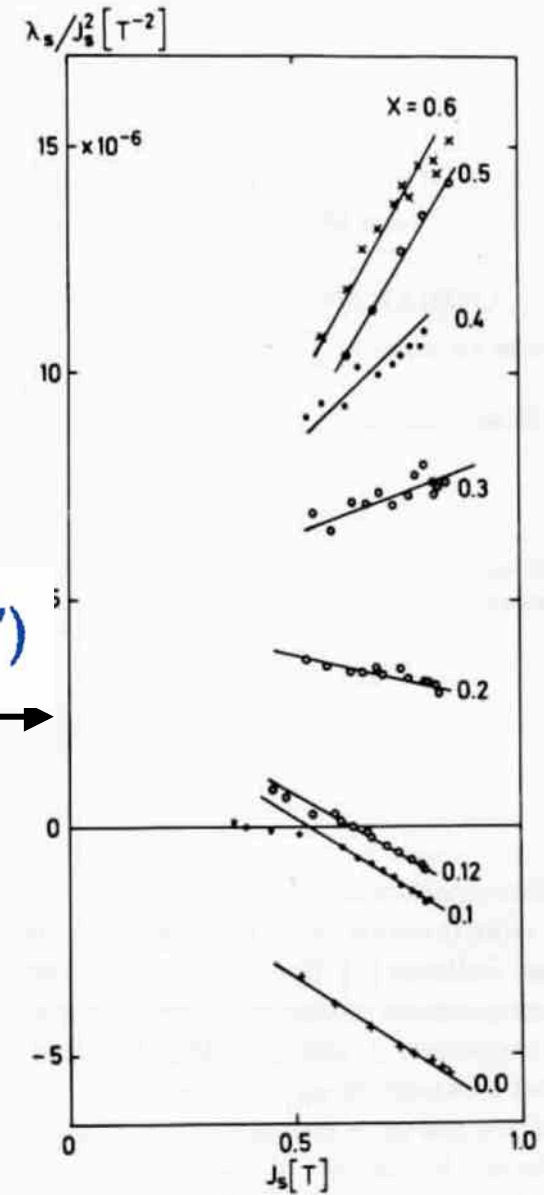
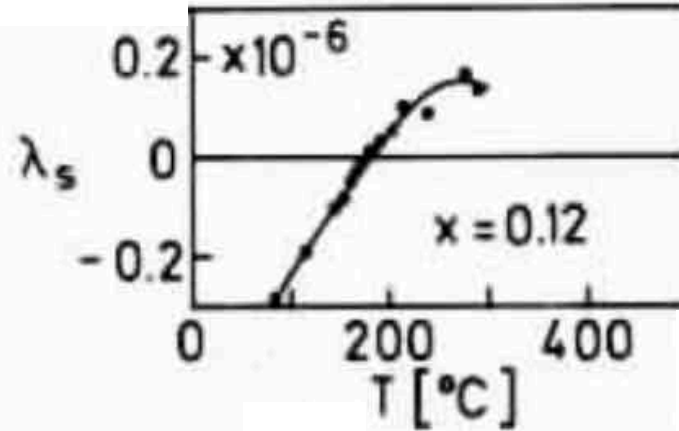
# Anisotropía inducida por tensión en aleaciones amorfas



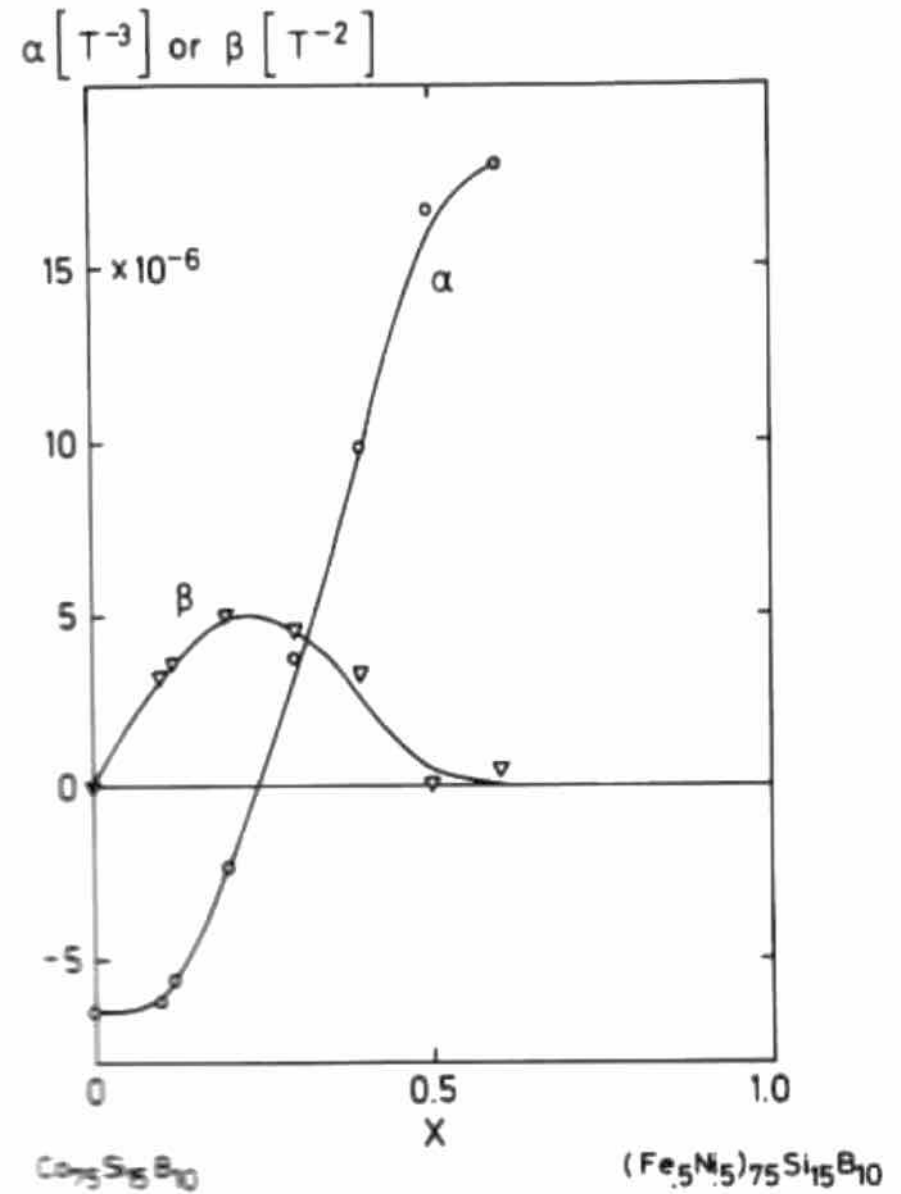
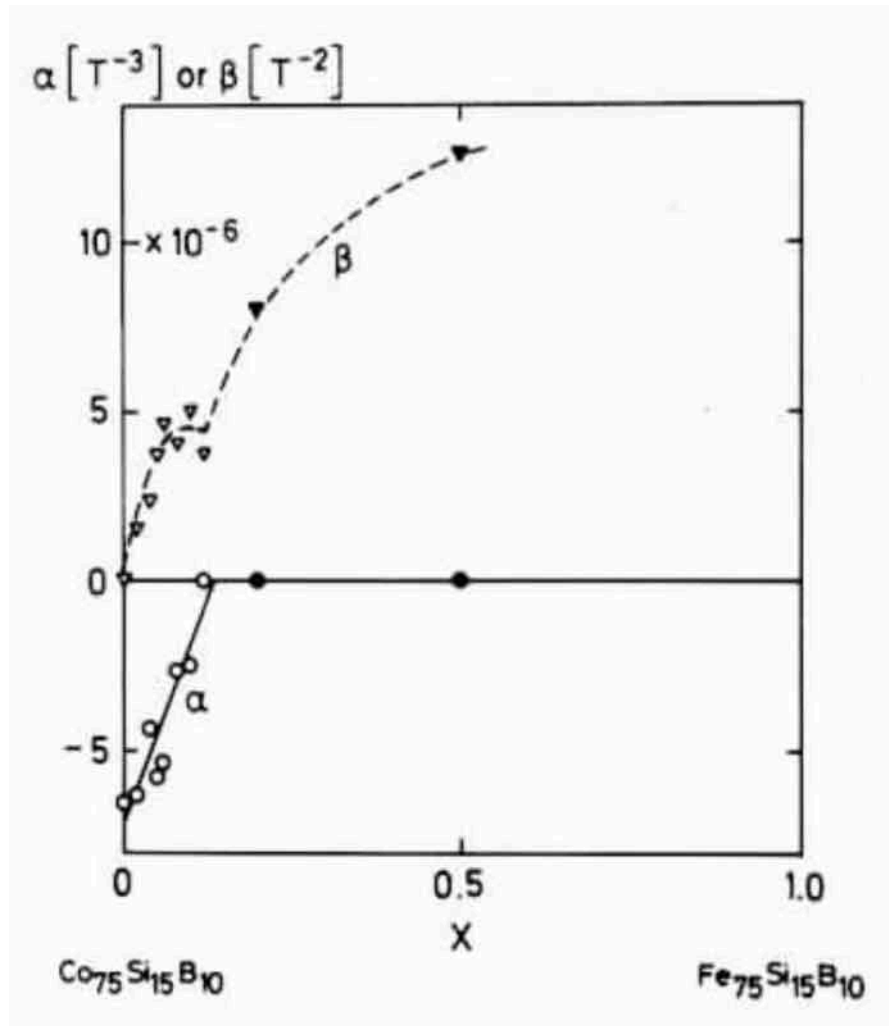
# Magnetostricción de aleaciones amorfas $(\text{Co}_{100-x}\text{M}_x)_{75}\text{Si}_{15}\text{B}_{10}$



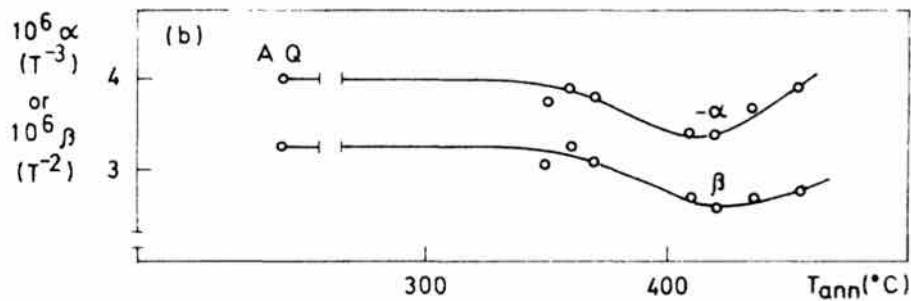
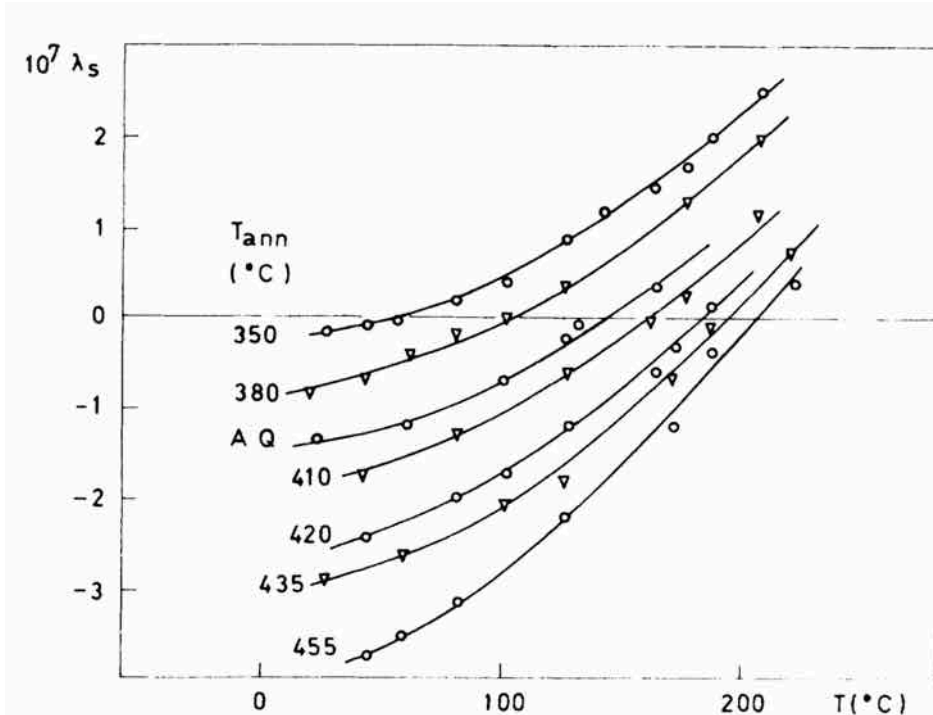
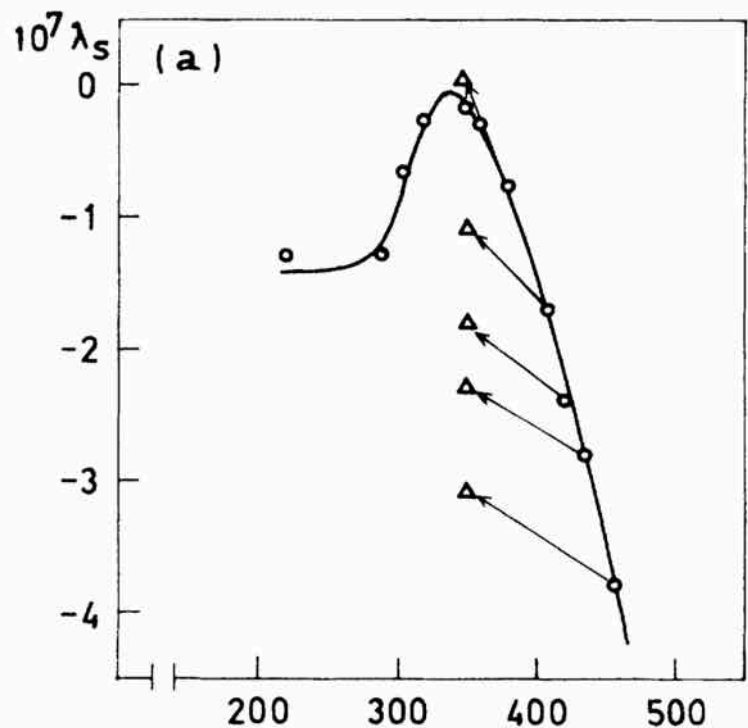
$$\lambda_s(T) = \alpha J_s^3(T) + \beta J_s^2(T)$$



# Magnetostricción de aleaciones amorfas $(\text{Co}_{100-x}\text{M}_x)_{75}\text{Si}_{15}\text{B}_{10}$

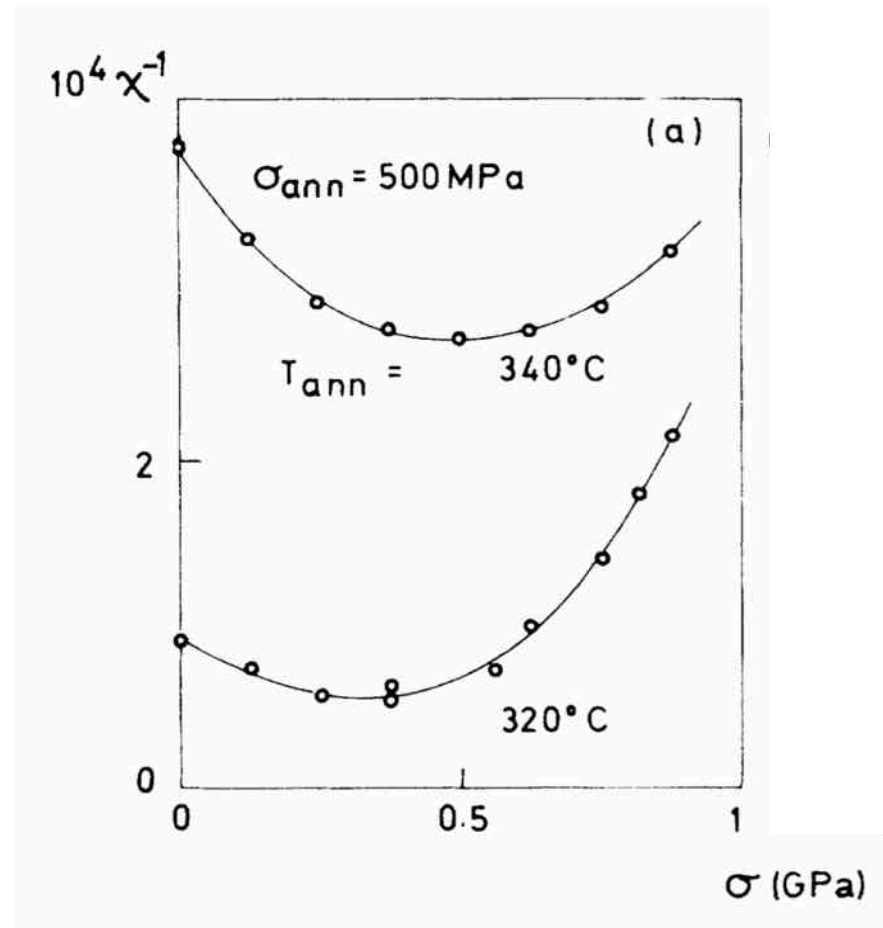
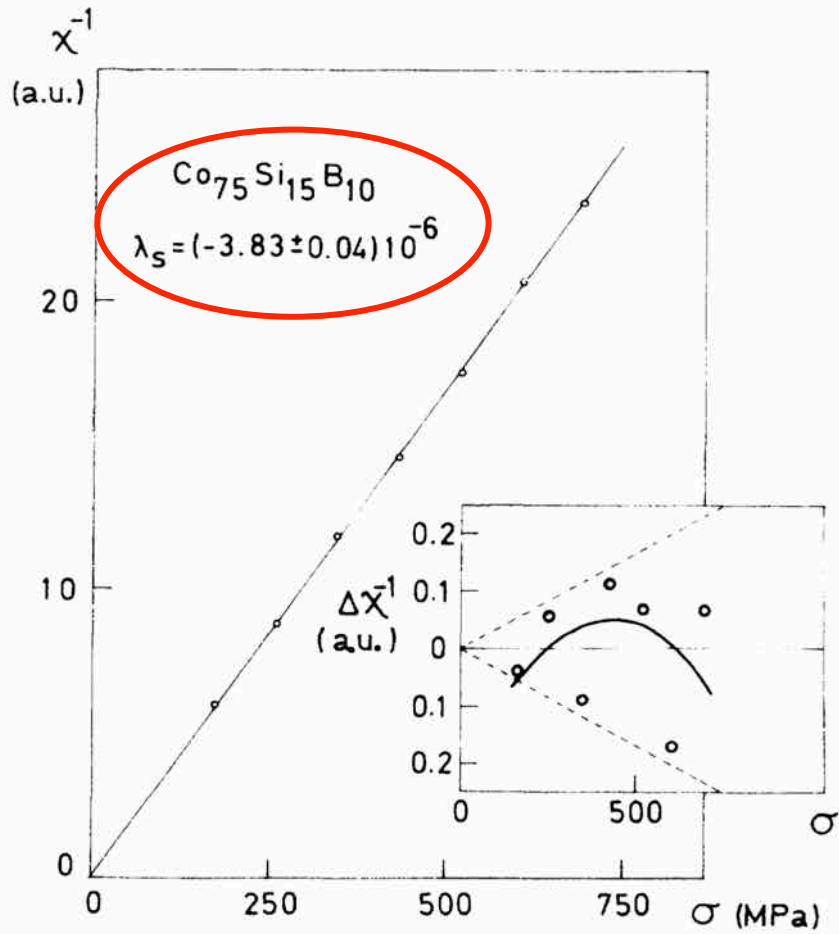


### Temperature, stress, and structural-relaxation dependence of the magnetostriction in $(\text{Co}_{0.94}\text{Fe}_{0.06})_{75}\text{Si}_{15}\text{B}_{10}$ glasses

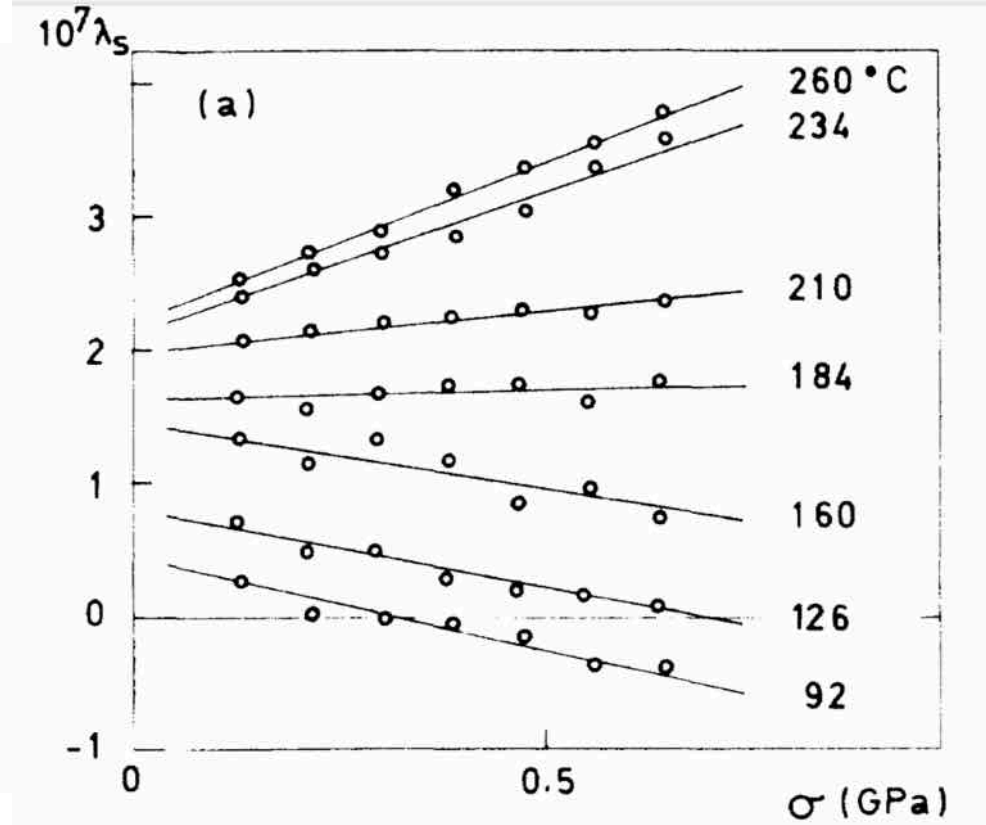
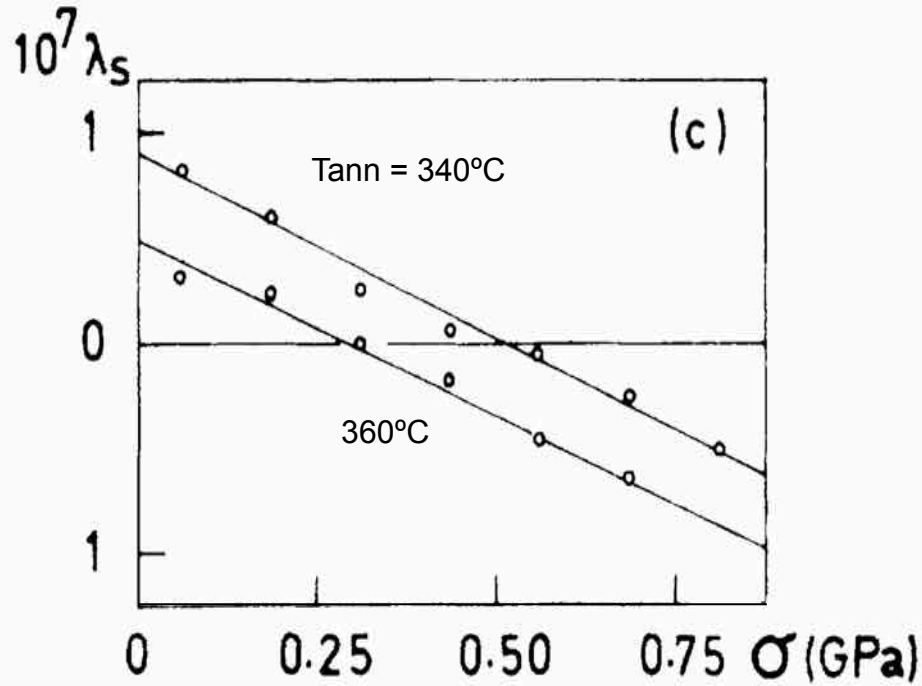




# Temperature, stress, and structural-relaxation dependence of the magnetostriction in $(\text{Co}_{0.94}\text{Fe}_{0.06})_{75}\text{Si}_{15}\text{B}_{10}$ glasses



Temperature, stress, and structural-relaxation dependence of the magnetostriction  
in  $(\text{Co}_{0.94}\text{Fe}_{0.06})_{75}\text{Si}_{15}\text{B}_{10}$  glasses



$$\lambda_s(\sigma) = \lambda_0 + \gamma \cdot \sigma$$

$$\gamma \approx 1-2 \times 10^{-7} \text{ GPa}^{-1}$$

Efecto "mórfico"

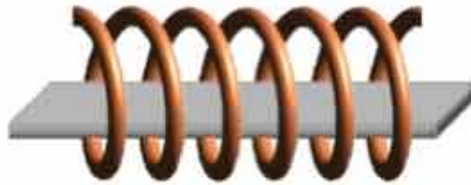
# RESONANCIA MAGNETOELÁSTICA



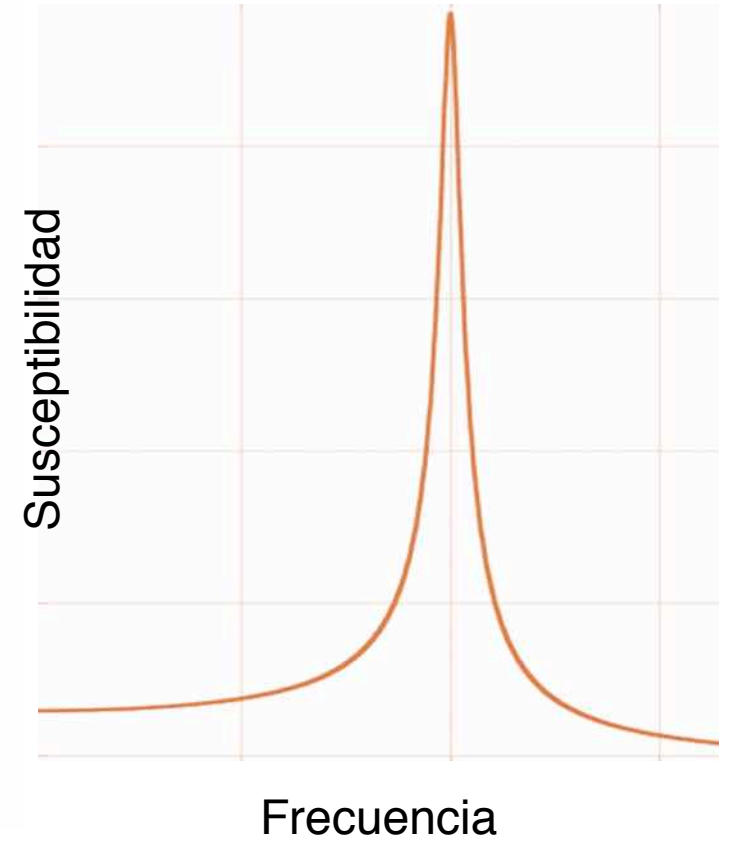
$$f_r = \frac{1}{2l} \sqrt{\frac{E}{\rho}}$$



Excitación

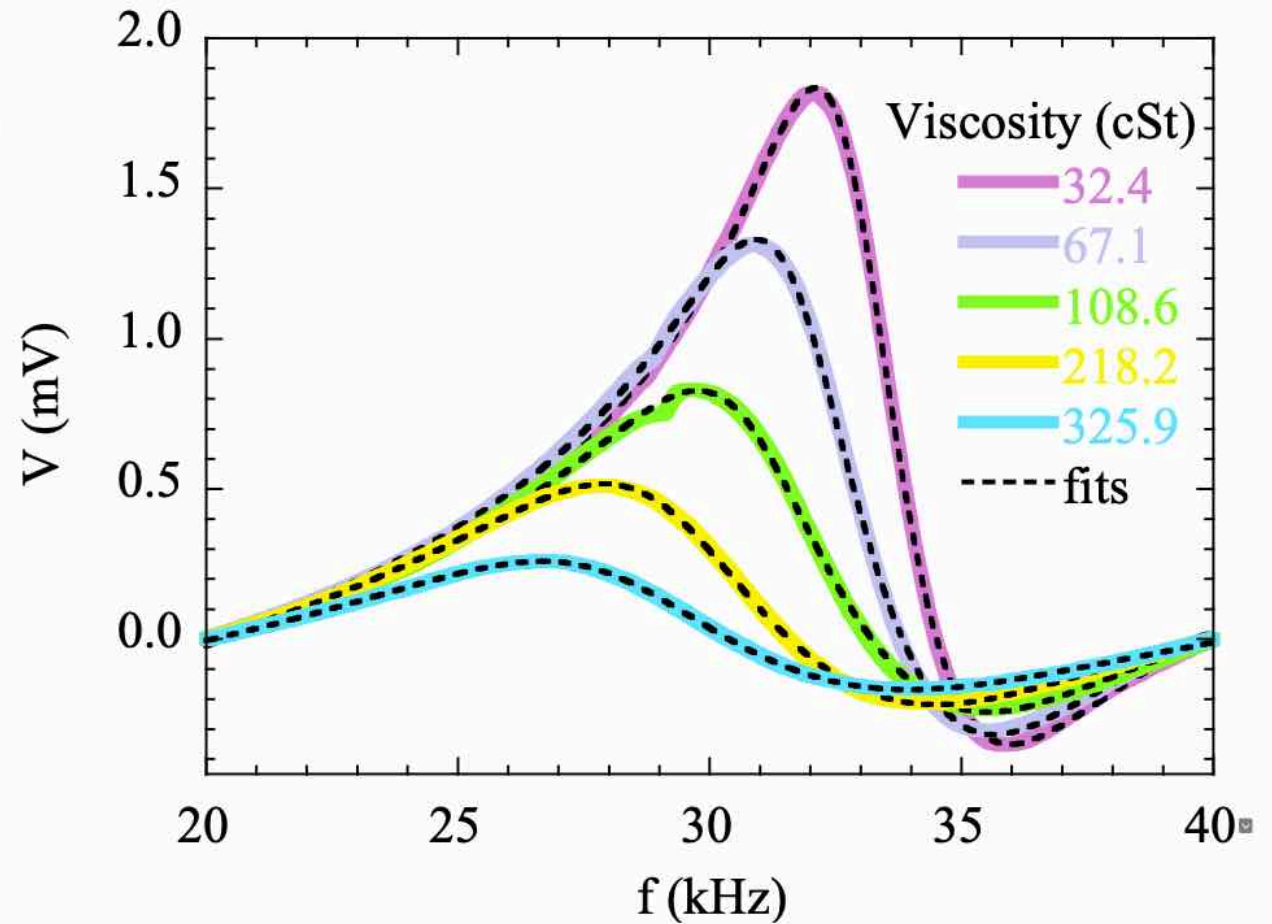


Vibración



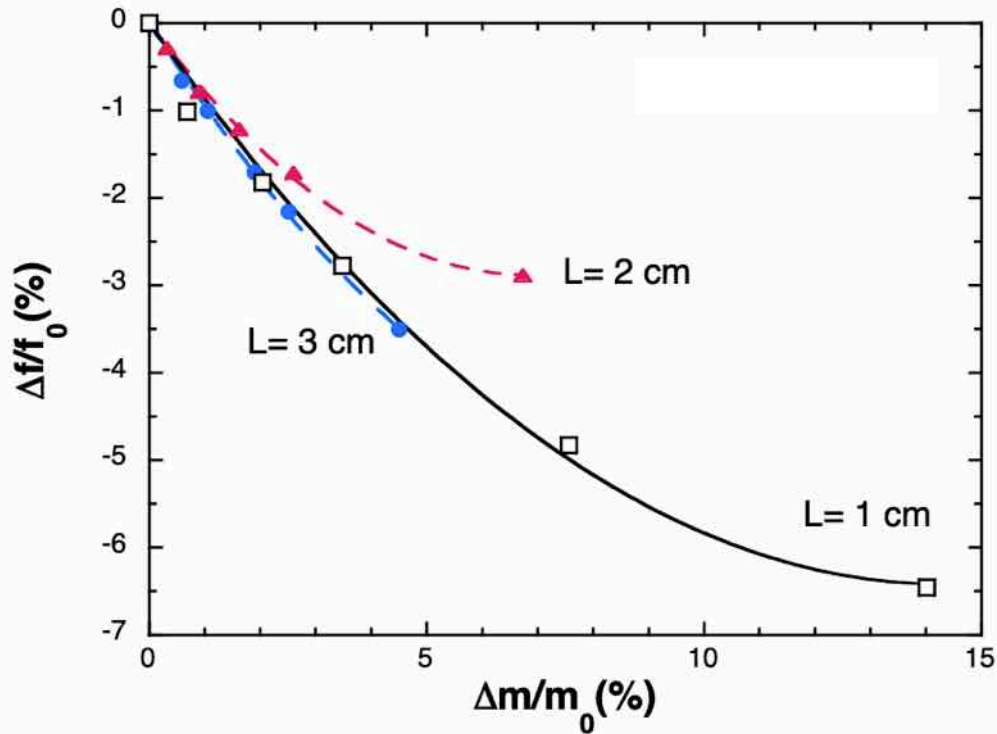
# RESONANCIA MAGNETOELÁSTICA

## *Oil Viscosity Sensor*



# RESONANCIA MAGNETOELÁSTICA

## Mass Sensor



$$\frac{f}{f_0} = \left[ 1 + \frac{\Delta m}{M} \right]^{-1/2}$$

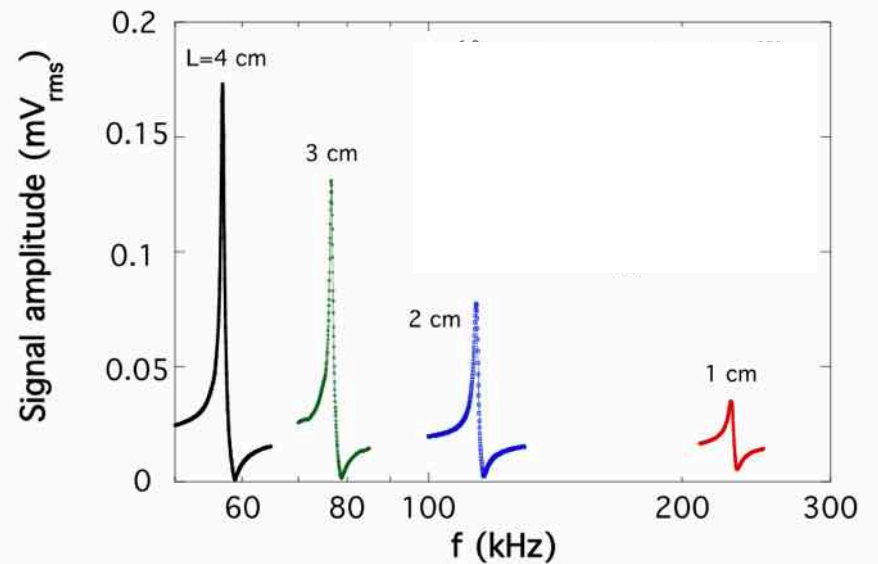
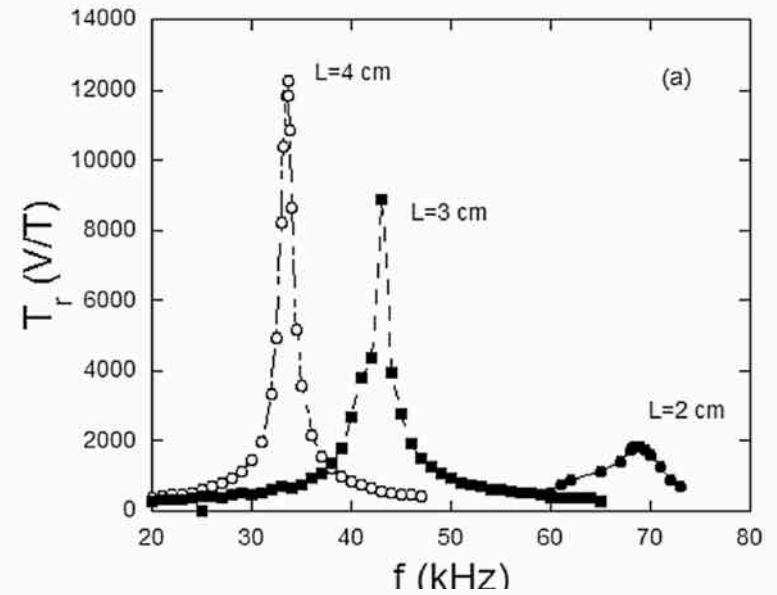
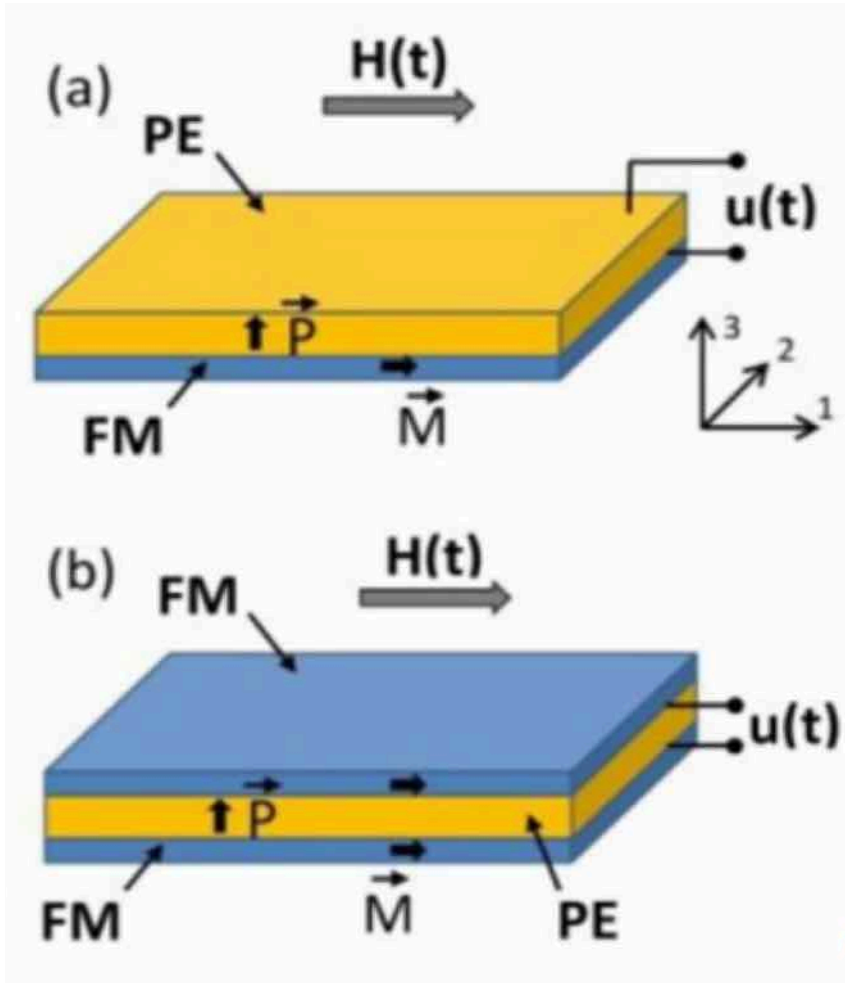
$$\frac{\Delta f}{f_0} = -\frac{1}{2} \frac{\Delta m}{M}$$

$$\frac{\Delta f}{f_0} \approx -a \left( \frac{\Delta m}{M} \right) + b \left( \frac{\Delta m}{M} \right)^2$$

TABLE II  
*a* AND *b* COEFFICIENTS-OBTAINED FROM  
 THE FIT TO EQUATION (3)

<i>L</i> (mm)	<i>a</i>	<i>b</i>
30	0.955	0.0488
20	0.841	0.0613
10	0.896	0.0046

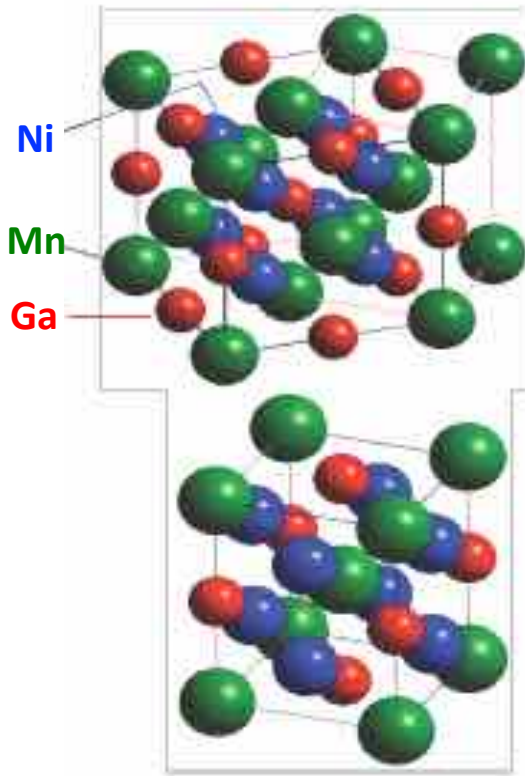
# MATERIALES MAGNETOELÉCTRICOS



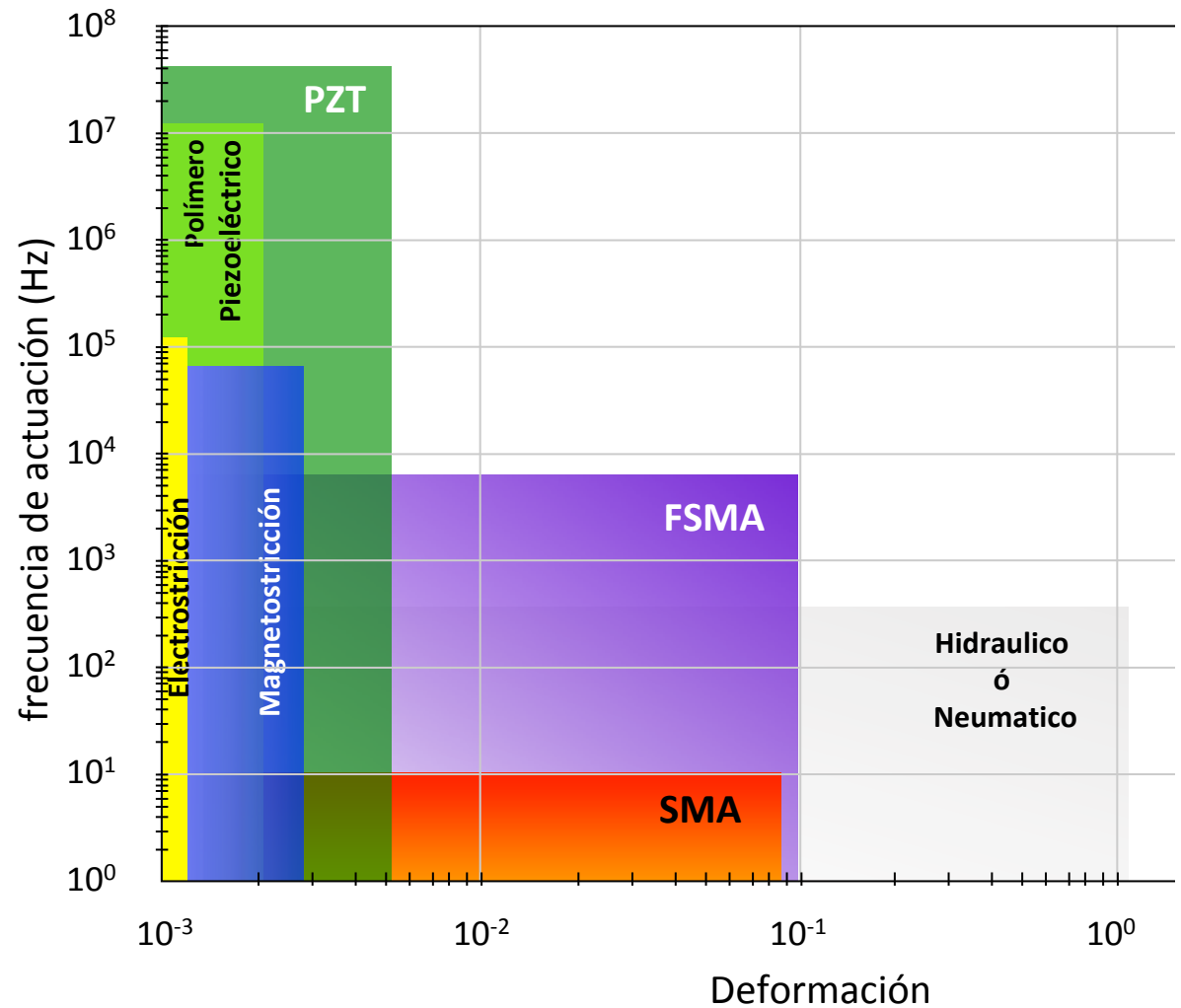
# Cambridge MA, 2005 (MIT) FSMA, Bob O'Handley

**Ni<sub>2</sub>MnGa**  
Estructura L2<sub>1</sub> (Heusler)

Austenita  
*Fm3m*



Martensita  
*I4/mmm*



# $\text{Ni}_{51.1}\text{Mn}_{24.9}\text{Ga}_{24.0}$ ( $\approx \text{Ni}_2\text{MnGa}$ ) polycrystal

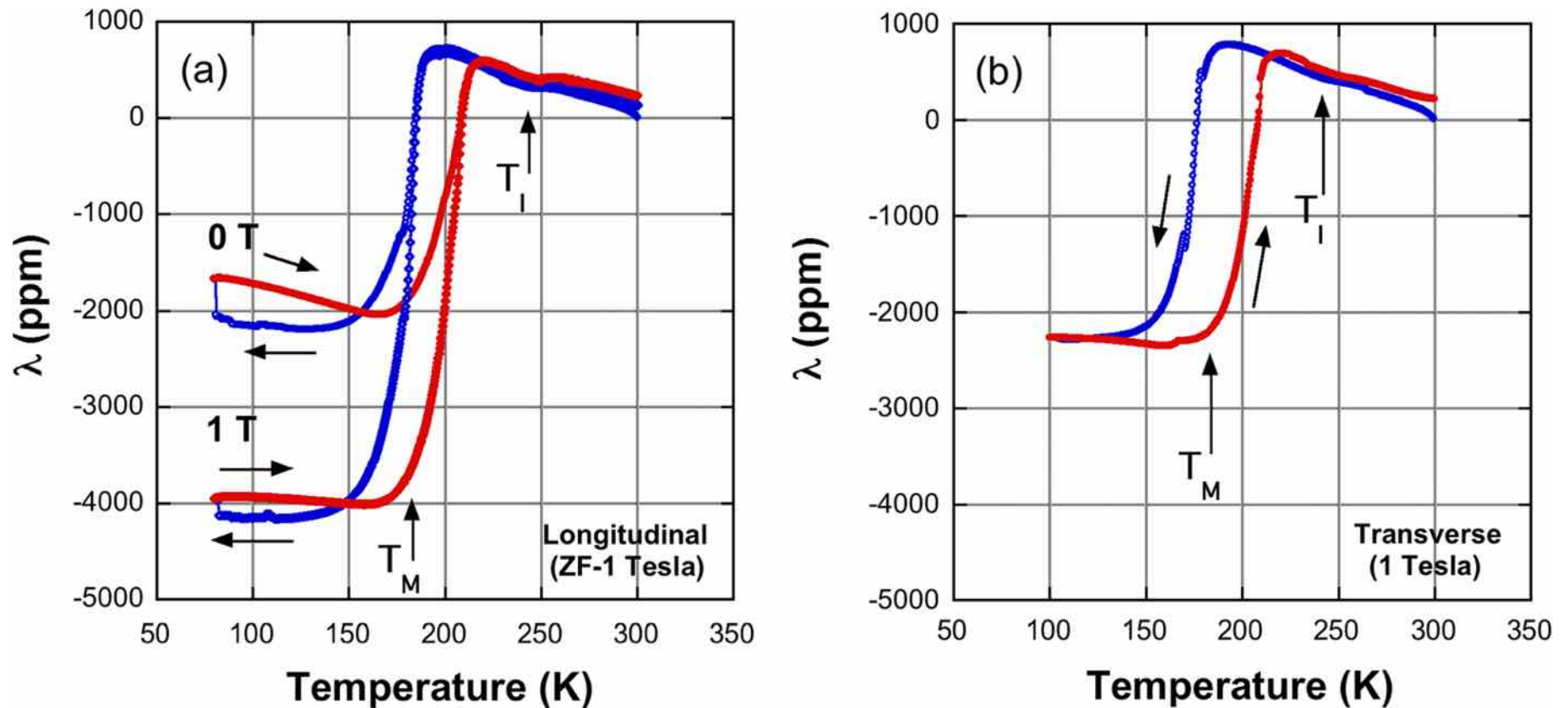


FIG. 1. Strain on cooling and heating under zero field and 1 T parallel or perpendicular to the measuring direction. The large contraction corresponds to the martensitic transformation.



# Ni<sub>51.1</sub>Mn<sub>24.9</sub>Ga<sub>24.0</sub> ( $\approx$ Ni<sub>2</sub>MnGa) polycrystal

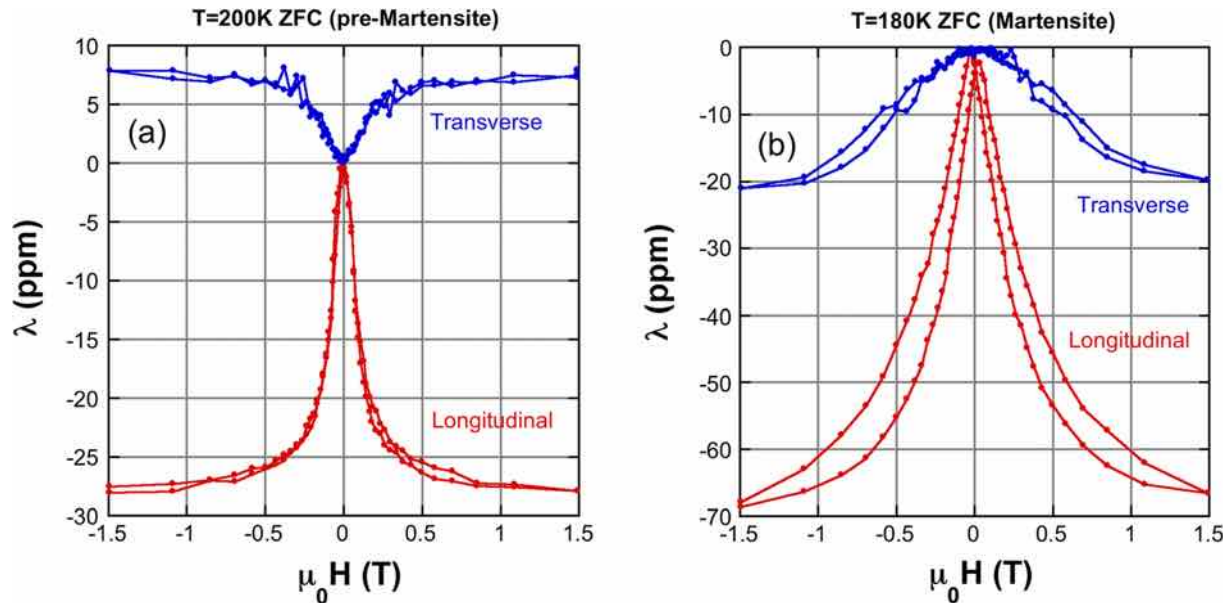


FIG. 3. Longitudinal and transverse magnetostriction measured at temperatures just above (a) and below (b) the martensitic transformation.

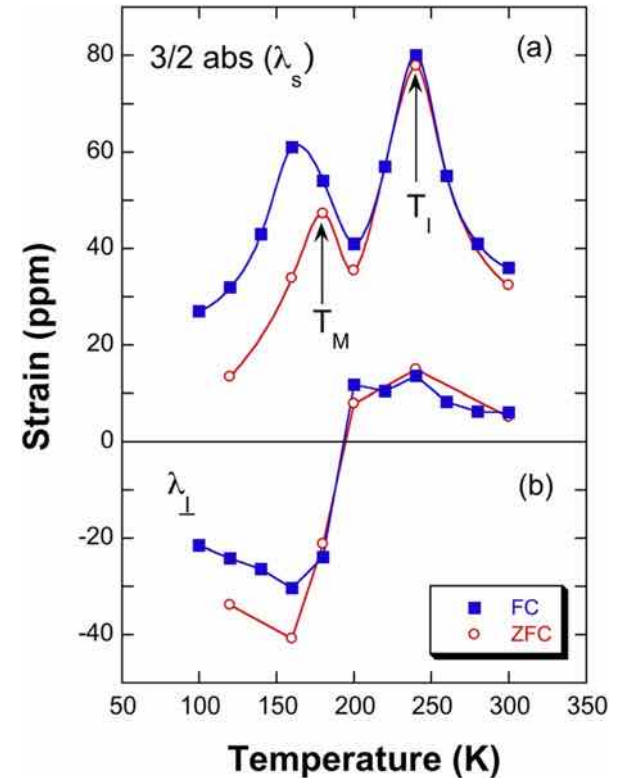
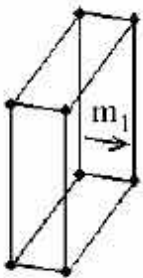


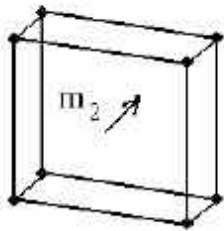
FIG. 4. (a) Saturation magnetostriction showing the large increase of their absolute value at the transitions. (b) Transverse magnetostriction values showing the change of sign at the martensitic transition.

# Magnetic field induced twin-boundary motion

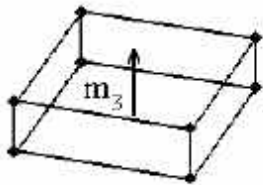
Austenita  
 $Fm3m$



E1

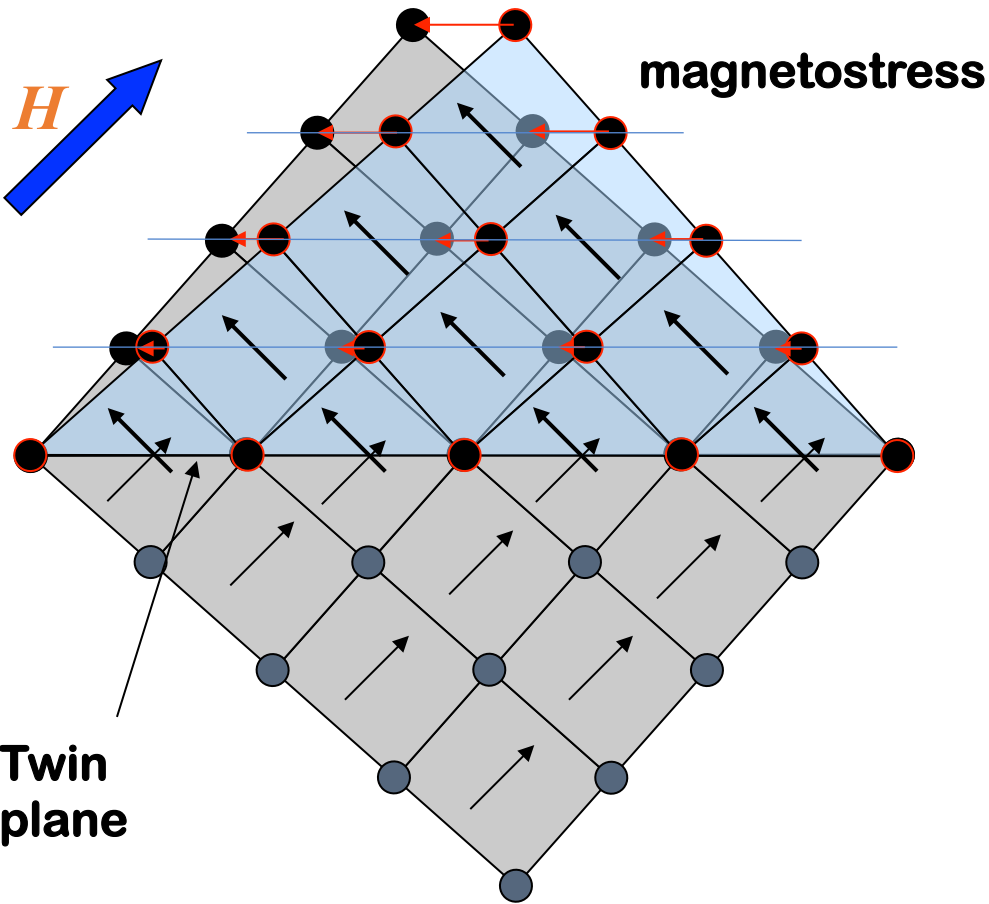


E2

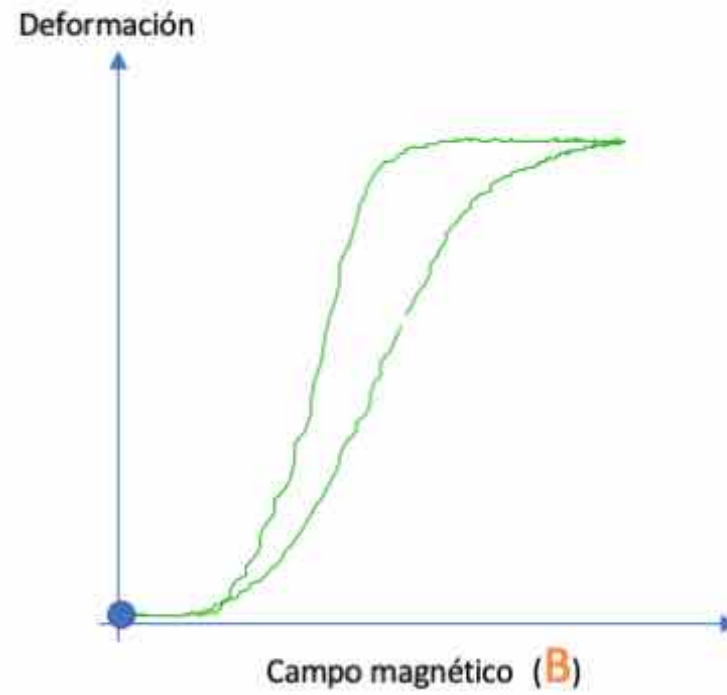
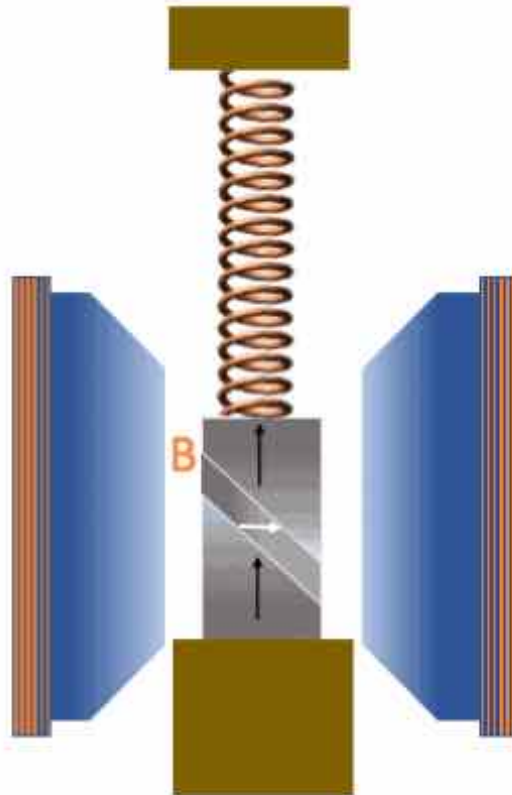


E3

Martensita  
 $I4/mmm$



# FSMA



**(1985...) GRENOBLE**



**Una colaboración muy duradera**

**A nivel familiar**



# y científico



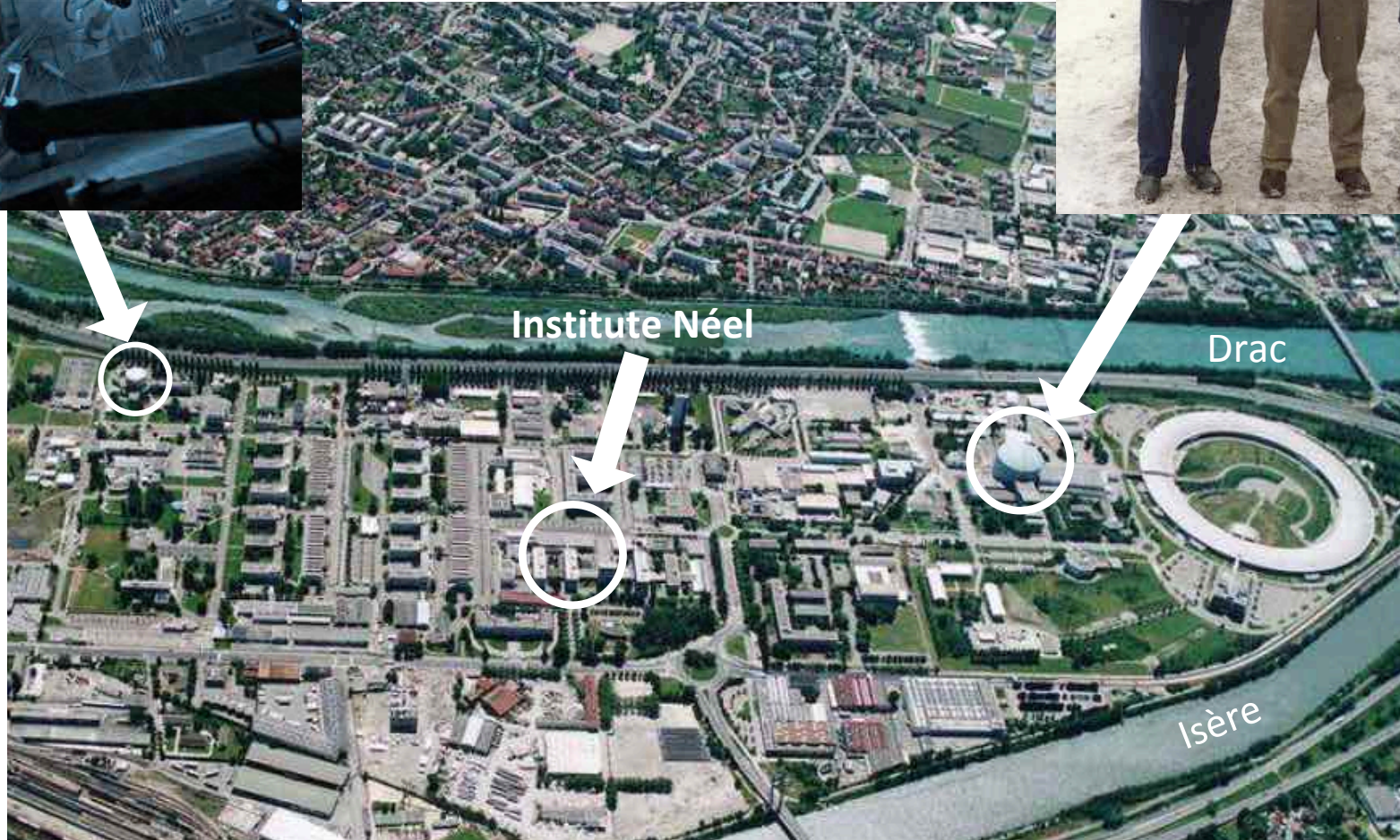
# NEUTRONES



SILOÉ  
(CEA)



ILL-1988

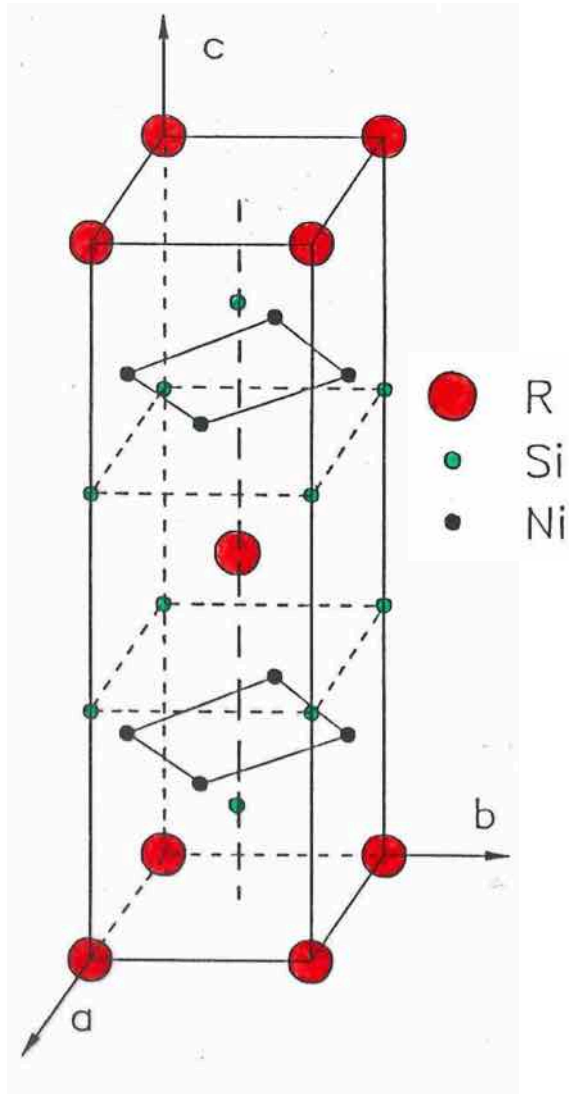


Institute Néel

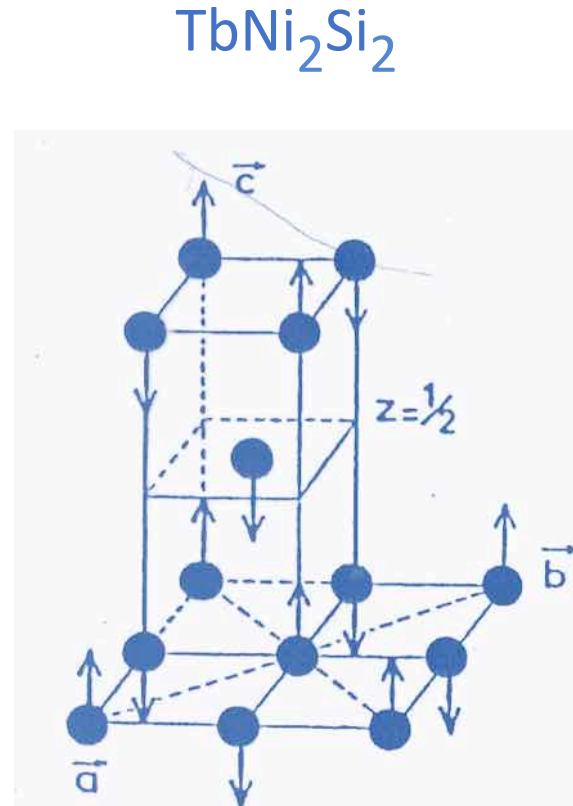
Drac

Isère

# ESTRUCTURAS $RNi_2Si_2$

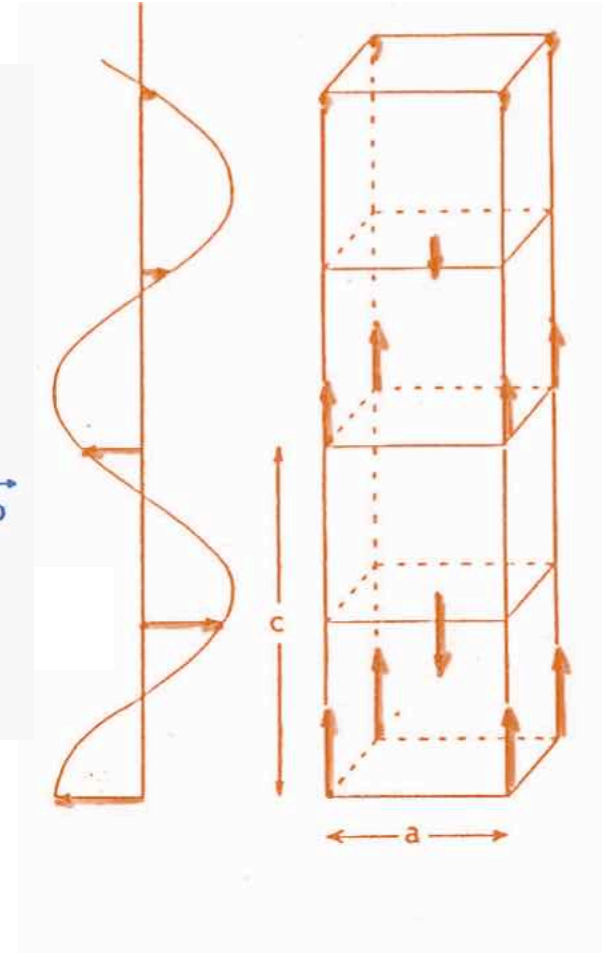


**CRISTALINA**



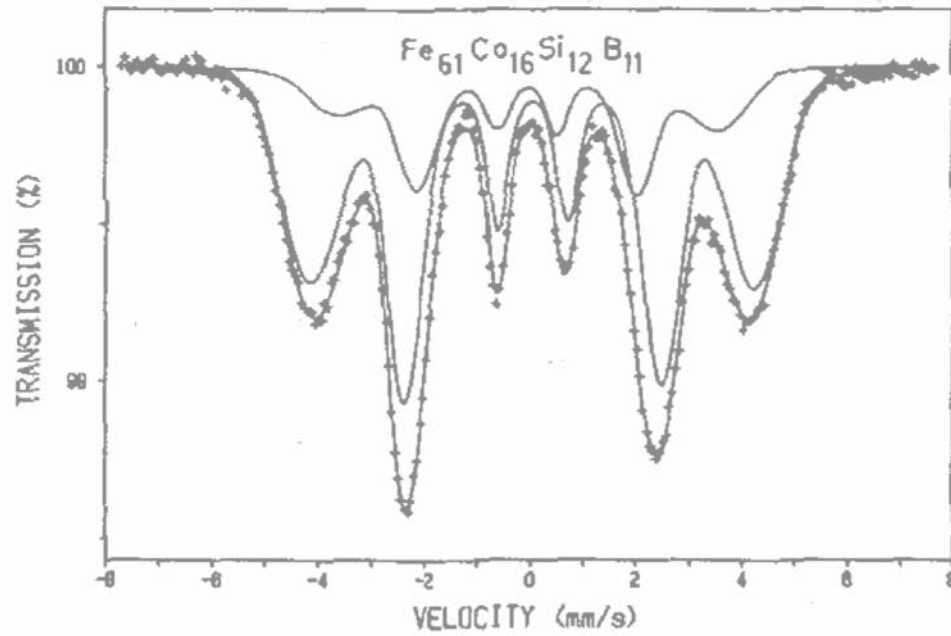
**MAGNÉTICAS**

$PrNi_2Si_2$

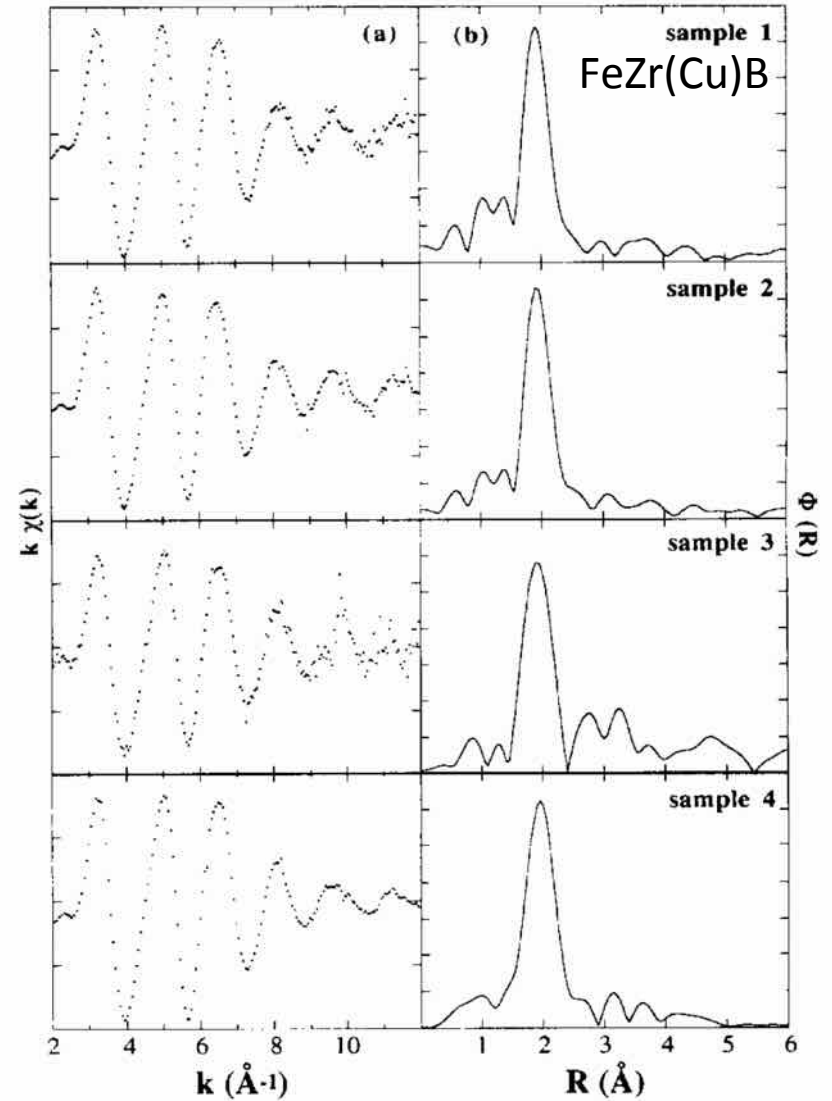


# ¿Neutrones en amorfos?

Mössbauer

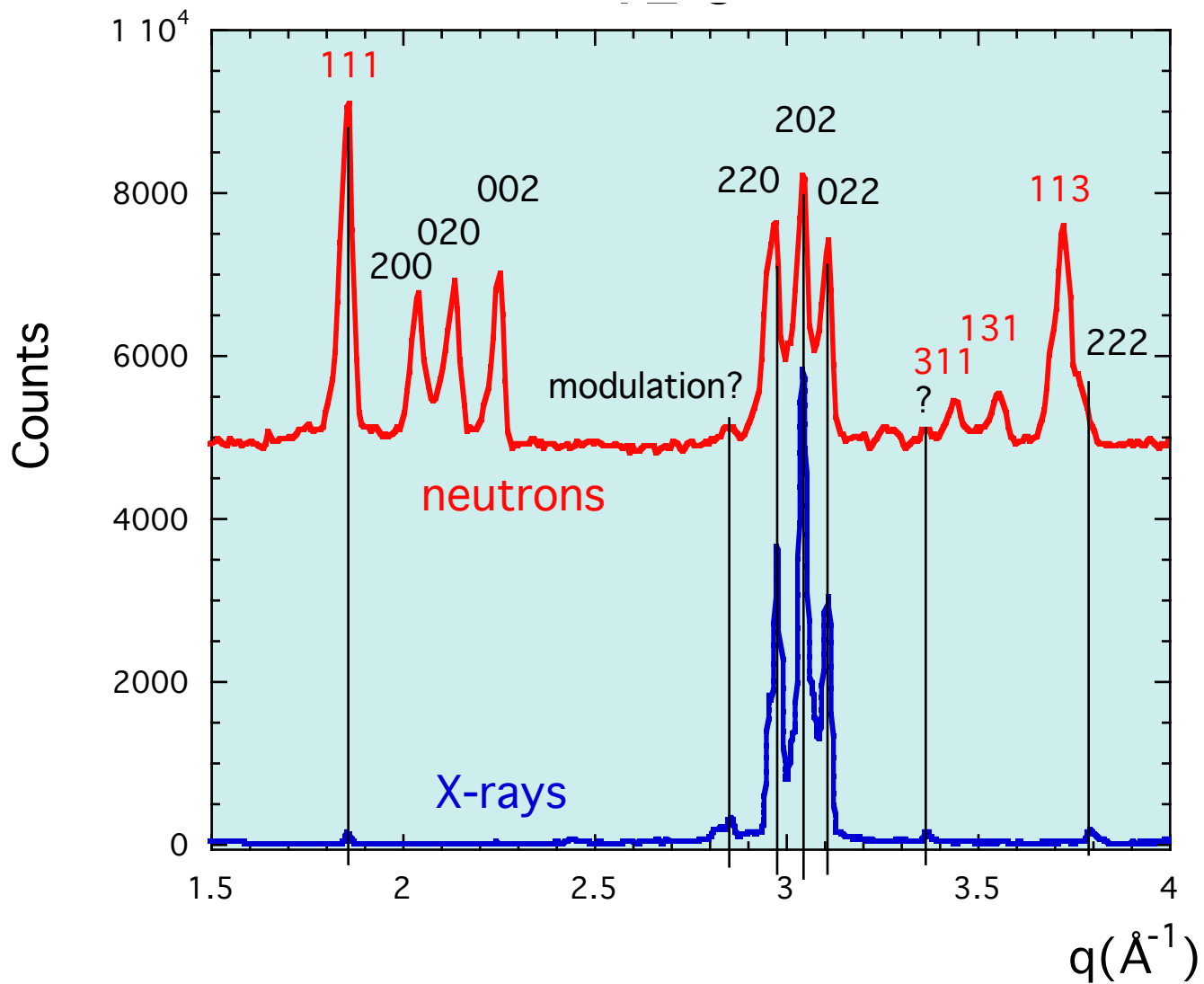
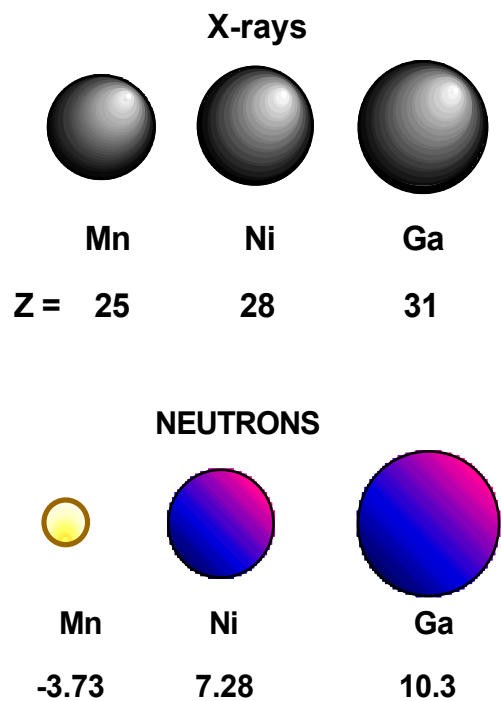


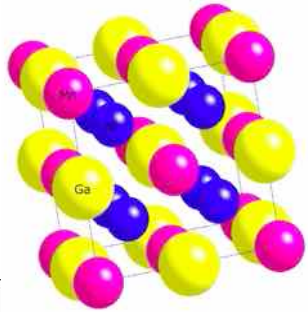
EXAFS





# Neutrones en FSMA





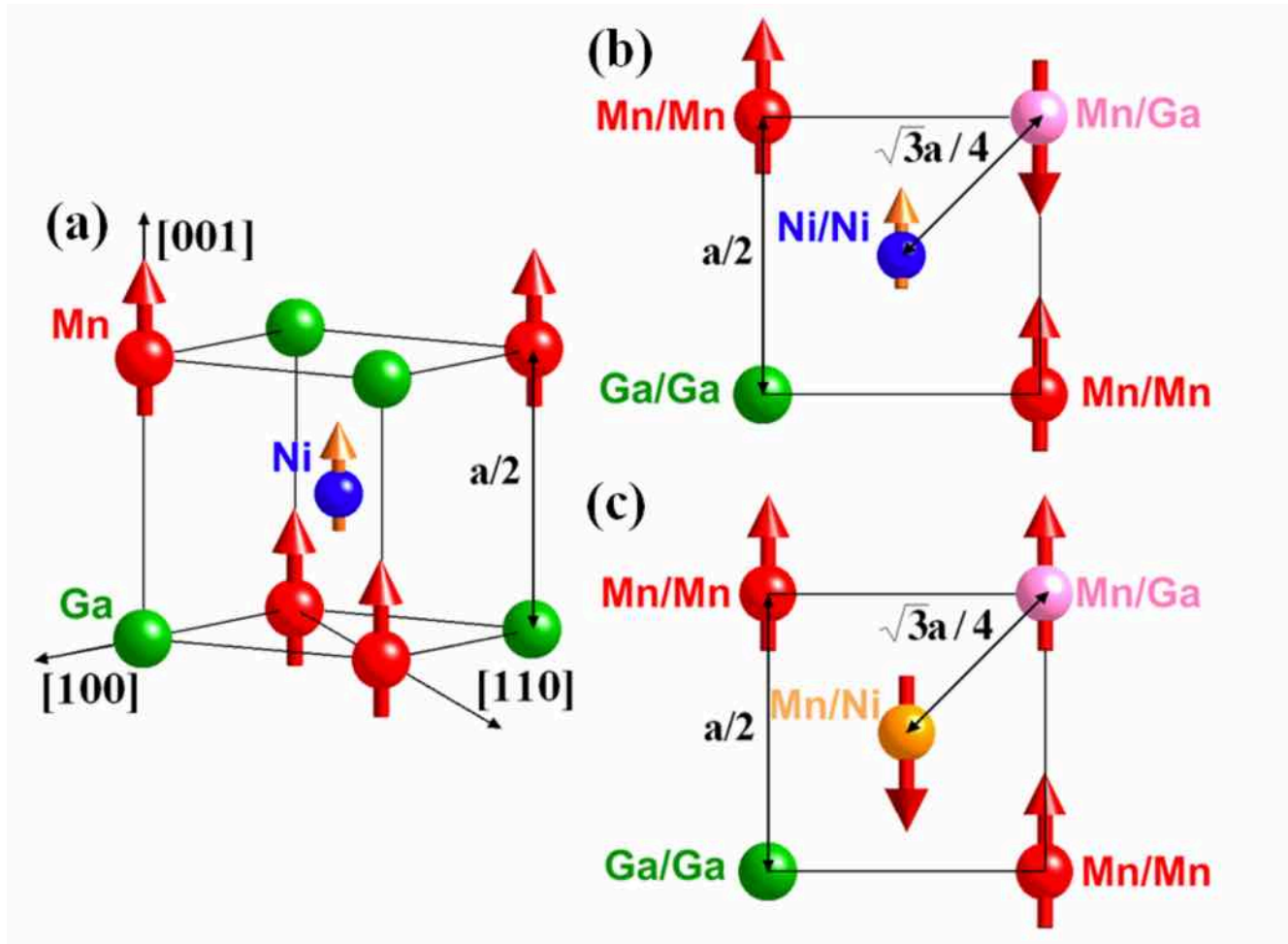
## Site occupation & magnetism (excess Ni)

	Heusler	Ni49	Ni50	Ni52
Composition Ni–Mn–Ga (at%)	50–25–25	49–31–20	50–29–21	52–26–22
$W = \text{amu}/\text{FU}$	245	241	242	243
Measured Magnetization, $\sigma$ (emu/g)	95	80.0	84.3	84.0
Measured $n_B$ ( $\mu_B/\text{FU}$ ) [ $\sigma W/N_A \mu_B$ ]	4.17	3.44	3.63	3.64
$n_B$ if excess Mn (and Ni) go to Ga sites, off-site Mn are antiferromagnetic (no neutron results)	4.17	3.42	3.61	4.06 (+11.4%)
$n_B$ if excess Ni goes to Mn sites (ferromagnetic) and 3 off-site Mn are at Ga (antiferromagnetic) (using neutron data)		-	-	3.49 (-4.0%)

↑  
All Mn couple  
ferromagnetically

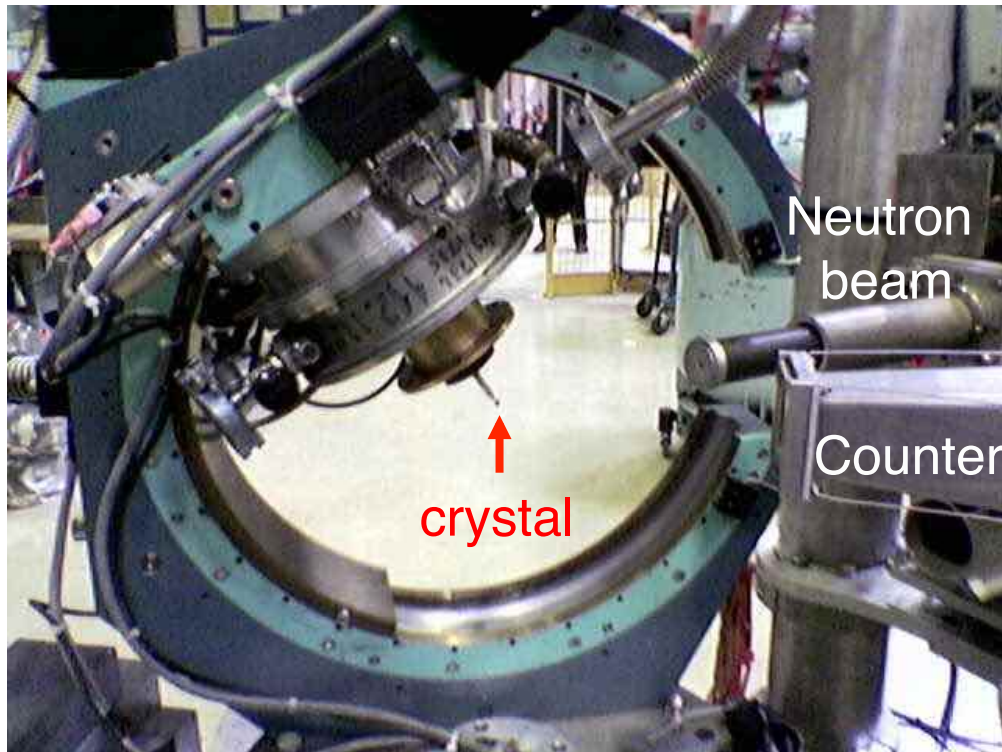
Excess Mn couples  
anti-ferromagnetically  
(Mn-Mn neighbors)

# Site occupation & magnetism (defect Ni)

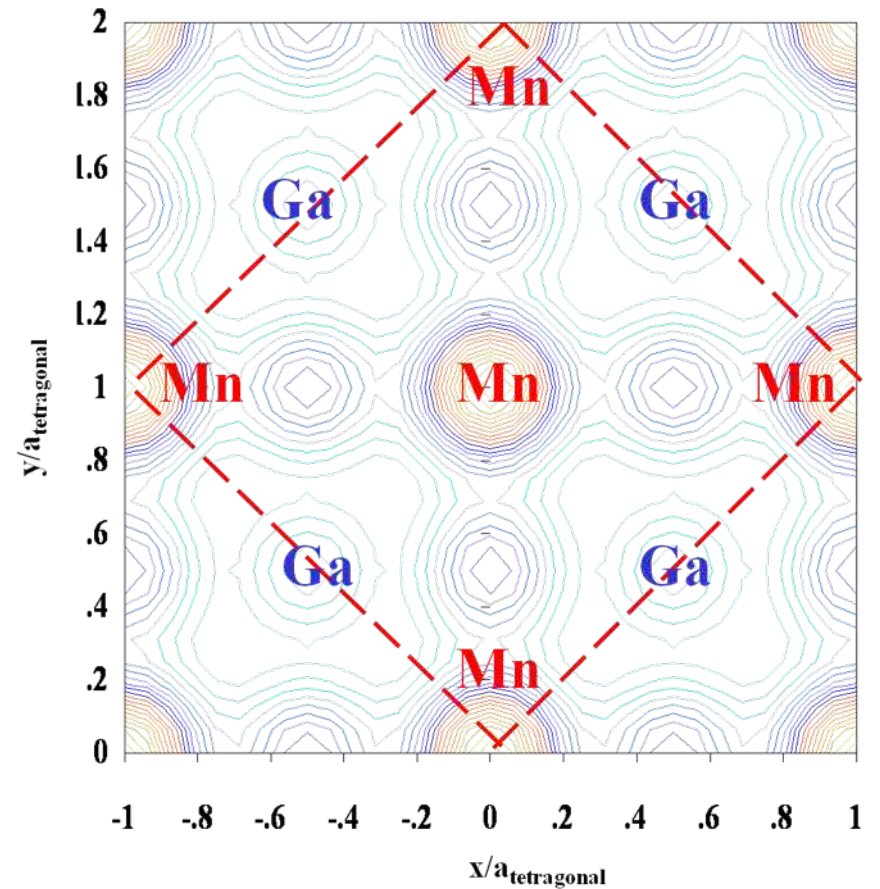


# Difracción de monocristal

## Cuatro círculos (D-10)



## Mapas de momento magnético (Austenita)



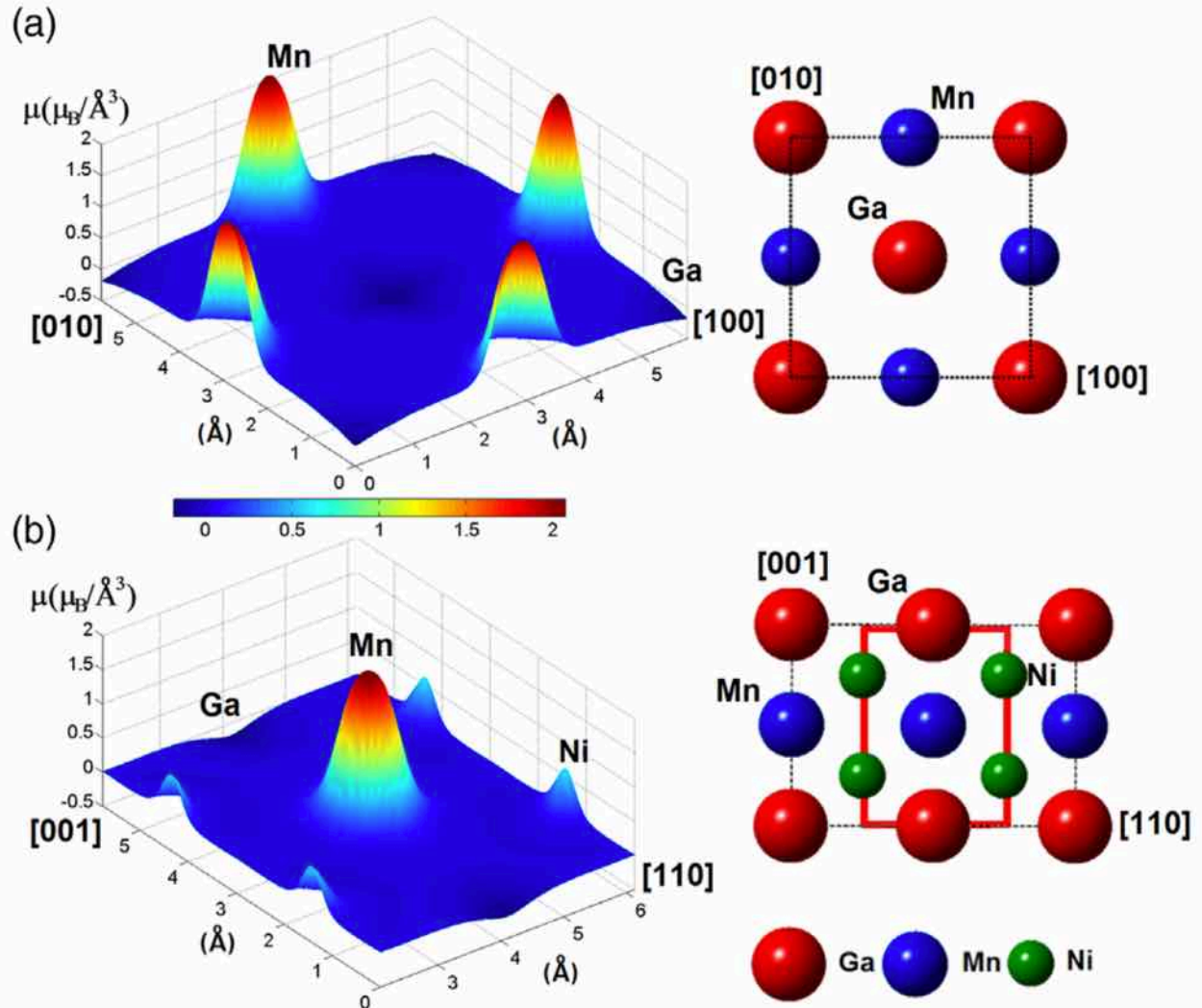
# Neutrones polarizados

## Momento magnético Austenita-Martensita

(D3)



(AF) 2.92 Å → (FM) 3.32 Å



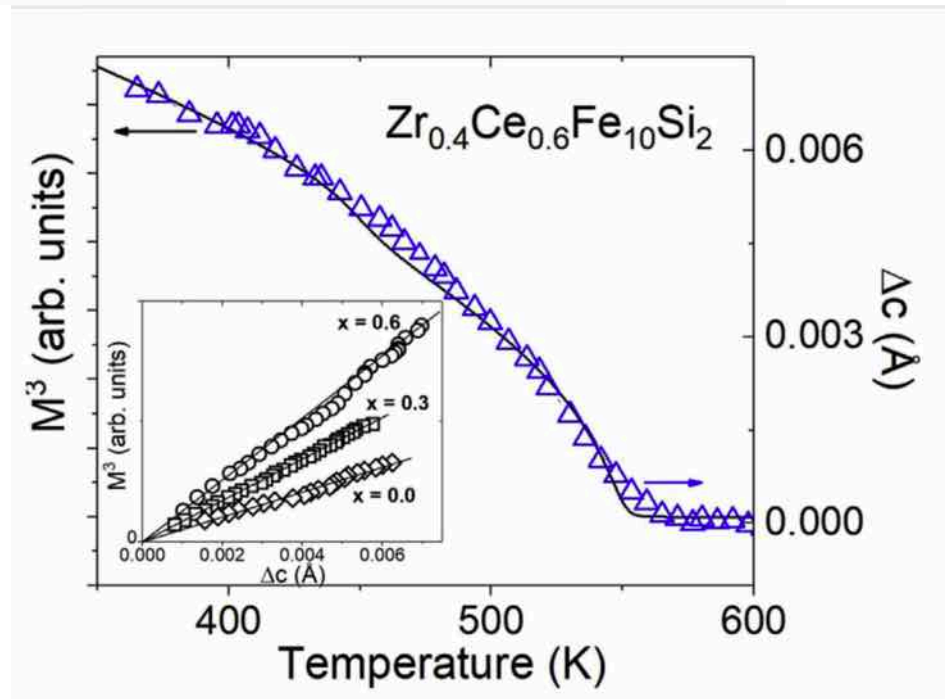
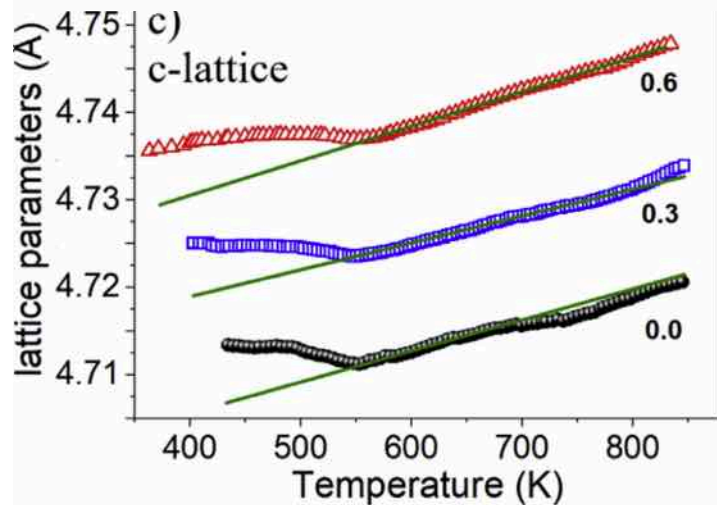
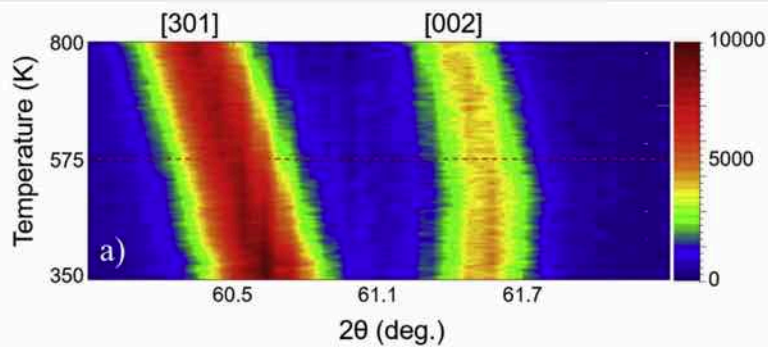
# Imanes permanentes sin Tierras Raras

$R(\text{FeM})_{12}$

$\text{Zr}_{1-x}\text{Ce}_x\text{Fe}_{10}\text{Si}_2$  ( $x=0.0, 0.3, 0.6$ )

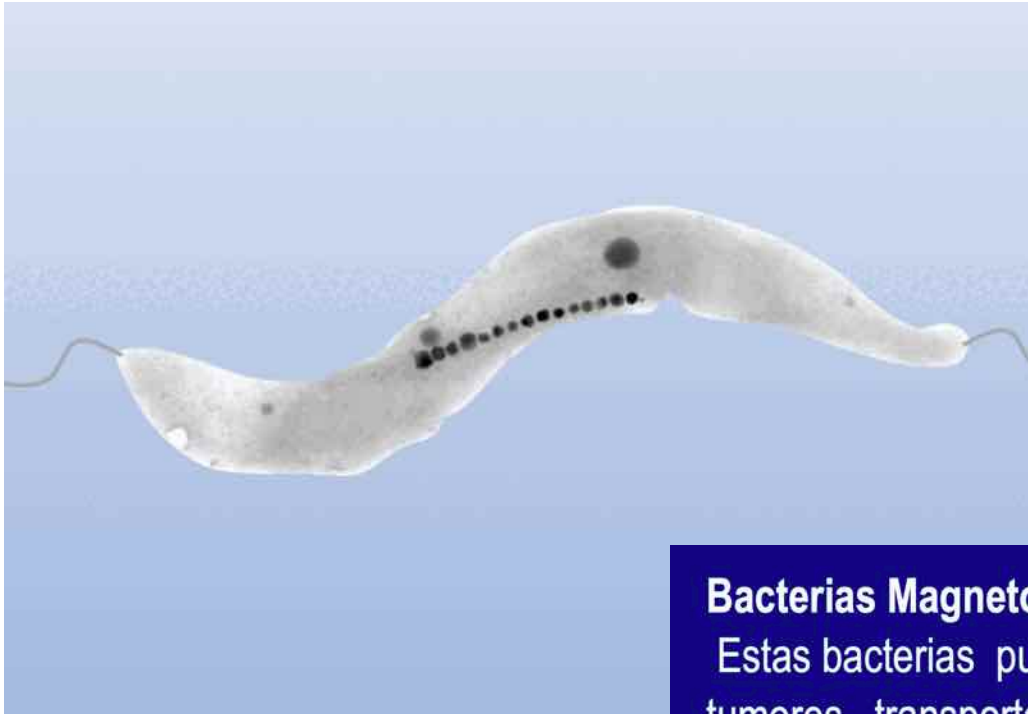
$[\text{ThMn}_{12}]$

Ce content	$M_s$ ( $\text{A} \cdot \text{m}^2 \text{kg}^{-1}$ )	$\mu_0 H_a$ (T)	$a$ ( $\text{\AA}$ )	$c$ ( $\text{\AA}$ )	$a/c$
$x = 0.0$	120	2.03	8.274	4.701	1.760
$x = 0.3$	120	2.31	8.303	4.707	1.764
$x = 0.6$	120	2.50	8.354	4.724	1.768



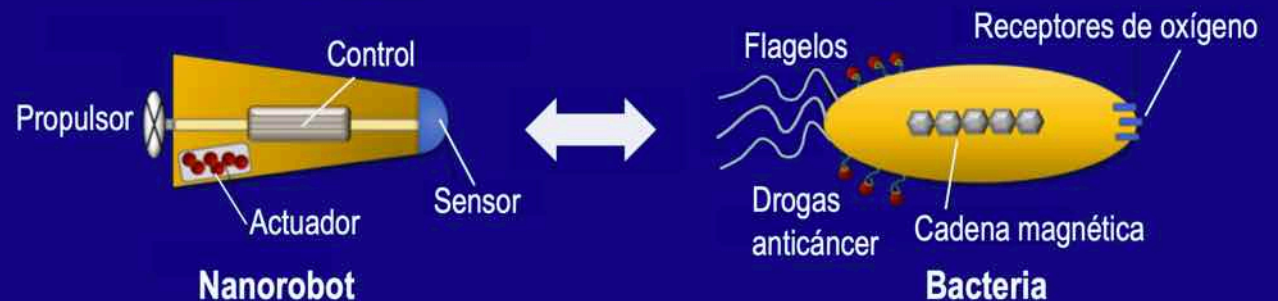
$\lambda_s \approx 1500 \text{ ppm} \propto M^3$ , campo cristalino El Ce no contribuye  
 Origen puramente geométrico de la anisotropía

# BACTERIAS MAGNETOTÁCTICAS



## Bacterias Magnetotácticas como nano-bio-robots

Estas bacterias pueden utilizarse como robots biológicos para localizar tumores, transportar drogas o para tratamientos de hipertermia en terapias anticancerígenas (teragnosis)





M<sup>a</sup> Leticia Fernández Guzmán

José Manuel Barreda

Juan Gutiérrez

Alfredo García Arribas

Elena Kufnerová

Vladimir Chernenko

Alicia Muñoz

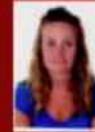
Ana García Prieto

Iván Orta

Patricia Laporte

David de Cos

Andrea Lubiano



María Gáratea

Eduardo Hernández

Lorena Mancano

David García

Lucía Gamero

Raquel Sainza

Anna León

Virginia Sallés

Alicia García

Departamento Electricidad y Electrónica;

Departamento Física Aplicada I;

Departamento Física Aplicada II;

Departamento de Inmunología Microbiología y Parasitología



eman ta zabal zazu



Universidad del País Vasco

Euskal Herriko Unibertsitatea

## Master Interuniversitario en Nuevos Materiales





# ASAMBLEA FUNDACIONAL

MADRID, 17 de Octubre de 2002



## *1ª REUNIÓN ANUAL*

BILBAO, 10 de Octubre de 2003


Jornada monográfica: Imágenes magnéticas

## *1ª CONVOCATORIA del PREMIO SALVADOR VELAYOS*

MADRID (2008): Agustín del Moral y Eloísa López



15 de Diciembre de 2006 Madrid, Salón de Actos del Edificio Central del CSIC



Remedando al replicante  
Roy Batty  
de Blade Runner...

He visto cosas que vosotros no creeríais: Las luces de los galvanómetros balísticos oscilando en la oscuridad en los sótanos de la Complutense, laminar cintas amorfas en la vía del expreso Madrid-Irún y escribir artículos a máquina con auténticas copias de papel carbón. Todas esas experiencias se perderán en el tiempo, como miles de artículos sin leer en las papeleras...

¡Muchas Gracias!