INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040-224572 TELEFAX 040-224575 TELEX 460449 APH I

H4.SMR/676-30

SECOND SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY: *"JOHN FUGGLE MEMORIAL"*

25 October - 19 November 1993

Miramare - Trieste, Italy

EXAFS V

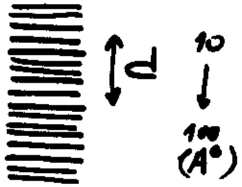
A. Fontaine
L.U.R.E.
Orsay, France

IV Structural Anisotropy & linear polarization of S.R.

IV.1 SUPERLATTICES & MULTILAYERS

- OPTICS for X. RAYS

"SYNTHETIC" BRAGG OPTICS



- MAGNETIC PROPERTIES

Recording
(Perpendicular magnetization)
(Noise and granular struct)

Reading
Giant magnetoresistance

Permalloy (Ni Fe) $\frac{\Delta R}{R} \sim 3\%$

Superlattices Co Cu $\frac{\Delta R}{R} \sim 100\%$ at 77K

- NEW PHYSICS 2d objects
(low dimensionality)

new Structure
Fe in Fe Ru superlattices
Co in Co Fe

VOLUME 67, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1991

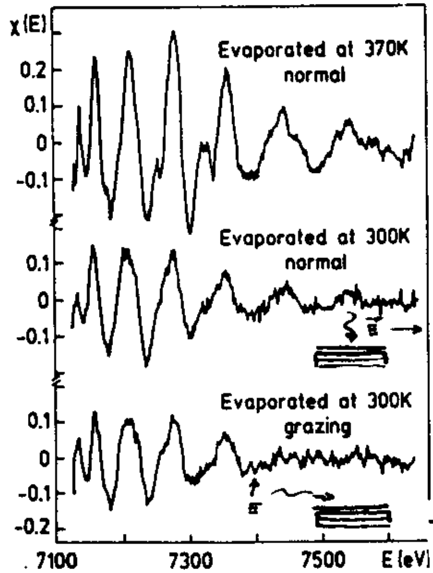
Structure of Thin Metastable Epitaxial Fe Films on Cu(100): Reconstruction and Interface Ordering by Coating

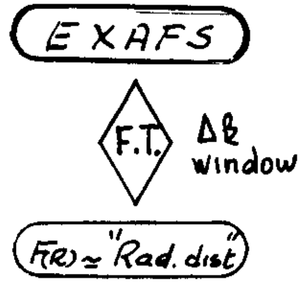
H. Magnan, D. Chandesris, B. Villette, O. Heckmann, and J. Lecante
Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Université de Paris-Sud, F-91405 Orsay, France and Service de Physique des Atomes et des Surfaces, Centre d'Etudes Nucléaires, F-91191 Gif-sur-Yvette, France

$$\chi(k) = -\frac{1}{k}\sum_j \frac{1}{R_j^2}\, 3\cos^2\theta_j \, \exp -2\sigma_j^2 k^2 \, \exp -\frac{2R_j}{\lambda(k)} \, f_j(\pi,k)\, \sin\left[2kR_j + \psi(k)\right]$$

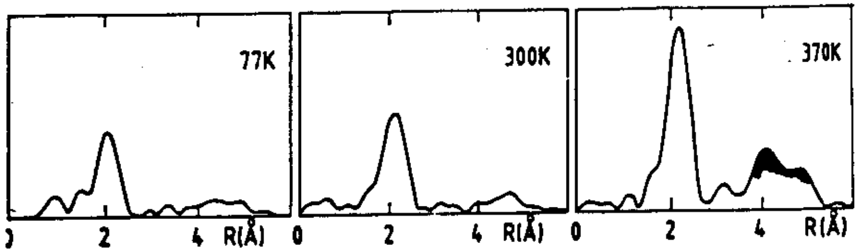
with

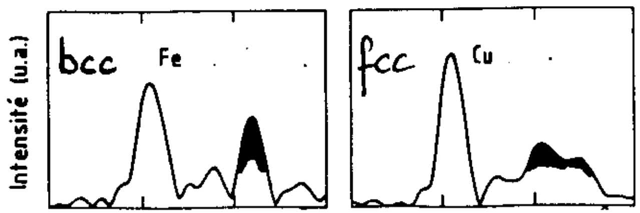
$$\psi(k) = 2\delta(k) + \arg f_j(\pi,k)$$





Fe K-edge : 3.5 ML on Cu(100)
(77K data)





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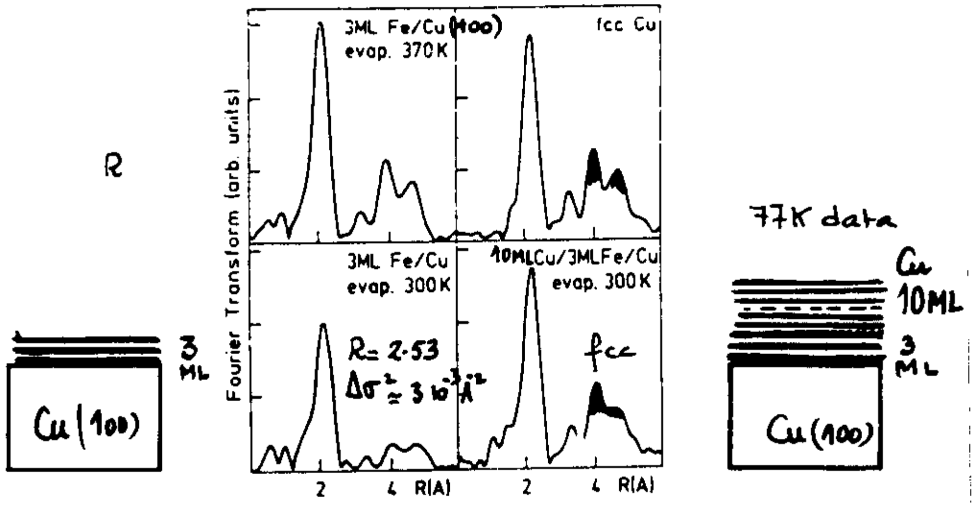
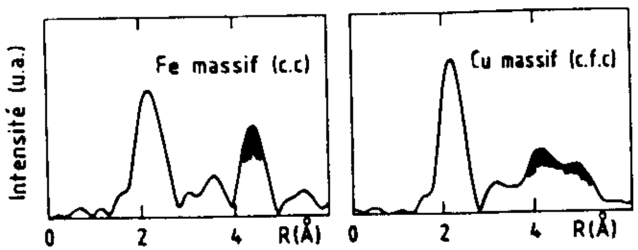


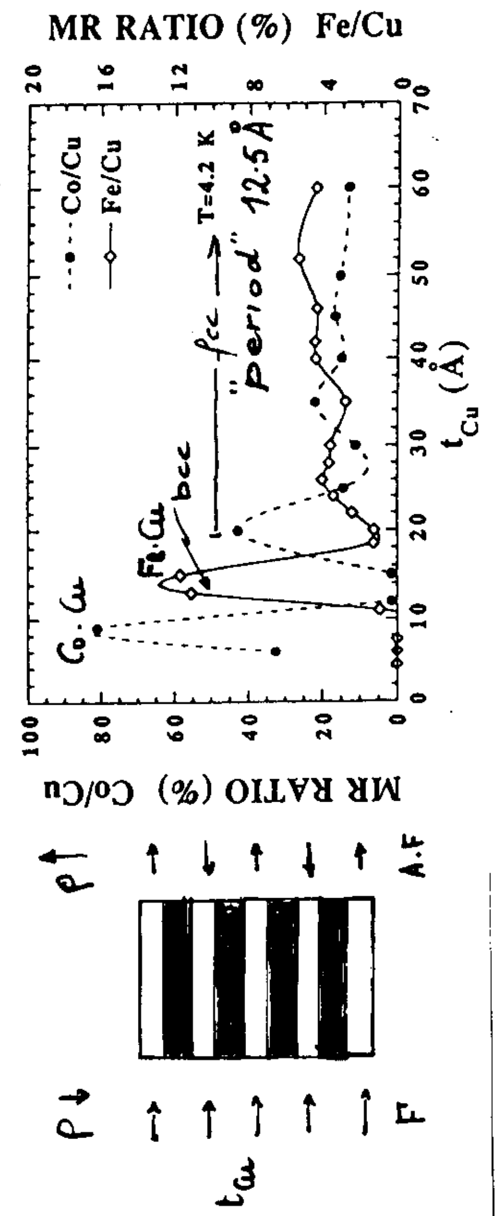


Oscillatory interlayer exchange and magnetoresistance in Fe/Cu multilayers

F. Petroff, A. Barthélemy, D. H. Mosca,* D. K. Lottis, and A. Fert
Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France

P. A. Schroeder, W. P. Pratt, Jr., and R. Loloee
Department of Physics and Astronomy and Center for Fundamental Materials Research, Michigan State University, East Lansing, Michigan 48824

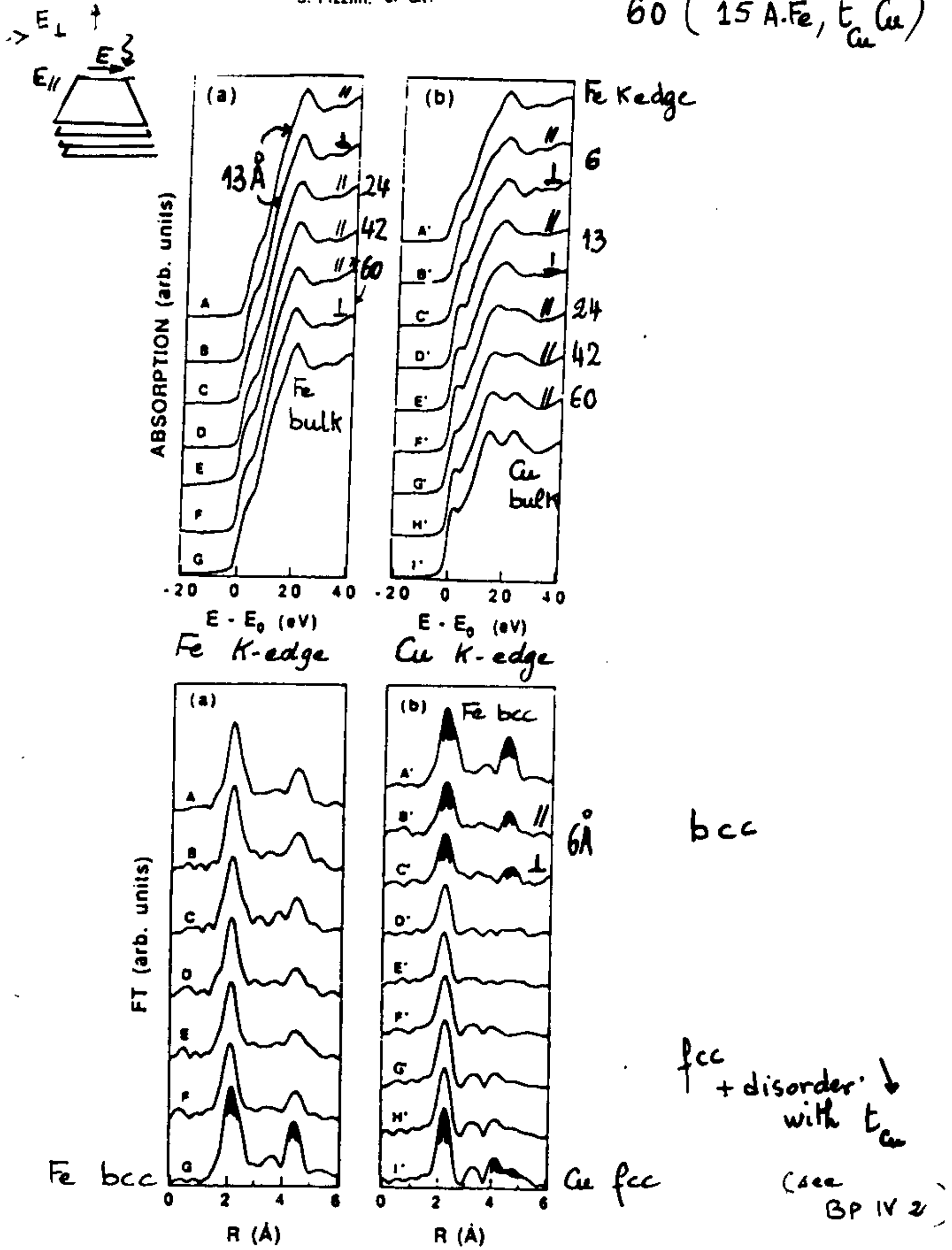
S. Lequien
Laboratoire Central de Recherches Thomson-CSF, 91404 Orsay, France



CAL REVIEW B VOLUME 46, NUMBER 1

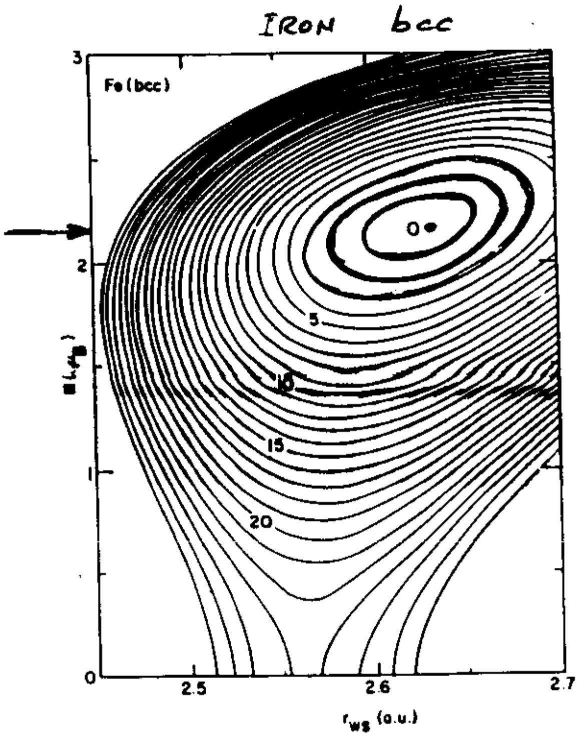
Structural characterization of Fe/Cu multilayers by x-ray absorption spectroscopy

S. Pizzini, et al.



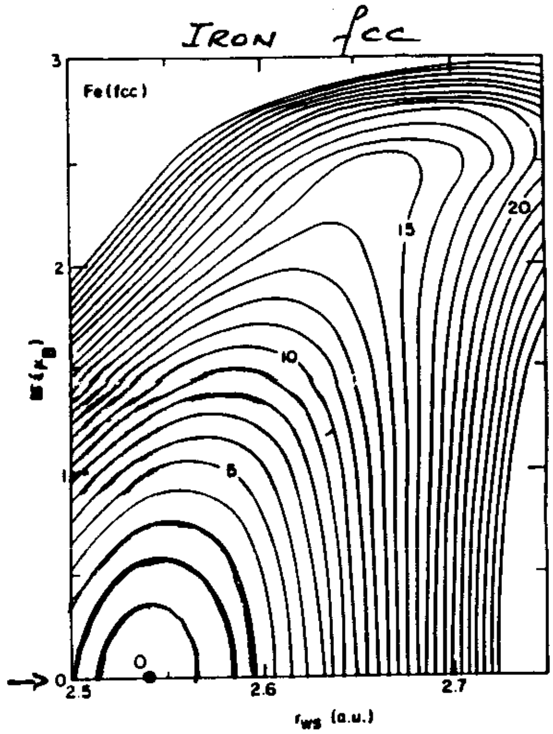
IV. 2 Fe in Fe-Ru superlattices

- Physics
- Aims of the EXAFS study
- Results
- Beatings
- Model of the new 2d stacking

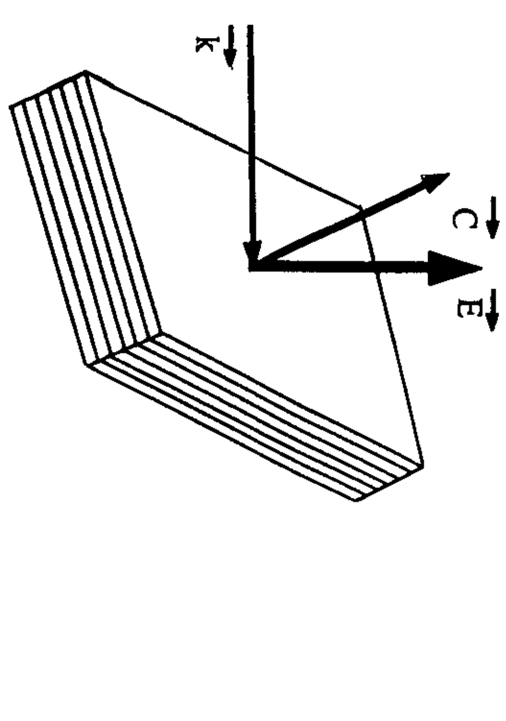


a-Contour d'égale énergie pour le fer bcc. Les contours sont tracés pour des intervalles constants de 1 mRy et la valeur est donnée par rapport à l'énergie minimum. L'équilibre est atteint pour un moment de 2.15 μ_B et une taille de cellule de Wigner r_{WS}=2.63 u.a. correspondant à $(\partial E/\partial M)_B=0$ (champ nul) et $(\partial V/\partial V)_M=0$ (pression nulle). Dans la structure bcc, le fer est magnétique pour tous les volumes considérés.

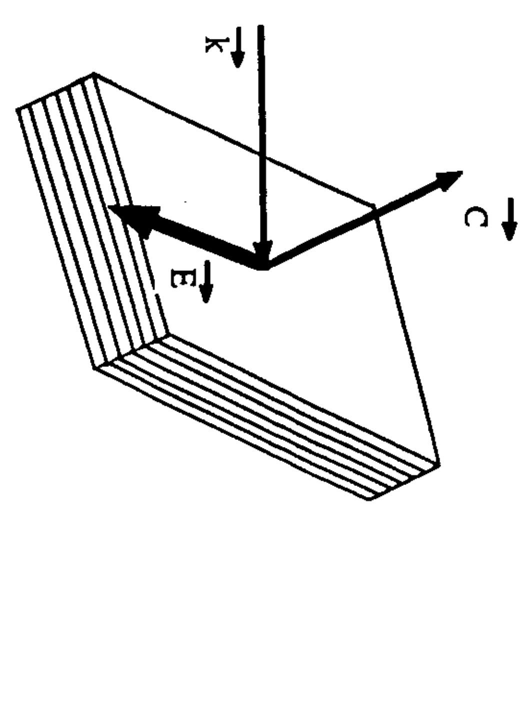
Figure II-2:



b-Contour d'égale énergie pour le fer fcc. Les contours sont tracés pour des intervalles constants de 1 mRy et la valeur est donnée par rapport à l'énergie minimum. L'équilibre atteint pour M=0 et une taille de cellule de Wigner r_{WS}=2.54 indique le fer fcc est non magnétique. L'épaule trouvée à large volume, haut champ est à l'origine de la phase magnétique qui peut se produire si le système est maintenu très dilaté.
Marcus et al Phys.Rev. B 34,3, p.1784. (1986)



Perpendicular to the plane polarisation



In plane polarisation

// Fe-K

⊥ Fe-K

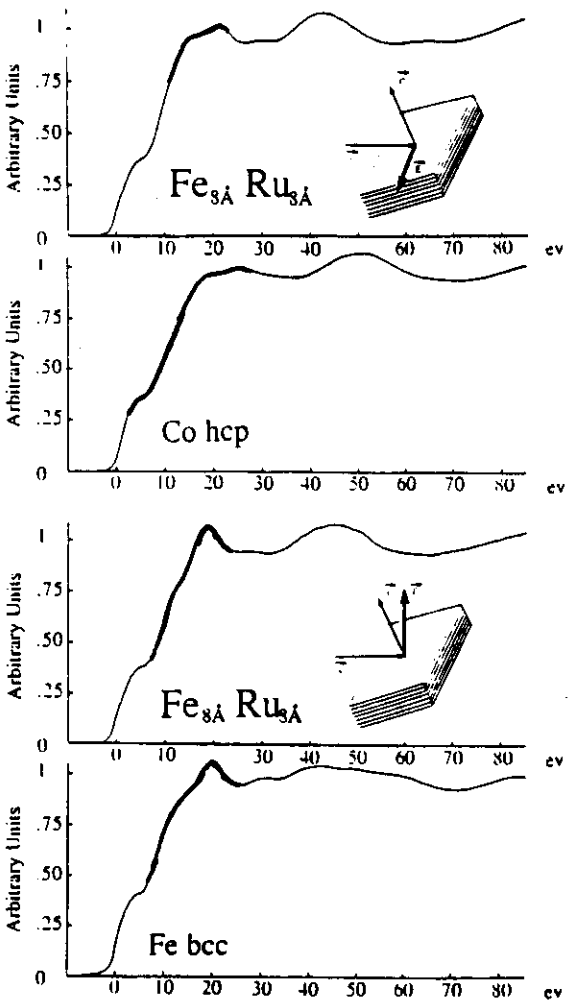


Figure V-3: Dichroïsme linéaire du XANES au seuil K du fer des superréseaux $Fe_{8Å}$-$Ru_{8Å}$. Le spectre mesuré avec la polarisation dans le plan des couches ressemble à celui du cobalt (hcp) tandis que celui mesuré avec la polarisation perpendiculaire au plan des couches est manifestement de type bcc.

Baudelet, Fontaine et al
PRB (1992)

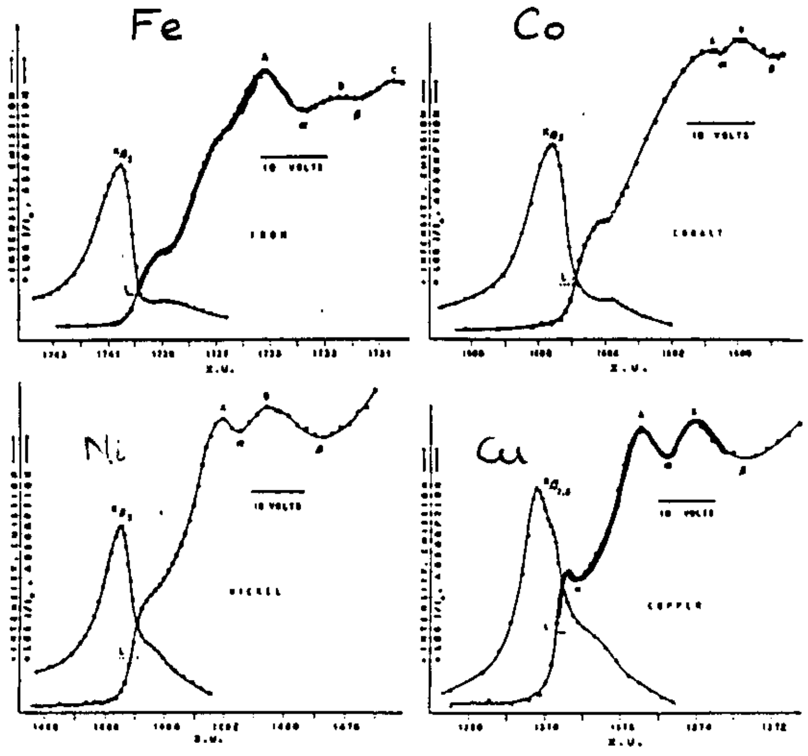
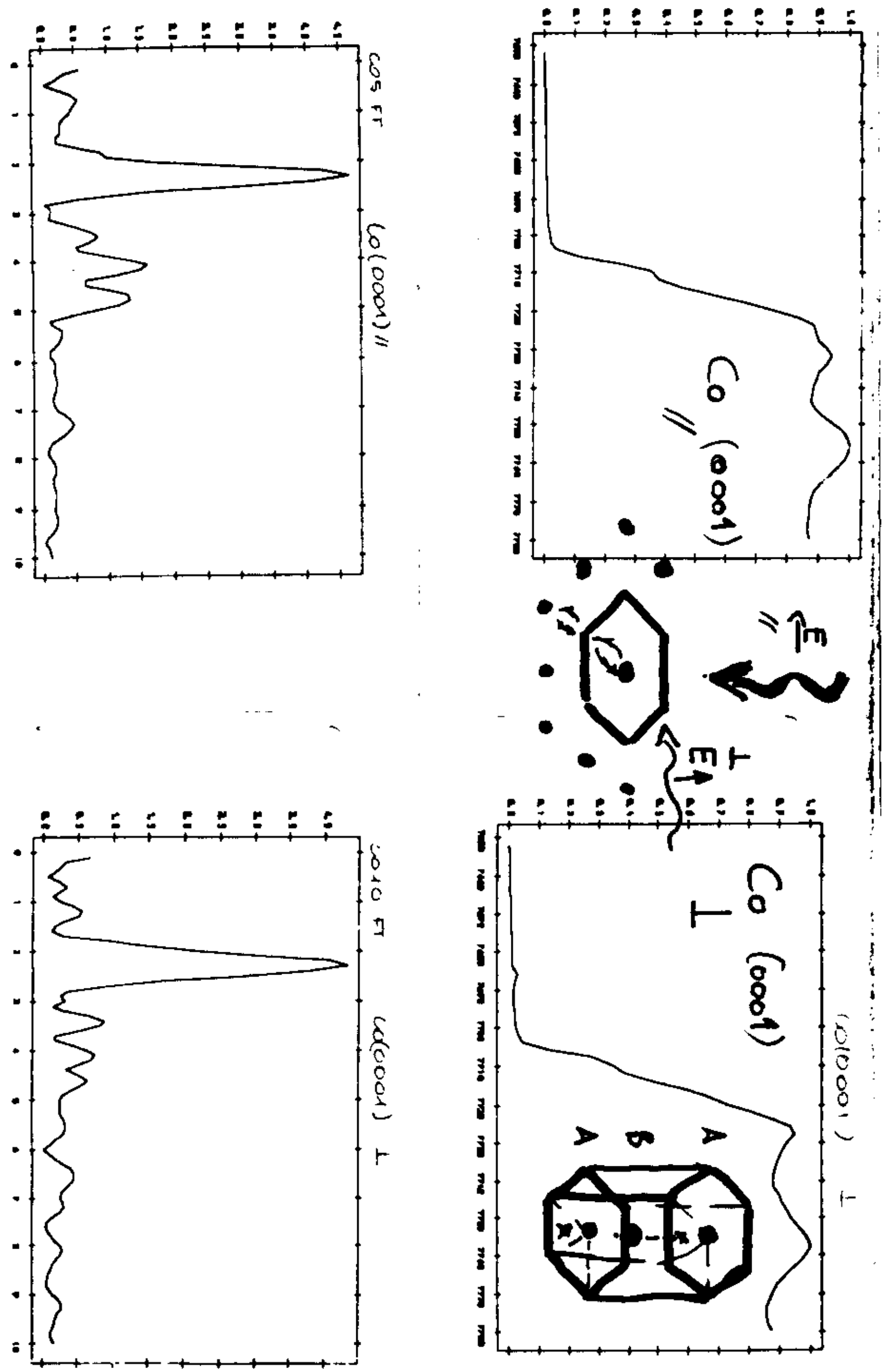


Figure III-9 Profils XANES et profils d'émission mesurés par Beeman et Freeman [5] dès 1939. On distingue bien le profil XANES du bcc de ceux de l'empilement dense hcp-fcc

XANES

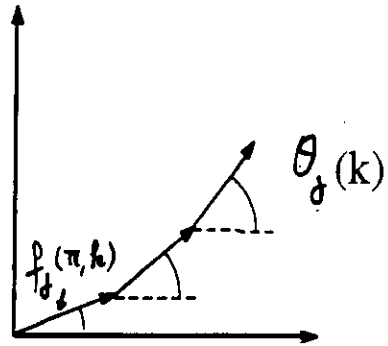
bcc / fcc or hcp

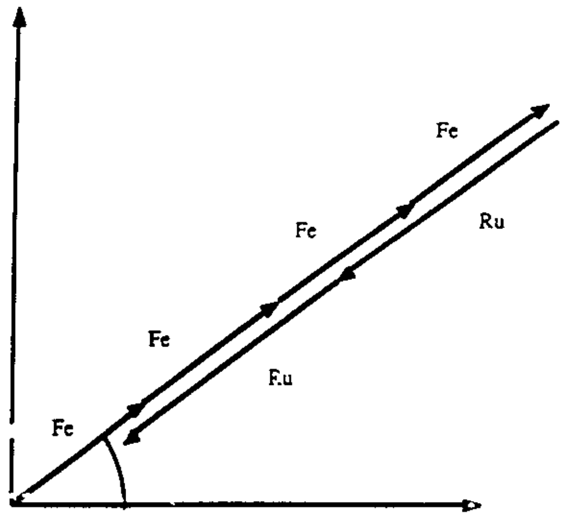
Beeman , Freeman (1939)



for a "k" value

SCHEMATIC FRESNEL DIAGRAM





Pour des valeurs de k supérieures à 3 ua^{-1}

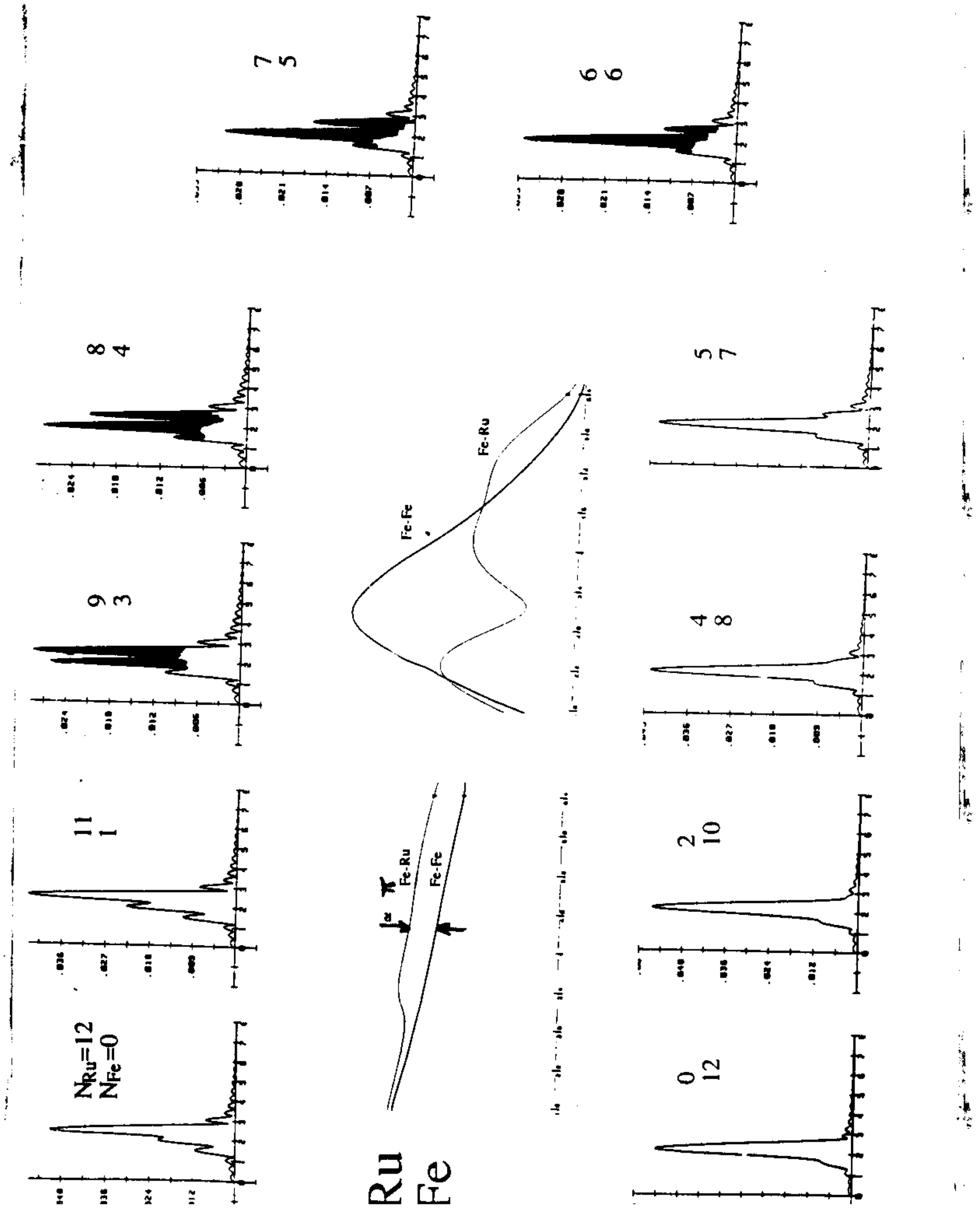
BEATING :

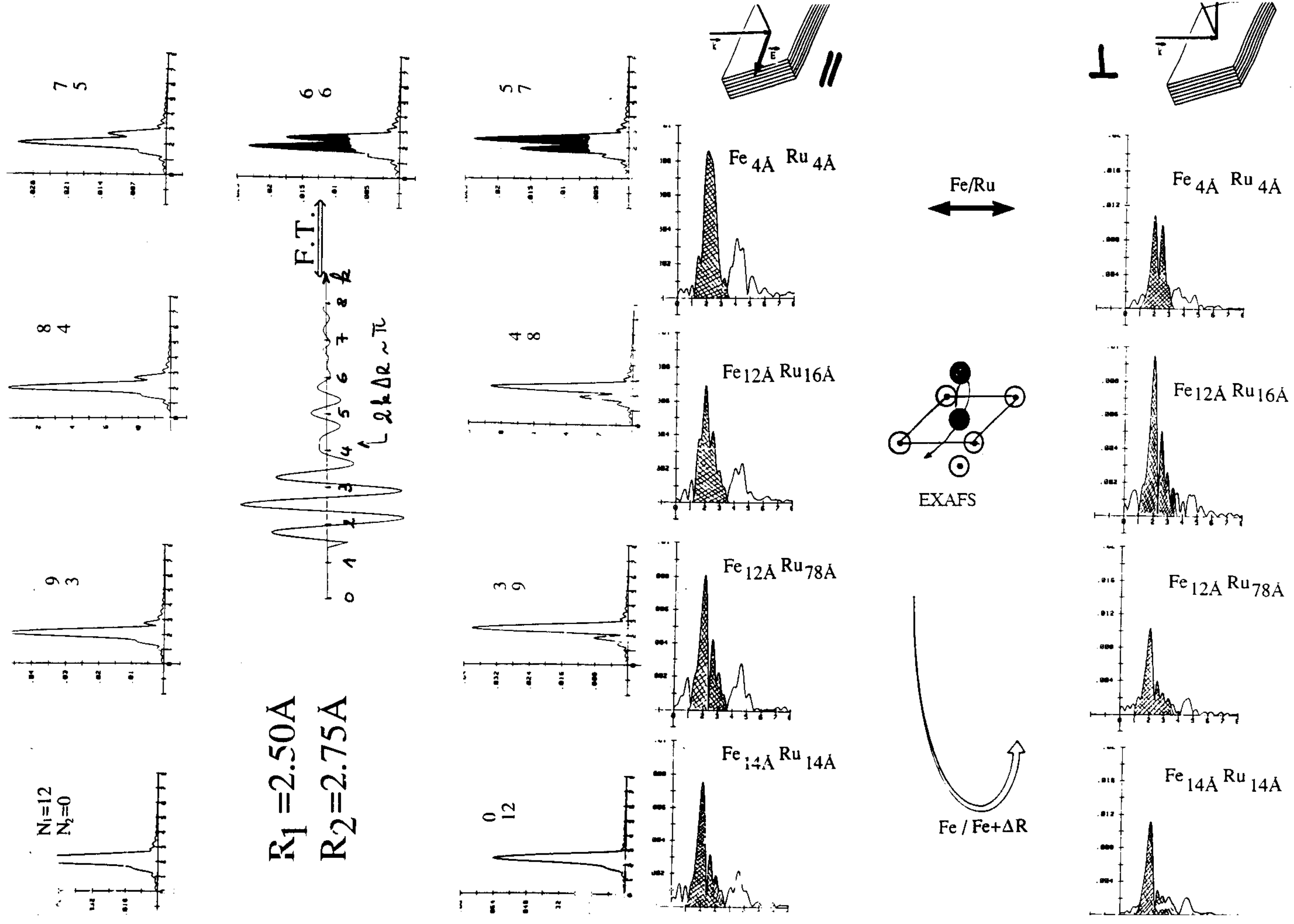
Interference between
2 non-resolved
subshells.

Fe-Ru superlattices

→ $\neq$ $\frac{Fe}{Ru}$ as first neighbours

→ $\neq$ Fe (∥) / Fe (⊥) as first neighbours

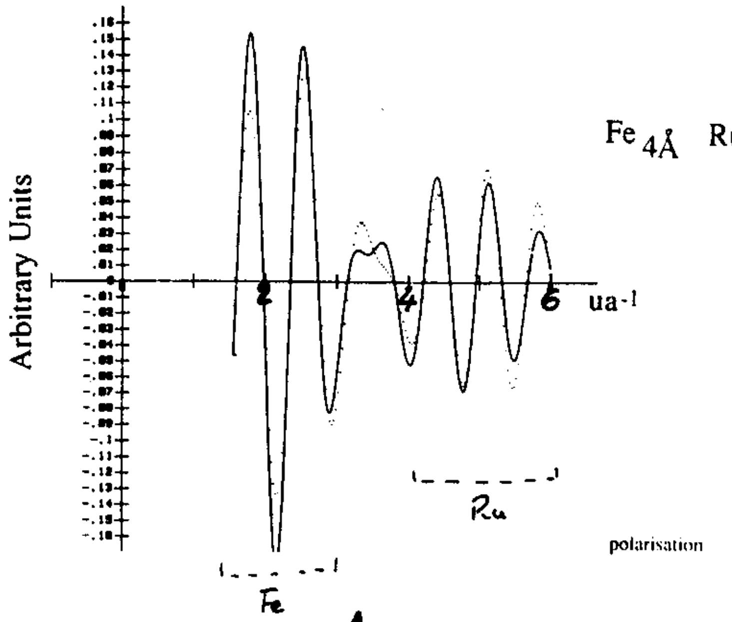


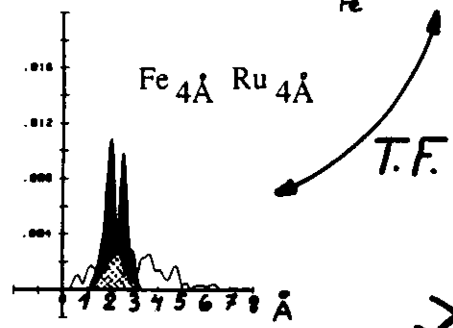


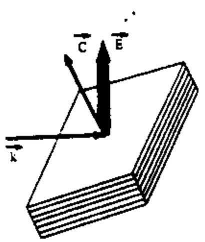
Fe 4Å Ru 4Å
Fe 12Å Ru 16Å
Fe 12Å Ru 78Å
Fe 14Å Ru 14Å
Fe/Ru
EXAFS
Fe / Fe+ΔR
F.T.
R1 =2.50Å
R2=2.75Å
N1=12
N2=0

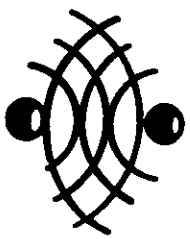
$$k) = -\frac{1}{k}\sum_j \frac{N_j}{R_j^2}\, 3\cos^2\theta_j \;\exp(-2\sigma_j^2 k^2)\,\exp\left(-\frac{2R_j}{\lambda(k)}\right)\left|f_j(\pi,k)\right| \times$$

$$\sin\left(2kR_j + 2\delta(k) + \arg\left(f_j(\pi,k)\right)\right)$$







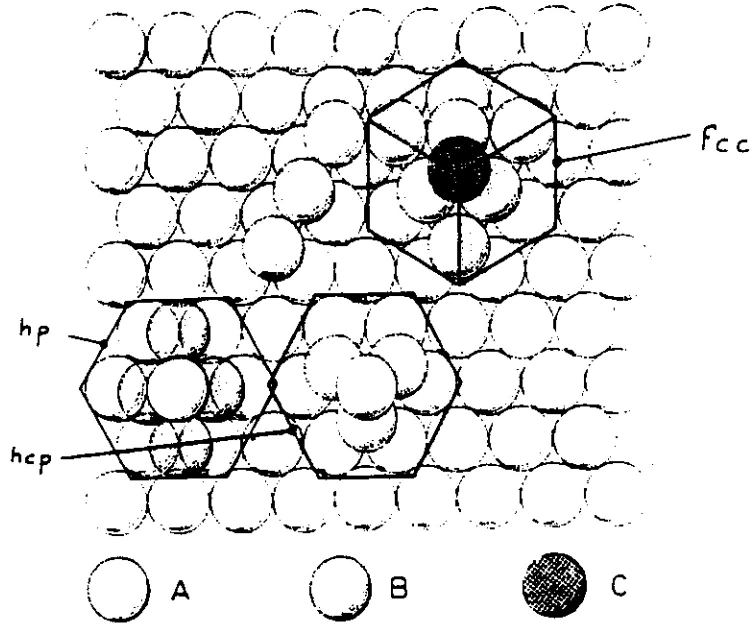


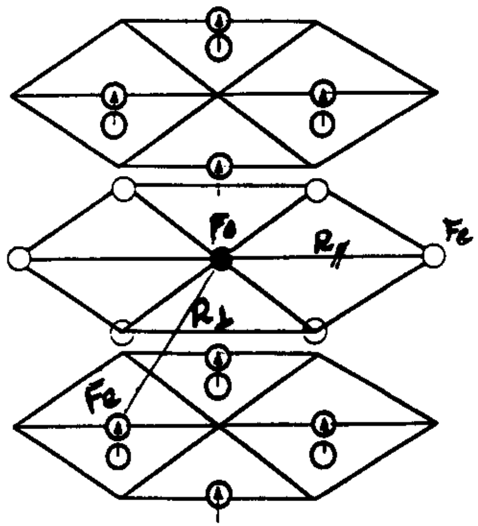
- diffraction 4.15 Å
- hcp 3.88 Å

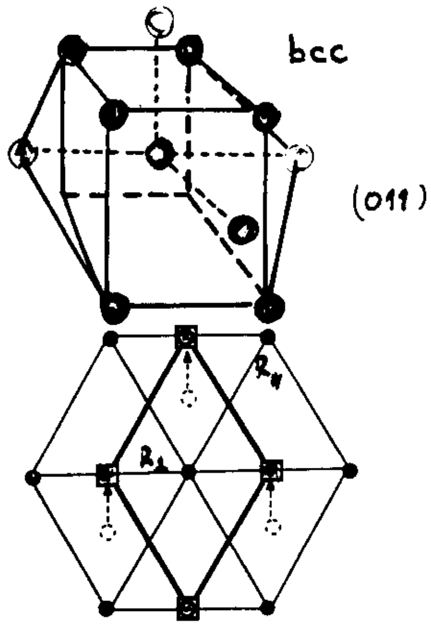
$R_\perp = 2.52 \pm 0.02$

$R_\parallel = 2.73 \pm 0.02$

→ $c = 4.18$ Å







F. BAUDELET et al.

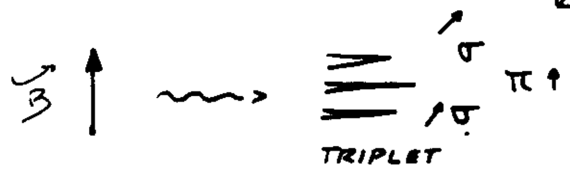
Magnetic circular X-ray dichroism

Circular Magnetic Dichroism

Zeeman 1896

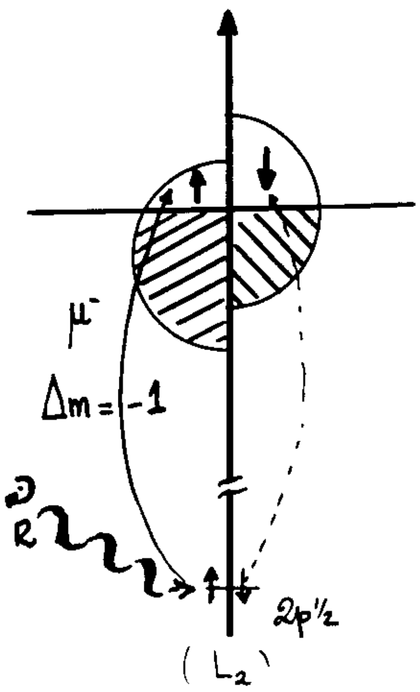
Emission ≠ Absorption (Inverse Zeeman Effect)

Na ions in a "magnetized flame"



Anomalous splitting (later on) 1925 ⇒ S.O

LORENTZ PREDICTION confirmed by Zeeman



2 step model

spin-polarized photoelectron

spin-splitted band ≈ spin detector

MCXD: $\frac{\mu^+ - \mu^-}{\mu^+ + \mu^-} \sim \frac{\rho\uparrow - \rho\downarrow}{\rho\uparrow + \rho\downarrow}$

LURE XAS 10, Brookhaven (Dragon)

SOFT X-rays 2p ⟶ 3d
itinerant magnetism

HARD X-rays 1s ⟶ 4p
conduction band

(RE 2p → 5d)
L_{III}, L_{II}

Related effects

FARADAY ROTATION

KERR EFFECT (Reflectivity → MOKE)

New Related experiments

CIRCULAR ~~Light~~-PHOTOEMISSION

SPIN-RESOLVED "

RESONANT MAGNETIC SCATTERING

Co-Fe alloys

Multilayers * Co / Cu   * Fe / Cu

Fe / Co   Fe / Ce

$$\overset{G}{\mathrm{M}}.\mathrm{X.D.} \equiv \frac{\Delta\sigma}{2\sigma} \simeq \overset{G}{P_c}\, P_e \;\frac{\Delta\rho^{\uparrow\downarrow}}{\rho}$$

We need:

- Magnetization $\Delta\rho/\rho \neq 0$
- Spin orbit coupling $P_e \neq 0$
- Circular polarization $P_c \neq 0$

Experiment on magnetic systems

- 5 ⟶ 10 **kev**
  - s ⟶ p Transition elt
  - p ⟶ d Rare Earth
- < 2 kev
  - p ⟶ d 3d itinerant
  - d ⟶ f 4f localized

▶ K or L_I **Edges**

S.O. in the final state (of the photo electron)

⟶ Small effect ~ 10^{-3}

▶ L_{II} or L_{III} Edges

S.O. mainly in the excited core level

⟶ few 10^{-2}

MAGNETIC X-RAY DICHROÏSM

Interests

Near edge magnetic dichroism:

double selectivity : - the element. - the final states.

hν Fe (7112 eV)

Select. RULES s ⟶ p, l ⟶ d

⇓

One probes directly the magnetic properties of the empty states in a given band of a given element.

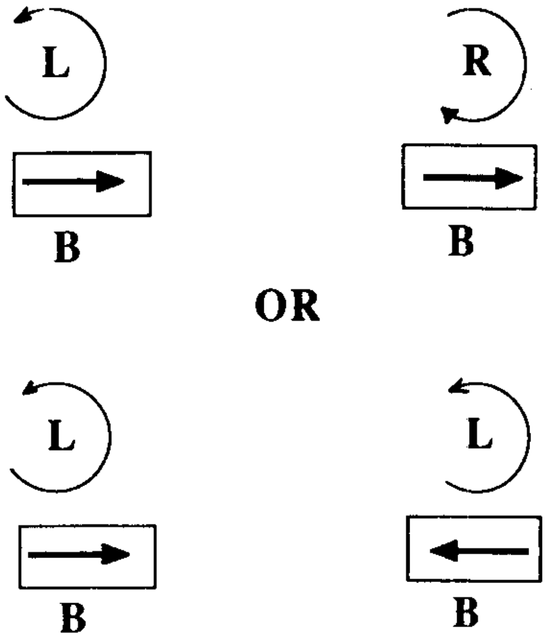
The integrated signal is "proportional" to the magnetic moment of empty states and then opposite to the magnetic moment of occupied states.

↳ $(A_x B_y)$

MXD MXD

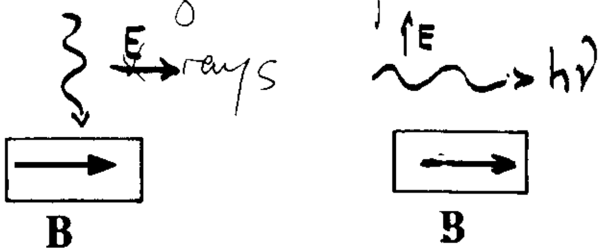
SIGN of the COUPLING

MAGNETIC CIRCULAR (X-ray) DICHROISM

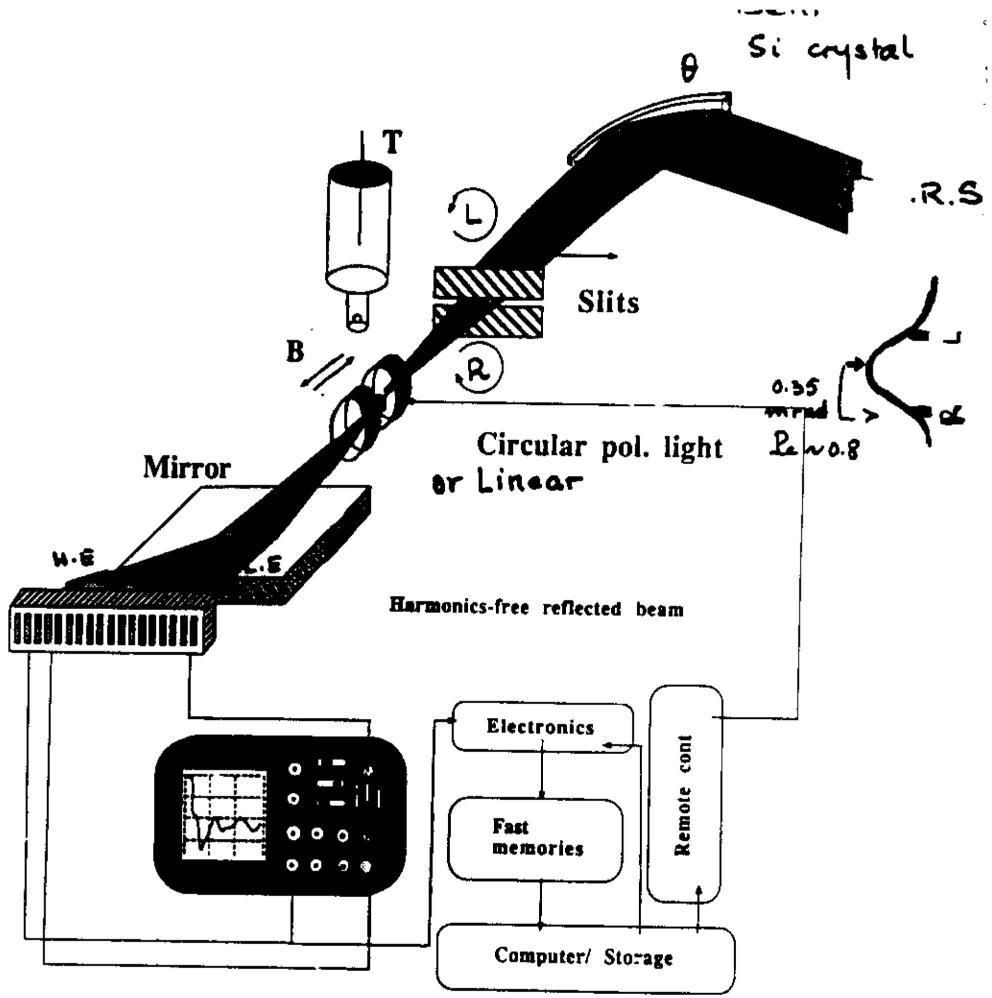


Pioneered by G. Schütz et al. (1987)

AND MLXD



Pioneered by Van der Laan et al. - 1986 -



Schematic layout of the Energy-Dispersive Spectrometer

- Time Resolution Theoretical 10 ms 100 ms --> 1s
- No mechanical movement - STABILITY
- Focus < 500 μm (B/T) ↑

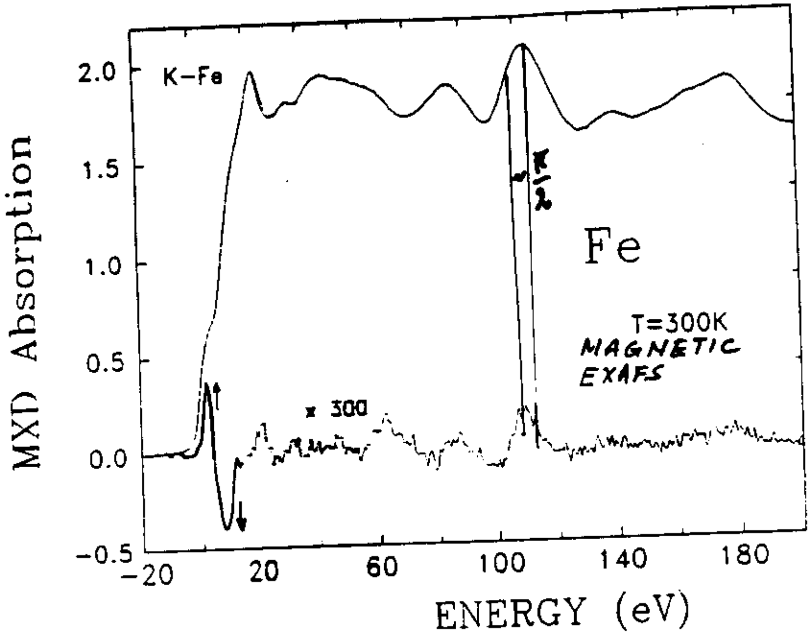
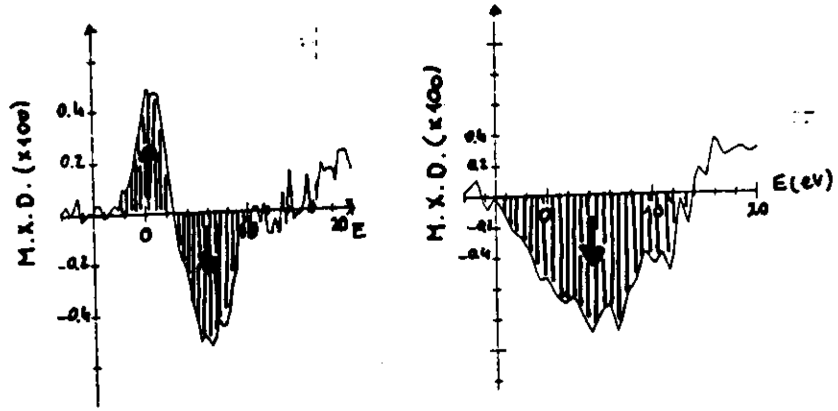
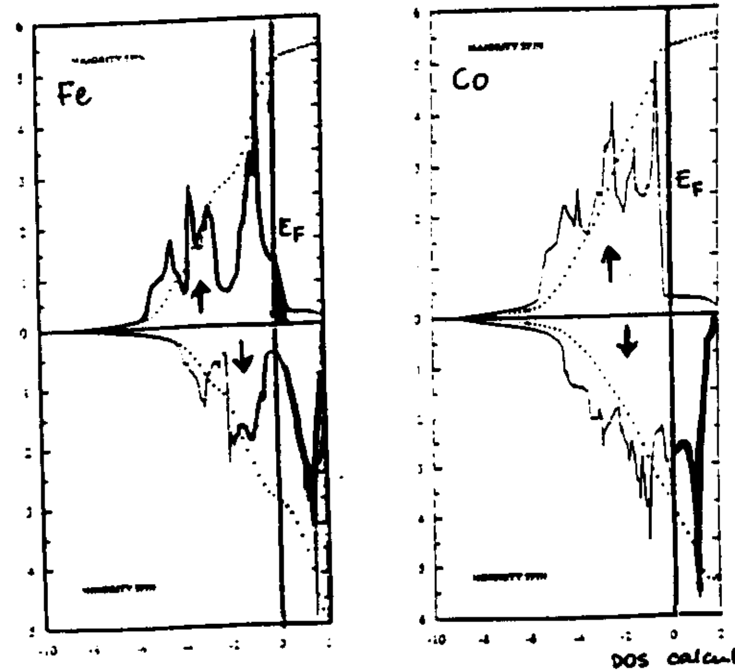


Figure VII-7: Dichroïsme magnétique du fer. Les oscillations EXAFS "sortent" bien du bruit. Le remarquable signal/bruit vient de la moyenne de 90 différences (μ^+-μ^-), chaque spectre individuel étant fait de 32 accumulations. Le temps total d' accumulations est 30 minutes avec le cristal Si(111) comme optique dispersive. Si on ajoute les temps morts nécessaires à l'inversion du champ magnétique le temps total de la prise de données de ce spectre est 35 minutes.
On remarquera que les pics du signal MXD sont quasi en quadrature de phases pour les oscillations dans le domaine des "hautes énergies" en particulier celle située autour de 105 eV.
Le signal MXD, au seuil K du fer est au mieux 2000 fois plus petit que la section efficace totale. Le rapport bruit reste supérieure à 10^{-4} en valeur absolue.

MAGN. EXAFS SIGNAL

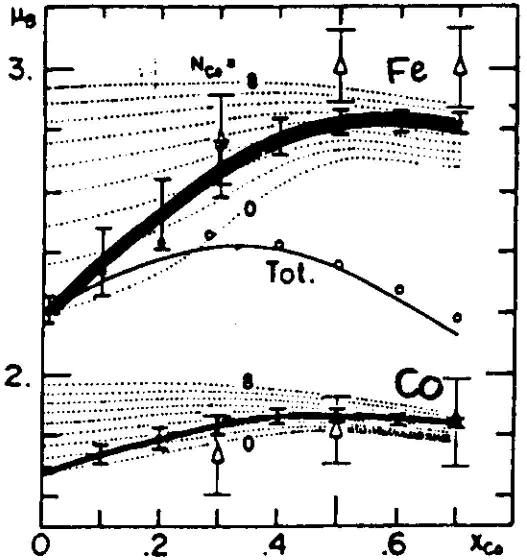
BUILT BY "MAGNETIC NEIGHBORS"



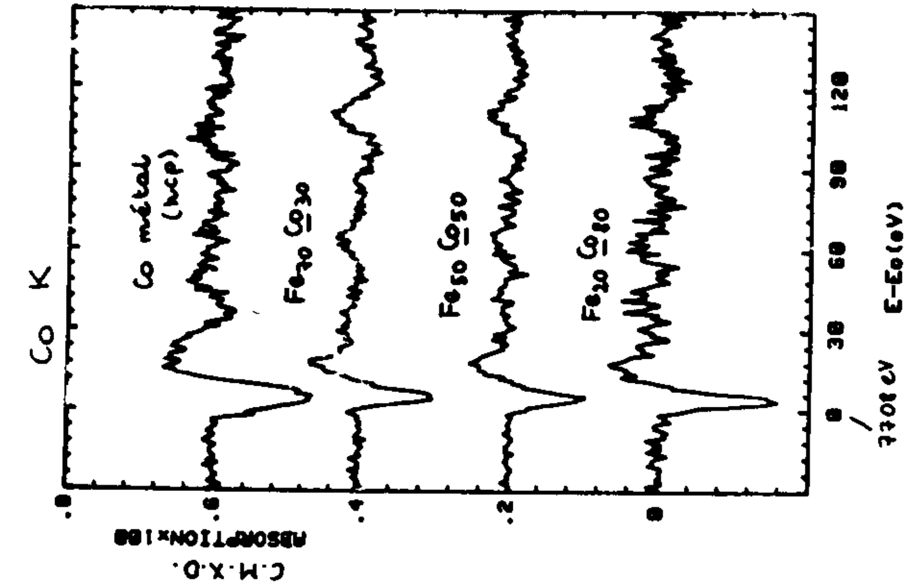


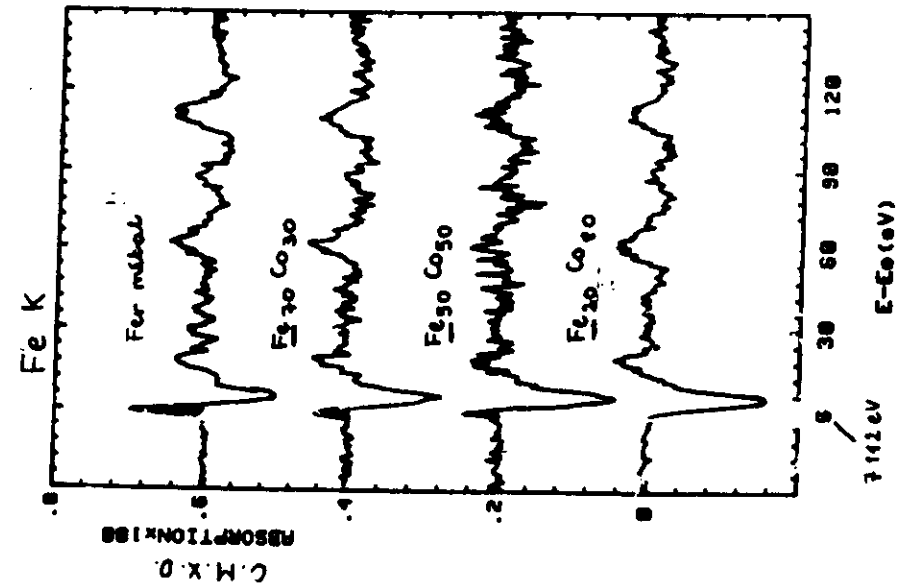
DOS calculations
Moruzzi et al.

Alliages Fe-Co



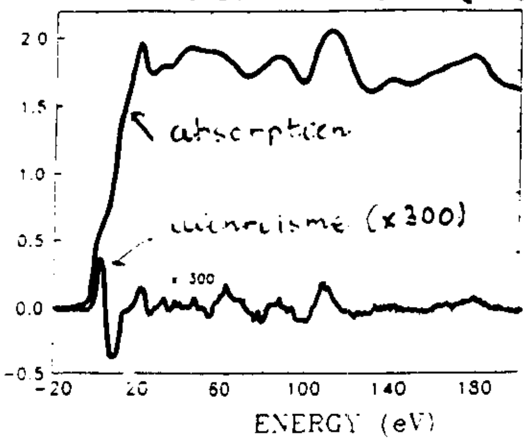
Hamada
J. Phys. Soc. Jap.
46 (1979) 1759





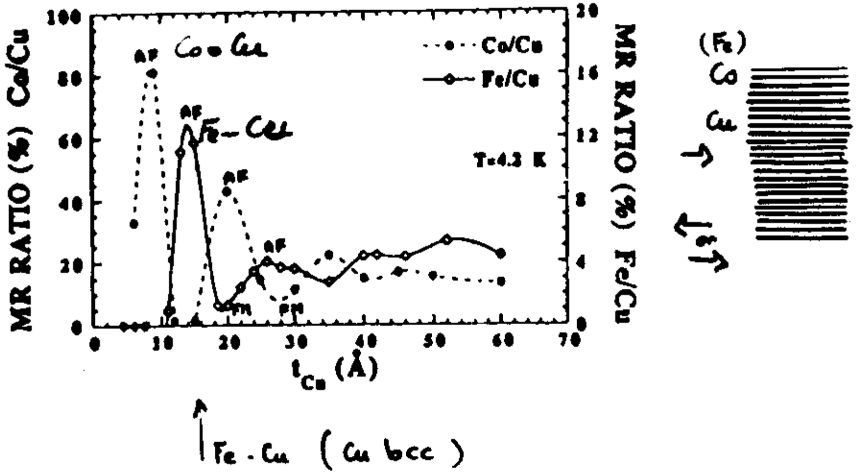
S. Pizzini, A.F. et al.

Fer métal (K)



Co/Cu and Fe/Cu multilayers

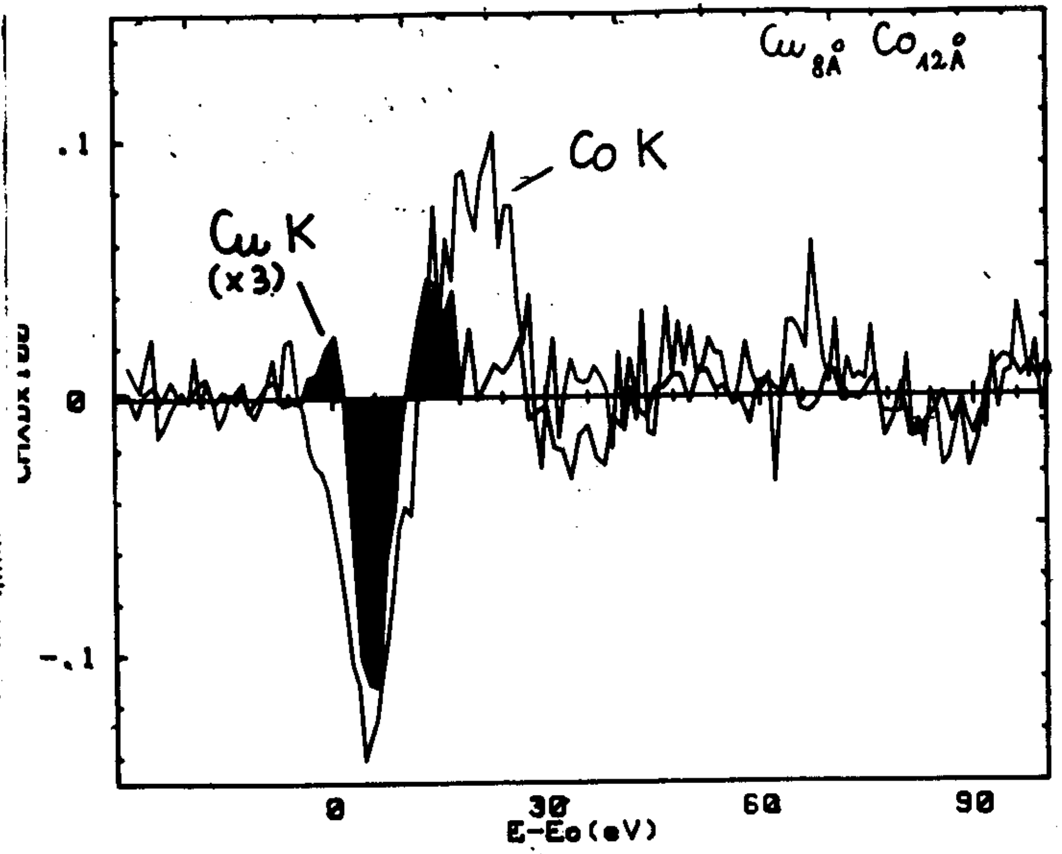
PROPERTIES:
- oscillatory magnetic coupling as a function of copper thickness
- large magneto-resistance



AIMS: to elucidate which electronic states of copper mediate the magnetic coupling;

to demonstrate that the conduction electrons of copper are spin-polarised

TOOL: Circular magnetic x-ray dichroism using Synchrotron Radiation

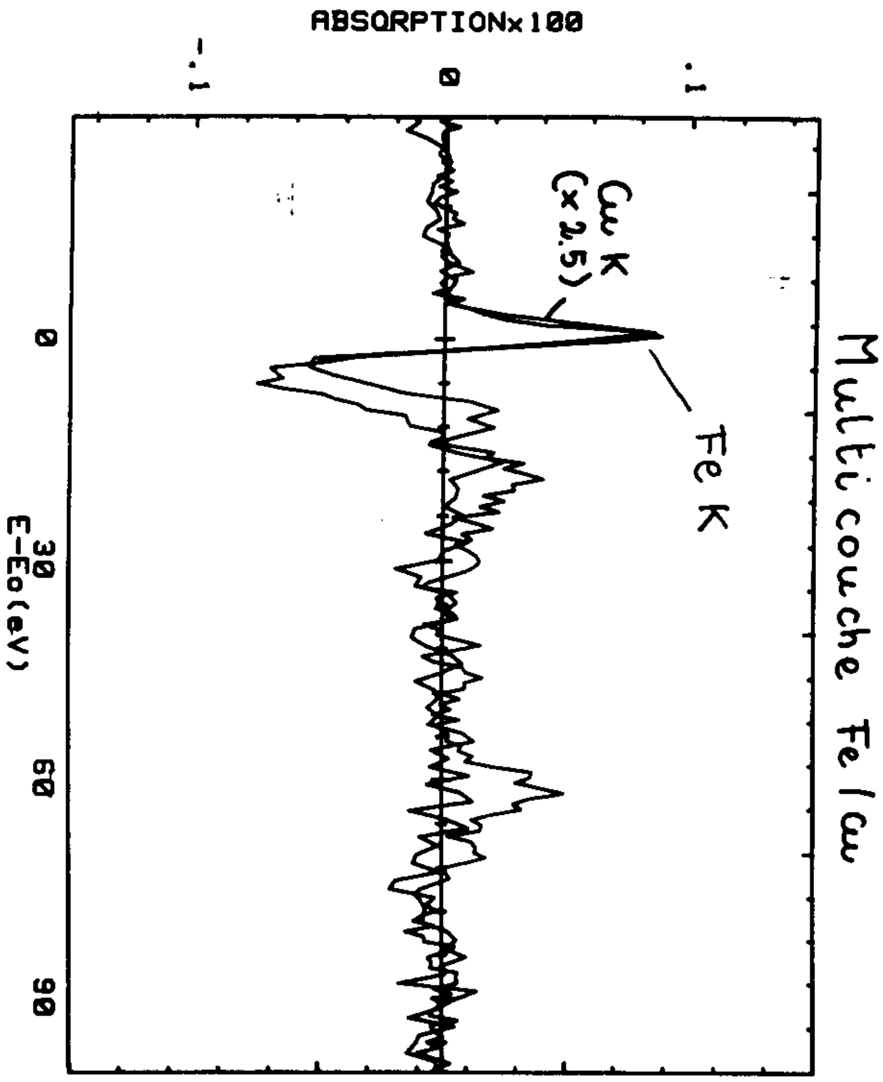


- the amplitude of the Cu K edge CMXD is not negligible: ≈ 30% of the Co K edge signal
- Cu K and Co K signal have the same sign: → parallel alignments between Cu and Co p-moments

$\mu^{4p}_{Cu} \sim 10^{-2} \mu_B$

Question:

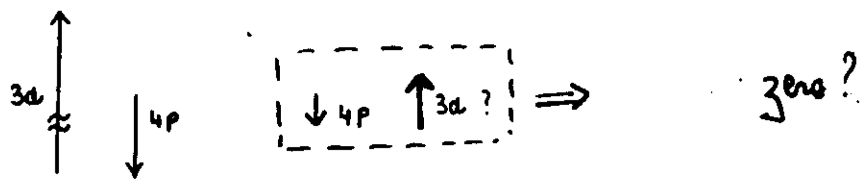
Are the *d*-bands of copper magnetically polarised?



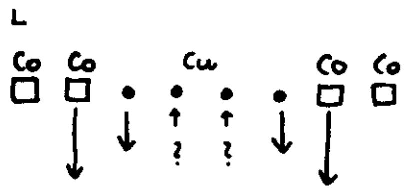
Main results

① **the conduction (*sp*) bands of copper** in Cu/Co are **spin-polarised**.

② the **spin-polarisation** of the ***d*-bands** of copper is **negligible**. compared with cobalt but it exists!

③


- CMXD signal is averaged over all the copper atoms in the layer.
  How is it modulated ?



Conclusions

MCXD useful for Magnetic Metallic Multilayers

Sign of coupling between $\vec{M}_A$ and $\vec{M}_B$

Surface sensitive (selectivities)

$(h\nu \searrow)$ High resolution

Sum rules P Carra et al. T. Thole μ_L μ_S

Depth of magnetic interface

M edges (R.E.) and L edges (3d)

MCXD and related techniques

Photoemission with circular light

Faraday rotation

Resonant magnetic X-ray scattering

XAS and spin polarized decay channels

AND FRIENDSHIP

干杯