X-ray Magnetic Circular Dichroism (XMCD):

Introduction and some typical results

Alok Banerjee

(alok@csr.res.in)

UGC-DAE Consortium for Scientific Research (CSR)

(Formerly: Inter University Consortium for DAE Facilities)

http://www.csr.res.in/

University Campus, Khandwa Road

Indore-452001, India.

X-ray Magnetic Circular Dichroism

Theoretical prediction → **1975**

Calculation of the M_{23} *magneto-optical absorption spectrum of ferromagnetic nickel, Erskine & Stern* Phys. Rev. B 12, 5016 (1975)

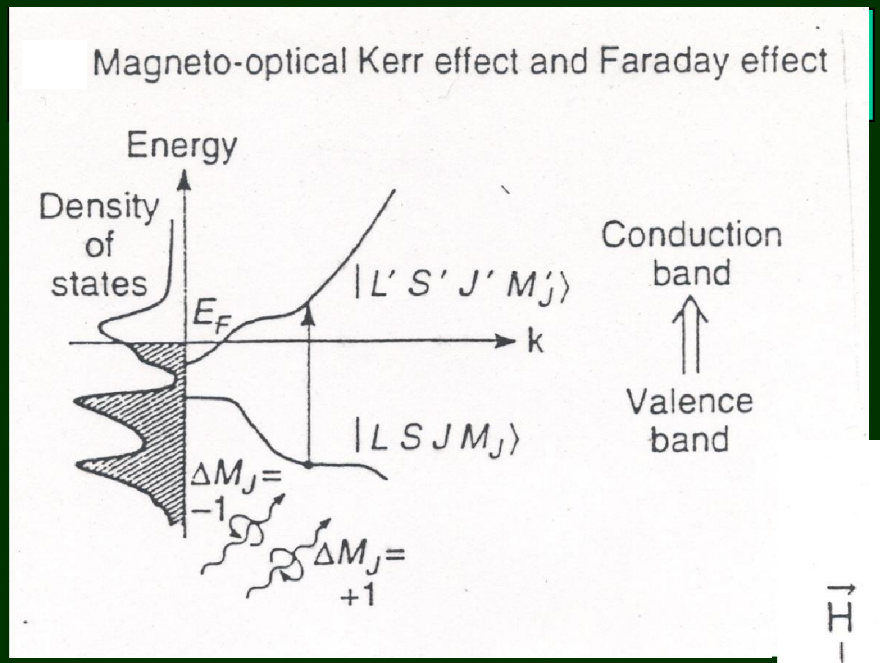
Experimental demonstration → **1987**

Absorption of circularly polarized x rays in iron Schütz et al., Phys. Rev. Lett. 58, 737 (1987).

Absorption of Circularly polarized x-ray by magnetic materials (magnetic atoms)

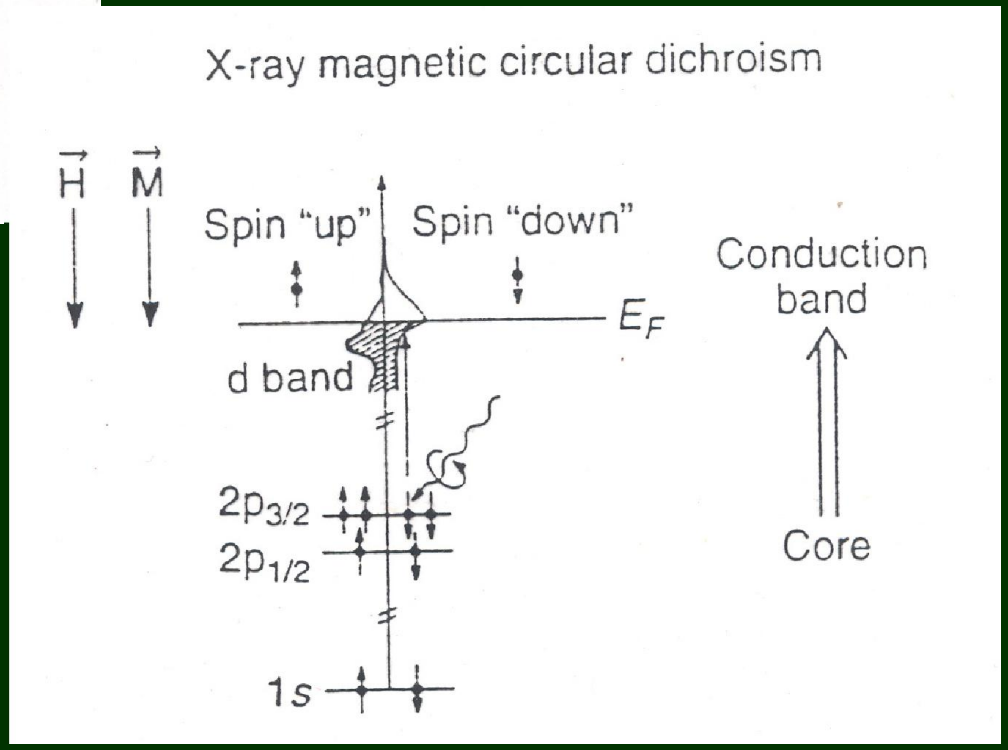
Advantages :

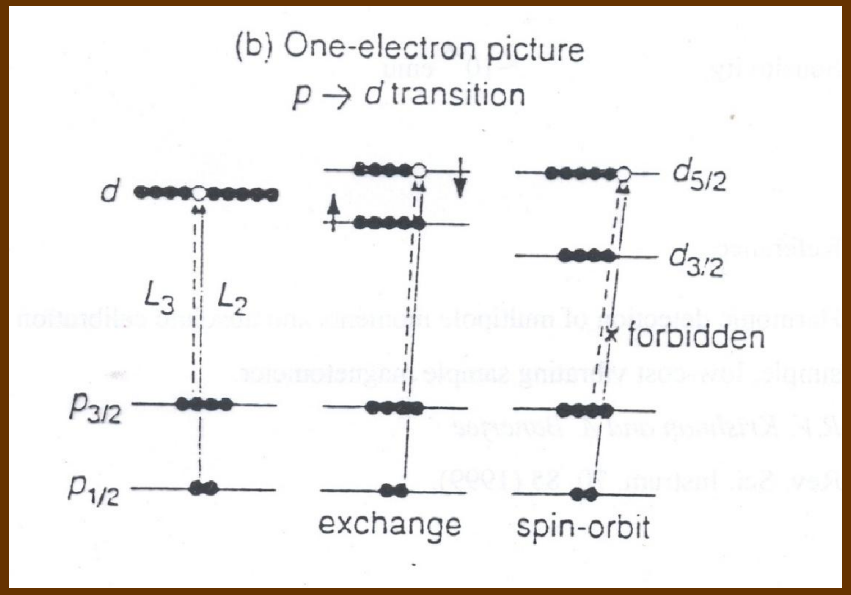
1. Element specific magnetic properties
2. Determination of spin and orbital moments separately
3. Very high sensitivity.

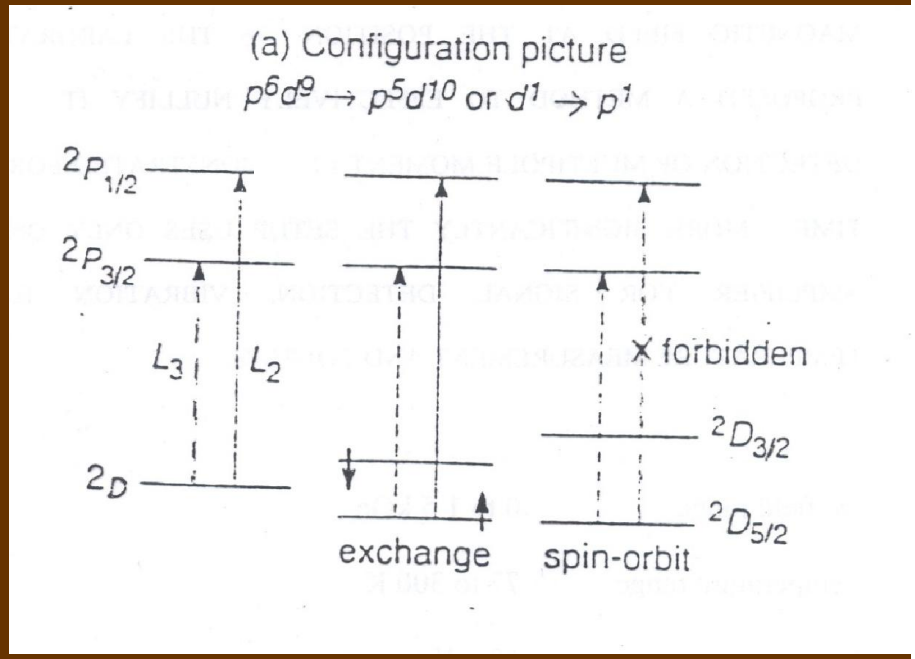

Magneto-optical Kerr effect and Faraday effect
Energy
Density of states
E_F
k
$|L' S' J' M_J'\rangle$
$|L S J M_J\rangle$
Conduction band
Valence band
$\Delta M_J = -1$
$\Delta M_J = +1$

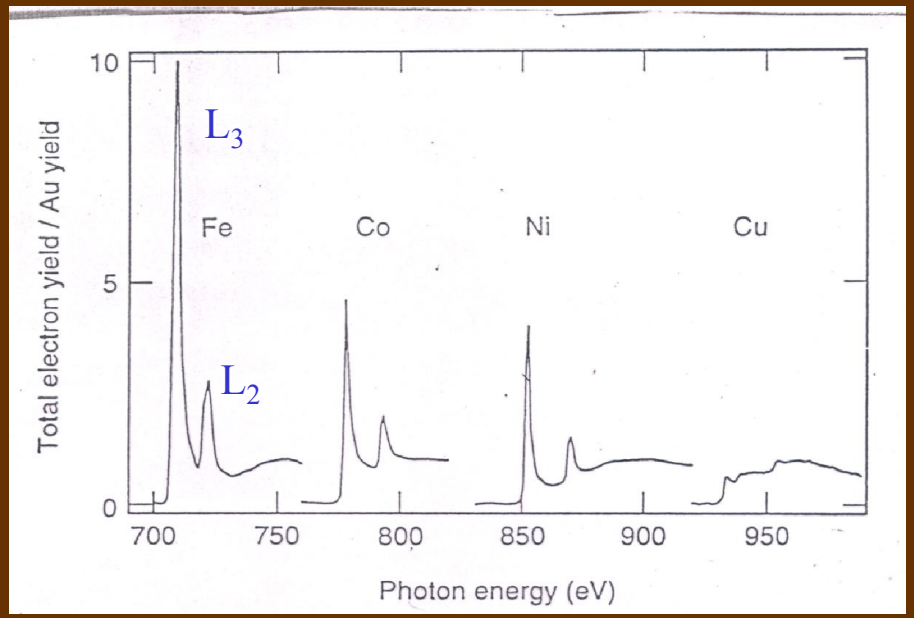
1846

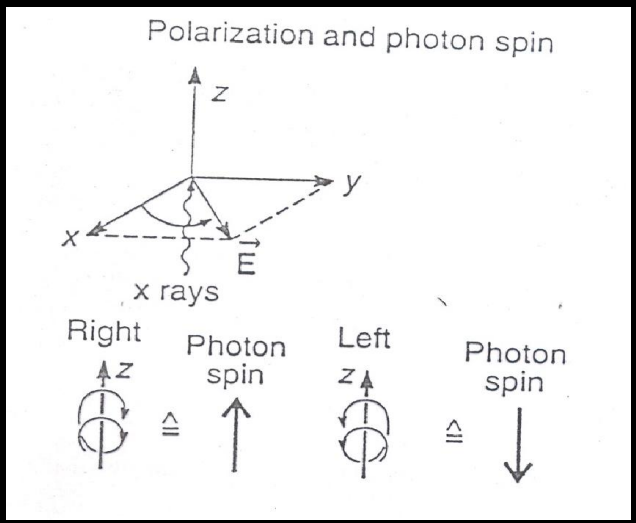
1987

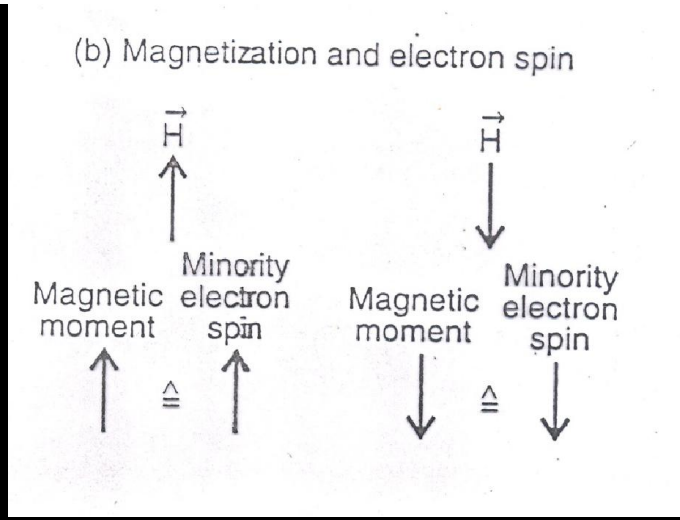

X-ray magnetic circular dichroism
$\vec{H}$
$\vec{M}$
Spin "up"
Spin "down"
E_F
d band
$2p_{3/2}$
$2p_{1/2}$
1s
Conduction band
Core

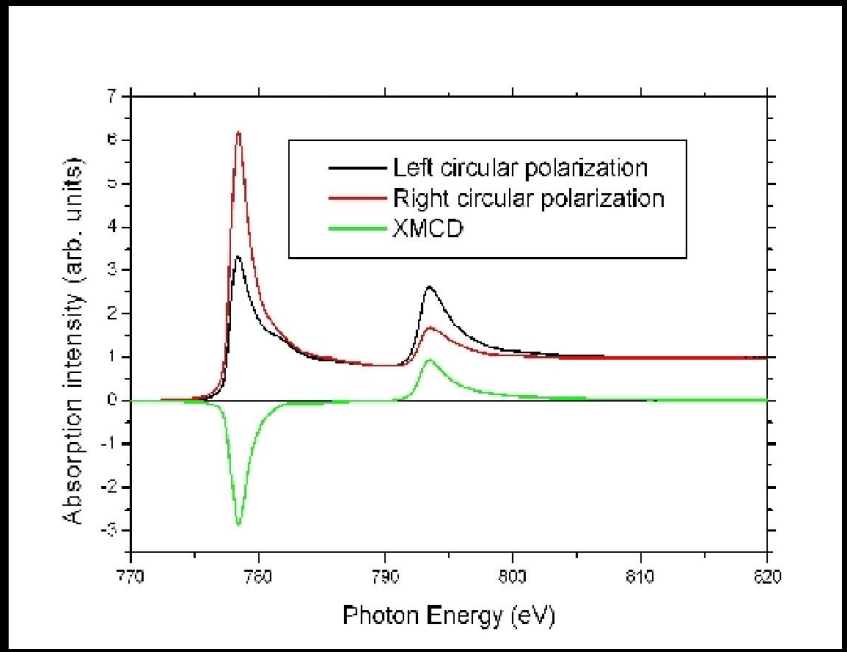

(b) One-electron picture
p → d transition
d
L3
L2
p3/2
p1/2
d5/2
d3/2
forbidden
exchange
spin-orbit

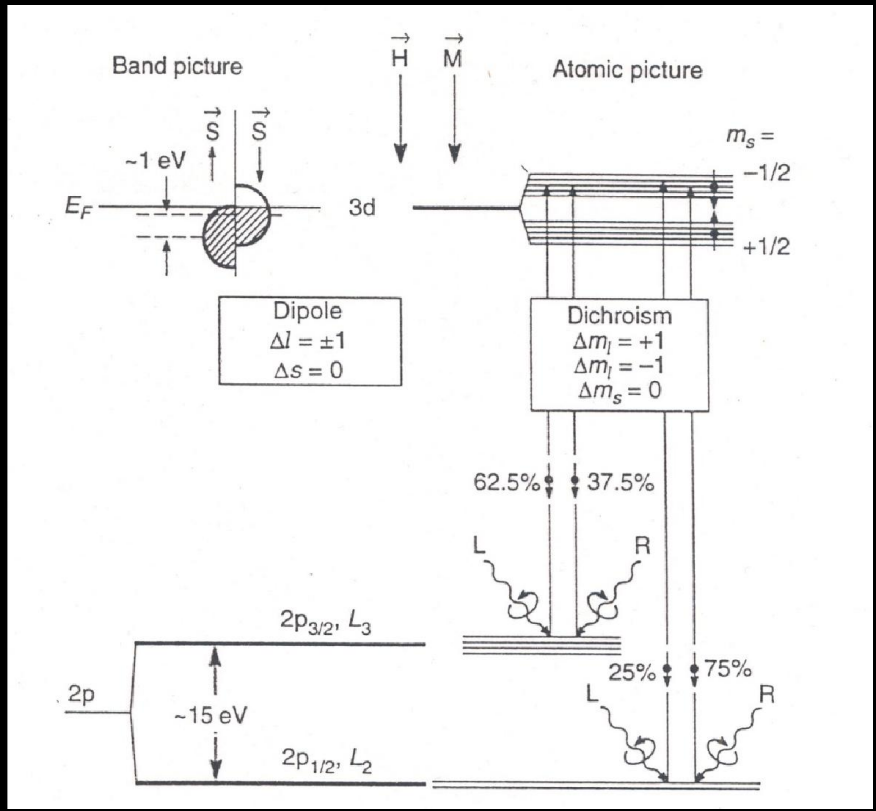

(a) Configuration picture
p6d9 → p5d10 or d1 → p1
2P1/2
2P3/2
2D
L3
L2
forbidden
2D3/2
2D5/2
exchange
spin-orbit

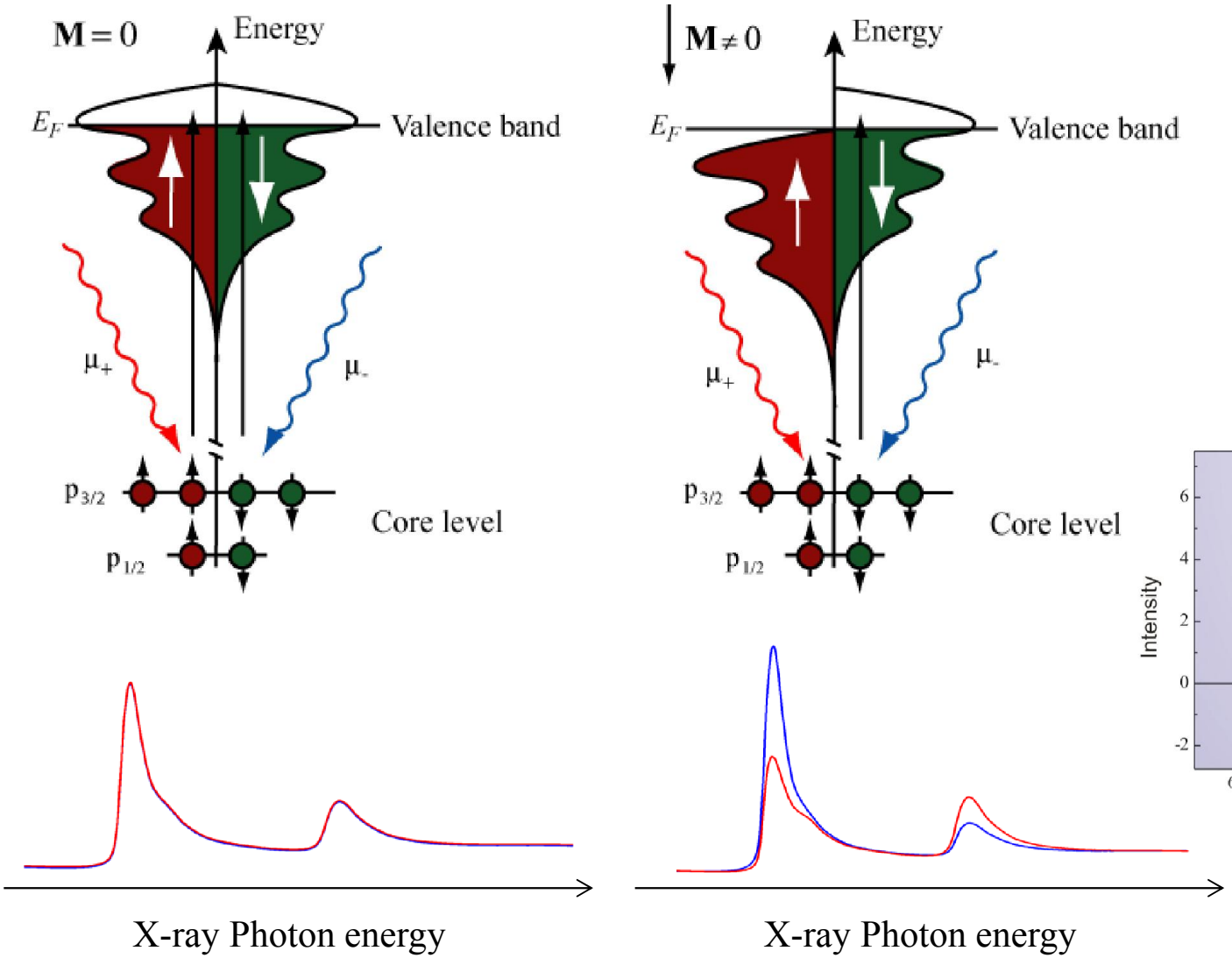

Total electron yield / Au yield
10
5
0
L3
L2
Fe
Co
Ni
Cu
700
750
800
850
900
950
Photon energy (eV)

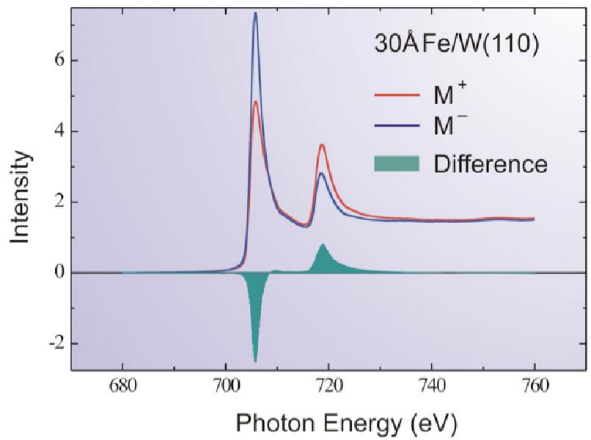

Polarization and photon spin
z
y
x
E
x rays
Right
Photon spin
Left
Photon spin


(b) Magnetization and electron spin
H
H
Magnetic moment
Minority electron spin
Magnetic moment
Minority electron spin

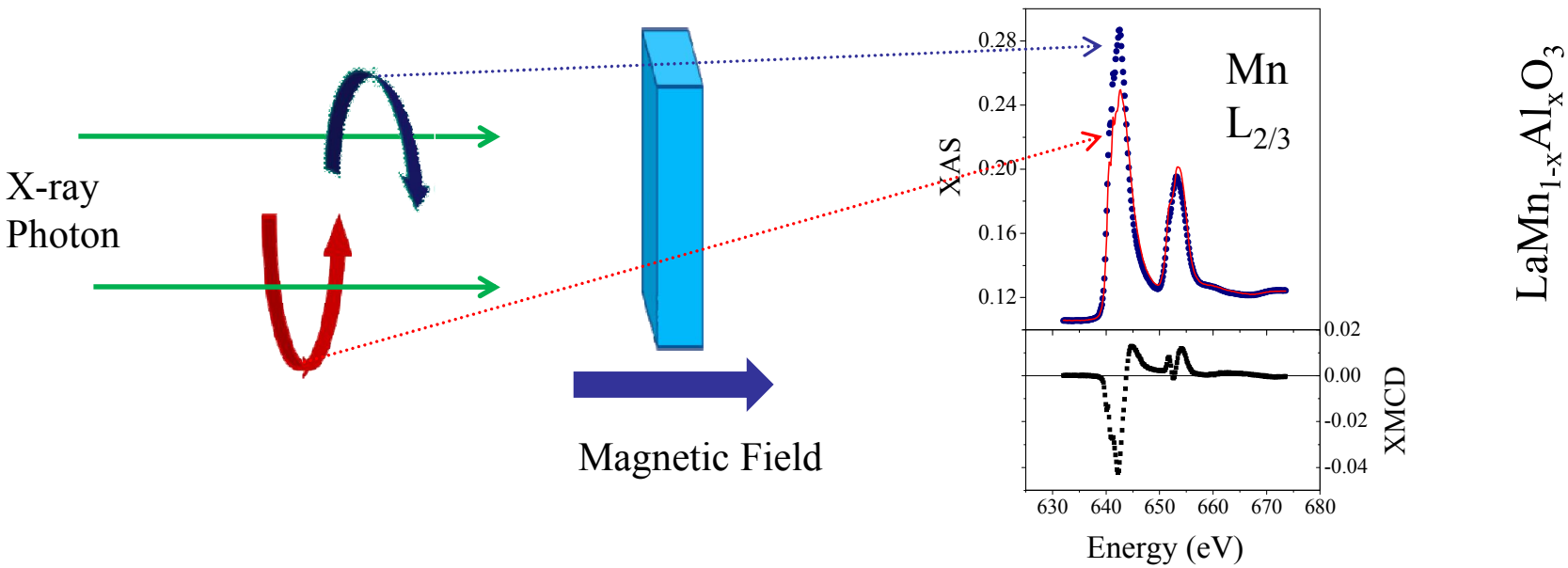

Left circular polarization
Right circular polarization
XMCD
Absorption intensity (arb. units)
Photon Energy (eV)


Band picture
Atomic picture
~1 eV
E_F
3d
m_s =
−1/2
+1/2
Dipole
$\Delta l = \pm 1$
$\Delta s = 0$
Dichroism
$\Delta m_l = +1$
$\Delta m_l = -1$
$\Delta m_s = 0$
62.5%
37.5%
L
R
$2p_{3/2}$, L_3
2p
~15 eV
$2p_{1/2}$, L_2
25%
75%
L
R

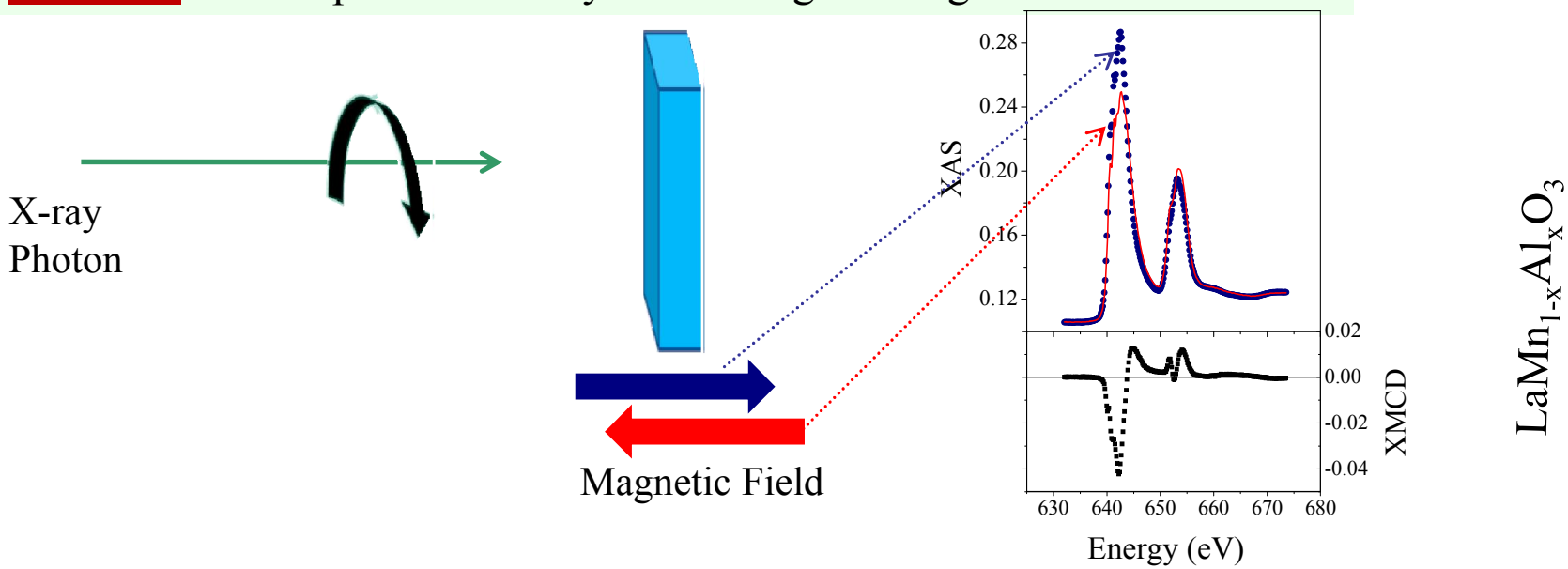

M = 0
Energy
E_F
Valence band
μ_+
μ_-
$p_{3/2}$
$p_{1/2}$
Core level
X-ray Photon energy
M ≠ 0
Energy
E_F
Valence band
μ_+
μ_-
$p_{3/2}$
$p_{1/2}$
Core level
X-ray Photon energy


30Å Fe/W(110)
M+
M−
Difference
Intensity
6
4
2
0
-2
680
700
720
740
760
Photon Energy (eV)

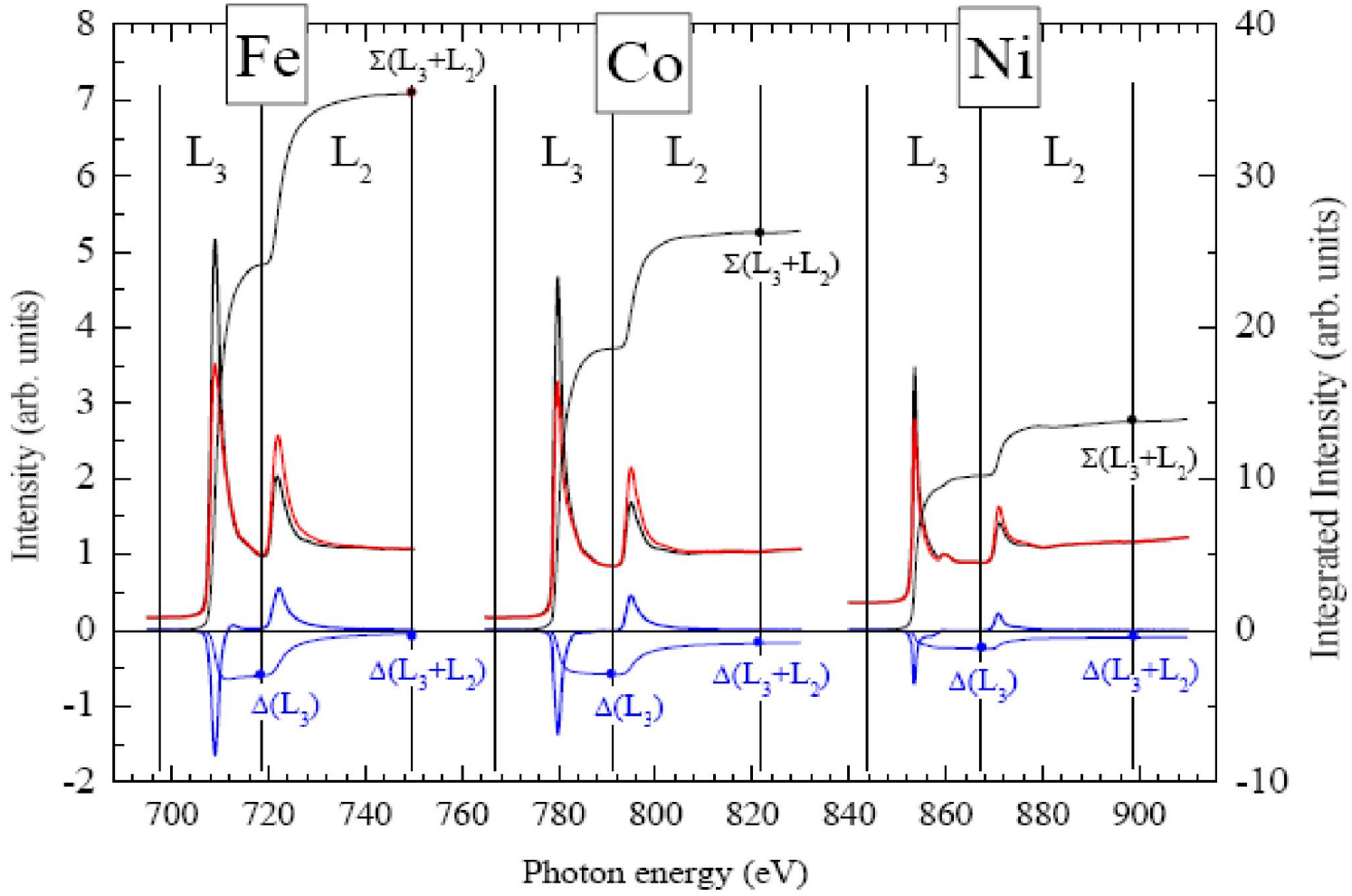
Case – I: Change in photon helicity with fixed magnetic field direction



Case – II: Fixed photon helicity with change in magnetic field direction



XAS-MCD: x-ray absorption magnetic circular dichroism



Requirements :

- Tunable Circularly Polarized X-Ray →

  Synchrotron Radiation Sources

  ↓

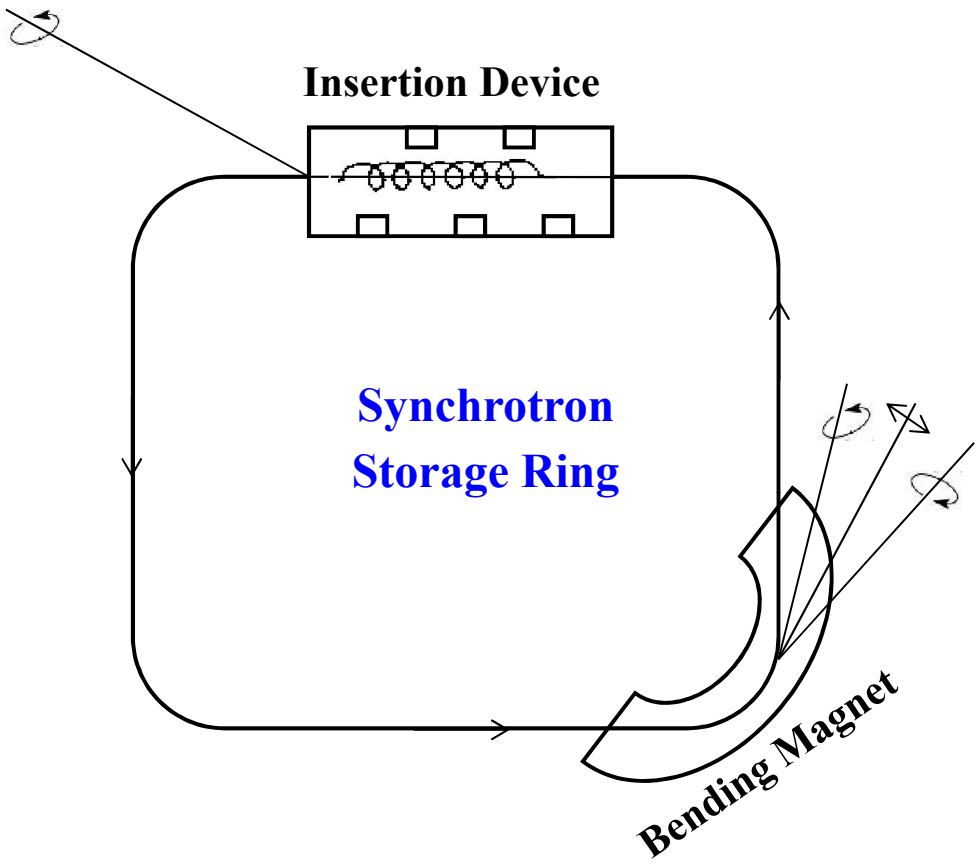
  1. Out of plane radiation from bending magnet
  2. Insertion devices like '**Undulators**' or '**Wigglers**'
  3. Quarter wave plates
  4. Graded multilayers

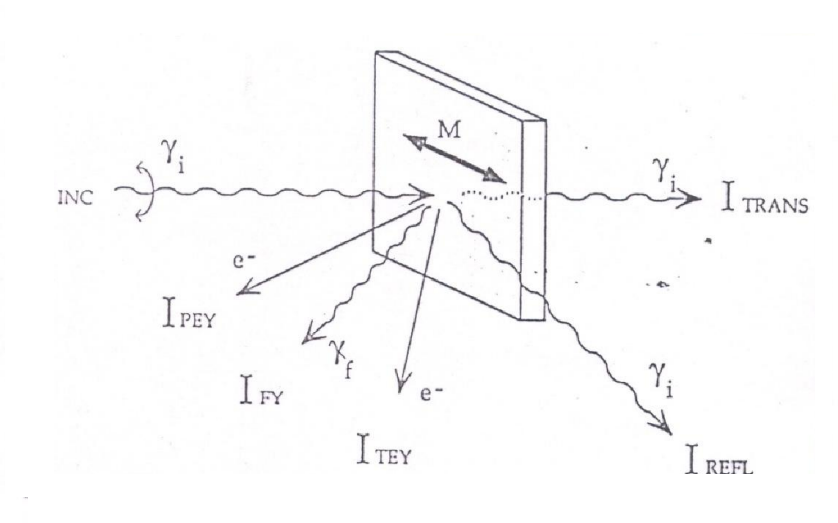
- Ultra-high vacuum (UHV) compatible x-ray Optics

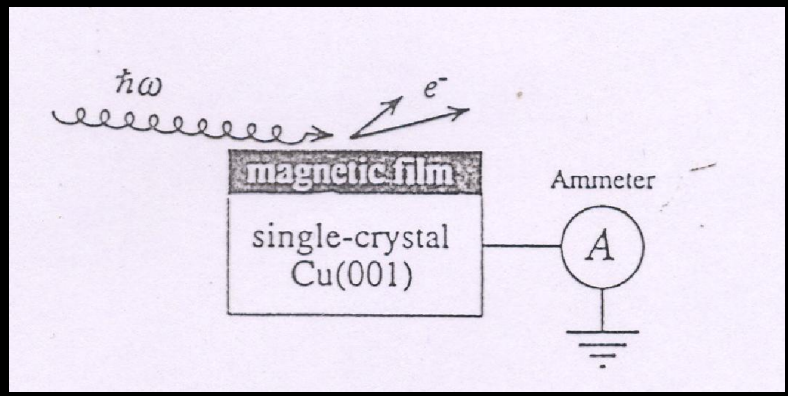
- UHV Experimental chamber with magnet

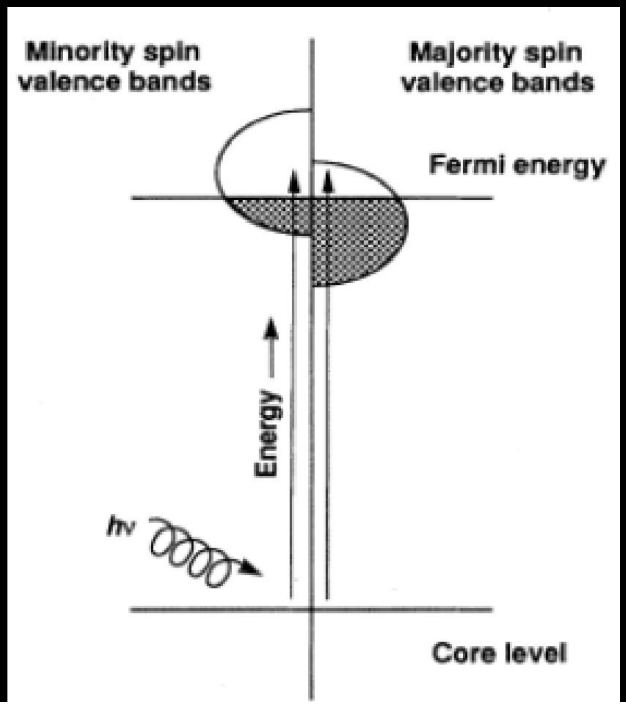
- Spectroscopic detection tools

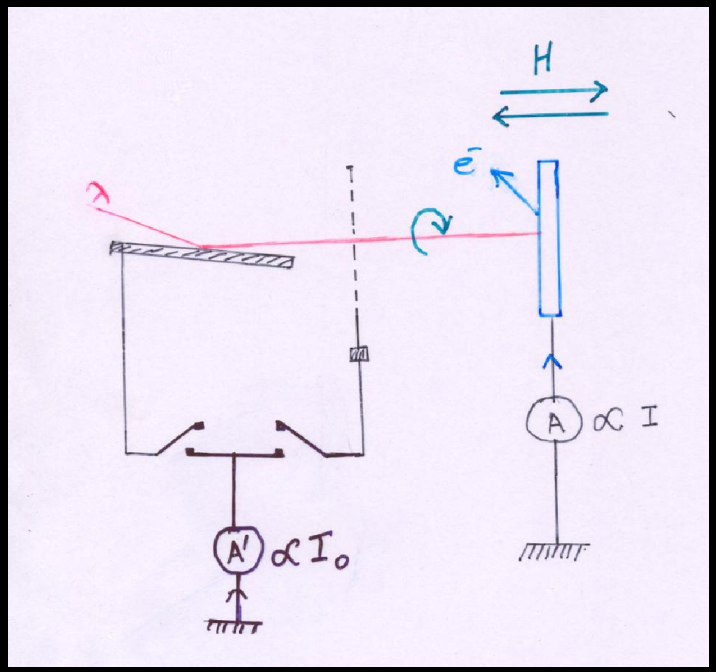
X-Ray Optics ↔ Spectroscopy ↔ Magnetism


Insertion Device
Synchrotron
Storage Ring
Bending Magnet


INC
γ_i
M
γ_i
I_{TRANS}
e^-
I_{PEY}
γ_f
I_{FY}
e^-
γ_i
I_{TEY}
I_{REFL}


$\hbar\omega$
e^-
magnetic film
single-crystal
Cu(001)
Ammeter
A


Minority spin
valence bands
Majority spin
valence bands
Fermi energy
Energy
hν
Core level


H
e^-
A
$\propto I$
A'
$\propto I_0$

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research B 199 (2003) 520–525

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

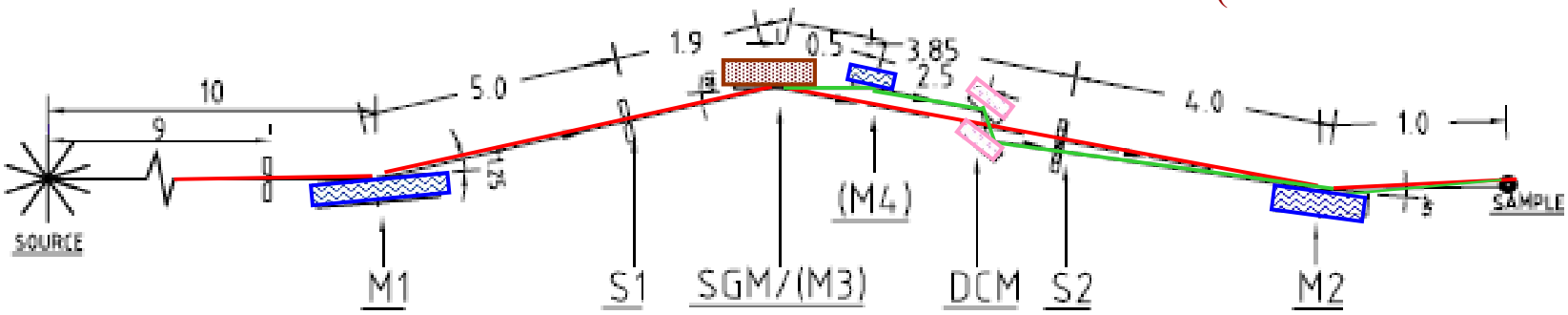
Design of a polarised light beamline in the energy range of 30–4000 eV

S.M. Chaudhari *, A. Banerjee, D.M. Phase, B.A. Dasannacharya

Inter University Consortium for DAE facilities, Khandwa Road, University Campus, Indore 452 017, India

MCD Beamline

(30 – 1500 – 4000 eV)



Abstract

This article describes the design of a possible polarised light beamline for magnetic circular dichroism and photoemission experiments on a bending magnet source of 2.5 GeV storage ring, Indus-2. It will have an energy range of 30–4000 eV and will deliver circular as well as linearly polarised light to perform absorption and photoemission experiments covering relevant L and M edges of most of the elements. The beamline optics consists of a vertically

Interaction of photons with electrons

$\vec{B}$ → Electron Spin, Orbital Moment ⟹ **Weak**

⇓ High photon flux

Non-resonant magnetic x-ray scattering

$\vec{E}$ → Orbital moment of electron → Spin-Orbit coupling → Spin of the electron

⇓

Electric dipole transition —**Strong**→ Absorption of x-ray

High photon flux is not necessary

X-ray absorption intensity (I) → Electric dipole matrix elements

Selection rules

Selection rules

$\Delta l = \pm 1$ & $\Delta m_l = 0, \pm 1$

$\Delta l = +1 \Longrightarrow$ Transitions $s \rightarrow p$, $p \rightarrow d$, $d \rightarrow f$

$\Delta l = -1 \Longrightarrow$ Transitions $p \rightarrow s$, $d \rightarrow p$, $f \rightarrow d$

$\Delta m_l = 0 \Longrightarrow$ Linearly polarized light

$\boxed{\mathbf{\Delta m_l = \pm 1} \Longrightarrow \text{Circularly polarized light}}$

Since electric dipole operator does not act on spin, the allowed transition have same s & m_s

$\Longrightarrow$ $\Delta s = 0$ & $\Delta m_s = 0$ $\Longrightarrow$ No spin flip

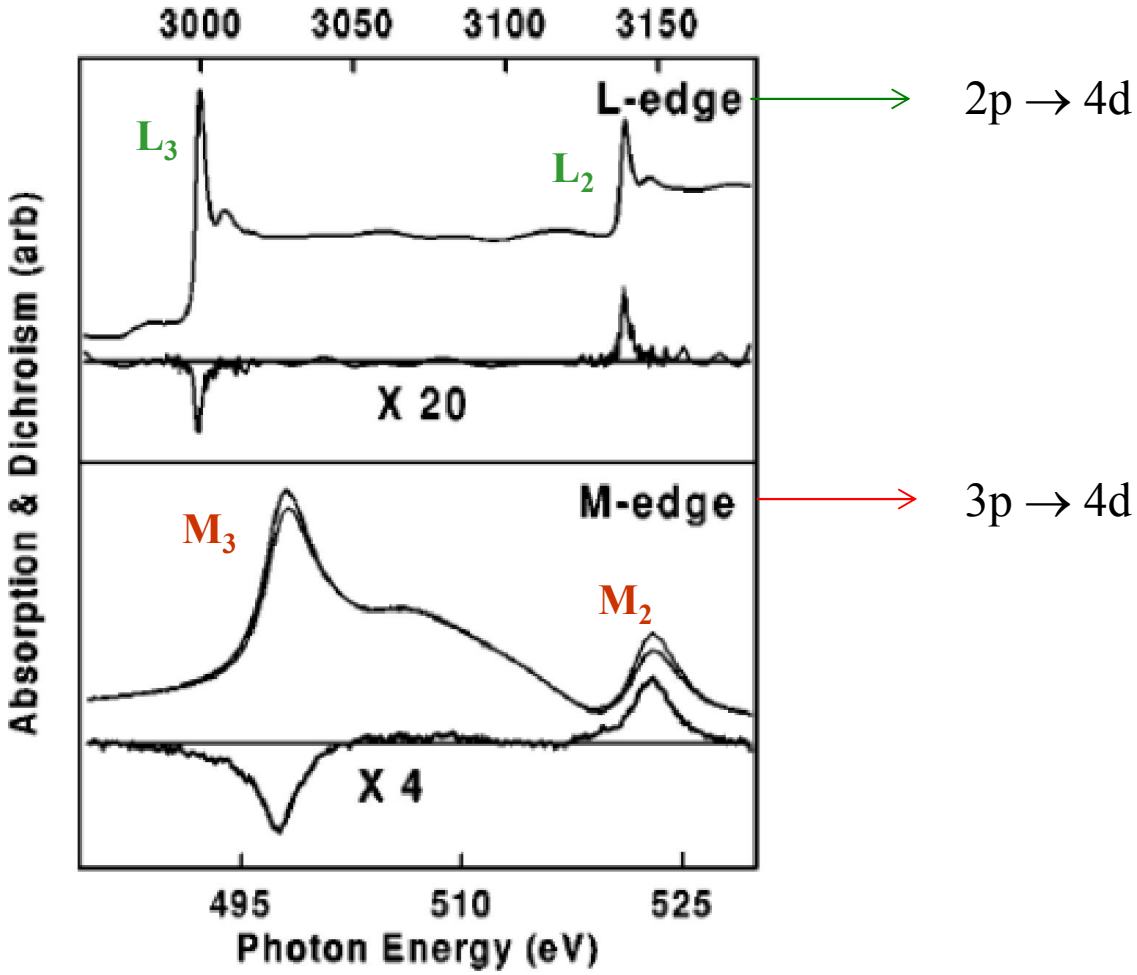
MCD is the difference in the absorption of x-ray of two opposite helicities.

Relevant absorption edges for XMCD

At. No.	*Symbol*	*Elect. Conf.*	*Edge*	*Transition*	*E (eV)*
5	B	$2s^2 2p^1$	K	1s→2p	188
6	C	$2s^2 2p^2$	K	1s→2p	284
7	N	$2s^2 2p^3$	K	1s→2p	410
8	O	$2s^2 2p^4$	K	1s→2p	543
9	F	$2s^2 2p^5$	K	1s→2p	697
13	Al	$3s^2 2p^1$	K	1s→3p	1559
14	Si	$3s^2 2p^2$	K	1s→3p	1839
15	P	$3s^2 2p^3$	K	1s→3p	2149
16	S	$3s^2 2p^4$	K	1s→3p	2472
17	Cl	$3s^2 2p^5$	K	1s→3p	2833
21	Sc	$3d^1 4s^2$	L_2/L	2p→3d	403/398
22	Ti	$3d^2 4s^2$	L_2/L	2p→3d	461/454
23	V	$3d^3 4s^2$	L_2/L	2p→3d	520/512
24	Cr	$3d^4 4s^2$	L_2/L	2p→3d	584/574
25	Mn	$3d^5 4s^2$	L_2/L	2p→3d	650/639
26	Fe	$3d^6 4s^2$	L_2/L	2p→3d	720/707
27	Co	$3d^7 4s^2$	L_2/L	2p→3d	793/778
28	Ni	$3d^8 4s^2$	L_2/L	2p→3d	870/853
29	Cu	$3d^{10} 4s^1$	L_2/L	2p→3d	952/932
39	Y	$4d^1 5s^2$	L_2/L_3	2p→4d	2156/2080
40	Zr	$4d^2 5s^2$	L_2/L_3	2p→4d	2307/2223
41	Nb	$4d^4 5s^1$	L_2/L_3	2p→4d	2456/2371
42	Mo	$4d^5 5s^1$	L_2/L_3	2p→4d	2625/2520
43	Tc	$4d^6 5s^2$	L_2/L_3	2p→4d	2793/2677
44	Ru	$4d^7 5s^1$	L_2/L_3	2p→4d	2967/2838
45	Rh	$4d^8 5s^1$	L_2/L_3	2p→4d	3146/3004
46	Pd	$4d^{10} 5s^0$	L_2/L_3	2p→4d	3330/3173
47	Ag	$4d^{10} 5s^1$	L_2/L_3	2p→4d	3524/3351

At. No.	*Symbol*	*Elect. Conf.*	*Edge*	*Transition*	*E (eV)*	*Edge*	*Trans.*	*E (eV)*
57	La	$5d^1 6s^2$	M_2/M_3	3p→5d	1209/1128			
58	Ce	$4f^2 5d^0 6s^2$	M_2/M_3	3p→5d	1274/1187	M_4/M_5	3d→4f	902/834
59	Pr	$4f^3 5d^0 6s^2$	M_2/M_3	3p→5d	1337/1242	M_4/M_5	3d→4f	948/929
60	Nd	$4f^4 5d^0 6s^2$	M_2/M_3	3p→5d	1403/1297	M_4/M_5	3d→4f	1003/980
61	Pm	$4f^5 5d^0 6s^2$	M_2/M_3	3p→5d	1403/1357	M_4/M_5	3d→4f	1052/1027
62	Sm	$4f^6 5d^0 6s^2$	M_2/M_3	3p→5d	1541/1420	M_4/M_5	3d→4f	1111/1083
63	Eu	$4f^7 5d^0 6s^2$	M_2/M_3	3p→5d	1614/1481	M_4/M_5	3d→4f	1159/1127
64	Gd	$4f^7 5d^1 6s^2$	M_2/M_3	3p→5d	1688/1544	M_4/M_5	3d→4f	1222/1190
65	Tb	$4f^9 5d^0 6s^2$	M_2/M_3	3p→5d	1768/1611	M_4/M_5	3d→4f	1277/1241
66	Dy	$4f^{10} 5d^0 6s^2$	M_2/M_3	3p→5d	1842/1676	M_4/M_5	3d→4f	1333/1292
67	Ho	$4f^{11} 5d^0 6s^2$	M_2/M_3	3p→5d	1923/1741	M_4/M_5	3d→4f	1392/1351
68	Er	$4f^{12} 5d^0 6s^2$	M_2/M_3	3p→5d	2006/1812	M_4/M_5	3d→4f	1453/1409
69	Tm	$4f^{13} 5d^0 6s^2$	M_2/M_3	3p→5d	2090/1885	M_4/M_5	3d→4f	1515/1468
70	Yb	$4f^{14} 5d^0 6s^2$	M_2/M_3	3p→5d	2173/1950	M_4/M_5	3d→4f	1576/1528
71	Lu	$4f^{14} 5d^1 6s^2$	M_2/M_3	3p→5d	2264/2064			
72	Hf	$4f^{14} 5d^2 6s^2$	M_2/M_3	3p→5d	2365/2107			
73	Ta	$4f^{14} 5d^3 6s^2$	M_2/M_3	3p→5d	2469/2164			
74	W	$4f^{14} 5d^4 6s^2$	M_2/M_3	3p→5d	2575/2281			
75	Re	$4f^{14} 5d^5 6s^2$	M_2/M_3	3p→5d	2682/2367			
76	Os	$4f^{14} 5d^6 6s^2$	M_2/M_3	3p→5d	2792/2457			
77	Ir	$4f^{14} 5d^7 6s^2$	M_2/M_3	3p→5d	2909/2551			
78	Pt	$4f^{14} 5d^{10} 6s^0$	M_2/M_3	3p→5d	3027/2645			
79	Au	$4f^{14} 5d^{10} 6s^1$	M_2/M_3	3p→5d	3148/2743			
80	Hg	$4f^{14} 5d^{10} 6s^2$	M_2/M_3	3p→5d	3279/2847			
89	Ac	$6d^1 7s^2$	N_2/N_3	4p→6d	1080/890			
92	U	$5f^3 6d^1 7s^2$	N_2/N_3	4p→6d	1271/1043	M_4/M_5	3d→5f	3728/3552

Rh XMCD



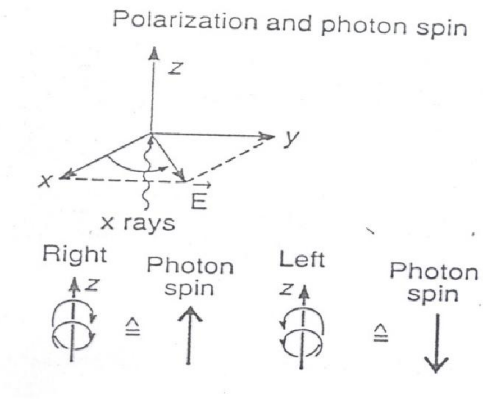
Magnetic properties of Co/Rh .001. multilayers studied by x-ray magnetic-circular dichroism
M. A. Tomaz el al., Phys. Rev. B 58, 11493 (1998)

X-ray absorption intensity per atom I

$$I = \frac{2m}{\hbar^2} \frac{(E_f - E_i)^2}{\hbar\omega} \; |\langle f | \hat{e} \cdot r | i \rangle|^2$$

Where ê is the electric field unit vector

↓



Right circularly polarized light:

$e = -1/\sqrt{2}\,(e_x + i\, e_y)$ ⇒ Photon spin points to propagation direction

Left circularly polarized light:

$e = -1/\sqrt{2}\,(e_x - i\, e_y)$ ⇒ Photon spin opposite to propagation direction

r is the electron position vector

$$I = \frac{m}{\hbar^2} \frac{(E_f - E_i)^2}{\hbar\omega} \; |\langle f | x \pm iy | i \rangle|^2$$

$$P_{\pm 1} \rightarrow Y_1^{\pm 1}$$

The polarization dependent dipole operators ($P_{\pm 1}$) can be expressed in terms of Racah's spherical tensors C^{l}_{ml} , with $l = 1$ and $m_l = \pm 1$.

Right circular polarization $P_{+1} = -1/\sqrt{2}\,(x + iy) = rC^{1}_{1} = r\sqrt{(4\pi/3)}\,Y^{1}_{1}$

Left circular polarization $P_{-1} = -1/\sqrt{2}\,(x - iy) = rC^{1}_{-1} = r\sqrt{(4\pi/3)}\,Y^{1}_{-1}$

TABLE 1. One-electron s, p, and d wave functions.

One-Electron Label l_j	Configuration Label $^{2S+1}L_J$	$\|lsjm_j\rangle$ Basis m_j	$\|lsm_lm_s\rangle$ Basis $Y_l^{m_l}\,\Phi_{m_s}$ *
$s_{1/2}$	$^2S_{1/2}$	$\frac{1}{2}$	$Y_0^0\alpha$
		$-\frac{1}{2}$	$Y_0^0\beta$
$p_{1/2}$	$^2P_{1/2}$	$\frac{1}{2}$	$\frac{1}{\sqrt{3}}(Y_1^0\alpha-\sqrt{2}Y_1^1\beta)$
		$-\frac{1}{2}$	$\frac{1}{\sqrt{3}}(\sqrt{2}Y_1^{-1}\alpha-Y_1^0\beta)$
$p_{3/2}$	$^2P_{3/2}$	$\frac{3}{2}$	$Y_1^1\alpha$
		$\frac{1}{2}$	$\frac{1}{\sqrt{3}}(\sqrt{2}\,Y_1^0\alpha+Y_1^1\beta)$
		$-\frac{1}{2}$	$\frac{1}{\sqrt{3}}(Y_1^{-1}\alpha+\sqrt{2}\,Y_1^0\beta)$
		$-\frac{3}{2}$	$Y_1^{-1}\beta$
$d_{3/2}$	$^2D_{3/2}$	$\frac{3}{2}$	$\frac{1}{\sqrt{5}}(Y_2^1\alpha-2Y_2^2\beta)$
		$\frac{1}{2}$	$\frac{1}{\sqrt{5}}(\sqrt{2}Y_2^0\alpha-\sqrt{3}Y_2^1\beta)$
		$-\frac{1}{2}$	$\frac{1}{\sqrt{5}}(\sqrt{3}Y_2^{-1}\alpha-\sqrt{2}Y_2^0\beta)$
		$-\frac{3}{2}$	$\frac{1}{\sqrt{5}}(2Y_2^{-2}\alpha-Y_2^{-1}\beta)$
$d_{5/2}$	$^2D_{5/2}$	$\frac{5}{2}$	$Y_2^2\alpha$
		$\frac{3}{2}$	$\frac{1}{\sqrt{5}}(2Y_2^1\alpha+Y_2^2\beta)$
		$\frac{1}{2}$	$\frac{1}{\sqrt{5}}(\sqrt{3}Y_2^0\alpha+\sqrt{2}Y_2^1\beta)$
		$-\frac{1}{2}$	$\frac{1}{\sqrt{5}}(\sqrt{2}Y_2^{-1}\alpha+\sqrt{3}Y_2^0\beta)$
		$-\frac{3}{2}$	$\frac{1}{\sqrt{5}}(Y_2^{-2}\alpha+2Y_2^{-1}\beta)$
		$-\frac{5}{2}$	$Y_2^{-2}\beta$

* $\Phi_{m_s=1/2}=\alpha$ (spin up), $\Phi_{m_s=-1/2}=\beta$ (spin down).

Lets consider a d^9 configuration where in exchange split d band all spin up states are filled and one hole in spin down state.

Here for a p→ d transition ⇒ $l \rightarrow l + 1$

$$T^{\uparrow} \rightarrow \langle n', l+1, m_l + 1 \mid P_{+1} \mid n, l, m_l \rangle$$

$$= - \sqrt{\frac{(l + m_l + 2)(l + m_l + 1)}{2(2l + 3)(2l + 1)}} \quad R \qquad \rightarrow (1)$$

and $T^{\downarrow} \rightarrow \langle n', l+1, m_l - 1 \mid P_{-1} \mid n, l, m_l \rangle$

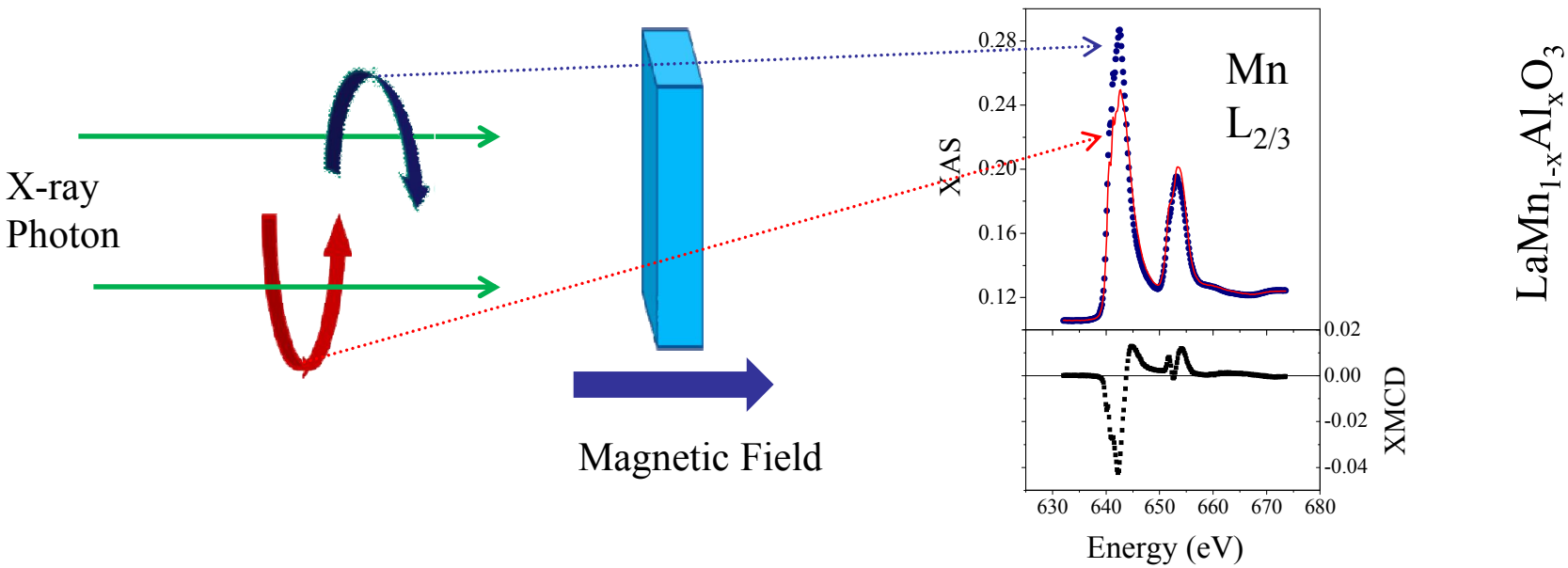
$$= - \sqrt{\frac{(l - m_l + 2)(l - m_l + 1)}{2(2l + 3)(2l + 1)}} \quad R \qquad \rightarrow (2)$$

Where $R = \int R^*_{nl}(r) R_{n'l'}(r) r^3 dr$

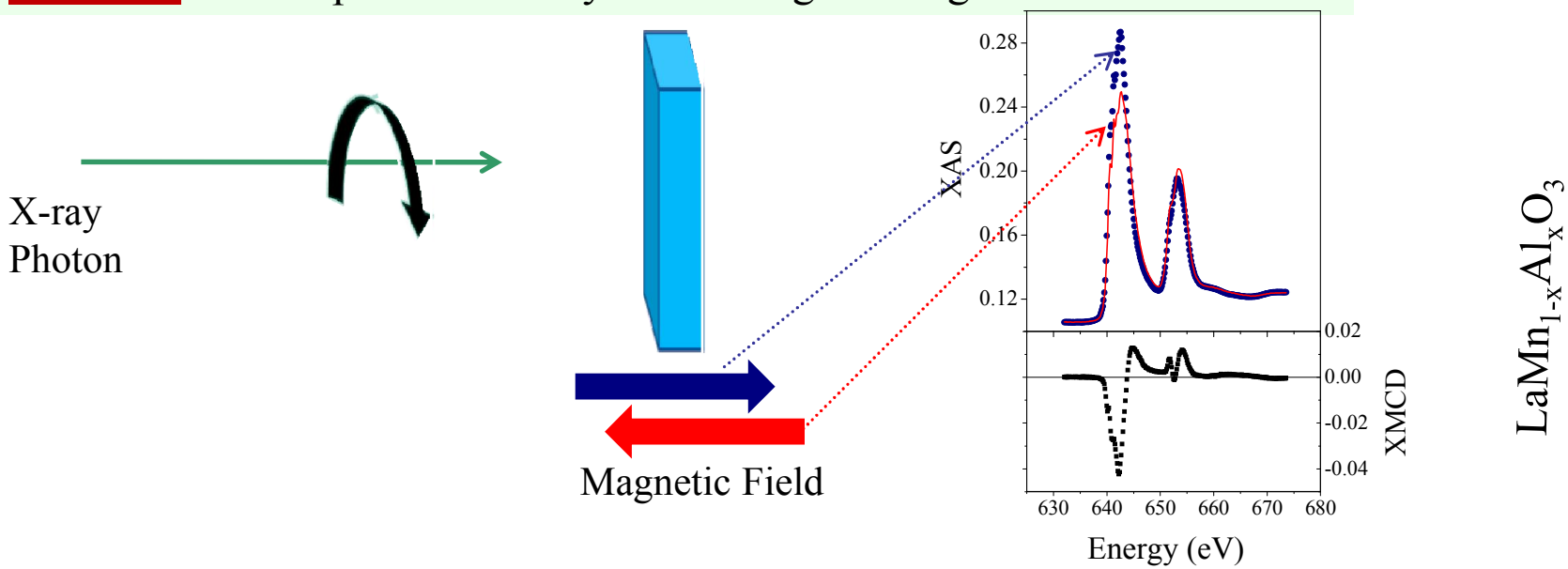
Eq (1) and (2) ⇒ The change in photon spin ($P_{+1} \rightarrow P_{-1}$) keeping the magnetization direction fixed is equivalent to change in magnetization direction $m_l \rightarrow m_{-l}$ keeping the photon spin fixed, i.e ,

$$\langle n', l+1, -m_l + 1 \mid P_{+1} \mid n, l, -m_l \rangle = \langle n', l+1, m_l - 1 \mid P_{-1} \mid n, l, m_l \rangle$$

Case – I: Change in photon helicity with fixed magnetic field direction



Case – II: Fixed photon helicity with change in magnetic field direction



For L_3 edge i.e, $p_{3/2} \rightarrow d$.

$$\mathbf{I}^{\uparrow}_{L_3} = \sum_{i,f} |T^{\uparrow}|^2 = 1/3 \ R^2$$

and $$\mathbf{I}^{\downarrow}_{L_3} = \sum_{i,f} |T^{\downarrow}|^2 = 5/9 \ R^2$$

$$\rightarrow \Delta \mathbf{I}_{L_3} = \mathbf{I}^{\uparrow}_{L_3} - \mathbf{I}^{\downarrow}_{L_3} = -2/9 \ R^2$$

For L_2 edge i.e, $p_{1/2} \rightarrow d$.

$$\mathbf{I}^{\uparrow}_{L_2} = \sum_{i,f} |T^{\uparrow}|^2 = 1/3 \ R^2$$

and $$\mathbf{I}^{\downarrow}_{L_2} = \sum_{i,f} |T^{\downarrow}|^2 = 1/9 \ R^2$$

$$\rightarrow \Delta \mathbf{I}_{L_2} = \mathbf{I}^{\uparrow}_{L_2} - \mathbf{I}^{\downarrow}_{L_2} = 2/9 \ R^2$$

The dichroism signal at L_3 and L_2 edges are identical **but opposite in sign**

At L_3 edge , left circularly polarized light (spin down photons) excites more spin down electrons than right circularly polarized light (spin up).

At L_2 edge, spin up photon excite more spin down electrons.

d orbitals	$< l_z >$ (ħ)	$< s_z >$ (ħ)	$<2s_z + l_z>$ (ħ)	$\Delta I_{L_3}/R^2$	$\Delta I_{L_2}/R^2$	$(\Delta I_{L_3} + \Delta I_{L_2})/R^2$
$Y_2^2\beta$	2	-1/2	1	$\frac{2}{15}$	$\frac{4}{15}$	$\frac{6}{15}$
$Y_2^1\beta$	1	-1/2	0	$\frac{2}{15}$	$\frac{1}{15}$	$\frac{3}{15}$
$Y_2^0\beta$	0	-1/2	-1	$\frac{2}{45}$	$-\frac{2}{45}$	0
$Y_2^{-1}\beta$	-1	-1/2	-2	$-\frac{2}{15}$	$-\frac{1}{15}$	$-\frac{3}{15}$
$Y_2^{-2}\beta$	-2	-1/2	-3	$-\frac{6}{15}$	0	$-\frac{6}{15}$
Sum	0	-5/2	-5	$-\frac{2}{9}$	$\frac{2}{9}$	0

MCD Measurement ⟹ Two step process

Step 1 ⟶ Source (electrons)

(a) Right or left circularly polarized light transfer their angular momentum ħ or – ħ to the excited photoelectron.

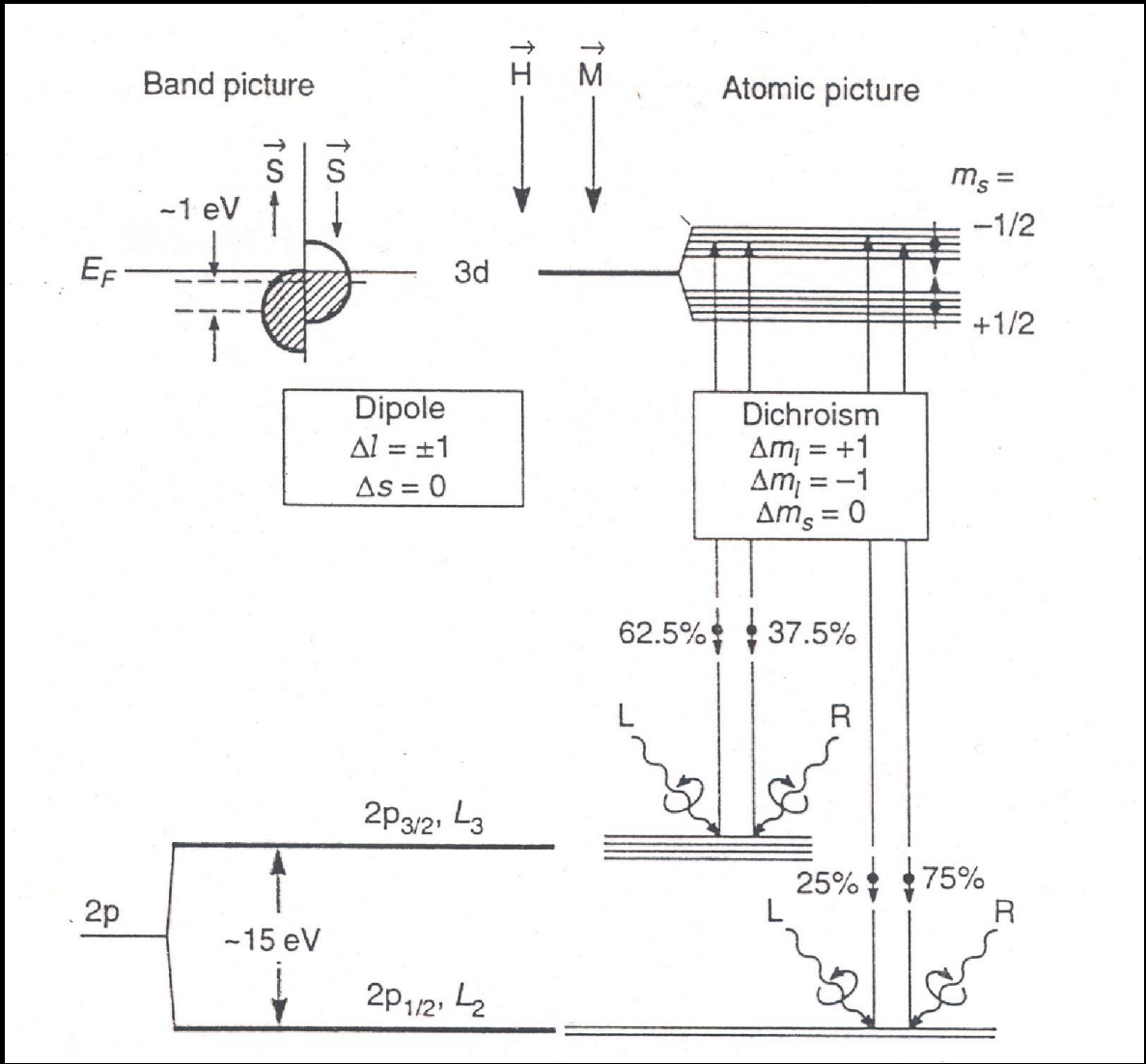
(b) If the core level is spin-orbit split (l ± s) then the angular momentum of the photon gets coupled to electron spin through S-O coupling.

⇨ Since left and right circularly polarized light transfer opposite angular momentum to electrons hence ***electrons with mostly opposite spins are excited for to helicities***

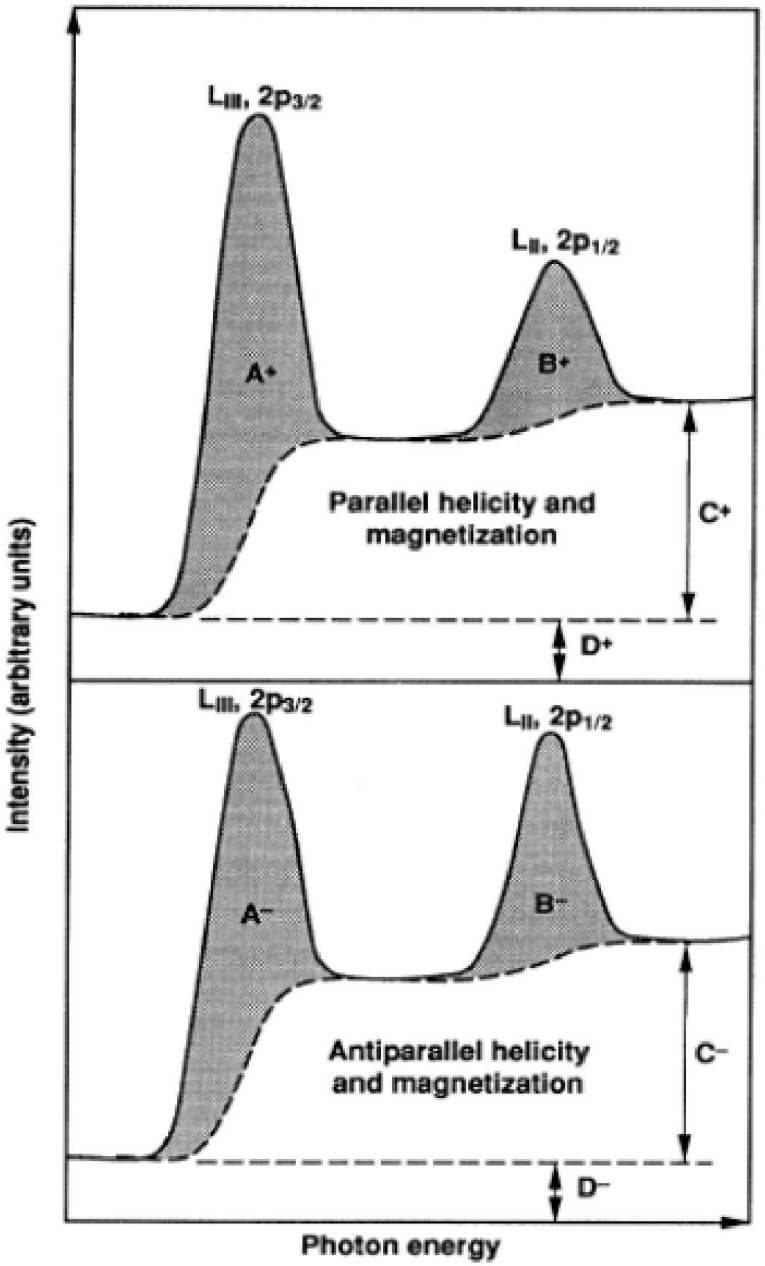
Step 2 ⟶ Detection (polarization : spin or orbital)

(a) When sample is magnetized then valence shell is split and there is an imbalance in spin up and spin down electrons. In this case two opposite spin polarized electrons are absorbed differently in valence shell ⇨ **Spin detector**

(b) If the valence shell has a net orbital moment i.e. the valence band density of empty states has an imbalance of angular momentum then a differential **"detector"** exists for excited electrons with opposite angular momentum. Sensitivity to magnetization in this case come from S-O coupling of valence shell.


Band picture
Atomic picture
H
M
S
S
~1 eV
E_F
3d
m_s =
−1/2
+1/2
Dipole
$\Delta l = \pm 1$
$\Delta s = 0$
Dichroism
$\Delta m_l = +1$
$\Delta m_l = -1$
$\Delta m_s = 0$
62.5%
37.5%
L
R
$2p_{3/2}$, L_3
2p
~15 eV
$2p_{1/2}$, L_2
25%
75%
L
R

Sum rules :



B. T. Thole, Paolo Carra, F. Sette, and G. van der Laan, Phys. Rev. Lett., 68, 1943 (1992).

Paolo Carra, B. T. Thole, Massimo Altarelli, and Xindong Wang, Phys. Rev. Lett., 70, 694 (1993)

Estimation of spin and orbital magnetic moments can be done using the respective <u>sum rules</u> →

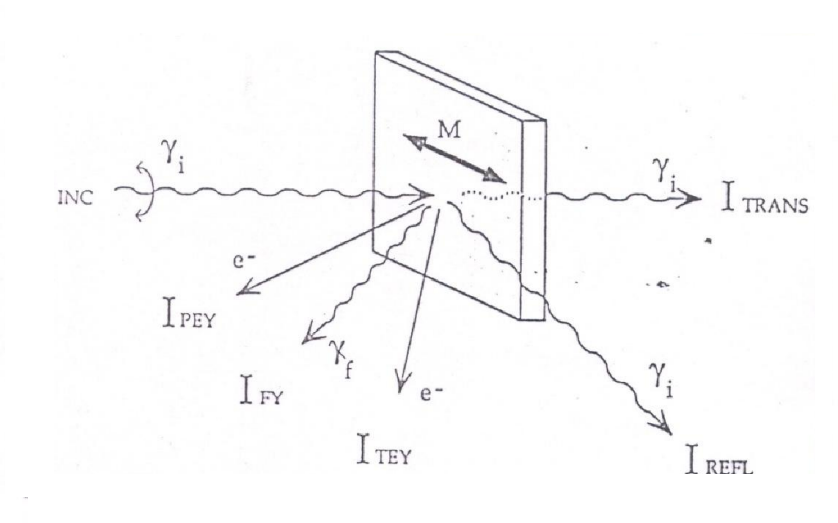
$$m_{orbital} = 4/3 \; \frac{\int_{L3+L2} (I^{\uparrow} - I^{\downarrow}) d\omega}{\int_{L3+L2} (I^{\uparrow} + I^{\downarrow}) d\omega} \; (10-n_{3d})$$

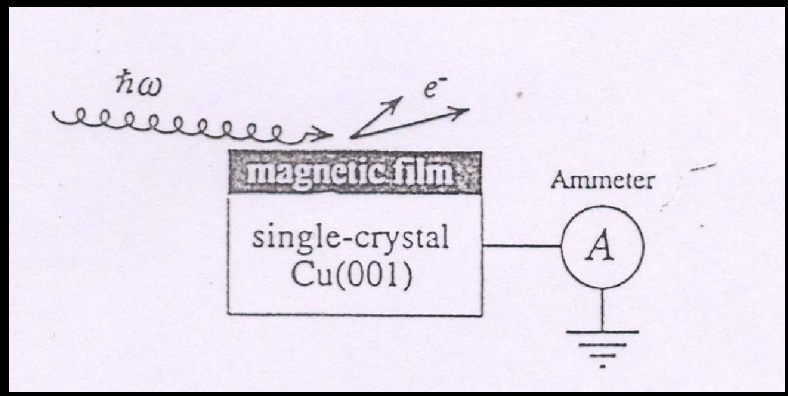
$$m_{spin} = \frac{6 \int_{L3+L2} (I^{\uparrow} - I^{\downarrow}) d\omega - 4 \int_{L3+L2} (I^{\uparrow} - I^{\downarrow}) d\omega}{\int_{L3+L2} (I^{\uparrow} + I^{\downarrow}) d\omega} \; x \; (10-n_{3d}) \left(1- \frac{7\langle T_z \rangle}{2\langle S_z \rangle}\right)^{-1}$$

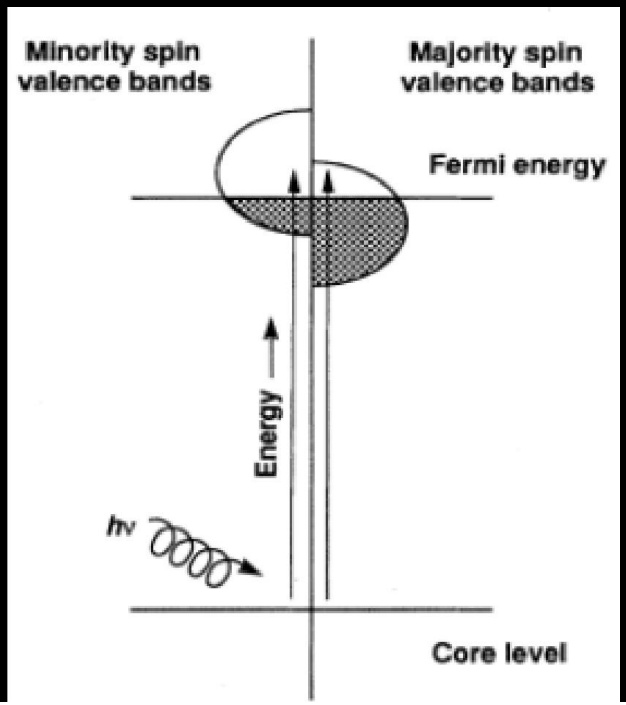
$$m_{orbital} = 4/3 \; \frac{\left[\left(\frac{A^+ + B^+}{C^+}\right) - \left(\frac{A^- + B^-}{C^-}\right)\right]}{\left[\left(\frac{A^+ + B^+}{C^+}\right) + \left(\frac{A^- + B^-}{C^-}\right)\right]} \; (10 - n_{3d})$$

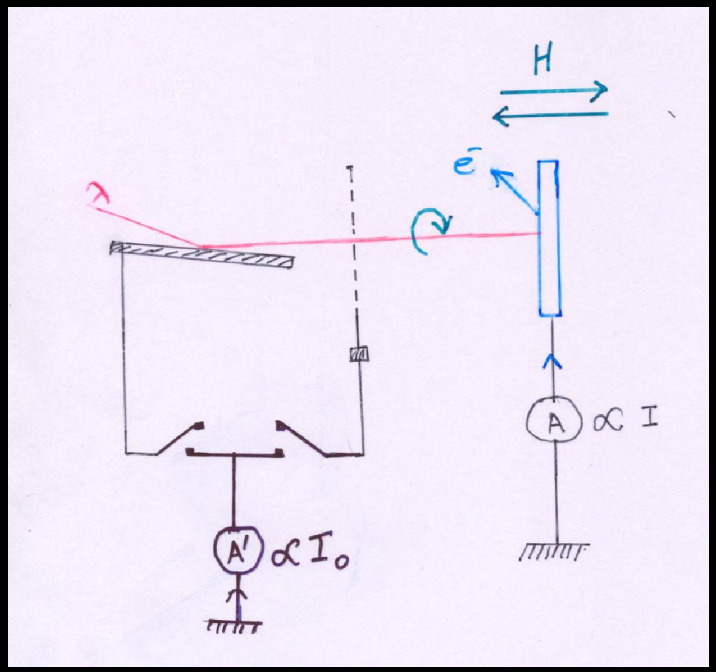
$$m_{spin} = \frac{6 \left[\frac{A^+}{C^+} - \frac{A^-}{C^-}\right] - 4 \left[\left(\frac{A^+ + B^+}{C^+} - \frac{A^- + B^-}{C^-}\right)\right]}{\left[\left(\frac{A^+ + B^+}{C^+}\right) + \left(\frac{A^- + B^-}{C^-}\right)\right]} \; x \; (10-n_{3d}) \left(1+ \frac{7\langle T_z \rangle}{2\langle S_z \rangle}\right)^{-1}$$

$\langle T_z \rangle$ = Magnetic dipole operator.

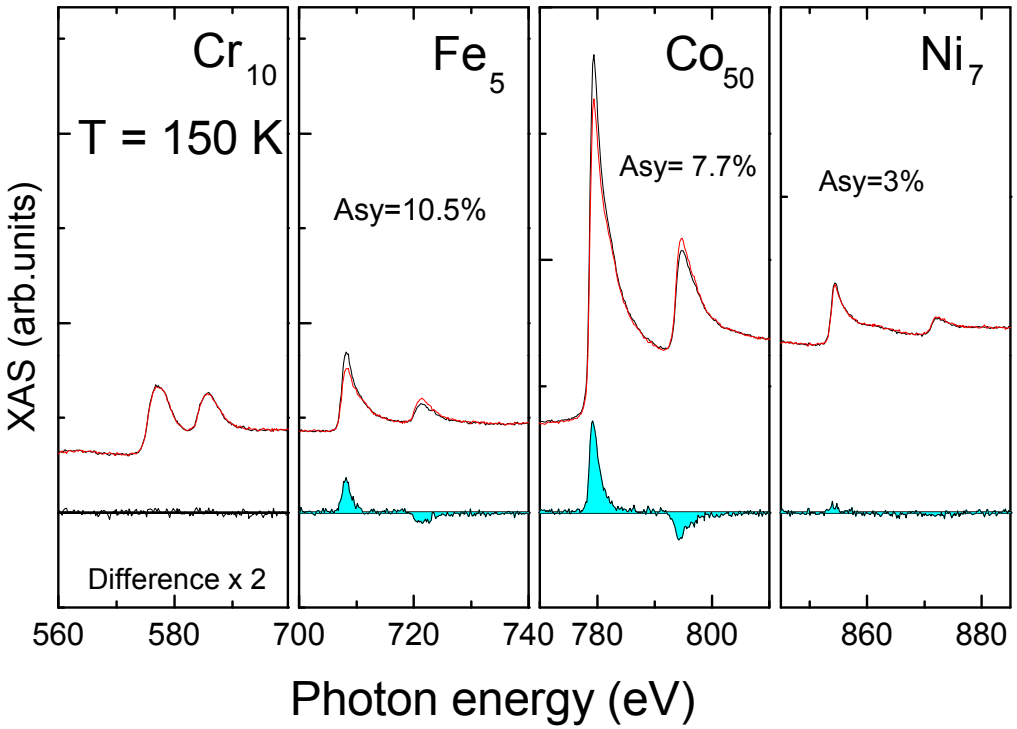

INC
γ_i
M
γ_i
I_{TRANS}
e^-
I_{PEY}
γ_f
I_{FY}
e^-
γ_i
I_{TEY}
I_{REFL}


$\hbar\omega$
e^-
magnetic film
single-crystal
Cu(001)
Ammeter
A

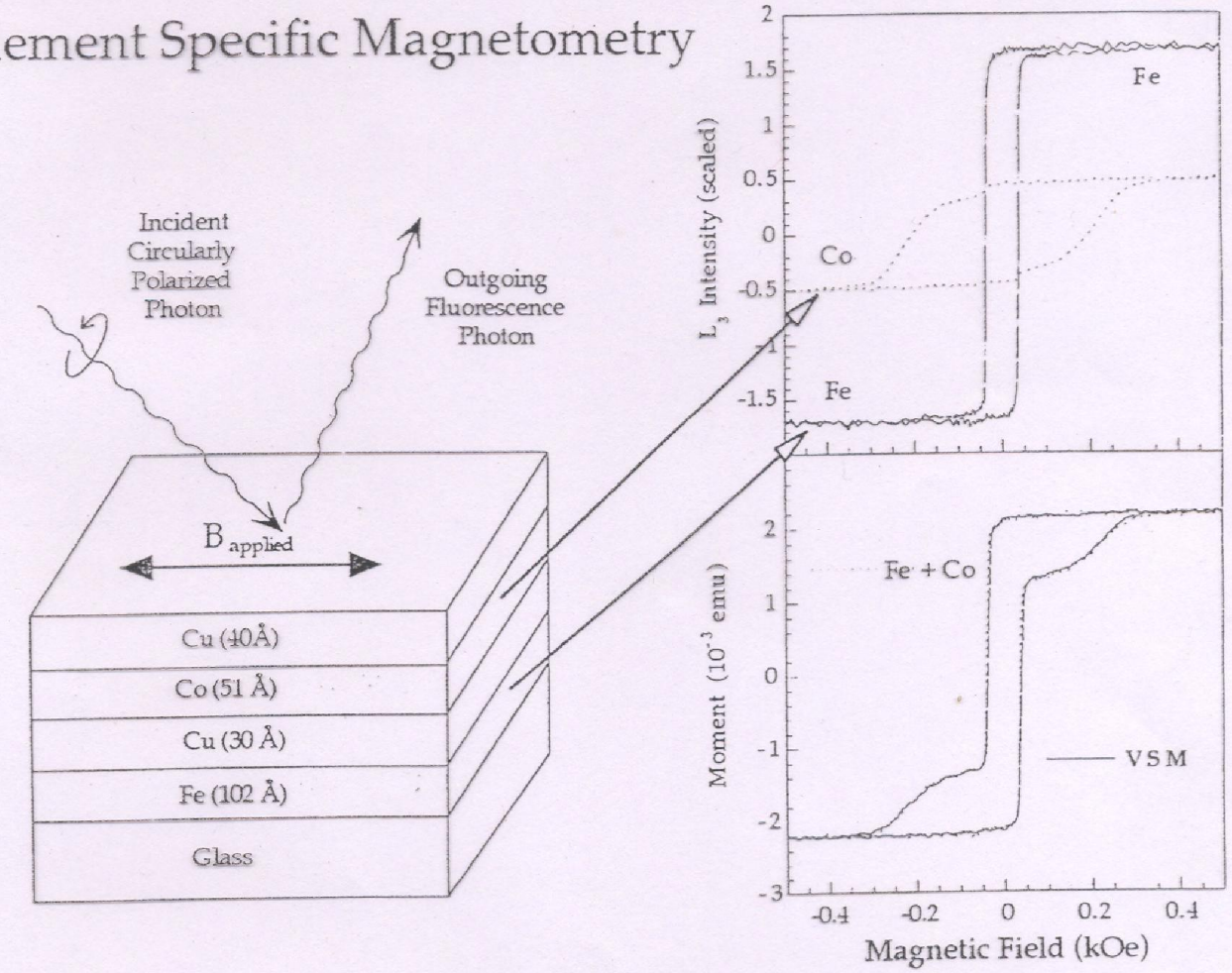

Minority spin
valence bands
Majority spin
valence bands
Fermi energy
Energy
hν
Core level

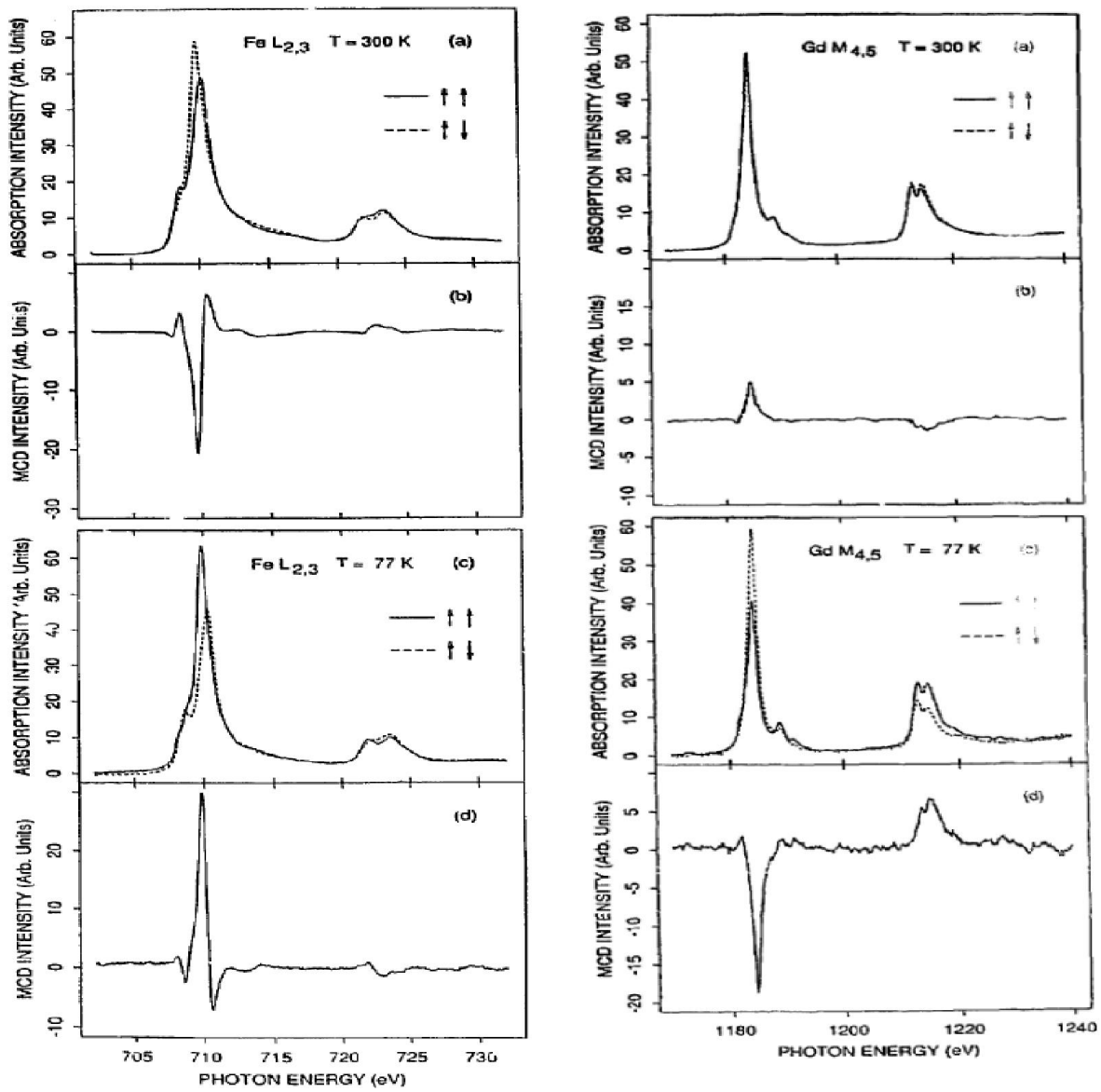

H
e^-
A
$\propto I$
A'
$\propto I_0$

$Fe_5Co_{50}Ni_7Cr_{10}B_{16}Si_{12}$ ⟶ Metallic glass



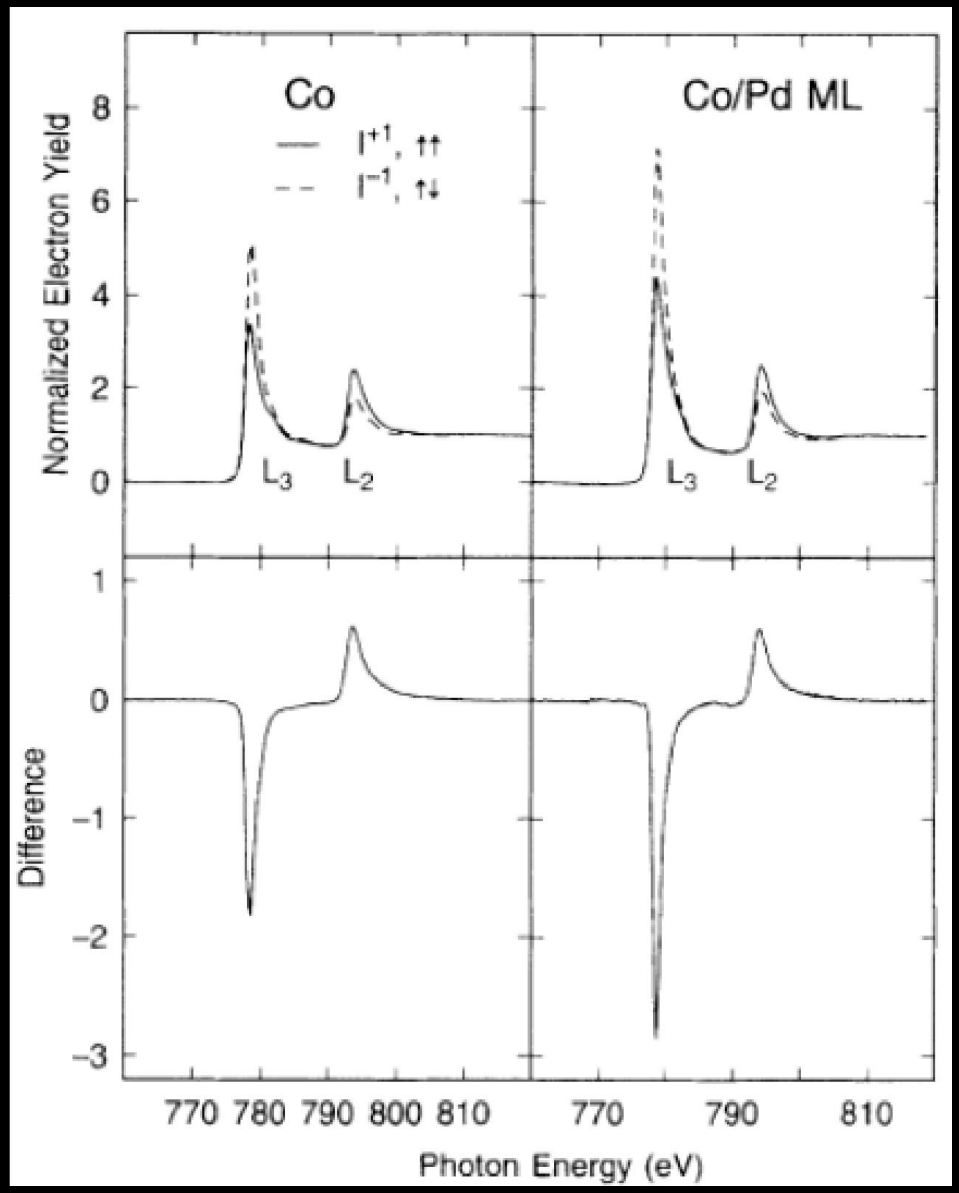
Element Specific Magnetometry



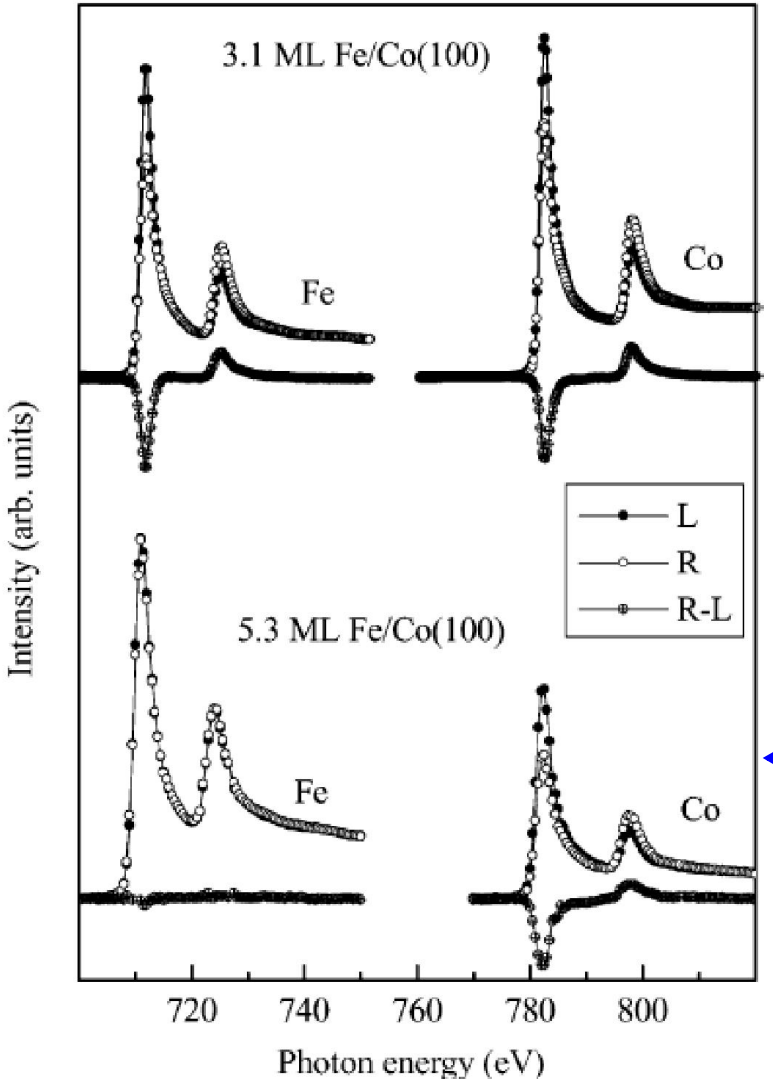


$Gd_3Fe_5O_{12}$

P. Rudolf, F. Sette [1], L.H. Tjeng, G. Meigs and C.T. Chen, J. Magn. Magn. Mater, **109**, 109 (1992)


Co
Co/Pd ML
I^{+1}, ↑↑
I^{-1}, ↑↓
Normalized Electron Yield
Difference
L_3
L_2
8
6
4
2
0
1
0
−1
−2
−3
770 780 790 800 810
770
790
810
Photon Energy (eV)

Magnetism of *FCC Iron*



3.1 ML FCC-Fe
8 ML Co (100)
→ Magnetic

5.3 ML FCC-Fe
8 ML Co (100)
→ Almost Non-Magnetic

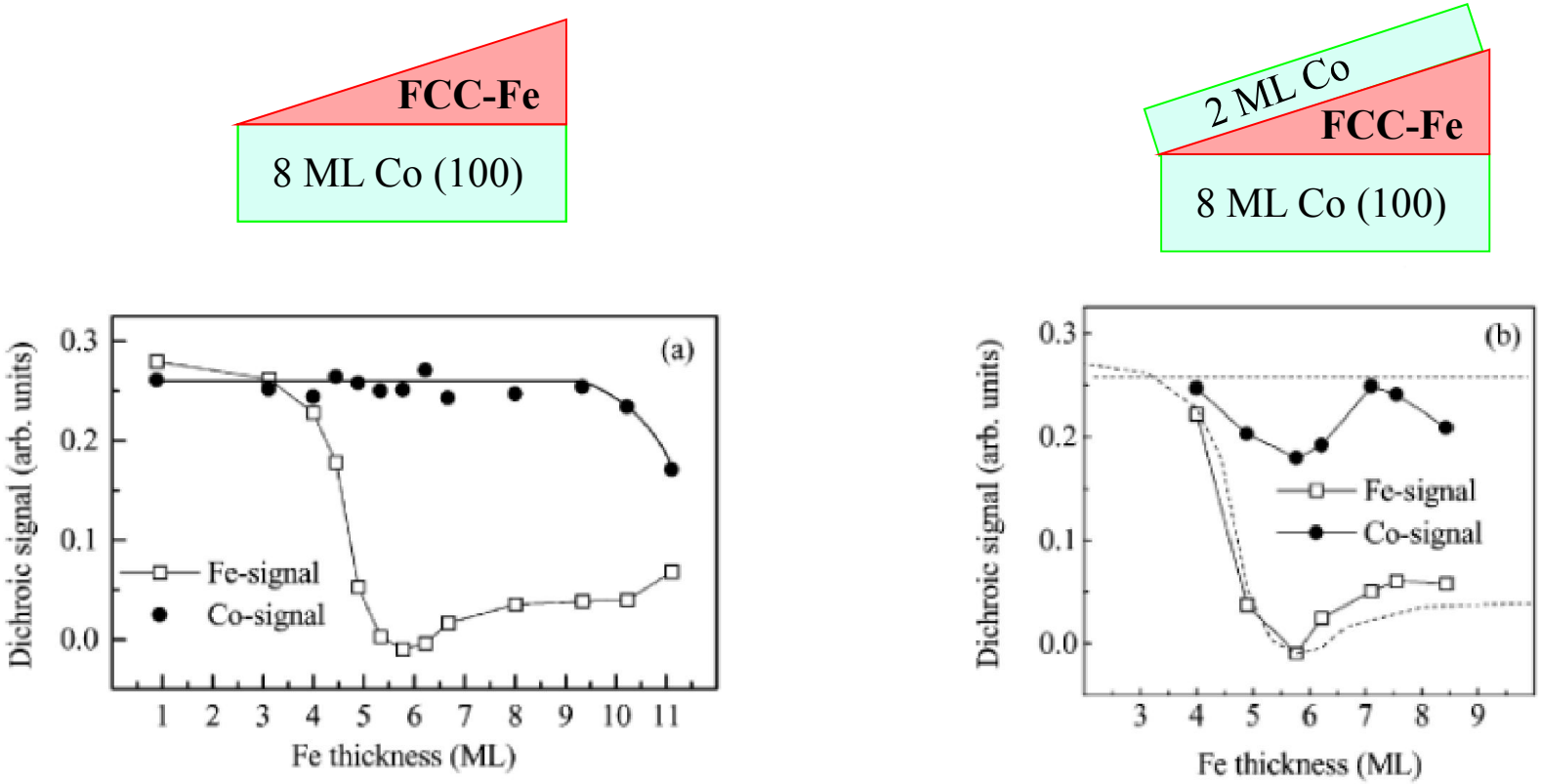
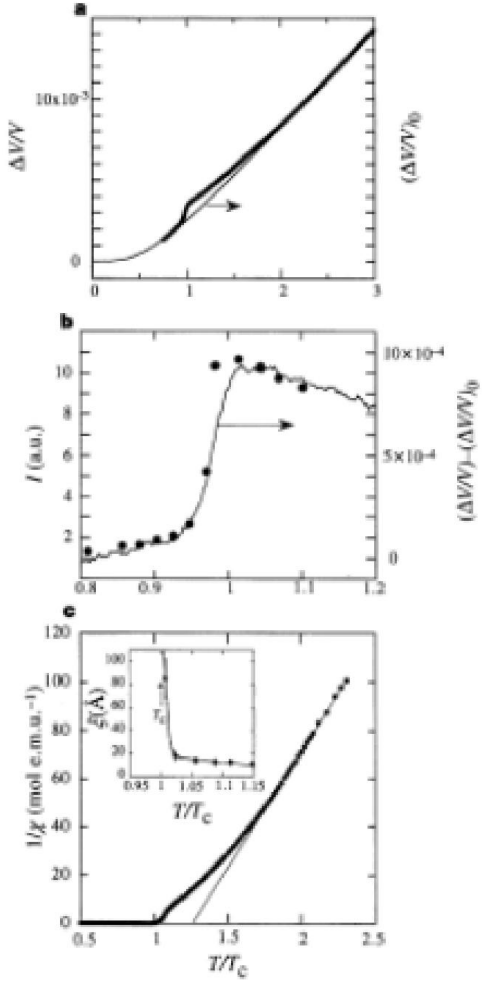
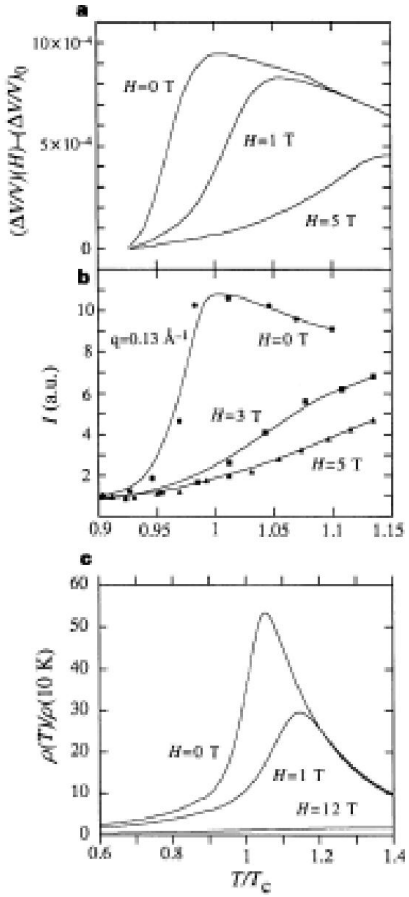


Fig. 2. (a) Fe and Co dichroic signals (open squares and solid circles, respectively) determined for the Fe/Co(1 0 0) system as a function of Fe film thickness; (b) Fe and Co dichroic signals (open squares and solid circles, respectively) determined for the trilayer 2 ML Co/Fe/8 ML Co(1 0 0) system as a function of Fe film thickness in comparison with the results of the Fe/8 ML Co(1 0 0) system (dashed lines).





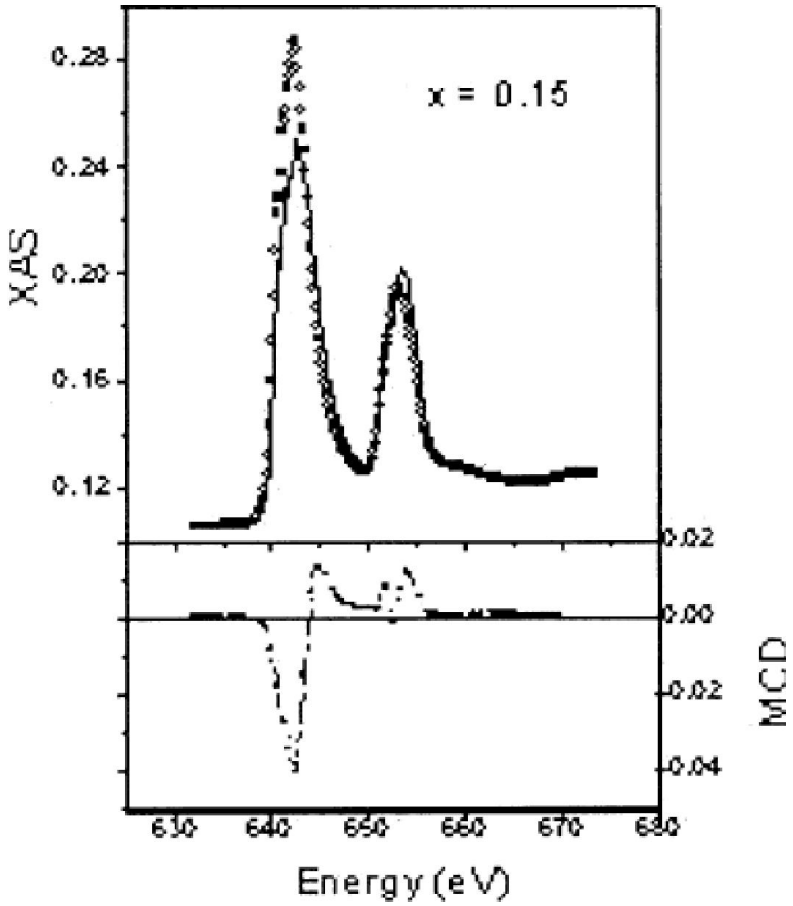
Evidence for magnetic polarons in the magnetoresistive perovskites

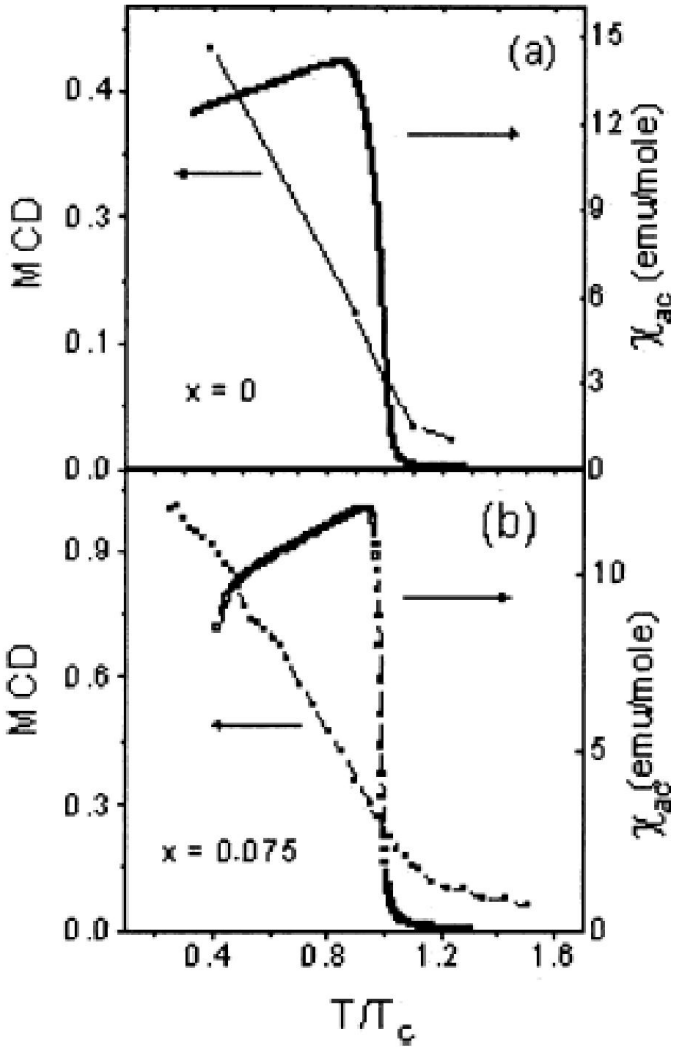
J. M. De Teresa*, M. R. Ibarra*, P. A. Algarabel*, C. Ritter†, C. Marquina*, J. Blasco*, J. García*, A. del Moral* & Z. Arnold*

NATURE | VOL 386 | 20 MARCH 1997

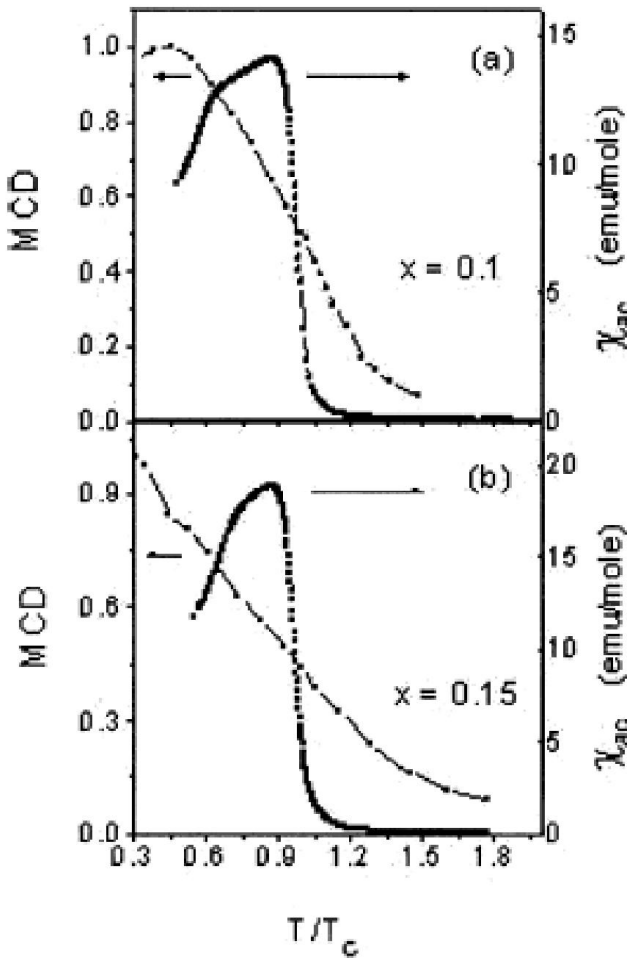
Magnetic circular dichroism of $LaMn_{1-x}Al_xO_{3+\delta}$ series of samples

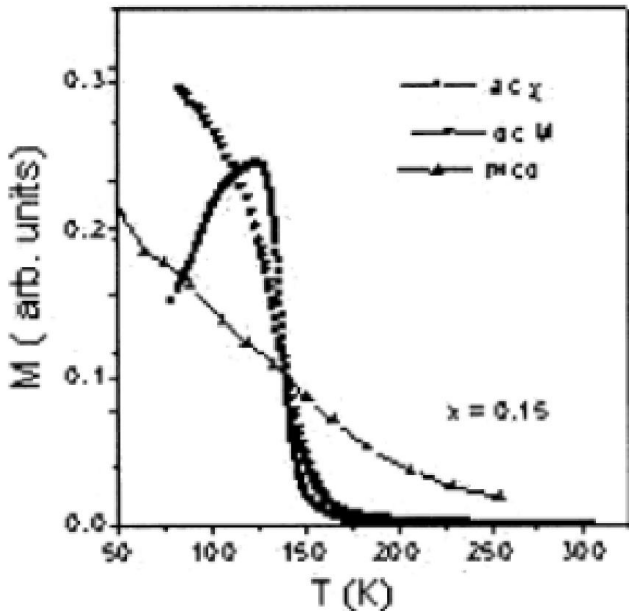
A. Banerjee [a,*], S.M. Chaudhari [a], R.V. Krishnan [a], B.A. Dasannacharya [a], T. Muro [b], Y. Saitoh [c], S. Imada [d], S. Suga [d]



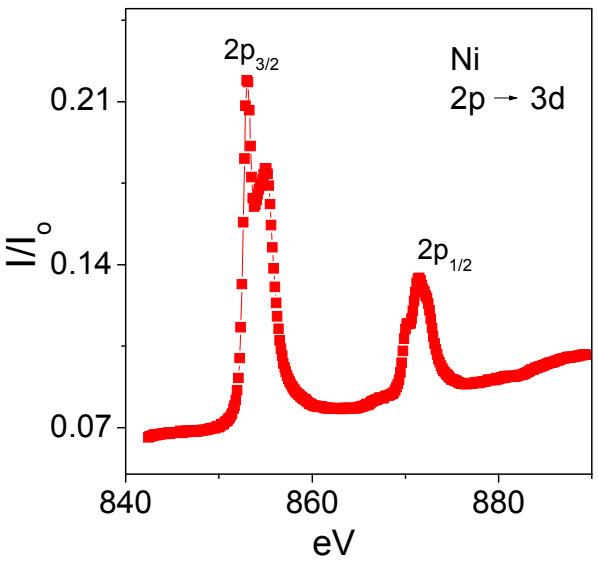


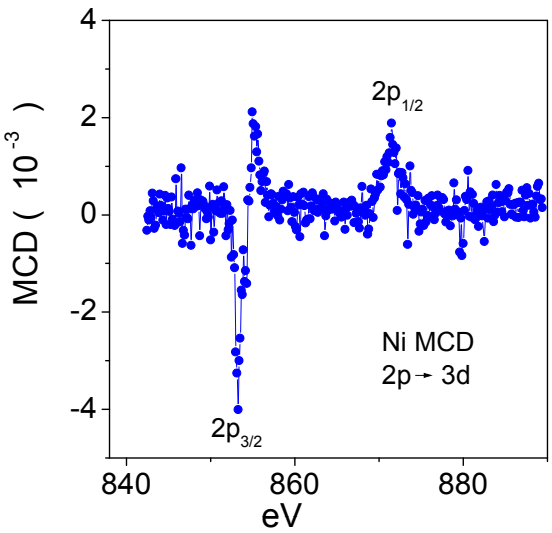
$LaMn_{1-x}Al_xO_{3+\delta}$

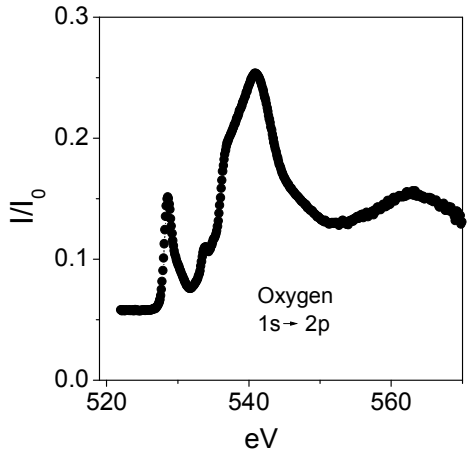


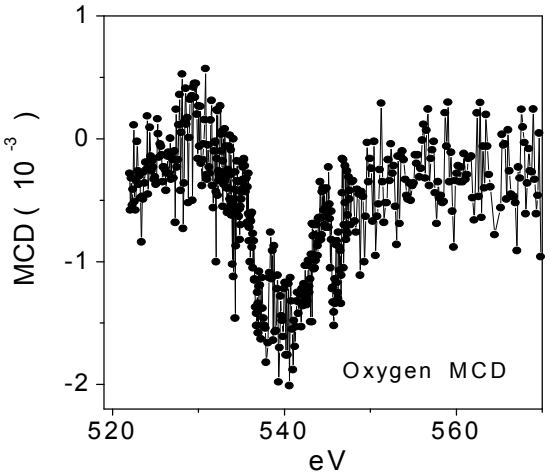


$Li_{0.5}Ni_{0.5}O$


2p3/2
Ni
2p → 3d
2p1/2
I/Io
0.21
0.14
0.07
840
860
880
eV


2p1/2
MCD (10-3)
4
2
0
-2
-4
Ni MCD
2p → 3d
2p3/2
840
860
880
eV


I/I0
0.3
0.2
0.1
0.0
Oxygen
1s → 2p
520
540
560
eV


MCD (10-3)
1
0
-1
-2
Oxygen MCD
520
540
560
eV

INDUS-II

Future plans → Element specific magnetic microscopy

For imagination

↓

Element specific magnetic ac-susceptibility

Element specific higher order magnetic susceptibility

Thank You