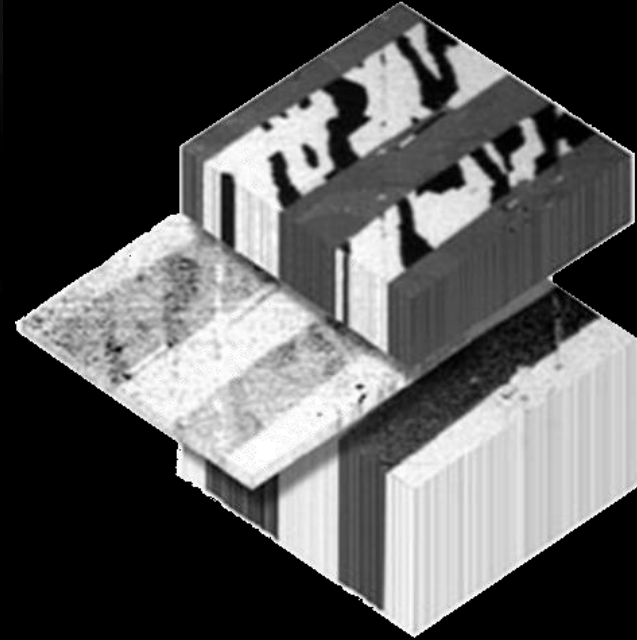


Magnetism as seen with X Rays



Elke Arenholz

Lawrence Berkeley National Laboratory
and

Department of Material Science and Engineering, UC Berkeley

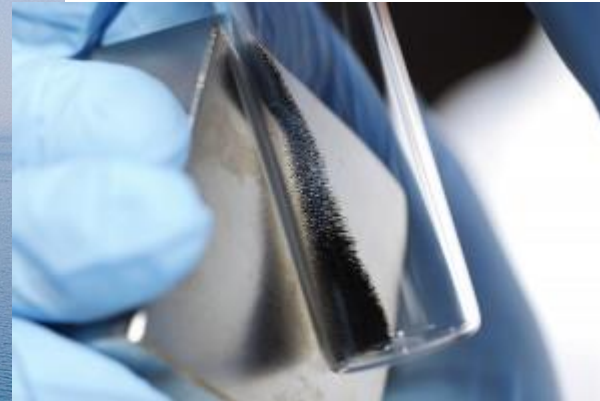
What to expect:

- + **Magnetic Materials Today**
- + **Magnetic Materials Characterization Wish List**
- + **Soft X-ray Absorption Spectroscopy – Basic concept and examples**
- + **X-ray magnetic circular dichroism (XMCD)**
 - **Basic concepts**
 - **Applications and examples**
 - **Dynamics: X-Ray Ferromagnetic Resonance (XFMR)**
- + **X-Ray Linear Dichroism and X-ray Magnetic Linear Dichroism (XLD and XMLD)**
- + **Magnetic Imaging using soft X-rays**
- + **Ultrafast dynamics**

Magnetic Materials Today



**Magnetic materials
for
energy applications**

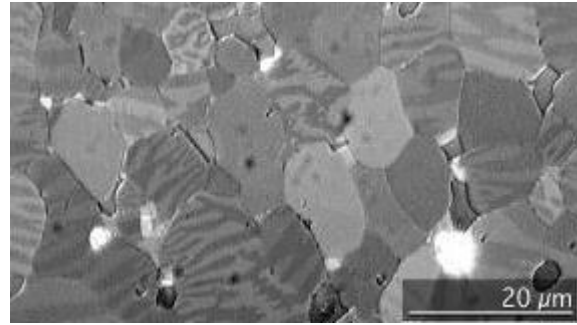
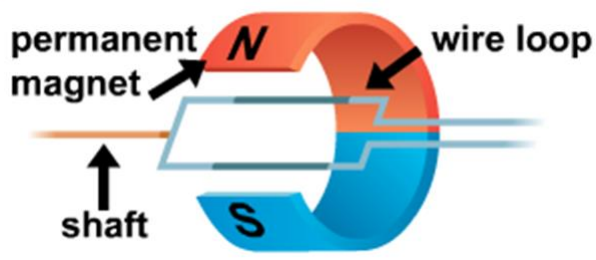
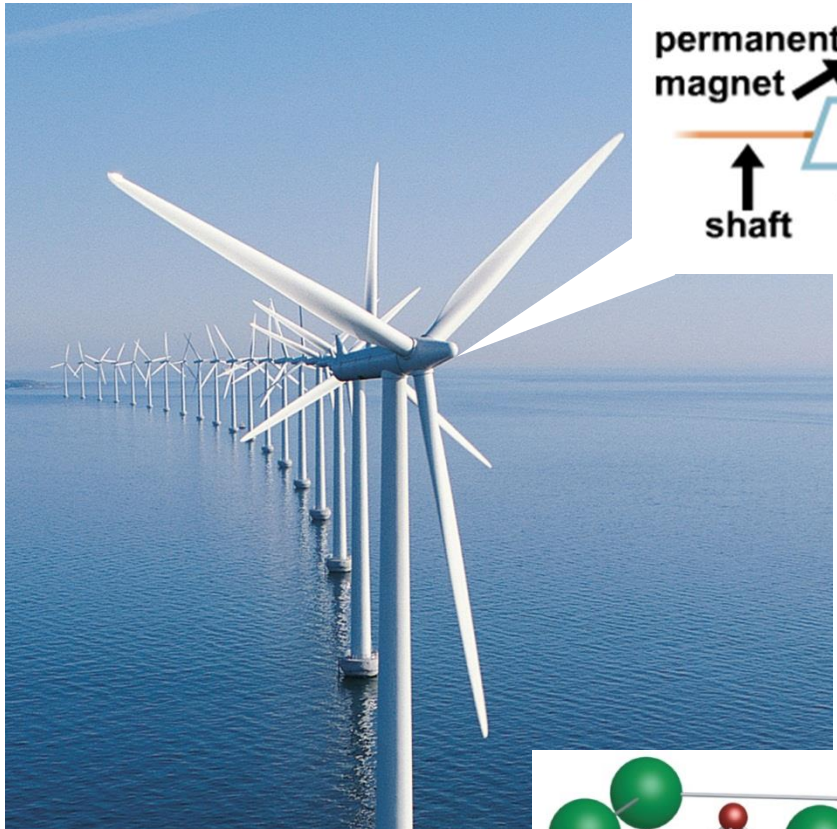


**Magnetic
nanoparticles
for
biomedical and
environmental
applications**

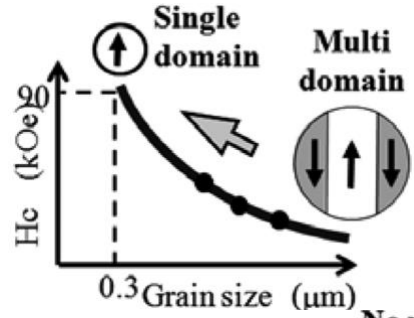
**Magnetic thin films
for
information storage
and processing**



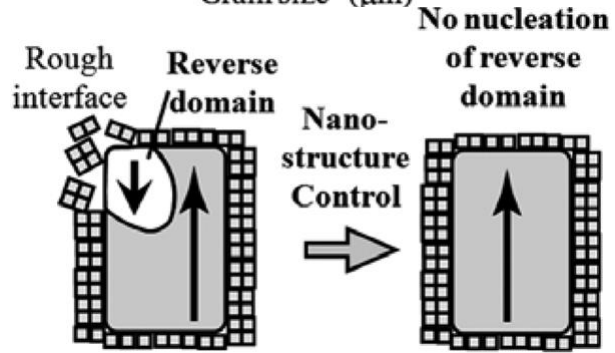
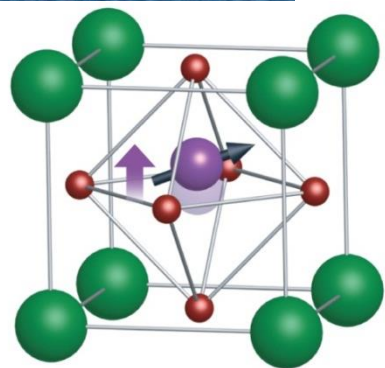
Permanent and Hard Magnetic Materials



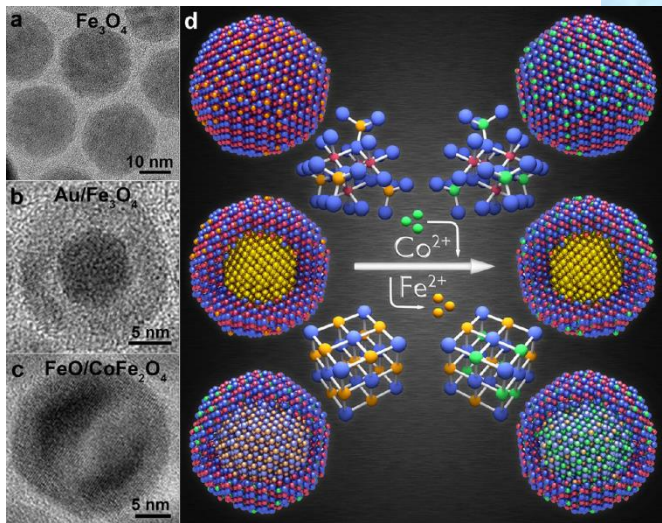
Controlling grain and domain structure on the micro- and nanoscale



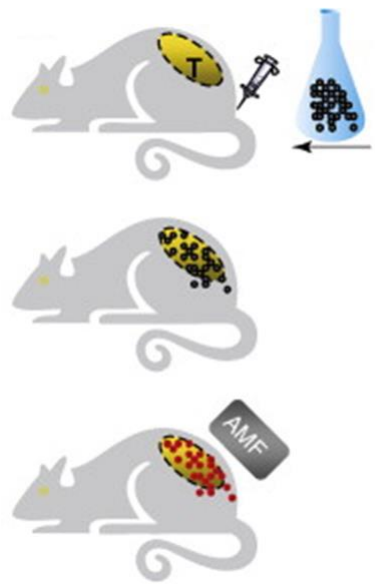
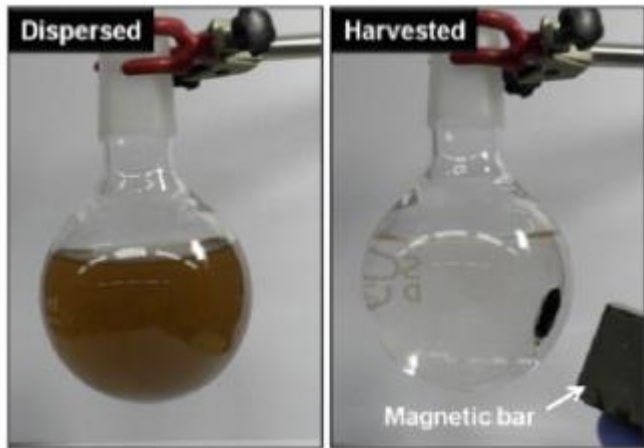
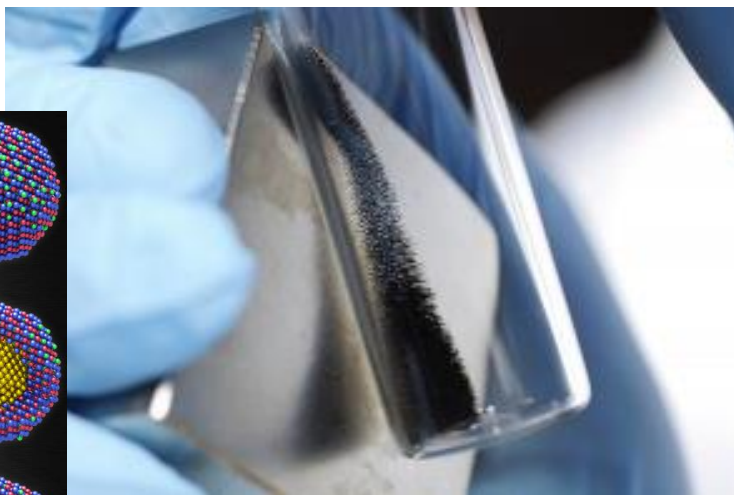
Engineering magnetic anisotropy on the atomic scale



Magnetic Nanoparticles

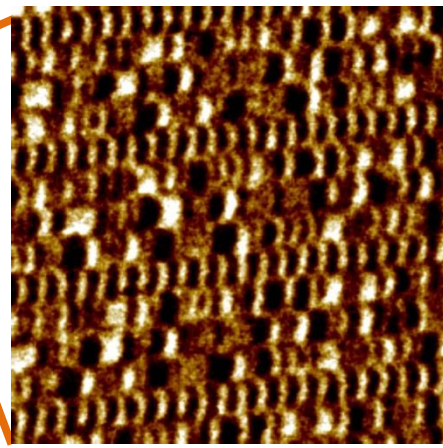


Tailoring magnetic nanoparticles for environmental applications



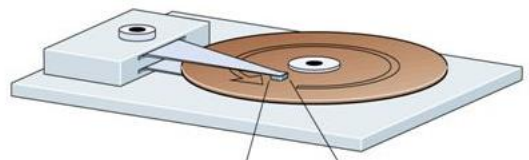
Optimizing magnetic nanoparticles for biomedical applications

Magnetic Thin Films

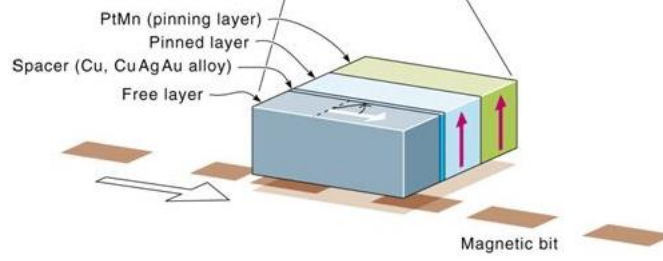


Magnetic domain structure on the nanometer scale

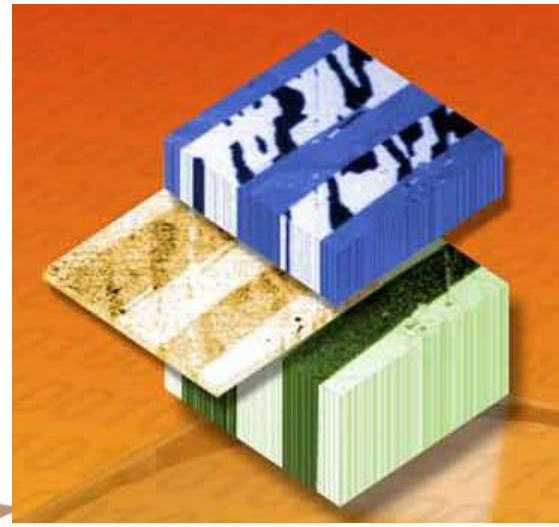
Magnetic coupling at interfaces



Ultrafast magnetization reversal dynamics

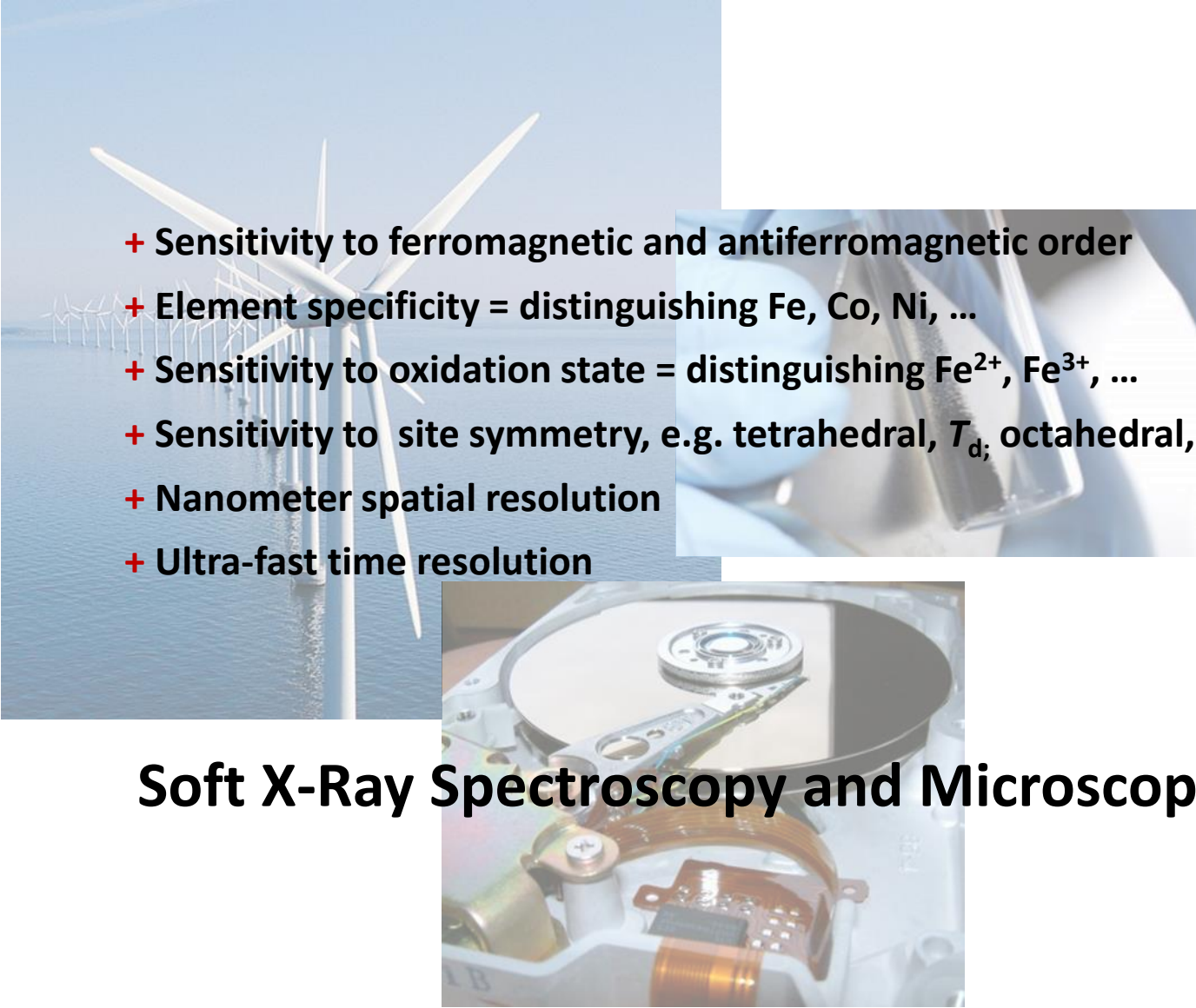


GMR Read Head Sensor



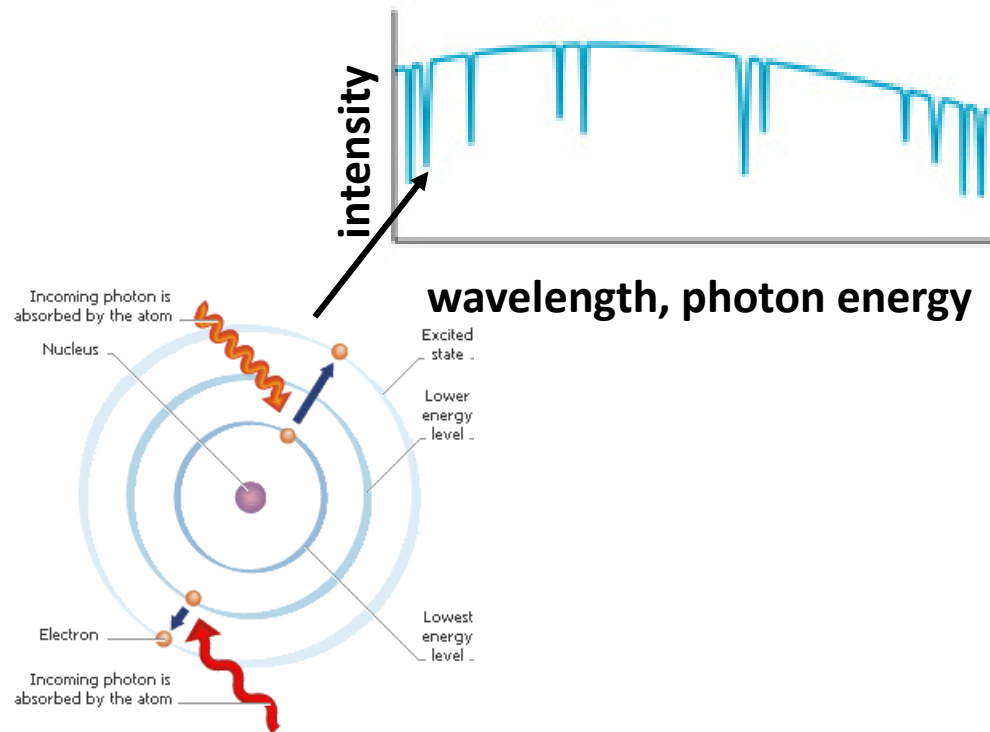
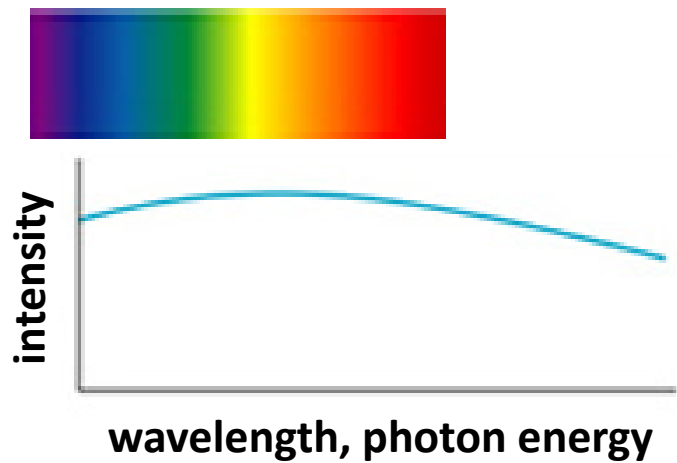
Unique magnetic phases at interfaces

Magnetic Materials Characterization Wish List

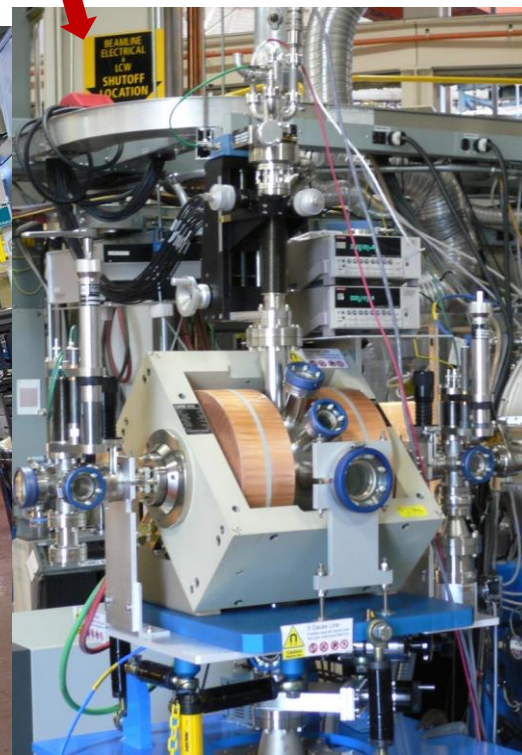
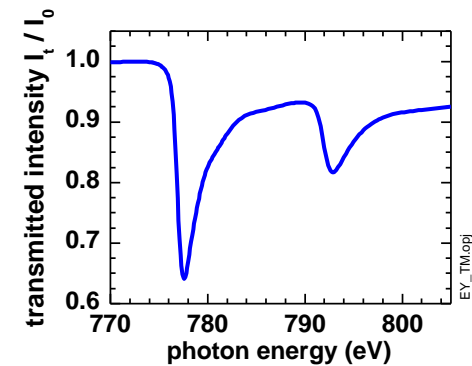
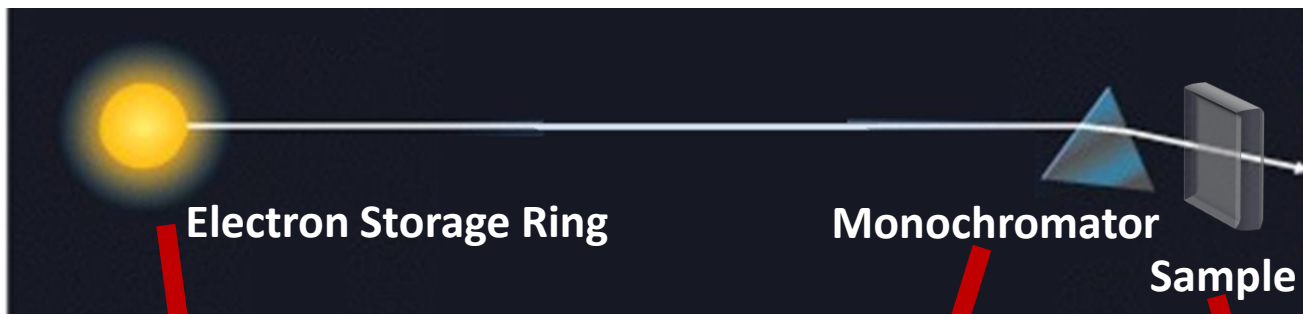
- 
- + Sensitivity to ferromagnetic and antiferromagnetic order
 - + Element specificity = distinguishing Fe, Co, Ni, ...
 - + Sensitivity to oxidation state = distinguishing Fe^{2+} , Fe^{3+} , ...
 - + Sensitivity to site symmetry, e.g. tetrahedral, T_d , octahedral, O_h
 - + Nanometer spatial resolution
 - + Ultra-fast time resolution

Soft X-Ray Spectroscopy and Microscopy

Spectroscopy

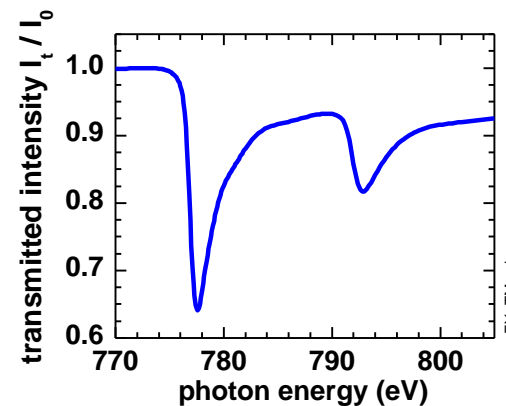
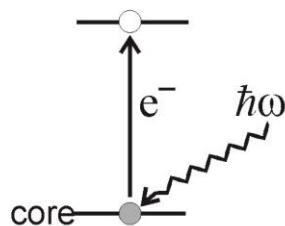
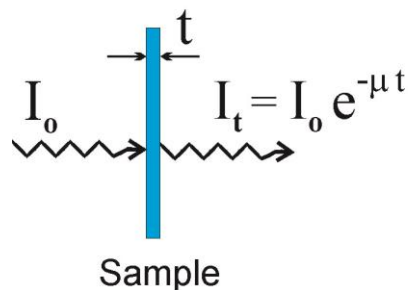


Soft X-Ray Spectroscopy ($h\nu \approx 500\text{-}1000\text{eV}$, $\lambda \approx 1\text{-}2\text{nm}$)



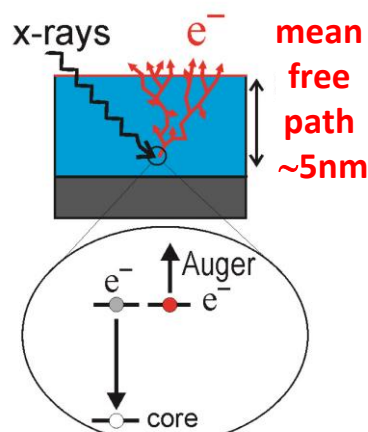
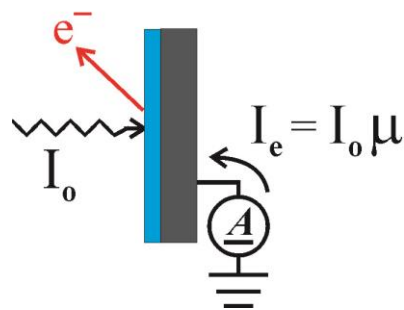
X-Ray Absorption – Detection Modes

Transmission

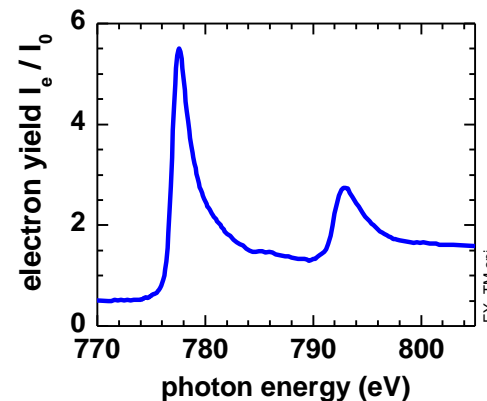


Photons absorbed

Electron Yield



Magnetism (Springer)

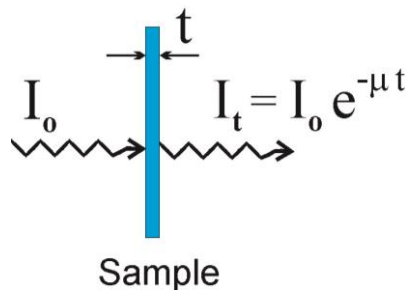


Electrons generated

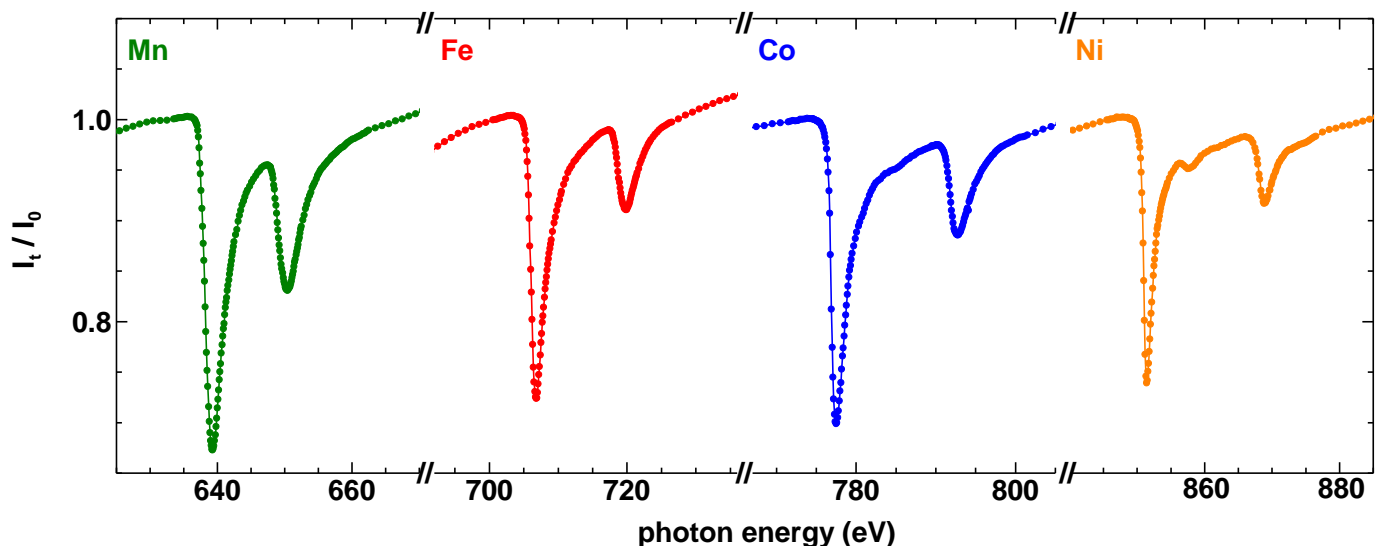
Electron yield:

- + Absorbed photons create core holes subsequently filled by Auger electron emission
- + Auger electrons create low-energy secondary electron cascade through inelastic scattering
- + Emitted electrons \propto probability of Auger electron creation \propto absorption probability

Soft X-Ray Absorption – Probing Depth

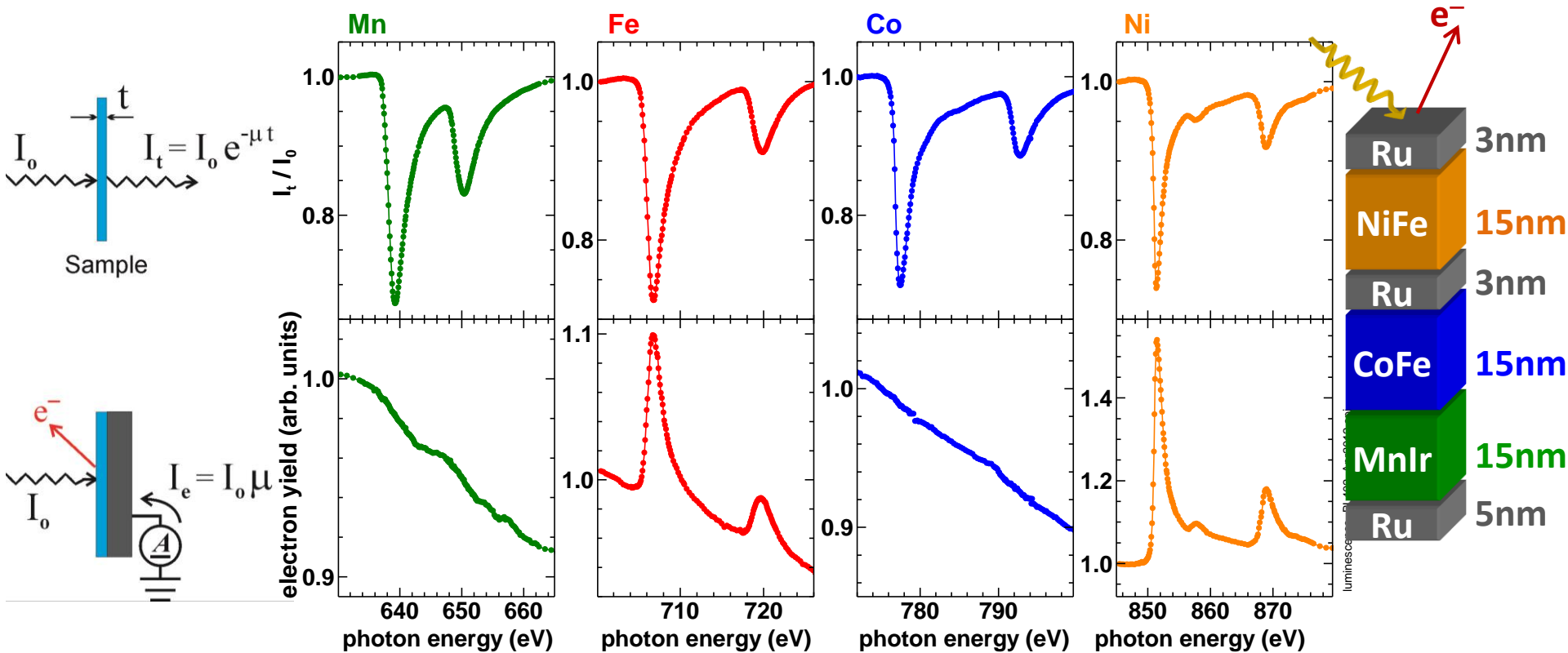


Element	10eV below L_3 $1/\mu$ [nm]	at L_3 $1/\mu$ [nm]	40 eV above L_3 $1/\mu$ [nm]
Fe	550	17	85
Co	550	17	85
Ni	625	24	85



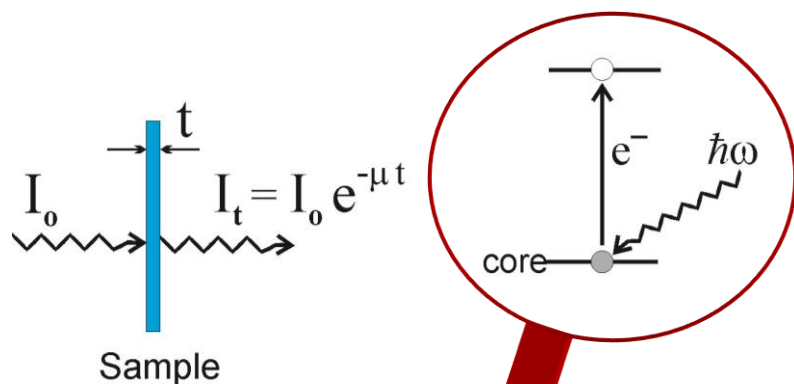
~10-20 nm layer thick films supported by substrates transparent to soft X rays

X-Ray Absorption – Detection Modes and Probing Depth



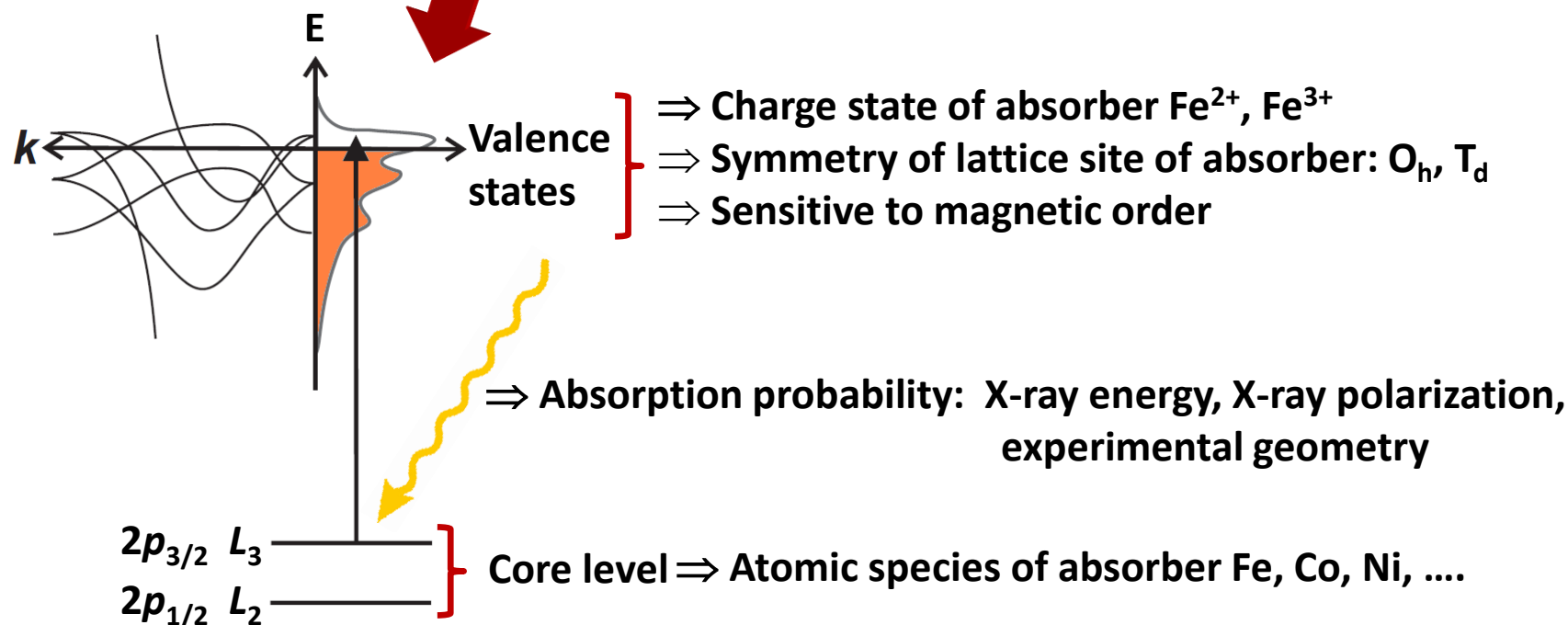
- + Electron sample depth: 2-5 nm in Fe, Co, Ni
- ⇒ 60% of the electron yield originates from the topmost 2-5 nm

X-Ray Absorption – Fundamentals

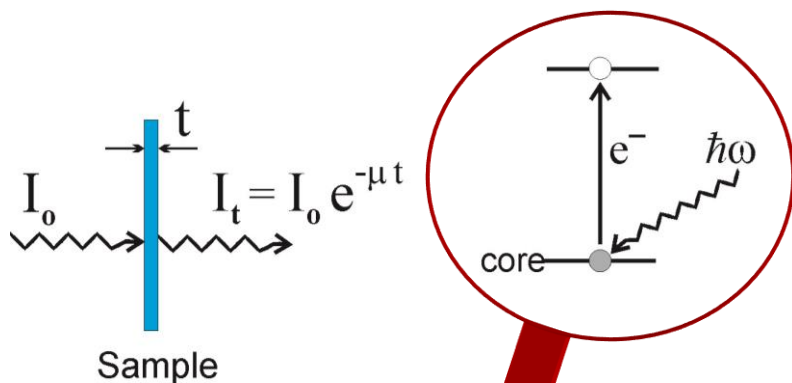


Experimental Concept:

Monitor reduction in X-ray flux transmitted through sample as function of photon energy

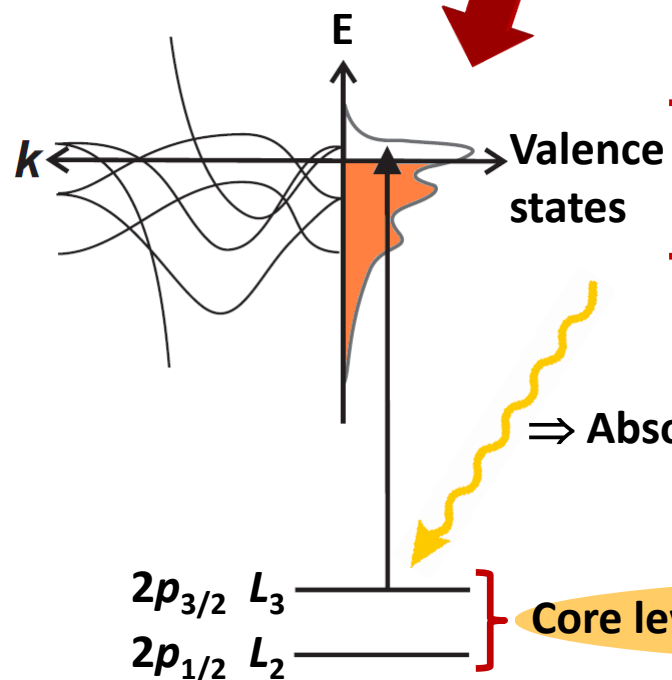


X-Ray Absorption – Fundamentals



Experimental Concept:

Monitor reduction in X-ray flux transmitted through sample as function of photon energy

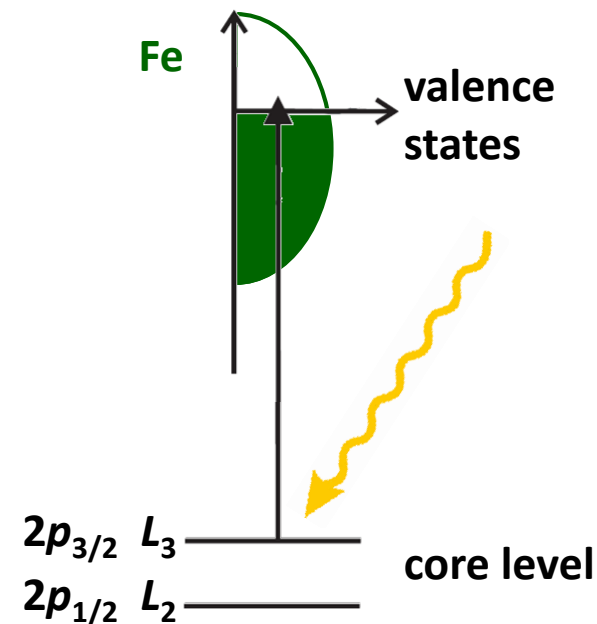
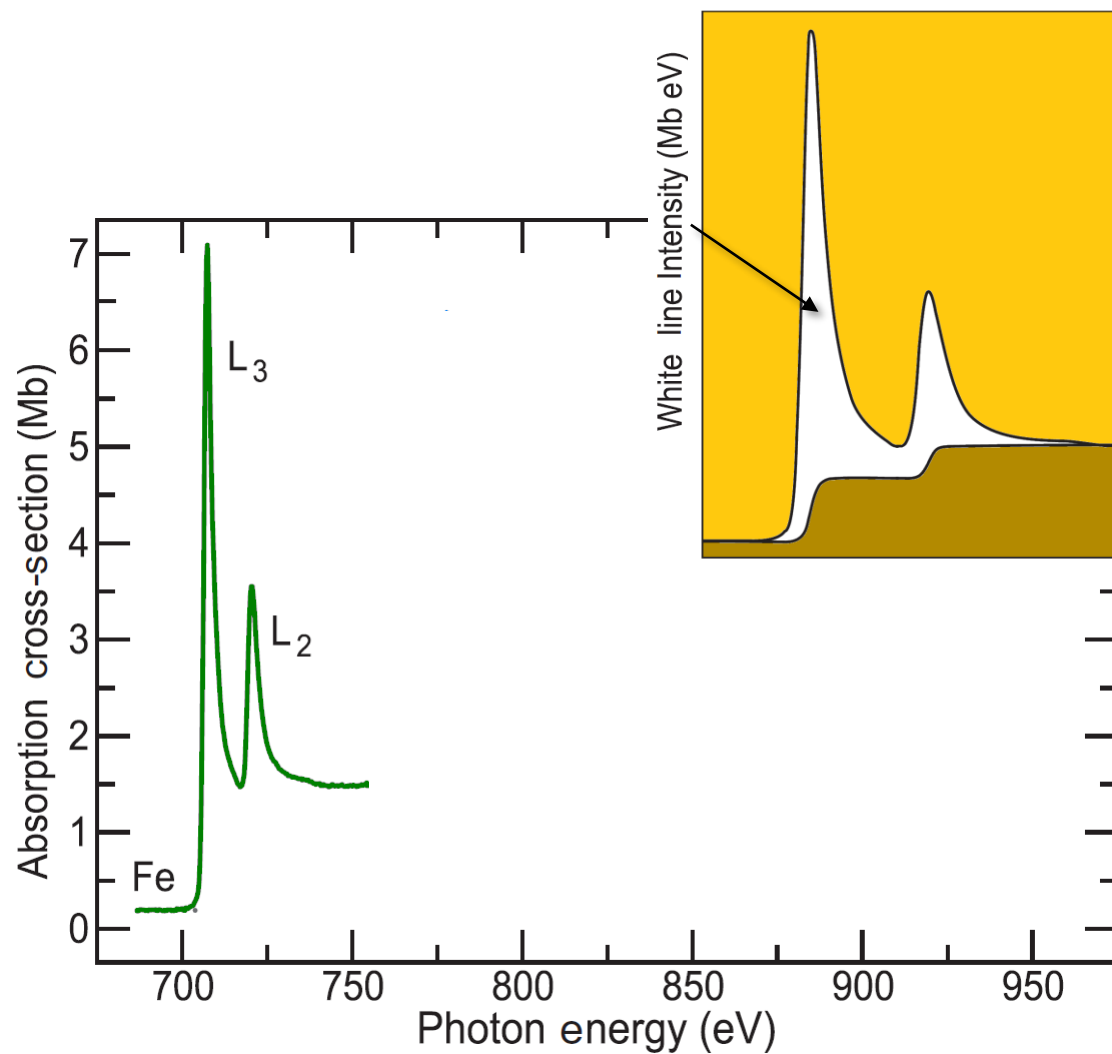


⇒ Charge state of absorber Fe^{2+} , Fe^{3+}
⇒ Symmetry of lattice site of absorber: O_h , T_d
⇒ Sensitive to magnetic order

⇒ Absorption probability: X-ray energy, X-ray polarization, experimental geometry

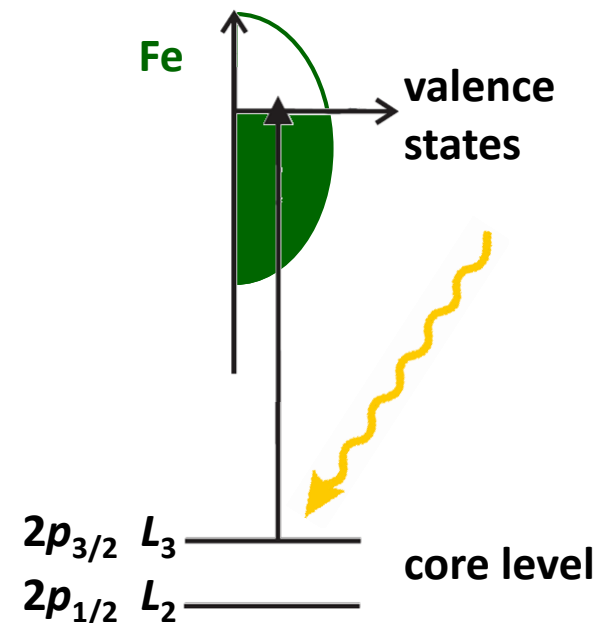
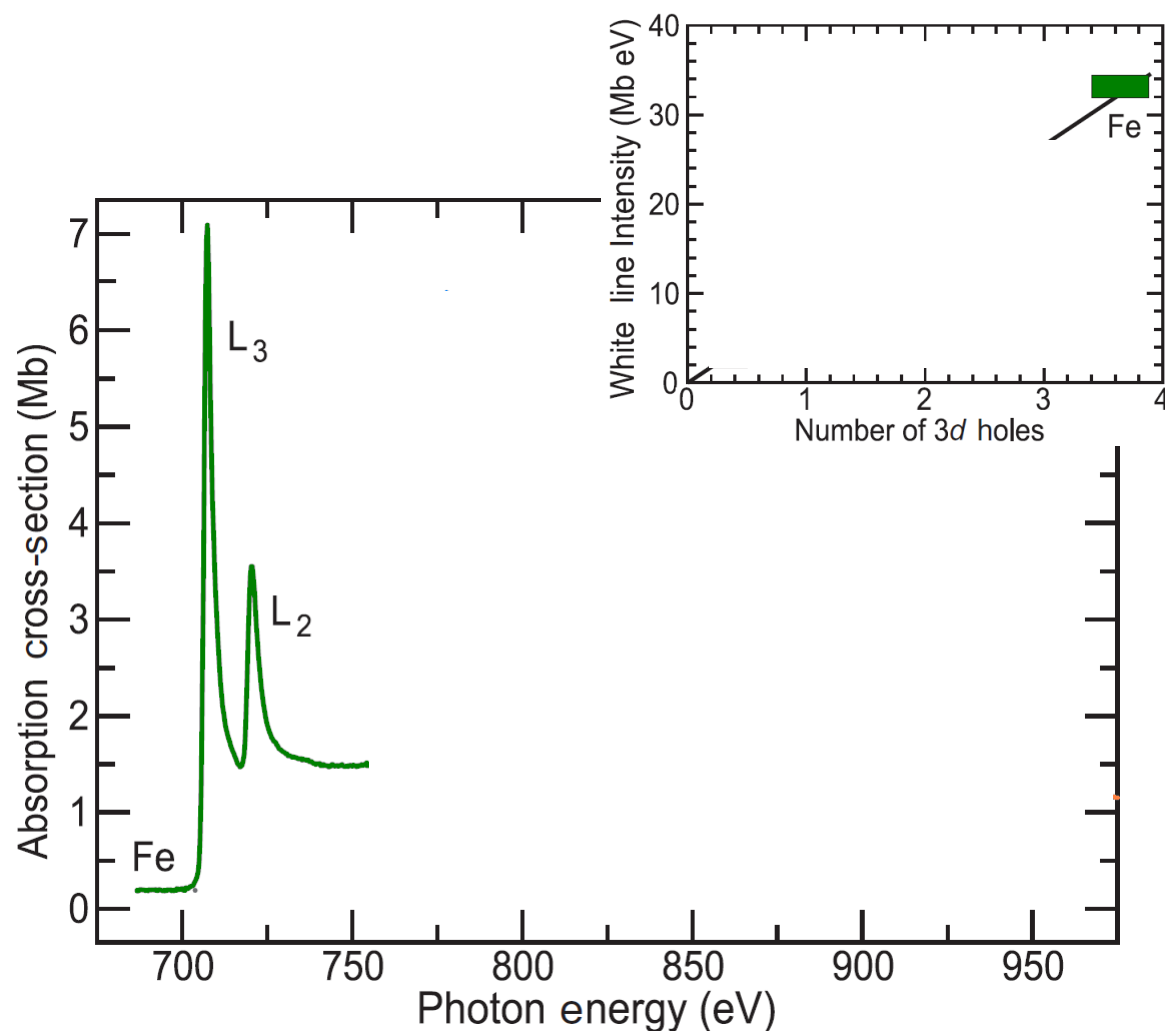
Core level ⇒ Atomic species of absorber Fe, Co, Ni,

'White Line' Intensity



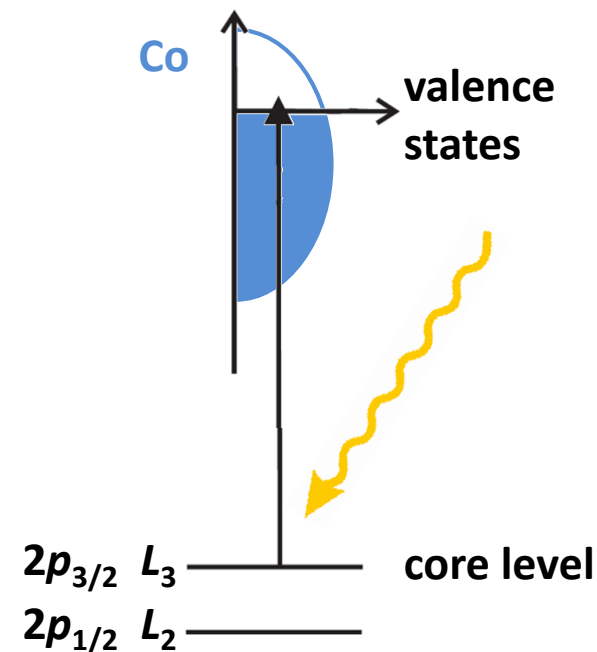
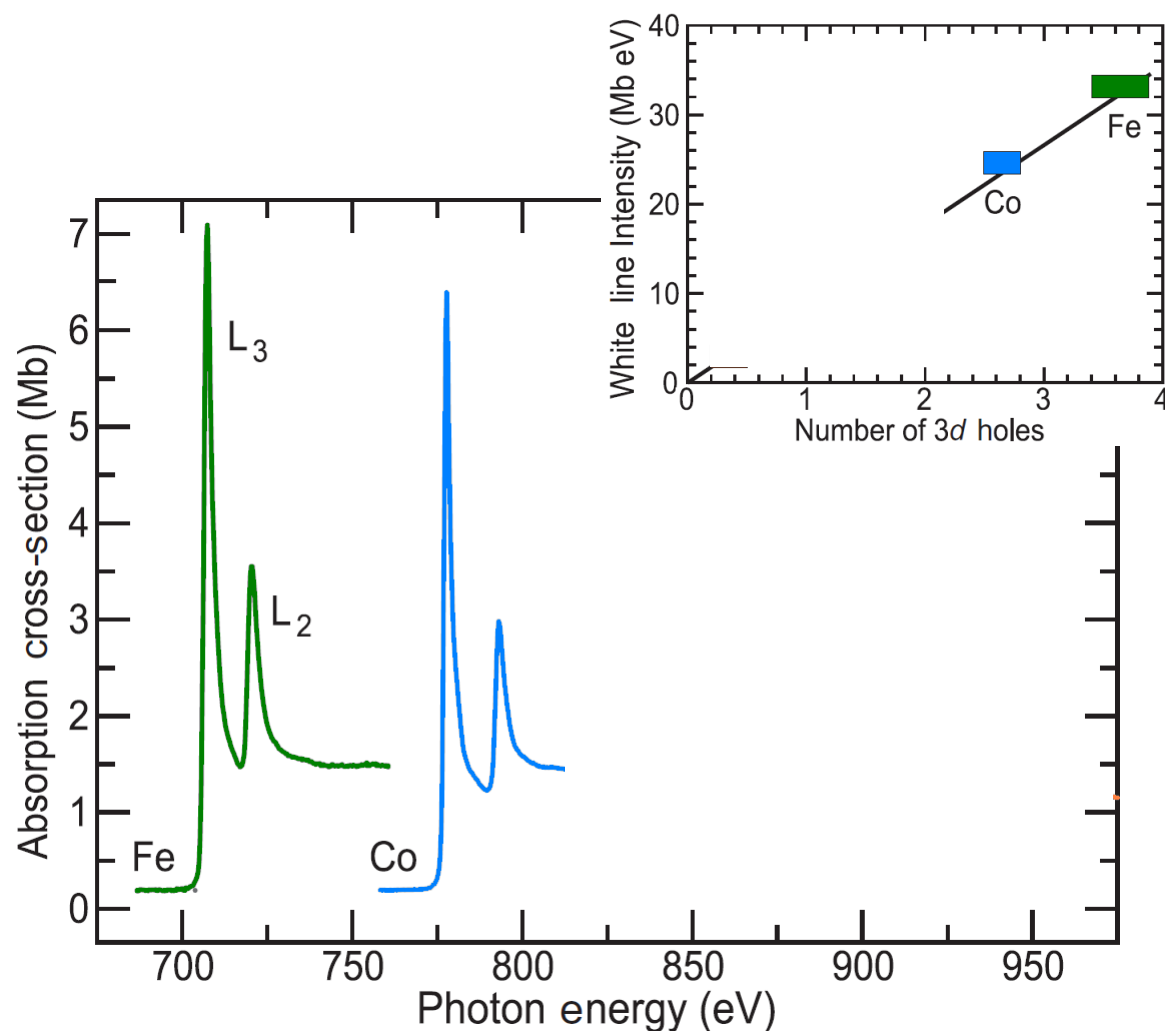
Intensity of $L_{3,2}$ resonances is proportional to number of d states above the Fermi level, i.e. number of holes in the d band.

'White Line' Intensity



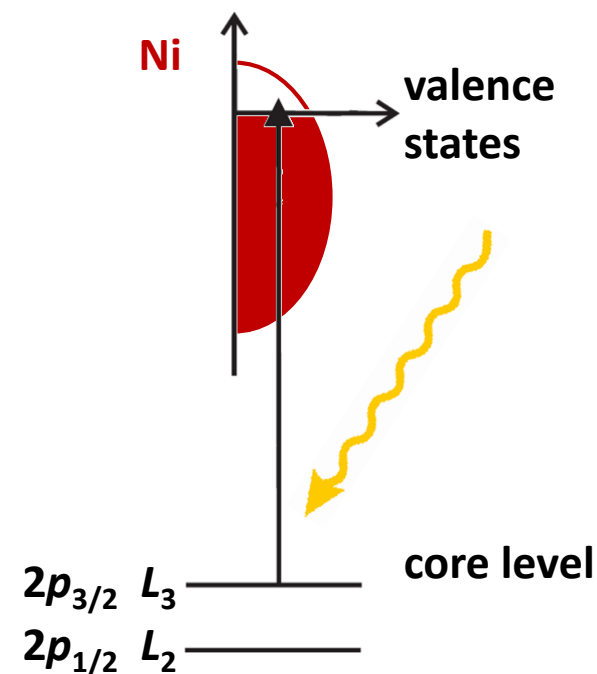
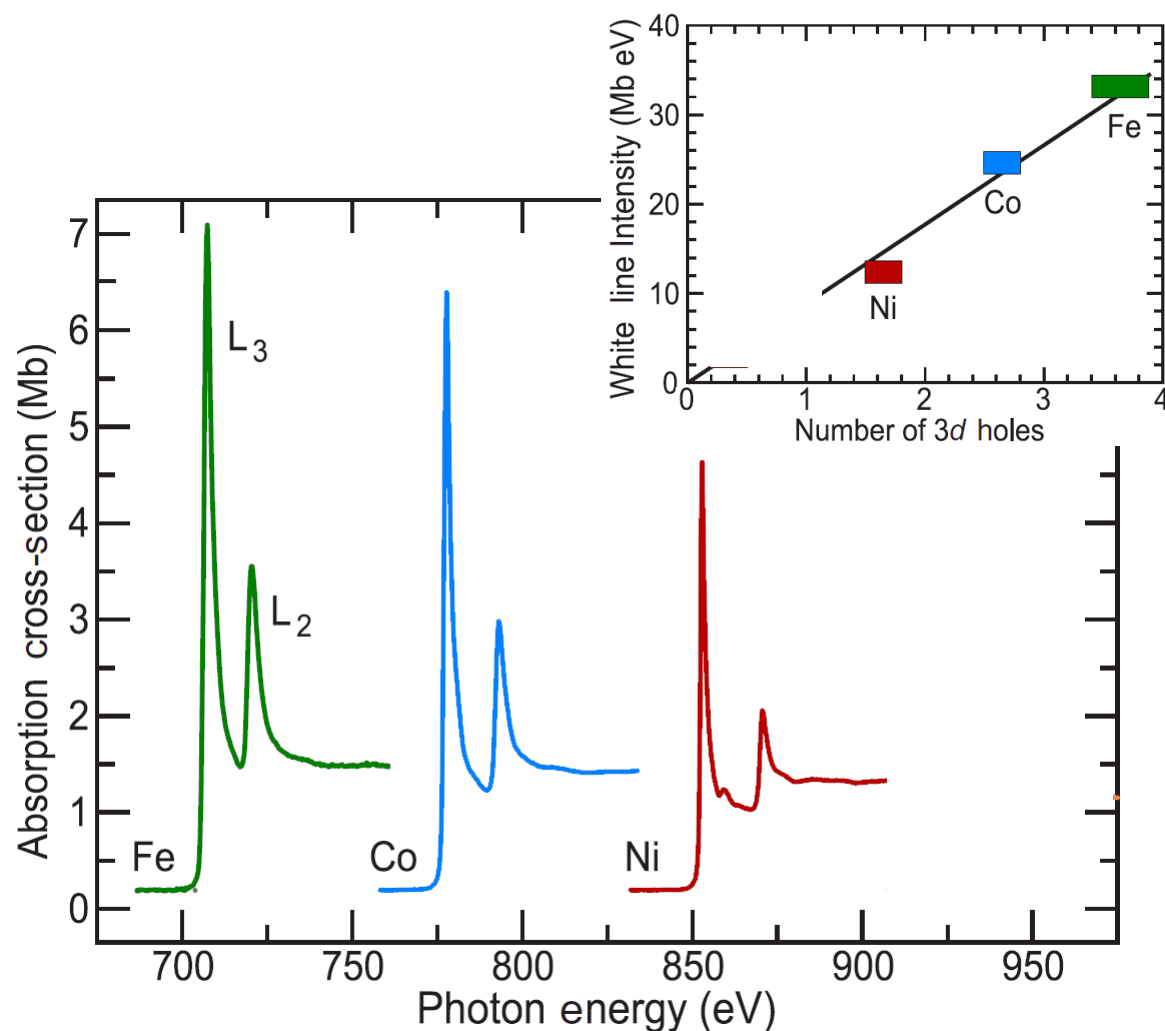
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'White Line' Intensity



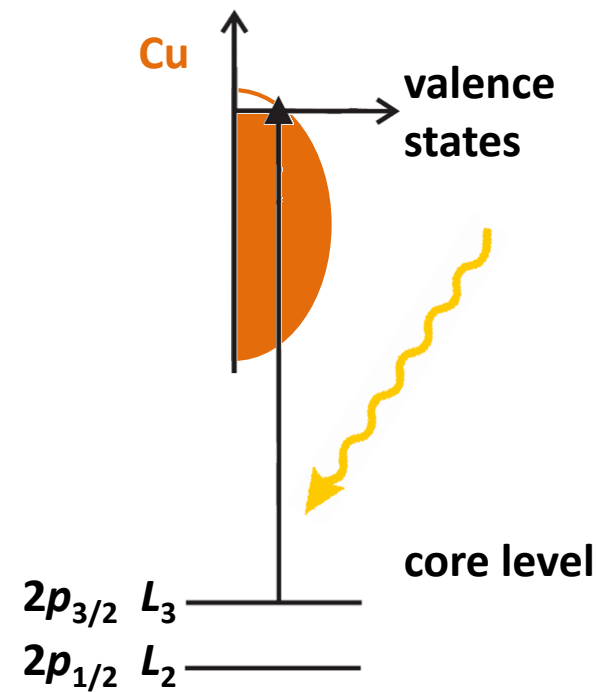
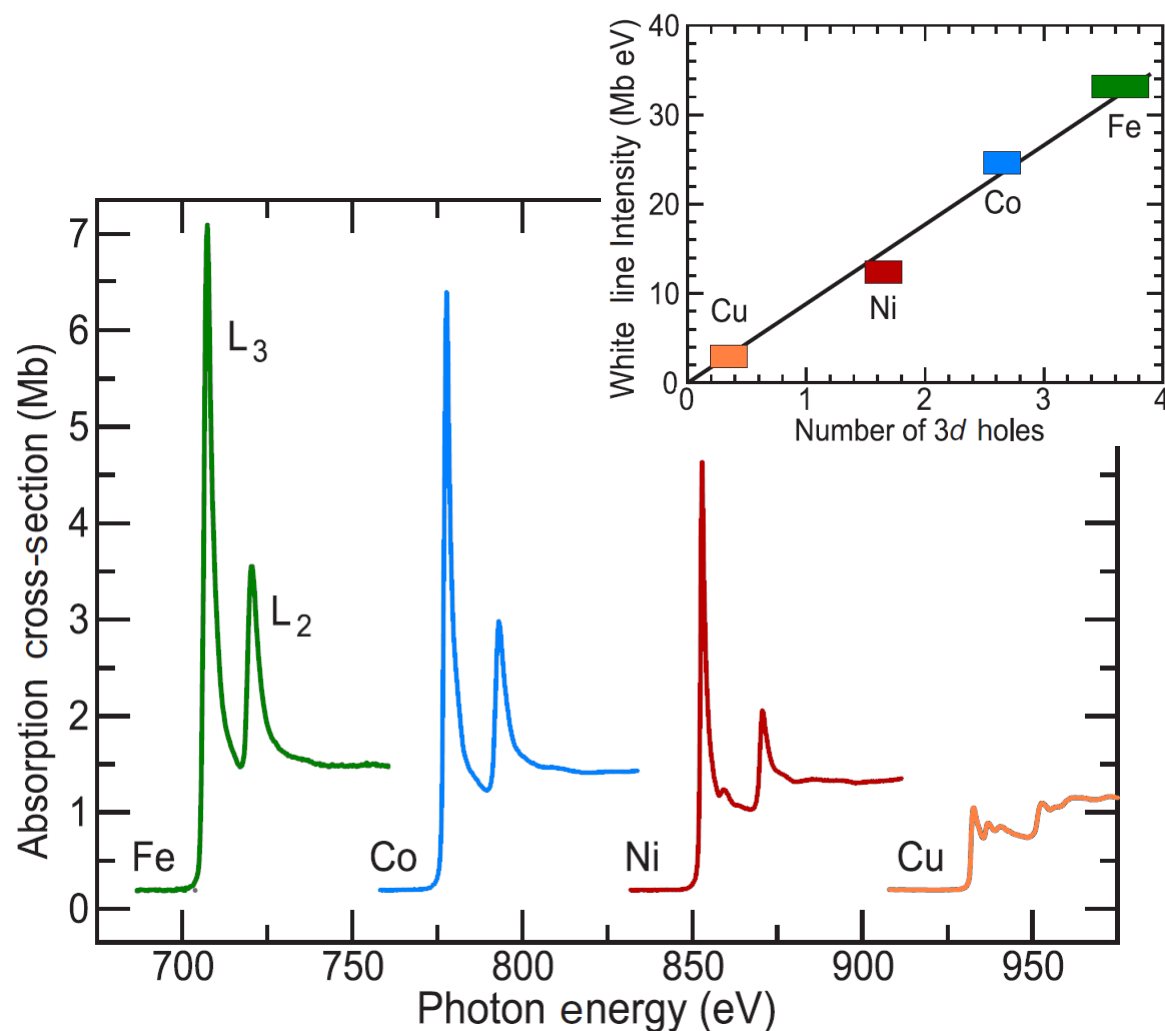
Intensity of $L_{3,2}$ resonances is proportional to number of d states above the Fermi level, i.e. number of holes in the d band.

'White Line' Intensity



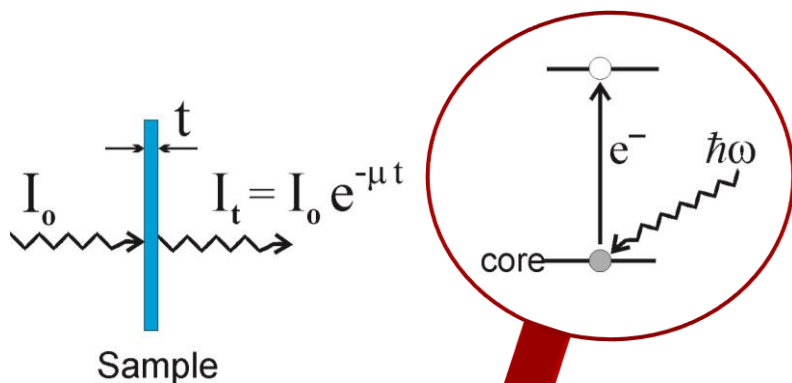
Intensity of $L_{3,2}$ resonances is proportional to number of d states above the Fermi level, i.e. number of holes in the d band.

'White Line' Intensity



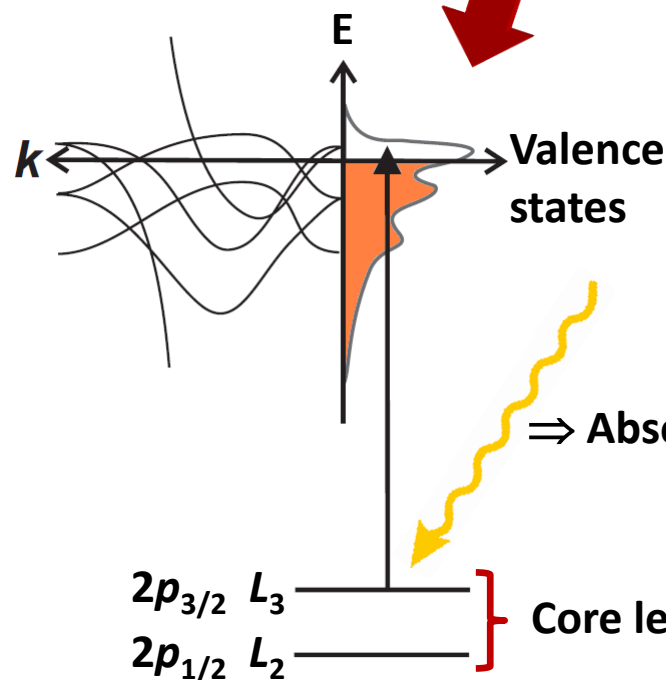
Intensity of $L_{3,2}$ resonances is proportional to number of d states above the Fermi level, i.e. number of holes in the d band.

X-Ray Absorption – Fundamentals



Experimental Concept:

Monitor reduction in X-ray flux transmitted through sample as function of photon energy



⇒ Charge state of absorber Fe^{2+} , Fe^{3+} , ...

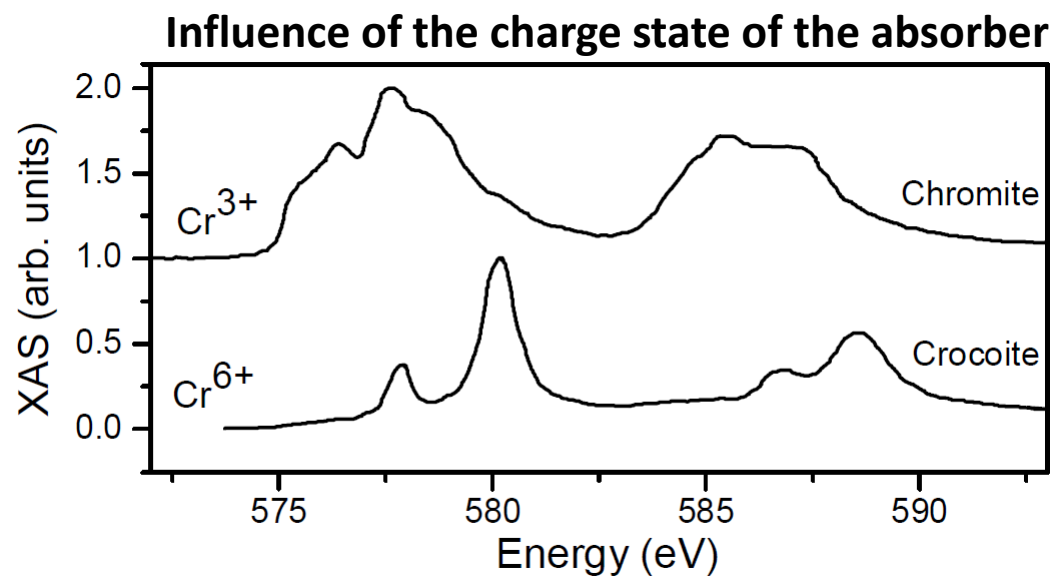
⇒ Symmetry of lattice site of absorber: O_h , T_d

⇒ Sensitive to magnetic order

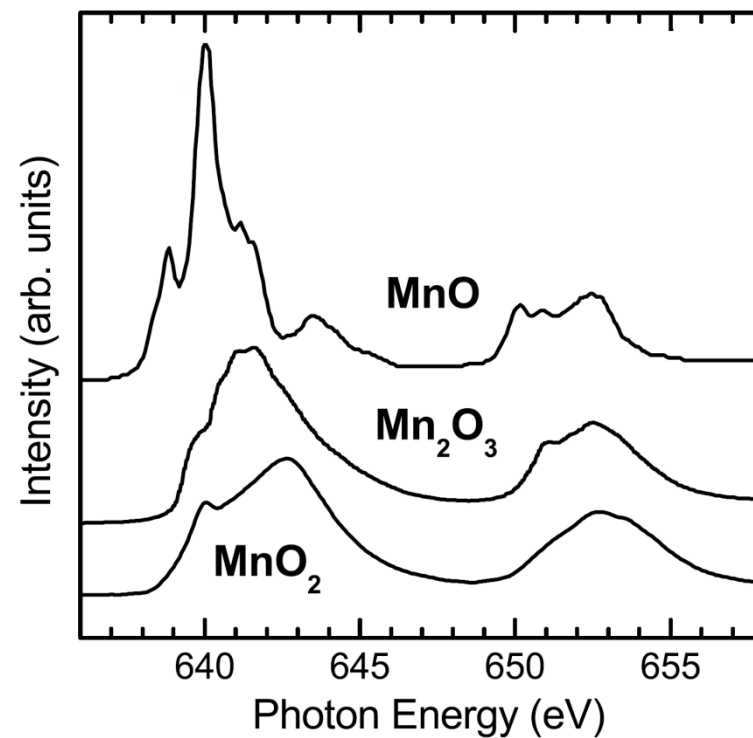
⇒ Absorption probability: X-ray energy, X-ray polarization, experimental geometry

Core level ⇒ Atomic species of absorber Fe, Co, Ni,

X-ray Absorption – Valence State

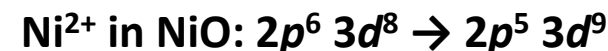


N. Telling *et al.*,
Appl. Phys. Lett. **95**, 163701 (2009)



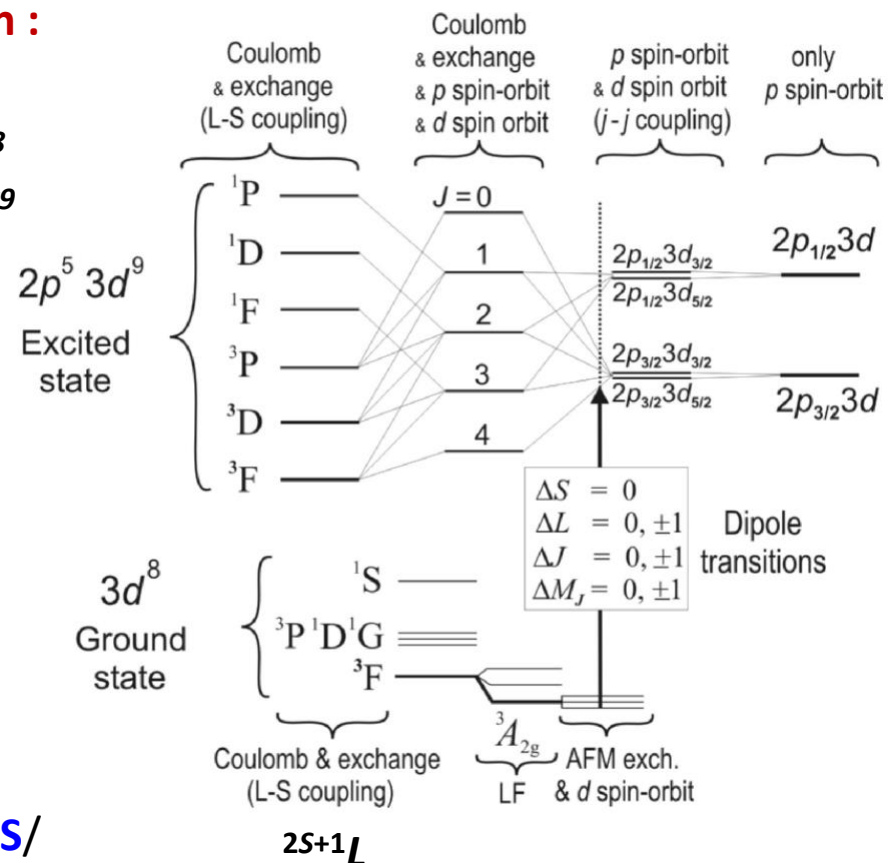
J.-S. Kang *et al.*, *Phys. Rev. B* **77**, 035121 (2008)

X-Ray Absorption – Configuration Model



Configuration model, e.g. L edge absorption :

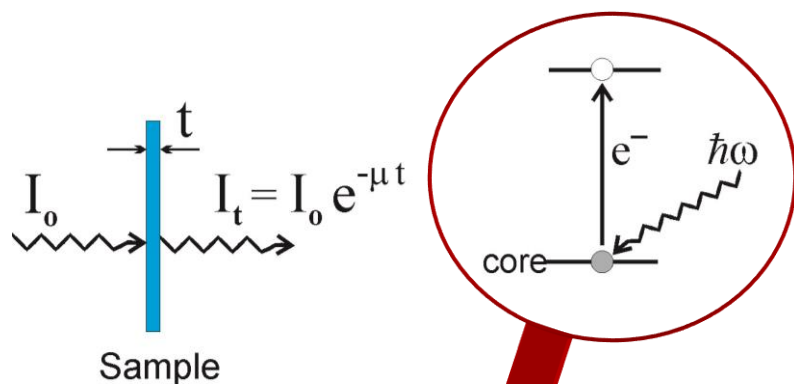
- + Excited from ground/initial state configuration, $2p^6 3d^8$ to excited/final state configuration, $2p^5 3d^9$
- + Omission of all full subshells (spherical symmetric)
- + Takes into account correlation effects in the ground state as well as in the excited state
- + Leads to multiplet effects/structure



<http://www.anorg.chem.uu.nl/CTM4XAS/>

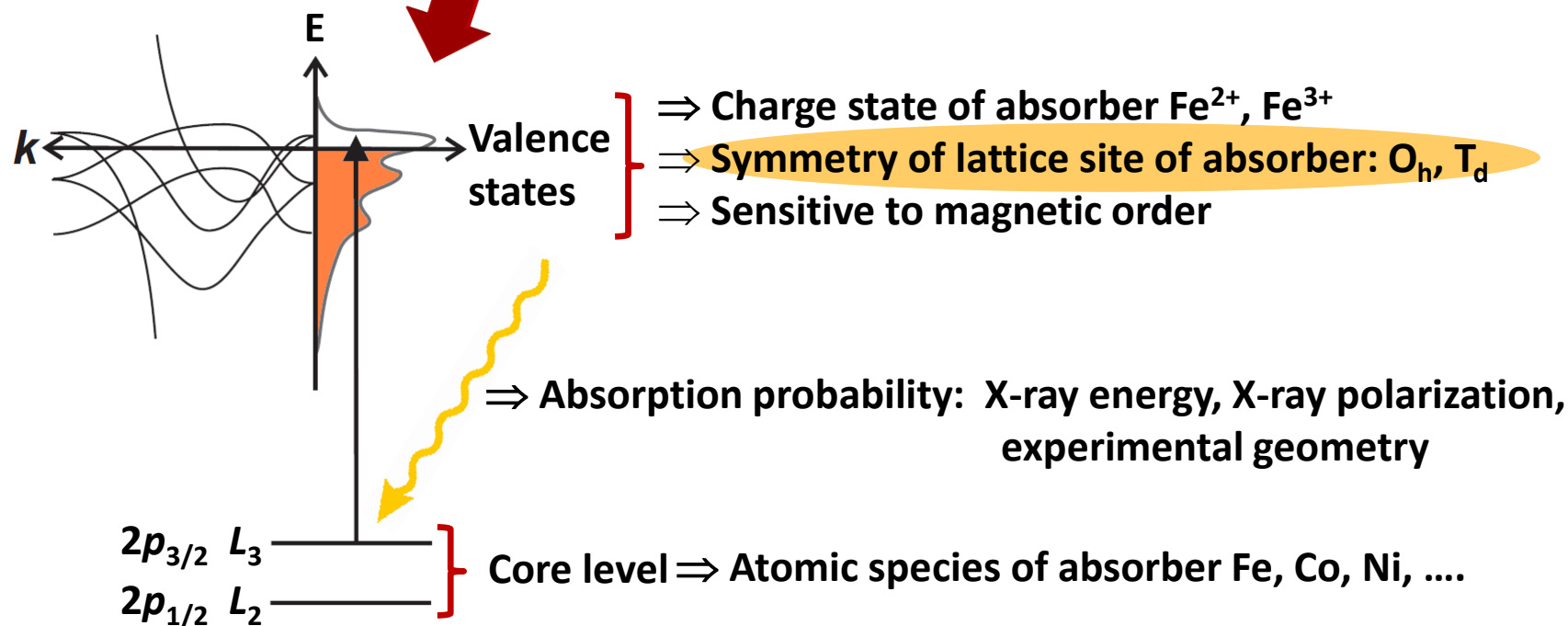
J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

X-Ray Absorption – Fundamentals

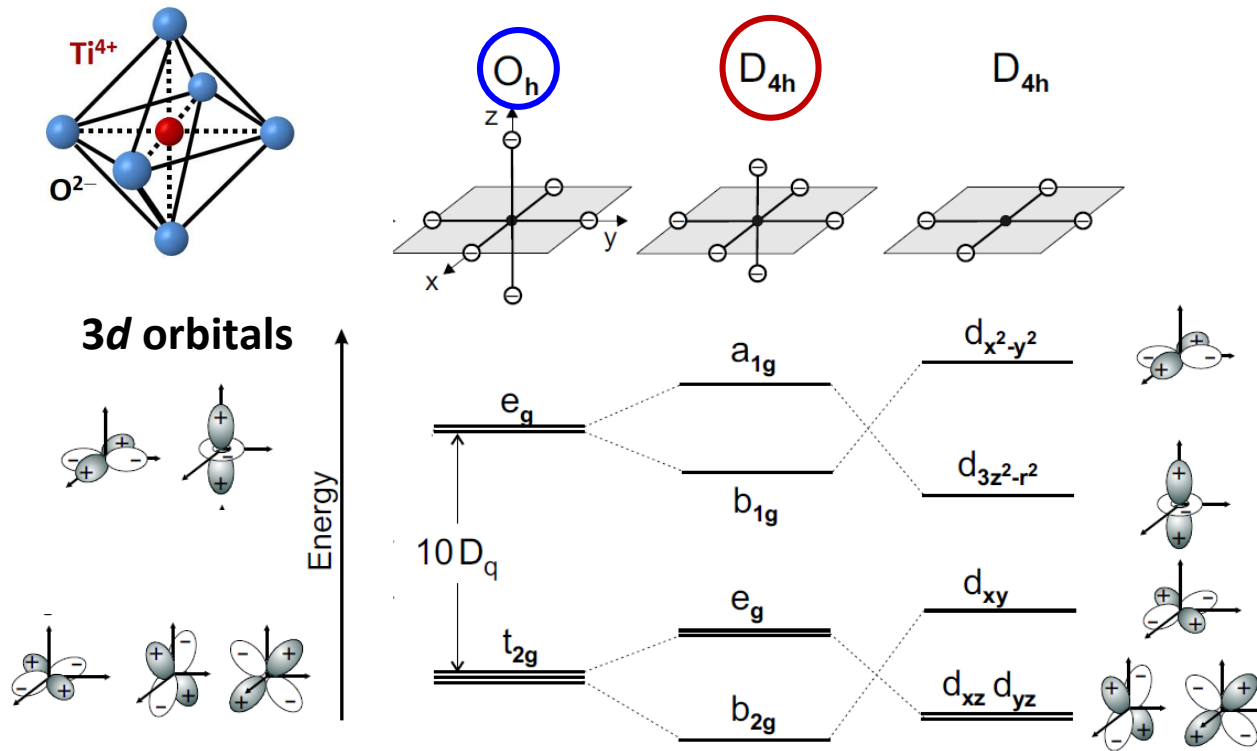


Experimental Concept:

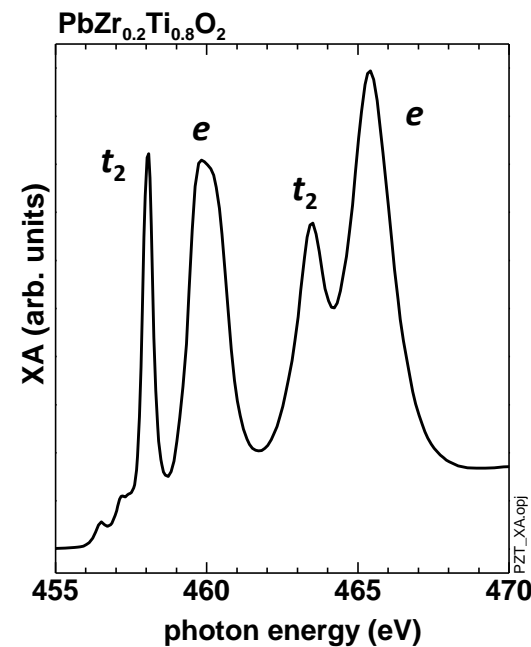
Monitor reduction in X-ray flux transmitted through sample as function of photon energy



Sensitivity To Site Symmetry: $\text{Ti}^{4+} L_{3,2}$



J. Stöhr, H.C. Siegmann,
Magnetism (Springer)



+ Electric dipole transitions: $d^0 \rightarrow 2p^5 3d^1$

+ Crystal field splitting $10Dq$ acting on 3d orbitals:

Octahedral symmetry:

e orbitals towards ligands \rightarrow higher energy

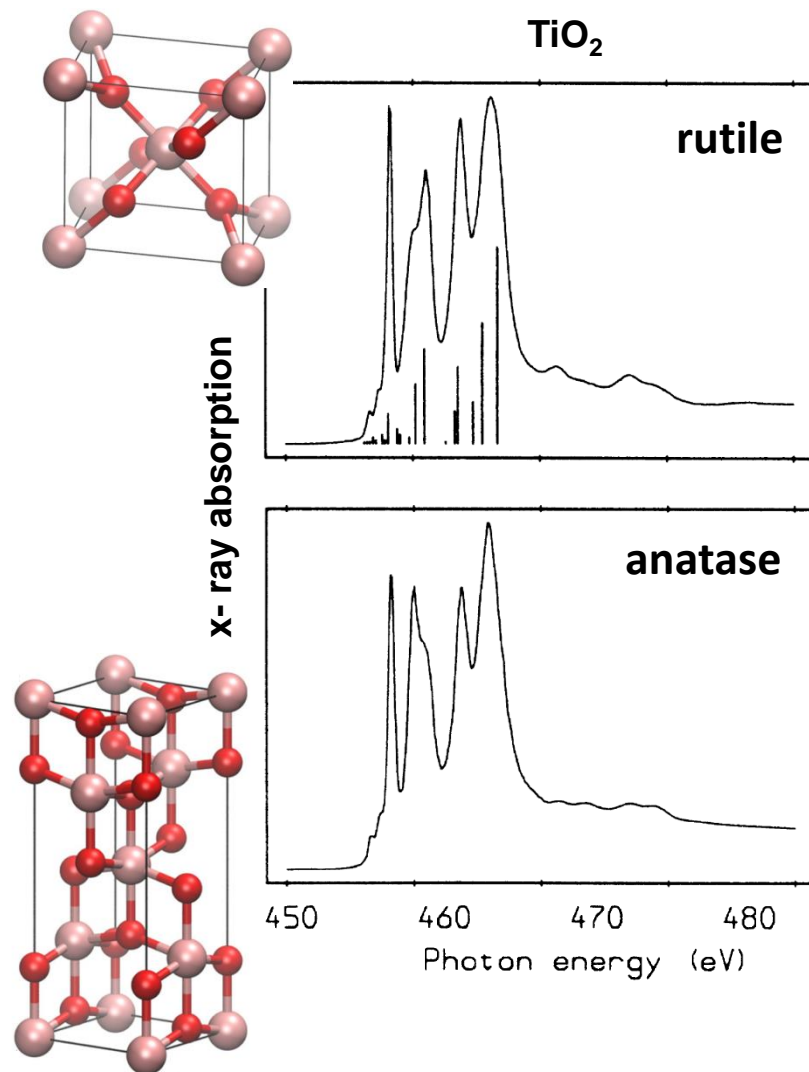
t_2 orbitals between ligands \rightarrow lower energy

Tetragonal symmetry:

e orbitals $\rightarrow b_2 = d_{xy}, e = d_{yz}, d_{yz}$

t_2 orbitals $\rightarrow b_1 = d_{x^2-y^2}, a_1 = d_{3z^2-r^2}$

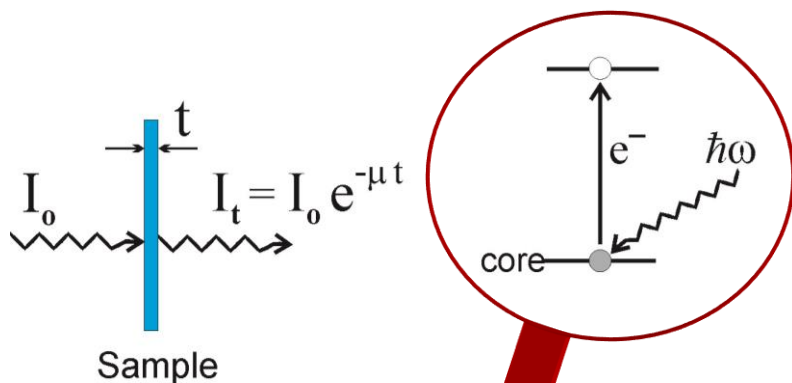
X-Ray Absorption – Lattice Symmetry



Influence of lattice site symmetry at the absorber

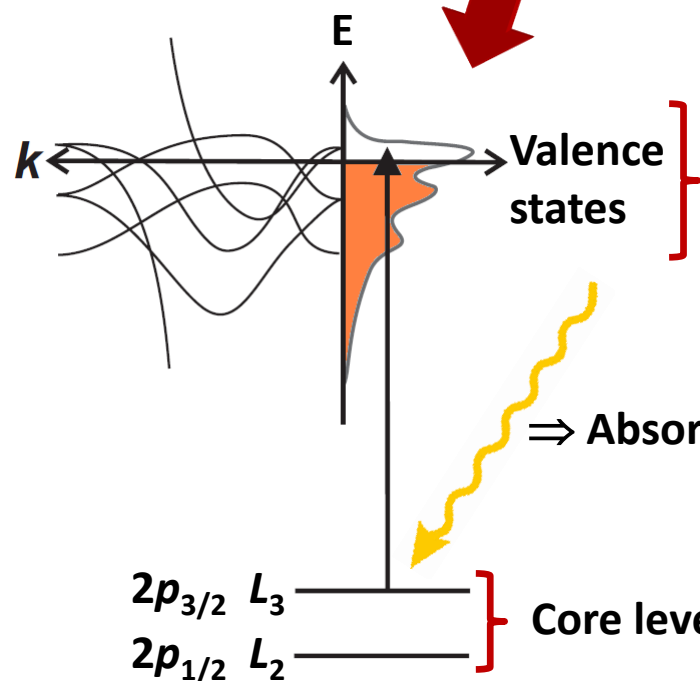
G. Van der Laan
Phys. Rev. B 41, 12366 (1990)

X-Ray Absorption – Fundamentals



Experimental Concept:

Monitor reduction in X-ray flux transmitted through sample as function of photon energy

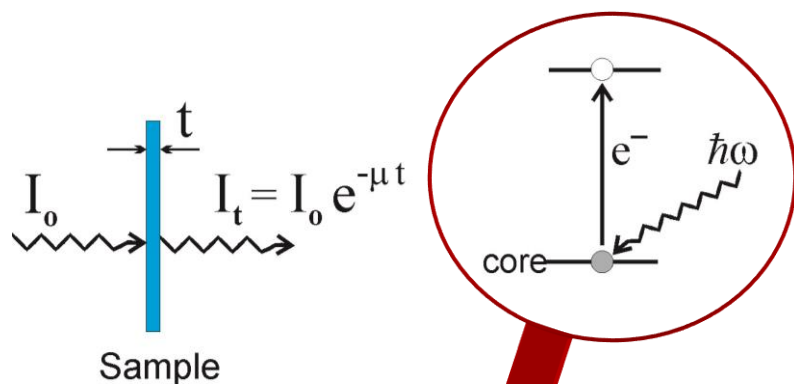


- ⇒ Charge state of absorber Fe^{2+} , Fe^{3+}
- ⇒ Symmetry of lattice site of absorber: O_h , T_d
- ⇒ Sensitive to magnetic order

⇒ Absorption probability: X-ray energy, X-ray polarization, experimental geometry

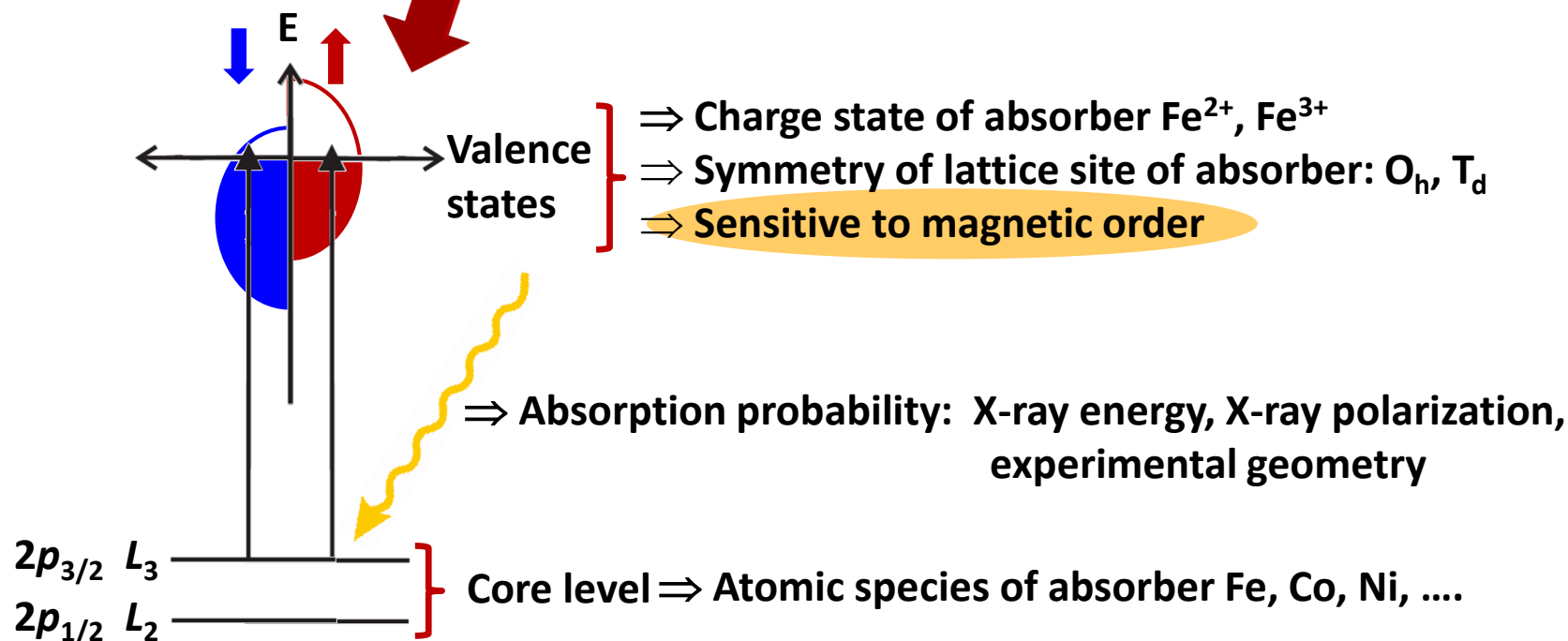
$2p_{3/2}$ L_3
 $2p_{1/2}$ L_2 } Core level ⇒ Atomic species of absorber Fe, Co, Ni,

X-Ray Absorption – Fundamentals

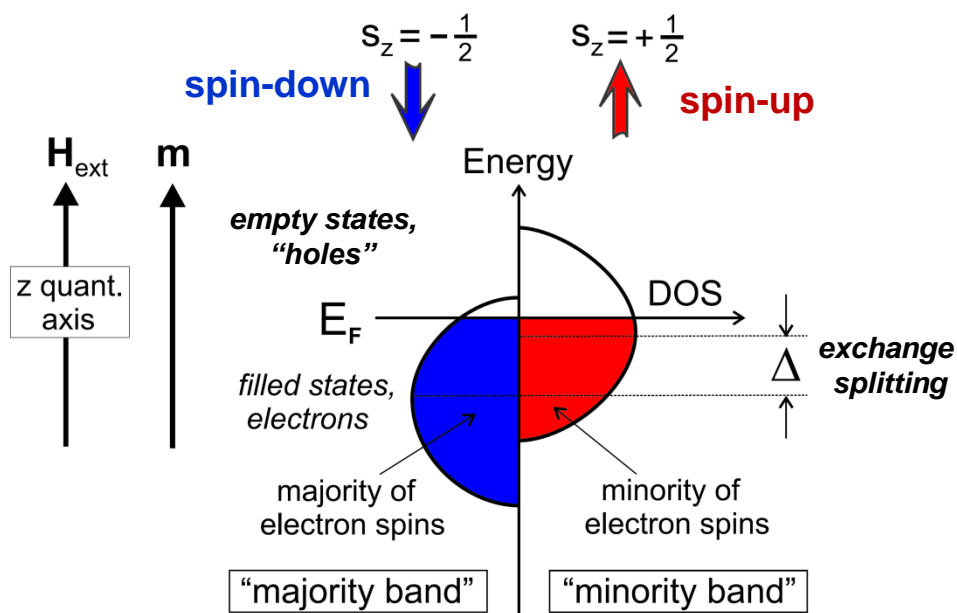


Experimental Concept:

Monitor reduction in X-ray flux transmitted through sample as function of photon energy



Stoner Model For Ferromagnetic Metals



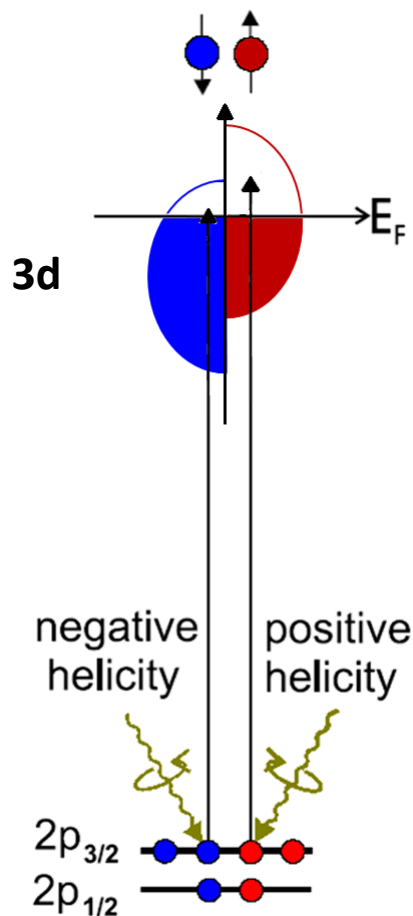
J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

3d shell

- + Magnetic moments in Fe, Co, Ni well described by Stoner model: *d*-bands containing up and down spins shifted relative to each other by exchange splitting
- + Spin-up and spin-down bands filled according to Fermi statistics
- + Magnetic moment $|m|$ determined by difference in number of electrons in majority and minority bands

$$|m| \propto \mu_B (n_e^{\text{maj}} - n_e^{\text{min}})$$

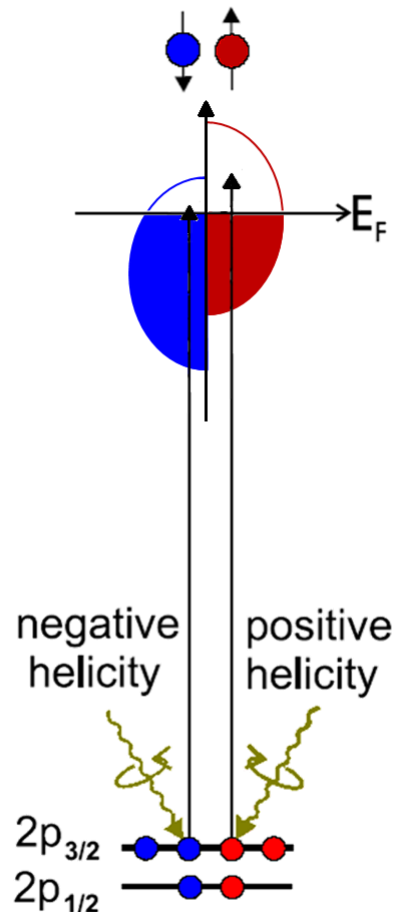
Origin of X-ray Magnetic Circular Dichroism



2-Step Model for photoexcitation of electrons from $2p_{3/2}$, $2p_{1/2}$ to $3d$ states by absorption of circularly polarized X rays:

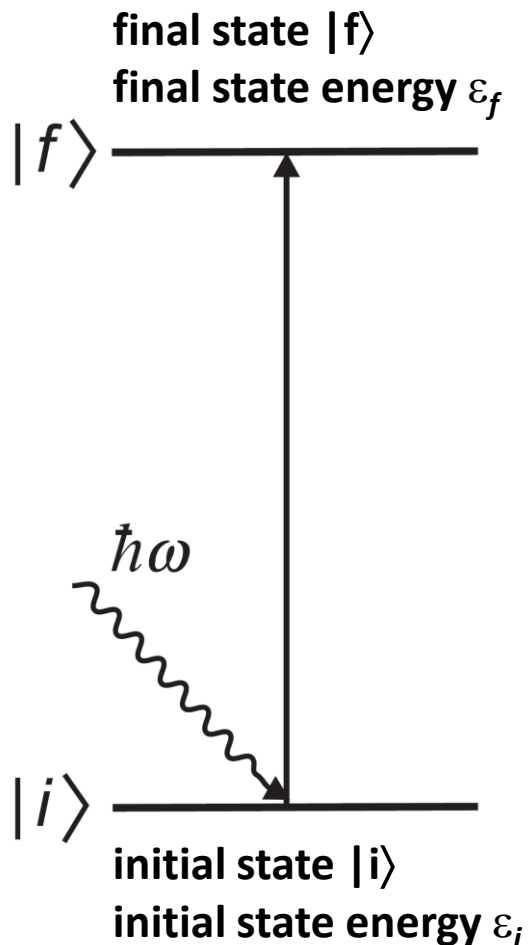
- + Transfer of angular momentum of incident circular polarized X rays to excited electrons (angular momentum conservation, selection rules)
- + Spin polarization of excited electrons opposite for incident X rays with opposite helicity.
- + Unequal spin-up and spin-down populations in exchange split valence shell acts as detector for spin of excited electrons.

Origin of X-ray Magnetic Circular Dichroism



- + Calculate transition probabilities from filled $2p_{3/2}$ and $2p_{1/2}$ states to empty states in d -band for circularly polarized X rays using **Fermi's Golden Rule**

Origin of X-ray Magnetic Circular Dichroism



- + Wave functions describe electronic and photon states
Energies include electronic and photon energies
- + Calculate transitions probabilities T_{if}
considering photon as time-dependent perturbation,
i.e. an electromagnetic (EM) field

Fermi's Golden Rule

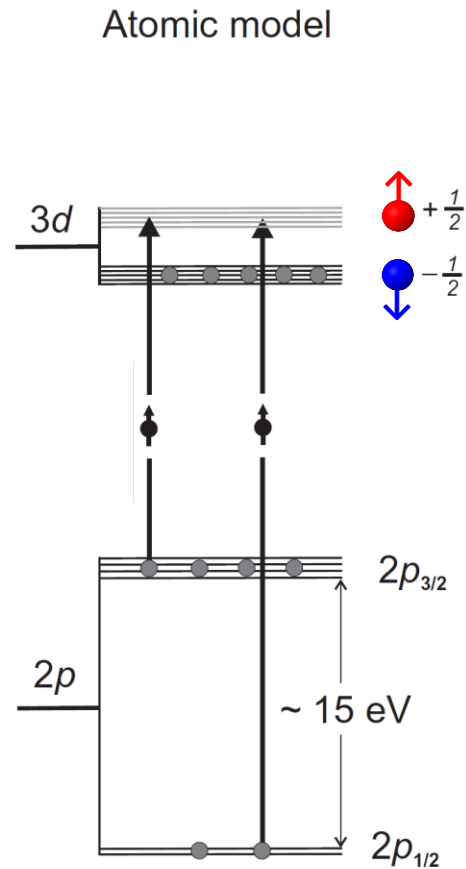
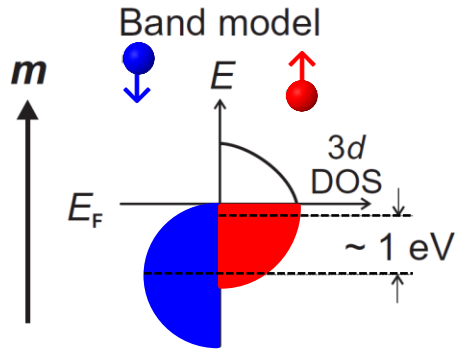
$$T_{if} = \frac{2\pi}{\hbar} \left| \langle f | \mathcal{H}_{\text{int}} | i \rangle \right|^2 \delta(\varepsilon_i - \varepsilon_f) \rho(\varepsilon_f)$$

$\rho(\varepsilon_f)$ = density of final states per unit energy

T_{if} Dimension [time⁻¹]

$$\mathcal{H}_{\text{int}} = \frac{e}{m_e} \mathbf{p} \cdot \mathbf{A}$$

Origin of X-ray Magnetic Circular Dichroism

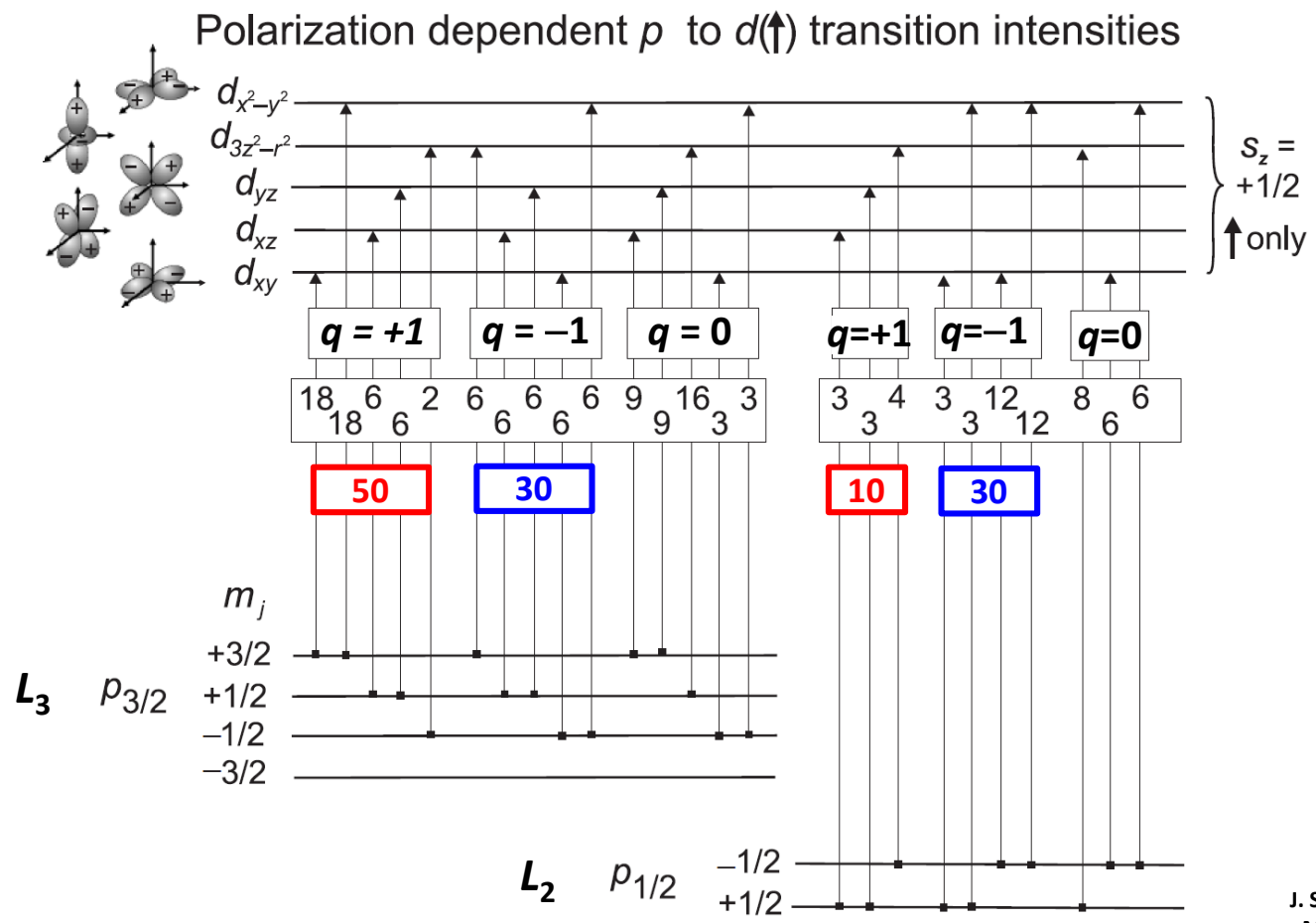


X-ray absorption of circularly polarized photons with angular momentum $q = \pm 1$ in units of \hbar

- + Consider strong ferromagnet with one filled spin band:**
 - All spin down d states filled
 - Spin up d states partially filled
- + This specific case:**
 - Only spin up electron excited

J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

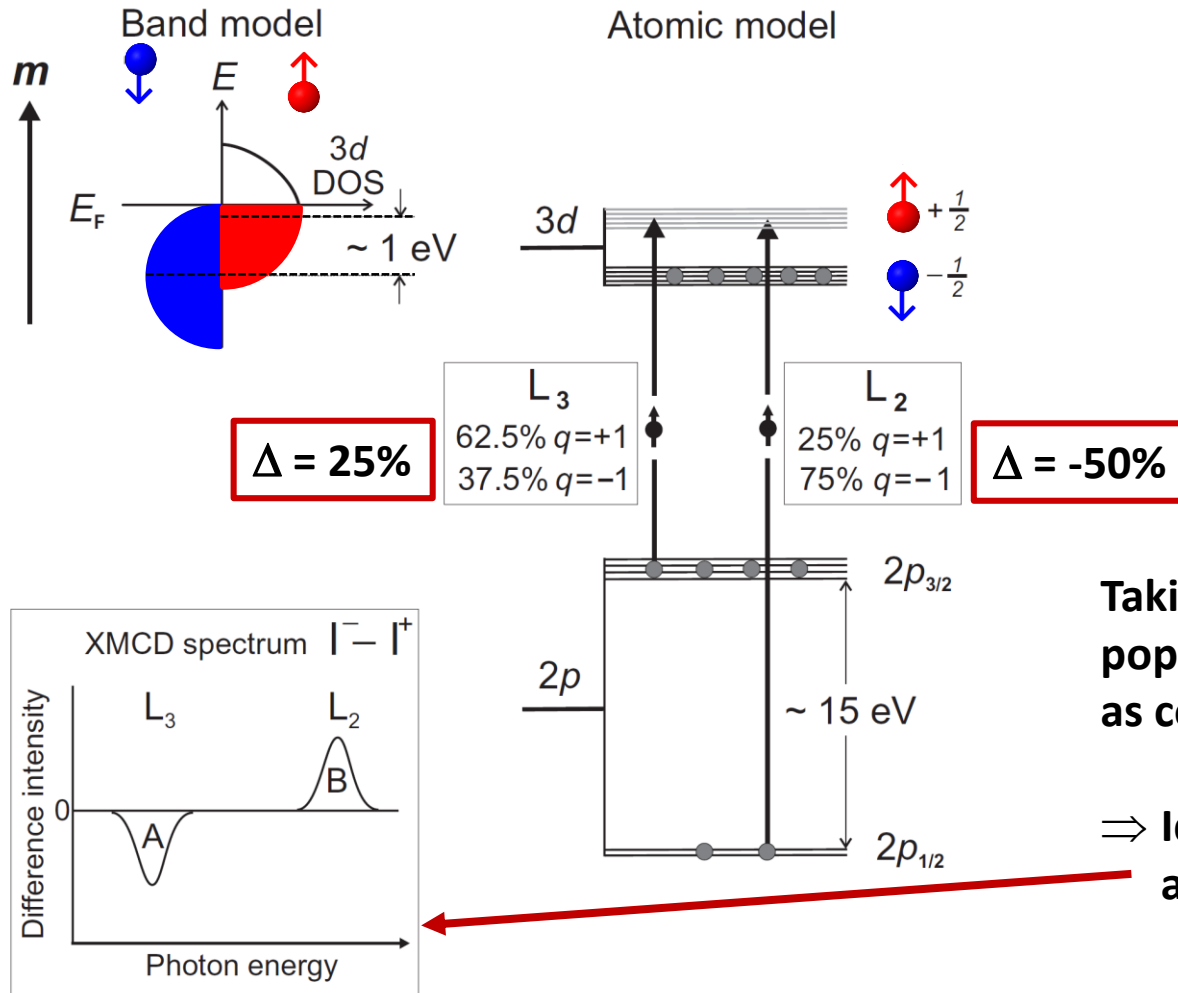
Origin of X-ray Magnetic Circular Dichroism



J. Stöhr, H.C. Siegmann, Magnetism (Springer)

- L_3 : X rays with $q = +/-1$ excite 62.5%/37.5% of the spin up electrons
- L_2 : X rays with $q = +/-1$ excite 25%/75% of the spin up electrons

Origin of X-ray Magnetic Circular Dichroism

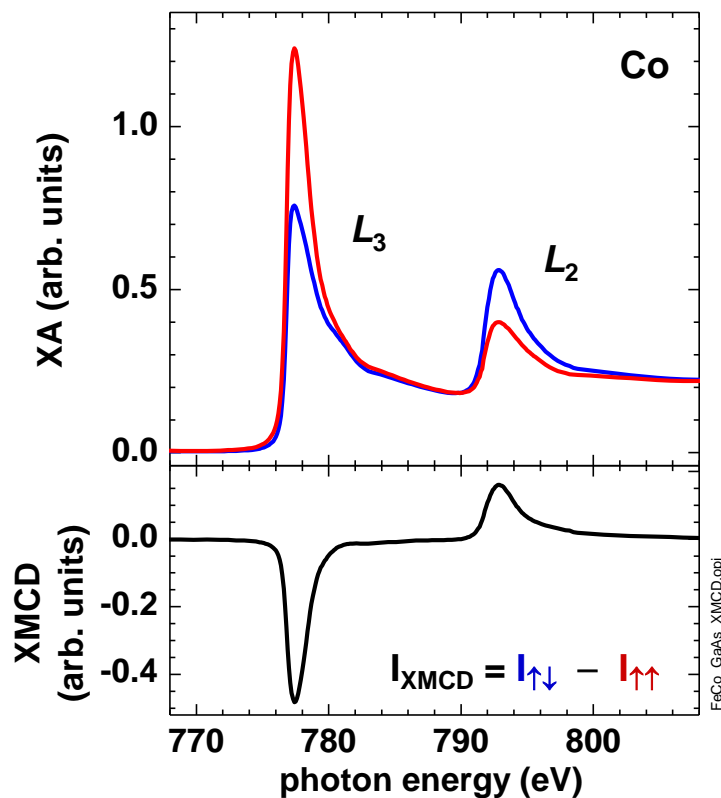
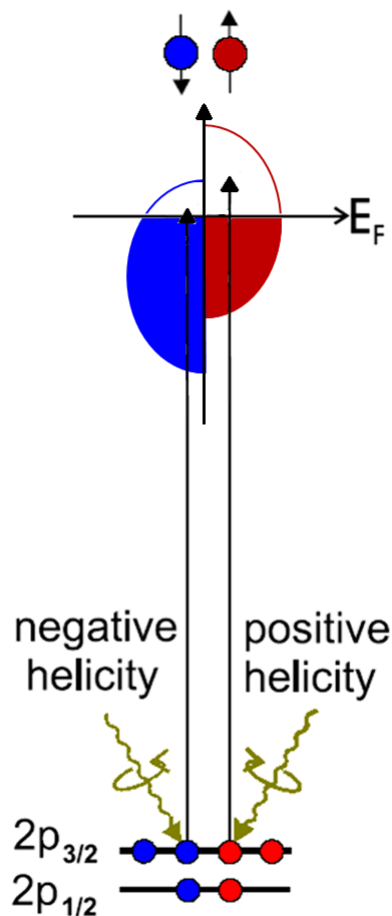


Taking into account 2x higher population of $2p_{3/2}$ state as compared to $2p_{1/2}$ state:

⇒ Identical magnitude XMCD at L₃ and L₂ with opposite sign

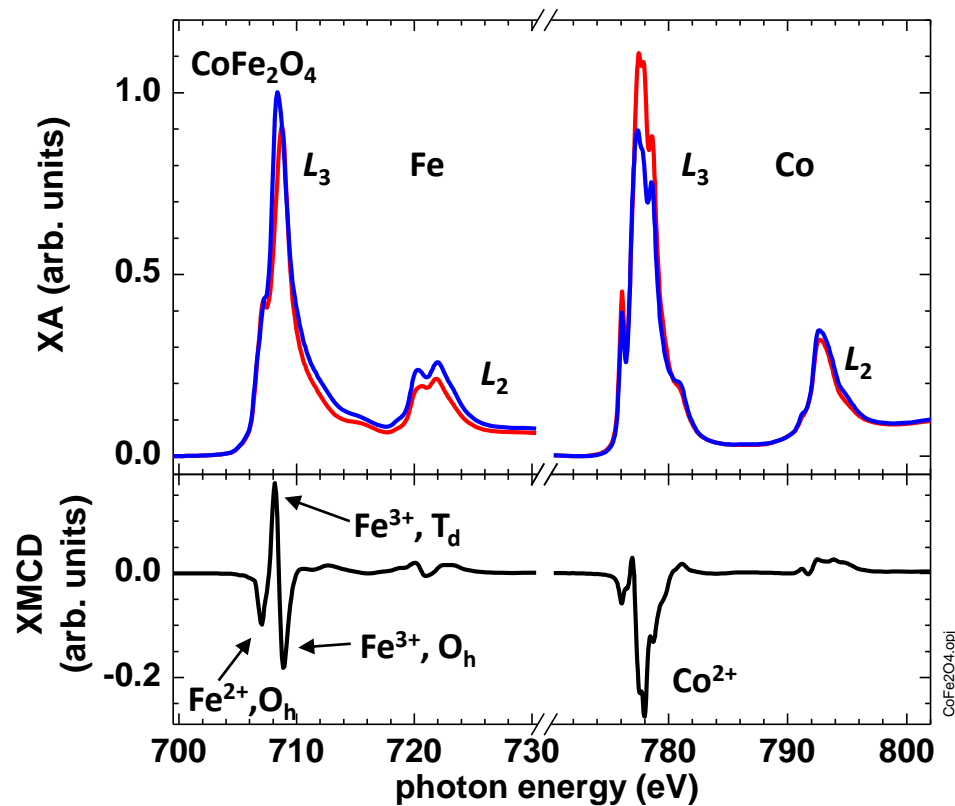
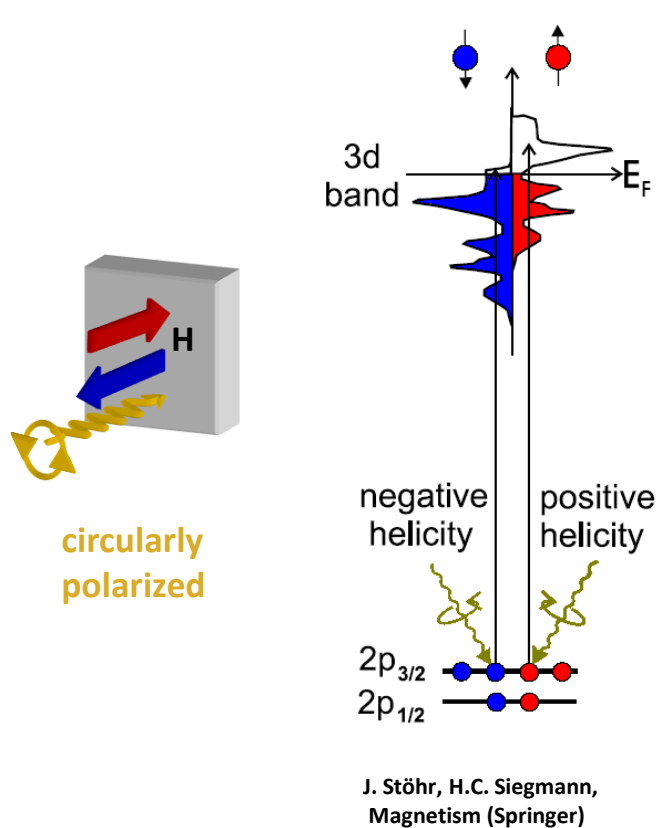
J. Stöhr, H.C. Siegmann, Magnetism (Springer)

X-Ray Magnetic Circular Dichroism (XMCD)



- Magnitude of XMCD depends on
- + expectation value of $3d$ magnetic moment
 - + degree of circular photon polarization, P_{circ}
 - + geometry

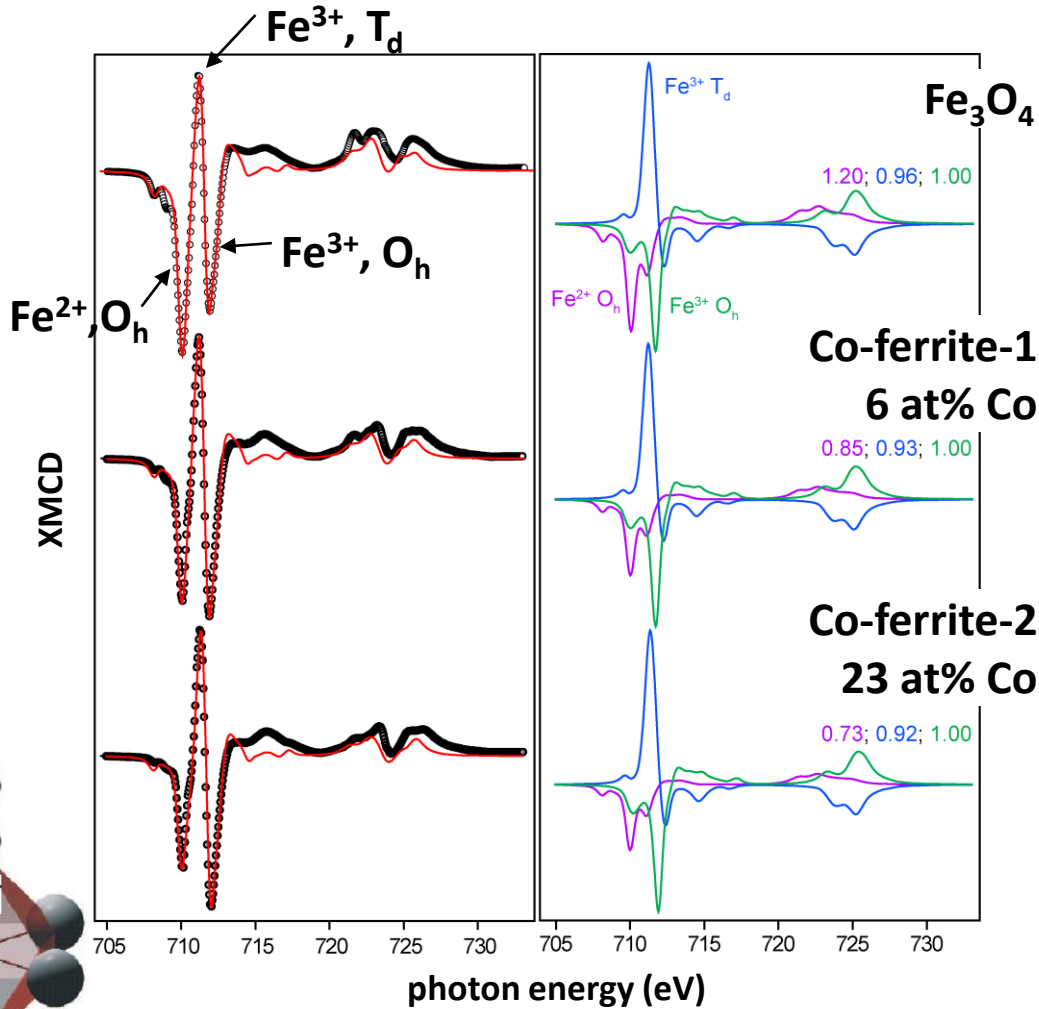
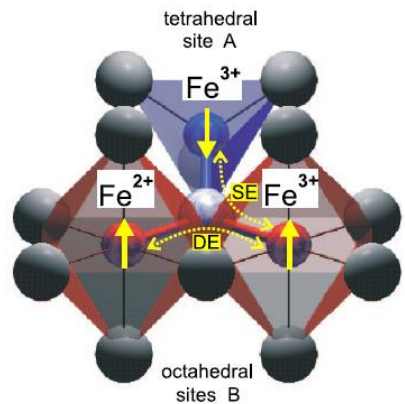
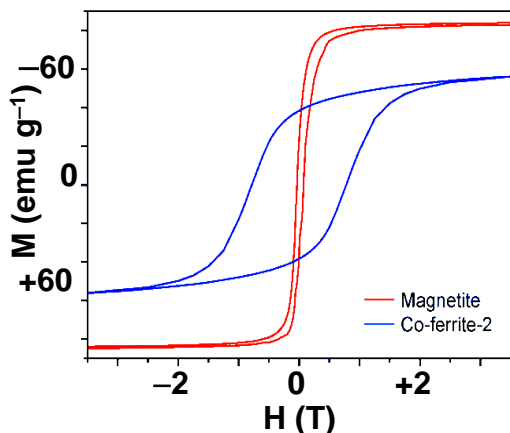
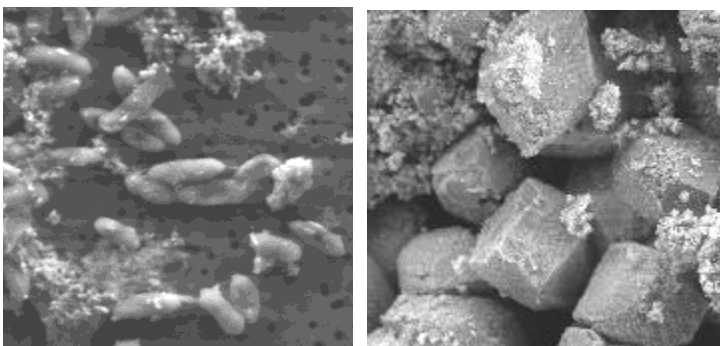
X-Ray Magnetic Circular Dichroism (XMCD)



- + XMCD provides magnetic information resolving
 - elements Fe, Co, ...
 - valence states: Fe²⁺, Fe³⁺, ...
 - lattice sites: octahedral, O_h, tetrahedral, T_d,

Magnetic Bionanospinels

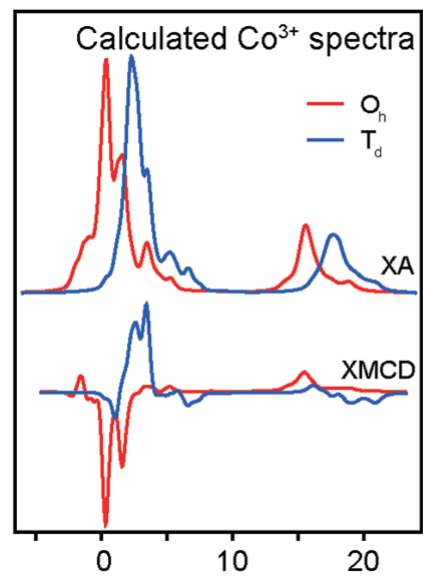
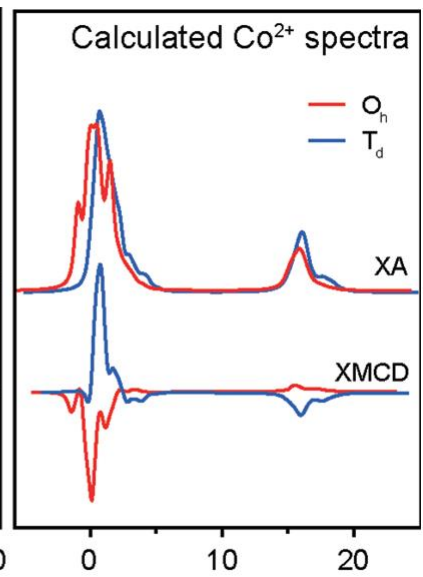
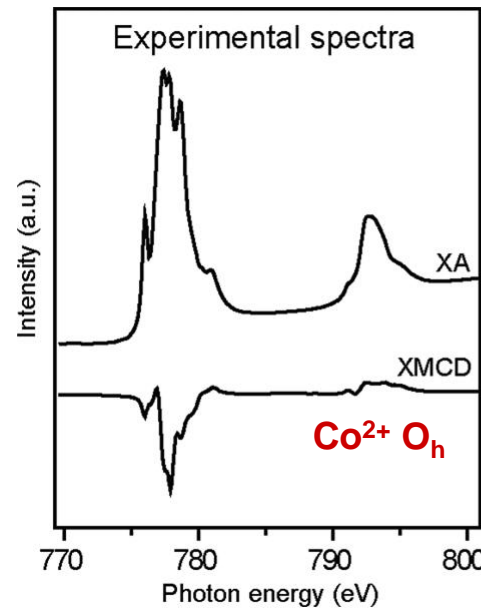
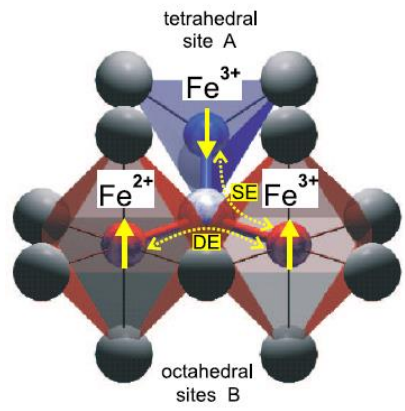
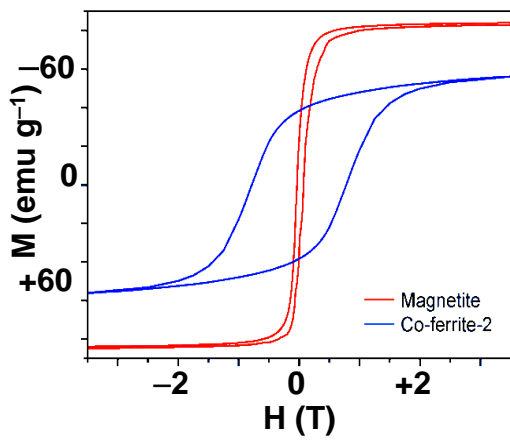
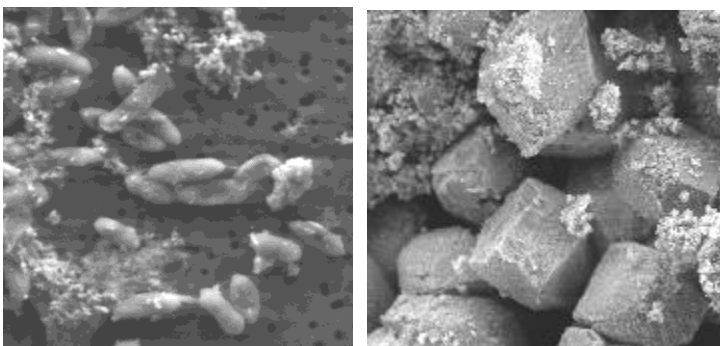
+ *Geobacter sulfurreducens* bacteria form magnetite nanocrystals (15nm) via extracellular reduction of amorphous Fe(III)-bearing minerals



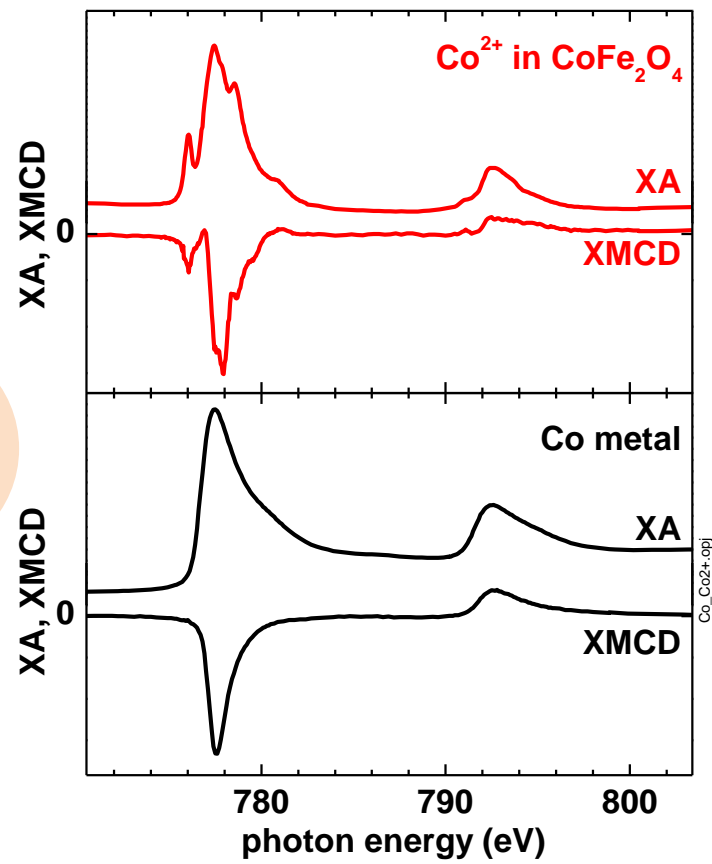
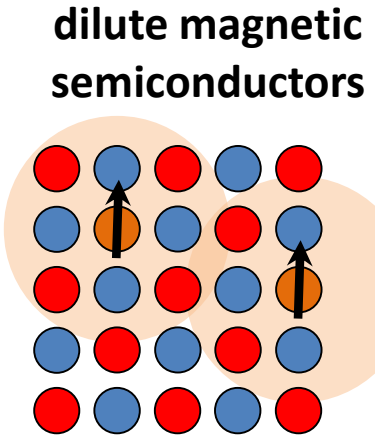
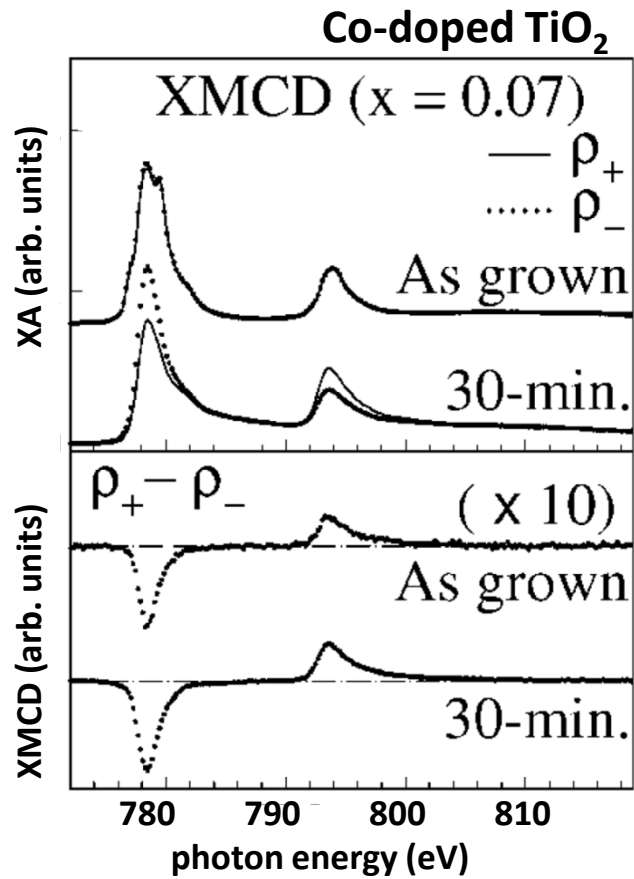
V. Cocker *et al.*,
Eur. J. Mineral. **19**, 707–716 (2007)

Magnetic Bionanospinels

+ **Geobacter sulfurreducens** bacteria form magnetite nanocrystals (15nm) via extracellular reduction of amorphous Fe(III)-bearing minerals



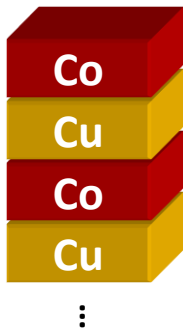
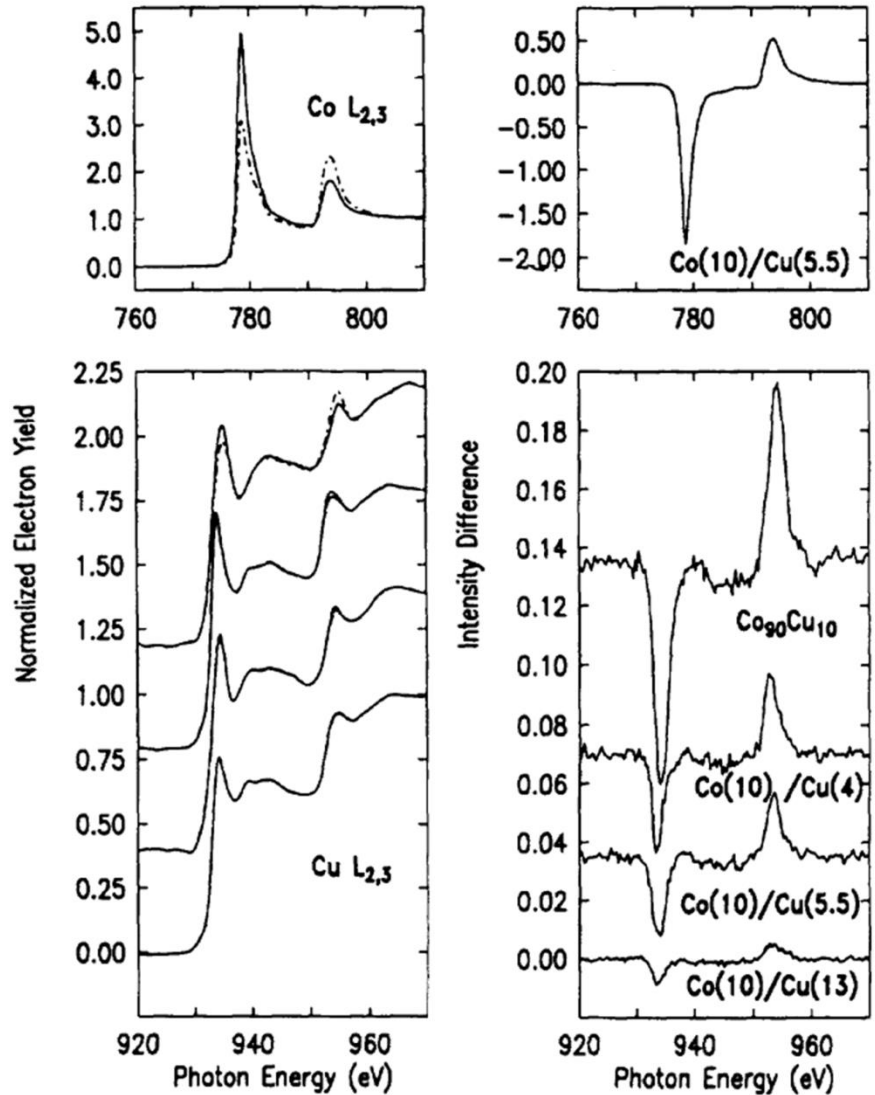
Co-doped TiO₂



J.-Y. Kim *et al.*,
 Phys. Rev. Lett. **90**, 017401 (2003)

+ Comparing XMCD spectra with model compounds and/or calculations
⇒ Identifying magnetic phases

Induced Moments At Co/Cu Interfaces

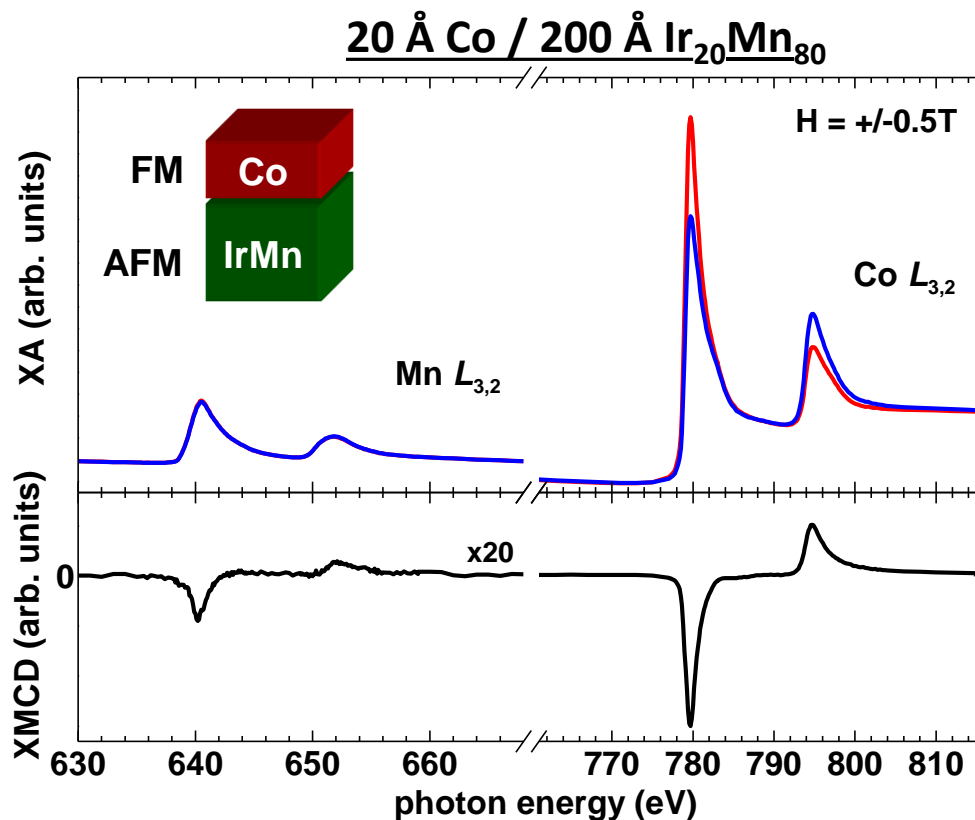


+ The element-specificity makes XMCD measurements an ideal tool to determine induced moments at interfaces between magnetic and non-magnetic elements.

M. G. Samant *et al.*,
Phys. Rev. Lett. 72, 1112 (1994)

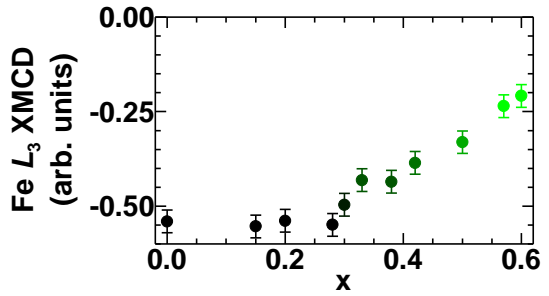
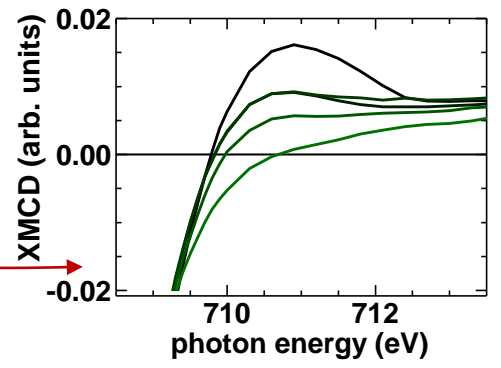
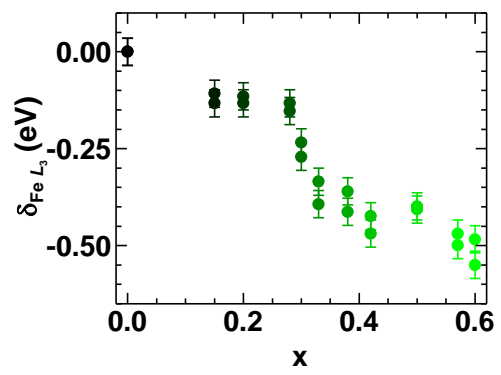
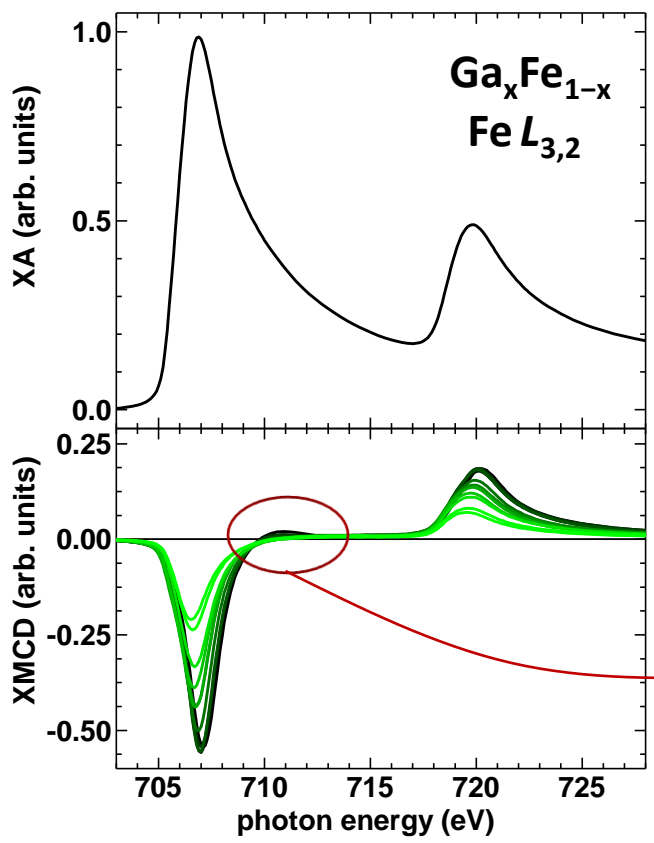
Magnetic Interfaces

- + Weak Mn XMCD signal
- ⇒ Uncompensated Mn at Co/IrMn interface
- + Same sign of XMCD signal for Co and Mn
- ⇒ Parallel coupling of Co and Mn moments
- + Nominal thickness of uncompensated interface moments: $(0.5 \pm 0.1)ML$

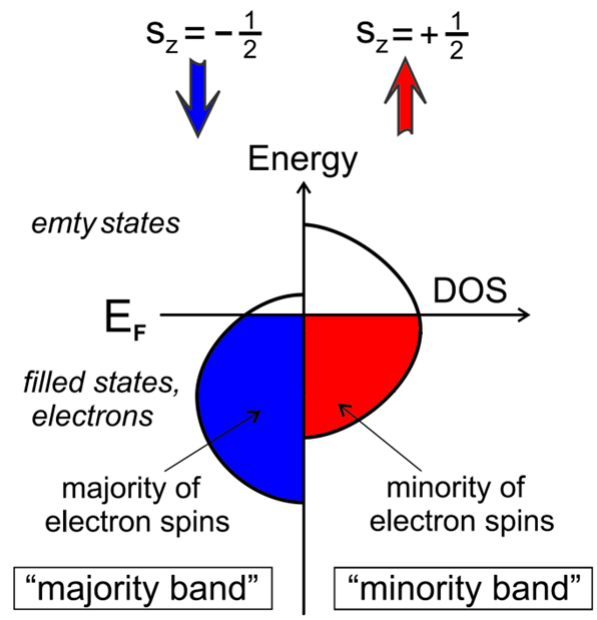


H. Ohldag *et al.*,
Phys. Rev. Lett. **91**, 017203 (2003)

Band Filling In $\text{Ga}_x\text{Fe}_{1-x}$



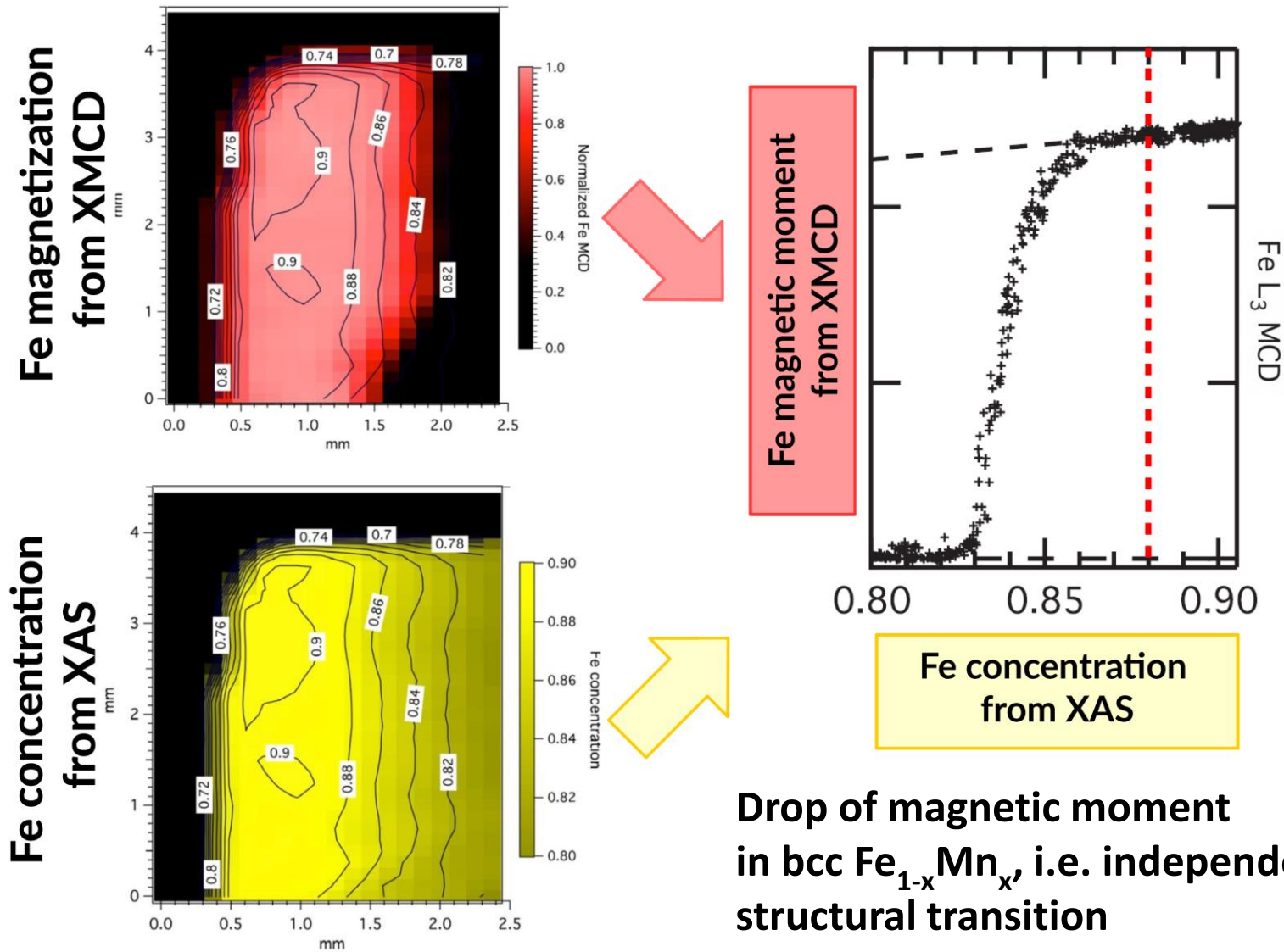
E. Arenholz *et al.*,
Phys. Rev. B **82**, 180405 (2010)



J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

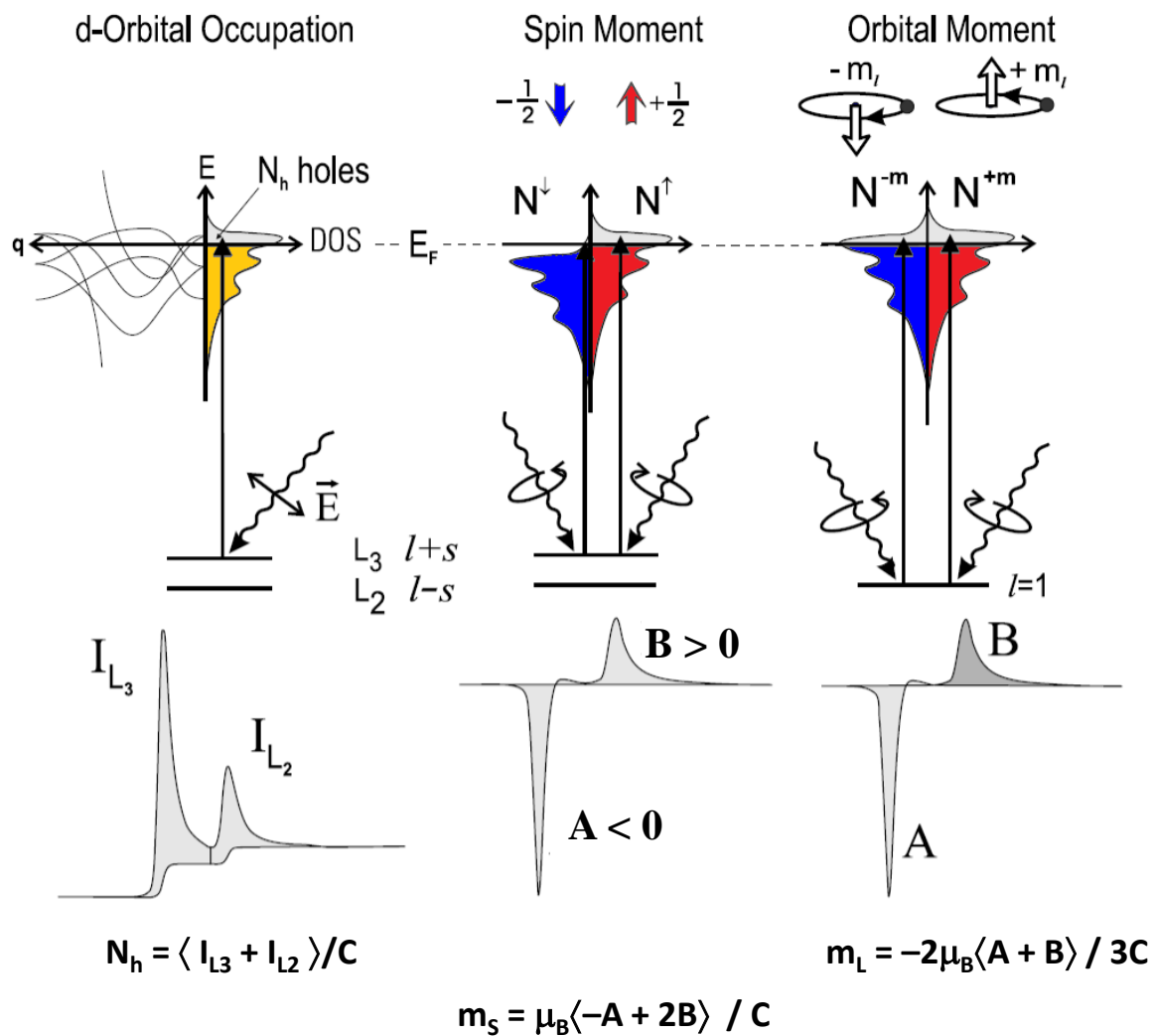
- + Fe majority-spin filled for $x=0.3$
- + $x > 0.3$: Fe moment decrease strongly, Formation of D03 precipitates

Composition Dependence of Fe moment in $\text{Fe}_{1-x}\text{Mn}_x$



Drop of magnetic moment in bcc $\text{Fe}_{1-x}\text{Mn}_x$, i.e. independent of structural transition

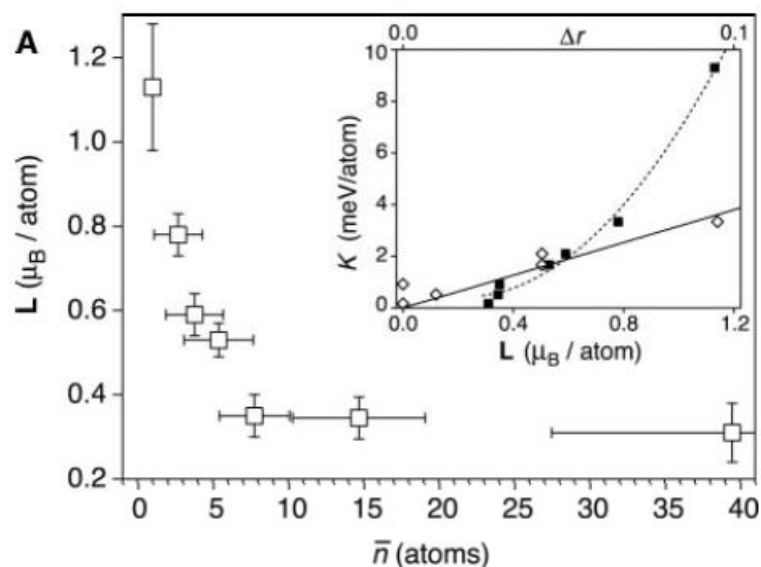
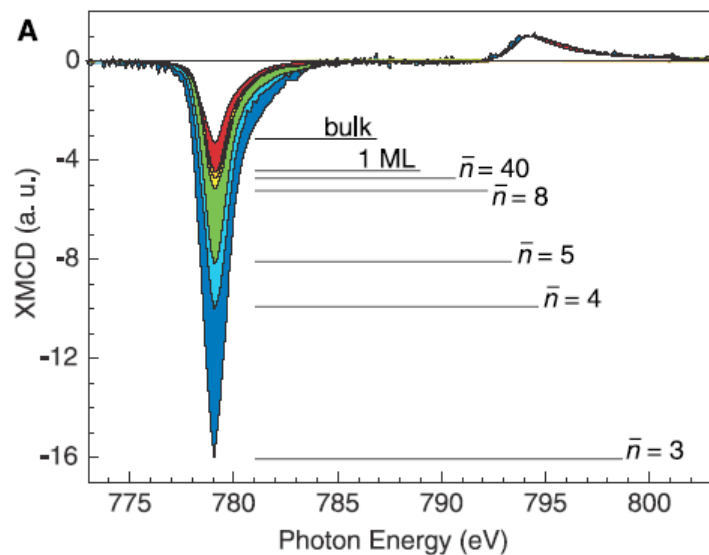
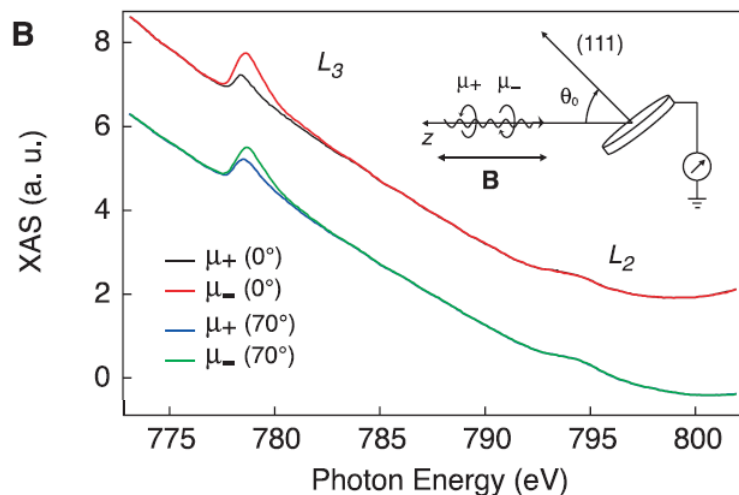
Sum Rules



+ Theoretically derived sum rules correlate XMCD spectra with spin and orbital moment providing unique tool for studying magnetic materials.

J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

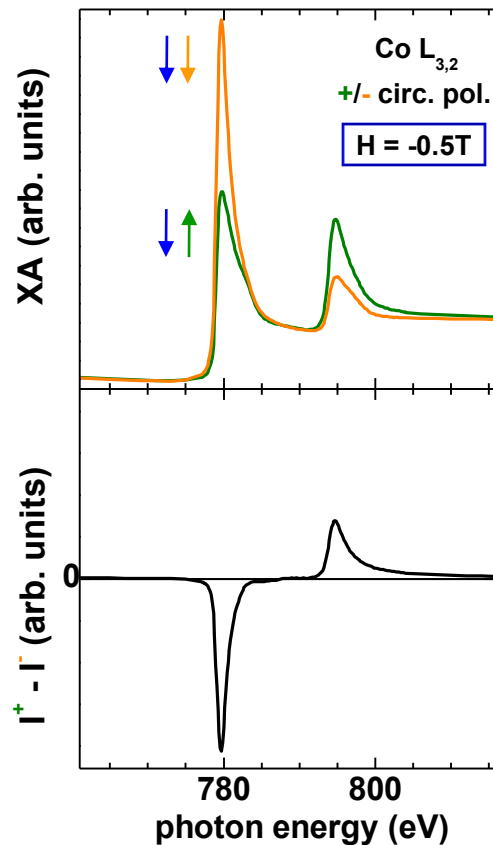
Orbital Moment Of Co Nanoparticles



- + Strong variation of orbital and spin magnetic moment observable as change in relative L_3 and L_2 intensity in XMCD spectrum.
- + Co atoms and nanoparticles on Pt have enhanced orbital moments up to $1.1 \mu_B$

P. Gambardella *et al.*,
 Science **300**, 1130 (2003)

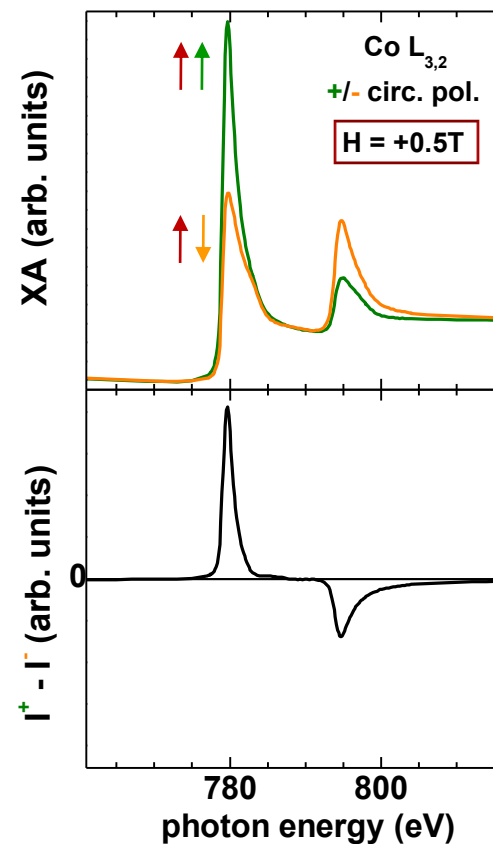
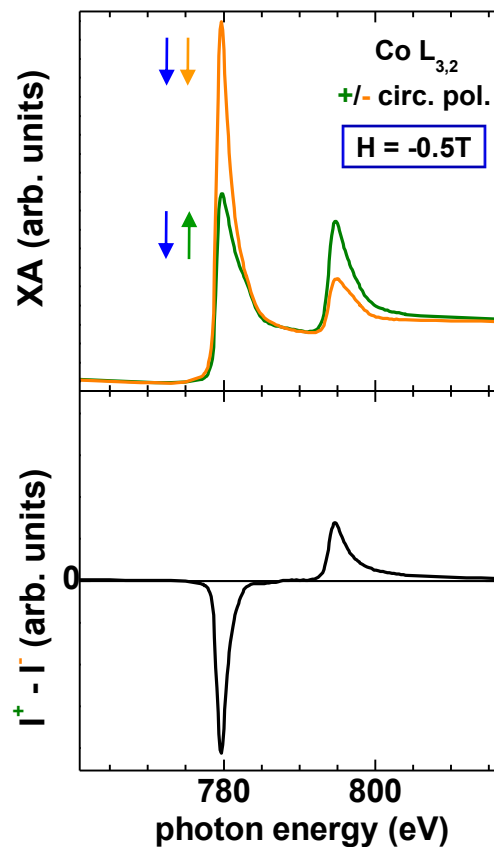
Element-specific Magnetization Reversal



+ Monitoring field dependence of XMCD

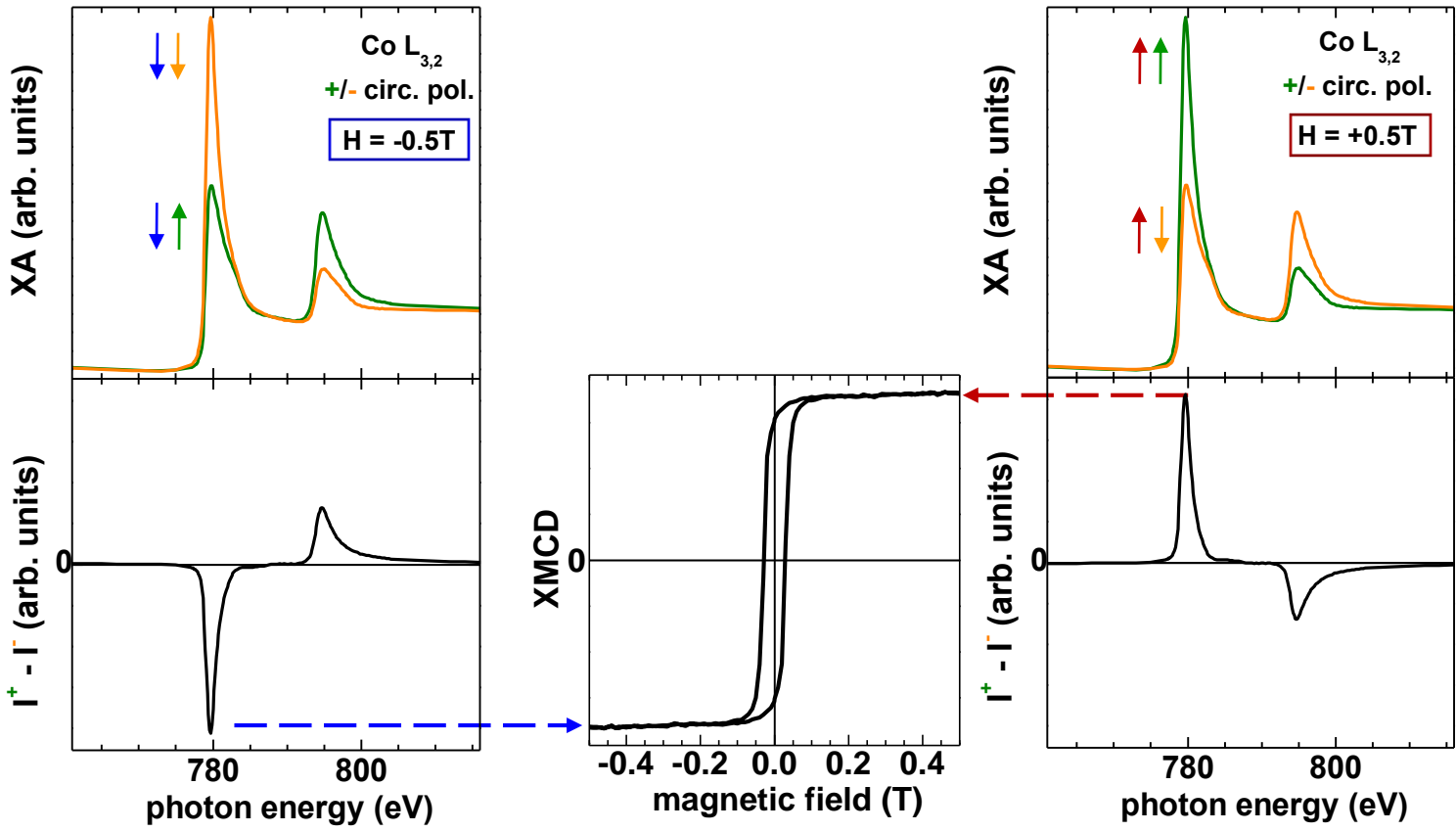
⇒ Element-specific information on magnetization reversal in complex magnetic nanostructures.

Element-specific Magnetization Reversal



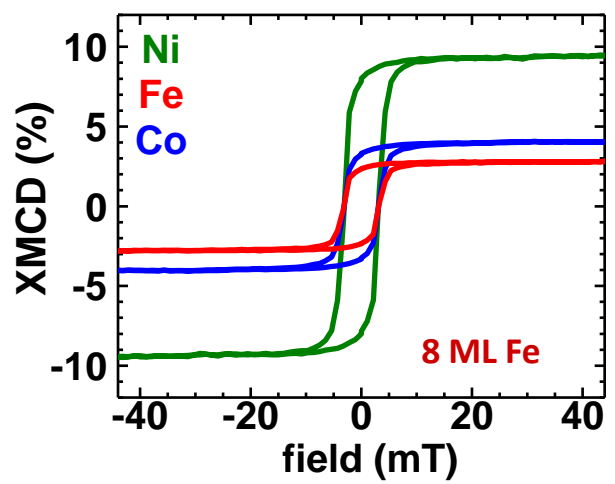
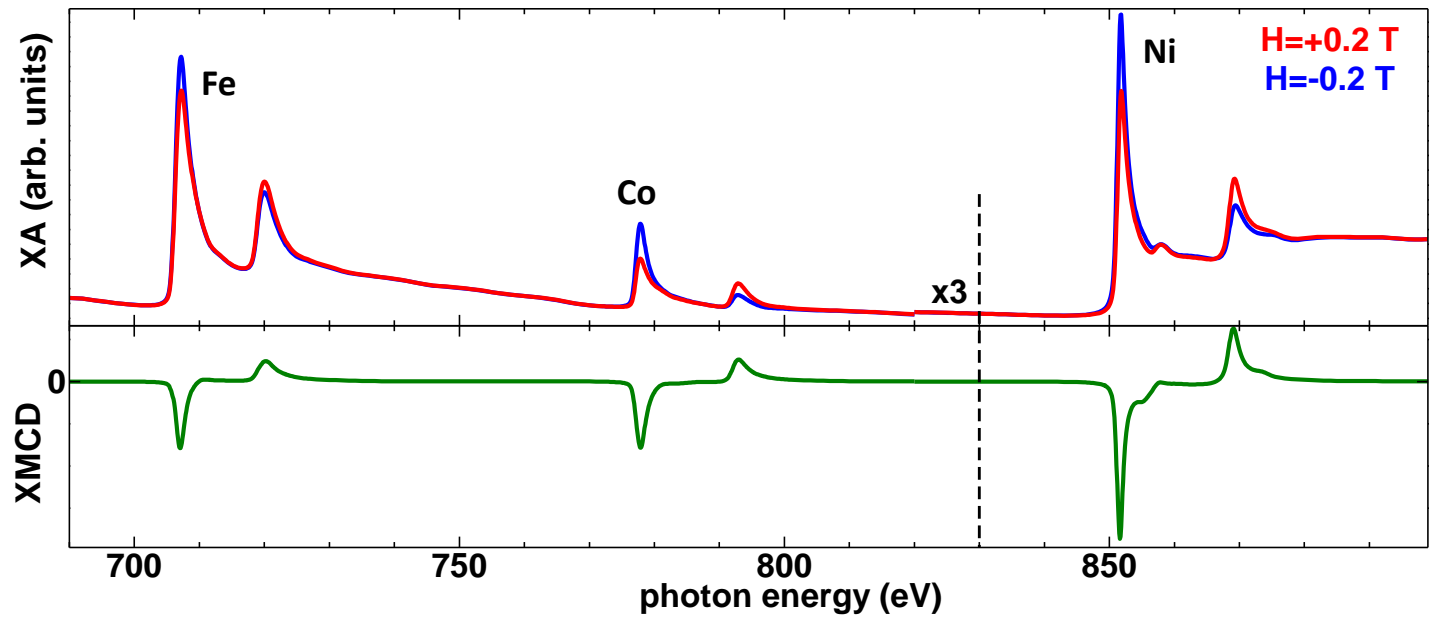
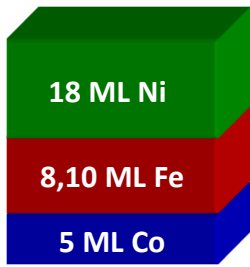
- + Monitoring field dependence of XMCD
- ⇒ Element-specific information on magnetization reversal in complex magnetic nanostructures.

Element-specific Magnetization Reversal

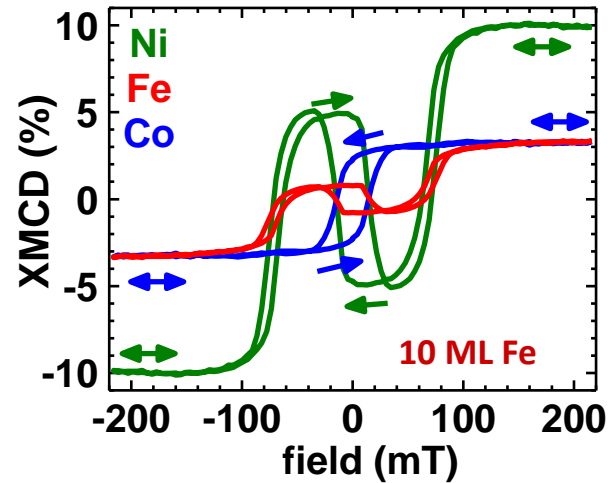
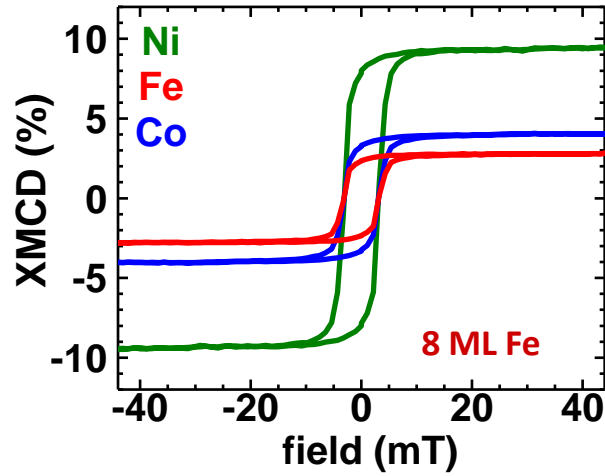
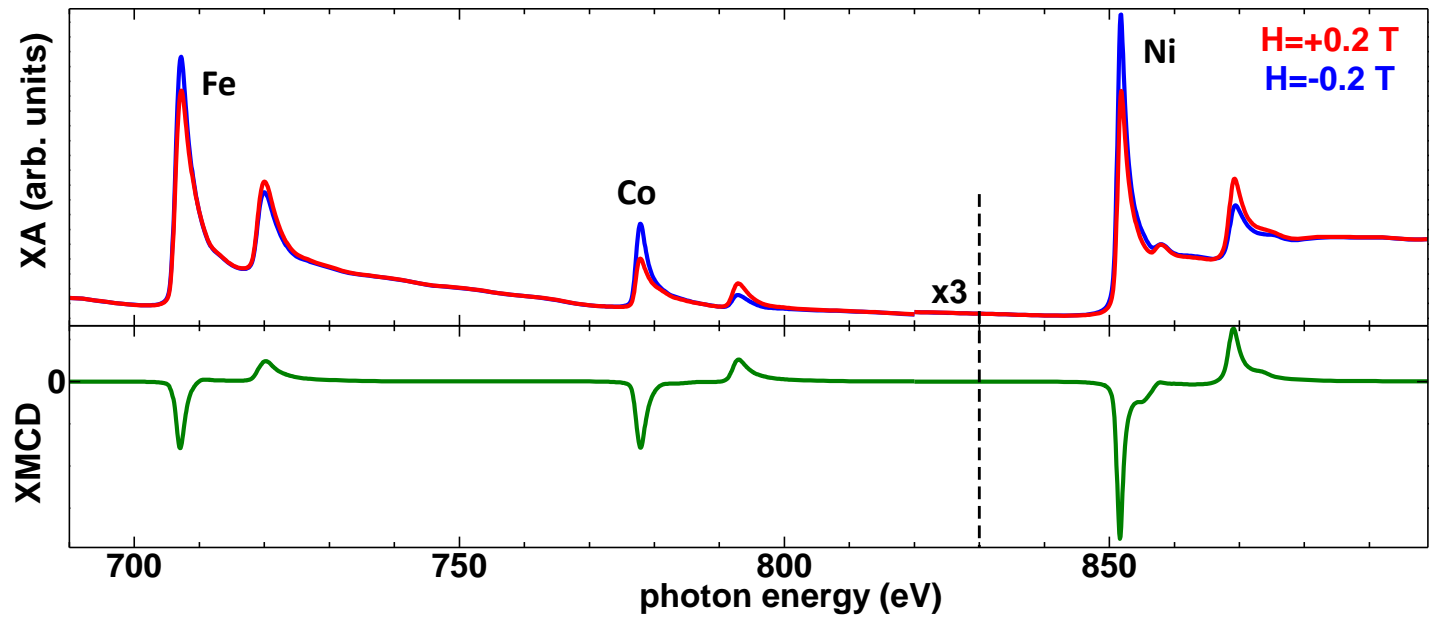
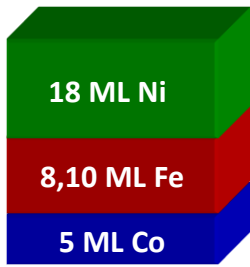


- + Monitoring field dependence of XMCD
- ⇒ Element-specific information on magnetization reversal in complex magnetic nanostructures.

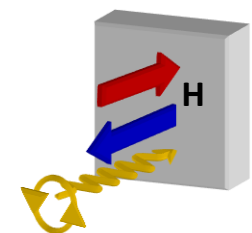
Element-specific Magnetization Reversal



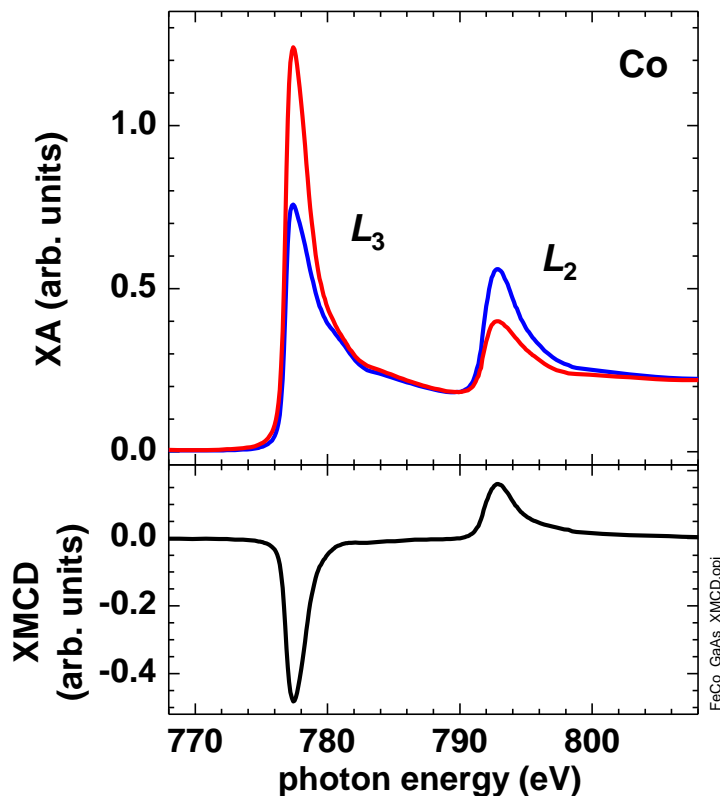
Element-specific Magnetization Reversal



X-Ray Ferromagnetic Resonance

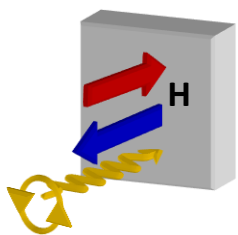


circularly polarized

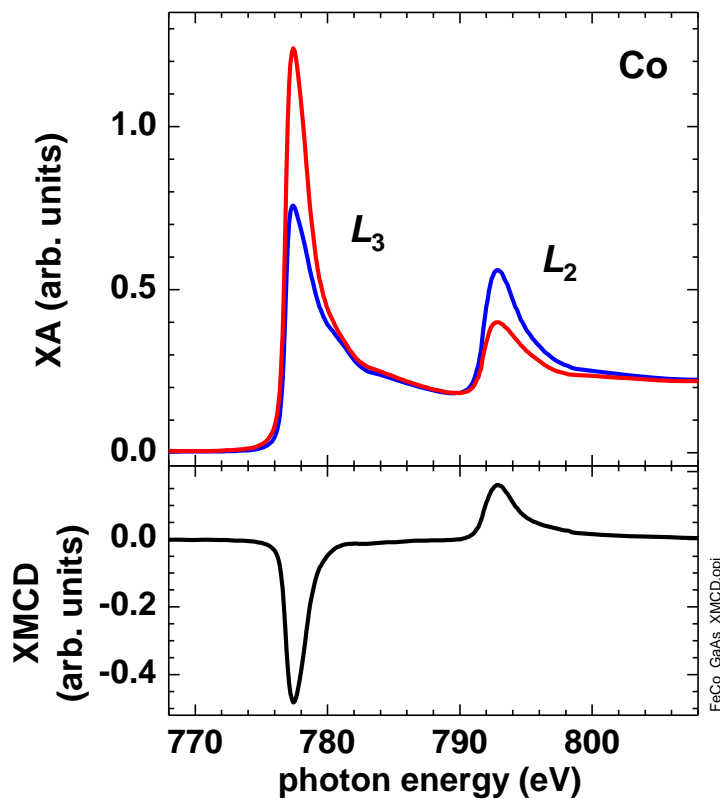


- + XMCD is the difference in X-ray absorption between antiparallel and parallel orientation of magnetic moment and photon spin.
- + The XMCD magnitude reflects the magnetic moment aligned parallel to the X ray beam.

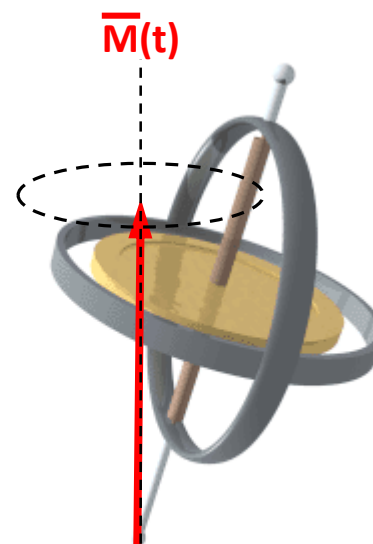
X-Ray Ferromagnetic Resonance



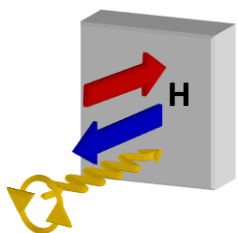
circularly polarized



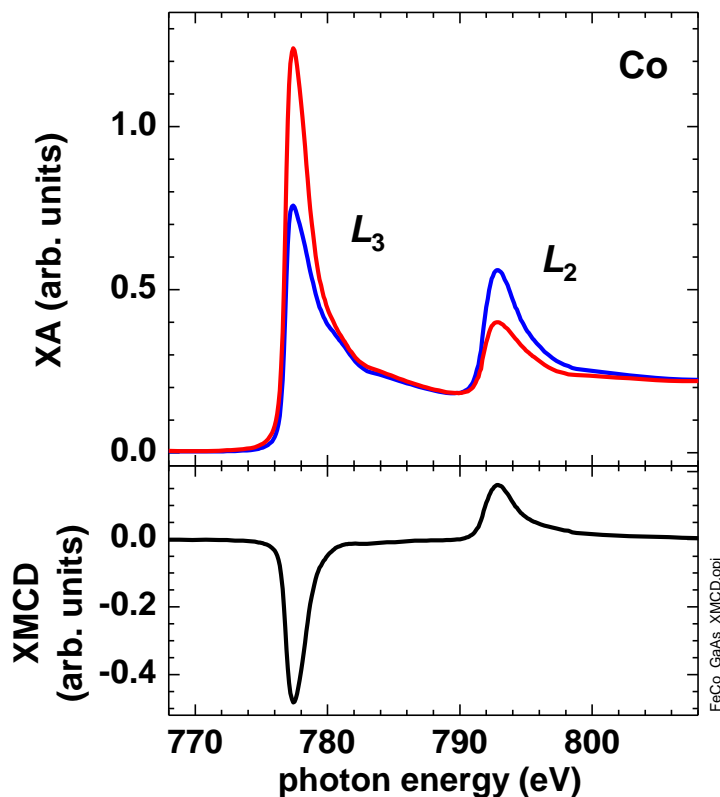
+ In fact:
Magnetic moments are not fully aligned with applied fields but precess around them.



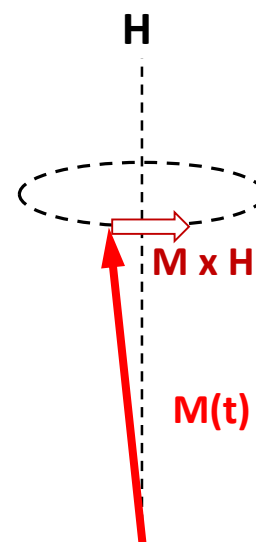
X-Ray Ferromagnetic Resonance



circularly polarized



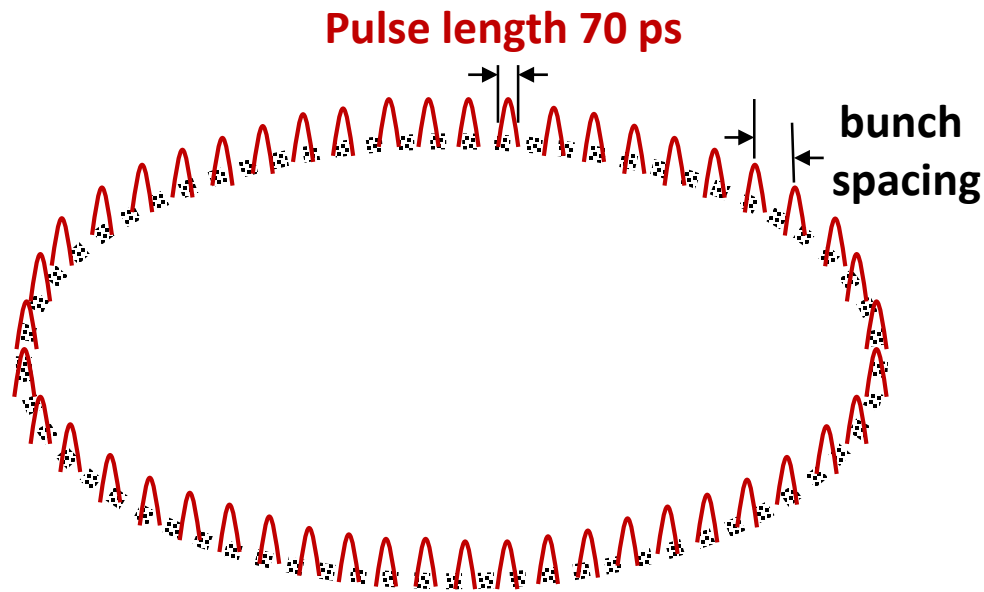
+ In fact:
Magnetic moments are not fully aligned with applied fields but precess around them.



+ Is it possible to measure the precession of magnetic moments making use of the pulsed nature of synchrotron radiation and XMCD? (!)

X-Ray Ferromagnetic Resonance

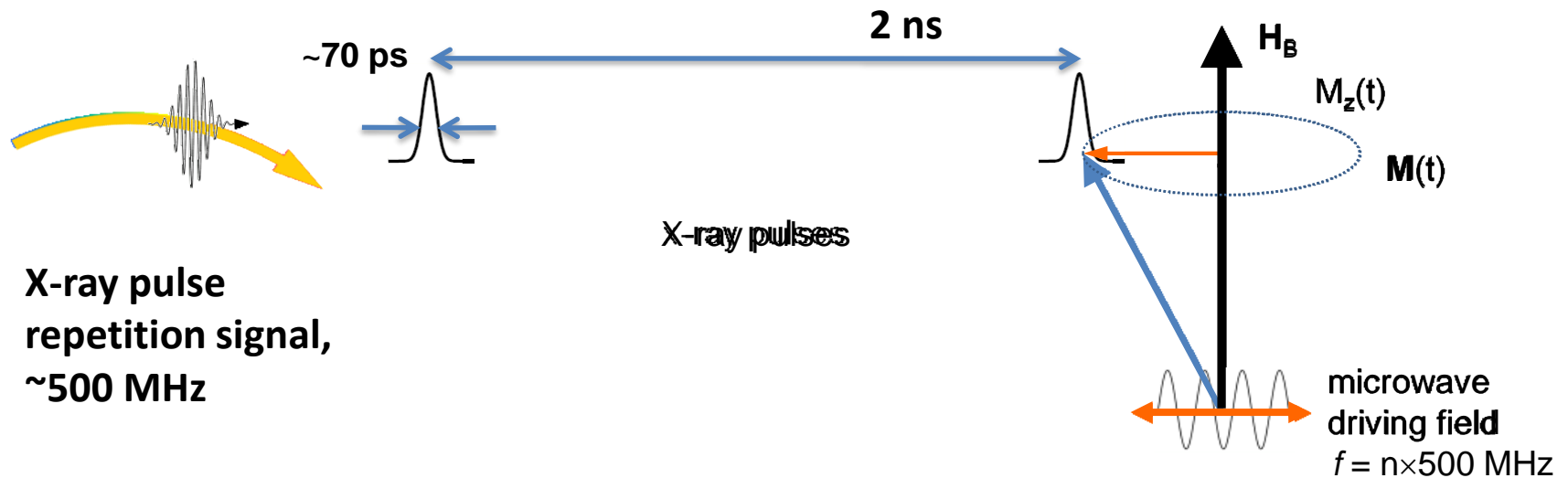
Pulsed nature of synchrotron radiation Example: Advanced Light Source



- + 256-320 bunches for 500mA beam current
- + Bunch spacing: 2 ns (500MHz)
- + Pulse length 70ps

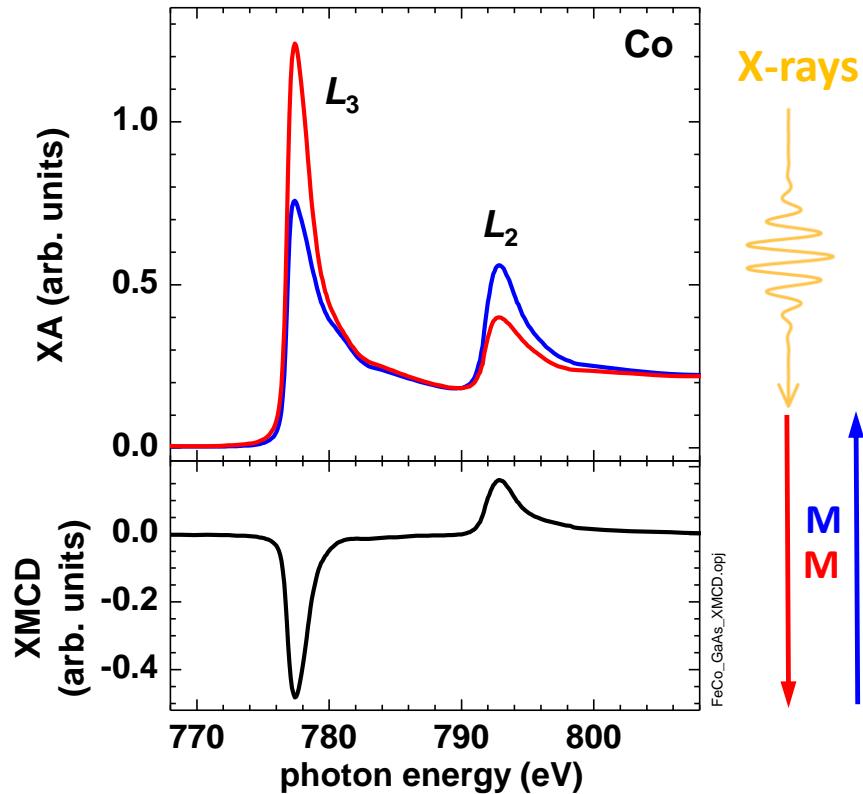
X-Ray Ferromagnetic Resonance

Dynamic XMCD measurement, i.e. synchronize X-ray pulses with FMR precession

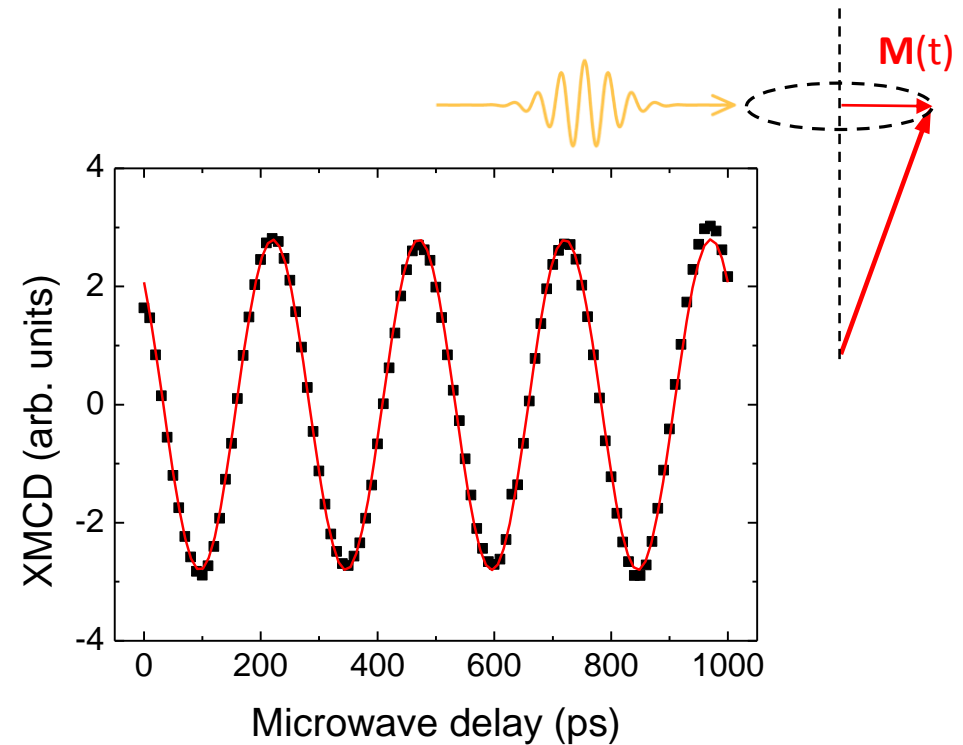


X-Ray Ferromagnetic Resonance

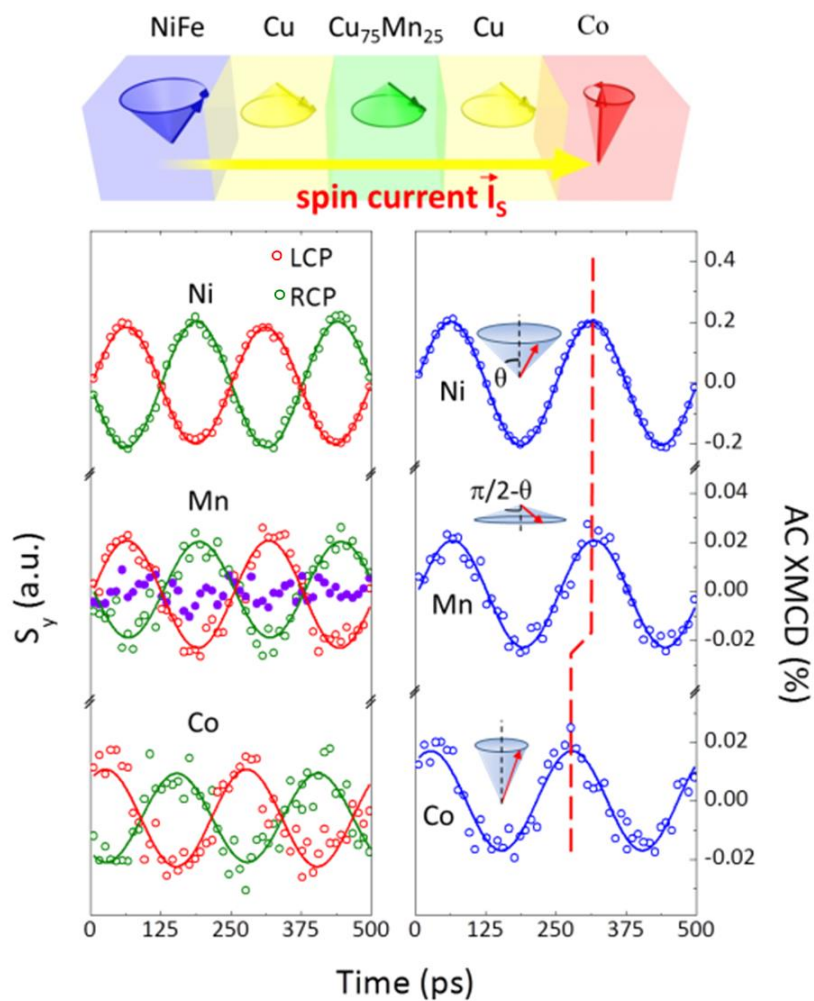
Static XMCD



Dynamic XMCD

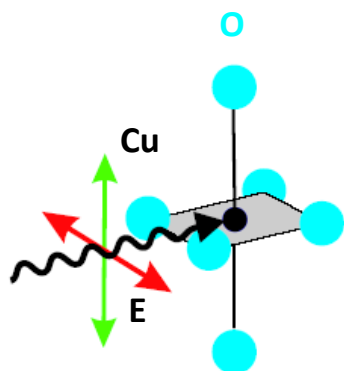


X-Ray Ferromagnetic Resonance

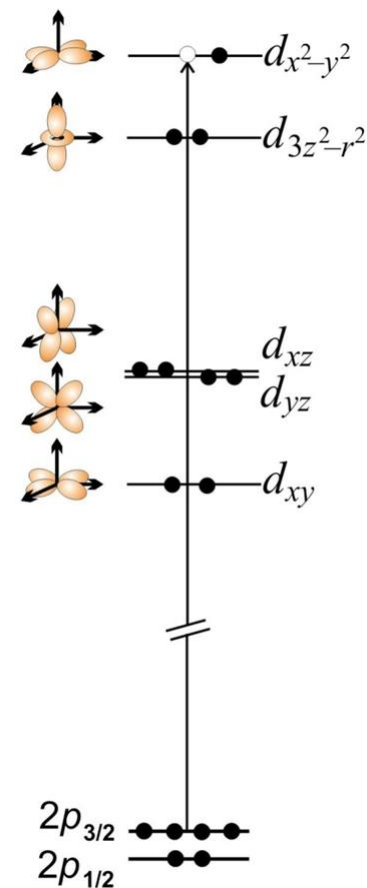
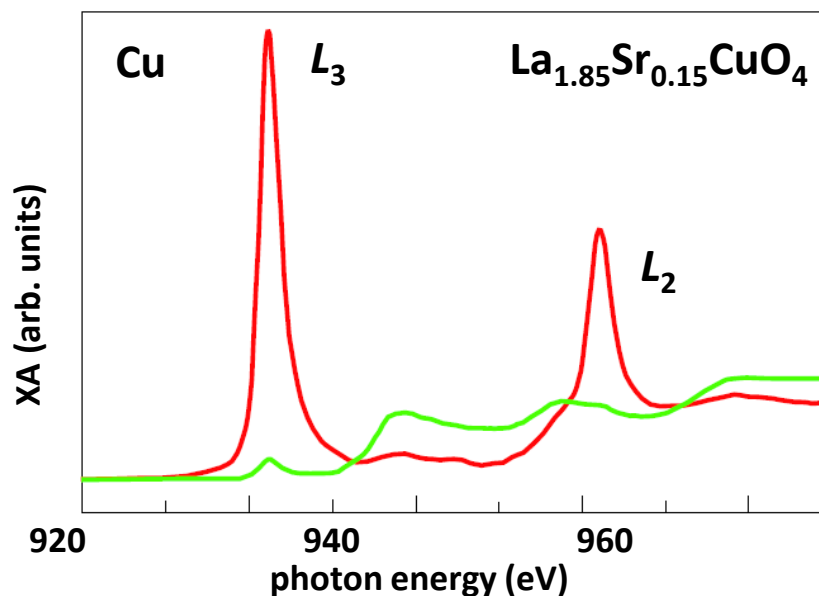


- + Precession is resonantly excited in the NiFe layer with an 4 GHz RF field.
- + The resonance field of the CO layer is higher, i.e. no precession is excited in the Co layer.
- + Precession in Py, Cu₇₅Mn₂₅, and Co layers are probed by XMCD using left- and right-circularly polarized X-rays at Ni, Mn, and Co edges, respectively.
- + The Cu₇₅Mn₂₅ spin precession is a direct indicator of the AC spin current through the structure.

X-Ray Linear Dichroism



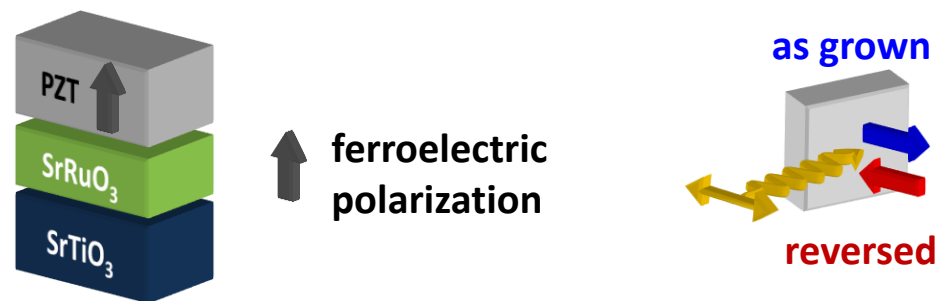
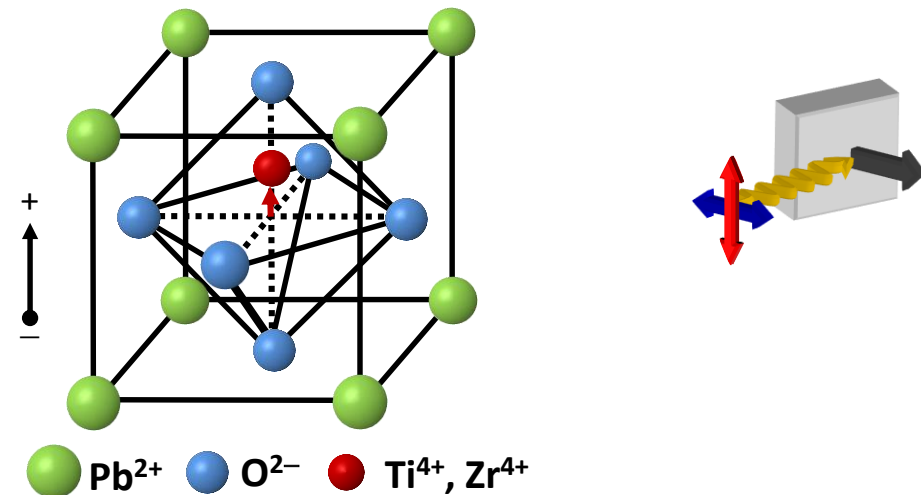
C. T. Chen *et al.*
PRL **68**, 2543 (1992)



X-Ray Linear Dichroism:

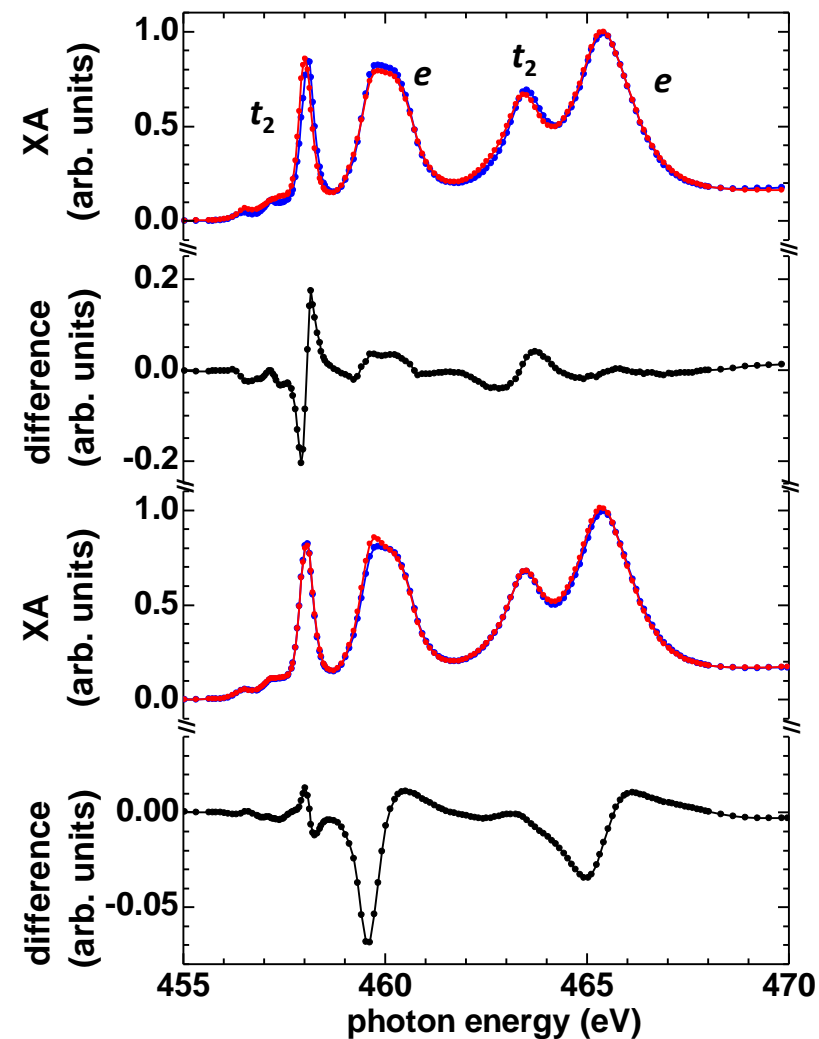
- + Difference in X-ray absorption for different linear polarization direction relative to crystalline and/or spin axis.
- + Due to the anisotropic charge distribution about the absorbing atom caused by bonding and/or magnetic order.
- + “Search Light Effect”: X-ray absorption of linear polarized X rays proportional to density of empty valence states in direction of electric field vector E.

Structural Changes In $\text{PbZr}_{0.2}\text{Ti}_{0.8}\text{O}_3$



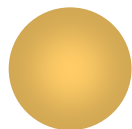
+ Spontaneous electric polarization due to off-center shift of $\text{Ti}^{4+}, \text{Zr}^{4+}$ associated with tetragonal distortion \Leftrightarrow linear dichroism

+ Reversing ferroelectric polarization changes XA \Leftrightarrow Change in tetragonal distortion

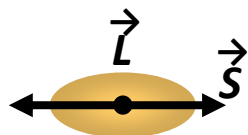


E. Arenholz *et al.*,
 Phys. Rev. B **82**, 140103 (2010)

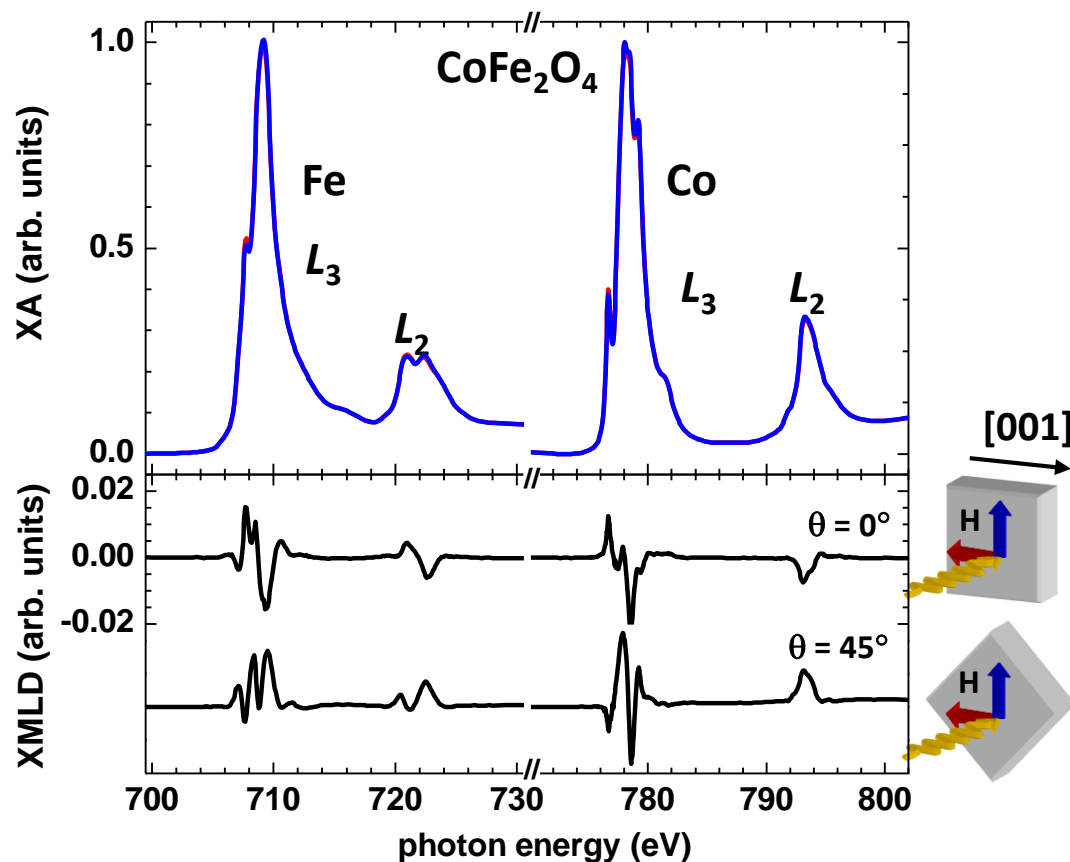
X-Ray Magnetic Linear Dichroism



Isotropic d electron charge density
 \Rightarrow No polarization dependence

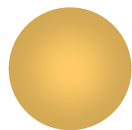


Magnetically aligned system
 \Rightarrow Spin-orbit coupling distorts
 charge density
 \Rightarrow Polarization dependence

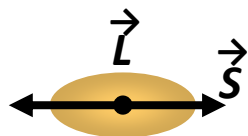


- + $I_{\text{XMLD}} = I_{\parallel} - I_{\perp} \propto \langle m^2 \rangle$, $\langle m^2 \rangle =$ expectation value of square of atomic magnetic moment
- + XMLD allows investigating ferri- and ferromagnets as well as antiferromagnets
- + XMLD spectral shape and angular dependence are determined by magnetic order and lattice symmetry

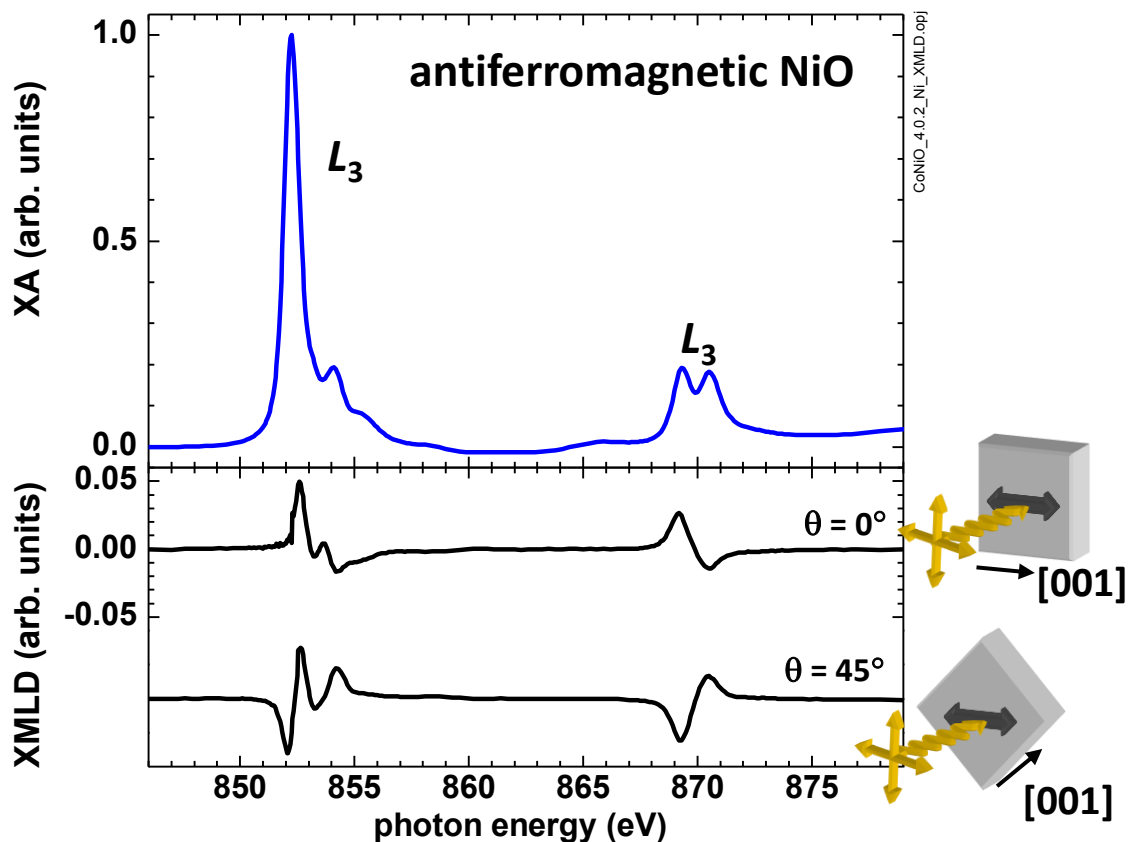
X-Ray Magnetic Linear Dichroism



Isotropic d electron charge density
 \Rightarrow No polarization dependence

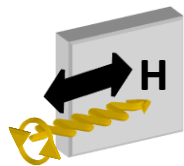
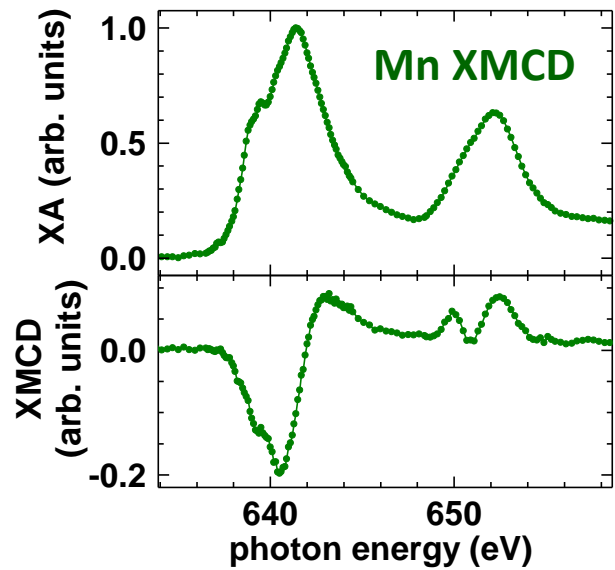


Magnetically aligned system
 \Rightarrow Spin-orbit coupling distorts charge density
 \Rightarrow Polarization dependence

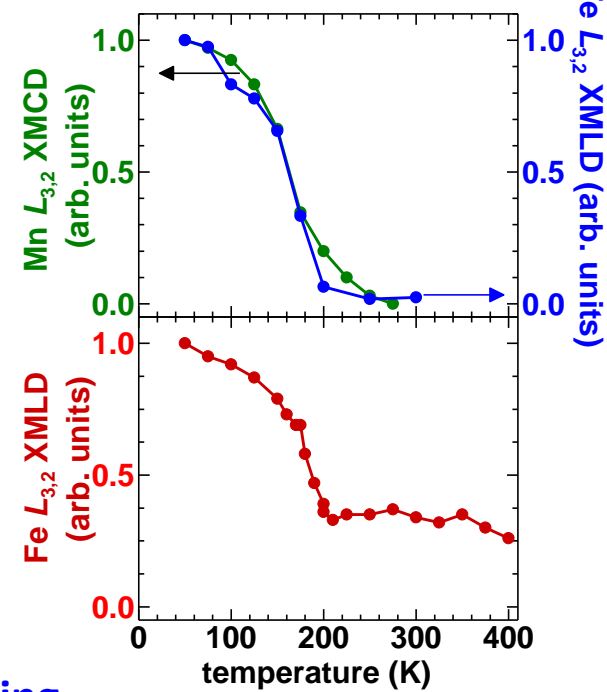
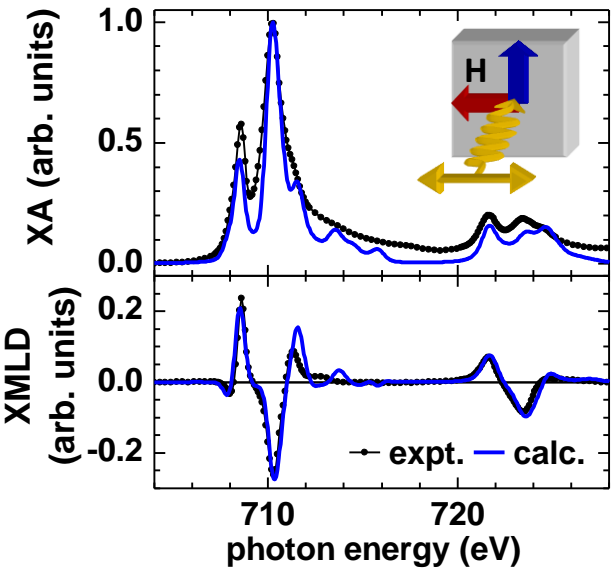
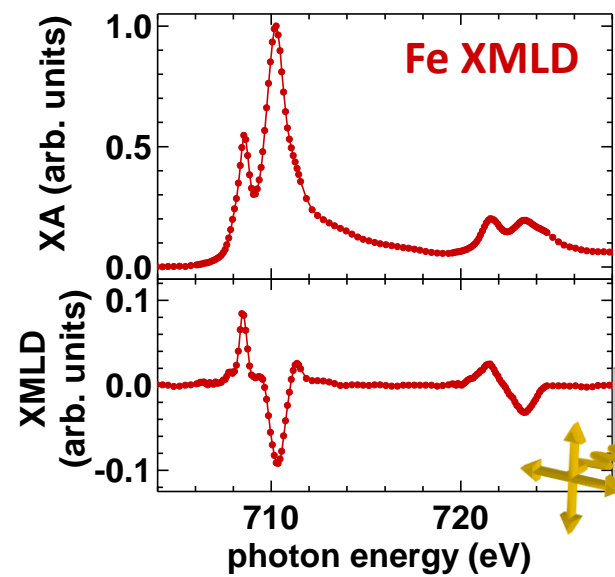


- + $I_{\text{XMLD}} = I_{\parallel} - I_{\perp} \propto \langle m^2 \rangle$, $\langle m^2 \rangle =$ expectation value of square of atomic magnetic moment
- + XMLD allows investigating ferri- and ferromagnets as well as antiferromagnets
- + XMLD spectral shape and angular dependence are determined by magnetic order and lattice symmetry

Magnetic Coupling At Interfaces



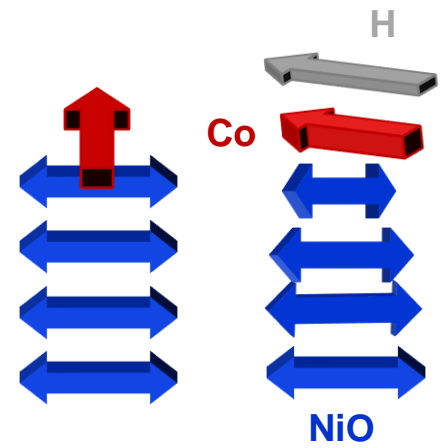
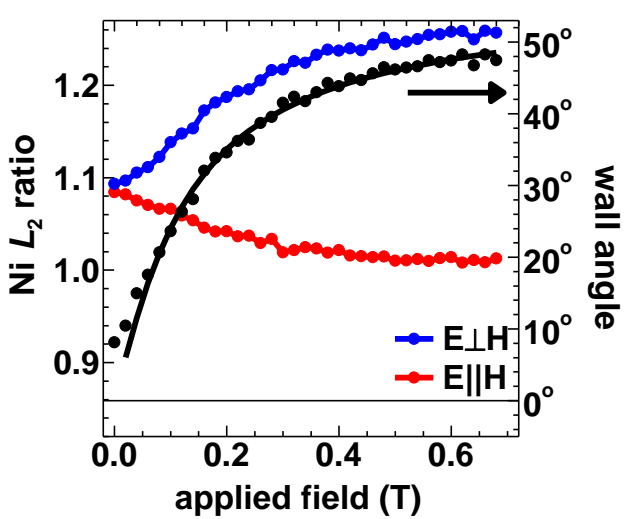
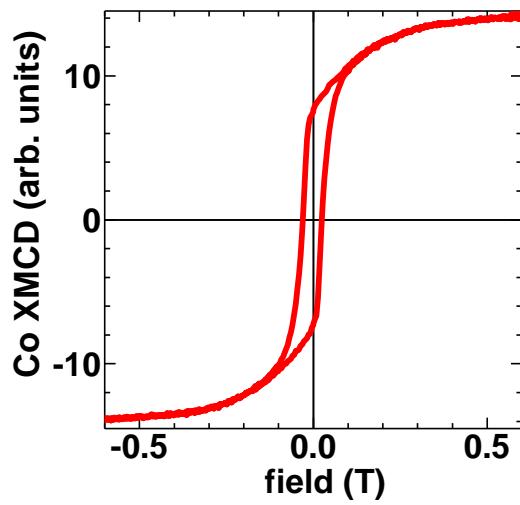
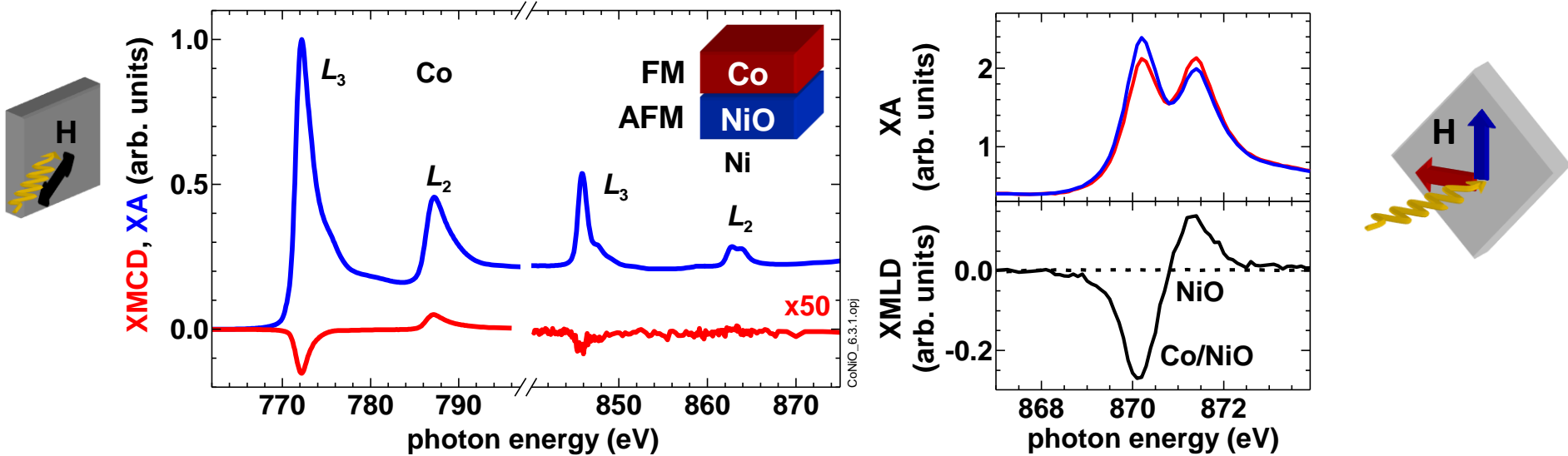
$\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO)
ferromagnet
 $\text{La}_{0.7}\text{Sr}_{0.3}\text{FeO}_3$ (LSFO)
antiferromagnet



⇒ Perpendicular coupling at LSMO/LSFO interface

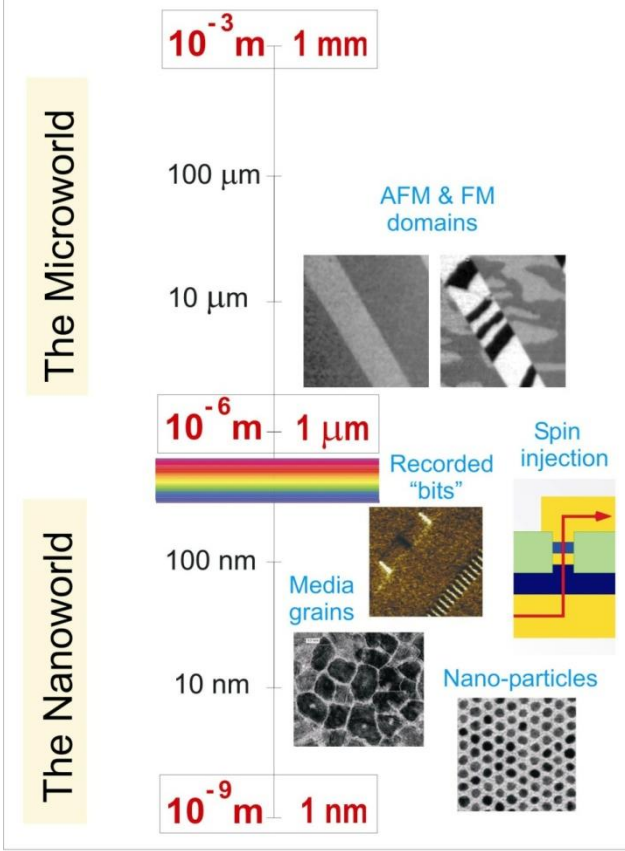
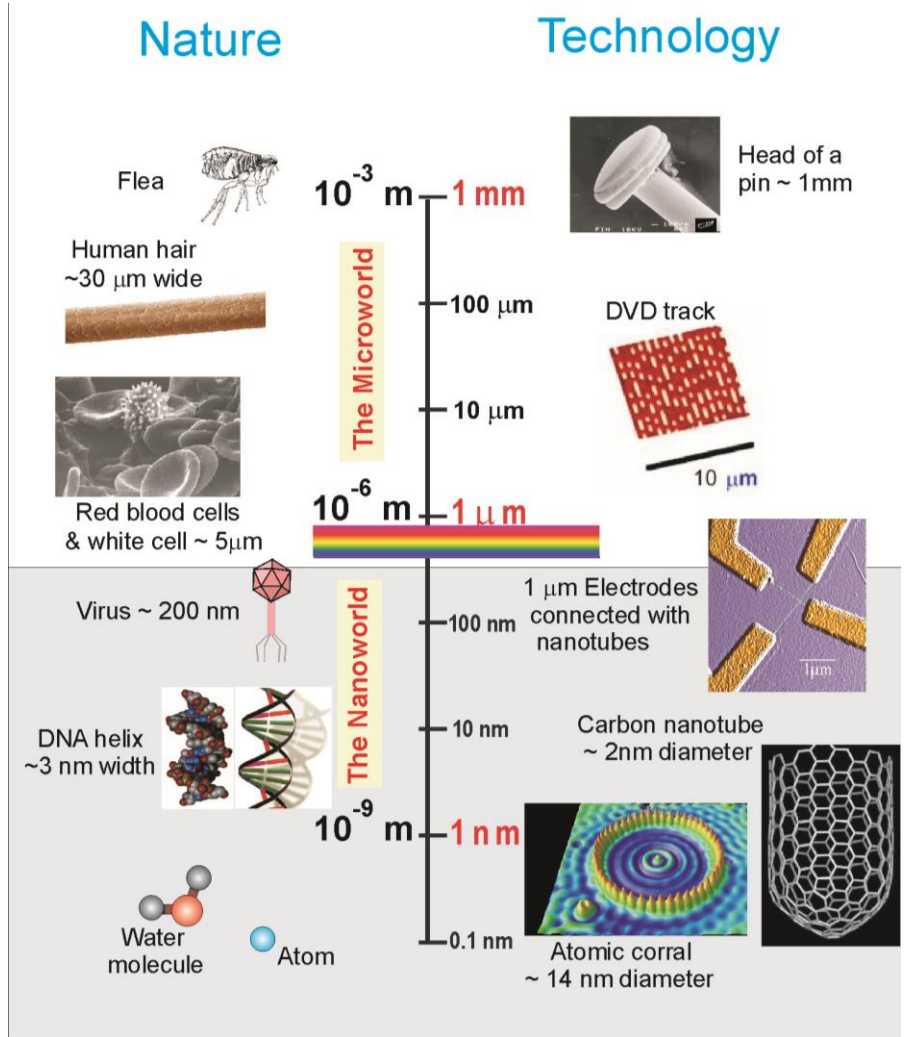
E. Arenholz et al.,
Appl. Phys. Lett. 94, 072503 (2009)

Planar Domain Wall

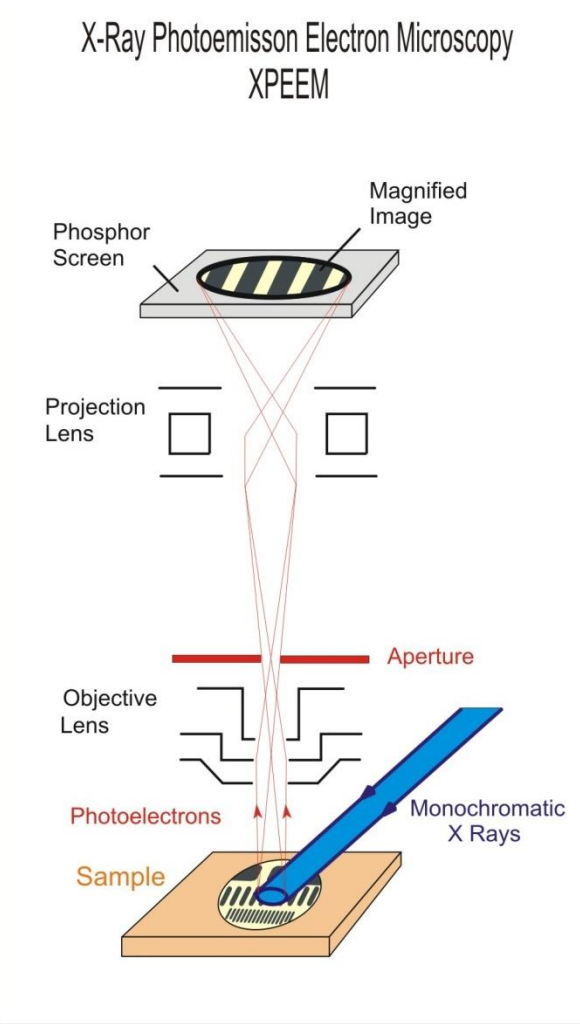
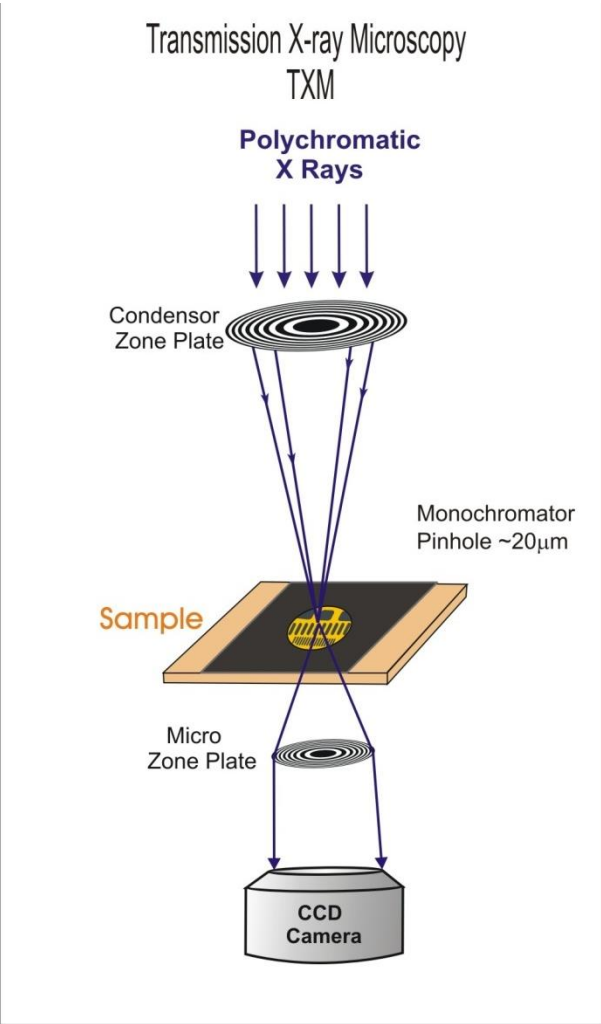
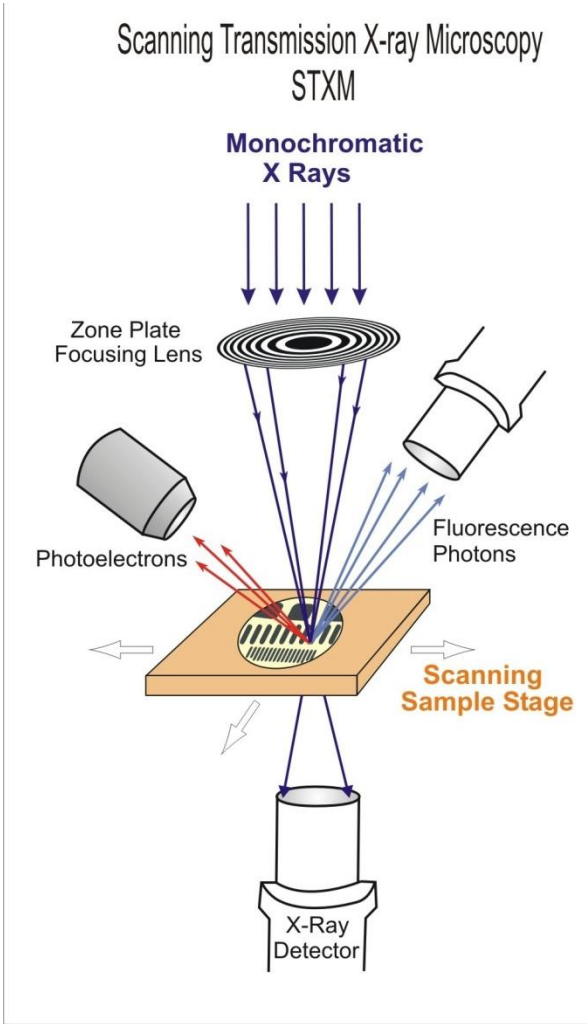


A. Scholl et al., Phys. Rev. Lett. 92, 247201 (2004)

Magnetic Microscopy



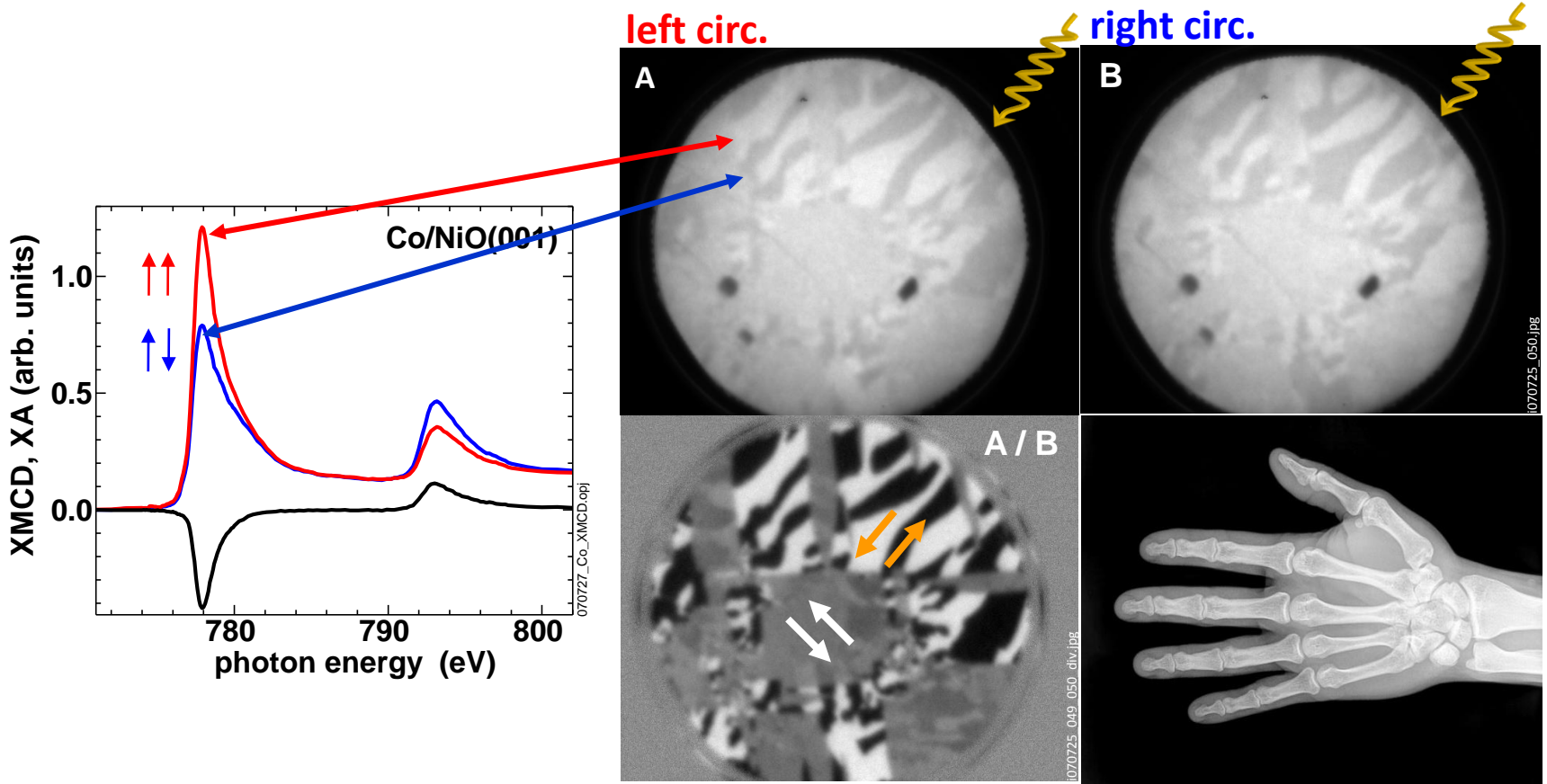
Magnetic Microscopy



10-50 nm spatial resolution

J. Stöhr, H.C. Siegmann,
Magnetism (Springer)

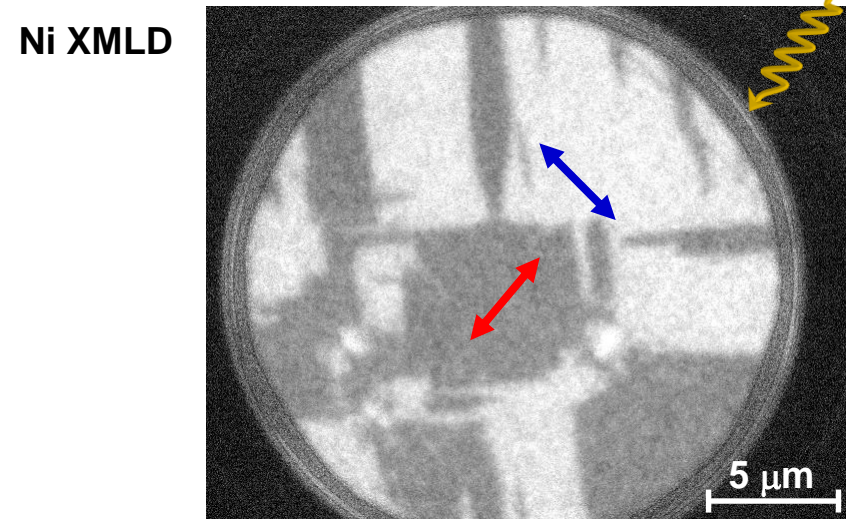
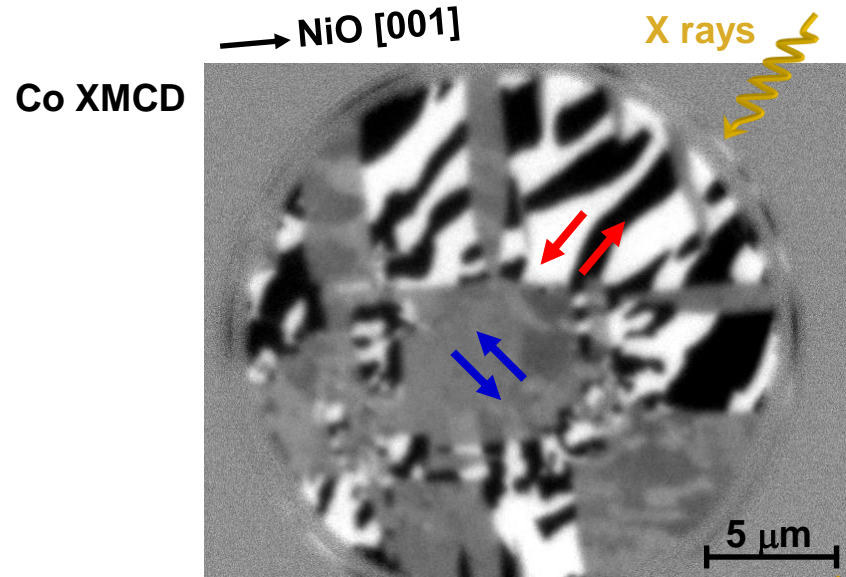
Imaging Magnetic Domains Using X-Rays



E. Arenholz *et al.*,
Appl. Phys. Lett. **93**, 162506 (2008)

+ Images taken with left and right circularly polarized X-rays at photon energies with XMCD, i.e. Co L_3 edge, provide magnetic contrast and domain images.

Magnetic Coupling At Co/NiO Interface



probing in-plane

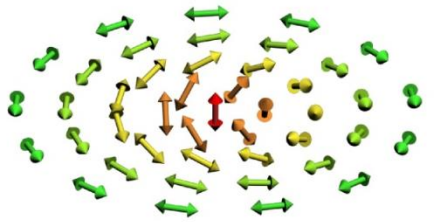
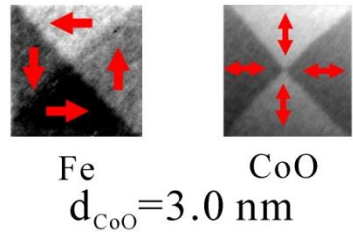
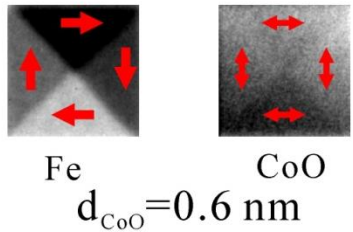
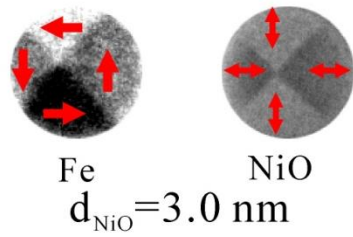
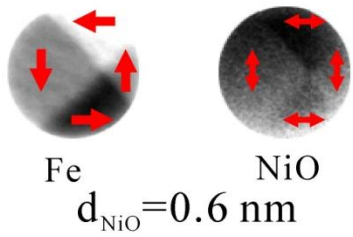
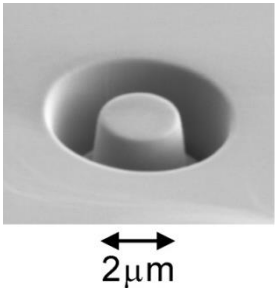
+ Taking into account the geometry dependence of the Ni XMLD signal
⇒ Perpendicular coupling of Co and NiO moments at the interface.

E. Arenholz *et al.*,
Appl. Phys. Lett. 93, 162506 (2008)

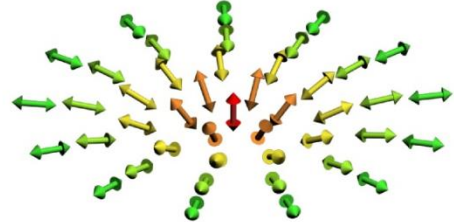
Magnetic Vortices

+ First direct observation of vortex state in antiferromagnetic CoO and NiO disks in Fe/CoO and Fe/NiO bilayers using XMCD and XMLD.

- + Two types of AFM vortices:
 - conventional curling vortex as in ferromagnets
 - divergent vortex, forbidden in ferromagnets
 - thickness dependence of magnetic interface coupling



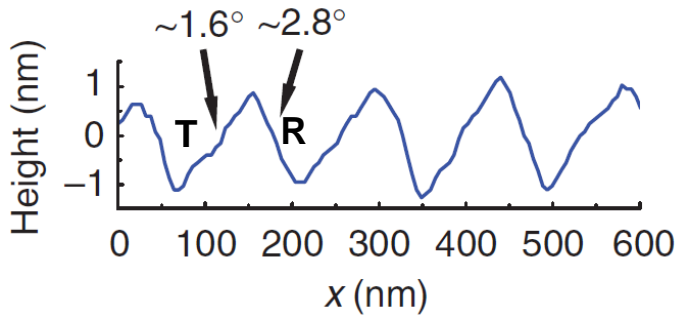
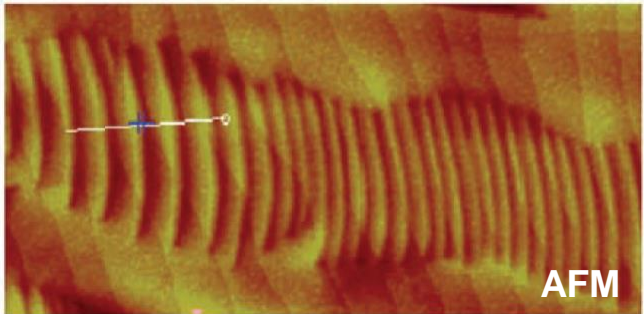
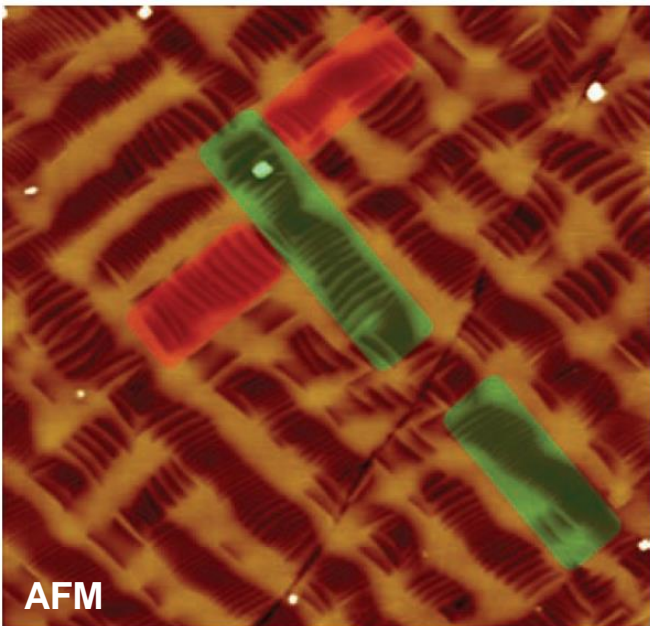
conventional curling vortex



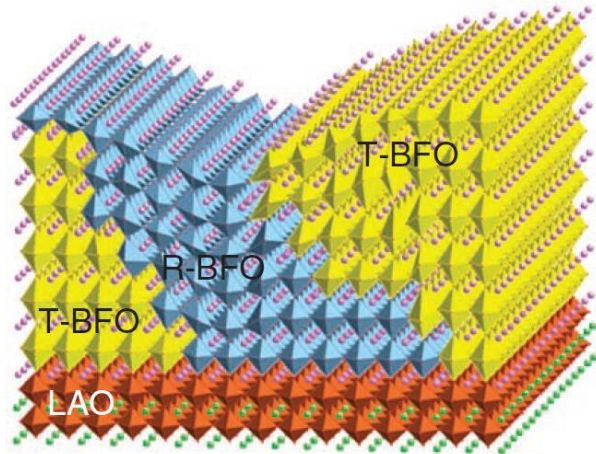
divergent vortex

J. Wu et al.,
Nature Phys. Z, 303 (2011)

Nanoscale Magnetic Phases

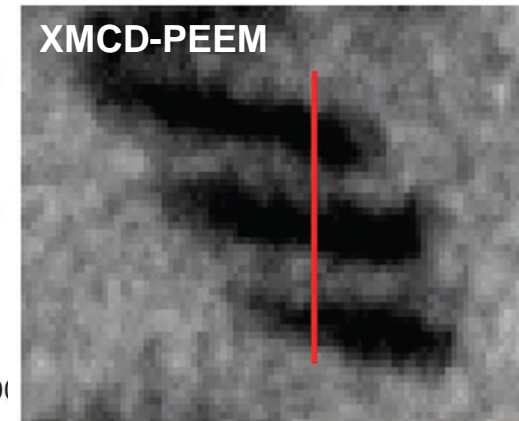
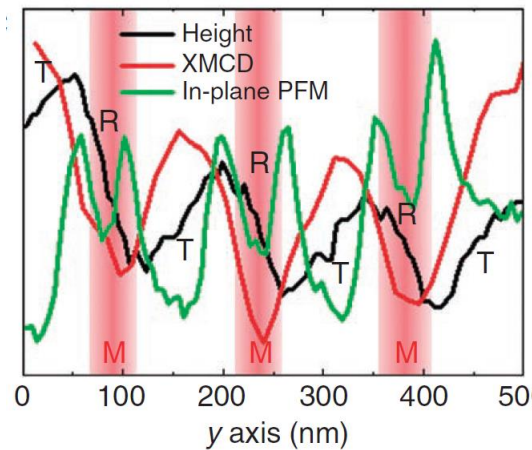
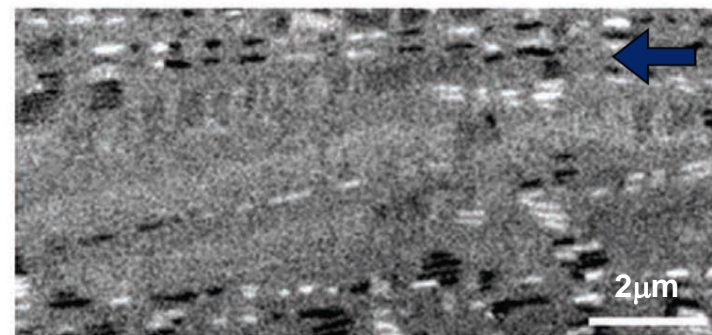
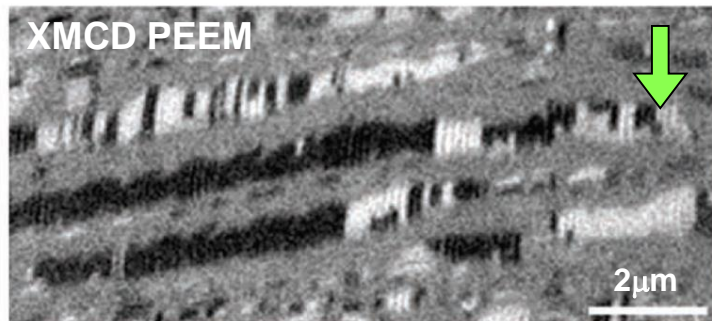
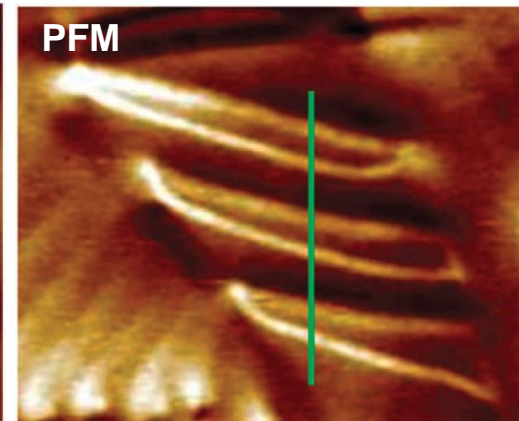
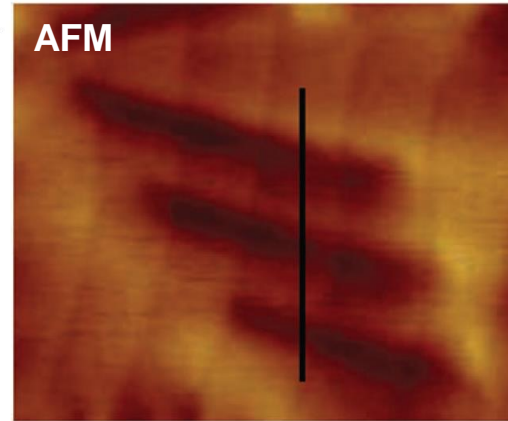
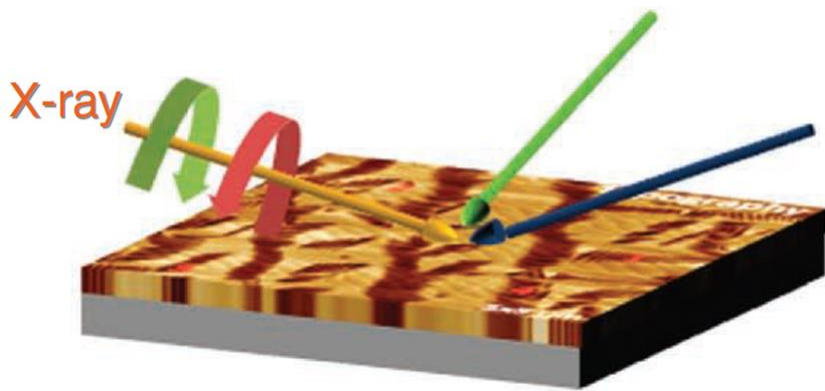


- + BiFeO₃ – multiferroic = ferroelectric + antiferromagnetic
- + Compressive strain on rhombohedral phase (R-phase) induced by substrate
- ⇒ tetragonal-like phase (T-phase)
- + Partial relaxation of epitaxial strain
- ⇒ Formation of a nanoscale mixture of T- and R-phases



Q. He et al., Nature Comm. 2, 225 (2011)

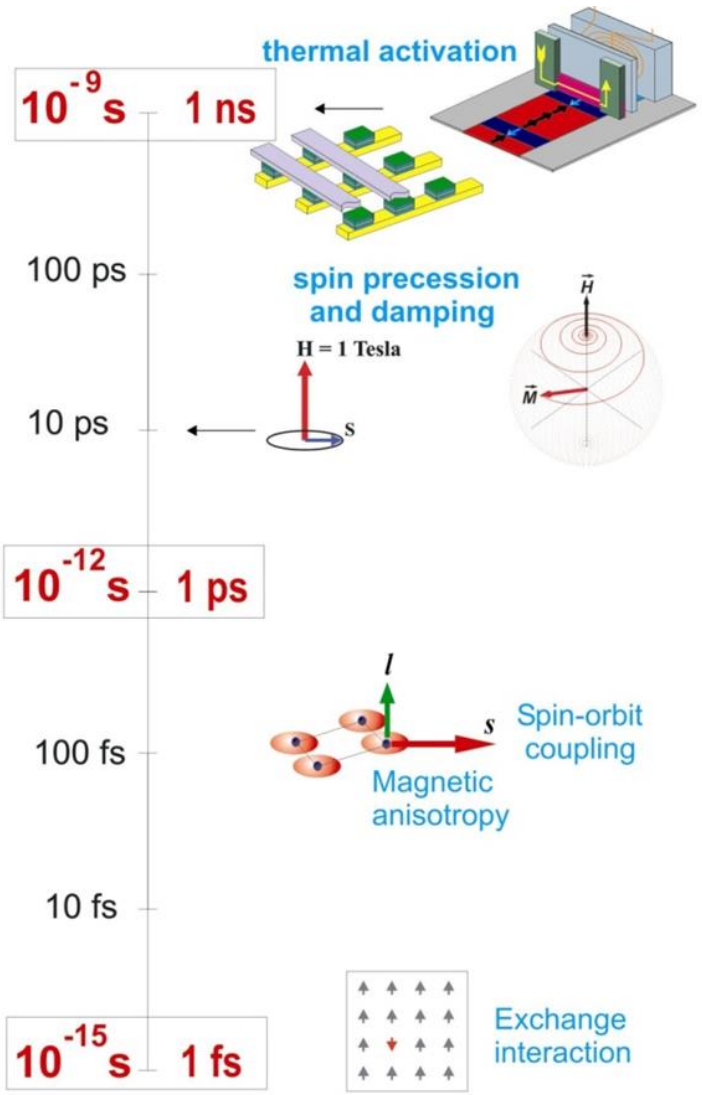
Nanoscale Magnetic Phases



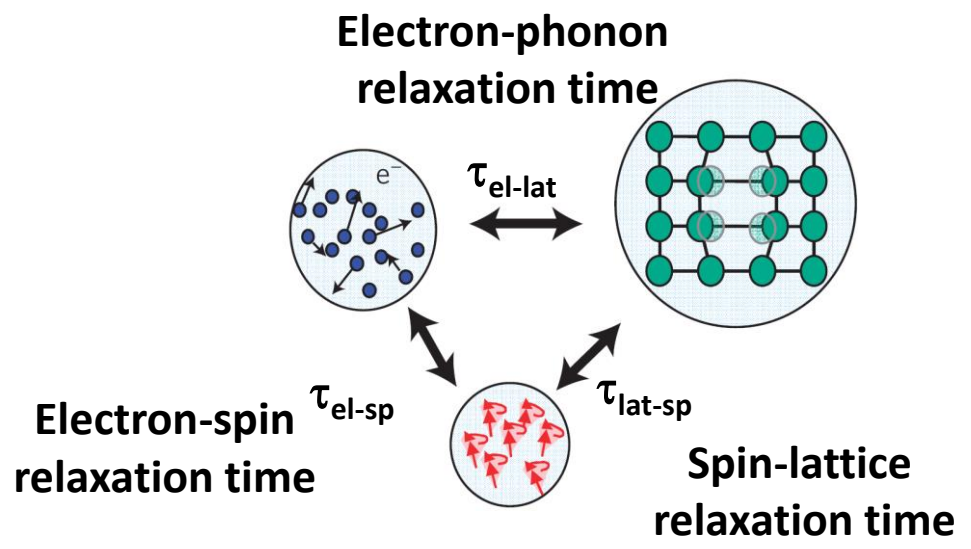
+ Highly distorted R-phase is the source of enhanced magnetic moment in the XMCD image.

Q. He *et al.*,
Nature Comm. **2**, 225 (2011)

Ultrafast Magnetism

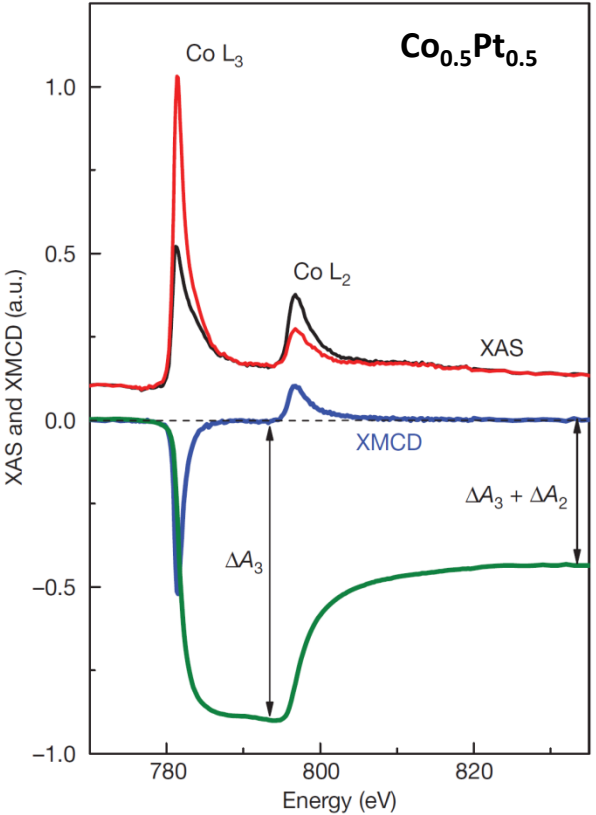


- + Energy reservoirs in a ferromagnetic metal
- + Deposition of energy in one reservoir
- ⇒ Non-equilibrium distribution and subsequent relation through energy and angular momentum exchange



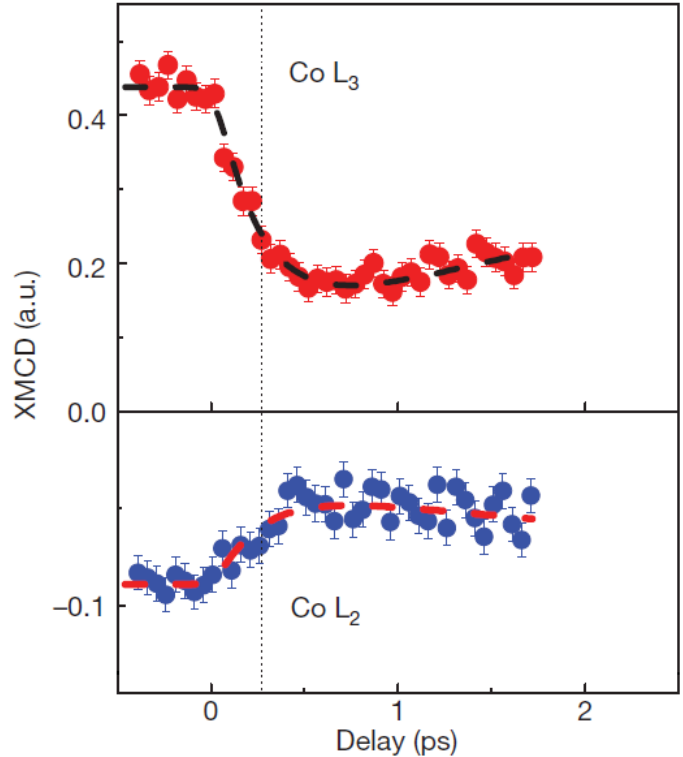
J. Stöhr, H.C. Siegmann, Magnetism (Springer)

Ultrafast Dynamics Of Spin And Orbital Moments

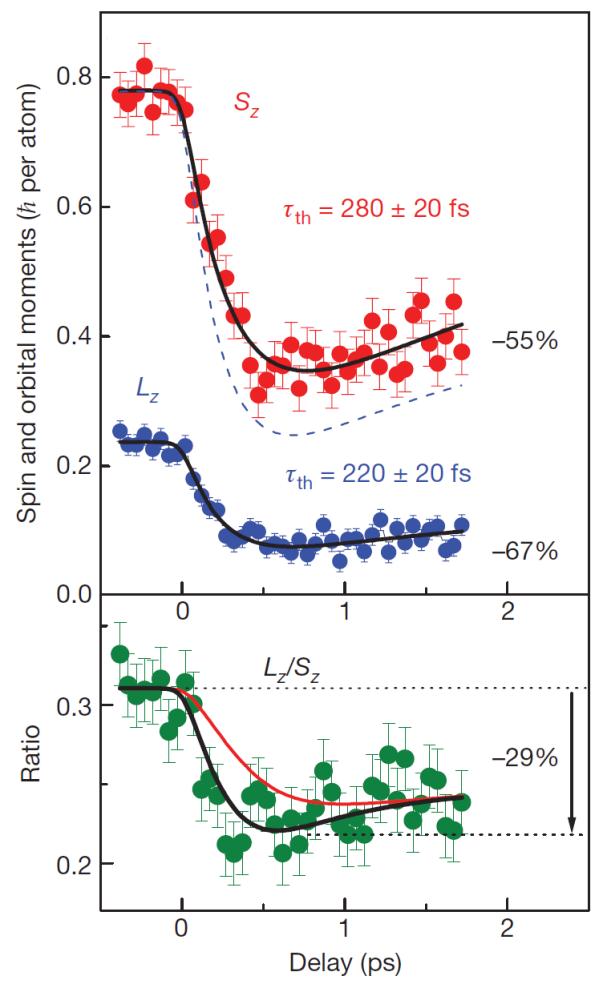


C. Boeglin, *et al.*,
Nature **465**, 458 (2010)

- + Orbital (L) and spin (S) magnetic moments can change with total angular momentum is conserved.
- + Efficient transfer between L and S through spin-orbit interaction in solids
- + Transfer between L and S occurs on fs timescales.
- + $\text{Co}_{0.5}\text{Pt}_{0.5}$ with perpendicular magnetic anisotropy
- + 60 fs optical laser pulses change magnetization
- + Dynamics probed with XMCD using 120fs X-ray pulses
- + Linear relation connects $\text{Co } L_3$ and L_2 XMCD with L_z and S_z using sum rules

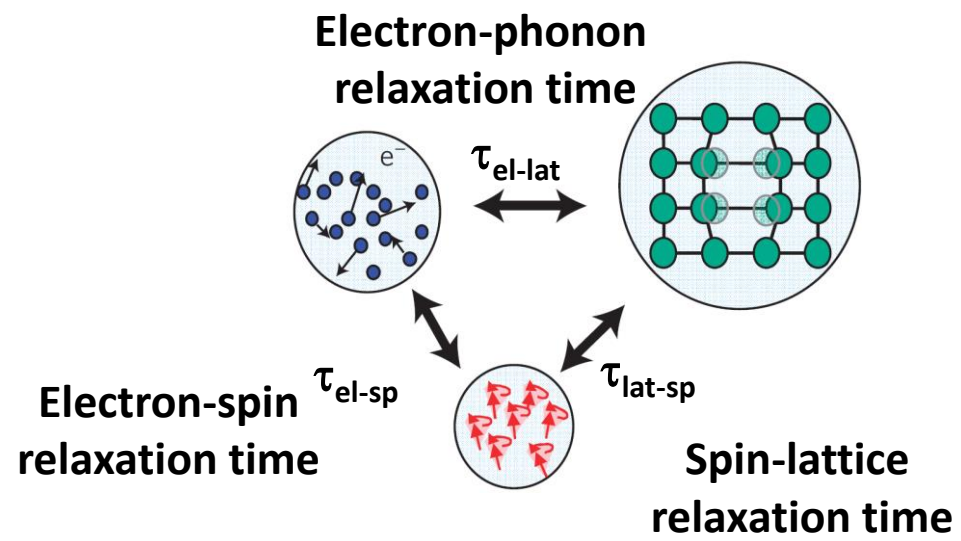


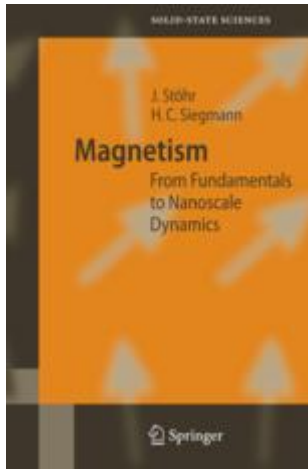
Ultrafast Dynamics Of Spin And Orbital Moments



C. Boeglin, et al.,
Nature 465, 458 (2010)

- + Thermalization: Faster decrease of orbital moment
- + Theory: Orbital magnetic moment strongly correlated with magnetocrystalline anisotropy
- + Reduction in orbital moment
 \Leftrightarrow Reduction in magnetocrystalline anisotropy
- + Typically observed at elevated temperatures in static measurements as well





J. Stöhr, H.C. Siegmann
Magnetism— From Fundamentals to Nanoscale Dynamics
Springer