PAUL SCHERRER INSTITUT

PSI

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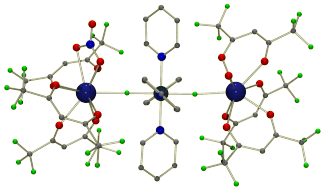
Magnetism properties at interfaces investigated by XMCD and XLD

HElmholtz SEsame Beamline in the soft x-ray regime Workshop, March 16th 2021

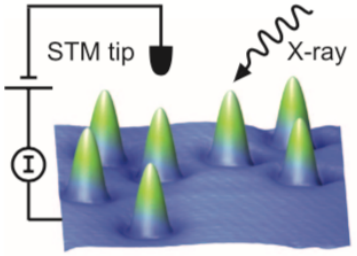
Magnetism

How to make a single magnet smaller?



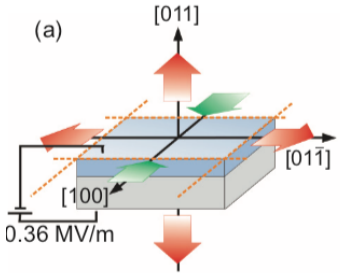
Chem. Sci. **3,** 1024 (2012)

PRL **110,** 087207 (2013).



Science **344,** 988 (2014).

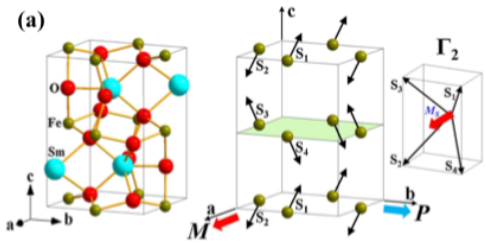
How to create new properties?



PRB **91,** 024406 (2015).

arXiv:2101.01940

How to understand complex magnetic structures?



PRL **107,** 117201 (2011).

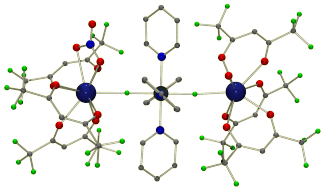
XMCD, XMLD contribution

Element Specific

Spin and orbital moment

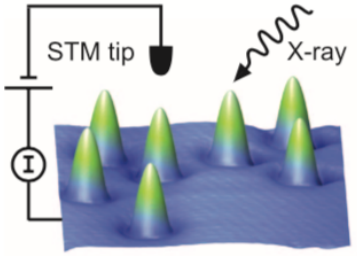
Surface sensitivity

Ferro and Antiferro ordering

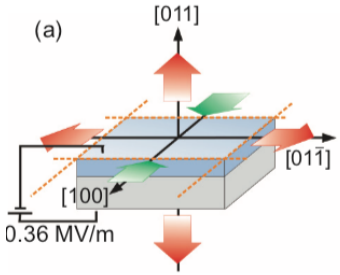


Chem. Sci. **3,** 1024 (2012)

PRL **110,** 087207 (2013).



Science **344,** 988 (2014).



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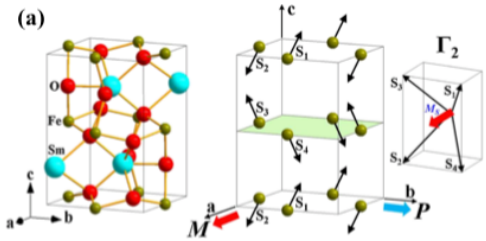
arXiv:2101.01940



PRL **107,** 117201 (2011).

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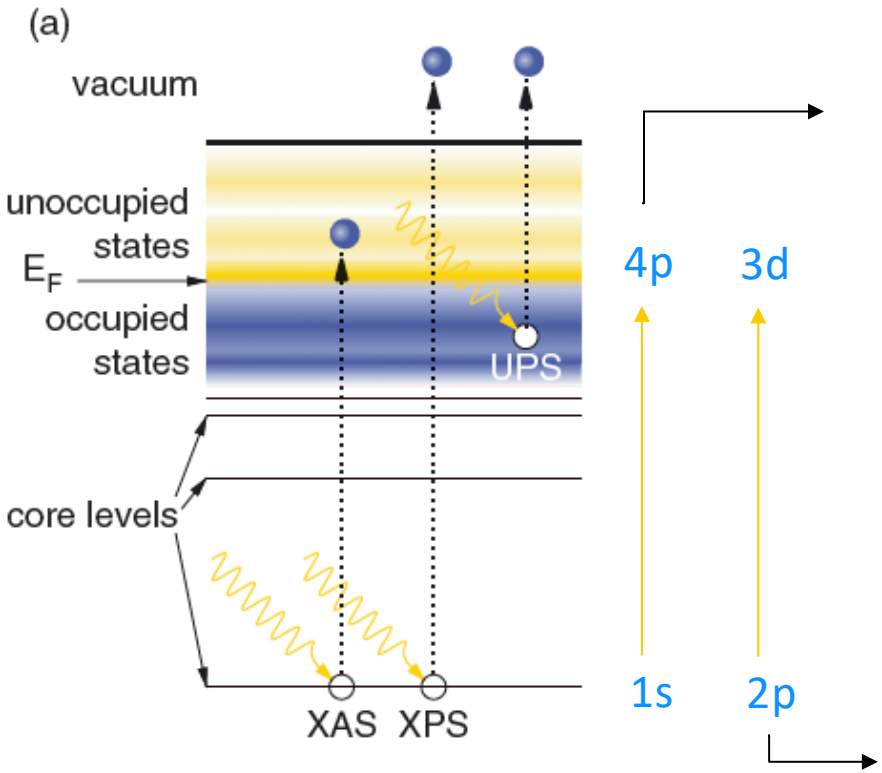
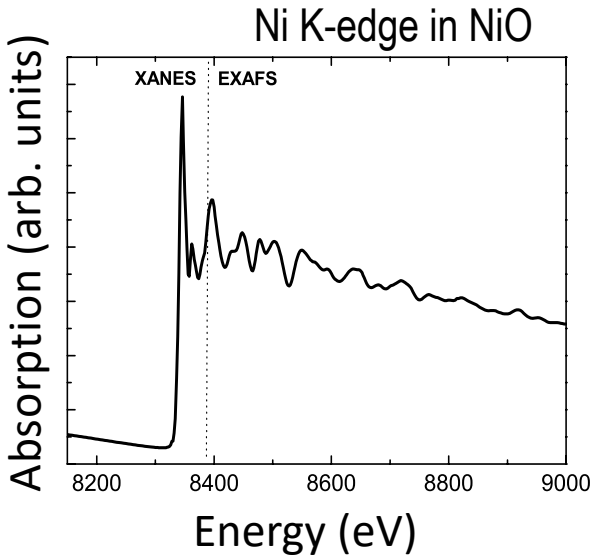
Outline

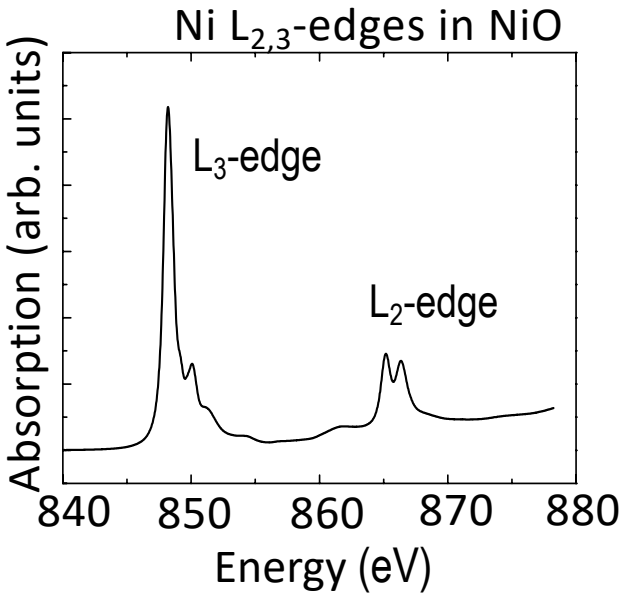
- X-ray absorption Spectroscopy
  - soft X-rays
  - X-ray magnetic circular dichroism (XMCD)
  - X-ray linear dichroism (XLD)

- Examples
  - $SmFeO_3$ (XMLD)
  - SRO/LBMO/SRO (XMCD, element specific magnetization)
  - LSMO/PMN-PT (XMCD,XNLD)

X-ray Absorption Spectroscopy





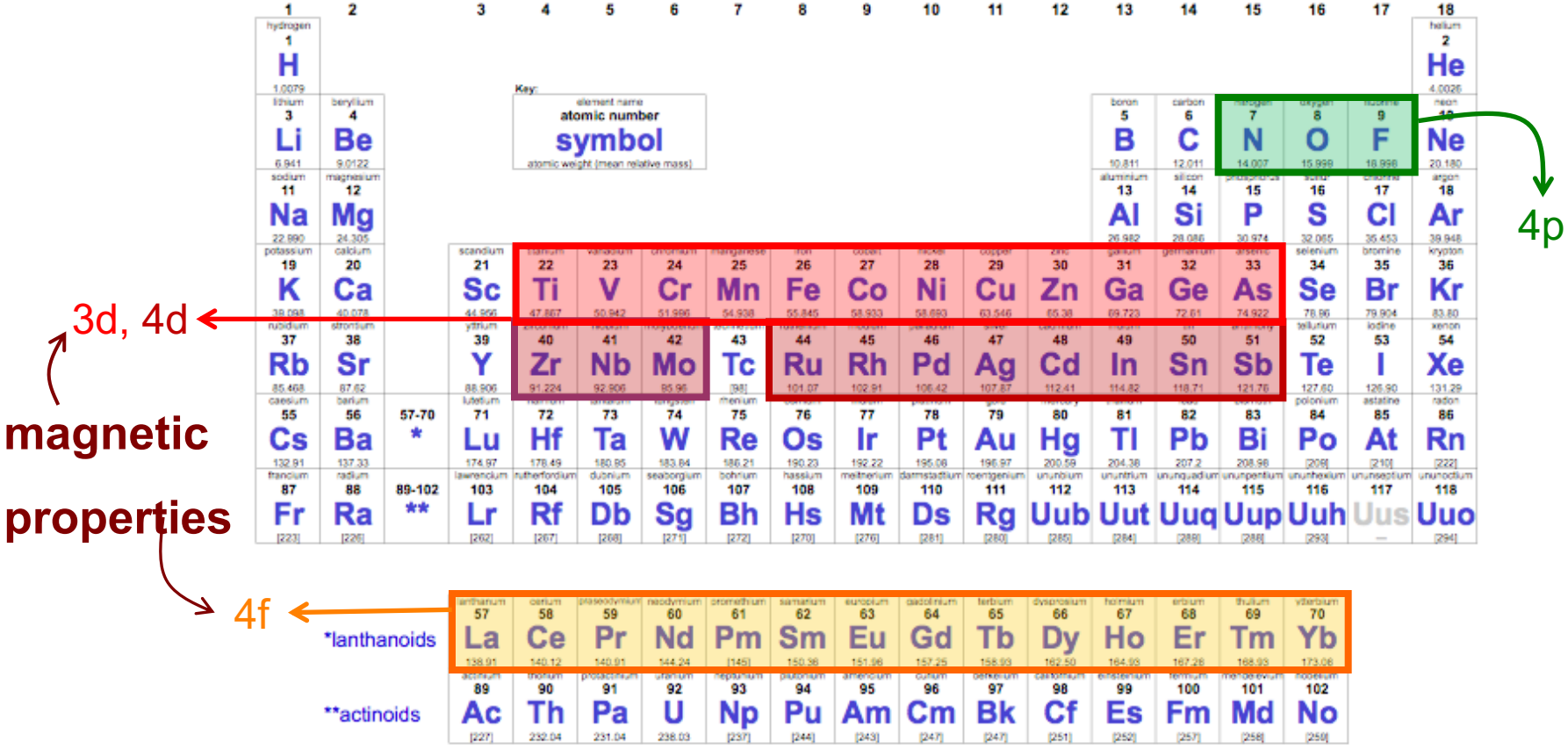


Willmott, P. *An Introduction to Synchrotron Radiation*.

Soft X-ray range

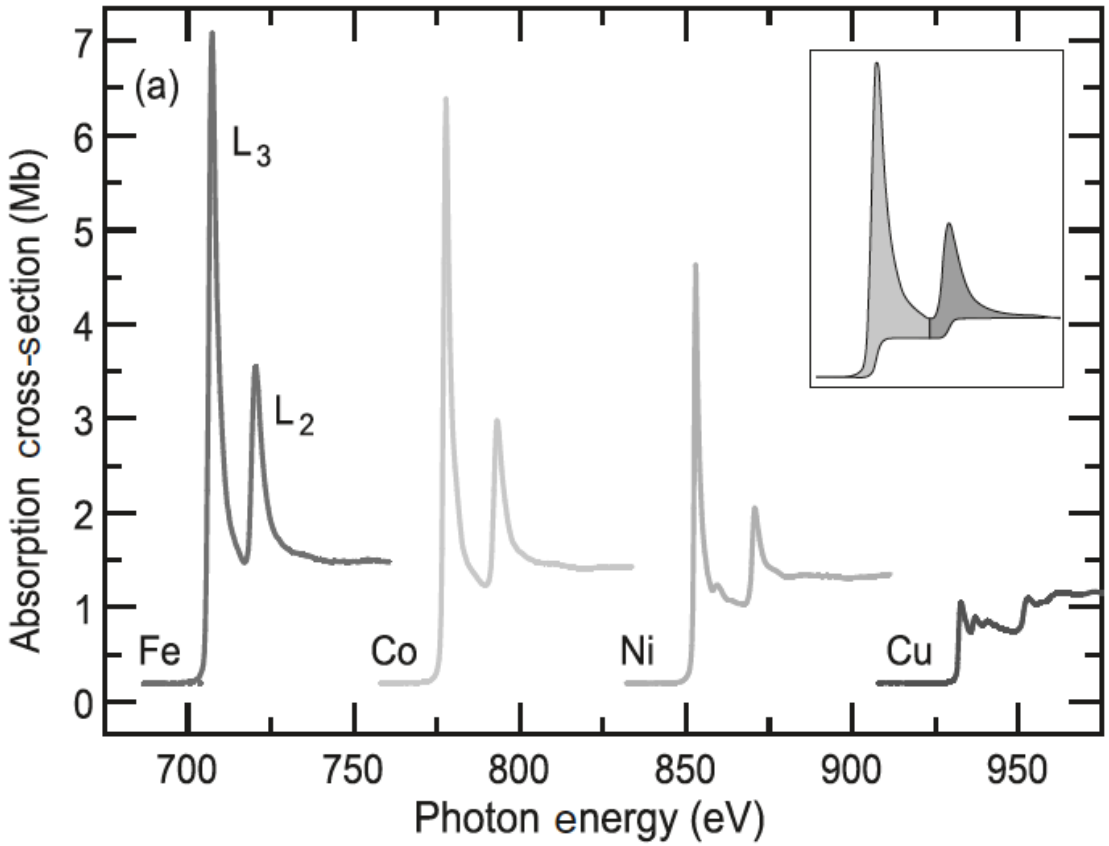
Dipolar Selection Rules

- K-edges: 1s →*n***p**
- $L_{2,3}$-edges: 2p →*n***d**
- $M_{2,3}$-edges: 3p →*n***d**
- $M_{4,5}$-edges: 3d → *n***f**



Soft x-ray absorption

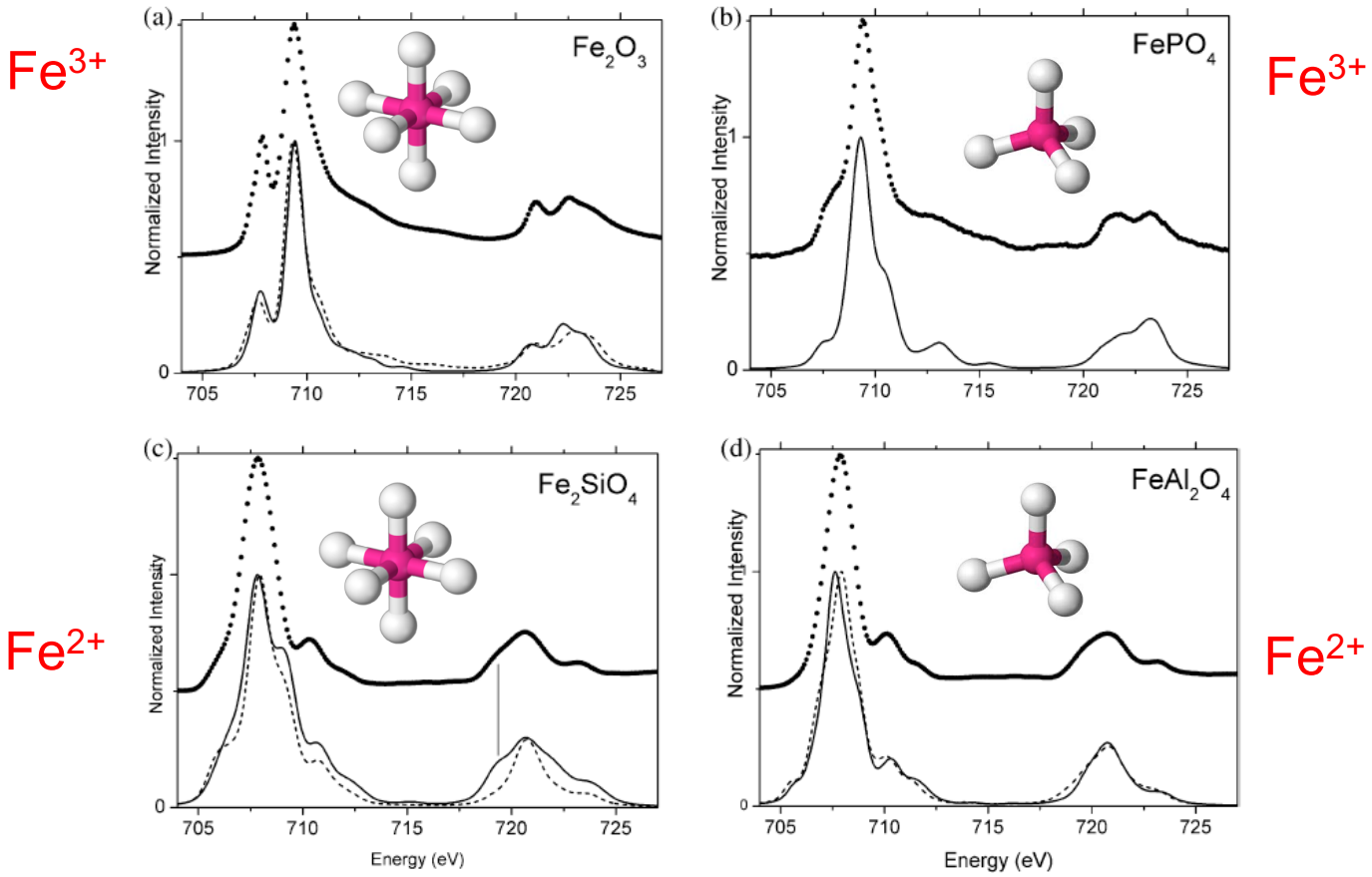
- Element specific



J. Stöhr and H. C. Siegmann, *Magnetism: From Fundamentals to Nanoscale Dynamics*

Soft x-ray absorption

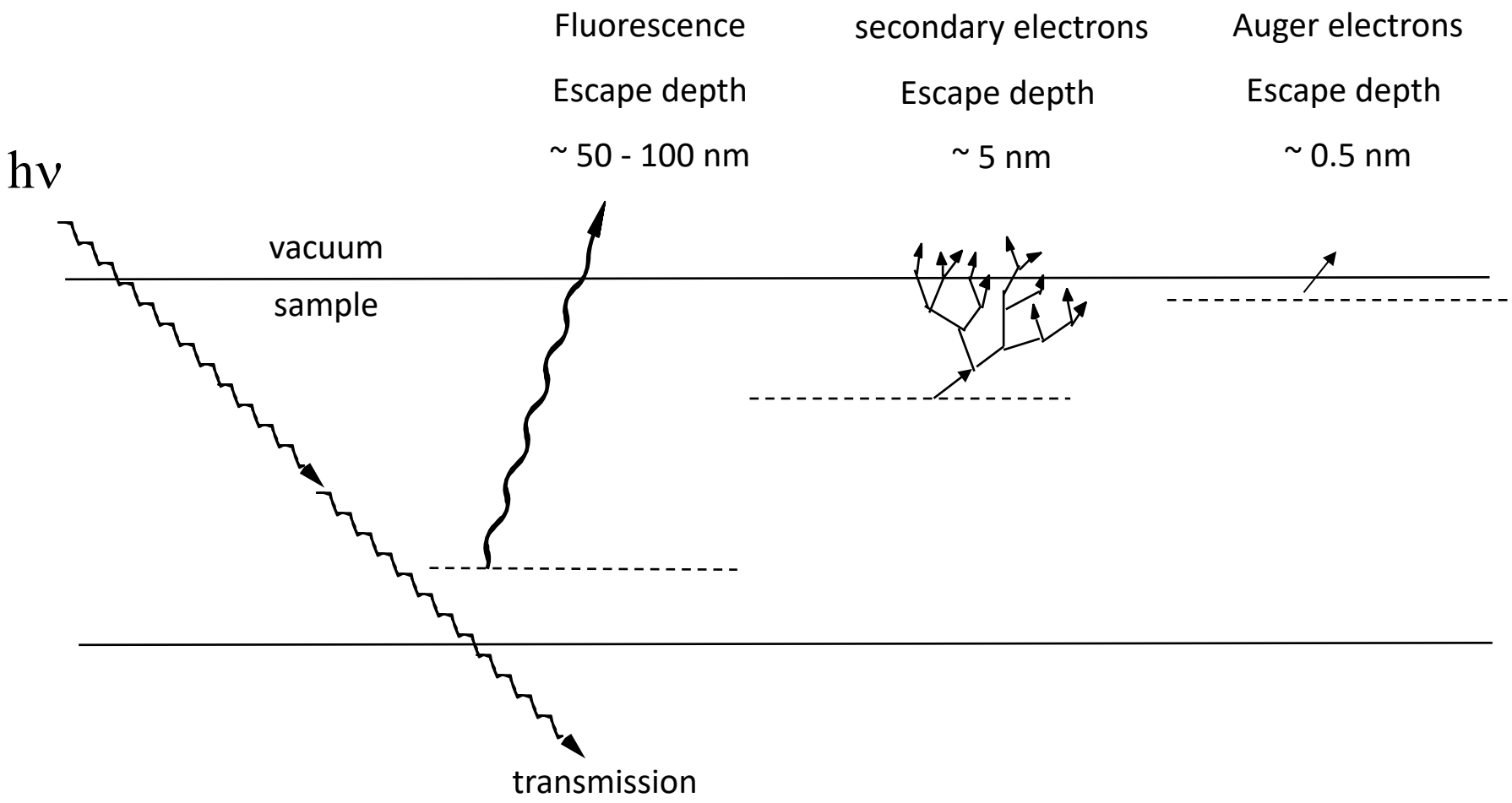
- Element specific
- Sensitive to valence and site symmetry



F. M. F. de Groot *et al.* J. Phys. Chem. B **109** 20751 (2005)

Sampling depth

- Surface sensitivity + Element specificity
  - => allows measurement of a few % of one monolayer

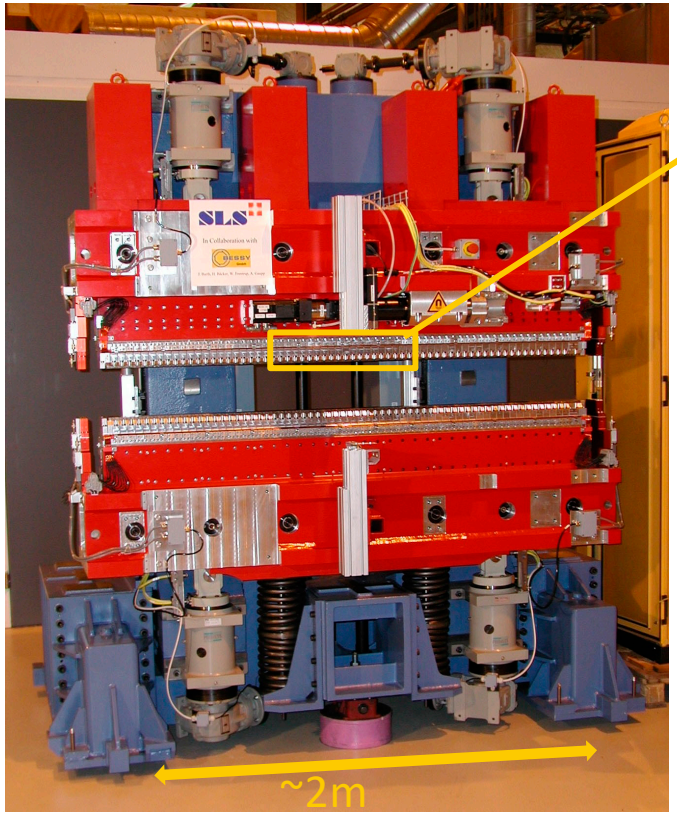


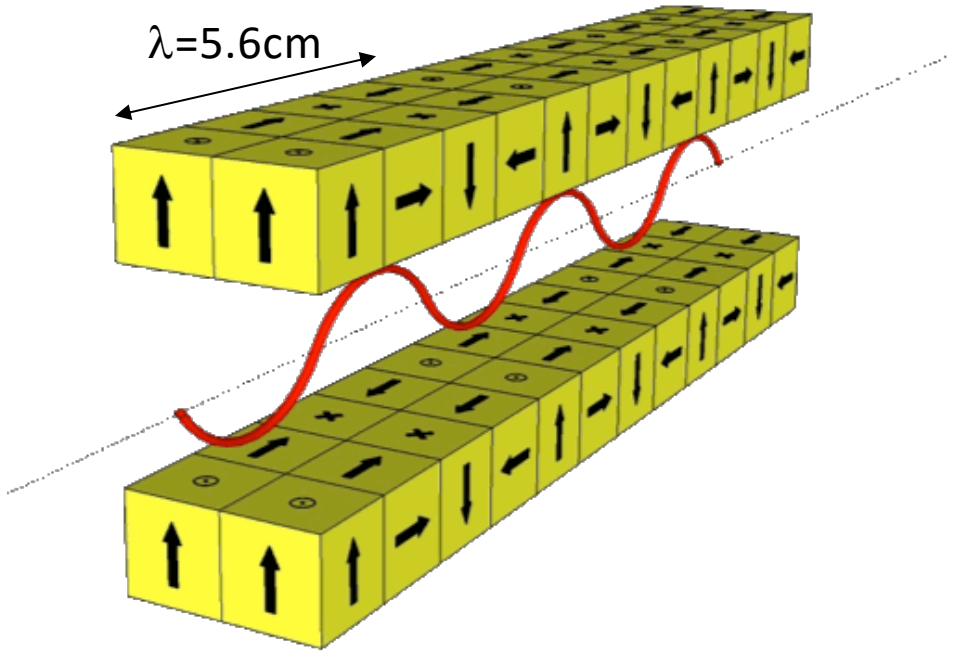
Dichroism

In optics, a **dichroic** material is one in which light rays having different polarizations are absorbed by different amounts.

Wikipedia

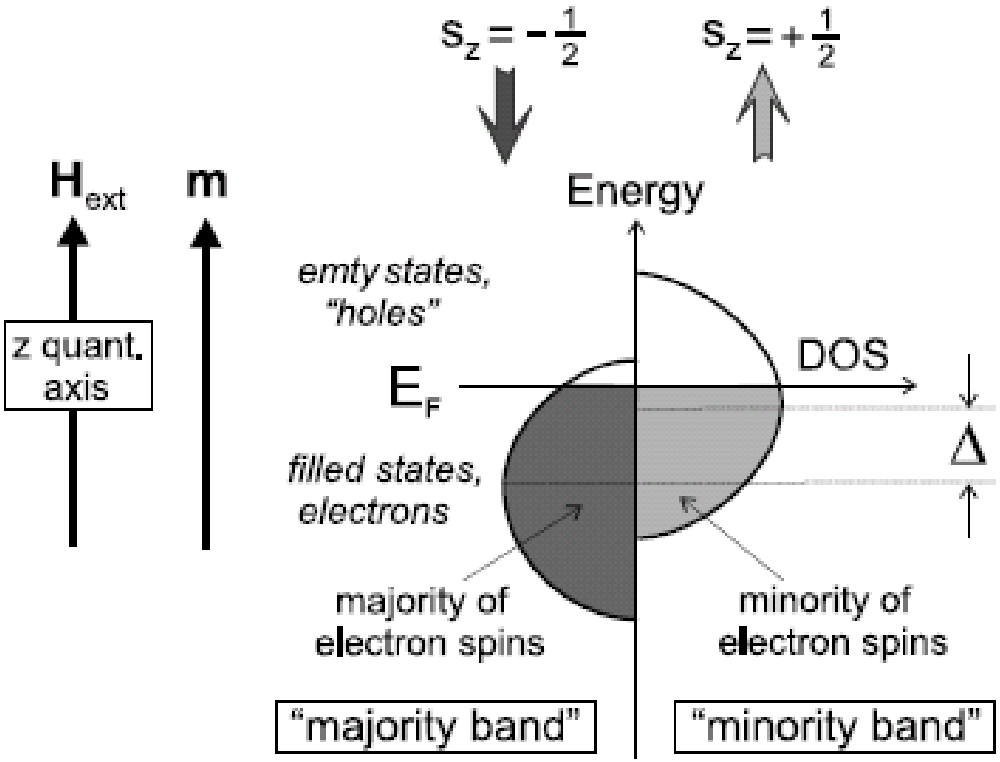
APPLE undulator principle





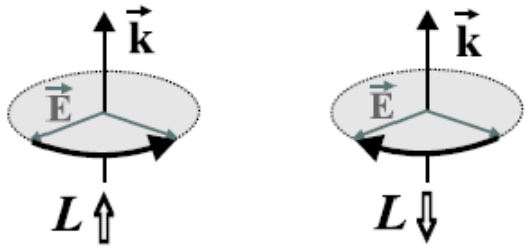
Courtesy T. Schmidt

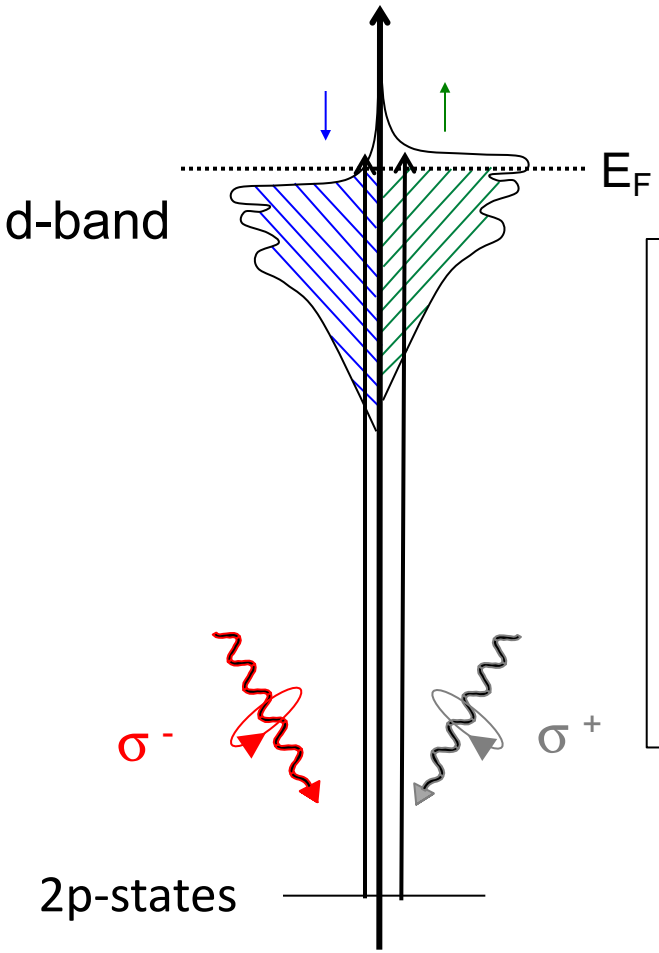
Stoner model for magnetism



$$|\boldsymbol{m}| = \mu_{\mathrm{B}} \left(N_{\mathrm{e}}^{\mathrm{maj}} - N_{\mathrm{e}}^{\mathrm{min}}\right) = \mu_{\mathrm{B}} \left(N_{\mathrm{h}}^{\mathrm{min}} - N_{\mathrm{h}}^{\mathrm{maj}}\right).$$

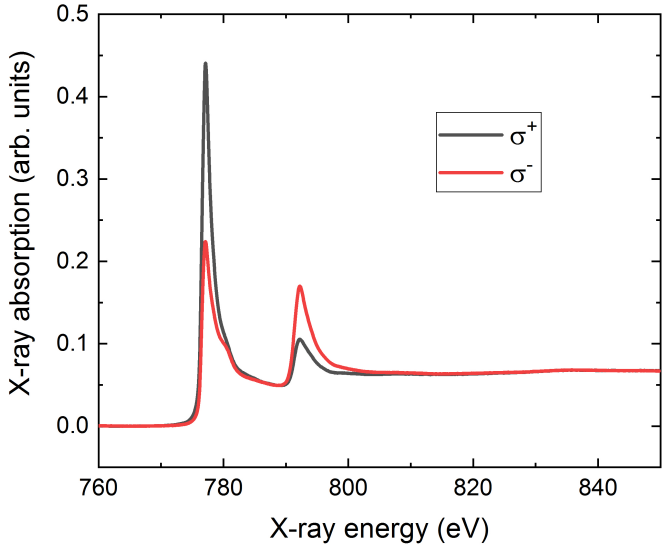
X-ray Magnetic Circular Dichroism

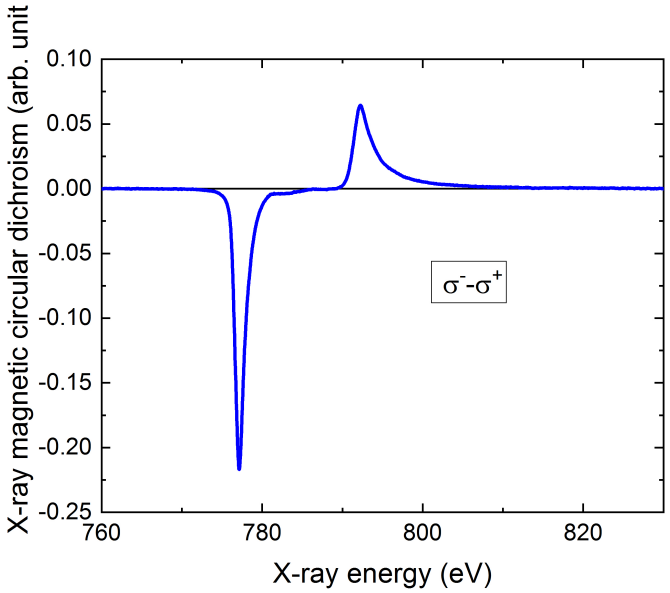




in l.s coupling dipole selection rules turn to:
$\Delta J = \pm 1$ or 0

for circular light:
$\Delta Mj = \pm 1$ for $\sigma\pm$





Sum rules

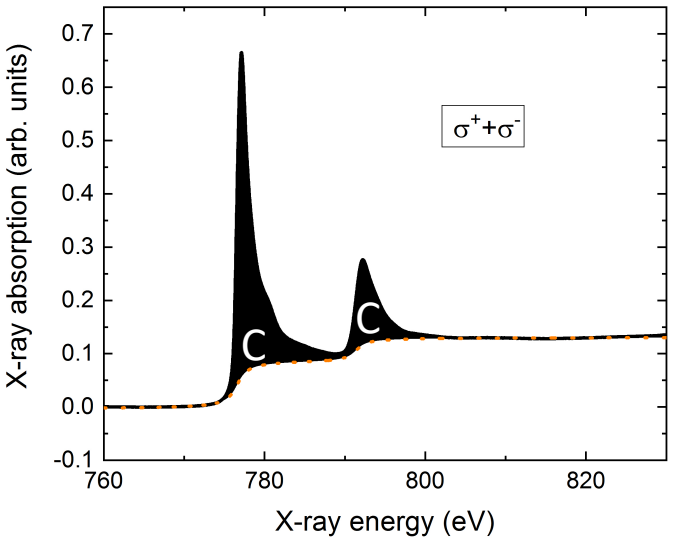
intra-atomic magnetic dipole

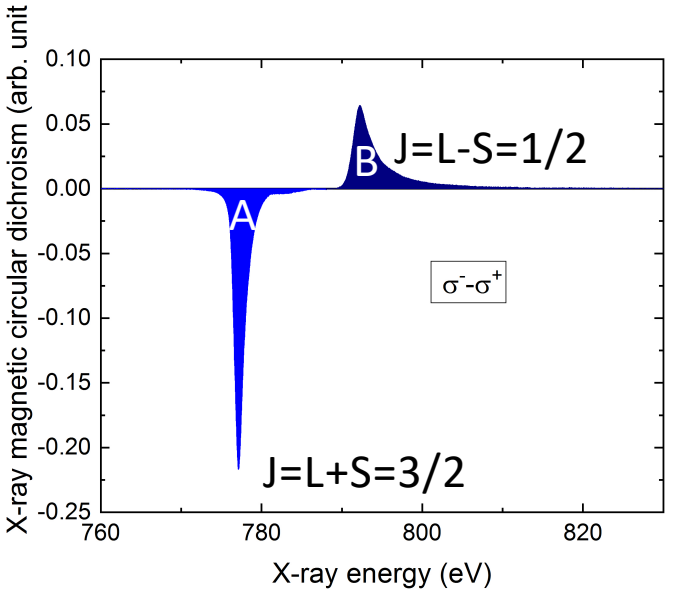
$$\langle S_{eff} \rangle = \langle S_z \rangle + \frac{7}{2}\langle T_z \rangle = \frac{A-2B}{C} n_h$$

$$\langle L_z \rangle = \frac{4(A+B)}{3C} n_h$$

Separately determine **spin** and **orbital** magnetic moments

n_h=number of holes in 3d band





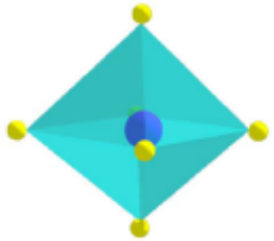
B. T. Thole *et al*. PRL **68** 1943 (1992)

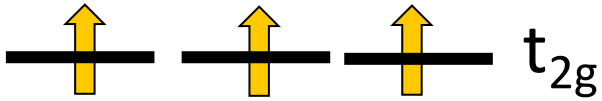
P. Carra *et al*. PRL **70** 694 (1993);

C. T. Chen *et al.* PRL **75** 152 (1995);

X-ray Natural Linear Dichroism (XNLD)

Mn^{3+} $3d^4$





D. Pesquera, *et al.*, Nat. Comm. **3**, 1189 (2012).

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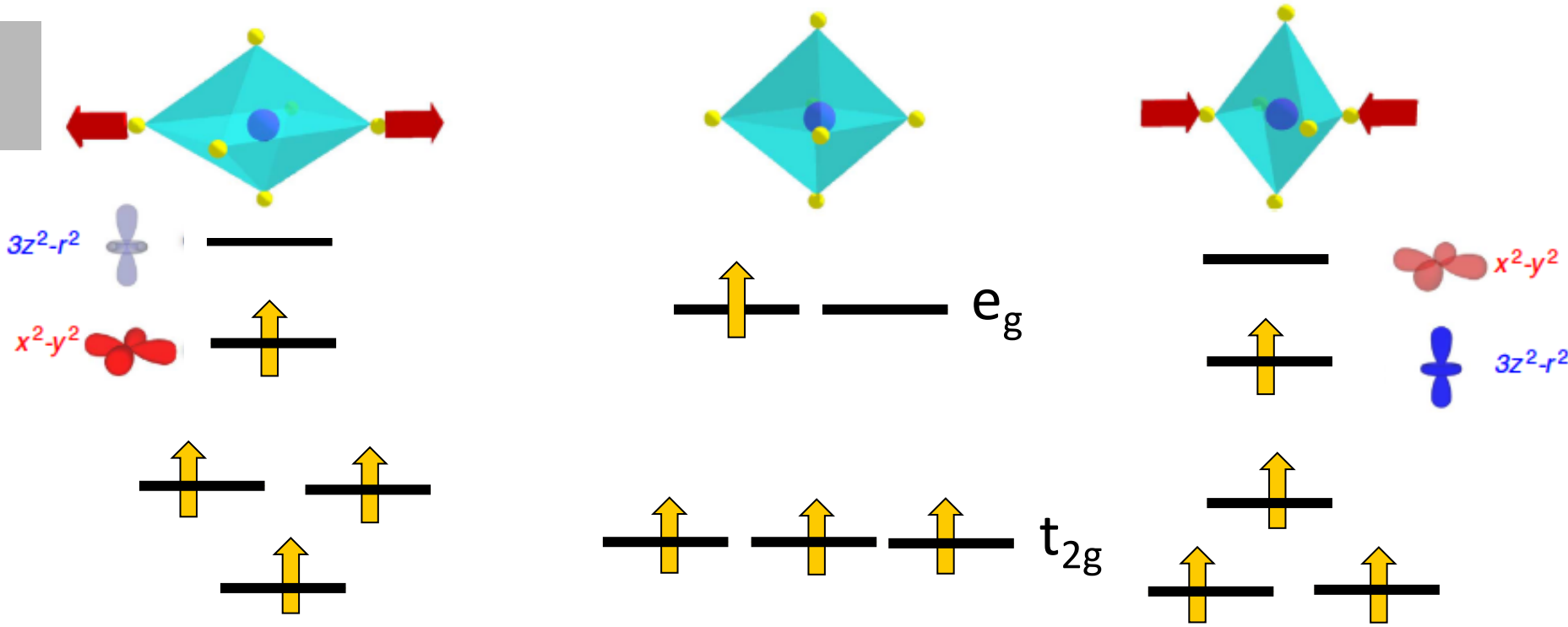

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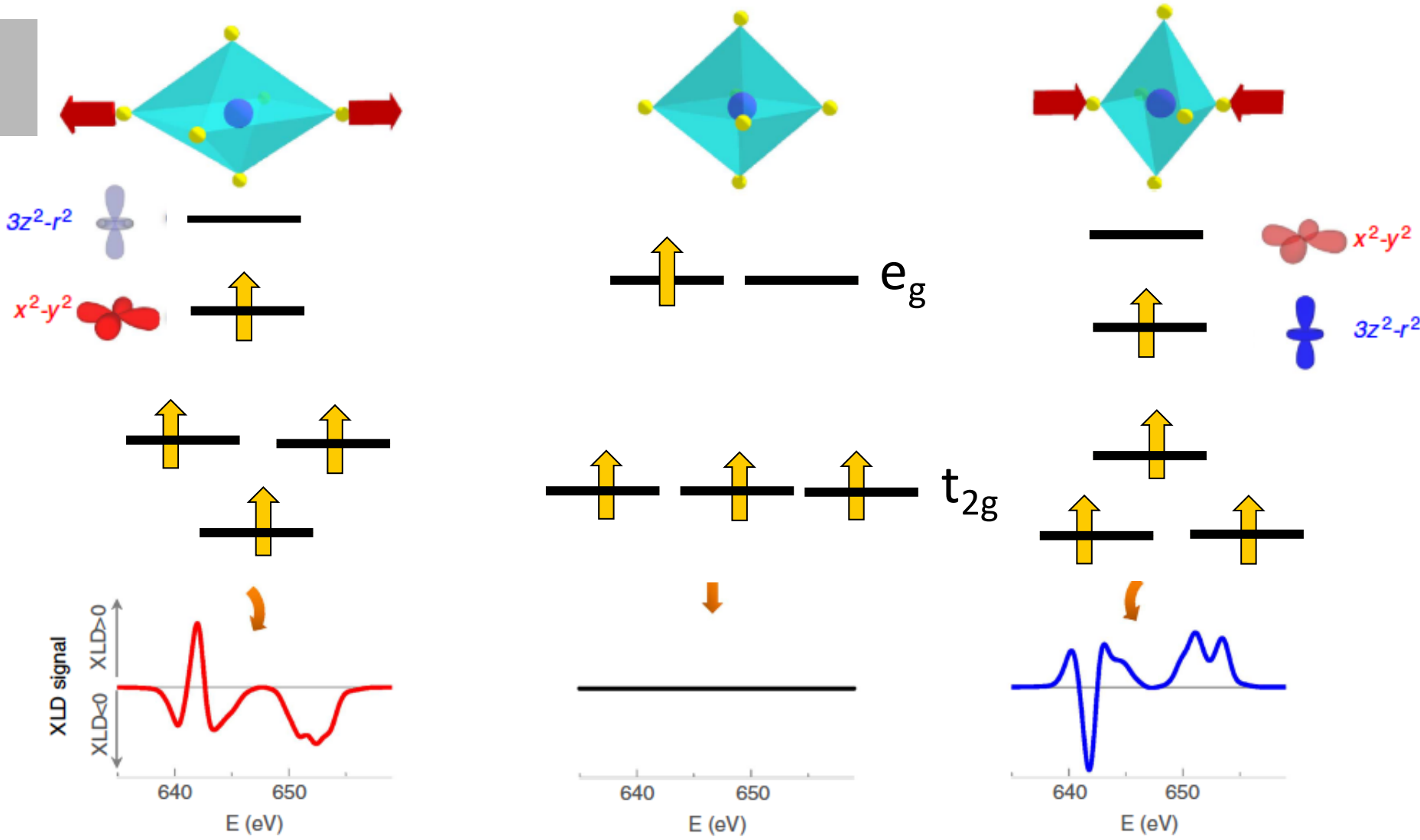
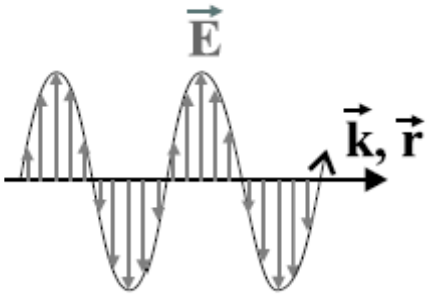


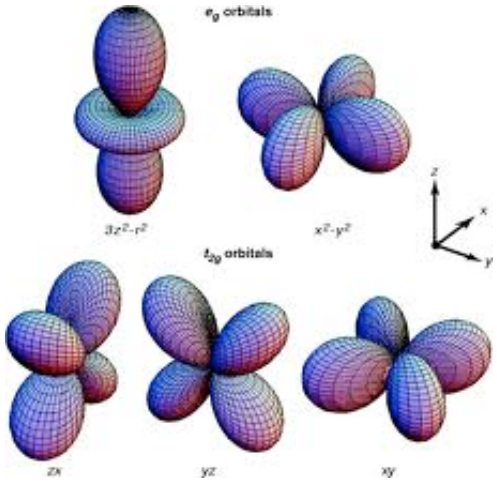
D. Pesquera, *et al.*, Nat. Comm. **3**, 1189 (2012).

Linear Dichroism

Probe:

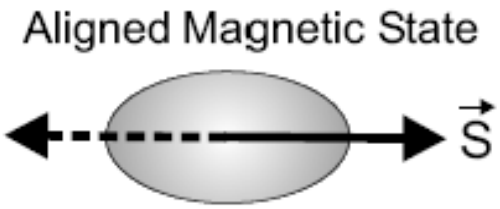
Linearly polarized x-rays





Natural linear dichroism:

probes orbital anisotropy



Magnetic linear dichroism:

probes anisotropy due to magnetic moment

Proportional to $\langle m^2 \rangle$: sensitve to antiferromagnetic ordering

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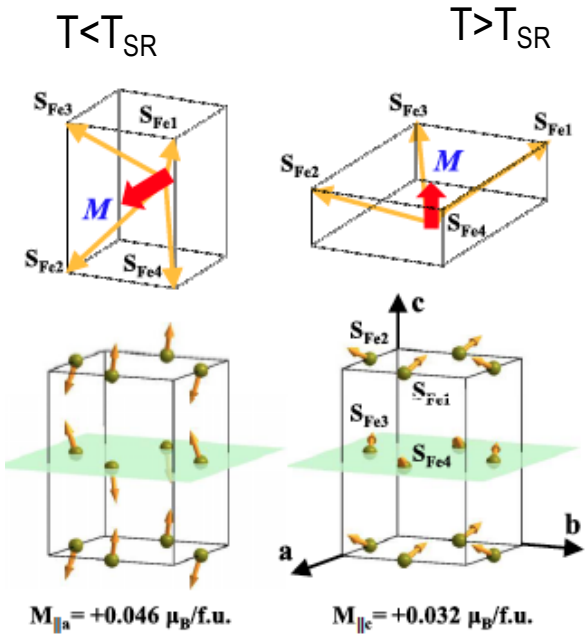
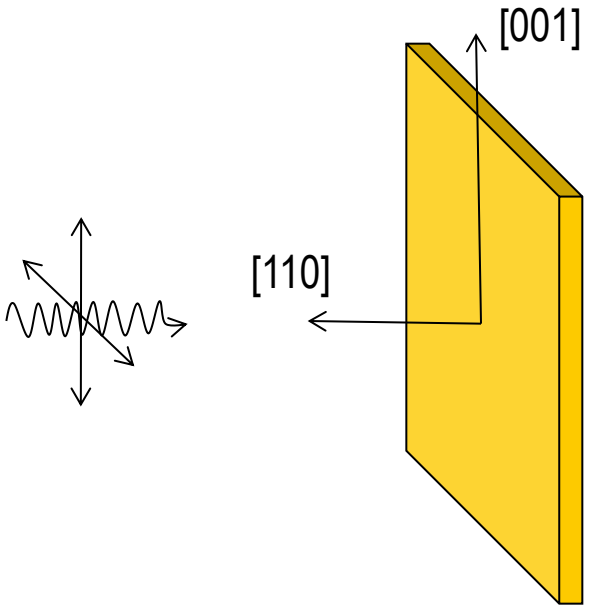
$SmFeO_3$

Spin reorientation transition



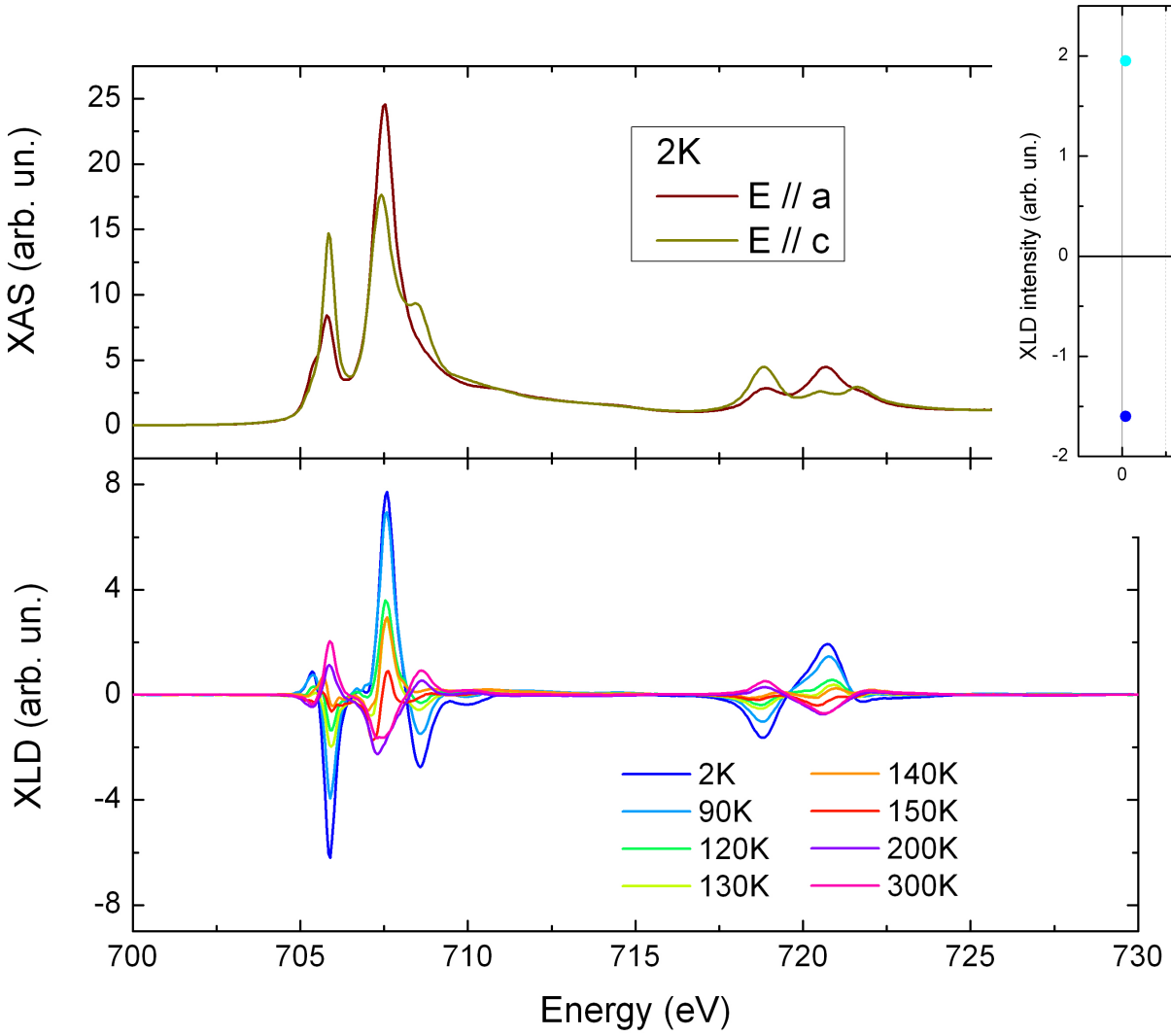
Sample:

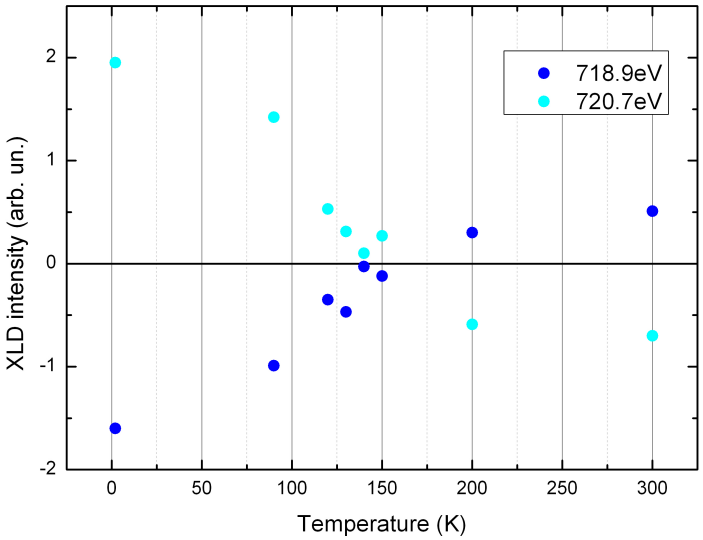
$SmFeO_3$ on $SrTiO_3$[110]



Lee *et al. PRL* **107,** 117201 (2011).

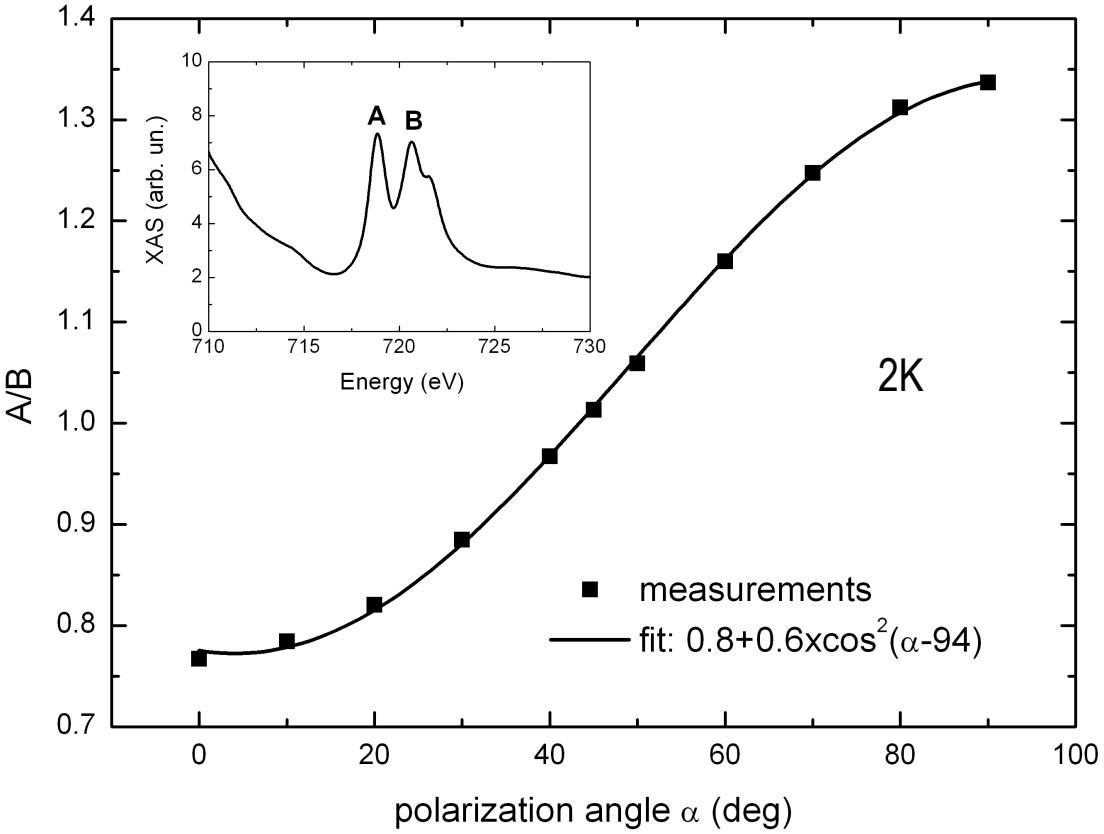
XMLD on $SmFeO_3$

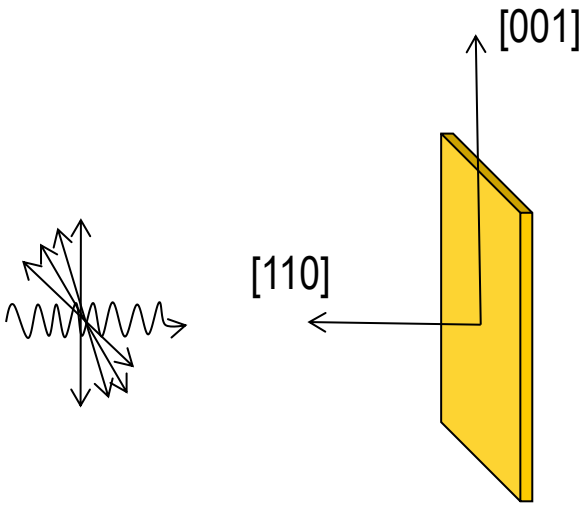




Piamonteze, C. *et al. J. Synch. Rad.* **19,** 661 (2012).

XMLD on $SmFeO_3$





proportional to $\cos^2\theta$

θ: angle between polarization and **M**

Piamonteze, C. *et al. J. Synch. Rad.* **19,** 661 (2012).

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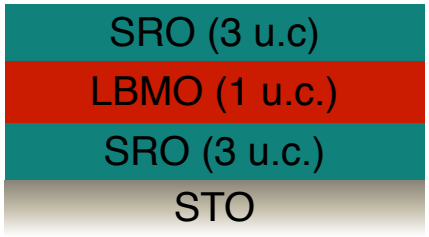
SRO/LBMO/SRO trilayers

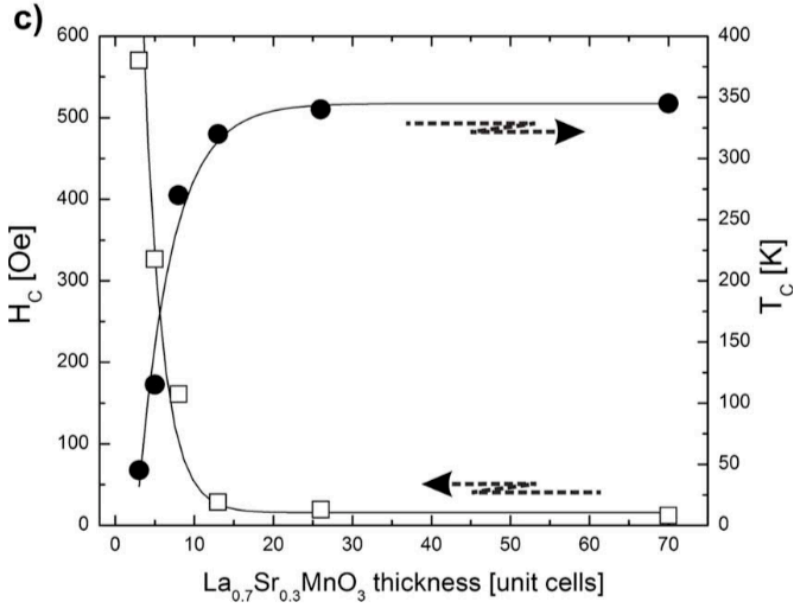


SRO= $SrRuO_3$

LBMO=$La_{0.7}Ba_{0.3}MnO_3$

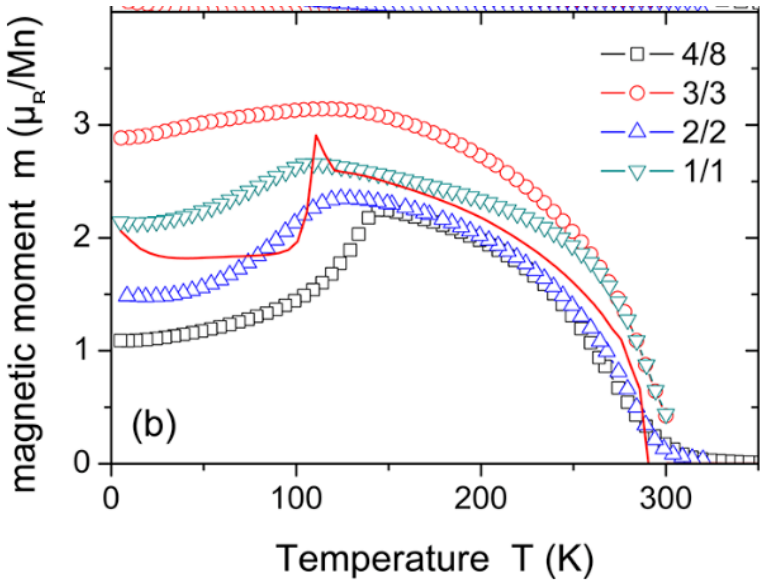
STO=$SrTiO_3$

LSMO/STO => magnetic "dead" layer



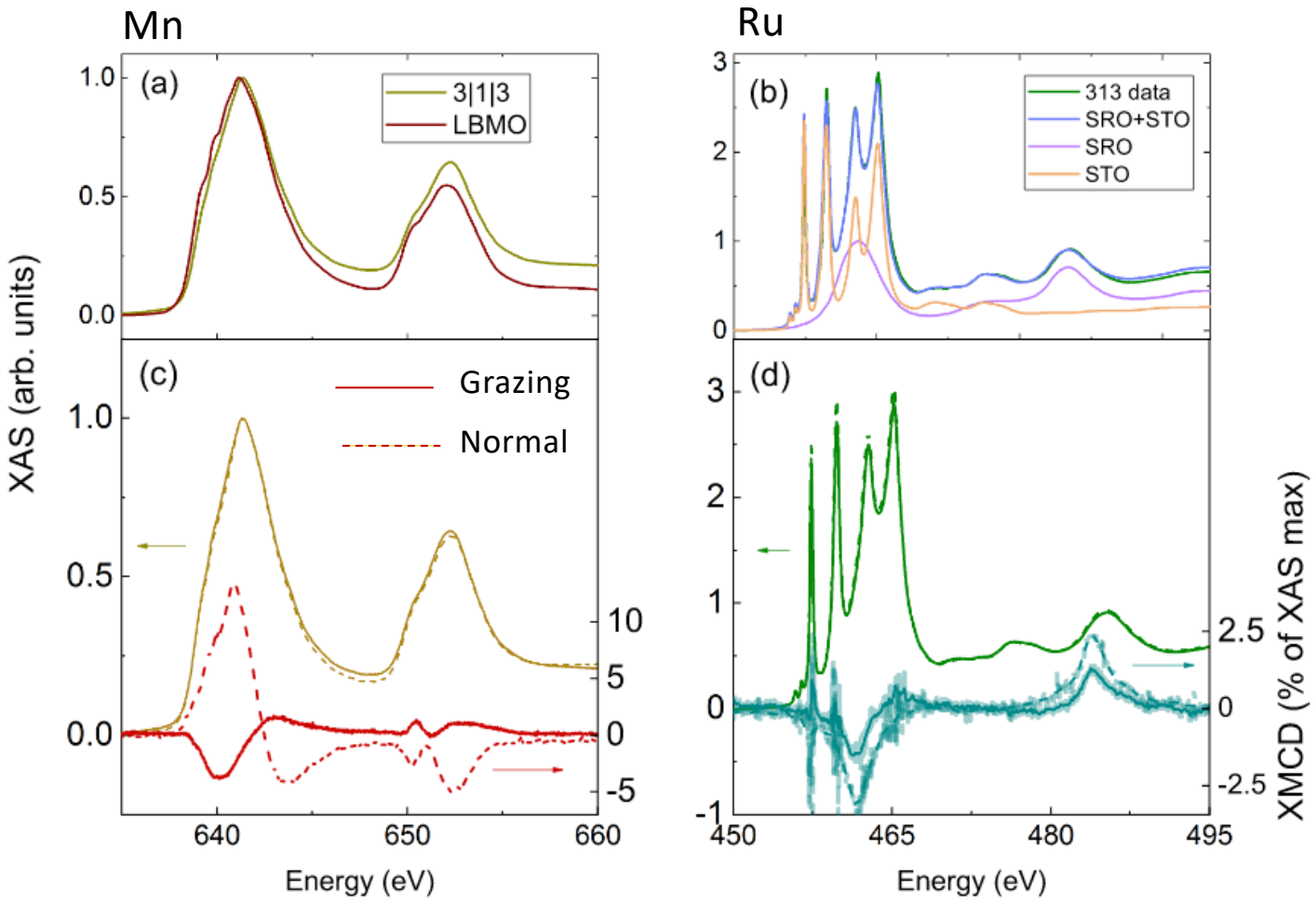
Huijben, M. *et al. PRB* **78,** 094413 (2008).

LSMO/SRO superlattices



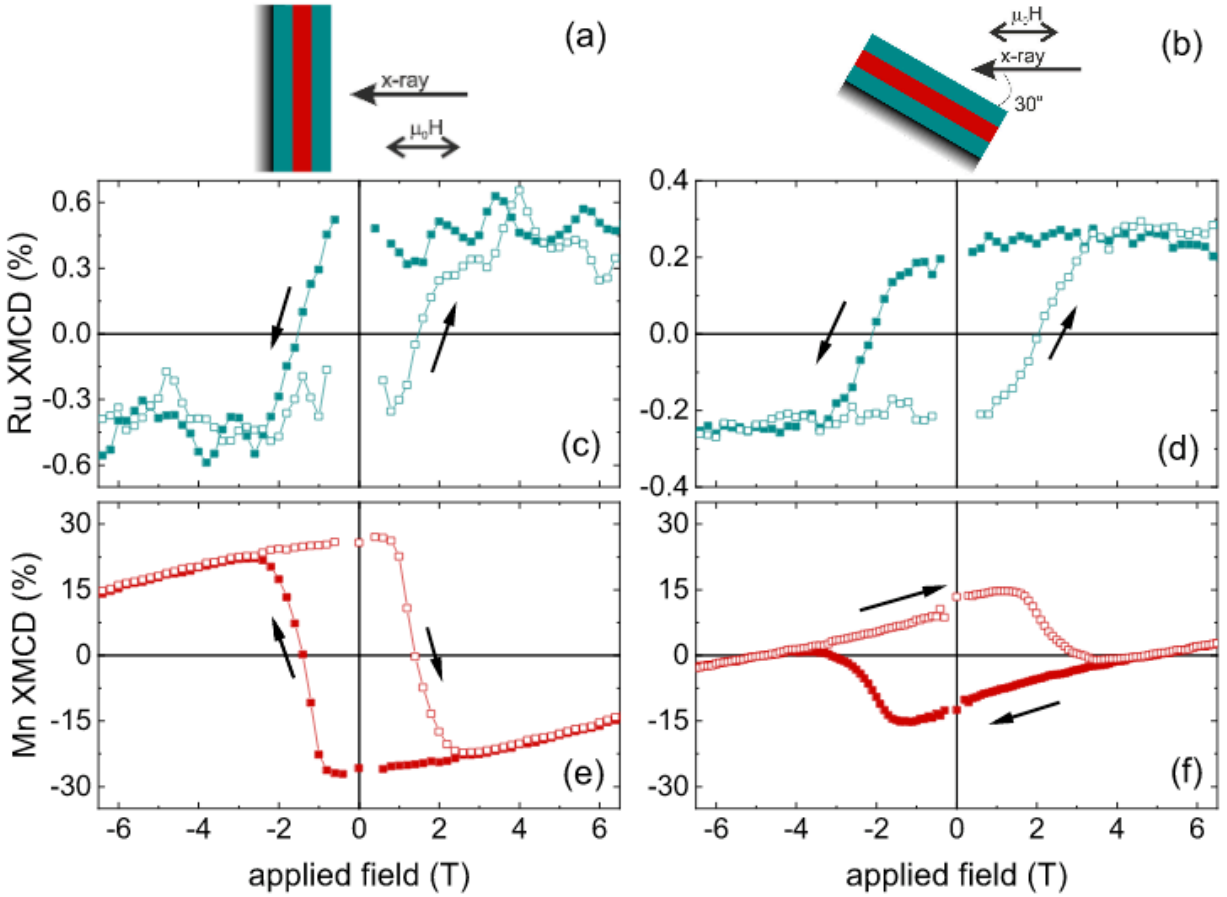
Ziese, et al *Nano Letters* **12,** 4276 (2012).

SRO/LBMO/SRO - XMCD



Piamonteze et al., arXiv:2101.01940

SRO/LBMO/SRO – element specific magnetization

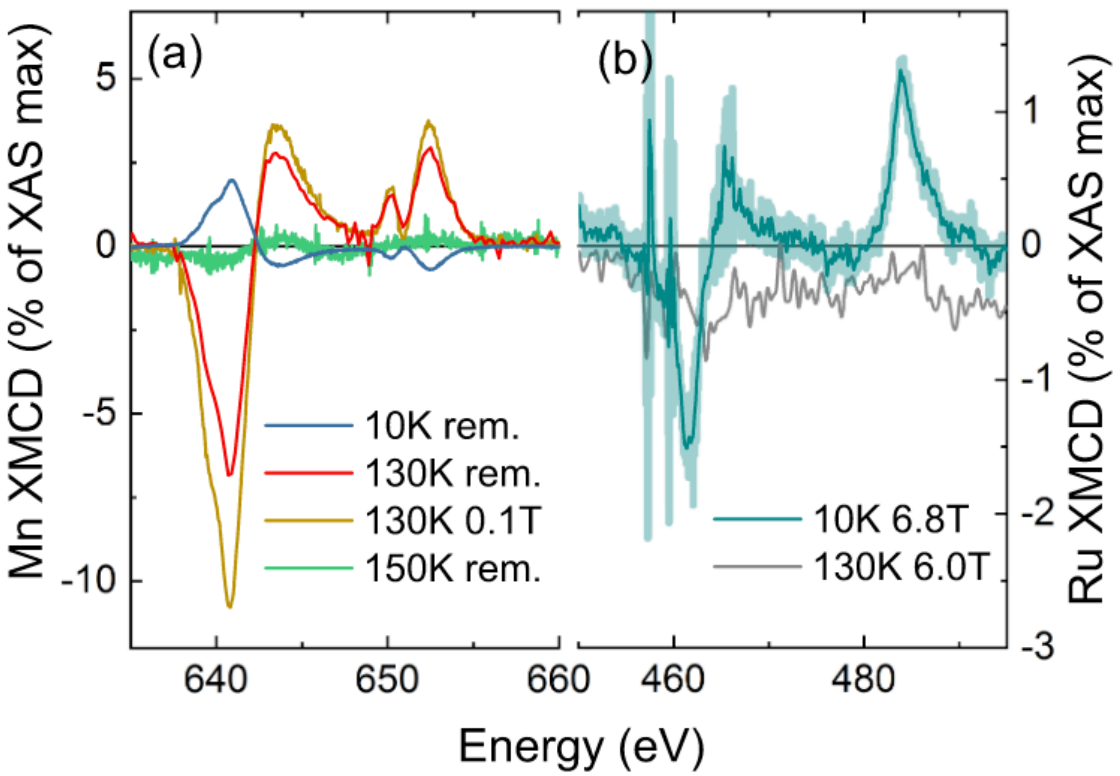


SRO easy axis is out of plane

Ru-Mn antiferromagnetic coupling

Piamonteze et al., arXiv:2101.01940

SRO/LBMO/SRO – XMCD T dependence



1ML of LBMO shows magnetic remanence at 130K

Piamonteze et al., arXiv:2101.01940

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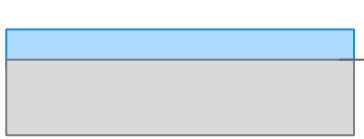
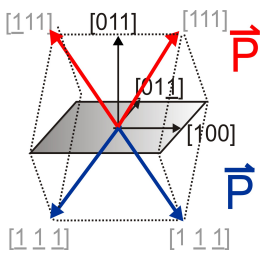
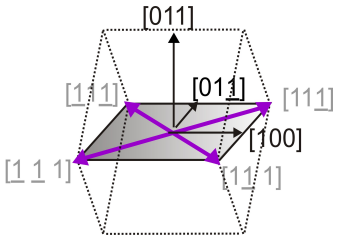
LSMO/PMN-PT

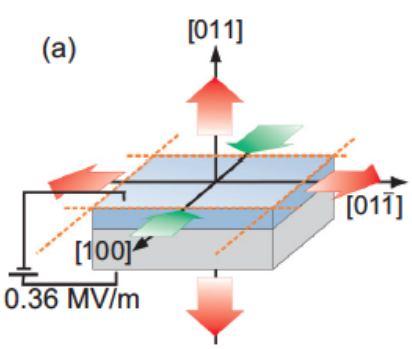


Relaxor/Ferroelectric
$[Pb(Mg_{1/3}Nb_{2/3})O_3]_{0.68}$-$[PbTiO_3]_{0.32}$ (011)

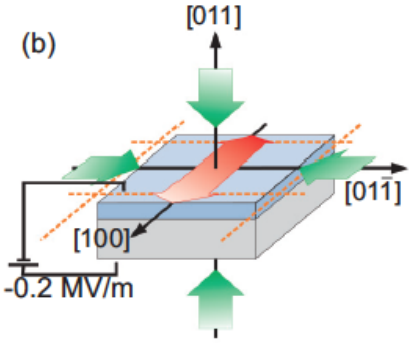




T. Wu *et al.*, J. Appl. Phys. **109**, 124101 (2011)



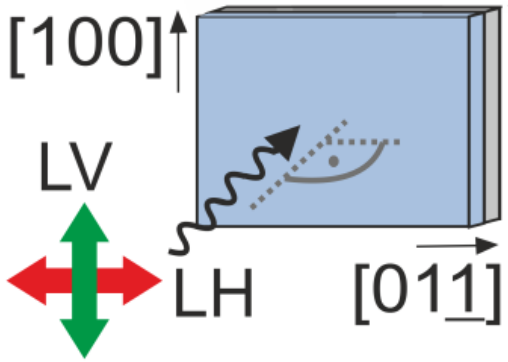
strain upon out of plane FE poling

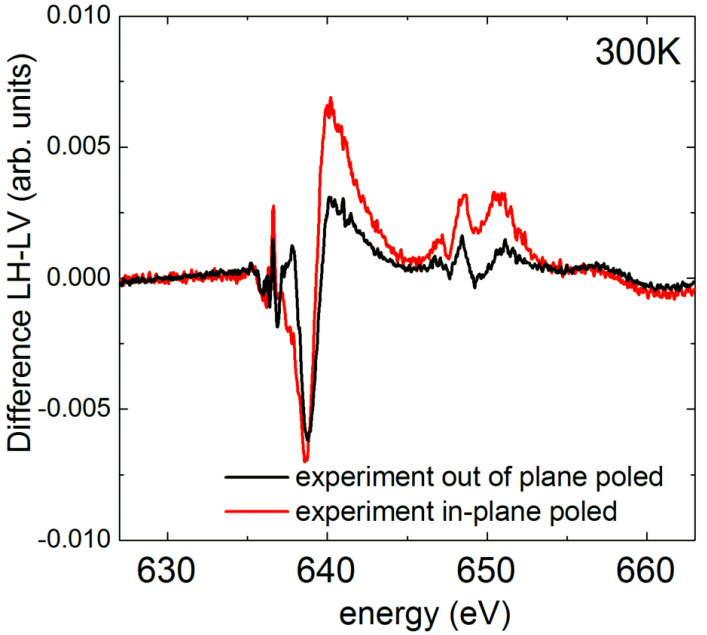


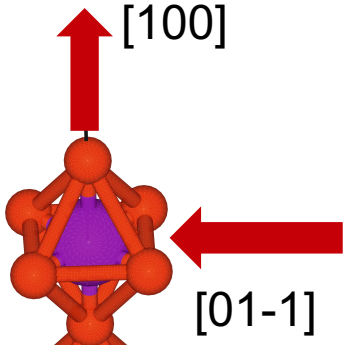
strain upon in plane FE poling

X-ray natural linear dichroism (XNLD)

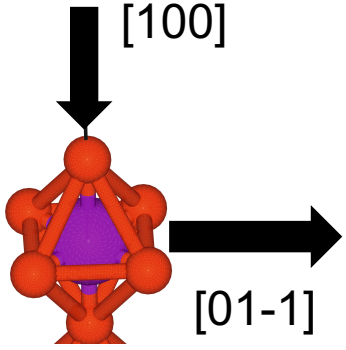
$$XNLD = I^{[01\text{-}1]} - I^{[100]}$$







In plane poled



out of plane poled

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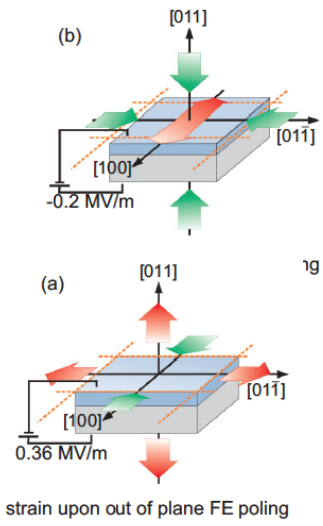
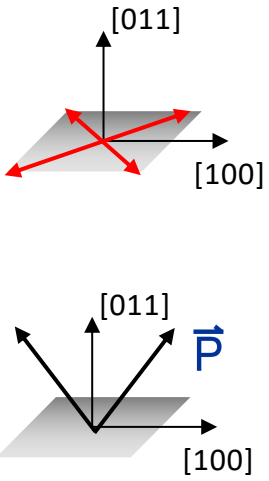
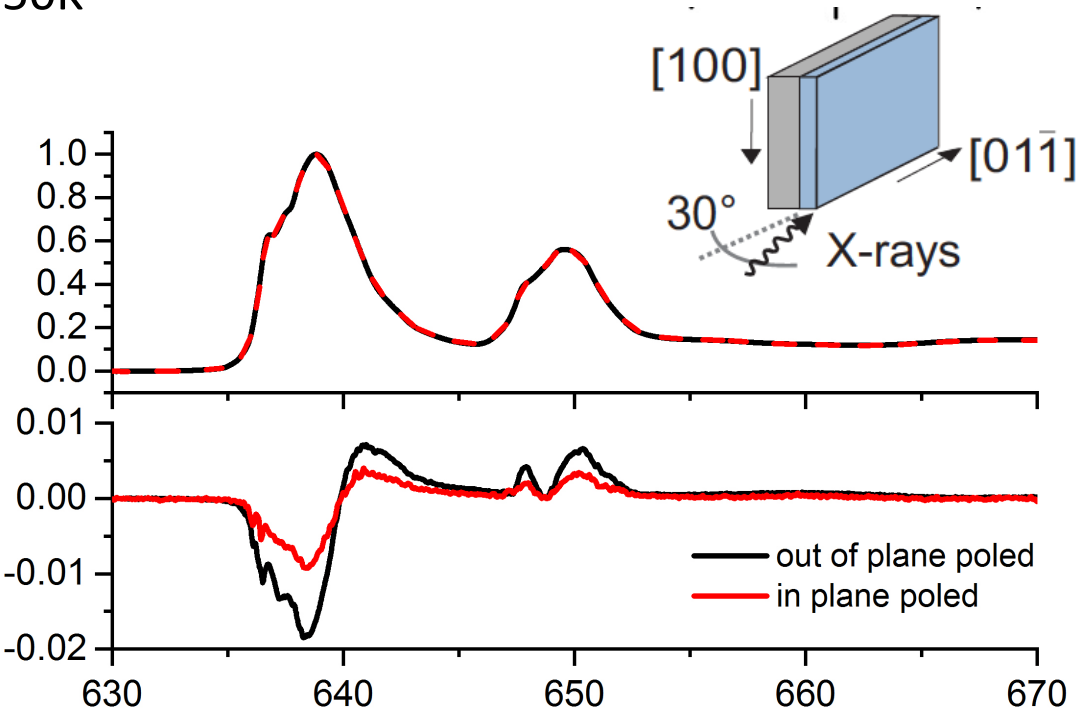
Magnetic response vs. FE polarization

Switching FE Polarization in plane vs. out of plane

XMCD in remanence at 250K







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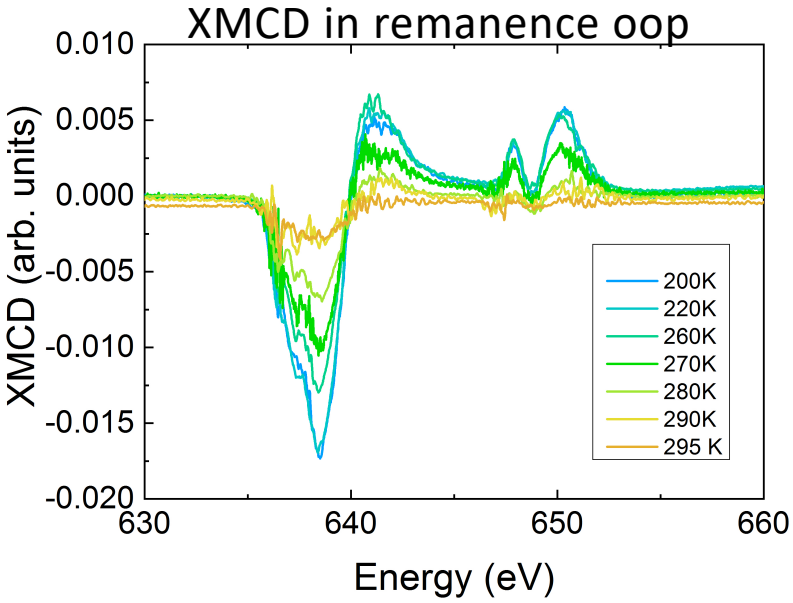
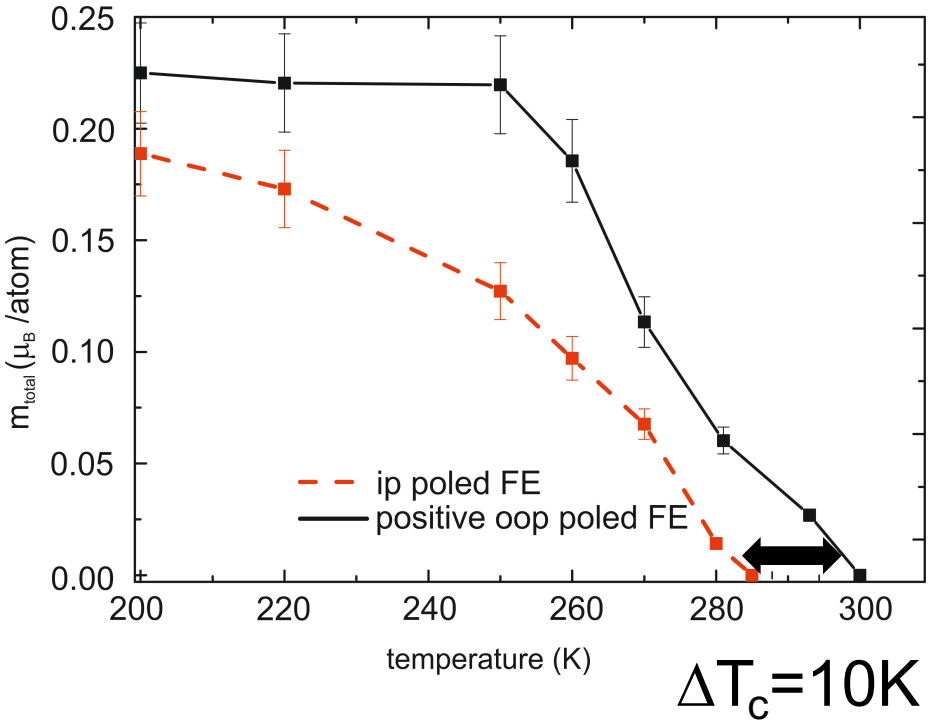
Curie temperature for different FE polarizations





ΔT_c=10K

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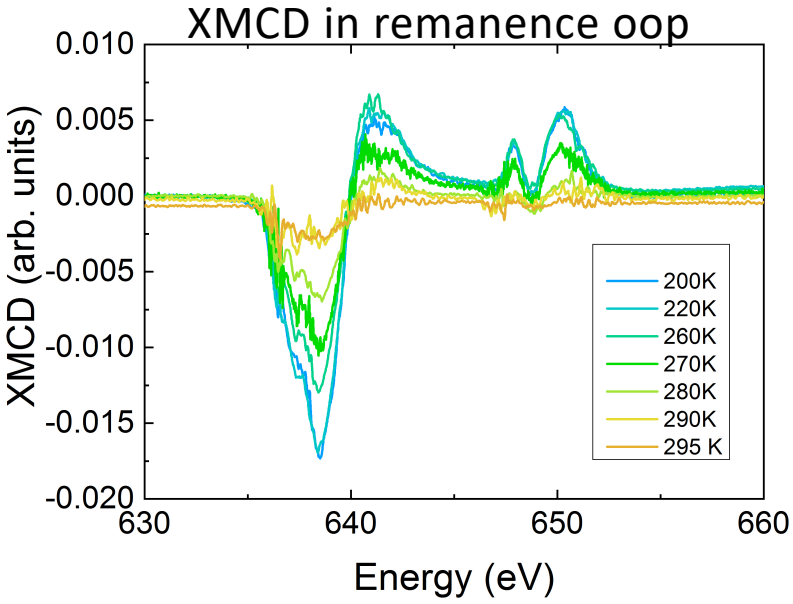
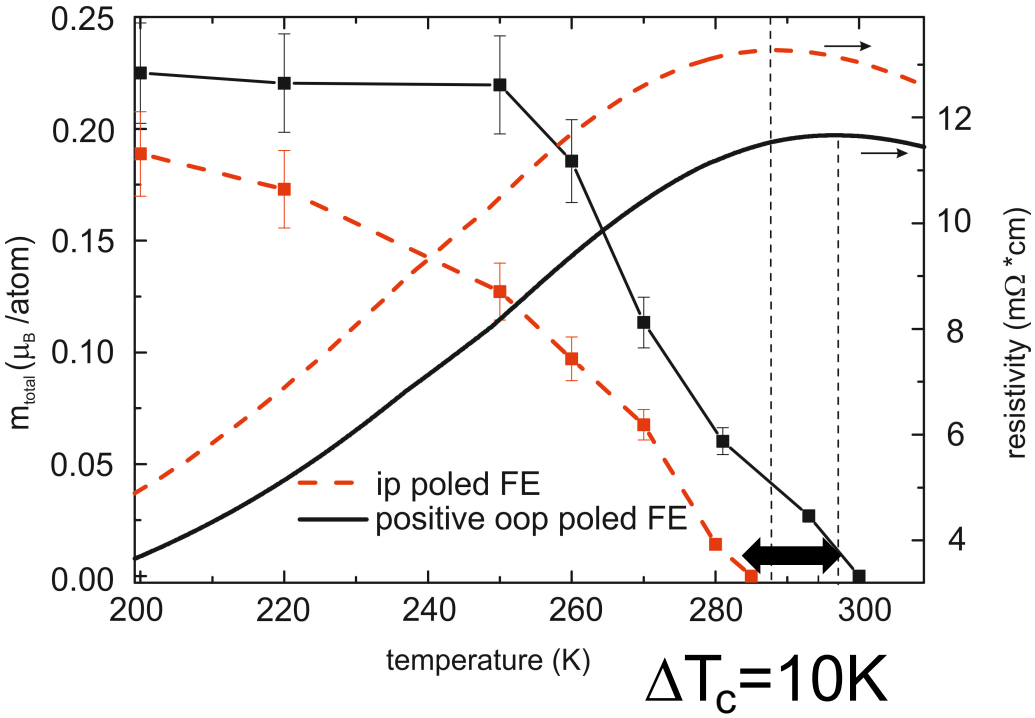
Curie temperature for different FE polarizations





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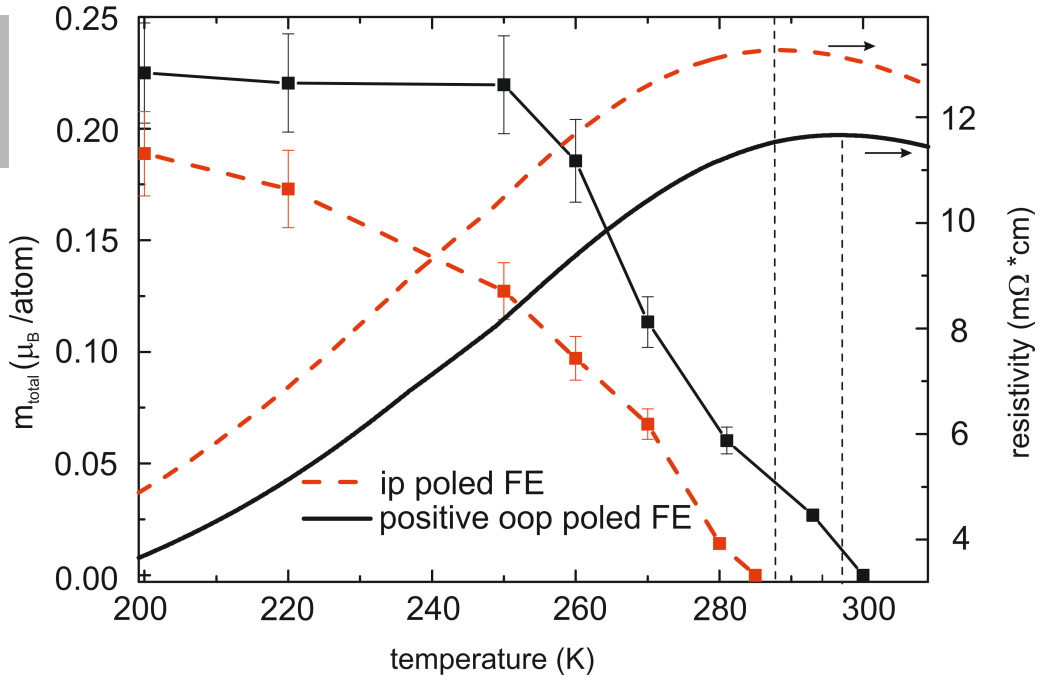
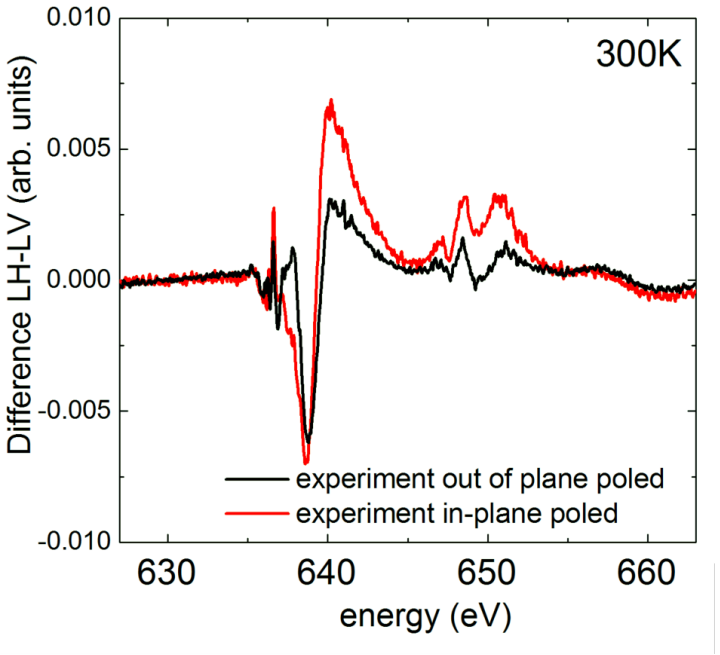
LSMO/PMN-PT





In-plane polled state increases the in-plane orbital anisotropy causing electron localization and reduction in Tc

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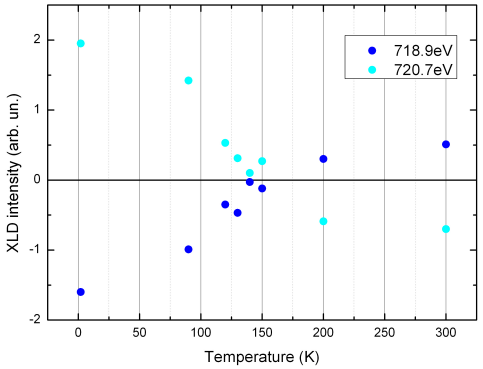
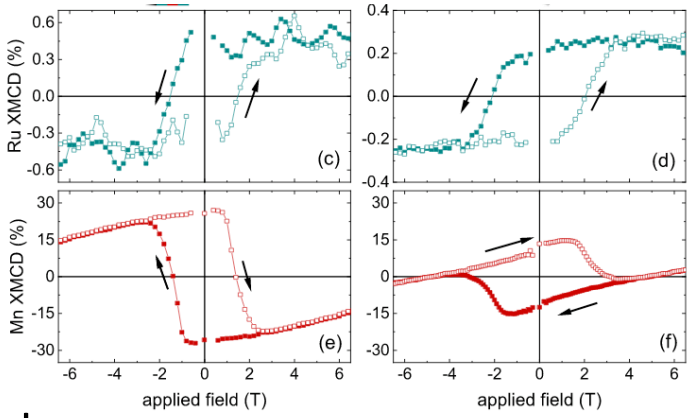
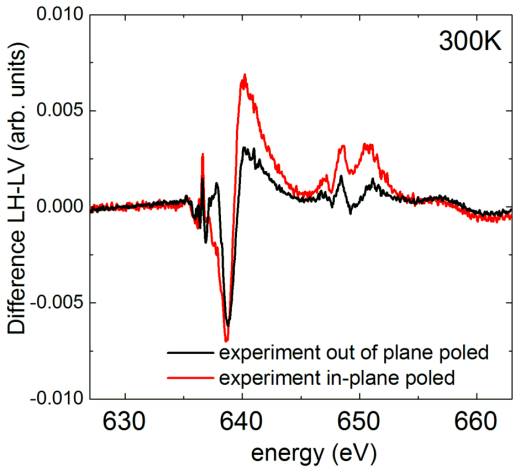
Summary

- XAS characteristics
  - Element specific
  - Information on valence and site symmetry
- XMLD:
  - Probes antiferromagnetism (as well as ferromagnetism)
- XMCD:
  - Probes ferromagnetism
  - Element specific magnetization curves
  - Quantification of magnetic moment through sum rules
- XNLD:
  - Probes orbital anisotropy







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