Soft X-ray Physics

• Overview of research in Prof. Tonner’s group
• Introduction to synchrotron radiation physics
• Photoemission spectroscopy: band-mapping and photoelectron diffraction
• Magnetic spectroscopy
• X-ray microscopy and spectro-microscopy
The Three Principle Soft X-ray Spectroscopies

- X-ray Absorption Fine Structure (XAFS)
- X-ray Fluorescence Spectroscopy (XRF)
- X-ray Photoemission Spectroscopy (XPS)
Note the increases in absorption at characteristic energies.
Three methods of XAS measurement
(X-ray Absorption Spectroscopy)

(a) Transmission—bulk properties

\[ I_t = I_0 e^{-\mu(\hbar\omega)d} \]
\[ \mu(\hbar\omega) = -\frac{1}{d} \ln \left( \frac{I_t}{I_0} \right) \]

(b) Total electron yield—surface properties

(c) Fluorescence—dilute species; Buried interfaces
Electron yield X-ray Absorption Spectroscopy

\[ i_{\text{yield}} \propto \hbar \omega \mu(\hbar \omega) \]
Information in X-ray Absorption Spectroscopy

- Near-edge region
  - 0-50 eV
  - Valence transitions
  - Multiple-scattering theory
  - Chemical bonds
    - (NEXAFS or XANES)

- Extended X-ray Absorption Fine Structure (EXAFS)
  - >50 eV to several 100’s of eV
  - Near-neighbor geometry

“White” lines
Background Removal of Continuum Contributions

![Graph showing Mn L\textsubscript{2,3} Absorption Intensity vs. Photon Energy for 0.8 ML Mn/Cu(001) and 21 ML Mn/Cu(001).]
Mn L-edge XAFS of Bio-inorganic compounds

L-edge structure from 2p to 3d dipole allowed transitions

Structure in near-edge can often be explained by atomic theory of crystal field effects

Many materials do not agree with atomic theory, because they have more de-localized orbitals—need a many-body theory
Above plane, +

Below plane, -

Photons carry angular momentum (spin), which is parallel or anti-parallel to the direction of propagation for circularly polarized light.

\[ I_{\text{XMCD}} \propto \vec{\Sigma} \cdot \vec{M} \]

The effect is an atomic physics effect: Spin-orbit splitting of d-shell electrons.

Fe L-edge absorption

Absorption Intensity

[Graph showing Fe L-edge absorption with photon energy in eV on the x-axis and absorption intensity on the y-axis, with peaks at different energies and a label for \( I_{\text{XMCD}} \).]
The technique of X-ray Magnetic Circular Dichroism (XMCD)

\[ I_{XMCD} \propto \sum \cdot \vec{M} \]
XMCD: Element specific magnetometry

Absorption Intensity

Photon Energy (eV)

XMCID

2 ML Fe
8 ML fcc Co
Cu(001)

20
40
60

0
20
40
60

Fe
Co

-40
-20
0
20
40
60

XMCID Intensity
Spin and Orbital Contributions to Magnetic moment

- Total moment is $M = (L + 2S)\mu_B$.
- For (Fe, Co, Ni), $L/2S$ is about 1/10, so the orbital moment is small, but....
- Orbital moments contribute significantly to the magnetic anisotropy (spin-orbit)

Orbital moments may be enhanced at surfaces or interfaces.
Dichroism sum rules

\[ M_{\text{orbit}} = L_3 + L_2 \]

\[ M_{\text{spin}} = |L_3| + 2|L_2| \quad \text{L}_3 \]

\[ M_0 = \frac{4}{3} \hbar \frac{\int \sigma_M d\omega}{\int (\sigma_+ + \sigma_-) d\omega} \]

\[ M_S + 7M_D = 2\hbar \frac{\int \sigma_M d\omega}{\int (\sigma_+ + \sigma_-) d\omega} \]

\[ \frac{M_0}{M_S + 7M_D} = \frac{2}{3} \cdot \frac{\int \sigma_M d\omega}{\int \sigma_M d\omega} \]

Absorption Intensity

Photon Energy (eV)
Schulz and Baberschke* have already determined $K_I+K_S$ (Interface plus surface anisotropy) to be -0.38 ergs/cm$^2$

Note this favor in-plane M

Using this value and the results presented here we determine that

$K_I$=-0.16 ergs/cm$^2$

$K_S$=-0.22 ergs/cm$^2$

This means: both interface and surface anisotropy are negative.

*PRB 50 13468 (1994).
XMCD Magnetometry of Ultrathin films

- Main features are film independent
- Coercivities rise sharply near the critical thickness
XMCD Microscopy

X-RAYS

OBJECTIVE

INTERMEDIATE

PROJECTIVE

DETECTOR

Stigmator / Deflector

Pinhole

SAMPLE

(A) Linear polarization: Topographical information

(B) Circular polarization difference image: Magnetic bit information
Step bunches can explain anomalous uniaxial anisotropy

Two different sites for atoms
• near steps - strong uniaxial anisotropy
• terrace - weaker uniaxial anisotropy (non-zero)

Magnetization Reversal along anomalous axis: Schematic explaining the magnetization reversal along the anomalous “easy” axis of magnetization for miscut fcc Co films. There are two spin sites, a terrace site which has a weak uniaxial anisotropy which may or may not be zero and a step site which has a strong uniaxial anisotropy.
XMCD microscopy of step bunch domains
Co/Cu ultrathin films

Spontaneous domain formation

Hard-axis magnetization

110 Easy axis

20 µ

Ordinary easy axis

Anomalous easy axis

20 µ

10 µ