Magnetic and Atomic Structures
Studied by
Soft X-ray Spectroscopies

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Outline

1. Magnetic structure (XMCD)
2. Surface and Interface (depth-resolved XAFS)
3. Future plans at a new soft X-ray beamline, PF-BL-16A
Magnetic Structures Studied by L/T Geometry Angle-dependent XMCD

XMCD (X-ray Magnetic Circular Dichroism)

Element selectivity
Quantitative determination of spin & orbital magnetic moments by using the sum rules

Angle-dependent XMCD
⇒ Magnetic anisotropy
Separation of $m_s$ from $m_T$

Angle-dependent XMCD in Longitudinal (L) Geometry

Au/Co(2 ML)/Au(111)

Self-assembled Co islands due to a reconstruction of Au surface

All Co atoms are regarded to “interface” because of 2 ML thickness

⇒ Direct observation of interface magnetism

Angle-dependent XMCD

⇒ Direct determination of $m_s$, $m_{\|}$, $m_{\perp}$, $m_{\|}$, $m_{\perp}$
Sum rules in Longitudinal (L) geometry

Orbital sum rule (L geometry)

\[
\frac{[\Delta I_{L_3} + \Delta I_{L_2}]^\theta}{I_{L_3} + I_{L_2}} = -\frac{3 \cdot m_{\text{orb}}^\theta}{4 n_h \cdot \mu_B}
\]

Spin sum rule (L geometry)

\[
\frac{[\Delta I_{L_3} - 2 \cdot \Delta I_{L_2}]^\theta}{I_{L_3} + I_{L_2}} = -\frac{(m_{\text{spin}} + 7 \cdot m_T^\theta)}{2 n_h \cdot \mu_B}
\]

P. Carra et al., PRL 70, 694 (1993).
Angle-dependent XMCD Measurements


Angle dependence in XMCD

Anisotropy in $m_l$, $m_T$

$$m_j^\theta = m_j^\perp \cos^2 \theta + m_j^\parallel \sin^2 \theta$$

(j = l or T)

$$m_T^\perp + 2 m_T^\parallel = 0$$

⇒ Determination of all moments including their anisotropy
Determined Magnetic Moments

Cluster-size dependent phase transition
Angle-dependent Sum Rules

\[ L_{\parallel} = \langle L_{\parallel}^z \rangle \cos^2 \theta + \langle L_{\parallel}^z \rangle \sin^2 \theta \]

Transverse sum rule

\[ L_{\perp} = \frac{1}{2} \left[ \langle L_{\perp}^z \rangle - \langle L_{\perp}^z \rangle \right] \sin 2\theta \]

\[ T_{\parallel} = \frac{1}{2} \left( \frac{7}{2} \langle T_z \rangle - 3\sin^2 \theta - 1 \right) \]

Spin sum rule

\[ S_{\parallel}^{\text{eff}} = \frac{3}{4} \left( \frac{7}{2} \langle T_z \rangle \right) \sin 2\theta \]

\[ S_{\perp}^{\text{eff}} = \hat{S} \cdot \hat{T} + \frac{7}{2} \hat{S} \cdot \hat{T} \]

\[ \theta = 45^\circ \]

// → Longitudinal
⊥ → Transverse
Outline

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   PF-BL-16A
Principle of Depth-resolved XAFS (XMCD)

X-rays → Surface

Circularly polarized X-rays

Sample

Microchannel plate
Phosphor screen
CCD camera

Auger electrons

Surface sensitive

XMCD spectrum

Electron yield XMCD measurements at different detection angles

A set of XMCD spectra with different probing depths
Feasibility Study: Magnetic Depth Profile of Fe/Cu(100)

3 ML Fe

7 ML Fe


(Normal Incidence, 130 K)

Fe

Cu(100)

Uniform Magnetization

Surface Magnetization
Extraction of Surface and Interface XMCD spectra

Amemiya et al., PRB 72 (2005) 201404(R).

Ni 8 ML (Grazing Incidence)

(a) Cu/Ni/Cu(100)
- Interface $n_h = 1.48(5)$
- Inner layers $n_h = 1.45(5)$

(b) Ni/Cu(100)
- Surface $n_h = 1.59(6)$
- Inner layers $n_h = 1.44(5)$

Ni 9 ML (Normal Incidence)

(a) Cu/Ni/Cu(100)
- Interface $n_h = 1.46(5)$
- Inner layers $n_h = 1.45(5)$

(b) Ni/Cu(100)
- Surface $n_h = 1.59(6)$
- Inner layers $n_h = 1.45(5)$

Similar spectra for Interface and inner layers

Surface spectrum is drastically different
Large in-plane surface orbital moment
Depth-resolved Observation of Atomic Structures

Co L-edge EXAFS

Co (3 ML)/Ru(0001)

Intensity (arb. units)

Photon Energy (eV)

1st (surface)
2nd
3rd (interface)

Depth dependence of layer spacing
Outline

1. Magnetic structure (XMCD)

2. Surface and Interface
   (depth-resolved XAFS)

3. Future plans at a new soft X-ray beamline,
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Soft X-ray Beamline BL-16A

Variable Polarization
Circular & Linear (vertical/horizontal)
Construction: Jun.-Oct. 2007
Expected Photon Flux at BL-16A

L edges of 3d transition metals

M edges of rare-earth elements

Photon Energy (eV)

Photon Flux (photons/s)

G1 (undulator: 1st)

G2 (1st)

G2 (3rd)

E/ΔE = 4000

E/ΔE = 8000

L edges of 3d transition metals

M edges of rare-earth elements

Photon Energy (eV)

Photon Flux (photons/s)
Experimental Facilities

X-ray Resonant Magnetic Scattering

Angle-dependent XMCD (Superconducting magnet)

Three-dimensional XAFS/XMCD

Depth-resolved XAFS/XMCD XMCD-PEEM Soft X-ray Holography
Resonant Magnetic Scattering

Observation of periodic structures in nm scale
Simultaneous determination of atomic and magnetic structures

Commissioning from Oct. 2008
(T. Koide et al.)
Three-dimensional information on
Atomic Structure (EXAFS)
Electronic Structure (XANES)
Magnetic Structure (XMCD)

Commissioning from Nov. 2008
(Amemiya et al.)

X-ray Microbeam + Depth Resolution ⇒ 3D micro XMCD (XAFS)
Imaging-type Electron Detector

Surface Insensitive
Surface Sensitive
Fast Polarization-Switching Project

Twin APPLE-II type undulators for fast polarization switching (~10 Hz)

Lock-in technique $\Rightarrow$ Observation of small ($\sim 10^{-4}$) dichroism

Undulator II will be installed in 2010

Detection of Small XMCD Signals


Observation of weak ferromagnetism

Precise investigation for phase transition phenomena
Summary

Angle-dependent L/T geometry XMCD
Determination of $m_s$, $m_l$ and $m_T$ including their anisotropy

Depth-resolved XAFS/XMCD
Atomic, electronic and magnetic Structures at surface and interface

Future plans
Resonant Magnetic Scattering  Three-dimensional XAFS/XMCD  Fast polarization switching