Surface and Thin Film Magnetism
Studied by Magnetic Circular Dichroism

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Magneto-Optical Rotation & Circular Dichroism

Faraday rotation

Magnet or Chiral matter

Complex Faraday rotation angle

\[ \Phi_F = \theta_F + i \eta_F \]

Faraday Rotation, Faraday Ellipticity

\[ \eta_F (\omega) = -\frac{2\omega}{\pi} P \int_0^\infty \frac{\theta_F (\omega')}{\omega'^2 - \omega^2} d\omega' \]

Magnetic Circular Dichroism (MCD)

\[ A = \frac{\mu_{\text{left}} - \mu_{\text{right}}}{\mu_{\text{left}} + \mu_{\text{right}}} \]

\( \mu: \) absorption coefficient

\[ \eta_F = -\frac{1}{4} (\mu_{\text{left}} - \mu_{\text{right}}) \]

Magneto-Optical Kerr Effect (MOKE)

Polar Perpendicular M

Longitudinal M

Transverse In-plane M

Comparison with Natural CD

<table>
<thead>
<tr>
<th></th>
<th>Dipole Approx.</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCD</td>
<td>Invalid</td>
<td>( D ) depends on ( H ) ( B ) depends on ( E ).</td>
</tr>
<tr>
<td>MCD</td>
<td>valid</td>
<td>( \varepsilon ) is tensor</td>
</tr>
</tbody>
</table>

Requirements for large MCD

1) Intense allowed transition
2) Large spin-orbit interaction
3) Magnetization
High-Field X-ray Magnetic Circular Dichroism

XMCD

* Intense MCD
  strong LS coupling in core
* Element specific
  Multicomponent magnet
* Spin & orbital magnetic moments separately obtainable
  Magnetic anisotropy
  Needs high magnetic field
* Surface sensitive
  Surfaces & thin films

* Installed at UVSOR-II
* All ultrahigh vacuum
* 7T split superconducting magnet
* 360 degree rotatable
  liq. He cryostat  $T_s$  5 K
* Surface preparation

Co nanorods on Cu(110)-(2x3)N

STM of 0.8 ML Co/N/Cu(110)
Spin Reorientation Transition in Co/Pd(111) Induced by CO Adsorption

MOKE of 5 ML Co/Pd(111) at 90 K

Longitudinal in-plane

Polar perpendicular

Co ~5ML

No transition above ~250 K

Adsorption Structure of CO/Co/Pd(111)

C1s XPD

200 K  Spin transition
300 K  No transition

C1s XPS

Bridge-site adsorption induces the spin reorientation transition, while the atop-site adsorption shows no contribution at all.


Co 3d Orbital Magnetic Moments by XMCD

**Co3d orbital magnetic moment**

![Graph showing Co3d orbital magnetic moment vs Co thickness (ML) for CO/Co/Pd(111) clean and CO-ads.](image)

- **CO ads.**
  - $\perp$ surface less change
  - $\parallel$ surface significantly reduced

**Speculations**

- Consider chemical bonds between partially-filled Co3d & CO5$\sigma$. 

![Speculation diagrams for Co3d$\delta$ and Co3d$\pi$.](image)

- **Co 3d$\delta$**
  - no bonds with bridge or atop CO 5$\sigma$
  - $\implies$ No change in perpendicular $m_{\text{orb}}$

- **Co 3d$\pi$**
  - no bond with atop CO 5$\sigma$
  - $\implies$ no change in parallel $m_{\text{orb}}$
  - strong bond with bridge CO 5$\sigma$
  - $\implies$ strong reduction in parallel $m_{\text{orb}}$

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Magnetism of Co nanorods on Cu(110)-(2x3)N

Self-assembled Co nanorods on Cu(110)-(2x3)N

Cu(110)-(2x3)N

0.8 ML Co

Height: 2 atoms

Width: 5 atoms

Height: 1 atom

Distance (Å)

0.0 0.4 0.8 1.2 1.6

~22 Å

Height (Å)

33x49 nm²

[110] [001]

3.87 Å

4.39 Å

[110] [001]

[110] [001]


Results of XMCD in Co/Cu(110)-(2x3)N

MH curve analysis
Easy axis: [001] not along the rod [1-10]
Hardest axis: [110]

\[ E_a = K_P \cos^2 \theta + K_A \sin^2 \sin^2 - \mu \cdot H \]
\[ \rho = \exp\left[-N E_a / k_B T\right] \]
Film \( K_P = 120 \) (\( \mu eV/\text{atom} \))
Rod \( K_A = 20 \) (\( \mu eV/\text{atom} \))
Size \( N = 15 \) (atom)

Spectroscopic analysis

<table>
<thead>
<tr>
<th>crystal axis</th>
<th>( m_{\text{orb}} (\mu_B) )</th>
<th>( m_T (\mu_B) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>[001] 0.23(3) -0.005(5)</td>
<td></td>
</tr>
<tr>
<td>y</td>
<td>[1-10] 0.19(3) 0.011(5)</td>
<td></td>
</tr>
<tr>
<td>z</td>
<td>[110] 0.16(3) -0.006(5)</td>
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</tbody>
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3d hole number
cf. Co bulk \( n_h = 3.20 \)
\( n_h = 2.50 \)

Orbital magnetic moment
[001] > [1-10] > [110] easy in-plane hardest hard

Spin magnetic moment rather small
\( m_{\text{spin}} = 1.01(10) \mu_B \)

cf. Co bulk 1.55 \( \mu_B \)

Consistent with magnetic anisotropy
Formation of surface nitride
Possibility of UV MCD PEEM

XMCD PEEM
XMCD PhotoElectron Emission Microscopy
Spatial resolution: 10~100 nm

UV MCD PEEM
No UV MCD PEEM has been reported

UV MLD PEEM
Magnetic Linear Dichroism

Advantages
- Strong MCD >10%
  due to large LS coupling in the core shell
- Element specific

Disadvantages
- Need Third Generation Synchrotron Light Sources
- Time resolution limited by the SR pulse (>> 1ps)

Fe L edge Fe(3.55 ML)/Ni(10.6 ML)/Cu(001)

Polycrystalline Fe thick (~500 nm) film
Hg arc lamp

Photoemission MCD & UV MCD PEEM from Ni/Cu(001)

MCD as a function of $h\nu - \Phi$


First Observation of UV MCD PEEM


MCD max. -10 ~ -12%
$10^2$-$10^3$ times larger than MOKE

MCD asymmetry $A$

$$A = \frac{|L| - |R|}{|L| + |R|}$$

Elmitec PEEM Spector
Spatial resolution ~35nm

HeCd, Ti:Sa 4th

Ti:sapphire 2nd 400nm 2sec x2

$M \perp$

$M$
First observation of 2PPE MCD
To extend the available $h\nu$ range

Clean Ni(15ML)/Cu(001)

Max. MCD as much as \(\sim\)7%
Similar to 1PPE MCD

Maximum MCD as much as -28% !!
By far larger than the 1PPE (\(\sim\)10%)
Stronger MCD at grazing inc.
is useful for MCD PEEM

2PPE MCD PEEM

2PPE MCD PEEM

First trial of ultrafast UV MCD PEEM


Pump 800nm, \(\sim\)100fs
Probe 400nm, \(\sim\)200fs


Magnetization Recovery

Delay time (ps)
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