빛을 이용한 자기현상의 연구

MOKE & XMCD & SXRMS

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1. The polarization of light.
2. The polarization dependent response of light to materials.
3. Magneto optical Kerr effect (MOKE).
4. X-ray absorption spectroscopy
5. X-ray Magnetic Circular Dichroism (XMCD)
6. Application of XMCD
7. Soft X-ray resonant magnetic scattering
8. Summary
1. The polarization of light

Light ~ wavelength, energy, frequency, \textbf{polarization}

polarization : Oscillation direction (usually electric field) of electromagnetic wave.
H,V Linear polarization (x,y basis)

\[
\begin{pmatrix}
E_x \\
0
\end{pmatrix}
\quad \begin{pmatrix}
0 \\
E_y
\end{pmatrix}
\]

45° Linear polarization

\[
\begin{pmatrix}
E \\
-E
\end{pmatrix}
\quad \begin{pmatrix}
E \\
+E
\end{pmatrix}
\]

Circular polarization

\[
\begin{pmatrix}
E \\
-iE
\end{pmatrix}
\quad \begin{pmatrix}
E \\
+iE
\end{pmatrix}
\]
2. The polarization dependent response of light to materials.
Pohang Accelerator Laboratory
Kung Fu Hustle
Yuen Qiu as Landlady
Photo by: Saeed Adyani

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Polarization dependence of reflectivity

The reflection coefficients are different for waves parallel and perpendicular to the plane of incidence.

When light is incident at the Brewster angle, the reflected light is linearly polarized because the reflection coefficient for the II component is zero.

Brewster angle

Reflectance vs AOI (@ 633 nm)

- P-Polarization
- S-Polarization

Angle of Incidence (Deg)
Nonmagnetic materials

$$\begin{pmatrix} E_S^r \\ E_P^r \end{pmatrix} = \begin{pmatrix} r_{SS} & 0 \\ 0 & r_{PP} \end{pmatrix} \begin{pmatrix} E_S^i \\ E_P^i \end{pmatrix}$$
3. Magneto optical Kerr effect (MOKE)

Ferromagnetic materials

\[
\begin{pmatrix}
E_S^r \\
E_P^r
\end{pmatrix}
= \begin{pmatrix}
r_{SS} & r_{SP} \\
r_{PS} & r_{PP}
\end{pmatrix}
\begin{pmatrix}
E_S^i \\
E_P^i
\end{pmatrix}
\]

Magneto-Optical Kerr Effect
The origin of Magneto optical Kerr effect

Classical description

Quantum mechanical description

\[ \begin{pmatrix} E_L^r \\ E_R^r \end{pmatrix} = \begin{pmatrix} r_{LL} & 0 \\ 0 & r_{RR} \end{pmatrix} \begin{pmatrix} E_L^i \\ E_R^i \end{pmatrix} \]

\[ \begin{pmatrix} E_S^r \\ E_P^r \end{pmatrix} = \begin{pmatrix} r_{SS} & r_{SP} \\ r_{PS} & r_{PP} \end{pmatrix} \begin{pmatrix} E_S^i \\ E_P^i \end{pmatrix} \]
Why is MOKE so popular?

1. Simple !!

Faraday’s. When he was presented with the Royal Medal, his presenter said it was a wonder that Kerr learned so much with the “comparatively simple and ineffectual apparatus at his disposal.” Kerr responded, “Simple it may be, but not ineffectual; rude, but not crude.”

This statement might represent the nature of this technique as used in the present day adaptations that are the subject of this article, especially when compared to many of the elegant techniques of modern surface science and nonlinear optics. But simplicity is a ma-

2. Film sensitive (sub-atomic layer ~ 100 nm)

SMOKE ~ in situ measurement of ultra thin films

MOKE microscope
4. X-ray absorption spectroscopy

XAS measures the DOS of unoccupied state

empty level : electron detector

Core level : electron source

Dipole Selection rule

3d Transition Metal $L_{2,3}$-edge: $2p \rightarrow 3d$

4f Rare Earth $M_{4,5}$-edge: $3d \rightarrow 4f$

O K-edge : $1s \rightarrow 2p$

Etc.

Strong multiplet by the exchange & Coulomb interaction between core hole & balance electron
XAS of 3d transition metal L edges

Finger Print of the Ground States
Ground State Valence
Ground State Symmetry
Spin State

Fe L edges M. Abbate, PRB(1992)

Co L edges (2+, d7)

Ti L edges
Van der Laan, PRB(1990)

SrTiO3
Rutile TiO2
Anatase TiO2
5. X-ray magnetic Circular Dichroism (XMCD)

**Dichroism**

: Polarization dependence of the absorption of the light

**XMCD**

: The difference of the absorption coefficient between circularly polarized x-rays with opposite helicities

\[ \mu_M = \mu^+ - \mu^- \]

**The main strengths of XMCD**

1. element & chemical specific measurement
2. Separation of orbital and spin moment
3. Surface Sensitive (not volume dependent)
A simplified diagram of XMCD effect

Spin-Up

Spin-Up
62.5%

Spin-up
25%

Spin-down
37.5%

Spin-down
75%

Spin-imbalance
In photo-electrons

Population difference

Exchange Splitting

Spin-orbit Splitting

Momentum transfer from Circular polarization

Spin polarized electrons generated by circular polarized photon

L, S parallel

L, S anti-parallel

2p_{3/2}

2p_{1/2}

E_F

Left Circ.
Element specific separation of the Orbital and Spin Moments

**Sum rule:**

\[
m_{\text{orb}} = -\frac{4 \int_{L_3+L_2} (\mu_+ - \mu_-) d\omega}{3 \int_{L_3+L_2} (\mu_+ + \mu_-) d\omega} (10 - n_{3d}), \tag{1}
\]

\[
m_{\text{spin}} = \frac{6 \int_{L_3} (\mu_+ - \mu_-) d\omega - 4 \int_{L_3+L_2} (\mu_+ + \mu_-) d\omega}{\int_{L_3+L_2} (\mu_+ + \mu_-) d\omega} \times (10 - n_{3d}) \left(1 + \frac{7\langle T_z \rangle}{2\langle S_z \rangle}\right), \tag{2}
\]

| Table 1: Orbital and spin magnetic moments of bcc Fe and hcp Co in units of \( \mu_B/\text{atom} \). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( m_{\text{orb}}/m_{\text{spin}} \) (bcc) | \( m_{\text{orb}} \) | \( m_{\text{spin}} \) | \( m_{\text{orb}}/m_{\text{spin}} \) (hcp) | \( m_{\text{orb}} \) | \( m_{\text{spin}} \) |
|--------------------------------------------------------------------------------|
| MCD and sum rules | 0.043 | 0.085 | 1.98 | 0.095 | 0.154 | 1.62 |
| Gyorrosagyt's ratio [16] | 0.044 | 0.092 | 2.08 | 0.097 | 0.147 | 1.52 |
| OP-LSDA [17] | 0.042 | 0.091 | 2.19 | 0.089 | 0.140 | 1.57 |
| OP-LSDA (with OP eff) [17] | 0.027 | 0.059 | 2.19 | 0.057 | 0.090 | 1.57 |
| SPR-LMTO [10] | 0.020 | 0.043 | 2.20 | 0.054 | 0.087 | 1.60 |
| FLAPW [11] | 0.023 | 0.050 | 2.16 | 0.045 | 0.071 | 1.58 |
| MCD and sum rules (corrected) | 0.043 | 0.086 | 1.98 | 0.099 | 0.153 | 1.55 |

Chen et al. PRL (1995)
6. Application of XMCD

**Ferrimagnetic ordering in double perovskite $\text{Sr}_2\text{FeMoO}_6$**

The directions of XMCD spectra are opposite.

$\rightarrow$ Ferrimagnetic ordering between Fe and Mo atoms.

The element specific magnetization measurement
Spectroscopic Characterization of magnetic Nano-Particles

~ site specific magnetization 


TEM images of 6nm ~ 13nm Fe-oxide nanoparticles

XRD of 11 nm spinel Iron Oxide Nano-particle

XRD peaks are too broad to characterize the chemical compositions. We need a local probe.
Spinel Iron Oxide \((\text{Fe}_{3-\delta}\text{O}_4)\)

Magnetite\((\text{Fe}_3\text{O}_4)\) : \(\delta = 0 : \text{Fe}^{3+}(\text{Fe}^{2+}\text{Fe}^{3+})\text{O}_4\)

Maghemite\((\gamma\text{-Fe}_2\text{O}_3)\) : \(\delta = 1/3 : \text{Fe}^{3+}(\text{Fe}^{3+}_{5/3})\text{O}_4\)

Ferrimagnet (\(O_h\) & \(T_d\) sites have the opposite moment)

XMCD line shape is more distinguishable than XRD result
Amount of Fe$^{2+}$ systematically increases with the particle size!!

(γ-Fe$_2$O$_3$)$_{1-x}$(Fe$_3$O$_4$)$_x$

- 4nm (x = 0.20±0.05)
- 6nm (x = 0.35±0.05)
- 8nm (x = 0.44±0.05)
- 9nm (x = 0.52±0.05)
- 11nm (x = 0.62±0.05)
- 12 nm (x = 0.64±0.05)
- 13nm (x = 0.65±0.05)
Ferromagnetism induced by clustered Co in Co-doped anatase TiO$_2$ thin films


XMCD reflects only the ferromagnetic components!
Magnetic anisotropy is modified by the interface.
Charge transfer from Pd to Ni enhances the ratio of \( d^9 \) with higher orbital magnetic moment.

J.-S. Lee et al, PRB (2007)
Pohang Accelerator Laboratory

The origin of magneto-electric coupling in a multiferroic material

Ferrimagnetism & piezoelectricity

MCA & ME effect are unexpected in GaFeO$_3$. The ionic state is Fe$^{3+}$ with a half-filled d$^5$ configuration, in which orbital momentum $L=0$. But the properties are highly related with spin-orbit coupling.

What is the microscopic origin?

$\rightarrow$ XAS & XMCD measurement

Strong Magneto-electric effect
(T. Arima et al. PRB 2004)

Strong Magneto-crystalline anisotropy

M(5K) = 0.87µ$_B$/Fe

$H//c$, $T$=150 K

$T_C \approx 260$K

$H//a$, $H//b$
Fe $L_{2,3}$-edge XMCD of GaFeO$_3$

Separation of orbital and spin magnetic moment

According to the MCD sum rule,

$M_S = 0.37 \pm 0.05 \mu_B/Fe$

$M_O = 0.017 \pm 0.002 \mu_B/Fe$

$M = 0.39 \pm 0.05 \mu_B/Fe$

(SQUID: $M=0.43 \mu_B/Fe$ at 190 K)

$L = 0.23 \pm 0.04$ (S=5/2)

: Unexpectedly Large for half-filled $d^5$
1. *L* edges of transition metals and *M* edges of rare earths reside in the soft X-ray region. We can expect a resonant enhancement of scattering intensity.

2. The wavelengths of soft X-rays are a few nano-meters.
   - They agree well with the periods of spin and orbital ordering.
   - They agree well with the length scale of artificial magnetic structures.
   - They are accessible with low index Bragg peak!!

3. An order specific spectra (local information) are available.
Soft X-ray scattering chamber of 2A beamline

Longer wavelength of soft X-ray $\rightarrow$ It covers very narrow $q$ space with full rotations of $\theta$ and $2\theta$ $\rightarrow$ shorter arm length $\sim$ arm length of 100 mm. $\rightarrow$ small chamber (easier operation and better vacuum condition)

1. DPRP for $\theta$ and $2\theta$ rotation
2. A pair of Slit for alignment
3. Detector housing
4. Electromagnet
5. Rotary driver
Performance of soft X-ray scattering chamber

Angular resolution of \( \theta \) & \( 2\theta \) : 0.005°

Temperature : 5.5 K in 30 minutes.

Magnetic field : 1500 gauss in all directions parallel to the scattering plane.

UHV : \( 1 \times 10^{-10} \) torr is recovered after overnight baking.
LaSr$_2$Mn$_2$O$_7$
(Double layered perovskite)

The result of test run

AFM-ordering (0,0,1) @ T=80K

$\Delta = 0.00748 \text{ Å}^{-1}$

S.B. Wilkins, PRL, 2003
Uncompensated spins in trilayer CoFe/IrMn/NiFe

J.-S. Lee et al., J. Phys.: Condens. Matter (2011)

Oscillation in q scan: thickness, roughness
Field scan at a fixed q: layer specific hysteresis

Co L edge

Scattering Intensity (arb. units)
Asymmetry Ratio (arb. units)

H-field (Oe)

MOKE

H_{EB1}
H_{EB2}
Two uncompensated spin layers are formed inside IrMn layer with finite thickness. No noticeable magnetic interaction between these two layers.
Novel spin structures are picked up with chiral dichroism or linear dichroism in soft X-ray resonant scattering intensity. $bc$ cycloid (TMO) & $bc$ sinusoid (EYMO). They are believed to induce the ferroelectricity in these samples.
Remark

Scattering guy: “The atomic structure is …..“
“Soft X-ray scattering is very good. Scattering intensity is enhanced at the resonant edges.”

Spectroscopy guy: “The electronic structure is… “
“Soft X-ray scattering is very useful because it gives us an local information of specifically ordered ions. Great”

Now, we are facing at an unprecedented combination of structure factor(scattering) and atomic form factor(spectroscopy) from soft X-ray scattering. A close collaboration is required to interpret the experimental results.
Summary

1. MOKE and XMCD effect are based on the interaction of circular polarized light and magnetic moments of ferromagnetic materials through spin-orbit coupling.
2. MOKE ~ simple and film sensitive
3. XMCD ~ microscopic origin of ferromagnetic phenomena.
4. SXRMS ~ order specific, interface specific local information.

Thank you!!