Coherent soft x-ray scattering from magnetic nanostructures

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Outline

1. Soft x-ray resonant magnetic scattering with a coherent beam
   - Motivations
   - Basics of soft x-ray resonant magnetic scattering
   - Basics of coherent x-ray scattering
   - A quick example on magnetic stripe domains

2. Study of a grating of magnetic nanolines
   - Experimental set-up
   - Magnetic memory
   - Reconstruction

3. XPCS for magnetic materials: brief review of recent works from other groups
Motivation: to develop an x-ray technique to study the exact magnetic configuration of nanostructures
→ Defects of periodicity in nearly periodic domains
→ Magnetic memory

**Soft X-ray Resonant Magnetic Scattering**
+ **Coherent X-ray Diffraction**

⇒ Magnetic imaging in the Fourier space (and possibly in the real space...)

Brand new technique for the study of magnetic systems

⇒ New information on well-known magnetic systems
   (global processes → local processes)

⇒ Study of small magnetic objects such as patterned nanostructures

⇒ Instrumentation and methodology to be developed in 2 directions:
   Intensity fluctuations
   Imaging
Soft X-ray Resonant Magnetic Scattering (SXRMS)

XRMS is exactly the same process as XMCD, but XMCD measures only the imaginary part of the atomic resonant factor.

⇒ chemical selectivity
⇒ shell selectivity

Transmission or reflection geometry?

Transmission: \( f^\text{mag} \) proportional to \( M_z \)

\[
f \rightarrow f^{\text{res}} = F^{(0)}(\hat{e}_f^*, \hat{e}_i) - iF^{(1)}(\hat{e}_f^* \wedge \hat{e}_i) \hat{m}
\]

charge scattering including anomalous terms

\( m \): local magnetisation unit vector
\( \hat{e}_i \): polarisation of incident photons
\( \hat{e}_f \): polarisation of scattered photons

⇒ magnetic component analysis by selecting the polarizations

⇒ Thin films with perpendicular magnetic magnetization

Reflection: \( f^\text{mag} \) mixes the magnetic components

⇒ Thick samples and/or in-plane magnetic components
Incoherent light: intensities are summed
⇒ Properties are averaged over the illuminated area
⇒ Defects contribute to the broadening of the diffraction peaks
Diffraction with a coherent beam

**Coherent light:** amplitudes are summed
⇒ Interference over the illuminated area
⇒ Defects contribute to the splitting of the diffraction peaks into **speckles**
⇒ **Speckle pattern** = unique signature of the diffracting object

\[ I(\vec{q}) = \left| \int_D f(\vec{r}) \exp(i\vec{q}.\vec{r}) d\vec{r} \right|^2 \]

D : domain of coherence
Example: SXRMS from stripe domains in FePd

Average magnetic periodicity: $\tau \approx 100 \text{ nm}$

Magnetic lateral correlation length
$\Lambda \approx 1000 \text{ nm}$

Circular dichroïsm
$\to$ closure domains
Dürr et al, Science 284, 2166 (1999)
Coherent SXRMS from stripe domains
1 domain structure ↔ 1 speckle pattern

No central spot = no correlation
Study of a grating of ferromagnetic nanolines

\[ \text{Pt}_{25}/(\text{Co}_6/\text{Pt}_{25})_{12} \]

MFM image (10x10 μm) after demagnetization

Nanolines etched in Silicon

Periodicity: 175 nm

AFM image (10x10 μm)

Normalized magnetization vs. Magnetic field (kOe)

- nanolines
- continuous multilayer
Experimental set-up for coherence at ESRF-ID08

- Longitudinal coherence:
  \[ \xi_l = \frac{\lambda^2}{2\Delta\lambda} = \frac{\lambda}{2} \frac{\lambda}{\Delta\lambda} \approx 2.4 \, \mu m \]

- Transverse coherence after focusing:
  vertical: \( \sim \) fully coherent
  horizontal: \( \sim 20 \, \mu m > \) pinhole
  (beam size = 1 mm (h) x 0.3 mm (v))

Pinhole Ø10 μm 7 mm ahead
Magnetic speckles from nanolines

- $q_x = -2\pi/d$
- $q_x = 0$
- $q_x = 2\pi/d$
- $q_x = 4\pi/d$
- $q_x = 6\pi/d$
- $q_x = 8\pi/d$

Specular peak

Pinhole 10 µm

More than 25 rings around the specular

$\sim$1250 photons
Magnetic reversal of nanolines
Magnetic memory after saturation

The magnetization reversal process from the saturated state is not reproducible.
Magnetic memory in a minor loop

- Pulse 0.95 kOe
- Pulse -0.975 kOe
- Pulse 1 kOe
- Pulse -1 kOe
- Pulse 1 kOe
- Pulse -1 kOe
- Pulse 1 kOe
- Pulse -1 kOe
- Pulse 1 kOe
Without holographic encoding, the phase of the FT is lost in the measurement.

But oversampling + algorithm can in principle retrieve the phase of the FT
And thus the scattering function in the real space.
Simulation

Scattered intensity: \( I(\vec{q}) = \left| \int S(\vec{r}) f^{\text{res}}(\vec{r}) \exp(i\vec{q} \cdot \vec{r}) d\vec{r} \right|^2 \)

Scattering factor: \( f^{\text{res}}(\vec{r}) = F^{(0)}(\hat{e}^* \cdot \hat{e}) - iF^{(1)}(\hat{e}^* \wedge \hat{e}) \hat{m}(\vec{r}) \)

Incident amplitude: \( A(\vec{r}) = \int_{\text{pinhole}} \exp \left[ \frac{(X_p - X_r)^2 + (Y_p - Y_r)^2}{2d} \right] dX_p dY_p \)

\[ d \approx 7 \text{ mm} \]
\[ D = 560 \text{ mm} \]

Far field

\[ \frac{a^2}{2\lambda d} \approx 4.5 > 1 \]
\[ \frac{a^2}{2\lambda (d + D)} \approx 0.06 << 1 \]
Simulation of the charge scattering
**Reconstruction with a Monte Carlo method**

**Definition of the problem**
- lines monodomain ⇒ 1 dimension problem
- perpendicular magnetization ⇒ 1 unknown per line
- saturation up or down ⇒ Value +1 or –1

**Simulated annealing**
- Start with a random configuration
- Error criterion $E$
- Each step, a line is chosen randomly and its reversal probability is proportional to $\exp(-\Delta E/kT)$
- $T$ decreases step by step

![Plot of $|A_p^y(x_s)|$ vs. $x$ (μm)](image)
Results of reconstruction in the reciprocal space
Study of the solution space

\[ \sum_j \left( I_j^{\text{cal}} - I_j^0 \right)^2 \]

Study with a simulated “experimental” intensity, calculated from a reference magnetic configuration (64 lines)
Some more recent work from other groups

• Study of the magnetic memory in Co/Pt multilayers as a function of the multilayer roughness
  Pierce et al

• Study of the magnetic memory induced by exchange bias in Co/PdIrMn multilayers
  Chesnel et al
Magnetic memory vs. roughness in Co/Pt multilayers

Study of the magnetic memory in Co/Pt multilayers as a function of the roughness:
Magnetic memory via exchange coupling

Conclusions

New information on well-known magnetic systems: global processes → local processes

• Experimental set-up for Soft X-ray Coherent and Resonant Magnetic Scattering developed on ID08 (ESRF)

• Speckle pattern correlations
  → study of slow dynamics and response to magnetic field / electric current / temperature
  → magnetic memory induced by structural defects / exchange bias

• Algorithmic reconstruction or FT holography
  → magnetic (spectroscopic) imaging