

Phase Sensitive X-ray Imaging: Basic Physics and An Overview of Current Implementations

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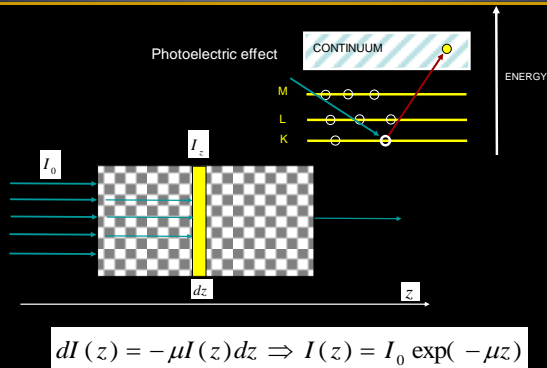


Outline

- Basics of x-ray propagation in matter
- Basic experimental principles to extract phase sensitive signals
- Dark field signal associated with phase sensitive imaging
- Summary

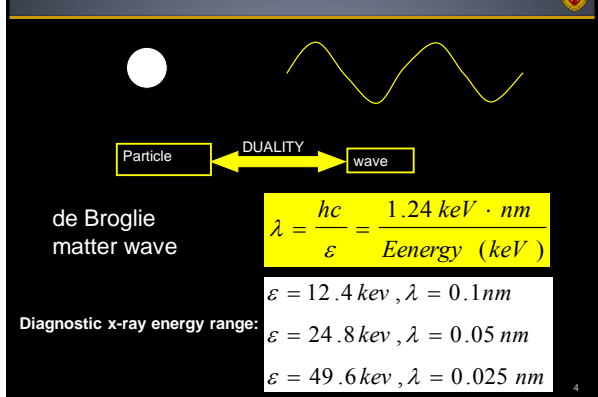
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Interactions between X-rays and matter: Absorption Contrast Mechanism



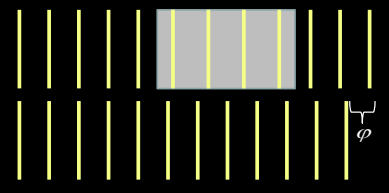

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Particle or wave: Particle-Wave Duality



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Wave-Matter Interaction

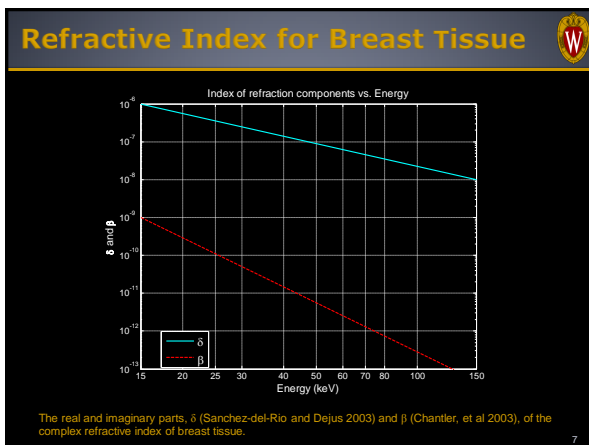
$$\varphi = \frac{2\pi}{\lambda} \int_l \delta(l) dl = \lambda r_e \int_l \rho_e(l) dl$$

$$n = 1 - \delta + i\beta$$

$\delta = \frac{\rho_e r_e \lambda}{2\pi}$ Real Part (refraction)
 $\beta = \frac{\lambda}{4\pi} (\sigma_p + \sigma_e)$ Imaginary Part (absorption)

Refraction of visible and x-ray photons

- Why has δ been neglected in x-ray medical imaging while β has been used for more than a hundred years?
- Consider the following:
 - At visible wavelengths (~600 nm), the refractive index of water is 1.33. In this case the refraction angle can be as large as **50 degrees**
 - For water at 30 keV (0.04 nm), the real part of the refractive index, $1 - \delta$, is about 0.9999997. As a result, the corresponding refraction angle is just about one millionth of a degree. Historically, this has been very difficult to experimentally measure!



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Phase-contrast tomography: Anastasio Lab

- **Grating-based tomography**
- **In-line tomography**

Collaborative work with Xiaochan Pan and Emil Sidky (UChicago):

Image reconstruction exploiting object sparsity in boundary-enhanced X-ray phase-contrast tomography, Emil Y. Sidky, Mark A. Anastasio, and Xiaochan Pan, Optics Express, Vol. 18, Issue 10, pp. 10404-10422 (2010)

NIH R01 EB009715
NSF CBET 0854430

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Method 3.1: Bragg Diffraction

Wave meets periodic structures

Additional phase shift is generated by the periodic crystal structure allowing the beam to interfere and generate an intensity modulation.

$$2d \sin \theta_B = N\lambda$$

Measurements at a slightly detuned angle at the FWHM gives the refraction angle:

$$\Theta_R \sim \theta_D \frac{I_L - I_H}{I_L + I_H} \sim \theta_D \frac{\Delta I}{I}$$

$$\sim 10^{-6} \theta_D$$

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How does DEI generate phase contrast?

- Analyzer crystal converts angular shift in x-ray beam into an intensity change in an image.
- Requires the use of an x-ray beam that is:
 - Monochromatic
 - Collimated

Courtesy of Dr. Zhong Zhong and Dr. Dean Connor, Jr.

Method 3.2: Refraction via transmission

Wave incident on a periodic structure

Transmission of any periodic structure can be decomposed into different Fourier components:

$$T(x) = \sum_{n=-\infty}^{\infty} a_n \exp(-j \frac{2\pi n}{p} x)$$

With an image object present, the wave field at zero distance is given by:

$$E(x, y, 0) = A \sum_{n=-\infty}^{\infty} a_n \exp(-j \frac{2\pi n}{p} x) \bullet e^{sh(x,y)}$$

Under the smooth phase change approximation, the phase distortion generated by the object can be decomposed as a local constant and its spatial change component:

$$e^{j\Phi(x,y)} \approx e^{j\Phi(x_0,y_0)} e^{j[\frac{\partial\Phi(x,y)}{\partial x}(x-x_0) + \frac{\partial\Phi(x,y)}{\partial y}(y-y_0)]}$$

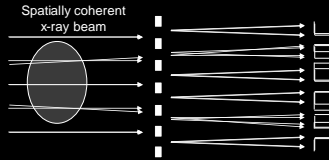
Method 3.2: Refraction via transmission Wave incident on a periodic structure

The wave field downstream at distance Z is given by:

$$E(x, y; Z) = A e^{ikZ} \sum_{n=-\infty}^{\infty} a_n e^{-j \frac{2\pi n}{p} (x - \frac{Z}{k} \frac{\partial \Phi(x, y)}{\partial x}) - j \frac{Z}{2k} \left(\frac{2\pi n}{p} \right)^2}$$

Presence of an image object leads to a local squeezing or stretching of the periodic structure. Namely, a local displacement of intensity. The displacement is dependent on the local distortion of the wave front caused by image object:

$$d = \frac{Z}{k} \frac{\partial \Phi(x, y)}{\partial x}$$



Method 3.2: Refraction via transmission Wave incident on a periodic structure

As a result, up to the first harmonic, the intensity modulation measured at a downstream distance Z is given by:

$$I = |E|^2 \sim I_0 + I_1 \cos\left[\frac{2\pi}{p} \left(x - \frac{Z}{k} \frac{\partial \Phi(x, y)}{\partial x} \right) \right]$$

By definition, the beam refraction angle from the incident beam direction is given by

$$\Theta_r = \frac{\lambda}{2\pi} \frac{\partial \Phi(x, y)}{\partial x} = \frac{d}{Z}$$

Therefore, any experimental method to resolve the above intensity modulation after a periodic structure and image object will measure the local refraction angle caused by the image object.

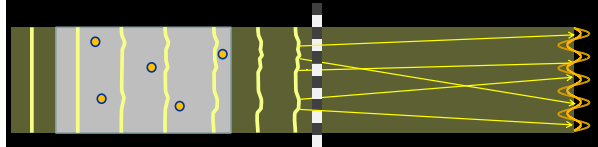
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Dark Field Signal Associated with Phase Sensitive Measurements

$$I = |E|^2 \approx I_0 + I_1 \cos\left[\frac{2\pi}{p} \left(x - \frac{Z}{k} \frac{\partial \Phi(x, y)}{\partial x} \right) \right]$$



$$\ln(V_{SAS}) = - \frac{\mu^2}{4} \int dz \frac{\sigma_{SAS} \rho_{SAS}}{R^2(z)}$$

Chen, G.-H., Bevins, N., Zambelli, J. & Qi, Z. Small-Angle Scattering Computed Tomography (SAS-CT) using a Talbot-Lau Interferometer and a Rotating Anode X-ray Tube. Theory and Experiments Opt. Express, 2010, Vol. 18, pp. 12960-12970

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Method 3.2.1: Talbot-Lau Interferometry

Wave meets periodic structure(s)

Dr. Joe Zambelli, University of Wisconsin-Madison, will talk more on progress in this direction.

Standard x-ray source

Spatially coherent x-ray beam

G_0 G_1 G_2

$$\Theta = \frac{p_2}{2\pi d} \cdot \varphi_d$$

$$\Theta = 4.28 \times 10^{-6} \cdot \varphi_d$$

F. Pfeiffer, et al. "Phase retrieval and differential phase-contrast imaging with low-brilliance x-ray sources," Nature Physics 2, pp. 258-261, Apr 2006.

Momose et al. (2005)

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Method 3.2.2: Fourier harmonic method

Incident beam

Horizontal grating

image

Laboratory of Imaging Physics,
Biophysics and Biochemistry Center,
National Heart, Lung and Blood Institute, National
Institutes of Health, Bethesda, MD, USA
APS, Argonne National Laboratory, Chicago, IL, USA

IP Courtesy of Dr. Harold Han Wen, NIH

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Single-shot Fourier harmonic method

Wen H, Bennett E, Hegedus MM, Carroll SC. Spatial harmonic imaging of x-ray scattering - initial results. IEEE Transactions on Medical Imaging 2008;27(8):997-1002.

2D Fourier spectrum of raw image

Inverse 2D FT

1st harmonic A_1

phase(A_1)

Absorption A_0

$-\ln(|A_1|/|A_0|)$

Phase-contrast image

Dark-field image

IP Courtesy of Dr. Harold Han Wen, NIH

Fourier imaging with 2D gratings

Wen HH, Bennett EE, Kopace R, Stein AF, Pal V. Single-shot x-ray differential phase-contrast and diffraction imaging using two-dimensional transmission gratings. Optics Letters 2010;35(12):1932-1934

Raw image

Fourier transformation

$A_{0,1}$

$A_{1,0}$

$A_{0,0}$

Dark-field from $A_{0,1}$

Dark-field from $A_{1,0}$

IP Courtesy of Dr. Harold Han Wen, NIH

Particle-size selectivity of dark-field signal

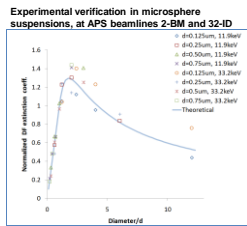
Lynch, Pal, Ausier, Stein, Bennett, Kemble, Xiao, Lee, Morgan, Wen, Interpretation of dark-field contrast and particle-size selectivity in grating interferometers, Applied Optics 50(22), 2011.

$$\text{Dark field extinction } \mu_d = \frac{4\pi^2}{\lambda^2} [R(0) - R(d)]$$

λ – x-ray wavelength,

$R(x)$ – auto-correlation function of the refractive index at distance x ,

d – auto-correlation distance, equals $\lambda^2(\text{sample-detector distance})/(\text{fringe period})$

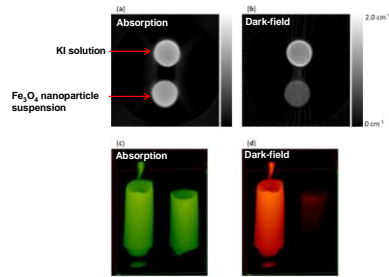


Courtesy of Dr. Harold Han Wen, NIH

Selective imaging of nano-particles

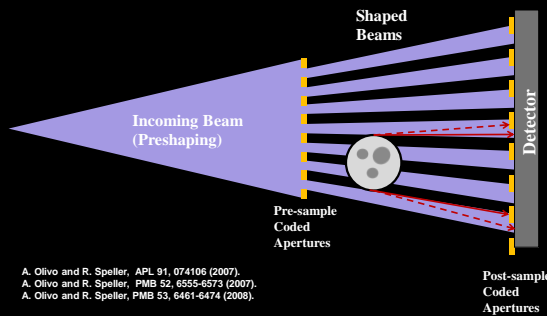
Lynch, Pal, Ausier, Stein, Bennett, Kemble, Xiao, Lee, Morgan, Wen, Interpretation of dark-field contrast and particle-size selectivity in grating interferometers, Applied Optics 50(22), 2011.

Stein AF, Ilavsky J, Kopace R, Bennett EE, Wen H. Selective imaging of nano-particle contrast agents by a single-shot x-ray diffraction technique. Optics Express 2010;18(12):13271-13278.



Courtesy of Dr. Harold Han Wen, NIH

Method 3.2.3: Coded Aperture Imaging Wave meets periodic structure(s)



A. Olivo and R. Speller, APL 91, 074106 (2007).
 A. Olivo and R. Speller, PMB 52, 6555-6573 (2007).
 A. Olivo and R. Speller, PMB 53, 6461-6474 (2008).

Summary

$$I = |E|^2 \sim I_0 + I_1 \cos\left[\frac{2\pi}{p}\left(x - \frac{Z}{k} \frac{\partial\Phi(x,y)}{\partial x}\right)\right]$$

- Absorption contrast mechanism: The DC term of the measured signal (I_0)
- Refraction contrast mechanism: Phase offset of the measured signal
- Dark field contrast mechanism: Amplitude of the measured signal (I_1)

Three contrast mechanisms from the same data acquisition!

Summary and transition to other speakers



Key things to differentiate the above explained methods:

1. Source requirements / Spatial coherence requirements
2. Detector requirements / Sensitivity of the measurements
3. Compactness of the imaging system
4. Potential quantification capabilities of the method
5. Radiation dose efficiency: CNR/Dose
6. Interpretation of the image
7. ...

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Thank you for your attention!



Please contact
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information!



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