Imaging with Neutrons

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Neutron Imaging Team

19th National School on
Neutron and X-ray Scattering
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Acknowledgement

• The Neutron Imaging Team

Hassina
Lou, Jean, Shawn, Gian, Indu
Jiao
Goals

• Compare neutron imaging to other imaging techniques, and know when to choose it

• Understand the basic instrument layout and principals of neutron image acquisition and analysis

• Learn by example
  – Review some recent neutron imaging projects
Imaging throughout Nobel Prize History

- 1901: Roentgen, FIRST Nobel Prize in Physics, Discovery of X-rays
- 1979: Cormack and Hounsfield, Nobel Prize in Medicine, Computed Tomography (CT)
- 1986: Ruska, Binnig, Rohrer, Nobel Prize in Physics, Electron Microscopy
- 2003: Lauterbur and Mansfield, Nobel Prize in Medicine, Magnetic Resonance Imaging (MRI)
- 2009: Boyle and Smith, Nobel Prize in Physics, Imaging semi-conductor circuit, the CCD* sensor

(*) Charge-Coupled Device
What about Neutron Imaging?

• The Nobel Prize for neutron imaging has yet to be won
  – An opportunity for you!

• NI started in the mid 1930’s but only the past 30 years has it come to the forefront of non-destructive testing

• World conferences and workshops being held regularly
Obtaining a Transmission Image

Medical Imaging

Neutron Imaging
- Measures “shadows” based on neutron attenuation through the object
- One shadow is a radiograph
- These “shadows” are collected at different angles and reconstructed in 3D, called the computed tomography or CT

Figure from http://www.fda.gov
Distinctive Features of Neutron Imaging

[Image of neutron radiograph of a rose in a lead flask]

- **X-rays (100 keV)**
- **Thermal neutrons**

![Graph showing mass attenuation coefficient vs. atomic number for various elements.](attachment:Neutron-Radiography-Graph.png)

- **H, B, Li, Ni, Co, Pt, Fe, Gd**

**Neutron Radiograph of Rose in Lead Flask!**

[Courtesy of E. Lehmann, PSI]

Distinctive Features of Neutron Imaging

**Diffraction**
- Crystal structures
- Characterization of biological membranes, colloids, porosity, etc.
- SANS used to construct protein kinase A (PKA)

**Scattering**
- You can directly see the structure.
- How easy!
- Inferred structure (indirect)

**Real-space imaging**
- Fluid interactions in plant-groundwater systems
- Ice/water segregation in permafrost structures
- Direct structure

<table>
<thead>
<tr>
<th>Dimension (meters)</th>
<th>10^{-11}</th>
<th>10^{-9}</th>
<th>10^{-7}</th>
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<td>1.0nm</td>
<td>0.1µm</td>
<td>10.0µm</td>
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Distinctive Features of Neutron Imaging

- **Diffraction**
  - Crystal structures

- **Scattering**
  - Characterization of biological membranes, colloids, porosity, etc.

- **Inferred structure (indirect)**

- **Real-space imaging**
  - Fluid interactions in plant-groundwater systems
  - Ice/water segregation in permafrost structures

- **Direct structure**

- **Spatial resolution is limited!**

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<td>$10^{-5}$</td>
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</tr>
</tbody>
</table>
Quantitative Neutron Imaging

Lambert-Beer Law:

\[ T = \frac{I(\lambda)}{I_0(\lambda)} = e^{-\mu(\lambda)\Delta x} \]

\[ \mu(\lambda) = \sigma_i(\lambda) \frac{\rho N_A}{M} \]

*\( \mu \) is the attenuation coefficient
*\( \Delta x \) is the thickness of the sample
*\( \sigma_i(\lambda) \) is the material’s total cross section for neutrons,
*\( \rho \) is its density,
*\( N_A \) is Avogadro’s number, and
*\( M \) is the molar mass.
Neutron Transmission Depends Upon . . .

- Sample composition, thickness, and neutron wavelength

![Graph showing neutron transmission through metals](image-url)
Neutron Transmission Depends Upon . . .

- Sample composition, thickness, and neutron wavelength

Time-of-flight imaging allows one to exploit the wavelength dependent transmission

Transmission depends upon sample composition, thickness, and neutron wavelength.
Goals

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CG-1D Neutron Imaging Facility
Sample Area

Sample (Automobile part)

Rotation/Translation Stage

Neutrons
Detection of “Imaging” Neutrons

- Neutron scintillators
  - Emit light after capturing neutrons
  - Good signal-to-noise ratio
  - Large Field Of View
  - Spatial resolution limited by the dissipation of particles
Detection of “Imaging” Neutrons (cont’d)

• Micro-Channel Plate (MCP)
  – In the direct path of the beam
  – Encodes events at x, y position and time of arrival, at high temporal resolution ~ 1 MHz
    – Enables time-of-flight imaging
  – Detection efficiency has improved for both cold (~70%) and thermal (~50%) energy range
  – Absence of readout noise
  – Not as gamma sensitive
  – Becoming commercial
  – Limited FOV
CG-1D polychromatic beam

CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. [Bilheux et al., ITMNR-7, Canada, June 2012]
CG-1D polychromatic beam

<table>
<thead>
<tr>
<th>Neutron classification</th>
<th>Energy (meV)</th>
<th>Velocity (m/s)</th>
<th>( \lambda ) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-cold</td>
<td>0.00025</td>
<td>6.9</td>
<td>570</td>
</tr>
<tr>
<td>Cold</td>
<td>1</td>
<td>437</td>
<td>9</td>
</tr>
<tr>
<td>Thermal</td>
<td>25</td>
<td>2187</td>
<td>1.8</td>
</tr>
<tr>
<td>Epithermal</td>
<td>1000</td>
<td>13,832</td>
<td>0.29</td>
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</tbody>
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CG-1D spectrum measured with the MCP detector at a flight path distance of approximately 5.5 m, with the chopper running at a frequency 40 Hz and an 5 mm aperture. [Bilheux et al., ITMNR-7, Canada, June 2012]
Data Normalization for Imaging

- 2D – Radiography
  - Normalization

\[
I_N(i, j) = \frac{I(i, j) - DF(i, j)}{OB(i, j) - DF(i, j)}
\]

Normalized Image

Image

Transmission

Open Beam

Dark Field

Dark Field

Dark Field
Computed/Computerized Tomography (CT)

- Several techniques:
  - Filtered Back Projection
    - Radon transform
    - Works well with high signal to noise ratio measurements
    - Easy-to-use commercial, semi-automated software available
    - Quick
  
  - Iterative Reconstruction
    - Direct approach
    - Less artifacts
    - Can reconstruct incomplete data
    - High computation time
Computed/Computerized Tomography (FBP)

- Filtered back projection method

**Raw Data:**
- 2048x2048 pixels, 721 projections

**Normalized Data:**
- 2048x2048 pixels, 721 projections

**Sinograms:**
- 2048x721 pixels, 2048 files

**Slices:**
- 2048x2048 pixels, 2048 slices

**3D reconstruction:**
- 2048x2048x2048 voxels

Counts: ~700 to ~20700
Transmission: 0 to 1
Attenuation: 0 to ∞
Conventional Neutron Imaging Techniques at Steady-State Sources

- Radiography
- Tomography

• Stroboscopic Imaging
• Imaging of processes that happen fast

- Polarized Neutron Imaging
- Energy selective techniques possible with double-monochromator configuration

- Phase Contrast Imaging
  – Under development

Routinely available at CG-1D

Available at CG-1D using the MCP detector

Newly implemented at CG-1D
Goals

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A Wide Range of Applications

Applications

Additive Manufacturing
Porosity; internal structure; quantitative comparative analysis of neutron-computed tomography data with engineering drawings

Energy Storage
Ion transport in energy storage materials; three-dimensional mapping of ions in electrodes

Technologies
Particulate deposition in vehicle parts; two-phase transport in heat pipes; multiphase constrained jet flows; metal casting, reservoir flow, creation, and production

Plant Systems Biology
Partitioning, transport, and fate of carbon fixed by plants; carbon biosequestration; modeling impacts of rising CO2 levels; modified bioenergy feedstock plants; cavitation and gas embolism in plants

Plant-Soil-Groundwater Systems
Transport and interactions of fluids in porous media; water infiltration and aquifer recharge; plant-plant and plant-fungal interactions; change in pore structure and voids after repeated thawing and freezing of permafrost soil

Biological and Forensic Studies
Structural, contrast agent, and cancer research

Food Science and Archeology

Applications include . . .
CG-1D Cancer Research Application

Photograph of tissue sample

Greyscale neutron image

Photo of stained tissue slice

Colorized* neutron image

Several Biological Tissues Have Been Studied at CG-1D

• No animals are ever hurt or sacrificed for these experiments
• Post mortem studies help researchers battle disease
• Neutrons reveal important features
• Non-destructive 3D evaluation

Fig. 5.
Volume rendered images computed tomogram of the canine kidney slice from fig. 5.
Forensic Science Example

Forensic Science Example

Rapid Imbibition of Water in Fractures within Unsaturated Sedimentary Rock

- **Dynamic neutron radiography**
  - Directly quantify the sorptivity and dispersion coefficients of liquids in fractured, porous media
  - The findings can be applied in modeling hydraulic fracturing

Time sequence of neutron radiographs showing the rapid uptake of water into a longitudinal, air-filled fracture zone in Berea sandstone. FOV is \( \approx 28 \times 28 \text{ mm}^2 \).

Work performed at the High Flux Isotope Reactor Imaging beam line (CG1D) was supported by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy.

Fabrication tolerance studies comparing CAD drawing to neutron computed tomography

Engineering drawing

Neutron CT

In orange/yellow: AUTOCAD outline
In gray: neutron data
Time-resolved studies

• Rapid image acquisition and synchronization with operating devices
  – Micro-channel plate detector technology

• Recent applications include fuel injector operation and water propagation through porous media
More Examples

• More examples may be presented at the live talk
Summary
Imaging is a Small but Growing Part of the ORNL Neutron Program

High Flux Isotope Reactor (HFIR)
Intense steady-state neutron flux and a high-brightness cold neutron source

Spallation Neutron Source (SNS)
World’s most powerful accelerator-based neutron source

CG-1D
Steadily improving capabilities
Expanded support

Techniques such as Bragg-edge imaging are being implemented here
Diverse Science and Engineering Applications

- Trends at CG-1D are similar other facilities
- Are we missing any opportunities? Your science!

Based upon recent publications
Summary

• Neutrons are ideal for *certain* imaging applications, especially those requiring
  – Sensitivity to hydrogen and other light elements
  – Isotope sensitivity
  – Penetration into large samples and/or sample environments

• Spatial resolution is a key consideration
  – CG-1D routine capability of ~ 80 µm
  – Radiography at ~ 20 µm (with the trade-off of long counting time) is now available

• Imaging capabilities are steadily improving
Thank you

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