Neutron imaging
Neutron imaging
Neutron imaging

Introduction

One of the first X-ray experiments late in 1895 performed by Konrad Röntgen was a film of a hand.

The bones and also finger rings deliver much higher contrast than the soft tissue.
Neutron imaging

Introduction

Photo of experimenters taking an X-ray with an early Crookes tube apparatus, from the late 1800s.
Neutron imaging

Roots of neutron radiography

Comparison between x-ray and neutron images

- Berlin, 1935 – 1938
  - H. Kallmann & Kuhn with Ra-Be and neutron generator

- Berlin until Dec. 1944
  - O. Peter with an accelerator neutron source

But the real programs with neutrons started after World War II at research reactors
Sample image: X-ray showing frontal view of both hands.

Why neutrons?
Neutron imaging

Neutron interaction with matter

X-rays

- **photo electron absorption**
- scattering

**neutrons**

- absorption
- scattering

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**Mass attenuation coefficient, (cm$^2$/g)**

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

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**Atomic number**

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**Mass attenuation coefficient, (cm$^2$/g)**

- **Light elements**: $^1$H, Li
- **Metals**: Co, Ni, Fe, Pb
- **Heavy elements**: Gd, Cd, Pb

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N. Kardjilov, Oxford School on Neutron Scattering, 11. September 2019
Neutron imaging

Neutron interaction with matter

X-rays

- photo electron
- absorption

neutrons

- absorption
- scattering

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Portion

Elements with increasing mass number

Normalized absorption cross section
Normalized scattering cross section
The example for a camera helps to explain differences in neutron (left) and X-ray (right) radiography. Whereas the hydrogen containing parts can be visualised with neutron even at thin layers, thicker metallic components are hard to penetrate with X-rays.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)
Observation of a lead container. The neutron image on the left was obtained after 20 s. On the right, the gamma radiography with Co-60 (1100 keV) needed 120 minutes of exposure.

Images courtesy: Dr. Eberhard Lehmann (Paul-Scherrer-Institute, Switzerland)
Contrast

- Beam optimisation
- Detector development

Resolution

- Neutron interaction with matter
  - absorption
  - scattering
  - magnetic interaction
Beam optimisation

Source → Collimator → Object → Detector

\[ I_0 \sim I_0 e^{-\int \Sigma(x)dx} \]

\( I_0 \) – primary beam
\( \Sigma(x) \) – attenuation coefficient

\( x \) – propagation direction
Beam optimisation

- $D$ – Collimator aperture
- $L$ – Distance Collimator-Object
- $l$ – Distance Object-Detector

$$d = \frac{l}{L/D}$$
Radiographs of a 3,5" floppy drive in 0 cm, 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with $L/D=71$.

Beam optimisation

Radiographs of a small motor taken at different beam positions with different L/D ratios.

Neutron flux: $2.4 \times 10^7$ n/cm$^2$s (L/D=350)
Beam size: 30 cm x 30 cm
Exposure times: 10-30 s / image
Beam optimisation

CONRAD-2

*: instrument under construction
Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter
  - absorption
  - scattering
  - magnetic interaction
Detector system

**Standard setup**

- Scintillator: 200 µm 6LiF
- Lens system: 50 mm
- Pixel size: 100 µm
- Exposure time: 20 s

Detector development

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The ZnS+\(^6\)LiF scintillation screen is the limit of resolution.

The reaction products of \(^6\)Li(\(n,\alpha\)) \(\rightarrow\) \(^3\)H + \(^4\)He + 4.7 MeV

have to be stopped in the ZnS scintillation screen. Their average range is in the order of 50-80 \(\mu\)m.

About 177,000 photons are generated per detected neutron.

With thinned scintillation screens, we can achieve resolution in the order of 20-30 \(\mu\)m.
Capture reactions for thermal / cold neutrons

\[ ^3\text{He} + ^1\text{n} \rightarrow ^3\text{He} + ^1\text{p} + 0.77 \text{ MeV} \]

\[ ^6\text{Li} + ^1\text{n} \rightarrow ^3\text{H} + ^4\text{He} + 4.79 \text{ MeV} \]

\[ ^{10}\text{B} + ^1\text{n} \rightarrow ^7\text{Li} + ^4\text{He} + 2.78 \text{ MeV} \quad (7\%) \\
\rightarrow ^7\text{Li}^* + ^4\text{He} + 2.30 \text{ MeV} \quad (93\%) \]

\[ ^{155}\text{Gd} + ^1\text{n} \rightarrow ^{156}\text{Gd} + \gamma\text{´s} + \text{CE´s} \ (7.9 \text{ MeV}) \]

\[ ^{157}\text{Gd} + ^1\text{n} \rightarrow ^{158}\text{Gd} + \gamma\text{´s} + \text{CE´s} \ (8.5 \text{ MeV}) \]

\[ ^{235}\text{U}, ^{239}\text{Pu} \ ^1\text{n} \rightarrow \text{fission products} + 80 \text{ MeV} \]
Detector development

Nikkor Makro-Objektiv - 105 mm - F/2.8

- $FOV_{\text{max}}$: 10 cm x 10 cm, pixel size: 50 µm
- $FOV_{\text{min}}$: 6 cm x 6 cm, pixel size: 30 µm

Nikon Micro Nikkor 200mm f/4 D (IF) ED

- 1:1 imaging
- $FOV_{\text{max}}$: 2.8 cm x 2.8 cm, pixel size: 13.5 µm
Detector development

Standard setup

- Scintillator: 200 µm 6LiF
- Pixel size: 100 µm
- Exposure time: 20 s

Improved lenses + Improved screen

- Scintillator: 200 µm 6LiF
- Pixel size: 30 µm
- Exposure time: 20 s

- Scintillator: 5 µm Gadox
- Pixel size: 30 µm
- Exposure time: 120 s

High resolution

<table>
<thead>
<tr>
<th>Obj. Lens/Img. Lens</th>
<th>$M$</th>
<th>$P_{\text{eff}}$ ($\mu m$)</th>
<th>FOV (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>105 mm / 50 mm</td>
<td>2.10</td>
<td>6.429</td>
<td>13.2 x 13.2</td>
</tr>
<tr>
<td>200 mm / 100 mm</td>
<td>2.00</td>
<td>6.750</td>
<td>13.8 x 13.8</td>
</tr>
<tr>
<td>200 mm / 50 mm</td>
<td>4.00</td>
<td>3.375</td>
<td>6.9 x 6.9</td>
</tr>
</tbody>
</table>

S. H. Williams et al, J. of Instrumentation (2012)
Adaptive high-resolution imaging

S.H. Williams et al., Journal of Instrumentation 7, (2012)

Camera: Andor DW436
Lens system: Magnification
Pixelsize = 3.375 µm
Szintillator: GGG
Resolution: 7.9 µm (63.2 lp/mm)
Resolution
• Beam optimisation
• Detector development

Contrast
• Neutron interaction with matter
  - absorption
  - scattering
  - magnetic interaction
Attenuation Contrast

[Image of an X-ray of a mechanical component with a scale of 1 cm]
Absorption tomography

Source → Collimator → Object → Detector

$\int_{x}^{x} e^{\Sigma(x)} \, dx$

$I_0$ — primary beam

$\Sigma(x)$ — attenuation coefficient

$x$ — propagation direction

Tomography
Neutron imaging

Single tomographic projections
Neutron imaging

Tomographic reconstruction
How to optimize water management in a PEM fuel cell?

- *In-operando* visualization of water distribution
- Diffusion dynamics revealed with D-H contrast
- Photons: tailor-made microporosity improves water transport

→ Optimized electrode design

→ Improved performance under varying operation conditions
How to optimize water management in a PEM fuel cell?

- In-operando visualization of water distribution
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How to optimize water management in a PEM fuel cell?

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Diffusion dynamics revealed with D-H contrast

Photons: tailor-made microporosity improves water transport

Optimized electrode design

Improved performance under varying operation conditions

N. Kardjilov, Oxford School on Neutron Scattering, 11. September 2019

Neutron tomography slice
(pixel size: 6.5 µm, 600 projections /360°, time: 8 h)

J. Haußmann et al., Journal of Power Sources 239 (2013) 611
How to optimize water management in a PEM fuel cell?

Best case: 40% performance increase
Typical: 10-20% increase

- In-operando visualization of water distribution
- Diffusion dynamics revealed with D-H contrast
- Photons: tailor-made microporosity improves water transport

Material now in production

- Optimized electrode design
- Improved performance under varying operation conditions

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ELECTROLYSER ELECTRODES

Ni mesh
polymer coating

High-resolution tomography @ ILL (D50)

pixel size: 1.8 µm, 1000 projections, 10 hours
Plant’s physiology

How to observe the water uptake in plant’s root

- In-operando 3D visualization of water distribution
- Water uptake dynamics revealed with D-H contrast
- Insights in the water uptake mechanisms in the root system

➔ Observation of the dynamic processes in root system
➔ Learning about the root-soil interaction mechanisms

N. Kardjilov, Oxford School on Neutron Scattering, 11. September 2019
Plant’s physiology

How to observe the water uptake in plant’s root

High-speed (on-the-fly) neutron tomography

resolution: 150 µm
exposure: 0.05 s
200 projections/180°

10 s / tomography

➔ Observation of the dynamic processes in root system
➔ Learning about the root-soil interaction mechanisms

N. Kardjilov, Oxford School on Neutron Scattering, 11. September 2019
How to observe the water uptake in plant’s root

High-speed (on-the-fly) neutron tomography

resolution: 150 µm
exposure: 0.05 s
200 projections/180°
10 s / tomography

Time series of neutron tomograms at (a) 0 min; (b) 5 min; (c) 8 min and (d) 10 min after feeding D₂O.

Observation of the dynamic processes in root system
Learning about the root-soil interaction mechanisms

All routes lead to Rome: A map of Roman ports and trade routes

https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png
Shipwrecks

All routes lead to Rome: A map of Roman ports and trade routes

https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png
Lead blocks recovered near the UNESCO World Heritage Site Syracuse. Presumably I century B.C. (Roman Imperial Age).

Lead blocks recovered near the UNESCO World Heritage Site Syracuse. Presumably I century B.C. (Roman Imperial Age).
Attenuation Contrast

https://commons.wikimedia.org/wiki/File:Europe_180ad_roman_trade_map.png

Neutron tomography of bronze statues
Resolution

- Beam optimisation
- Detector development

Contrast

- Neutron interaction with matter
  - absorption
  - scattering
  - magnetic interaction
Diffraction Contrast

\[ \lambda = 4.0 \, \text{Å} \]
Beam monochromatisation

Double crystal monochromator: PCG crystals (mosaicity of 0.8°)

Range: 2.0 – 6.5 Å

Resolution ($\Delta \lambda / \lambda$): ~ 3%

Neutron flux: ~ $4 \times 10^5$ n/cm$^2$/s
(at $\lambda = 3.0$ Å)

Beam size: 5 x 20 cm$^2$
Coherent scattering – Bragg edges

Bragg’s law

$$2d_{hkl}\sin \theta = \lambda$$
Coherent scattering – Bragg edges

Bragg’s law

\[ 2d_{hkl} \sin 90° = \lambda \]

Cross-sections of iron per atom

\[ 2d_{hkl} = \lambda \quad \text{(110)} \]
Energy-selective radiography

Weld (photo)

- 3.8 Å
- 4.0 Å
- 4.2 Å

1 cm

3D Phase mapping in metals

Energy-selective neutron tomography of TRIP-steel

R. Woracek et al., Advanced Materials 26 (2014)
Diffraction Contrast

- **Tensile sample**: Graph showing neutron diffraction and tomography results with a peak labeled "VIRGIN sample".
- **Martensite [%]**: Line profile through cross-section with a gauge volume size of 2x2x2mm³ and 21 measurement points.

- **Torsion sample**: Graph showing neutron diffraction and tomography results with a peak labeled "VIRGIN sample" and the Olson-Cohen model.
- **Martensite [%]**: Line profile through cross-section with a gauge volume size of 2x2x2mm³ and 13 measurement points.

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Neutron imaging

Resolution
- Beam optimisation
- Detector development

Contrast
- Neutron interaction with matter
  - absorption
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Magnetic Contrast
### Magnetic Contrast

#### Principle

- **Neutrons**
- **Spin polariser**
- **Magnet**
- **Spin analyser**
- **2D-detector**

$\varphi = \omega_L t = \frac{\gamma_L}{\nu} \int_{path} H ds$

### Experimental parameters

- Solid state polarizing benders
- Beam size (WxH): 20 x 4 cm²
- Exposure times: ~10 min / image

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Magnetic Contrast

Principle

Biot-Savart law

\[ d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{I} \times \hat{r}}{r^2} \]

Spin rotation

\[ \varphi = \frac{y_L}{v} \int_{\text{path}} B ds \]

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Experiment</th>
<th>Spin rotation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>1.0 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0 A</td>
</tr>
</tbody>
</table>

1 cm
Flux pinning at cooling down below $T_c$ while applying a homogenous magnetic field of 10 mT perpendicular to the beam.

The images were recorded after switching off the magnetic field.
Tensor tomography. **a** Schematic drawing of the setup used for tensor tomography with spin-polarized neutrons, comprising spin polarizers (P), spin flippers (F) and a detector (D). **b** Selected magnetic field lines around an electric coil (calculation). A. Hilger, et al, *Nature Communications* 9.1 (2018): 4023
Magnetic Contrast

Analysis of Spin component:

<table>
<thead>
<tr>
<th>Rotation angle of the sample:</th>
<th>X Simulation</th>
<th>X Experiment</th>
<th>Y Simulation</th>
<th>Y Experiment</th>
<th>Z Simulation</th>
<th>Z Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Initial spin direction: X

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TMART Reconstruction

Magnetic vector field $\vec{B}_i$ in volume element $\alpha_i$

Iterative algorithm TMART

$$T_{\text{final}}(\vec{n}, \alpha) = T(\vec{n}_N, \alpha_N) \cdots T(\vec{n}_1, \alpha_1) = \prod_{i=N}^{1} T(\vec{n}_i, \alpha_i).$$

$$\vec{P}_{\text{final}} = T_{\text{final}}(\vec{n}, \alpha) \cdot \vec{P}_0.$$
Tensorial reconstruction

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Quantitative magnetic tomography

Magnetic vector field inside a superconducting lead sample measured at $T = 4.3 \text{ K}$.  

**a** Some selected magnetic field lines show the location of the magnetic field inside the sample indicated by the cuboid.  

**b** Magnetic field lines in a selected $xy$ plane (silhouette of the lead sample marked by dotted lines). Scale bar, 5 mm.  

**c** Magnetic field lines in a selected $xz$ plane. Scale bar, 5 mm.

Thank you!