Neutron Instruments I & II

• Overview of source characteristics
• Concepts and Technologies
  – De Broglie relations
  – Bragg’s Law
  – Guides, Monochromators, Choppers, Detectors
• Elastic scattering: diffractometers
  – Continuous sources
  – Pulsed sources
• Inelastic scattering: spectrometers
  – Continuous sources
  – Pulsed sources
• Non-scattering techniques
  – Fundamental physics
  – Activation analysis
  – Imaging
## Neutrons vs Light

<table>
<thead>
<tr>
<th></th>
<th>light</th>
<th>neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$&lt; \mu m$</td>
<td>$&lt; \text{nm}$</td>
</tr>
<tr>
<td>$E$</td>
<td>$&gt; \text{eV}$</td>
<td>$&gt; \text{meV}$</td>
</tr>
<tr>
<td>$n$</td>
<td>$1 \rightarrow 4$</td>
<td>$0.9997 \rightarrow 1.0001$</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>$90^\circ$</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$\Phi/\Delta\Omega$</td>
<td>$10^{18} \text{p/cm}^2/\text{ster/s}$ (60W lightbulb)</td>
<td>$10^{14} \text{n/cm}^2/\text{ster/s}$ (60MW reactor)</td>
</tr>
<tr>
<td>$P$</td>
<td>left-right</td>
<td>up-down</td>
</tr>
<tr>
<td>spin</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>interaction</td>
<td>electromagnetic</td>
<td>strong force, magnetic</td>
</tr>
<tr>
<td>charge</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Neutron Moderators

ILL

ISIS

Ambient Temperature Water Moderators

Reflector

Target Flange

Proton Beam

Beam Entry Window

Target Pressure Vessel

100 K Methane Moderator

Target Plates

20 K Hydrogen Moderator

2.5m

1m
Pulsed-source time structures

Cold neutrons

log(Intensity)

0            20           40           60            80          100         120

0            20           40           60            80          100         120

time (ms)

0            20           40           60            80          100         120

1            10            100           1000

0.1            10           1000

0.1            10           1000

ILL

ISIS-TS1

ISIS-TS2
## De Broglie relations

<table>
<thead>
<tr>
<th>Particle</th>
<th>Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p = mv$</td>
<td>$p = ħk = h/λ$</td>
</tr>
<tr>
<td>$E = \frac{1}{2}mv^2$</td>
<td>$E = ħω = hf$</td>
</tr>
</tbody>
</table>

\[
ℏ = h/2π \\
h = 6.6 \times 10^{-34} \text{ J s} \\
m_n = 1.67 \times 10^{-27} \text{ kg}
\]
De Broglie relations

<table>
<thead>
<tr>
<th>Particle</th>
<th>Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p = mv$</td>
<td>$p = \hbar k = h/\lambda$</td>
</tr>
<tr>
<td>$E = \frac{1}{2} mv^2$</td>
<td>$E = \hbar \omega = hf$</td>
</tr>
</tbody>
</table>

$\hbar = h/2\pi$

$h = 6.6 \times 10^{-34} \text{ J} \cdot \text{s}$

$m_n = 1.67 \times 10^{-27} \text{ kg}$

$\lambda = h / mv$

$\lambda[\text{Å}] = 3.956 / v[\text{m/ms}]$

$t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956$
The time-of-flight (TOF) method

\[ \lambda = \frac{h}{mv} \]

\[ = \frac{3.956}{v} \]

[Å]  [m/ms]
Diffraction: Bragg’s Law
Diffraction: Bragg’s Law
Diffraction: Bragg’s Law

Wave 1

Wave 2

Incident angle

Reflected angle

Atomic plane

$d$

$d \sin \theta$

$n=2$

©1998 Encyclopaedia Britannica, Inc.
Diffraction: Bragg’s Law

\[ \lambda = 2d \sin \theta \]
Diffraction: Bragg’s Law

\[ \lambda = 2d \sin \theta \]
Diffraction: Bragg’s Law

Wavevector:

\[ k = \frac{2\pi}{\lambda} \]

\[ p = \hat{h} k \]

\[ \lambda = 2d \sin \theta \]
Diffraction: Bragg’s Law

Wavevector: \[ k = \frac{2\pi}{\lambda} \]

\[ p = \hbar k \]

\[ \lambda = 2d \sin \theta \]

\[ |\vec{k}_i| = |\vec{k}_f| = k \]

\[ \vec{k}_i \]

\[ \vec{k}_f \]
Diffraction: Bragg’s Law

\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]

\[ \Rightarrow \vec{Q} = \vec{k}_i - \vec{k}_f \]
Diffraction: Bragg’s Law

\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]

\[ \Rightarrow \quad \vec{Q} = \vec{k}_i - \vec{k}_f \]

\[ Q = 2k \sin \theta \]

\[ \lambda = 2d \sin \theta \]

\[ k = \frac{2\pi}{\lambda} \]

Bragg’s Law:

\[ Q = \frac{2\pi}{d} \]
Diffraction: Bragg’s Law

\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]

\[ \Rightarrow \vec{Q} = \vec{k}_i - \vec{k}_f \]

Bragg’s Law:

\[ Q = 2k \sin \theta \]

\[ \lambda = 2d \sin \theta \]

\[ k = \frac{2\pi}{\lambda} \]

Conversion:

\[ Q = \frac{2\pi}{d} \]

\[ Q = 4\pi \sin \theta / \lambda \]
Reflection: Snell’s Law

incident \quad n=1 \quad \theta \uparrow \quad \text{reflected}

refracted \quad n'<1

critical angle of total reflection \theta_c
Reflection: Snell’s Law

incident \quad n=1 \quad \theta \quad \text{refracted}

critical angle of total reflection $\theta_c$

$n'<1 \quad \text{refracted}$

$$
\cos \theta_c = \frac{n'}{n} = n' \\
n' = 1 - \frac{N \lambda^2 b}{2\pi} \\
\cos \theta_c \approx 1 - \frac{\theta_c^2}{2} \implies \theta_c = \frac{\lambda \sqrt{N b}}{\pi}
$$
Reflection: Snell’s Law

incident \quad n=1 \quad reflected

\theta

\text{critical angle of total reflection } \theta_c

\begin{align*}
\cos \theta_c &= n'/n = n' \\
n' &= 1 - \frac{N \lambda^2 b}{2 \pi} \\
\cos \theta_c &\approx 1 - \theta_c^2/2 \implies \theta_c = \sqrt{\frac{N b}{\pi}} \lambda
\end{align*}

for natural Ni,

\begin{align*}
\theta_c &= \lambda[\text{Å}] \times 0.1^\circ \\
Q_c &= 0.0218 \text{ Å}^{-1}
\end{align*}
Distribution by Guides
Distribution by Guides

Neutron transport by total internal reflection
~ 100m at present sources
Focusing

guide $\sim 100$ cm$^2$

samples $< 1$ cm$^2$
Neutron Supermirrors

![Graph showing reflectivity (R) as a function of q/Å⁻¹ with Q_c labeled.]

Courtesy of J. Stahn, PSI
Neutron Supermirrors

\[ Q = \frac{2\pi}{d} \]

Courtesy of J. Stahn, PSI
Neutron Supermirrors

\[ Q = \frac{2\pi}{d} \]

Courtesy of J. Stahn, PSI
Neutron Supermirrors

\[ Q = \frac{2\pi}{d} \]

Courtesy of J. Stahn, PSI
An Fe/Si multilayer

Silicon substrate

Layer of element A

Multilayer material

Layer of element B
Diffractometers

• Measure structure (d-spacings)
• Assume $k_i = k_f$
• Measure $k_i$ or $k_f$:
  – Bragg diffraction
  – Time-of-flight
  – Velocity selection

• Samples:
  – Crystals
  – Powders
  – Liquids
  – Large molecules or structures
  – Surfaces
Powder diffractometers

- Measure crystal structure using Bragg’s Law
- Large single crystals are rarely available

\[ Q = \frac{2\pi}{d} \quad \lambda = 2d \sin \theta \]
Time-of-flight (TOF) method

\[ \lambda = 2d \sin \theta \]

\[ \lambda = \frac{h}{mv} = 3.956/v \]

[Å] [m/ms]
Time-of-flight (TOF) method

FIG. 1: Flight-path scheme with new chopper positions on the right and elliptical beam guide system on the left. The...
Time-of-flight (TOF) method
## Crystal Monochromators

<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>d-spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanium 333</td>
<td>1.089 Å</td>
</tr>
<tr>
<td>Copper 200</td>
<td>1.807 Å</td>
</tr>
<tr>
<td>Silicon 111</td>
<td>3.135 Å</td>
</tr>
<tr>
<td>Graphite 002</td>
<td>3.355 Å</td>
</tr>
</tbody>
</table>

### Diagram

- **Graphite 002**
  - Image of graphite crystal array.
- **Copper 200**
  - Image of copper crystal array.

### Equations

The d-spacing can be calculated using the Bragg's Law:

\[ d \sin \theta = \lambda \]

Where:
- \( d \) is the d-spacing in Ångström (Å)
- \( \theta \) is the angle of reflection
- \( \lambda \) is the wavelength of the incident radiation
Constant-Wavelength Diffraction

Powder Diffractometer Optimization:

Figure from L.D. Cussen, NIMA 554, 406 (2005)
Constant-Wavelength Diffraction
Constant-Wavelength Diffraction

\[ Q = 4 \pi \sin \theta / \lambda \]

\[ n\lambda = 2d \sin \theta \]
Constant-Wavelength Diffraction

2theta
Powder Diffraction

• Determining the structure
  – Rietveld refinement
• Measuring strain
  – Engineering applications
Diffuse Scattering

\[ Q = \frac{2\pi}{d} \]
Resolution in Diffraction

\[ d = \frac{\lambda}{2 \sin \theta} \]

\[ (\Delta d)^2 = \left( \frac{\partial d}{\partial \lambda} \Delta \lambda \right)^2 + \left( \frac{\partial d}{\partial \theta} \Delta \theta \right)^2 \]

\[ \frac{\Delta Q}{Q} = \frac{\Delta d}{d} \approx 0.2\% \]

\[ \frac{\Delta Q}{Q} = \frac{\Delta d}{d} \approx 2\% \]
Mosaic-Crystal Monochromators

\[ \lambda = 2d \sin \theta \]

\[ \Rightarrow \frac{\Delta \lambda}{\lambda} = \cot \theta \Delta \theta \]

\[ \Delta \lambda/\lambda \rightarrow 0 \quad ! \]

*Perfect crystal*

\[ \Delta \lambda/\lambda = \cot \theta_B \Delta \theta \]

*Mosaic crystal*
Time-of-flight Resolution

\[ d = \frac{\lambda}{2 \sin \theta} \]

\[ (\Delta d)^2 = \left( \frac{\partial d}{\partial \lambda} \Delta \lambda \right)^2 + \left( \frac{\partial d}{\partial \theta} \Delta \theta \right)^2 \]

\[ \lambda = \frac{h}{mv} \]

\[ \lambda [\text{Å}] = \frac{4}{\nu [\text{m/ms}]} = \frac{4t [\text{ms}]}{L [\text{m}]} \]

\[ \Rightarrow \Delta \lambda = \frac{4 \Delta t [\text{ms}]}{L [\text{m}]} \]
To improve resolution,
• increase the length: long guides
• move to a different moderator
Single-Crystal Diffraction

- Availability of large (mm$^3$) crystals
- No loss of information from powder average
- Direct and unambiguous structural determination
  - Complex structures
Constant-Wavelength Single-Crystal Diffraction

D9 @ ILL

Monochromator

Filters Collimator

Eulerian cradle

Beam stop

Sample

Area detector (64 mm x 64 mm)
Laue Diffraction

- White-beam method
- No prior knowledge of $k_i$ or $k_f$

Peak position depends only on angle of crystal plane, not on d-spacing

Good for crystal orientation, and looking for odd reflections
Laue Diffraction
TOF-Laue Diffraction

- TOF determination of $k_i$, $k_f$
- Large solid-angle coverage
  - Lower flux than standard Laue method
Small-Angle Neutron Scattering

Nanomaterials  Macromolecules  Filter materials

Semiconductors  Protein conformation  Drug-targeting
Small-Angle Neutron Scattering

Probing the longest length scales available to neutrons

\[ \lambda = 2d \sin \theta \]

\[ \Rightarrow d = \frac{\lambda}{2 \sin \theta} \]
Small-Angle Neutron Scattering

- Access to smallest angles: remove direct beam
- Good collimation required
- Access to smallest angles: remove direct beam
- Good collimation required

Soller collimator

Pin-holes separated by distance

5 cm < 30 m

5 cm > 0.1°
Constant-Wavelength SANS

\[ \Delta \lambda / \lambda \approx 10\% \]
Constant-Wavelength SANS

\[
\frac{\lambda}{2 \sin \theta} \approx \frac{\lambda}{2 \theta}
\]

\[
\left( \frac{\Delta d}{d} \right)^2 = \left( \frac{\Delta \lambda}{\lambda} \right)^2 + \left( \frac{\Delta \theta}{\theta} \right)^2
\]

Direct beam spot \( \sim 10\% \) of detector size
\[\Rightarrow \Delta \theta/\theta > 10\%\]

\[\Delta \lambda/\lambda \approx 10\%\]
Time-of-Flight SANS

- Collimation and detectors basically the same as CW SANS
- Large increase in Q-range: 2 orders of magnitude
  - 4-20Å in single measurement
  - Same or larger coverage of detector angles
Reflectometry

Reflection from surfaces and interfaces

Specular: \( \theta_{in} = \theta_{out} \)
Off-specular: \( \theta_{in} \neq \theta_{out} \)

Depth profile of the scattering-length density
Specular Reflectometry

Monochromati

$\lambda$ fixed

$\theta$ fixed

scan through $\theta$

scan through $\lambda$

Time-of-flight
Specular Reflectometry

Horizontal sample geometry
all samples (including free liquids)
limited range of $\theta$

Vertical sample geometry
no free liquids (fine for magnetism)
straightforward to vary $\theta$
Off-Specular Reflectometry

Measure in-plane correlations

Replace single detector with position-sensitive detector
Neutron Instruments I & II

- Overview of source characteristics
- Concepts and Technologies
  - De Broglie relations
  - Bragg’s Law
  - Guides, Monochromators, Choppers, Detectors
- Elastic scattering: diffractometers
  - Continuous sources
  - Pulsed sources
- Inelastic scattering: spectrometers
  - Continuous sources
  - Pulsed sources
- Non-scattering techniques
  - Fundamental physics
  - Activation analysis
  - Imaging
Neutron Spectroscopy

• Excitations: vibrations and other movements
• Structural knowledge is prerequisite
  – Measure diffraction first
• \( k_i \neq k_f \)
• Measure \( k_i \) and \( k_f \):
  – Bragg Diffraction
  – Time-of-flight
  – Resonant absorption
  – Larmor precession
• Methods:
  – Fix \( k_i \) and scan \( k_f \) – ”direct geometry”
  – Fix \( k_f \) and scan \( k_i \) – ”indirect geometry”
• Energy scales: \(< \mu \text{eV} \rightarrow > \text{eV}\)
Scattering triangle

Before:

\[ E_i, \hbar \vec{k}_i \]

After:

\[ E_f, \hbar \vec{k}_f \]

\[ \hbar \omega, \hbar \vec{Q} \]
Scattering triangle

Conservation of energy & momentum

Before:

\[ E_i, \hbar \vec{k}_i \]

After:

\[ E_f, \hbar \vec{k}_f \]

\[ E_i = E_f + \hbar \omega \]
\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]
Scattering triangle

Conservation of energy & momentum

Wavevector transfer

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]

Energy transfer

\[ \hbar \omega = E_i - E_f \]

\[ E_i = E_f + \hbar \omega \]

\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]
Scattering triangle

Conservation of energy & momentum

\[ E_i = E_f + \hbar \omega \]
\[ \vec{k}_i = \vec{k}_f + \vec{Q} \]

Wavevector transfer

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]
\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

Energy transfer

\[ \hbar \omega = E_i - E_f \]
Chopper Spectrometers
Chopper Spectrometers

Direct geometry:
fix $k_i$ by chopper phasing
scan through $k_f$ by time-of-flight

Pulsed Source
Crystal-Monochromator Chopper Spectrometers

Continuous Source

Distance

Time

Detector

Sample Chopper

Monochromator
Choppers

Fermi choppers

\[ f < 600 \text{ Hz} \]
\[ \Delta t \geq 1 \mu s \]

Disk choppers

\[ f < 300 \text{ Hz} \]
\[ \Delta t > 10 \mu s \]
Chopper Spectrometers

- General-Purpose Spectrometers
  - Incident energy ranges from 1meV to 1eV
- Huge position-sensitive detector arrays
  - Single-crystal samples
**Detectors**

**3He gas tubes**
- \(n + ^3\text{He} \rightarrow ^3\text{H} + ^1\text{H} + 0.764\text{ MeV}\)
- >1mm resolution
- High efficiency
- Low gamma-sensitivity
- \(^3\text{He} \) supply problem

**Scintillators**
- \(n + ^6\text{Li} \rightarrow ^4\text{He} + ^3\text{H} + 4.79\text{ MeV}\)
- <1mm resolution
- Medium efficiency
- Some gamma-sensitivity
- Magnetic-field sensitivity
Direct-geometry kinematics

\[ Q = k_i - k_f \]

\[ \hbar \omega = E_i - E_f \]

0 0 0

Wavevector transfer

Energy transfer
\[ Q^2 = (k_i - k_f)^2 \]

\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]
Direct-geometry kinematics

\[ Q^2 = (k_i - k_f)^2 \]

\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

\[ \hbar \omega = E_i - E_f \]

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]
Direct-geometry kinematics

\[ \hbar \omega = E_i - E_f \]

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]

\[ Q^2 = \left( k_i - k_f \right)^2 \]

\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

\[ \frac{\hbar Q^2}{2m_n} = E_i + E_f - 2 \sqrt{E_i E_f} \cos 2\theta \]
Direct-geometry kinematics

\[ \mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f \]

\[ \hbar \omega = E_i - E_f \]

\[ \mathbf{Q}^2 = (\mathbf{k}_i - \mathbf{k}_f)^2 \]

\[ \mathbf{Q}^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

\[ \frac{\hbar Q^2}{2m_n} = E_i + E_f - 2 \sqrt{E_i E_f} \cos 2\theta \]
Direct-geometry kinematics

\[ \hbar \omega = E_i - E_f \]

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]

\[ Q^2 = (\vec{k}_i - \vec{k}_f)^2 \]

\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

\[ \frac{\hbar Q^2}{2m_n} = E_i + E_f - 2\sqrt{E_i E_f} \cos 2\theta \]
Direct-geometry kinematics

\[ Q = k_i - k_f \]

\[ Q^2 = (k_i - k_f)^2 \]

\[ Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta \]

\[ \frac{\hbar Q^2}{2m_n} = E_i + E_f - 2\sqrt{E_i E_f} \cos 2\theta \]
Direct geometry:
fix $k_i$ by chopper phasing
scan through $k_f$ by time-of-flight
Indirect geometry:

- fix $k_f$
- scan through $k_i$ by time-of-flight

Alternative to direct geometry
Indirect-geometry kinematics

\[ \hbar \omega = E_i - E_f \]

\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]

Energy transfer

Wavevector transfer

Q

\( 2\theta = 0 \)

\( 2\theta = 180^\circ \)
Use resonant absorption to define $k_f$. TOF defines $k_i$.

1) Measure with absorber in and out. Count neutrons. Take difference

2) Measure with absorber in. Count gammas.
Chemical spectroscopy

TOSCA@ISIS

Density-of-states measurements

Biphenylene, BS Hudson, Syracuse University
High Resolution 1: Backscattering

\[ \lambda = 2d \sin \theta \]

\[ \Rightarrow \frac{\Delta \lambda}{\lambda} = \frac{\Delta d}{d} + \cot \theta \Delta \theta \]

\[ \theta \rightarrow \frac{\pi}{2} \]

\[ \cot \theta = \frac{\cos \theta}{\sin \theta} \rightarrow 0 \]

Use single crystals in as close to backscattering as possible to define \( k_f \).
Scan through \( k_i \) with as good energy resolution.
Pulsed-Source Backscattering

High $k_i$ resolution: long instrument on sharp moderator

exact backscattering

near-backscattering
Backscattering
Continuous-Source Backscattering
Fix $k_f$ by backscattering analysers
Scan $k_i$ by Doppler-shifting backscattering monochromator

Energy resolution < 1μeV
Energy range ~ ± 15 μeV
High Resolution 2: Neutron Spin Echo

High energy resolution < 1 μeV

Larmor precessions encode energy transfer

\[ \omega_L = \gamma_L B \]

Precession of polarisation vector

\[ P_z \]

\[ \pi\text{-flipper} \]

\[ L_0 \rightarrow L_1 \]
• Only at continuous sources
• Very flexible
• Measures a single point in $\vec{Q}$ -E space at a time
• Scans:
  – Constant $\vec{Q}$ : Scan E at constant $k_i$ or $k_f$
  – Constant E: Scan $\vec{Q}$ in any direction
TAS with Multiplexing

IN20 flat-cone multi-analyser

Top view

31 channels
75º angular range

Sample

Side view

$k_f = 3 \text{ Å}^{-1}$

$k_f = 1.5 \text{ Å}^{-1}$
Non-Scattering Techniques: Fundamental Physics
Non-Scattering Techniques: Fundamental Physics

- Tests of quantum mechanics, e.g. by interferometry
- Precision tests of the Standard Model of particle physics
  - cold or ultra-cold neutrons (E<μeV)
  - neutron electric dipole moment
  - neutron β-decay
Non-Scattering Techniques: Activation Analysis

- Irradiate and measure gamma spectrum
  - very sensitive to trace elements ($10^{-9}$ level)
- Wide range of applications
  - archeology (autoradiography of paintings)
  - biomedicine
  - environmental sciences
  - forensics
  - geology
Non-Scattering Techniques: Activation Analysis

- Irradiate and measure gamma spectrum
  - very sensitive to trace elements (10^{-9} level)
- Wide range of applications
  - archeology (autoradiography of paintings)
  - biomedicine
  - environmental sciences
  - forensics
  - geology
Non-Scattering Techniques: Activation Analysis

- Irradiate and measure gamma spectrum
  - very sensitive to trace elements (10^{-9} level)
- Wide range of applications
  - archeology (autoradiography of paintings)
  - biomedicine
  - environmental sciences
  - forensics
  - geology

St. Sebastian ca 1649, Georges de la Tour?
Non-Scattering Techniques: Activation Analysis

x-ray radiography

autoradiography after neutron activation

St. Sebastian ca 1649, Georges de la Tour?
Non-Scattering Techniques: Activation Analysis

Results: Stroke analysis
Painting technique
Paint composition
Conclusion: Copy of original by Georges de la Tour himself

St. Sebastian ca 1649, Georges de la Tour?

x-ray radiography
autoradiography after neutron activation
Imaging: Neutron Radiography & Tomography

source  collimator  object  detector

Neutrons  X-rays
Imaging: Neutron Radiography & **Tomography**

**Neutrons**

**X-rays**
Imaging: Neutron Radiography & Tomography
Thank you!

Ken Andersen
Neutron Instruments Division, ESS