Neutron Generation and Detection/Neutron Optics and Instrumentation

• How to build a neutron scattering instrument from scratch:
  – Make neutrons! (Source)
  – Transport neutrons! (Guide + Optics)
  – Scatter neutrons! (other people will tell you about this)
  – Detect neutrons! (Detectors)

• Simulate Neutron Instruments

• Simulate X-rays Instruments
New high-brightness tube moderator

Neutron Sources in the world

\[ \lambda = 1.8 \, \text{Å} \]

\[ \lambda = 5 \, \text{Å} \]
Make neutrons!

- We don’t make neutrons, we “liberate” them
- …by breaking atoms!
- Heavy atoms have disproportionally more neutrons
  - Split them into smaller atoms, and you have a surplus of neutrons!
- At HFIR: FISSION Process nuclear chain reaction (Uranium)
- At SNS: SPALLATION Process high power accelerator (Protons -> Mercury)
Pulsed vs Continuous Neutron Sources

Spallation Neutron Source (pulsed)

The peak neutron production of the SNS is about 10x that of the HFIR.

High Flux Isotope Reactor (continuous)

The HFIR neutron production is about 15x the time averaged production of the SNS.
Make **useful** neutrons!

<table>
<thead>
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<th>Energy (meV)</th>
<th>Velocity (m/s)</th>
<th>Temp (K)</th>
<th>Wavelength (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 – 5</td>
<td>100-1000</td>
<td>1 – 120 (&quot;Cold&quot;)</td>
<td>4 – 30</td>
</tr>
<tr>
<td>5 – 100</td>
<td>1000-4000</td>
<td>120 – 1000 (&quot;Thermal&quot;)</td>
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<tr>
<td>100 – 500</td>
<td>4000-40000</td>
<td>1000 – 6000 (&quot;Hot&quot;)</td>
<td>0.4 – 1</td>
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> MeV ~1E7 1E9 < mÅ

You are here!

We Need to Moderate Them
Moderators

usually: LH₂ or H₂O

Within a few collisions, the energies will have equilibrated around the temperature of the moderator.

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Proton beam
Ideally, we want **100%** Para-Hydrogen in our moderators
Spectra H2 vs H2O @ SNS

Fast neutrons

The difference is in the tail
Two instrument concepts

Diffractometer (elastic scattering)
- Characteristic changes in angle
- No change in wavelength

Spectrometer (inelastic scattering)
- Isotropic change in angle
- Characteristic change in wavelength
Let’s build an instrument already!

Source | Sample | Detector

Bragg’s law: \( n\lambda = 2d \sin \theta \)

What does this tell us?
At a pulsed source: Time Of Flight (TOF) - elastic

Velocity <-> Energy <-> Wavelength

\[ v = \frac{(L_1 + L_2)}{(T_{\text{event}} - T_0)} \]

Bragg's law: \( n\lambda = 2d \sin \Theta \)

An amazing amount of work goes into perfectly recording \( T_0 \) and \( T_{\text{event}} \) for every single event.
At a pulsed source: Time Of Flight (TOF) - inelastic

Requires knowledge of Energy before AND after sample!

Use $T_0$ and velocity to calculate $T_{\text{sample}}$, then use $(T_{\text{event}} - T_{\text{sample}})/L_2$ to calculate final wavelength.

“monochromator” (e.g. Fermi Chopper, double disk Chopper)
Detour: Crystal monochromators

• Bragg’s law: $n\lambda = 2d \sin \theta$
  • Known d-spacing, can select $\lambda$ by choosing $\theta$

• Can re-use the transmitted beam for other wavelengths!

USANS @ SNS
Reactor instruments - elastic

Bragg's Law
\[ n\lambda = 2d\sin\theta \]

Momentum Transfer
\[ \vec{Q} = \vec{k}_i - \vec{k}_f \]
Reactor instruments - inelastic

Bragg’s Law

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

Momentum Transfer

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

\[ \Delta E = \frac{h^2}{2m} \left( |k_i|^2 - |k_f|^2 \right) \]
Questions / Break

Lecture (11:00 – 12:00)
Neutron Generation and Detection/Neutron Optics and Instrumentation - Gabriele Sala

https://forms.office.com/g/p5TXaaa542
Neutron Generation and Detection/
Neutron Optics and Instrumentation - Part 2

Gabriele Sala
CHESS Instrument Scientist

July 2022
Transport neutrons!

Moderator
FTS: 10 cm x 12 cm,
STS: 3 cm x 3 cm

Gravity: $1/r^2$

Also: air scattering!

Sample
$\sim 1\text{ cm}^3$

20 m – 60 m
Why not build closer to the source?

- Real estate
- Background
- TOF Resolution:

~4m?
Neutron guides

• Like any wave, neutrons can reflect off a surface under certain conditions (see reflectometry lecture!)
  – Low angles, long wavelengths
  – Ni-58 layers deposited on glass

• Invented by Heinz Maier-Leibnitz at FRM reactor

Transport neutrons – with guides!

Source
10 cm x 12 cm,
3 cm x 3 cm

Sample
~1 cm³

20m – 60m
Neutron Guides allow unparalleled Utilization of Neutron Beams

https://www.ill.eu/

ORNL STS conceptual design

https://neutrons.ornl.gov/sts
Typical Guides currently available!

80m Guide for HRPD at J-PARC
Fabricated by Swiss Neutronics

30m Guide for CHESS at STS
Fabricated by Swiss Neutronics

Multichannel Curved Guide
Fabricated by Swiss Neutronics
Not just straight!

Getting out of direct line of sight reduces background from source.

\[ L = \sqrt{8Rd} \]

Length of direct sight
Advanced neutron optics

• Parabola: focusing

• Elliptic: focusing and avoid optical aberrations

• Zig-Zag (half ellipses):
  – Imaging + line of sight
BUT!

• Angle/wavelength limited
• Liouville is watching you!
  – No free lunches.
  – Increase in neutron flux comes with decreased resolution
  – Finding the balance is a large part of instrument design

Source
10 cm x 12 cm

Sample
~1 cm³
Other problems: Frame overlap

- There is usually more than one pulse in a beam line.
- It is important (and difficult) to keep track of which pulse started when for TOF analysis.
- Fast neutrons from one pulse can overtake the slow ones from the previous pulse “Frame overlap”.
- TOF analysis becomes impossible.
- The longer the beam line and the higher pulse frequency the worse.

Source

- Solution: Get rid of those neutrons (fast/slow/fast+slow)!
- Use a chopper in phase with the pulsed source.
- Select time offset to choose spectrum.
- Might need to measure twice for full spectrum.
T0 choppers

- Fast neutrons and gammas arrive first after proton pulse delivery
- 20-50 cm thick steel blade attenuates these
- Requires well-balanced flywheel for good lifetime and prevention of vibrations

Unit running at JPARC
Detectors

• Several types of detectors

• Idea: trigger a nuclear reaction that releases an energetic charged particle that can then be detected (e.g. through an ionization event)

• Requirements:
  – Position resolution
  – Timing resolution
  – Not sensitive to background
  – They are NOT Cheap

ARCS Detectors @ SNS
Overview of the CHESS instrument
More Questions

Slack Channel: nxs2022-gabrielesala

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Thank you for your kind attention,
Enjoy the rest of the School