Neutron Instrumentation

Dean Myles, Director
Neutron Scattering Science Division
OUTLINE

• Neutrons
• Neutron Sources SNS & HFIR
  • Instrument Suite and Science Examples
• Beam lines – components and optics
• Instrumentation
• other exotic things with neutrons…. 
Oak Ridge – has been developing neutron scattering from the beginning ....

In the 1940’s Wollan and Shull applied the ideas of x-ray diffraction to neutrons (Oak Ridge Graphite Reactor)

The Diffraction of Neutrons by Crystalline Powders
E. O. Wollan and C. G. Shull

The Physical Review, Vol. 75 No 8, 830-841, April 15, 1948

1994 Nobel Prize in Physics for the development of the neutron scattering technique
...and continues today as the world’s foremost center for the study of materials using neutrons

- SNS and HFIR provide unprecedented capabilities for understanding the structure and properties of materials across the spectrum of biology, chemistry, physics, and engineering.
- Stay at the leading edge of neutron science by developing new capabilities, instruments, and tools.
Neutrons: microns to angstroms!
Structure: From Atoms to Materials
The ORNL Elastic Instrument Suite

**STRUCTURE:**

- scattering is independent of $Z$
  
  *(good for light atoms)*

- scattering lengths are constant with $Q$ *(better structural precision)*

- neutrons scattered by electron Spin
  
  *(magnetic structure)*

- many metals are “transparent”
  
  *(in situ, high & low T, H field)*

- reflectometry: contrast vs depth
  
  *(direct phasing)*
**Dynamics: Time and Distance too!**

The ORNL Inelastic Instrument Suite

**DYNAMICS:**

**Spectroscopy:**

- scattering intensity cross-section \((easy to model)\)
- no selection rules
- simultaneously measure \(\Delta Q\) (momentum) & \(\Delta \omega\) (energy)

\[ \Rightarrow \text{time & distance} \]

- greatest sensitivity for H
- time scale spans \(10^7\)
- distance scale spans \(10^3\)

\((Unique capability)\)

\((Fast measurements or dilute systems)\)
How do we produce neutrons?

**Fission**
- chain reaction
- continuous flow
- 1 excess neutron/fission
- 180 MeV/neutron

**Spallation**
- no chain reaction
- pulsed operation
- 40 neutrons/proton
- 30 MeV/neutron
The High Flux Isotope Reactor

- Constructed in 1965
- Operating power: 85 MW
- Steady-state thermal neutron flux: $1.0 \times 10^{15}$ neutrons/(cm²•s) (among the world’s highest)
- $70$M upgrade completed in 2007
  - State-of-the-art instruments
  - World class cold neutron source
Nine instruments in the user program
- 4 Triple axis Spectrometers
- 2 SANS
- Powder diffraction
- Single Crystal Diffraction
- Strain Scanner (HTML)

Commissioning two new instruments in 2010

Full User program underway

Two-dimensional scattering pattern of a polymer blend taken on the new HFIR SANS instrument
High Flux Isotope Reactor  - Capacity for Growth

**HB-1A**
Ames Lab Triple-Axis Spectrometer
Low-energy excitations, magnetism, structural transitions
Jené Zaremba - 565.774.3025
jarenek@lbl.gov

**HB-1**
Triple-Axis Spectrometer
Polarized neutron studies of magnetic materials, low-energy excitations, structural transitions
Andy Diederich - 565.281.0036
sheldout@lanl.gov

**HB-2A**
Powder Diffractometer (2008*)
Structural studies, magnetic structures, texture and phase analysis
Ovidiu Delcea - 565.574.5941
gnafocalian.gov

**HB-2C**
U.S./Japan WAND
Diffuse-scattering studies of single crystals and time-resolved phase transitions
Jaime Fernández-Recio - 565.279.8459
fernandez@mit.edu

**HB-2D**
Future Development

**HB-2B**
Residual Stress Mapping
Strain and phase mapping in engineering materials
Camden Hubbard - 565.774.4473
hubbarddor@ornl.gov

**HB-3**
Triple-Axis Spectrometer
Medium- and high-resolution inelastic scattering of thermal energies
Mark Lumsden - 565.274.3309
lumsden@mit.edu
Jaime Fernández-Recio - 565.279.8459
fernandez@mit.edu

**HB-3A**
Four Circle Diffractometer (2007)
Small unit-cell crystal structural studies, particularly H-bonding
Brian Chakoumakos - 565.274.5135
chakoumakos@ornl.gov

**CG-1**
Future Development
Highly correlated electronic systems, quantum magnetism, molecular and nanocluster magnetic systems

**CG-2**
SANS (2007)
Polymer blends, flux lattices in high-Tc materials, soft materials processing and structure
Ken Litrell - 565.274.6030
litrellk@ornl.gov
Valerie Shcheglova - 565.274.7790
valerie.shcheglova@ornl.gov
George Wright - 565.274.9327
wrightg@ornl.gov

**CG-3**
BioSANS (2007)
Biomaterials, pharmaceuticals, polymers
Volker Urban - (865) 298-1078
urbanv@ornl.gov
Gary Lynn - 565.241.0083
lynng@ornl.gov
William Hopper - 565.241.0093
hopperw@ornl.gov

**CG-4A**
Highly correlated electronic systems, quantum magnetism, molecular and nanocluster magnetic systems, superconductivity
Larry Winn - 565.241.0003
winnl@ornl.gov

**CG-4B**
Future Development

**CG-4C**
U.S./Japan Cold Triple-Axis

*Date shown is the scheduled commissioning date.

**LEGEND**
- Installed, commissioning, or operating
- In design or construction
- Under consideration
HFIR Cold Instrument Guidehall
The Spallation Neutron Source

- Construction completed May 2006
- User operations began in 2007
- At 1.4 MW (in 2010): the world’s most powerful pulsed spallation source
- Room for 25 instruments spanning physics, chemistry, biology, and materials science
- Upgradable to higher power and a second target station
Full Energy linac and Accumulator Ring

Design Criteria

1) Produce H⁻ beam pulse in source
2) Accelerate beam pulse in linear accelerator to 1 GeV
3) Accumulate 1060 pulses in the accumulator ring
4) Extract and fire the accumulated beam at the target
5) Do this 60 times per second!

Operational Goal

High proton density on target – goal is \(1.4 \times 10^{14}\) protons per pulse!

High Availability and Reliability
Mercury Target

- Inflatable seals tested
- Mercury loaded in December
- Hg flow tests completed
**Inner Reflector Plug**

- Contains moderators and reflectors around the target. Three H moderators running at ~20K and one H$_2$O moderator running at 290K.

- Neutrons produced by spallation in the Hg are high energy, ~1GeV, must be cooled to 1meV $\rightarrow$ 1eV range for use in thermal neutron scattering.
Target Region Within Core Vessel

- Target Module with jumpers
- Outer Reflector Plug
- Moderators
- Target
- Core Vessel water cooled shielding
- Core Vessel Multi-channel flange
We’ve reached 800 kW; ultimate goal is 1.4 MW in FY 2010

SNS beam power has more than tripled since Oct 2007
Reactor or pulsed source?

Pulsed source

Reactor

Reactor

Reactor

Intensity

Wavelength

time
Differences between TOF and steady-state

Steady-state
- uses single wavelength
- bandwidth (bw) = resolution width (res)
- range of data requires multiple angles

TOF
- uses range of wavelengths
- bandwidth (bw) >> resolution width (res)
- range of data at single angle

\[ \Delta \lambda_{res} = \Delta \lambda_{bw} \]
Neutrons have both Particle-like and Wave-like Properties

- Mass: $m_n = 1.675 \times 10^{-27}$ kg

- Charge = 0; Spin = $\frac{1}{2}$

- Magnetic dipole moment: $\mu_n = -1.913 \, \mu_N$

- Kinetic energy ($E$), Velocity ($v$), Wavelength ($\lambda$), Wavevector ($k$)

\[
E = m_n v^2/2 = k_B T = (\hbar k/2\pi)^2/2 \, m_n; \quad k = 2\pi/\lambda = m_n v/ (\hbar/2\pi)
\]

<table>
<thead>
<tr>
<th></th>
<th>Energy (meV)</th>
<th>Temperature (k)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>0.1 – 10</td>
<td>1 – 120</td>
<td>0.4 – 3</td>
</tr>
<tr>
<td>Thermal</td>
<td>5 – 100</td>
<td>60 – 1000</td>
<td>0.1 – 0.4</td>
</tr>
<tr>
<td>Hot</td>
<td>100 - 500</td>
<td>1000 - 6000</td>
<td>0.04 – 0.1</td>
</tr>
</tbody>
</table>

Room temperature ~ 25 meV ~ 0.18 nm ~ 2200 m/s
Neutron Instrumentation

Essentially 2 types of Instrument:

Diffractometers: - measure Elastic Scattering

Structure:
  - Neutrons as waves
  - Based on Bragg’s Law
  - No change of energy detected

Spectrometers: - measure Inelastic Scattering

Dynamics
  - Neutrons as particles
  - Based upon Newton’s laws
  - Change of energy detected
Diffractometers: - Elastic Scattering

$k, \lambda, E$ → Sample → Detector

$Q = k_f - k_i$  \hspace{1cm} \textit{Wavevector transfer}

$|k_f| = |k_i|$  \hspace{1cm} \textit{“Elastic” scattering} $I(Q)$

$|Q| = 2|k| \sin \theta$

Since $|k| = 2\pi/\lambda$; where $\lambda = h/(mnv)$ \{de Broglie\}

Then $|Q| = Q = (4\pi/\lambda) \sin \theta$
Spectrometers: Inelastic Scattering

- **Wavevector transfer:** 
  \[ \mathbf{Q} = \mathbf{k}_f - \mathbf{k}_i \]

- **Energy transfer:** 
  \[ \hbar \omega = E_f - E_i \]

- **“Inelastic” scattering:** 
  \[ I(Q, \omega) \]

- **Energy transfer equation:** 
  \[ \hbar \omega = E_i - E_f = \frac{\hbar^2}{2m} (k_i^2 - k_f^2) \]
Some Typical Components of Neutron Scattering Instruments

- **Monochromators**
  - Monochromate or analyze the energy of a neutron beam using Bragg’s law

- **Collimators**
  - Define the direction of travel of the neutron

- **Guides**
  - Allow neutrons to travel large distances without suffering intensity loss

- **Choppers**
  - Define a short pulse or pick out a small band of neutron energies

- **Detectors**
  - Neutron is absorbed by $^3$He and gas ionization caused by recoiling particles is detected

- **Spin turn coils**
  - Manipulate the neutron spin using Lamor precession

- **Shielding**
  - Minimize background and radiation exposure to users
Diffractometers - Elastic scattering

Single Crystal Diffractometer

(Continuous source)
Angular Resolution - Collimation

**Natural Collimation**
Angular uncertainties are determined by source-sample and sample-detector distance.
Uncertainties increase as the distance decreases.

**Pinhole Collimation**
Angular uncertainty is determined by apertures.

**Soller Collimation**
Angular uncertainty and aperture decoupled.
Beam delivery over long distances – Neutron Guides

Index of refraction

\[ n = 1 - \frac{\lambda^2 \rho}{2\pi} \]

\[ \rho = N_b = \text{scattering length density} \]

\[ n < 1 \text{ for most materials, so there is a critical angle } \alpha_c \text{ for total external reflection} \]

For Nickel

\[ \alpha_c (^o) = 0.1 \lambda \text{ (Å)} \]
Beam delivery – Neutron Guides
Detection of neutrons

• Since neutrons have zero charge they cannot be detected directly, instead a charge particle needs to be produced and then detected.

• Counters:
  - $\text{BF}_3 \quad ^{10}\text{B}_5 + ^1\text{n}_0 \rightarrow ^7\text{Li}_3 + ^4\text{He}_2 + 2.7 \text{ MeV}$
  - $^3\text{He} \quad ^3\text{He}_2 + ^1\text{n}_0 \rightarrow ^3\text{He}_1 + ^1\text{H}_1$

• Film/scintillators:
  - $^6\text{Li}_3 + ^1\text{n}_0 \rightarrow ^3\text{H}_1 + ^4\text{He}_2$

• Most detectors need bulky shielding as they are sensitive also to $\gamma$-rays
Neutron Detectors

- We are using four detector types:
  - Multiwire proportional chambers
  - Position sensitive proportional tubes
    - Commercially available tubes
    - Electronics and packaging done in house
  - Scintillation detectors with wavelength shifting fiber readout
    - New development
  - Anger cameras with position sensitive PMTs
    - New development
Determining the Wavelength – reactor (continuous) source

crystal monochromator (Bragg diffraction)

\[ \lambda = \frac{2d_c \sin(\theta_B)}{n} \]

\[ \Delta \lambda/\lambda \sim \delta d/d + \cot(\theta)\delta \theta \]
Resolution

- crystal monochromator
- collimator
- monochromator
  - e.g. graphite (002)
  - $d = 3.35 \text{ Å}$
- soller slit collimator
  - $\Delta \theta_c$

use Bragg's Law

$$\lambda = 2d \sin \theta$$

resolution

$$\frac{1}{2} \frac{\Delta E}{E} = \frac{\Delta \lambda}{\lambda} \sim \cot \theta \Delta \theta_c$$
Put in some numbers:

\[
\text{so if } 2\theta_M = 74.14 \quad \text{(5 meV)} \\
\cot \frac{2\theta_M}{2} = 1.6 \\
\text{and for } \Delta \theta_c = 0.5^\circ = 0.0087 \text{ rad} \\
\text{and } \frac{\Delta \lambda}{\lambda} \sim 1\% \\
\text{advantages: high } \frac{\Delta \lambda}{\lambda} \\
\text{disadvantages: high } \frac{\Delta \lambda}{\lambda} \\
\text{poorer reflectivity (transmission)} \\
\frac{\lambda}{n} \text{ contamination}
\]
Small Angle Scattering – a special case

\[ \lambda = 2d_c \sin(\theta_B) \]

\[ Q = 4\pi \sin\theta/\lambda; \quad (\delta Q/Q)^2 = (\delta \lambda/\lambda)^2 + (\cot\theta \delta \theta)^2 \]

- Small diffraction angles to observe large objects => long (20 m) instrument

- Poor monochromatization ($\delta \lambda/\lambda \sim 10\%$) sufficient to match obtainable angular resolution (1 cm$^2$ pixels on 1 m$^2$ detector at 10 m => $\delta \theta \sim 10^{-3}$ at $\theta \sim 10^{-2}$)
Mechanical Velocity selector provides large $\Delta \lambda / \lambda$

\[ \Rightarrow \text{velocity selector} \]

\[ \begin{align*}
\text{rotation} & \quad \theta \\
\text{traverse time for } n & \quad t = \frac{L}{v_n} \\
\text{and } s = v_s \cdot t = 2\pi r \cdot \omega \cdot t & \quad = \frac{2\pi r \omega L}{v_n} \\
\text{w controls } & \quad \frac{\Delta v_n}{v_n} \text{ and transmission}
\end{align*} \]

\[ \frac{\Delta v}{v} = \frac{\Delta \lambda}{\lambda} \]

Advantages:
- high transmission coarse (5% - 30%)

Disadvantage:
- coarse \[ \frac{\Delta v}{v} = \frac{\Delta \lambda}{\lambda} \]

Typically, \( \sim 1000 \text{ rpm} \)
Reflectometry – another special case
- also can use large $\Delta \lambda/\lambda$

• **Refractive index**
  \[ n = 1 - \delta - i\beta \]

• **x-rays**
  \[ \delta = \frac{\lambda}{2\pi} r_e \rho \]

• **Neutrons**
  \[ \delta = \frac{\lambda}{2\pi} N_b \]

• **Total external reflection** will occur for grazing angles of incidence $\theta_{in} < \theta_c = (2\delta)^{1/2}$ since $n<1$

• For $\theta_{in} < \theta_c$ only an *evanescent wave* propagates below the surface (depth $\sim nm$) and surface sensitivity is greatly enhanced
Inelastic scattering - Spectrometers

Triple Axis Spectrometer

(Continuous source)

**Workhorse** for the study of $S(q,\omega)$ at a given $q$ vector in *single crystals*: $k$ and $k'$ selected in-dependently in the system of sample
The Triple Axis Spectrometer

HFIR TAS

HB1a – Fixed Ei (14.6 meV) triple-axis,
Resolution typical ~1 meV, 0.5 meV (Be analyzer),
HB1 – Polarized (soon) triple-axis, vertical focusing
HB3 – triple-axis, three available monochromators, vertical focusing
Slowing down time or $T_0(\lambda)$ or $T_0(E)$

- Neutrons emerging from moderators have a distribution of energies = a Maxwellian + a $1/E$ (epithermal) tail.

- But different neutron energies (wavelengths) emerge from the moderator with different time distributions (see example on right).

- Need to calibrate a $T_0(E)$ function for each moderator and use this in data reduction.

- Now the neutrons are emerging out of the monolith and into the beamlines for the neutron scattering instruments…..

Example: MCNPX results for coupled cryogenic $H_2$ moderator on SNS target station 1
Beam Selection/conditioning
T0 Choppers and Curved Guides

- When the proton beam strikes the target (time T0) a burst of ~1GeV neutrons and a flash of gamma rays are produced. Some are neutrons are moderated but some emerge into the beamline at time T0. Have to get rid of the fast neutrons and gamma rays.

- Two methods - T0 chopper or curved guide

- T0 chopper – rotating plug of Inconel (200 → 300mm) that blocks the beam at time T0.

- Curved guide, low energy neutrons are reflected but not higher energies. The guide is curved so that final sample position does not have a line of sight to the source and fast neutrons must collide/be absorbed in, shielding around beamline. BASIS, CNCS and HYSPEC have curved guides.

- Note T0 choppers are phased (electronically) to the source “T0” signal.
A Generic Pulsed Source Instrument – introducing choppers

Diagram showing the components of a pulsed source instrument: Moderator, $T_0$ Chopper, Bandwidth Limiting Choppers, Neutron Guide, Sample, Detector.
Rotating Choppers Are Used to Tailor Neutron Pulses

Fast neutrons from one pulse can catch-up with slower neutrons from a succeeding pulse and spoil the measurement if they are not removed. This is called “frame-overlap”

- **T-zero choppers** are used at spallation sources to absorb the prompt high-energy pulse of neutrons
- **Cd** is used in frame overlap choppers to absorb slower neutrons
Determining the wavelength – pulsed source

\[ \lambda = \frac{4000}{v} = \frac{4000}{L} \, (t-t_0) \]

\( \delta \lambda \sim \delta t_0, \delta t, \delta L \)

Powgen3 at SNS

L = 60 m
SNAP – Single Crystal Diffractometer for high pressures (>50 Gpa)

Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderator</td>
<td>Decoupled poisoned supercritical hydrogen</td>
</tr>
<tr>
<td>Source to sample distance</td>
<td>15 m</td>
</tr>
<tr>
<td>Sample to detector distance</td>
<td>50 cm</td>
</tr>
<tr>
<td>Angular coverage</td>
<td>38°-142° \ 98°-150° horizontal ±34° vertical</td>
</tr>
</tbody>
</table>
| Wavelength range (bandwidth)| Frame 1: 0.5 – 3.65 Å  
|                            | Frame 2: 3.7 – 6.5 Å                       |
| Pressure range             | From ambient pressure to >50 GPa (500 kbar) |
| Focused beam size          | From 1 cm to <100 μm                       |
Wavelength-resolved Laue Data in Detector Space

Diffraction patterns are 3D: \((x, y, \lambda)\)

Reduced reflection overlap.

Reduced background

Enhanced signal-to-noise

Red-Blue: 0.6A-6A
Backscattering spectrometer at SNS

Want high resolution, BASIS has $\Delta E = 3.5\text{ueV}$

Use time-of-flight to determine incident energy

Use Bragg diffraction to determine final energy

$pulsed$ $source$

$L_1 = 80\text{m}$

Crystal Analyzer

detector

\[ \lambda = \frac{4000}{v} = \frac{4000}{L} (t-t_0) \]

$\delta \lambda \sim \delta t_0, \delta t, \delta L$

\[ \lambda = \frac{2d_c \sin(\theta_B)}{n} \]

$\Delta \lambda/\lambda \sim \delta d/d + \cot(\theta)\delta \theta$
BASIS – backscattering spectrometer

- **Source/Moderator**
  - Decoupled supercritical Hydrogen, centerline poisoned

- **Incident Flight Path** - 84 m moderator-sample position
  - Curved Guide: 10 cm wide x 12 cm tall, 1000 π radius of curvature, line-of-sight at 31 m
  - Straight Guide: 10 cm wide x 12 cm tall
  - Converging Funnel exit: 3.25 cm x 3.25 cm, stops 27.5 cm from sample

- **Chopper System** - 3 bandwidth/frame overlap choppers

- **Sample** – nominal dimensions 3 x 3 cm²

- **Radial Collimator** – restricts analyzer view of the sample, Final Flight Path - 2.5 m sample - analyzer, ~2 m analyzer – detector

- **Detector Choice** – ³He LPSD tubes, peak count rate (elastic, 30% scatterer) 4000 counts/cm²/sec

- **Analyzer Crystals**
  - Si (111): λf= 6.267 Å, δd/d~3.5 x 10⁻⁴, 2.03 ster, 12.5 m², bandwidth 0.785 Å
A generic TOF spectrometer - again, but with a twist

Moderator

$T_0$ Chopper

Fermi Chopper
(essentially a rotating collimator)

Neutron Guide

Sample

Detector
SEQUOIA – high resolution chopper spectrometer

optimized for magnetic inelastic scattering (in forward direction), which falls off with increasing Q (angle).

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderator</td>
<td>Decoupled ambient water</td>
</tr>
<tr>
<td>Source to Fermi chopper distance</td>
<td>18 m</td>
</tr>
<tr>
<td>Chopper to sample distance</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Sample to detector distance</td>
<td>5.5 – 6.3 m cylindrical geometry</td>
</tr>
<tr>
<td>Incident energy range</td>
<td>10 – 2000 meV</td>
</tr>
<tr>
<td>Resolution (elastic)</td>
<td>1 – 5% E_i</td>
</tr>
<tr>
<td>Vertical detector coverage</td>
<td>-30 – 30°</td>
</tr>
<tr>
<td>Horizontal detector coverage</td>
<td>-30 – 60°</td>
</tr>
<tr>
<td>Minimum detector angle</td>
<td>3°</td>
</tr>
</tbody>
</table>
Detector Vessels: vacuum tanks – ARCS & SEQUOIA

- Air scatters neutrons strongly, over long flight paths want to remove the air → vacuum
- Wallpaper the detector vessel with LPSD tubes
CNCS (Cold Neutron Chopper Spectrometer)

- Designed for rapid data collection using a large position-sensitive detector array.

- Flexible chopper system can adapt the resolution to the problem of interest

- Example: Diffusion in biological gels
  - CNCS can study the temporal and spatial correlations of water undergoing translational and rotational motions.
High Speed Double Disk Choppers - CNCS

- In order to get high final energy resolution we need a short burst time for the chopper.

- If the 2 disks are rotating at 300Hz each then the effective frequency of the 2 choppers is 600Hz is this “counter-rotating” mode.

- Opening time is phased to T0 signal.
Each individual neutron has spin $s = \frac{1}{2}$ and an angular momentum of $\pm \frac{1}{2}\hbar$.

Each neutron has a spin vector $\vec{S}_n$ and we define the polarization of a neutron beam as the ensemble average over all the neutron spin vectors, normalised to their modulus:

$$\vec{P} = \langle \vec{S}_n \rangle / \frac{1}{2} = 2 \langle \vec{S}_n \rangle$$

If we apply an external field (quantisation axis) then there are only two possible orientations of the neutrons: parallel and anti-parallel to the field. The polarization can then be expressed as a scalar:

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

where there are $N_+$ neutrons with spin-up and $N_-$ neutrons with spin-down.
A Uniaxial PA Experiment

First attempted by Moon, Riste and Koehler (1969)

*Phys Rev. 181* (1969) 920
Production of polarized beams

There are three principal (passive) methods of beam polarization, each with specific advantages in particular experimental situations

1. polarizing crystals (e.g. Co\textsubscript{92}Fe\textsubscript{8}, Heusler crystals (Cu\textsubscript{2}MnAl)) using preferential Bragg reflection
2. polarizing mirrors and supermirrors (using preferential reflection)
3. polarizing filters (e.g. preferential absorption by polarized \textsuperscript{3}He nuclei)

See, e.g. Williams in Polarized Neutrons, Oxford
Polarizing monochromators

Reflected intensity \( I \sim \frac{d\sigma}{d\Omega} = F_N(Q)^2 + F_M(Q)^2 + 2F_N(Q) \cdot F_M(Q) \cdot (P \cdot \mu) \)

\[
\begin{align*}
\text{Intensity} & \sim (F_N + F_M)^2 \\
\text{Intensity} & \sim (F_N - F_M)^2 \\
\text{Polarization} & = \frac{(I_+ - I_-)}{(I_+ + I_-)} = \pm 2F_N(Q) \cdot F_M(Q)/[F_N(Q) - F_M(Q)]^2
\end{align*}
\]
## Polarizing crystal monochromators

### Heusler alloy

<table>
<thead>
<tr>
<th></th>
<th>Co$<em>{0.92}$Fe$</em>{0.08}$</th>
<th>Cu$_2$MnAl</th>
<th>Fe$_3$Si</th>
<th>$^{57}$Fe:Fe</th>
<th>HoFe$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matched reflection</td>
<td>(200)</td>
<td>(111)</td>
<td>(111)</td>
<td>(110)</td>
<td>(620)</td>
</tr>
<tr>
<td>$</td>
<td>F_N</td>
<td>\sim</td>
<td>F_M</td>
<td>$</td>
<td></td>
</tr>
<tr>
<td>d-spacing (Å)</td>
<td>1.76</td>
<td>3.43</td>
<td>3.27</td>
<td>2.03</td>
<td>1.16</td>
</tr>
<tr>
<td>Take-off angle $2\theta_B$ at 1 Å (deg)</td>
<td>33.1</td>
<td>16.7</td>
<td>17.6</td>
<td>28.6</td>
<td>50.9</td>
</tr>
<tr>
<td>Cut-off wavelength, $\lambda_{max}$ (Å)</td>
<td>3.5</td>
<td>6.9</td>
<td>6.5</td>
<td>4.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Polarized \(^3\)He based neutron spin filter

Polarized \(^3\)He neutron spin filter is based on the spin-dependence of the neutron absorption of \(^3\)He. If the \(^3\)He nuclear spin and the neutron spin are anti-parallel, the absorption is very strong: \(\sigma_a(\uparrow\downarrow) = 5931\) b for \(\lambda=1\) Å neutrons. If the spins are parallel, there is virtually no absorption. \(\sigma_a(\uparrow\uparrow) \sim 0\). The absorption cross-section is proportional to the neutron wavelength \(\lambda\).

\[ T_+ = T_{\text{glass}} e^{-(1-P_{\text{He}}) n \sigma \lambda l} \]
\[ T_- = T_{\text{glass}} e^{-(1+P_{\text{He}}) n \sigma \lambda l} \]
\[ P_n = \tanh(P_{\text{He}} n \sigma \lambda l) \]

- \(T\) = transmission
- \(P_n\) = neutron polarization
- \(P_{\text{He}}\) = \(^3\)He polarization
- \(n\) = number density of \(^3\)He
- \(l\) = cell length
- \(\sigma\) = absorption cross-section at 1 Å
- \(\lambda\) = neutron wavelength

Measured characteristics:
- \(^3\)He polarization = 75%
- Cell pressure=1.82 bar
- Cell length=8.1 cm
- Empty cell transmission \(T_e=0.88\)

A \(^3\)He spin filter cell
Polarized Neutron Technology: The Magnetism Reflectometer at SNS
Polarized Neutron Technology: The Magnetism Reflectometer at SNS
Some things we didn’t talk about: but others will

- Capillary Optics
- Compound Refractive Lens
- Magnetic Lens
- Polarized Neutrons
- Neutron Spin Echo
The beginnings of neutron spectroscopy

Bertram Brockhouse, Chalk River, Canada, 1950’s

“If the neutron did not exist, it would need to be invented.”

-B. Brockhouse