Spallation-Driven Cold Neutron Sources

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Accelerator-Driven Spallation Sources

- Produce neutrons for use in condensed matter and basic physics research
- Want neutron wavelengths about the dimensions of interest, or neutron energies that can probe the dynamics of interest
- The pulsed nature of the neutron beams allows for energy determination by time of flight (which you can’t do with a reactor source)
  - Exception noted for the SINQ source which uses the PSI cyclotron
What’s Important?

- Accelerator parameters
  - power on target – 7 kW (IPNS) to 1 MW (SNS)
  - proton energy – 450 MeV (IPNS) to 3 GeV (JSNS)
  - pulse rate 10 Hz (ISIS TS2) to 25 Hz (JSNS) to 60 Hz (SNS)
  - pulse length – sub-μs (short pulse), 1-2 ms (long pulse), CW (SINQ)
- Neutron economy in target (production, absorption)
- Moderator efficiency, coupling to target
- Neutron energy spectrum and emission time distribution
Neutron Production

- A fundamental truth – all neutrons are born fast
- Neutrons are produced by the processes of spallation, fission, and neutron multiplication
How Do We Make Cold Neutrons?

- Cold neutron production at the IPNS

\[ E_p = 450 \text{ MeV} \]

\[ E_n = 1 \text{ MeV} \]

\[ E_n = 5 \text{ meV} \]

(\sim 25 \text{ collisions})
Types of Accelerator-Driven Spallation Sources

- Linac + synchrotron (IPNS, ISIS, JPARC)
- Linac + accumulator (compression) ring (SNS, LANSCE, original ESS)
- Cyclotron (SINQ)
Intense Pulsed Neutron Source (ANL)

- IPNS was the first user-dedicated accelerator-driven neutron source in the world, commissioned in 1981
- Neutrons were produced by spallation/fission by 450-MeV protons striking depleted uranium target
- Proton beam pulsed at 30 Hz
- Average current 15 µA
- Target lifetime about four years operating 20-25 weeks per year
- Accelerated \(2.63 \times 10^{22}\) protons (1.17252 A-hrs) in 9,368,550,687 pulses
- Liberated 0.53 g neutrons
- 95.4% reliability from 10/89 to end of operation
ISIS

- Accelerator parameters
  - Linac 70 MeV, 200 μs, 50 Hz
  - RCS 800 MeV, 50 Hz, 160 kW, (2) 100 ns pulses

**ISIS** is a high power accelerator that fires high energy protons into two targets to release neutrons for experiments.

**Target Station 1**
Neutrons are released from both targets via spallation. Using neutrons, scientists can study the atomic structure of materials and can even measure the forces between atoms.

**Target Station 2**
The second target station is optimised for low-energy neutrons providing greater capacity at ISIS and opening up new areas of research.
Japan Spallation Neutron Source

- Accelerator parameters
  - Linac 400 MeV, 500 μs, 50 Hz
  - RCS 3 GeV, 25 Hz, 1 MW
Spallation Neutron Source (ORNL)
European Spallation Source

- Linear accelerator + compression ring (short pulse target station)
- Accelerator parameters
  - 10 MW
  - 1.33 GeV
- Short pulse target station
  - 5 MW
  - 1.4 us
  - 50 Hz
- Long pulse target station
  - 5 MW
  - 2 ms
  - 16 2/3 Hz
Paul Scherrer Institute - SINQ

PSI ACCELERATOR FACILITY

72 MeV Injector 2

870 keV Cockroft-Walton pre-accel.

72 MeV proton beam for isotope prod.

590 MeV Ringcyclotron

590 MeV beams to meson production targets and neutron spallation source

Variable energy Injector 1

beams for low energy exp.
What is the Optimum Target Material for Neutron Production?

- Higher atomic number targets favor greater neutron production
What is the Optimum Target Material for Neutron Production?

- Part of uranium’s advantage comes from fission, part from higher Z
Neutron Absorption of Candidate Target Materials

![Graph showing neutron absorption cross section versus neutron energy for various materials.](image)

- Tantalum
- Tungsten
- Mercury
- Lead
- Bismuth

The graph illustrates the macroscopic absorption cross section (1/cm) of different materials in relation to their neutron energy (MeV). The materials are plotted with distinct lines and colors, making it easy to compare their absorption properties across a range of neutron energies.
What is the Optimum Energy for Spallation Neutron Production?

- Discussed the matter in general terms, not as an engineering solution to the problem.
- Background of discussion is how best to reach high beam power, with high current or with high energy.
- Concludes that higher proton beam energy
  - has advantages in potentially lower capital costs, potentially lower operating costs, and potentially lower beam losses.
  - probably somewhat relieves radiation damage problems in accelerator and target beam windows.
  - has a possibly slight positive affect on target station design.
- Superconducting ion accelerators had not been demonstrated to high energies at the time – warm accelerator forces choice of high current to maximize wall plug to beam energy efficiency.
What is the Optimum Energy for Spallation Neutron Production?

- The fraction of proton energy that goes into producing neutrons decreases as the proton energy increases.

<table>
<thead>
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<th>$E_p$ (GeV)</th>
<th>$F_h$</th>
<th>$I_1$ (mA)</th>
<th>$I_n$ (mA)</th>
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</table>

$I_1$: current for 1 MW power

$I_n$: current for constant neutron production
Target Station - JSNS

- Target building must accommodate target, reflectors, moderators, beam gates, instruments, biological and instrument shielding, services
  
  - Thick roof shield without explicit metallic liners.
  - Seal plate on the top.
  - Concrete layer in steel shield.
  - Proton beam window near vessel.

Water-Cooled Portion in Helium Vessel.
- Middle section
- Shielding around reflector

Dry air ventilation
Moderator Coupling to Target

- Moderators can be in wing or slab or flux-trap configurations.
- Non-symmetric target shape improves coupling.
- Best results for target “radius” about 2.5 cm larger than beam “radius.”
Reflectors

- Reflectors are used to keep neutron population in the moderators high.
- Decouplers (e.g., cadmium) used to reduce low-energy neutrons entering moderator (sharpens pulse by reducing long tail of pulse).
- IPNS reflectors illustrated.
Moderators

- Moderators reduce the neutron energy to ~ meV levels
- High-power moderators are all liquid hydrogen due to heat load, rad damage
- Typical viewed area 10 x 10 cm (IPNS) or 10 x 12 cm (SNS)
Moderators

- Internal poison layers used to sharpen pulse (make moderator appear thinner for lower-energy neutrons)
- JSNS moderators illustrated
What is the Best Moderator Material?

- High hydrogen density – high moderating power
- Low neutron absorption
- Inelastic scattering modes in the range 0-10 meV
- Typical choices
  - Water
  - Methane (liquid or solid)
  - Hydrogen
  - Advanced materials – mesitylene, benzene, ammonia
- Lack of data on candidate moderator materials is a severely limiting factor in evaluating new concepts
Neutron Cross Sections for Moderator Materials

![Graph showing neutron cross sections for different materials](image)

- **ortho-hydrogen**
- **para-hydrogen**
- **ortho-deuterium**
- **para-deuterium**
- **solid methane 22 K**

Cross section (barns) vs. neutron energy (eV)
Neutron Spectral Intensities for IPNS Moderators

![Graph showing neutron spectral intensities for different moderators. The x-axis represents neutron energy in eV, and the y-axis represents neutron intensity $E \times \phi(E)$ in n/s-sr-pulse. The graph compares 'H', 'F', 'C' (horizontal coupled), and 'C' (vertical decoupled) moderators.]
Neutron Pulse Widths for IPNS Moderators

- 'H' moderator (decoupled)
- 'C' moderator (coupled)
- 'F' moderator (decoupled)
Neutron Spectral Intensities for SNS Moderators

![Graph showing neutron flux intensity across different moderator conditions](image-url)
Neutron Pulse Widths for SNS Moderators

![Graph showing neutron pulse FWHM vs neutron energy for different moderators: para-hydrogen, decoupled, poisoned (blue), para-hydrogen, no decoupler, no poison (red), water, decoupled, poisoned (green).]
A Very Cold Neutron Source

- Many problems at longer length scales and slower time scales can be addressed using an intense source of longer-wavelength neutrons
  - fundamental nuclear physics (neutron half-life, EDM)
  - spin dynamics in magnetic nanostructured materials
  - the motion of proteins and molecular motors within living cells
  - hydrogen transport in storage and photoproduction materials
  - direct-imaging neutron techniques (microscopy, tomography, holography, radiography)
- Present cold neutron sources peak in the range 2-4 Å
- The goal of VCNS is an intense peak flux around 20 Å and usable flux extending out to 100 Å
- Develop a source providing neutrons at the “lowest practical temperature” - implies the use of liquid helium as the moderator coolant
- Notional parameters – long pulse, 5-10 Hz
- A VCN moderator is being considered as a supplement to more conventional cold moderators for the second target station at SNS
Summary

- Spallation neutron sources for condensed matter research are complex interconnected systems
- Parameters for accelerator, target, moderators, etc. are dictated by the science to be conducted at the facility
  - Proton pulse repetition rate and pulse width are somewhat narrowly constrained
- Pulse rates 5 Hz to 60 Hz, with slower pulsing frequencies used for lower-energy neutrons
- Pulse lengths sub-µs for short-pulse sources or 1-2 ms for long-pulse sources
- While no one has yet build a long-pulse source, there continues to be considerable interest, since they offer the best possibility to utilize > 1 MW of proton beam power