SPALLATION NEUTRON SOURCES FOR SCIENCE AND TECHNOLOGY

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Spallation Neutron Facilities
Increasing interest has been noticed in spallation neutron sources (SNS) during the past 20 years. The system includes high current proton accelerator in the GeV region and spallation heavy metal target in the Hg-Bi region. Among high flux currently operating SNSs are: ISIS in UK (1985), SINQ in Switzerland (1996), JSNS in Japan (2008), and SNS in USA (2010). Under construction is the European spallation source (ESS) in Sweden (to be operational in 2020). The intense neutron beams provided by SNSs have the advantage of being of non-reactor origin, are of continuous (SINQ) or pulsed nature. Combined with state-of-the-art neutron instrumentation, they have a diverse potential for both scientific research and diverse applications.

Why Neutrons?
- Neutrons have wavelengths comparable to interatomic spacings (1-5 Å)
- Neutrons have energies comparable to structural and magnetic excitations (1-100 meV)
- Neutrons are deeply penetrating (bulk samples can be studied)
- Neutrons are scattered with a strength that varies from element to element (and isotope to isotope)
- Neutrons have a magnetic moment (study of magnetic materials)
- Neutrons interact only weakly with matter (theory is easy)

*Neutron scattering is therefore an ideal probe of magnetic and atomic structures and excitations*

Neutron Producing Reactions
Several nuclear reactions are capable of producing neutrons. However the use of protons minimises the energetic cost of the neutrons produced
<table>
<thead>
<tr>
<th>Nuclear Reactions</th>
<th>Incident Particle &amp; Typical Energies</th>
<th>Beam Currents (part./s)</th>
<th>Neutron Yields (n/inc.part.)</th>
<th>Target Power (MW)</th>
<th>Deposited Energy Per Neutron (MeV)</th>
<th>Neutrons Emitted (n/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(e,\gamma)$ =&gt; $(\gamma,n)$</td>
<td>100 MeV e- on 238U</td>
<td>5 x 1015</td>
<td>5 x 10-2</td>
<td>0.045</td>
<td>1500</td>
<td>2 x 10^{14}</td>
</tr>
<tr>
<td>3H(d,n)4He 2H (0.3 MeV)</td>
<td>6 x 1017</td>
<td>10-4 -10-5</td>
<td>0.02</td>
<td>10</td>
<td>10^{14}</td>
<td></td>
</tr>
<tr>
<td>Fission</td>
<td></td>
<td>2.4</td>
<td>57</td>
<td>190</td>
<td>2 x 10^{18}</td>
<td></td>
</tr>
<tr>
<td>Spallation (nonfissile target)</td>
<td>p</td>
<td>1015</td>
<td>14</td>
<td>0.09</td>
<td>30</td>
<td>2 x 10^{16}</td>
</tr>
<tr>
<td>Spallation (fissionable (800 MeV) target)</td>
<td>p</td>
<td>1015</td>
<td>30</td>
<td>0.4</td>
<td>55</td>
<td>4 x 10^{16}</td>
</tr>
</tbody>
</table>

**Time Evolution NS**

![Time Evolution NS Graph](Updated from Neutron Scattering, K. Skold and D. L. Price: eds., Academic Press, 1986)

**Why Pulsed Sources?**

Aims at enhancing efficiency:
- Pulsed reactors (IBR, Dubna 1960’s,…):
  - More efficient use of fewer neutrons produced.
- Spallation (1970’s,…):
  - Less heat per fast neutron produced and efficient slowing down.
- 2 orders of magnitude gain in efficiency:
  - Confirmed by ISIS, 1985 (< 0.5 % ILL power)
  - Leap in source power to surpass ILL, HIFR at ~ 2 % power.
  - MW class pulsed spallation sources (SNS, J-PARC).

### Reactors vs. Spallators

- **Spallation:**
  
  \[
  p + \text{ heavy nucleus} \rightarrow 1\text{GeV e.g. W, Pb, U} = 20 \sim 30\ n + \text{fragments} \approx 30\ \text{MeV/n (as heat)}
  \]

- **Comparison of Fluxes (n/cm^2.s), thermal:**

  **Reactors**
  - ILL Grenoble (steady) 1.5 x 10^{15}
  - IBR-2 Dubna (pulsed) average 8 x 10^{12}
    peak 5 x 10^{15}

  **Spallation sources**
  - ISIS @ 160 kW average 1.2 x 10^{13}
    peak 6 x 10^{15}
  - SNS @ 2 MW average 4 x 10^{13}
    peak 3 x 10^{16}

### Major Research Directions with Neutrons

- Solid state physics
- Soft matter
- Biomaterials
- Nanomaterials
- Astrophysics

**Mostly via neutron scattering experiments**

### Instruments of Neutron Scattering

- Large scale instrumentation (SANS, Reflectometry)
- Inelastic instrumentation (Cold/thermal TOF, backscatter)
- Diffraction (powder and single crystal)
- Engineering materials diffraction
- Polarization/polarization analyzers
- Larmor precession instruments
- Resonance spin-echo
- Imaging and tomography
- Instrument components (guides, choppers, detectors, etc)
Neutron Sources - Reactors

- About 10 major facilities worldwide.

- **Continuous:**
  - ILL (Institute Laue-Langevin) Grenoble, 3 Associate Member and 11 Scientific Member countries: 57 MWth, highly-enriched U, compact design for high brightness, heavy-water cooling, single control rod.
  - 48 instruments, 800 experiments a year.
  - Mostly condensed-matter physics, but increasingly also chemistry, biophysics, earth sciences, engineering, nuclear and particle physics.

- **Pulsed:**
  - IBR-2 (Pulsed fast reactor), JINR, Dubna Russia, JINR as multinational research institute (18 member and 7 associate member states).
  - 13 instruments, 150 experiments a year mostly condensed matter physics and biophysics.

Spallation Reactions

- Spallation reactions have recently gained interest not only due to their application as neutron or radioactive nuclear beam sources but also for their implications in understanding cosmic ray abundances or investigating the dynamics of nuclear matter.

- In the last decade spallation reactions have gained interest in several fundamental and applied research fields. They are considered as optimum neutron sources for solid-state physics or material-science investigations, or for energy production and nuclear-waste transmutation in accelerator-driven systems. These reactions have also been used to produce and investigate nuclei far from stability and are currently being proposed as a production mechanism for next generation exotic-beam facilities.

Fission vs. Spallation
The Spallation Process

- Refers to a complex of reactions initiated by interaction of high-energy (~ GeV) particles (p, n, π, ...) with (typically, in our context) heavy nuclei.
- W. H. Sullivan and G. T. Seaborg coined the term in April, 1947 to describe the phenomenon, whereby the target emits a fairly large number of neutrons in a multiple-collision process, which was already quite well known.
- Robert Serber qualitatively described the process in a brief 1947 paper.
- Enrico Fermi summarized important then-current information in his 1949 lectures.
- Depending upon the conditions, the number of emitted light particles, and especially neutrons, may be quite large.
- All this goes back to Victor Weisskopf’s description of nuclear evaporation processes.

Neutron Sources - Spallotors

- 4 major facilities operating + 3 under construction or planned.
- Avoids the use of fission reactors with their high radioactive inventory and proliferation concerns.
- Continuous
  - SINQ, PSI Switzerland
- Pulsed
  - Long pulses (3 ms): EES, 70 ms repetition)
  - Short pulses (10 µs): ISIS, SNS, J-PARC (18-20 ms repetition)

Why Spallation Sources?

- Spallation: 10x more neutrons per heat than fission
- 5 MW spallation source = 50 MW reactor
- P = IxV = 0.2-1 MW
  - efficient spallation requires proton E > 0.5 GeV and I = 0.2-1 mA
- Pulsed nature gives information which allows lower time-integrated flux

Equipment for Spallation Sources

- High energy high current particle accelerator:
  - AVF cyclotron for continuous mode
  - Linear accelerator followed by a synchrotron for pulsed mode
- Heavy metal target
- Reflector
- Moderators

Spallation Mechanisms

At GeV energies it is no longer correct to think of the nuclear reactions as proceeding through the formation of a compound nucleus.

- Fast Direct Process:
  - Intra-Nuclear Cascade (nucleon-nucleon collisions)
- Pre-Compound Stage:
Pre-Equilibrium
- Multi-Fragmentation
- Fermi Breakup

- Compound Nuclei:
  - Evaporation (mostly neutrons)
  - High-Energy Fissions

- Inter-Nuclear Cascade

- Low-Energy Inelastic Reactions
  - (n,xn)
  - (n,nf) etc...

Spallation Process Characterization
The relevant aspects of the spallation process are characterised by:

- **Spallation Neutron Yield** (i.e. multiplicity of emitted neutrons)
  determines the requirement in terms of the accelerator power
  (current and energy of incident proton beam).

- **Spallation Neutron Spectrum** (i.e. energy distribution of emitted neutrons)
  determines the damage and activation of the structural materials
  (design of the beam window and spallation target)

- **Spallation Product Distributions**
  determines the radiotoxicity of the residues (radioprotection requirements).

- **Energy Deposition**
  determines the thermal-hydraulic requirements (cooling capabilities and nature of the spallation target)

**Spallation Neutron Yield**
- The number of emitted neutrons varies as a function of the target nuclei and the energy of the incident particle saturates around 2 GeV.
- Deuteron and triton projectiles produce more neutrons than protons in the energy range below 1-2 GeV, however suffer of higher contamination of the accelerator.

The spectrum of spallation neutrons evaporated from an excited heavy nucleus bombarded by high energy particles is similar to the fission neutron spectrum but shifts a little to higher energy \(<\text{En}>=3-4 \text{ MeV}.)

**Spallation Product Distribution**
- The spallation product distribution varies as a function of the target material and incident proton energy. It has a very characteristic shape:
- At high masses it is characterized by the presence of two peaks corresponding to:
  (i) the initial target nuclei,
(ii) those obtained after evaporation

- Three very narrow peaks corresponding to the evaporation of light nuclei such as (d, t, \( \tau \) and \( \alpha \))
- An intermediate zone corresponding to nuclei produced by high-energy fission

**Energy Deposition**

- Largely contained within the small range of high energy incident heavy charged particles and spallated fragments
- For high energy protons on lead target:
  - 16 cm at 400 MeV
  - 53 cm at 1 GeV
  - 95 cm at 2 GeV
- Requires efficient heat removal techniques.

**Comparison of Reactors and Spallation Sources**

<table>
<thead>
<tr>
<th>Short Pulse Spallation</th>
<th>Source Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy deposited per useful neutron is ~ 20 MeV</td>
<td>Energy deposited per useful neutron is ~ 180 MeV</td>
</tr>
<tr>
<td>Neutron spectrum is “slowing down” spectrum – preserves short pulses</td>
<td>Neutron spectrum is Maxwellian</td>
</tr>
<tr>
<td>Constant, small dl/l at large neutron energy ( \Rightarrow ) excellent resolution especially at large Q and E</td>
<td>Resolution can be more easily tailored to experimental requirements, except for hot neutrons where monochromator crystals and choppers are less effective</td>
</tr>
<tr>
<td>Copious “hot” neutrons ( \Rightarrow ) very good for measurements at large Q and E</td>
<td>Large flux of cold neutrons ( \Rightarrow ) very good for measuring large objects and slow dynamics</td>
</tr>
<tr>
<td>Low background between pulses ( \Rightarrow ) good signal to noise</td>
<td>Pulse rate for TOF can be optimized independently for different spectrometers</td>
</tr>
<tr>
<td>Single pulse experiments possible</td>
<td>Neutron polarization easier</td>
</tr>
</tbody>
</table>

**Advantages/Disadvantages**

**CW SNS**

- **CW spallation source** - SINQ at Paul Scherrer Institut (PSI).
- 0.85 mA, 590 MeV, 0.9 MW
- 1x10^{14} n/(cm^2.s) average flux

**Advantages**

- High time averaged flux.
- Uses reactor type instrumentation (mature technology).
- Politically acceptable.
- piggy-backed on existing accelerator.

- **Disadvantages**
  - No time structure.
  - High background feared but not realized.

**Advantages/Disadvantages**

**Pulsed SNS**

- **Pulsed spallation sources** e.g. ISIS, SNS
- 200 µA, 0.8 GeV, 160 kW; 1.4 mA, 1.0 GeV, 1.4 MW
- ISIS 2x1013 (n/cm².s) average flux
- SNS 8x1015 (n/cm².s) peak flux

**Advantages**

- High peak flux.
- Advantageous time structure for many applications.
- Accelerator based – politics simpler than reactors.
- Technology rapidly evolving.

**Disadvantages**

- Low time averaged flux.
- Not all applications exploit time structure.
- Rapidly evolving technology.

**Earliest Pulsed SNS**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Proton Energy (MeV)</th>
<th>Pulsing Frequency (Hz)</th>
<th>Time-Average Beam Power (kW)</th>
<th>Startup Date/Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZING-P</td>
<td>Argonne, USA</td>
<td>300</td>
<td>30</td>
<td>0.1</td>
<td>1974-75 Shutdown</td>
</tr>
<tr>
<td>ZING-P'</td>
<td>Argonne, USA</td>
<td>500</td>
<td>30</td>
<td>3</td>
<td>1977-80 Shutdown</td>
</tr>
<tr>
<td>KENS</td>
<td>KEK, Japan</td>
<td>500</td>
<td>20</td>
<td>3.5</td>
<td>1980-2006 Shutdown</td>
</tr>
<tr>
<td>IPNS</td>
<td>Argonne, USA</td>
<td>450</td>
<td>30</td>
<td>7</td>
<td>1981/Operating</td>
</tr>
<tr>
<td>ISIS</td>
<td>Rutherford-Appleton Lab, UK</td>
<td>800</td>
<td>50</td>
<td>160</td>
<td>1985/Operating</td>
</tr>
<tr>
<td>MLNSC (Lujan Center)</td>
<td>Los Alamos, USA</td>
<td>800 (upgrade 3060 (upgrade underway to 160 kW))</td>
<td>20 (upgrade Hz)</td>
<td>1985/Operating</td>
<td></td>
</tr>
</tbody>
</table>
Pulsed SNS Construction, Proposals, and Studies

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Proton Energy (GeV)</th>
<th>Pulsing Frequency (Hz)</th>
<th>Proton Beam Power (MW)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPNS Upgrade</td>
<td>Argonne</td>
<td>2.0</td>
<td>30</td>
<td>1.0</td>
<td>Terminated</td>
</tr>
<tr>
<td>SNS</td>
<td>Oak Ridge</td>
<td>1.0</td>
<td>60</td>
<td>2.0</td>
<td>Operating since 2007</td>
</tr>
<tr>
<td>AUSTRON</td>
<td>Austria</td>
<td>1.6</td>
<td>25</td>
<td>0.2 (includes upgrades for up to 1 MW)</td>
<td>Study complete – Approval pending</td>
</tr>
<tr>
<td>JSNS</td>
<td>JAEA, Tokai-mura, Japan</td>
<td>3.0</td>
<td>25 (upgrade to 50 Hz)</td>
<td>0.6 (potential for upgrades to 5 MW)</td>
<td>First operation 2008</td>
</tr>
<tr>
<td>LPSS</td>
<td>Los Alamos</td>
<td>0.8</td>
<td>60</td>
<td>1.0 MW</td>
<td>Ongoing study</td>
</tr>
<tr>
<td>ESS</td>
<td>Lund, Sweden</td>
<td>1.33</td>
<td>50</td>
<td>5.0</td>
<td>Ongoing</td>
</tr>
<tr>
<td>CSNS</td>
<td>Dongguan, China</td>
<td>1.6</td>
<td>25</td>
<td>100 kW (potential for upgrade to ~1 MW)</td>
<td>Ongoing study</td>
</tr>
</tbody>
</table>

Energy Cost of Various Neutron Sources
- For high-power sources the driving issue is heat removal => use spallation for high power sources
- ~ 190 MeV per neutron for fission
- ~ 25 MeV per neutron for spallation with protons (threshold at Ep~ 120 MeV)
- ~ 1500 MeV per neutron for (n,p) on Be using 13 MeV protons
- ~ 3000 MeV per neutron for electrons
- Driving issue for low-intensity sources is cost (electric power, regulatory, manpower etc)
- Cost has to be kept “low” (i.e. construction ~$10-20M)
- Cost/benefit is still the metric
- Spallation and fission cost too much
- Use Be (p,n) or electrons on Ta

Sample Facilities
- ISIS UK
- SINQ Switzerland
- SNS USA
- J-PARC Japan
- ESS EU (under construction)
- CSNS China (under construction)

**ISIS UK**

- **Target station 1:**
  - solid W target
  - in operation since 1985
  - 22 end stations
- **Target station 2:**
  - solid W target
  - in operation from 2010
  - 17 end stations

**SINQ @ PSI**

- Running since 1996
- Pb/Bi target
- Number of available instruments: 19
- Number of instruments under construction: 3
SNS Oak Ridge, Tennessee, USA

SNS
(500kW in 2010, 1MW in 2012)
J-PARC, Tokai, Japan
(100kW in 2010, 1MW in 2014)

ESS Site, Lund Sweden
ESS, Lund Sweden

- ESS Reference Design:
  - 623 m long, 5MW, proton linear accelerator at 1.0 GeV, 5 mA
  - 2 ms pulses, 16.6 Hz (60 ms period)
  - Liquid metal target (mercury or lead/bismuth)
  - 22 neutron instruments
  - 450 staff
  - First neutrons 2018/2019
  - To support a 5000-strong user community
  - Capital Cost (Jan 2008) 1,478 M€
  - Operating Cost 103 M€ p.a.
  - Decommissioning Cost 344 M€

Chinese SNS

- China SNS Reference Design:
  - Location Dongguan, Guangdong.
  - The CSNS complex consists of an H-linear accelerator, a rapid cycling synchrotron accelerating the beam to 1.6 GeV, a solid-tungsten target station, and instruments for spallation neutron applications.
  - The facility operates at 25 Hz repetition rate with an initial design beam power of 120 kW and is upgradeable to 500 kW.
  - Scientific program includes muon, fast neutron, and proton applications as well as medical therapy and accelerator-driven subcritical reactor (ADS) applications to serve China's strategic needs in scientific research and technological innovation for the next 30 plus years

Future with Neutrons

- Scientific interests include:
  - Systematic rapid access to chemical and magnetic structure with medium cell size from powder and x-rays
  - Chemical and magnetic structure at the interfaces of nano-scale artificially structured systems
  - Excitations in materials patterned on the nano-scale
  - Protein structure (including D-positions) and dynamics
  - Complete 4D Q-E mapping of dynamic correlation function for spin and lattice in large single crystals $0 < E < 100$ meV
  - Systematic access to order parameters of weak or complex broken symmetry phases
  - Inelastic neutron scattering as a super-susceptometer for screening new materials
  - Parametric and complete information about structure of matter under extreme conditions
Future with SNS

Intense neutron beams provided by neutron spallation sources have a diverse potential for both basic research and diverse applications. Existing facilities and planned projects indicate the importance they have in promoting science and deepening our understanding in fields of new materials especially soft matter, biomaterials and nanomaterials. Other fields of interest include solid state physics and astrophysics.