Summary

• Neutron facilities
  – history, overview & trends
• Reactor-based sources
  – Institut Laue-Langevin
• Short-pulse spallation sources
  – ISIS
• Components of a spallation neutron source
  – accelerator
  – target
  – moderators
• Neutron source time structure
  – the time of flight method
• Long-pulse neutron sources
The first neutron source

James Chadwick: used Polonium as alpha emitter on Beryllium

\[ ^4\text{He} + ^9\text{Be} \rightarrow ^{12}\text{C} + \text{neutron} \]
Evolution of neutron sources

Nuclear Fission
Evolution of neutron sources

Evolution of neutron sources

Nuclear Spallation

first stage in nuclear cascade

Second stage: reaction

Third stage: fission

Final stage: residual oxidation
Evolution of neutron sources

Evolution of neutron sources

## Slow 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>$&lt; nm$</td>
</tr>
<tr>
<td>$E$</td>
<td>$&gt; eV$</td>
<td>$&gt; meV$</td>
</tr>
<tr>
<td>penetration</td>
<td>$\sim \mu m$</td>
<td>$\sim cm$</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>$90^\circ$</td>
<td>$1^\circ$</td>
</tr>
<tr>
<td>$B$</td>
<td>$10^{18}$ p/cm$^2$/ster/s (60W lightbulb)</td>
<td>$10^{14}$ n/cm$^2$/ster/s (60MW reactor)</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>
Why neutrons?

• Thermal neutron have wavelengths similar to inter-atomic distances
• Thermal neutrons have energies comparable to lattice vibrations
• Neutrons are non-destructive
• Neutrons interact weakly
  – they penetrate into the bulk
• Neutrons interact via a simple point-like potential
  – amplitudes are straightforward to interpret
• Neutrons have a magnetic moment
  – great for magnetism
• Neutrons see a completely different contrast to x-rays
  – e.g. hydrogen is very visible
Why neutrons?

Mass Attenuation Coefficient (cm/g) vs. Element (Z)
Main European neutron sources 2019
Main European neutron sources 2019
Major neutron sources in the world

- ILL (F)
- HZB (D)
- LLB (F)
- PSI (CH)
- FRM-II (D)
- HFIR (USA)
- NIST (USA)
- JRR-3 (J)
- PIK (RU)
- IBR-2 (RU)
- ISIS-TS1 (UK)
- ISIS-TS2 (UK)
- SNS-FTS (USA)
- SNS-STS (USA)
- J-PARC (J)
- CSNS (CN)
- ESS (SE)

2000 - 2010 - 2020

Continuous

Pulsed
## Major neutron sources in the world

<table>
<thead>
<tr>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL (F)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>HZB (D)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>LLB (F)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>PSI (CH)</td>
<td>Spallation</td>
<td>Fission</td>
</tr>
<tr>
<td>FRM-II (D)</td>
<td></td>
<td>Fission</td>
</tr>
<tr>
<td>HFIR (USA)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>NIST (USA)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>JRR-3 (J)</td>
<td>Fission</td>
<td>Fission</td>
</tr>
<tr>
<td>PIK (RU)</td>
<td></td>
<td>Fission</td>
</tr>
<tr>
<td>IBR-2 (RU)</td>
<td>Fission</td>
<td></td>
</tr>
<tr>
<td>ISIS-TS1 (UK)</td>
<td>Spallation</td>
<td>Spallation</td>
</tr>
<tr>
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<tr>
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<td></td>
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<tr>
<td>ESS (SE)</td>
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<td></td>
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ILL Reactor Neutron Source
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ILL Reactor Neutron Source

- Highly-enriched uranium
- Compact design for high brightness
- Heavy-water cooling
- Single control rod
- 57MW thermal power
- Cold, thermal, hot sources
### ILL Reactor Neutron Source

- Highly-enriched uranium
- Compact design for high brightness
- Heavy-water cooling
- Single control rod
- 57MW thermal power
- Cold, thermal, hot sources

<table>
<thead>
<tr>
<th>Moderator</th>
<th>cold</th>
<th>thermal</th>
<th>hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid $D_2$</td>
<td></td>
<td>Liquid $D_2O$</td>
<td>graphite</td>
</tr>
<tr>
<td>20K</td>
<td>300K</td>
<td>2000K</td>
<td></td>
</tr>
<tr>
<td>3→20Å</td>
<td>1→3Å</td>
<td>0.3→1Å</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of the ILL Reactor Neutron Source](image)

2 m
ILL Reactor Neutron Source

1st guide hall (20 instruments)

2nd guide hall (7 instruments)
ILL Reactor Neutron Source

Flux thermique ($E<0.625\text{eV}$)
- MCNP
- Ageron
- Mesures

Flux épi-thérmique ($0.625\text{eV}<E<1\text{MeV}$)
- MCNP
- Ageron

Flux rapide ($E>1\text{MeV}$)
- MCNP
- Ageron

Distance au cœur (cm)

Flux (n/cm$^2$.s)
ILL Moderator Brightnesses
Spallation vs Fission

Fission

200 MeV/fission
2.35 – 1 = 1.35 neutrons freed
=> 150 MeV/neutron
Spallation vs Fission

Fission

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Spallation

1 GeV proton in:
250 MeV becomes mass (endothermic reaction)
30 neutrons freed
=> 25 MeV/neutron
Spallation vs Fission

**Fission**

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**Spallation**

1 GeV proton in:
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6x more neutrons per unit heat
Spallation Sources

- Spallation: 10x higher neutron brightness per unit heat
  - about 6x more neutrons per unit heat
  - about ½ the production volume
- 1 MW spallation source = 10 MW reactor
  - e.g. 800 MeV at 1.25 mA (PSI)
  - e.g. 3 GeV at 0.4 mA (J-PARC)
- Peak brightness >> time-average brightness
Spallation Sources

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- Peak brightness >> time-average brightness

![Graph showing the difference between peak and time-average brightness](image)
### 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

\[ t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956 \]
Spallation Sources

• Ion source
  – H⁺ or H⁻

• Accelerator
  – linear accelerator “linac”
  – cyclotron

• Compressor ring (for short-pulse sources)
  – stripper to convert H⁻ to H⁺
  – synchrotron

• Target
• Reflector
• Moderators
Linear accelerator: LINAC
Linear accelerator: LINAC
SNS ion source: $H^-$
Different types of Linac

Drift-Tube Linac (DTL)

Elliptical cavities

Radio-Frequency Quadrupole (RFQ)

“Low β” / “High β”

\[ \beta = \frac{v}{c} \]
Cyclotrons

Patented by Lawrence, 1934

PSI 590 MeV cyclotron
Synchrotron

- Synchronise:
  - B-field: bend
  - E-field: accelerate
  - E & B field: focus
  - magnets to each other

- Injection
  - stripper foil

- Extraction
  - kicker magnet
Synchrotron

• Synchronise:
  – B-field: bend
  – E-field: accelerate
  – E & B field: focus
  – magnets to each other
• Injection
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• Extraction
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Synchrotron

- $\Delta t_{\text{linac}} \approx 1 \text{ ms}$
- $E_{\text{ring}} \approx 1 \text{ GeV}$
  - $v \approx 3 \times 10^8 \text{ m/s}$
- $L_{\text{ring}} \approx 200 \text{ m}$
- $\Delta t_{\text{ring}} \approx 1 \mu\text{s}$
ESS, Lund, Sweden (first neutrons in 2023)
SNS, Oak Ridge, USA (1MW)
J-PARC, Tokai, Japan (500kW)
J-PARC, Tokai, Japan (500kW)
ISIS target 1: solid tungsten
SNS Target Configuration

- Target Container
- Cooling Channels
- Mercury Main Flow
- Stainless Steel Target Container
- Proton Beam
SNS target: liquid mercury
ESS target

2.5m tungsten wheel
ISIS TS2 Target

Target: 66mm W
Target produces neutrons in > MeV range

Moderators contain H to thermalise neutrons
  - largest scattering cross-section (80b)
  - lower mass: same as neutron
  - on average, ½ energy lost per collision
  - 100 MeV -> 10 meV requires about 25 collisions

Moderators embedded in reflector, usually D$_2$O-cooled Be
  - minimal absorption
  - large scattering cross-section (8b)
  - little thermalisation
Target-Reflector-Moderator Neutronics

Be

protons in

Target plane

Target
protons in Be

10cm above/below Target
Target-Reflector-Moderator Neutronics

protons in

Be

10cm above/below Target
Target-Reflector-Moderator Neutronics

protons in Be 10cm above/below Target
Target-Reflector-Moderator Neutronics

protons in Be

10cm above/below Target
Decoupling

protons in

Cd

Cadmium absorption

Target-Reflector-Moderator Neutronics
Target-Reflector-Moderator Neutronics

Decoupling

Cadmium absorption

Cross section [ barns]
Target-Reflector-Moderator Neutronics

Decoupling
Poisoning

Cadmium absorption

Gadolinium absorption
Time-of-flight (TOF) resolution

\[ t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956 \]
Time-of-flight (TOF) resolution

\[ t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956 \]

\[ \Rightarrow \Delta \lambda[\text{Å}] = \Delta t[\text{ms}] \times 3.956 / L[\text{m}] \]
Moderator Decoupling and Poisoning

J-PARC H₂ moderators at 1MW

- Peak Structure at 5meV
- Coupled
- Decoupled
- Poisoned

Energy (eV)

- Coupled
- Decoupled
- Poisoned (center)
- ILL cold (56 MW)

Hg Target
Be reflector
1MW 25Hz

Pulse Peak Intensity (n/ cm² s/ sr/ eV/ pulse)
Moderator Decoupling and Poisoning

Intensity

\( \lambda = 1 \text{Å} \)

\( \lambda = 2 \text{Å} \)

\( \lambda = 5 \text{Å} \)

Energy (eV)

Pulse Peak Intensity (n/cm\(^2\)/s/sr/eV/pulse)

Moderator Decoupling and Poisoning

Hg Target

Be reflector

1MW 25Hz

Poisoned (center)

ILL cold (56 MW)
SNS moderators

decoupled poisoned H₂

coupled H₂

decoupled poisoned H₂O

coupled H₂

Top

Bottom

20 cm
ISIS TS2 Target

decoupled poisoned solid CH$_4$

coupled H$_2$

coupled solid CH$_4$
Moderator Temperature

ISIS-TS1 moderators at 160kW

![Graph showing brightness vs. wavelength for moderators at different temperatures: Water at 300K, Methane at 100K, and Hydrogen at 20K.](image)

- **Brightness (n/cm²/s/sr/Å)**
- **Wavelength (Å)**
- **Red line**: Water at 300K
- **Green line**: Methane at 100K
- **Blue line**: Hydrogen at 20K
Beyond Short-Pulse Limits

SNS instantaneous power on target:

\[ 17 \text{kJ in } 1 \mu\text{s: } 17 \times 1 \text{ GW} \]

Reaches limits of spallation source technology:
shock waves in target, space charge density in accelerator ring, ...
SNS instantaneous power on target:
17kJ in 1μs: \(17 \times 1 \text{ GW}\)

ESS instantaneous power on target: 125MW
360kJ in 2.86ms
Long-pulse performance

\[ \lambda = 5 \, \text{Å} \]

Brightness (n/cm²/s/sr/Å) \( \times 10^{13} \)

- ISIS TS1: 128 kW
- ISIS TS2: 32 kW
- SNS: 2 MW
- JPARC: 1 MW
- ESS 2MW
- ESS 5MW
- ILL 57 MW

Time (ms)
Adapting the pulse width

Short-Pulse Source
- set pulse width by choosing moderator

Long-Pulse Source (ESS)
- set pulse width using pulse-shaping chopper
Summary

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  - ISIS
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  - accelerator
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Thank You!