Neutron production, neutron scattering facilities

F. Mezei
ESS & Wigner RCP
Neutron can see deep inside matter…

Neutrons see (tensile) stress inside bulky metal parts that caused wheel failure: standard engineering theory of plastic deformation stresses in error in the 1990s!!

ICE accident, Eschede


Knowledge based society??
Safety philosophy??
Neutrons are non-destructive probes … etc, etc

Tiziano Vecellio (Tizian)

Neutron activation radiography
Fast neutrons produced / joule **heat deposited:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Neutrons Produced</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission reactors:</td>
<td>$3 \times 10^{10}$</td>
<td>(in ~ 50 liter)</td>
</tr>
<tr>
<td>Spallation (&gt; 400 MeV):</td>
<td>$2 \times 10^{11}$</td>
<td>(in ~ 2 liter)</td>
</tr>
<tr>
<td>Fusion:</td>
<td>$4 \times 10^{11}$</td>
<td>(in ~ 2 liter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(but neutron slowing down efficiency reduced by ~20 times)</td>
</tr>
<tr>
<td>Electron accel.: (50 MeV)</td>
<td>$2 \times 10^{9}$</td>
<td>(in ~ 0.01 liter)</td>
</tr>
<tr>
<td>Low energy p.: (5 MeV):</td>
<td>$2 \times 10^{8}$</td>
<td>(in ~ 0.001 liter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(35 MeV): $2 \times 10^{9}$</td>
</tr>
<tr>
<td>Laser induced fusion:</td>
<td>$\sim 10^{4}$</td>
<td>(in ~ $10^{-9}$ liter)</td>
</tr>
</tbody>
</table>

**Spallation: lowest cost per neutron**

**Compact source: lowest cost per facility**

**Energy costs are important:** 20 % of staff costs at ESS in operation
Fast neutrons produced / joule heat deposited in target station

**Fission reactors:** \( \sim 10^9 \) (in \( \sim 50 \) liter volume)

Spallation: \( \sim 10^{10} \) (in \( \sim 2 \) liter volume)

Fusion: \( \sim 1.5 \times 10^{10} \) (in \( \sim 2 \) liter volume)
  (but neutron slowing down efficiency reduced by \( \sim 20 \) times)

Photo neutrons: \( \sim 10^9 \) (in \( \sim 0.01 \) liter volume)

Nuclear reaction (p, Be): \( \sim 10^8 \) (in \( \sim 0.001 \) liter volume)

Laser induced fusion: \( \sim 10^4 \) (in \( \sim 10^{-9} \) liter volume)

**Spallation: most favorable for the foreseeable future**
Nuclear fission
(O. Hahn, L. Meitner, O. Frisch)

\[ ^{235}\text{U} \rightarrow ^{236}\text{U} \rightarrow ^{92}\text{Kr} \rightarrow ^{141}\text{Ba} + 190 \text{ MeV} \]

Chain reaction (L. Szilárd 1934)
Chain reaction (L. Szilárd 1934)

Abstract of GB630726 (A)

Translate this text into German

630,726. Producing neutrons. SZILARD, L. June 28, 1934, Nos. 19157 and 19721. [Class 39 (i)] A neutron chain reaction generates power and produces radio-active isotopes. The reaction takes place in a mass 3, Fig. 1, comprising indium and beryllium, bromine or uranium. Fast deuterons from a canalray tube 1 bombard a deuterium target 28 to produce initiating neutrons which react with In<115> to produce In<112> and “teta neutrons” of mass about 4.014. These teta neutrons react with the Be, Br or U to produce double the number of simple neutrons, thereby providing a chain reaction. Emerging neutrons transmute a layer 9 to produce radio-active substances. Alternatively, Fig. 3, the initiating neutrons may be produced by passing cathode-rays through a sheet 402 of Pb or U to generate hard X-rays which react with beryllium in the mass 3 (or an inner mass 407) to yield neutrons. The critical thickness of the layer 3 for a self-sustaining chain reaction is stated to be of the order of 50 cms. Teta neutrons are stated to be produced when neutrons of 100,000 e.v. to 8 m.e.v. energy react with the In<115>. Power is obtained by heat exchange from water or mercury passing through cooling tubes 107, 110, 111. Other methods of obtaining the initiating neutrons are described in Specification 440,023.

→ nuclear weapons
Secret patent: Szilárd delays nuclear arms race

→ research reactors

→ nuclear energy
Example of a fission reactor (HMI)

Shielding: ø 10 - 12 m

- Thermal neutron source (Be reflector)
- Cold neutron source (liquid H₂ bottle)

Fission fuel: enriched $^{235}\text{U}$
Fission fuel: enriched $^{235}$U
Low (<20 %) vs. High enrichment
Plutonium in waste
Neutrons for waste transmutation

Example of a fission reactor (HMI)

Shielding: $\varnothing$ 10 - 12 m

Bispectral beam extraction
- HZB EXED (60 m guide, measured)
- cold Maxwell spectrum (47 K)
- thermal Maxwell spectrum (270 K)

Thermal neutron source (Be reflector)

Cold neutron source (liquid $\text{H}_2$ bottle)
Neutron monochromatization - analysis

- Mechanical chopper devices
- Crystals – select desirable wavelength
Neutron monochromatization - analysis

After recent upgrade
Efficiency gain by pulsed neutron sources

5 MW spallation source:
coupled cold moderator flux ~ ILL cold source
Part of spectrum used by a diffractometer for large structures (e.g. biological membranes)

 continuous source

Flux $[\text{n/cm}^2\text{s/str/Å}]$

Wavelength $[\text{Å}]$

Time average flux
- ILL cold source (measured)
- ESS coupled $\text{H}_2$ moderator
Part of spectrum used by a D22 (ILL) class instrument (Small Angle Neutron Scattering)

Continuous source

<table>
<thead>
<tr>
<th>Wavelength [Å]</th>
<th>Flux [n/cm²/s/str/Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1x10¹²</td>
</tr>
<tr>
<td>4</td>
<td>5x10¹²</td>
</tr>
<tr>
<td>6</td>
<td>6x10¹²</td>
</tr>
<tr>
<td>8</td>
<td>5x10¹²</td>
</tr>
<tr>
<td>10</td>
<td>4x10¹²</td>
</tr>
<tr>
<td>12</td>
<td>3x10¹²</td>
</tr>
</tbody>
</table>

Time average flux
- ILL cold source (measured)
- ESS coupled H₂ moderator
Part of spectrum used by a SANS instrument

Continuous source 50 Hz pulsed source

Flux $[\text{n/cm}^2\text{s/str}/\text{Å}]$

Wavelength $[\text{Å}]$

Time average flux
- ILL cold source (measured)
- ESS coupled $\text{H}_2$ moderator
Part of spectrum used by a D22 (ILL) class instrument

14 Hz pulsed source
continuous source
50 Hz pulsed source

Time average flux
- ILL cold source (measured)
- ESS coupled \( \text{H}_2 \) moderator

Flux \([\text{n/cm}^2/\text{s/str/Å}]\)
Wavelength \([\text{Å}]\)
Part of spectrum used by a D22 (ILL) class instrument

14 Hz pulsed source

continuous source

50 Hz pulsed source

Efficiency gain by pulsing: \( \approx \frac{\delta \lambda}{\lambda} \sim 8-100 \)
Neutron production economy: pulsed reactor

IBR-2, Dubna

Pulsed reactor source

Time average power: 2 MW

Peak power in pulse: 850 MW

Great fuel economy!
Fast neutrons produced / joule heat deposited in target station

Fission reactors: \(~10^9\) (in ~ 50 liter volume)

**Spallation:** \(~10^{10}\) (in ~ 2 liter volume)

Fusion: \(~1.5\times10^{10}\) (in ~ 2 liter volume)
   (but neutron slowing down efficiency reduced by ~20 times)

Photo neutrons: \(~10^9\) (in ~ 0.01 liter volume)

Nuclear reaction (p, Be): \(~10^8\) (in ~ 0.001 liter volume)

Laser induced fusion: \(~10^4\) (in ~ \(10^{-9}\) liter volume)
Instantaneous power on target (e.g. 1 MW at 60 Hz, i.e. 17 kj in ~1 µs pulses on target): \(17 \times\) 

→ Pressure wave: 300 bar

Reaches limits of technology
Production of slow neutrons: the "source"

Two step process in the target station
A) Series of nuclear reactions:
   spallation → fast neutrons
   ~100 billion °C

B) Collisions with H atoms:
   moderation → slow neutrons
   "Hot": ~ 2000 °C
   "Thermal": ~ 20 °C
   "Cold": ~ -220 °C ≈ 50 K ≈ 1000 m/s

Time: << 1 μs

→ Ionization!

10 – 500 μs
State-of-the-art spallation target (SNS)

He gas: ~ 1 bar

Hg target

Moderators

Reflector
Safety of public, staff, environment ↔ cost & schedule

Example: accidents with probability > 1 in 1 million years and > 1 in 10 000 years → effect on public must be less than 4 years of natural radiation in Sweden. Includes > 6 scale earthquake.

Functions:
- Convert protons to neutrons
- Heat removal
- Confinement and shielding

Unique features:
- Rotating target
- He-cooled W target

Functions:
- Convert protons to neutrons
- Heat removal
- Confinement and shielding
Loss of Life Expectancy (LLE) by professions (40 years activity):

<table>
<thead>
<tr>
<th>Profession</th>
<th>LLE (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building demolition</td>
<td>1500</td>
</tr>
<tr>
<td>Coal mining</td>
<td>1100</td>
</tr>
<tr>
<td>Fire fighter</td>
<td>800</td>
</tr>
<tr>
<td>Railway</td>
<td>500</td>
</tr>
<tr>
<td>Agriculture, farmers</td>
<td>300</td>
</tr>
<tr>
<td>Construction (buildings)</td>
<td>200</td>
</tr>
<tr>
<td>Traffic, utilities</td>
<td>160</td>
</tr>
<tr>
<td>Average of all professions</td>
<td>60</td>
</tr>
<tr>
<td>Civil service</td>
<td>55</td>
</tr>
<tr>
<td>Airline crew (radiation only)</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Services / nuclear power plant operators</td>
<td>45</td>
</tr>
<tr>
<td>Commerce</td>
<td>30</td>
</tr>
<tr>
<td>One time 10 mSv radiation</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>Natural radiation in Europe (upper limit)</td>
<td>&lt; 8 – 25</td>
</tr>
<tr>
<td>Inhabitant of Chernobyl (radiation, upper limit)</td>
<td>&lt; 66</td>
</tr>
</tbody>
</table>

Accidents: banks are more dangerous than nuclear power plants.
Short pulse spallation sources

pulse parameters imposed by the source design and/or fixed at each beam-line
Next generation: long pulse spallation sources

But:
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 µs proton pulses at ~ 0.15 GW instantaneous power: 2 x ILL
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 µs proton pulses at ~0.15 GW instantaneous power → Leave the linac on for more neutrons per pulse and higher peak brightness...

~ 300 kJ/pulse
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 µs proton pulses at ~0.15 GW instantaneous power → Leave the linac on for more neutrons per pulse and higher peak brightness...

and use mechanical pulse shaping → Long Pulse source
Neutron beams with mechanical choppers (since Fermi, 1940s)

J-PARC (2011)

BER-II (reactor)
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 \( \mu \)s proton pulses at ~0.15 GW instantaneous power \( \rightarrow \) Leave the linac on for more neutrons per pulse and higher peak brightness...

and use mechanical pulse shaping \( \rightarrow \) Long Pulse source

**ESS:** 5 MW accelerator power \( \rightarrow \) more neutrons for the same costs and reduced complexity
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 μs proton pulses at ~0.15 GW instantaneous power → Leave the linac on for more neutrons per pulse and higher peak brightness...

and use mechanical pulse shaping → Long Pulse source

ESS: 5 MW accelerator power → more neutrons for the same costs and reduced complexity
Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 µs proton pulses at ~0.15 GW instantaneous power → Leave the linac on for more neutrons per pulse and higher peak brightness...

and use mechanical pulse shaping → Long Pulse source

**ESS:** 5 MW accelerator power → more neutrons for the same costs and reduced complexity
Safe target for high power spallation

No fissionable material….

but **significant afterheat (decay heat)**

**Safe solution: rotating target**

Unperturbed moderator brightness [a.u.]

Angle [deg]
Thermal neutrons arriving from the surroundings are transformed into cold ones within about 1 cm of the walls of the moderator vessel.

Direction of high brightness emission

Flat moderators: established practice with emission direction at 90° of preferential directions

(Kai et al, 2004)
Qualitatively new level of beam performance

Butterfly bi-spectral moderator:
- Cold, thermal ESS pulse shapes

\[ \lambda = 2.6 \text{ Å} \]
- Cold moderator: \( h=3 \text{ cm}, w=8 \text{ cm} \)

\[ \lambda = 1.1 \text{ Å} \]
- Thermal moderator: \( h=3 \text{ cm}, w=8 \text{ cm} \)

ESS 5 MW, 3 cm flat moderator
ESS 5 MW, TDR 2013
ISIS TS1 128 kW
ISIS TS2 32 kW
SNS 1 MW
J-PARC 300 kW
ILL 57 MW

(L. Zanini et al, ECNS, 2015)
New perspectives

ESS 5 MW long pulse source:
order of magnitude more neutrons 
for same costs

Instrumental progress (x70)
+ new source (x300):

4 h scans → will be made in 1 s

??☹️
New perspectives

ESS 5 MW long pulse source: order of magnitude more neutrons for same costs

Instrumental progress (x70) + new source (x300):
4 h scans → will be made in 1 s !!😊

Learn from life sciences how to study huge and one by one poorly understood data sets: look for systematics in the "raw" pictures
Next generation: ESS

- **Innovative use of established technologies:**
  - high environmental safety
  - lower complexity, **new power level** is a challenge
  - comparable costs to SNS, J-PARC or ILL operations
  - order(s) of magnitude higher intensity = sensitivity

- Large in-kind fraction, green field site: large challenges

- High energy efficiency (35 MW vs. 70 MW at ILL)

- Perspectives of European neutron research facilities for ~6000 users: **synergetic use:** high performance when needed / efficient
Fast neutrons produced / joule heat deposited in target station

Fission reactors:  ~ $10^9$  (in ~ 50 liter volume)
Spallation:       ~ $10^{10}$  (in ~ 2 liter volume)
Fusion:           ~$1.5\times10^{10}$  (in ~ 2 liter volume)
                  (but neutron slowing down efficiency reduced by ~20 times)

Photo neutrons:   ~ $10^9$  (in ~ 0.01 liter volume)

**Nuclear reaction (p, Be):**  ~ $10^8$  (in ~ 0.001 liter volume)
Laser induced fusion:  ~ $10^4$  (in ~ $10^{-9}$ liter volume)
Compact neutron sources

Costs: ~ 10 - 100 M€
Power: 5-50 kW
Flux: ESS / 1000, sufficient for some uses (e.g. radiography)
4. Compact Sources (for Retail Use)

UCANS: Union for Compact Accelerator-driven Neutron Sources (http://www.ucans.org/)

Long-term occupation and on-demand access enables pioneering works and practical applications in industry.

Japan Collaboration on Accelerator-driven Neutron Sources

JCANS

NUANS

KUANS

OUANS

THUANS

BNCT

UTYANS

JSNS

RANS

KURRI-LINAC

C-BENS

SHIEI-NRT

Researches: Optics R&D, principle proof

Applications:
ETN: Boron Neutron Capture Therapy
TN CN: Radiography
TN CN: Bragg-edge Imaging and Microscope
VCN: Focusing SANS, Imaging Reflectometry

Japan 2017: physics & materials: 9
medical: 10

of which multipurpose: 3
Fast neutrons produced / joule heat deposited in target station

Fission reactors: \(~10^9\) (in ~ 50 liter volume)

Spallation: \(~10^{10}\) (in ~ 2 liter volume)

Fusion: \(~1.5 \times 10^{10}\) (in ~ 2 liter volume)
(but neutron slowing down efficiency reduced by ~20 times)

Photo neutrons: \(~10^9\) (in ~ 0.01 liter volume)

Nuclear reaction (p, Be): \(~10^8\) (in ~ 0.001 liter volume)

Laser induced fusion: \(~10^4\) (in ~ 10^{-9} liter volume)
**Nanoaccelerator** by ultrashort, focussed laser pulse on 20 μm D₂O droplet: relativistic light intensities, **Field-strength: 1 MV/μm**

$10^{19}$ W/cm² power $\rightarrow$ plasma $\rightarrow$ deuterons accelerated to MeV $\rightarrow$ fusion !

Distribution of neutrons reveals plasma formation mechanism

Laser driven μ-size source of (fast) neutrons ($\sim 10^4$ neutron/ $\sim 0.5$ J pulse)

d + D $\rightarrow$ 3He (0.82 MeV) + n (2.45 MeV): Neutron – spectroscopy
Neutron research in Europe:
~ 5000 scientists, 11 facilities (and decreasing): ~ 330 M€/a
Neutron research in Europe:
~5000 scientists, 11 facilities (and decreasing): ~ 350 M€/a
Fast neutrons produced / joule heat deposited:

Fission reactors: \(3 \times 10^{10}\) (in ~ 50 liter volume)

→ Spallation (> 400 MeV): \(2 \times 10^{11}\) (in ~ 2 liter volume)

Fusion: \(4 \times 10^{11}\) (in ~ 2 liter volume)

(but neutron slowing down efficiency reduced by ~20 times)

Electron accel.: (50 MeV) \(2 \times 10^9\) (in ~ 0.01 liter volume)

→ Low energy p.: (5 MeV): \(2 \times 10^8\) (in ~ 0.001 liter volume)

(35 MeV): \(2 \times 10^9\) (in ~ 0.01 liter volume)

Laser induced fusion: \(~10^4\) (in ~ 10^{-9} liter volume)

Spallation: lowest cost per neutron
Compact source: lowest cost per facility

Energy costs are important: 20 % of staff costs at ESS in operation
Conclusions

Trends and opportunities

**Multi- MW long pulse spallation sources (e.g. ESS):**
- order of magnitude higher flux / sensitivity for the same costs
- order of magnitude better energy efficiency than ILL reactor
- 2 B€ + 150 M€ operation/year $\rightarrow$ ~100 k€/publication
- energy cost: ~ 15 M€ / year

**Mini (compact) accelerator sources**

~ 0.1- 5 % of costs for 0.01 – 0.1 % of neutron production

No use of fissionable materials: access / security simpler

**Great potential: neutrons for nuclear waste incineration**