Principles and examples of neutron production

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(with valuable help from Dr. Arnd Junghans, HZDR)

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What will we see today?

- Some general considerations
  - Neutron moderation process
  - Neutron energy ranges
  - Continuous vs. pulsed neutron beams

- Fission in nuclear reactors
- Nuclear reactions with ion accelerators of:
  - low energy (few MeV)
  - high energy (tens of MeV)
  - very high energy (GeV)
- Photoproduction with electron accelerators
- Laser-driven neutron sources

- ARIEL Transnational Access
Some general considerations
Continuous neutron scattering end up with the neutrons in thermal equilibrium with the medium:

MB distrib. with characteristic $kT$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\frac{E'}{E_n}$</th>
<th>$\sigma_{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2$H</td>
<td>0.56</td>
<td>30</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>0.86</td>
<td>116</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>0.89</td>
<td>15</td>
</tr>
</tbody>
</table>
Neutron energy ranges

Colonna et al., PPNP 2018

water moderated at room temperature $kT = 25 \text{ meV}$

stellar spectra at $kT = 5 \text{ to } 100 \text{ keV}$

thermal fission

fusion

DD DT

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Continuous vs. pulsed beams: time-of-flight

- **Continuous**: Neutrons of all energies “together”:
  
  => integral effects (not a problem if spectrum adequate)
  
  Examples:
  
  - Irradiation (thermal, atmospheric, etc.)
  - Production of radioisotopes
  - Activation for a given spectrum

- **Pulsed**: allows for time-of-flight

  => time of arrival provides neutron kinetic energy

  => differential experiments => \( X(E_n) \)

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Time-of-Flight to \( E_n \) relation (non-rel.): 

\[
ToF \propto \frac{L}{\sqrt{E_n}}
\]

=> \( E_n \) resolution increases with \( L \)
Fission in nuclear reactors
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ILL: $1.5 \times 10^{15} \text{n/cm}^2/\text{s} @ \text{core}$
BRR: $2 \times 10^{14}$ n/cm$^2$/s @core, $8 \times 10^7$ @PGAA
Nuclear reactions with low energy (few MeV) ion accelerators

See:

- “Classical” facilities:
  - PTB, NPL as metrology laboratories
  - Frascatti (14 MeV)
  - More humble facilities: DEMOKRITOS, CNA (HISPANOS), ...
Neutron producing nuclear reactions (I)

- In two-body reactions monoenergetic neutrons can be produced, e.g. DT-reaction: $^2\text{H}(\text{D},\text{n})^4\text{He}$, $Q = 17.16$ MeV
- Kinematics determines the angular distribution and energy spectrum
- The yield (neutrons / primary particles) is determined by the differential cross section $\frac{d\sigma}{d\Omega}(E_{\text{projectile}}, \Theta)$
- Realistic yield determination by integration over the target thickness and angular range (slowing down of the beam in the target material)
### Neutron producing nuclear reactions (II)

#### Table 2: Common nuclear reactions particle accelerators use to produce neutrons.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$^{2}\text{H} + ^{2}\text{H} \rightarrow ^{3}\text{He} + \text{n}$</td>
<td>$^{2}\text{H}(\text{d,n})^{3}\text{He}$</td>
<td>+3.269</td>
<td>NA</td>
<td>$^{3}\text{He}$: 0.82 n: 2.45$^*$</td>
</tr>
<tr>
<td>$^{2}\text{H} + ^{3}\text{H} \rightarrow ^{4}\text{He} + \text{n}$</td>
<td>$^{3}\text{H}(\text{d,n})^{4}\text{He}$</td>
<td>+17.589</td>
<td>NA</td>
<td>$^{4}\text{He}$: 3.54 n: 14.05</td>
</tr>
<tr>
<td>$^{1}\text{H} + ^{7}\text{Li} \rightarrow ^{7}\text{Be} + \text{n}$</td>
<td>$^{7}\text{Li}(\text{p,n})^{7}\text{Be}^+$</td>
<td>-1.644</td>
<td>1.880</td>
<td>$^{7}\text{Be}$: 0.21 n: 0.03</td>
</tr>
<tr>
<td></td>
<td>$^{1}\text{H}(^{7}\text{Li,n})^{7}\text{Be}^+$</td>
<td>-1.644</td>
<td>13.094</td>
<td>$^{7}\text{Be}$: 10.0 n: 1.44</td>
</tr>
<tr>
<td>$^{2}\text{H} + ^{7}\text{Li} \rightarrow ^{8}\text{Be} + \text{n}$</td>
<td>$^{7}\text{Li}(\text{d,n})^{8}\text{Be}$</td>
<td>+15.031</td>
<td>NA</td>
<td>$^{8}\text{Be}$: 1.68 n: 13.35</td>
</tr>
<tr>
<td>$^{1}\text{H} + ^{9}\text{Be} \rightarrow ^{9}\text{B} + \text{n}$</td>
<td>$^{9}\text{Be}(\text{p,n})^{9}\text{B}$</td>
<td>-1.850</td>
<td>2.057</td>
<td>$^{9}\text{B}$: 0.18 n: 0.023</td>
</tr>
<tr>
<td>$^{2}\text{H} + ^{9}\text{Be} \rightarrow ^{10}\text{Be} + \text{n}$</td>
<td>$^{9}\text{Be}(\text{d,n})^{10}\text{B}$</td>
<td>+4.361</td>
<td>NA</td>
<td>$^{10}\text{B}$: 0.40 n: 3.96</td>
</tr>
</tbody>
</table>
**Monoenergetic (& quasi) neutron beams**

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**Graphical Representation:**
- Blue line: $^7\text{Li}(p,n)^7\text{Be}$
- Red line: $^7\text{Li}(p,n)^7\text{Be}^*$
- Black line: $^3\text{He}$ breakup
- Green line: $^7\text{Li}(p,n)^7\text{Be}^{**}$

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**Table of Reactions:**

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<thead>
<tr>
<th>Reaction</th>
<th>$^7\text{Be}^*$ Exc. Energy (MeV)</th>
<th>$Q$-value (MeV)</th>
<th>Threshold (MeV)</th>
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<td>$^7\text{Li}(p,n)^7\text{Be}$</td>
<td>0</td>
<td>-1.644</td>
<td>1.881 forward 1.920 backward</td>
</tr>
<tr>
<td>$^7\text{Li}(p,n)^7\text{Be}^*$</td>
<td>0.429</td>
<td>-2.073</td>
<td>2.371 forward 2.421 backward</td>
</tr>
<tr>
<td>$^7\text{Li}(p,n)^3\text{He}^4\text{He}$</td>
<td>break-up</td>
<td>-3.229</td>
<td>3.692</td>
</tr>
<tr>
<td>$^7\text{Li}(p,n)^7\text{Be}^{**}$</td>
<td>4.57</td>
<td>-6.214</td>
<td>7.110 forward 7.260 backward</td>
</tr>
</tbody>
</table>
The PTB (& NPL) metrology facility

- 2 MV tandem accelerator with up to 50 uA
- p(\(^7\)Li,n), p(\(^3\)H,n), d(\(^2\)H,n) and d(\(^3\)H,n) reactions
- Large hall minimizes neutron scattering background

**Figure 7.** TOF distribution for neutrons produced by bombarding a Ti(T) and an unloaded Ti target with 2.682 MeV deuterons. The areal titanium mass of the two targets was 1.91 mg cm\(^{-2}\). The T/Ti loading ratio of the Ti(T) target was 1.42. The upper and the lower histograms show the neutron distributions measured using the Ti(T) target before and after subtraction of the distribution measured using the unloaded Ti target, respectively. The solid line is a simulation carried out using the TARGET code [23].
30 keV quasi-Maxwellian neutron beam


LiLiT ~ 1 mA (liquid Li target)

FZK ~ 100 uA
HISPANOS ~ 10 uA
Nuclear reactions with high energy (few tens of MeV) ion accelerators
Neutrons for Science (NFS) @GANIL’s SPIRAL2

GANIL’s SPIRAL-2, a Superconducting Linear Accelerator:

- 40 MeV deuteron and 33 MeV protons
- Beam current 5 mA, i.e. rotating target
- Flight path 5 to 10 meters
- Frequency=0.25-1 MHz

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Upgrades for complementary experiments under study
Photoproduction with e⁻ accelerators

- Historical facilities:
  - ORELA @ORNL
  - GELINA @JRC-Geel
  - More recently, nELBE @HZDR, ALTO@IPN-Orsay, ...
Photoproduction of neutrons with Bremsstrahlung

Electron beam energy

- 45 MeV
- 50 MeV
- 55 MeV
- 60 MeV
- 70 MeV

Bremsstrahlung flux (arb. unit)

Photon energy (MeV)

Energy (MeV)

Incident energy (MeV)

Cross-section (mb)

208\(^{\text{Pb}}\)

GDR

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I_e = 15 μA, 
E_e = 31 MeV 
L = 6.2 m 
Flux = 3 * 10^{11} n/s
GELINA@JRC-Geel

image of the facility

GAINS @200 m

image of the equipment

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Spallation with very high (GeV) ion accelerators

- nTOF@CERN (Europe)
- DANCE@LANL (USA)
- MLF@J-PARC (Japan)
- Back-n@CSNS (China)
Neutron production by spallation

Relativistic protons impinging on heavy target nuclei

Fast neutrons emitted during collision and afterwards from excited residual nuclei
\( \gamma \)-flash from pion decay

Nucleon-Nucleus collisions at relativistic energies

- \( T_{\text{coll}} < 10^{-22} \text{s} \) : Collisions of the projectile nucleon with nucleons in the target (Intranuclear Cascade, emission of fast particles \( \pi, n, p, \ldots \))
- \( T_{\text{equil}} > 10^{-21} \text{s} - 10^{-16} \text{s} \) : Reorganisation of the residual nuclei, thermalization, particle evaporation (\( n, p, d, \alpha, \ldots \)), gamma ray emission
Spallation neutron yield

Fig. 10. Compilation of thick-target $n/p$ values for p + Pb and Pb/Bi measured to date at all incident energies.

CERN nTOF ca. 300 $n/p$ 20 GeV protons on Pb
The n_TOF facility at CERN

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The n_TOF Facility at CERN: a view

PS 20 GeV Linac
50 MeV Booster
1.4 GeV Proton Beam
20 GeV/c
7x10^12 ppp
Pb Spallation Target
Neutron Beam
10° prod. angle
n_TOF - EAR1 200 meters
n_TOF - EAR2 20 meters
n_TOF - NEAR 3 meters
(back to) Some general considerations
Neutron flux: average vs. instantaneous
Resolution function affected by:
- Flight path length
- Pulse width
- Target geometry/size
- Moderator size/geometry
Laser-driven neutron sources
A future LDNS for time-of-flight?

Recent test experiments at:
- HZDR-DRACO (Germany)
- CLPU-VEGA3 (Spain)
H2020-ARIEL Transnational Access
H2020-ARIEL Transnational Access

**summary of the ARIEL facilities available for TAA**

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>accelerators</th>
<th>ion beams</th>
<th>research reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold (&lt;25 meV)</td>
<td>nELBE@HZDR</td>
<td>n_TOF@JRC</td>
<td>MONNET@JRC</td>
</tr>
<tr>
<td>thermal ((\langle E_n \rangle = 25) meV)</td>
<td>CEA-DAM</td>
<td>GENESIS@CNRS</td>
<td>ALTO@CNRS</td>
</tr>
<tr>
<td>epithermal (25 meV – 100 keV)</td>
<td>FNG@NEA</td>
<td>FNG@NPI</td>
<td>HISPANOS@CNA</td>
</tr>
<tr>
<td>fast (0.1-20 MeV)</td>
<td>U. Oslo</td>
<td>NPL</td>
<td>IFIN-HH</td>
</tr>
<tr>
<td>very fast (&gt;20 MeV)</td>
<td>IRSN</td>
<td>AGOR@UMCG</td>
<td>BRR@mtaEK</td>
</tr>
<tr>
<td>pulsed beam</td>
<td>TRIGA@JGU</td>
<td>LR-9/LVR-15</td>
<td>@CVR</td>
</tr>
<tr>
<td>time-of-flight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charged particles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radioactive beam</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Priority is given to PhD students and young postdocs!
Summary

• Neutron energies of interest:
  • meV to hundreds of MeV (9 orders of magnitude)
• Main characteristics:
  • pulsed vs. continuous
  • “monoenergetic” vs. “broad” vs. “white”
  • neutron energy (meV to hundreds of MeV)
  • neutron flux
  • for pulsed sources: flight path and resolution function
• Nuclear reactors
  • @core and external beam lines (cold, thermal & fast)
• Accelerator-based neutron sources
  • low energy ion accelerators (nuclear reactions)
  • high energy ion accelerators (nuclear reactions)
  • medium energy electron accelerators (photoproduction)
  • very high energy ion accelerators (spallation)
• Many Open Access facilities, priority to new users & students
Neutron sources in nature

- Neutron sources in nature:
  Neutrons can be formed in nuclear reactions of high-energetic cosmic particles in the upper atmosphere. The flux is inversely proportional to the solar activity (high solar activity deformes the earth’s magnetic field) and strongly dependent on the geographical latitude and altitude.

![Neutron spectrum](image)

**Fig. 4.** Neutron spectrum measured on the roof of the IBM T. J. Watson Research Center in Yorktown Heights, NY.

**Setup:**
Extended range Bonner spheres
14 different size PE moderators with $^3\text{He}$ proportional counters

G. Heusser, Low radioactivity background techniques
Gordon et. al. IEEE TNS 51 (2006) 3427
Monoenergetic neutron reference fields

\[ E_n(0°) = 14.8 \text{ MeV} \]

\[
\begin{align*}
&T(d,n)^4\text{He} & \text{relative Yield} \\
&7\text{Li}(p,n)^7\text{Be} & Y(0°) \text{ calculated for } \Delta E_n = 10 \text{ keV} \\
&T(p,n)^3\text{He} & T(d,n)^4\text{He}: \\
&D(d,n)^3\text{He} & \text{rather isotropic} \\
&7\text{Li}(p,n)^7\text{Be}: \\
& & \text{production of keV neutrons at } 0° \text{ (reduced yield)}
\end{align*}
\]

Parameters of reference fields
\((E_n, Y, \text{target, beam properties})\)
see table 2 of
R. Nolte, D. J. Thomas, Metrologia 48 (2011) S263

DROSG 2000 neutron source reactions code:
https://www-nds.iaea.org/public/libraries/drosg2000/
Relativistic two body kinematics:

- Lorentz-Transformation in beam direction with rapidity \( Y = \ln \frac{p_{cm} + \sqrt{m_1^2 + p_{cm}^2}}{m_1} \)

\[
p_{3,4} = \sqrt{m_{3,4}^2 + p_{cm}^2} \cos \Theta_{3,4} \sinh Y \pm \cosh Y \sqrt{p_{cm}^2 - m_{3,4}^2 \sin^2 \Theta_{3,4} \sinh^2 Y} \over 1 + \sin^2 \Theta_{3,4} \sinh^2 Y
\]

- Two solutions of \( p_{3,4} = f(\Theta_{3,4}) \)!

- For endothermic reactions \( Q = m_1 + m_2 - m_3 - m_4 < 0 \) MeV
  
  Forward threshold (minimum kinetic energy for the reaction to occur)
  
  derived from \( E_{3,cm} + E_{4,cm} \geq m_3 + m_4 \)
  
  \[
  T_f = -Q \left[ 1 + \left( \frac{m_2}{m_1} \right) - \left( \frac{Q}{2m_1} \right) \right]
  \]

- If the ejectile is slower than the c.m. velocity \( E_3 \) is a double-valued function of the lab angle \( \Theta_3 \). Equivalent: \( \Theta_3 \) is a double-valued function of \( \Theta_{cm} \)

up to the back threshold \( T_b = -Q \left[ 1 + \frac{m_2}{m_1-m_3} - \frac{Q}{2(m_1-m_3)} \right] \)
Energy range for neutron production

- „Monoenergetic“ neutrons from reactions with only one neutron group
- „Quasi-monoenergetic“ neutrons from reactions with a second group of neutrons from reactions to excited states of the recoil or nuclear break up
- Example: $^7\text{Li}(p,n)^7\text{Be}$

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- Energy levels of light nuclei, see [http://www.tunl.duke.edu/nucldata/index.shtml](http://www.tunl.duke.edu/nucldata/index.shtml)

- Monoenergetic neutrons from $E_p = 1.920 \text{ MeV} - 2.371 \text{ MeV}$
  $E_n = 121 \text{ keV} - 649 \text{ keV}$
\( ^7\text{Li}(p,n)^7\text{Be} : \text{neutron energy vs. angle} \)

- \( Q = -1.644 \text{ MeV} ; T_f = 1.881 \text{ MeV} ; T_b = 1.920 \text{ MeV} \)

Two neutron energy groups below \( T_b \)

[Graph showing neutron energy vs. angle for \( ^7\text{Li}(^1\text{H},^1\text{n})^7\text{Be} \)]
Neutron production in inverse kinematics

- light-ion beam required with higher energy (beam heating) e.g. $^1\text{H}(^7\text{Li},n)^7\text{Be}$

![Graph showing kinematical focusing increases neutron intensity in a forward cone. Licorne Facility at IPNO.]

$T_f = 13.096 \text{ MeV}$

**Fig. 1.** Kinematic curves relating the angle of neutron emission to neutron energy in the laboratory frame for different $^7\text{Li}$ bombarding energies from 13.15 to 16.5 MeV, calculated using two-body relativistic kinematics.
The differential neutron spectrum

\[
\frac{d^2 N}{dE_n d\Omega} = N_p n_{tar} \left( \frac{d\sigma}{d\Omega^{cm}} \right) \left( \frac{dE_p}{dx} \right) \left( \frac{d \Omega^{cm}}{d\Omega} \right)^{-1} \frac{dE_p}{dE_n}
\]

\[Y = \int \frac{d^2 N}{dE_n d\Omega} \frac{1}{N_p} dE_n\]

- Neutron yield depends on target thickness and purity:
  - Energy loss of the beam in the neutron producing target layer
  - Beam heating of the target
  - Thermal motion of target atoms e.g. in gaseous targets
    - Neutron energy spread
- Neutron scattering in target materials, backings, windows
- Opening angle and source and detector counting geometry
- Kinematic focussing for reactions in inverse kinematics
  - Monte Carlo neutron transport simulation to describe the neutron spectrum of quasimonoenergetic neutron sources

Time correlated associated particle method
  - Neutron yield measured independent from \(\frac{d\sigma}{d\Omega^{cm}}\)
Neutron reference fields are produced in open geometry without collimation
Very low room return due to large free space around source and detectors
Van der Graaff Ion accelerator for $1 - 4$ MeV protons, deuterons
with DC beam and pulsed beam $\Delta t = 1$-2ns, $\nu \approx 1$ MHz
pulsed primary beam $\approx 1-10$ ns

neutron producing target

emitted neutron pulses

collimator + shielding

detector and experiment

primary beams:

light charged particles with $>100$ MeV energy
  $\Rightarrow$ spallation neutron source

electrons $10 - 150$ MeV
  $\Rightarrow$ photoneutron source

Deuteron beams on Be/C converters
deuteron break up

quasimonoenergetic neutron sources e.g. $^7$Li($p,n$)
  $\Rightarrow$ pulsed beam
  background identification

Flight paths $10 - 200$ m
Energy resolved measurements by time of flight:

• Measurement of time-of-flight $t$ and flight path $l$

1. $\nu = \frac{l}{t}$

2. $\gamma = \frac{1}{\sqrt{1-(\frac{\nu}{c})^2}}$

3. $E = mc^2(\gamma - 1)$ (E is the neutron kinetic energy)

• Energy resolution

1. $\frac{\Delta E}{E} = (\gamma + 1)\gamma \frac{\Delta \nu}{\nu}$

2. $\frac{\Delta \nu}{\nu} = \sqrt{(\frac{\Delta t}{t})^2 + (\frac{\Delta l}{l})^2}$

• accelerator pulse length, time resolution of detectors, neutron transport in the neutron producing target and detector or sample

Schillebeeckx et al. NDS 113 (2012) 3054
Time-of-flight to Energy correlation

- Neutron transport code MCNP: Simulation of neutron scattering inside the neutron source and all surrounding materials e.g. collimators
- Neutron scattering can change the correlation of time of flight and neutron energy ➔ multiple scattering corrections
- Unscattered neutrons can be identified (in the simulation)
Neutron evaporation spectrum from Compound Nucleus decay

The emission spectrum depends on:

- The **level density** of the compound nucleus $\rho_c$
- The **level density** of the residual nucleus $\rho_B$
- and the inverse cross section of compound nucleus formation

For neutron emission $\sigma_{\beta c}$ is not strongly energy depend. ➔ Maxwellian energy spectrum

For charged particle emission: Transmission through the Coulomb-Barrier
Neutron evaporation spectra

Gugelot, Phys. Rev. 81 (1951) 51

Fig. 11. Relative level density of Hg$^{197}$.

Fig. 9. Relative level density of Co$^{56}$ and Fe$^{56}$. Curve 1: represents the relative level density for Co$^{56}$ obtained from the neutron spectrum; curve 2: shows the relative level density of Fe$^{56}$ as observed from the inelastic scattering of 16-Mev protons by iron (reference 38).
Photoproduction of neutrons with bremsstrahlung

Bremsstrahlung spectrum ➔ Photonuclear excitation of Pb through the Giant Dipole Resonance (GDR)

Neutron production by $(\gamma, xn)$ reactions

nELBE yield:
- 30 MeV 15µA: 3*10$^{11}$ n/s with 200 kHz
- 100 MeV 96µA (Target: U, Hg cooled): 3*10$^{13}$ n/s with 800 Hz

neutron production”
JS School, Sevilla, Spain 21/9/2022
Measurement time: 49.4 h \( I_e = 15 \, \mu\text{A} \), \( E_e = 31 \, \text{MeV} \)
Flight path 618 cm
Absorption dips: 78, 117, 355, 528, 722, 820 keV \(^{208}\text{Pb}\) scattering resonances
Emission peaks: 40, 89, 179, 254, 314, 605 keV near threshold photoneutron emission
In \(^{208}\text{Pb}\) (strong capture resonances of \(^{207}\text{Pb}\))

R. Beyer et al., NIM A723 (2013) 151
Prompt neutron production by fission

- Neutrons are mostly emitted from the accelerated fission fragments.
- Low energy fission shows saw-tooth behaviour of the average number of neutrons emitted from each fission fragment with mass number A.
- Fission fragments are excited neutron-rich compound nuclei that deexcite by neutron and gamma-ray emission.
- Neutron evaporation in statistical model.

Van de Graaff accelerator, JRC Geel
TFGIC + liquid scintillators
A. Al-Adili, Phys. Rev. C102 (2020) 064610

E.g. Los Alamos Model for prompt fission neutrons
D.G. Madland, Nuclear Physics A 957 (2017) 289–311
Accelerator-based Neutron Sources

- **Time-of-flight neutron sources**
  - High energy resolution for resolved resonance region: Gelina JRC Geel, nELBE HZDR Dresden, n_TOF CERN
  - Quasimonoenergetic and ‘white’ beams < 40 MeV: NFS Ganil
  - Dedicated detector systems for (n,n’γ) and (n,tot) measurements

  *New!* NFS (GANIL), n_TOF lead target 3 (CERN) + NEAR station

- **Ion accelerators**
  - Quasimonoenergetic and ‘white’ neutrons for unresolved resonance region
    - Electrostatic accelerators: CNRS-AIFIRA Bordeaux, CEA Bruyeres le Chatel, PTB Braunschweig, NPL London, CAN Sevilla, CNRS-ALTO Paris
    - Cyclotrons: PTB, NPI Rez
  - 14 MeV generators for high intensities: ENEA Frascati, UU Uppsala, CNRS-GENESIS Grenoble
  - Ion beams for surrogate method, ISOL and IBA: UO Oslo, JYU Jyväskylä, IFIN Budapest

  *New!* HISPAnoS D+d source CAN Sevilla, NESSA 14 MeV generator UU, TANJA 2 MV Tandetron PTB, MR-TOF mass separator JYU Jyväskyla
Research Reactors

- Thermal cross sections, fission neutron spectra, fundamental physics with neutrons
- Dedicated instruments: Penning traps, fission fragment and gamma spectrometers, cold neutron sources
- Ultracold, cold and thermal neutrons: MTA-EK Budapest, SCK CEN Mol, CVŘ, Řez
- High-flux reactor: ILL Grenoble
- Pulsed source: JGU TRIGA Mainz
- Instruments for nuclear data: Prompt Gamma Activation Analysis
  Neutron induced Prompt gamma-ray spectroscopy
  Fission product prompt gamma-ray spectrometer
  Fission Yield measurements
  Fission fragment spectrometer
### Beam properties of the ARIEL facilities

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>e⁻ beams</th>
<th>Ion beams</th>
<th>Research reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold (&lt;25 meV)</td>
<td>nELBE@H2ZDR, GELINA@JRC, MONNEI@JRC, AFIFRA@CNRS, ALTO@CNRS, GENESIS@CNRS, NFS@GANIL, CEA-DAM, FNG@NEA, PTB, FNG@NPI, HISPANOS@CNA, NESSA@UU, U. Oslo, NPL, IFIN-HH, JYU, IRSN, AGOR@UMCG, BRR@mtaEK, BR1@SCK-CEN, TRIGA@JGU, LR-0/LVR-15, @CVR, @ILL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>thermal ((\langle E_n\rangle = 25) meV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>epithermal (25 meV – 100 keV)</td>
<td></td>
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</tr>
<tr>
<td>fast (0.1-20 MeV)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>very fast (&gt;20 MeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pulsed beam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>time-of-flight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charged particles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radioactive beam</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LOHENGRIN Fission Fragment Spectrometer

FF recoil spectrometer

\[
\frac{A}{\Delta A} \approx 400; \quad \frac{E}{\Delta E} \approx 100
\]

- separation of ionic charge states \(\rightarrow\) fission yields

PGAA’s modular neutron flight tube applications

Removable modules enable to accommodate user supplied set up:

- Measurement of prompt fission gamma spectra of $^{233}\text{U}(n_{\text{cold}}, \gamma)$ with users from JRC Geel in 2018
- Fission chamber + gamma ray detectors (4 LaBr$_3$:Ce + HPGe)
- Relative $(n, \gamma)$ Xsection measurement ($^{242}\text{Pu}(n, \gamma)$ Univ. Sevilla, 2018)
- Isotopic analysis of samples (CERN, EFNUDAT)
- Gamma strength function ($^{242}\text{Pu}(n, \gamma)$ Univ. Sevilla, 2018) and ($^{232}\text{Th}(n, \gamma)$ Univ. Osmangazi, 2017, 2018)
- Gamma-gamma coincidence ($^{94}\text{Nb}(n, \gamma\gamma)$, Univ. Novi Sad, 2016 and 2017)
- Etc.
**CERN n_TOF Experiment**

- Spallation source using 20 GeV/c proton beam from CERN proton synchrotron

- New spallation target in 2021 > $10^6$ n / PS pulse

- Radioactive target capability at experimental stations (high instantaneous flux ➔ use of small number of target atoms)

Experimental capabilities:
- Radiative neutron capture ($n,\gamma$)
- Neutron induced fission ($n,f$)
- Neutron induced light charged particle emission ($n,p$) ($n,\alpha$)

NEAR station for irradiation

EAR-2:
- Short flight path 20 m for higher intensity
- 90° to the proton beam ➔ Background reduction

E.Chiaveri, EPJ Web of Conferences 239, 17001 (2020)

“Principles and examples of neutron production”
Carlos GUERRERO @H2020-ARIEL HISPANOS School, Sevilla, Spain 21/9/2022
Spallation neutron spectrum at CERN nTOF

Neutron evaporation (0.1 – 10 MeV)

Fast neutrons from intranuclear cascade stage > 10 MeV

Shaded range < 0.1 MeV
Neutrons slowed down by hydrogeneous materials

**ENERGY RESOLUTION**

<table>
<thead>
<tr>
<th>$E_n$ (eV)</th>
<th>$\frac{\Delta E_n}{E_n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$4.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>10</td>
<td>$4.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$4.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$7.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$1.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>$2.8 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Carlos GUERRERO @H2020-ARIEL HISPANOS School, Sevilla, Spain 21/9/2022
GELINA pulsed neutron source

Electron accelerator
- 150 MeV electron accelerator
- 10 ns burst, 10 A peak
- 800 bursts/s

Compression magnet
- Pulse compression magnet
- <1 ns burst, >100 A peak
Electron-neutron conversion target

- Uranium target – rotating, mercury cooled
- $4 \times 10^{10}$ neutrons / burst

Water-filled Be moderators

12 Flight paths 8 to 400 m

Moderated or fast neutron spectrum
24 h/d, 100 h/w
Fig. 4. Neutron flux per unit of lethargy in the flight-path. (a) 81°—60 m of the moderated neutron spectrum; (b) 90°—200 m of the fast neutron spectrum.

Fast neutron spectrum from 0.1 – 18 MeV

GELINA:
- width is dominated by the tof-resolution resonance total $\Gamma \approx 2$ eV
- Doppler width (FWHM) $\approx 13$ eV
- ToF resolution (FWHM) $\approx 40$ eV
- photoneutron sources tend to have a higher resolution than spallation neutron sources (larger target-moderators required)
Neutrons For Science at GANIL

- First facility at SPIRAL-2 superconducting LINAC proton (33 MeV), deuteron (40 MeV), helium (80 MeV) beams for neutron production
- $F_0 = 88$ MHz with single bunch selector for ToF measurements 150 kHz – 1 MHz beam current 5 mA / N up to < 50 µA
- Thin and thick converter targets Li, C, Be quasimonoenergetic and continuous neutron spectra
- Irradiation station
- Radioactive target capability

Flight path: 5 – 30 m
Energy range: 0.1- 40 MeV
Low γ-flash background
Low instantaneous flux
High repetition rates
**NFS neutron spectra**

- Quasimonoenergetic neutrons
  $p + ^7\text{Li}, \, ^9\text{Be}$ thin converters

- White spectrum 40 MeV deuterons on thick Be converter

Fast neutron range up to 40 MeV:
Reaction studies:
$(n,n'\gamma), (n,xn), (n,f), (n,p), (n,\alpha), (n,tot)$

Flux at 5 meters: $8.10^7 \, \text{n/s/cm}^2$

at 15 MeV: $5.10^6 \, \text{n/s/cm}^2/\text{MeV}$

at 30 MeV: $6.10^5 \, \text{n/s/cm}^2/\text{MeV}$
## Neutron time-of-flight facilities for cross section measurements

<table>
<thead>
<tr>
<th>Facility</th>
<th>Type</th>
<th>Particle energy (MeV)</th>
<th>Target</th>
<th>Pulse width (ns)</th>
<th>Frequency (Hz)</th>
<th>Flight Path Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GELINA</td>
<td>e-</td>
<td>80-140</td>
<td>U(Hg cooled)</td>
<td>1</td>
<td>40-800</td>
<td>10-400</td>
</tr>
<tr>
<td>nELBE</td>
<td>e-</td>
<td>40</td>
<td>Pb</td>
<td>0.01</td>
<td>100000-250000</td>
<td>4.10</td>
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<tr>
<td>NFS(GANIL)</td>
<td>d</td>
<td>40</td>
<td>Be,C</td>
<td>0.2</td>
<td>150000-1000000</td>
<td>5.30</td>
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<tr>
<td>n_TOF (CERN)</td>
<td>p</td>
<td>200000</td>
<td>Pb</td>
<td>6</td>
<td>0.4</td>
<td>20,185</td>
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<tr>
<td>RPI</td>
<td>e-</td>
<td>60</td>
<td>Ta</td>
<td>7 - 5000</td>
<td>500</td>
<td>10-250</td>
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<tr>
<td>LANSCE - MLNSC</td>
<td>p</td>
<td>800</td>
<td>W</td>
<td>135</td>
<td>20</td>
<td>7.60</td>
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<tr>
<td>LANSCE - WNR</td>
<td>p</td>
<td>800</td>
<td>W</td>
<td>0.2</td>
<td>13900</td>
<td>8.90</td>
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<tr>
<td>JPARC/MLF - ANNRI</td>
<td>p</td>
<td>3000</td>
<td>Hg</td>
<td>600</td>
<td>25</td>
<td>21,28</td>
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<tr>
<td>CSNS back-n</td>
<td>p</td>
<td>1600</td>
<td>W( H2O cooled)</td>
<td>50 (double pulse)</td>
<td>25</td>
<td>55, 76</td>
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<tr>
<td>KURRI</td>
<td>e-</td>
<td>20-46</td>
<td>Ta</td>
<td>2,5,..100</td>
<td>1-300</td>
<td>10,13,24</td>
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<tr>
<td>KURRI</td>
<td>e-</td>
<td>7-32</td>
<td>Ta</td>
<td>100-4000</td>
<td>1-100</td>
<td>10,13,24</td>
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<tr>
<td>ORELA</td>
<td>e-</td>
<td>140</td>
<td>Ta</td>
<td>2 - 30</td>
<td>1-1000</td>
<td>10-200</td>
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<tr>
<td>POHANG</td>
<td>e-</td>
<td>75</td>
<td>Ta</td>
<td>2000</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>
Literature

- Reference:

- Quasimonoenergetic neutrons:
  R. Nolte, D.J. Thomas, Metrologia 48 (2011) S263

- Neutron sources and resonance parameter determination
  P. Schillebeeckx, Nuclear Data Sheets 113 (2012) 3054–3100

- ARIEL webpage with links to many neutron beam facilities