FRANZ and Small-Scale Accelerator-Driven Neutron Sources

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Outline

1) Introduction: Neutron Production
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Introduction: Neutron Research

- Electrically neutral.
- Sensitivity for magnetic properties, different isotopes, light elements in particular.
- High penetration depth in material.
- Material Science.
- Neutron imaging.
- Understanding of neutron capture processes relevant for nuclear astrophysics.
- Cancer treatment (BNCT).

Introduction: Nuclear Astrophysics

Stellar nucleosynthesis:
• About 50% of the element abundances beyond iron are produced via the s-process.
• s-process takes place in AGB stars.
• Neutron temperature: $k_B T = 8$ keV to 90 keV [Reifarth et al., 2014].
• Modelling requires neutron capture cross-sections from 1 keV to 400 keV.
• Requires neutron sources with high flux in this energy region.

Picture: C. Arlandini et al., Nachr.,- FZK 33 2/2001,p. 178
Introduction: BNCT

- Boron Neutron Capture Therapy (BNCT): Boron-10 (which is selectively incorporated into tumor cells) captures n and decays into short-ranging α and $^7\text{Li}$ that destroy cancer cell.

- Currently, 8 initiatives to develop accelerator-based BNCT.

- Flux of $10^9 \frac{n}{s \cdot cm^2}$ required (high duty cycle).

- Epithermal neutrons: $W_n = 0.5$ eV to 10 keV

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Small-Scale Accelerator-Driven Facilities

- Neutrons produced via nuclear reactions using light-ion beams:
  - $^7\text{Li}(p,n)^7\text{Be}$ (threshold: 1.88 MeV; highest n yield, 1 keV..500 keV neutrons, Li difficult to handle)
  - $^9\text{Be}(p,n)^9\text{B}$ (threshold: 2.06 MeV; lower n yield, MeV neutrons)
  - $^9\text{Be}(d,n)^{10}\text{B}$ (no threshold, lower n yield, MeV neutrons).
- Neutron yield: $10^{11}..10^{12}$ n/mA/s
- Accelerator: p, d with $W_b \approx 2$ MeV..13 MeV
- Small-scale facilities (cost-efficient, affordable for hospital/university)

Time-of-Flight (TOF) Method

- TOF method allows to measure the neutron capture cross-sections as a function of the neutron energy.
- Pulsed primary beam required.
- Adequate neutron spectrum assures low background.

- 80 cm flight path
- $E_n = 1..200$ keV

Other Reactions

Prompt Flash

$(n,\gamma)$ on sample

$I$ [a.u.]

$E_n = 200$ keV  $E_n = 128$ keV

$\gamma$ BaF$_2$ detector at Frankfurt.
Challenges: High Intensity

Compact, cost-efficient, reliable facilities – with high primary beam intensity \( (I_b > 10 \text{ mA}) \), high-power target and flexible time structure.

\( a \) Electrostatic Accelerators

**NUANS**, Nagoya Univ., Japan:
Dynamitron, \( p \), 2.8 MeV, 15 mA

**TESQ**, Buenos Aires, Argentina:
\( p \), 2.8 MeV, 30 mA

Under construction.

Katsuya Hirota, IPAC’15, WEPWA019

High Intensity

**b) RFQ**

PKUNIFTY, Peking Univ., China:
- d, 2 MeV, 50 mA

LENOS, LNL, Legnaro, Italy:
- p, 5 MeV, 50 mA

4-rod RFQ: 201.5 MHz, 1%..10% duty cycle, Be target

4-vane RFQ: 352.2 MHz, CW, 7.1 m long, Be target


High Intensity

c) RFQ + DTL

**CPHS**, Tsinghua Univ., China:
- p, 50 mA
- 3 MeV RFQ, 13 MeV DTL,
- 2.5% duty factor, $W_b = 16$ kW,
- Be target

**FRANZ**, Frankfurt Univ., Germany:
- p, 2 MeV, 50 mA.
- 700 keV RFQ, 2 MeV DTL,
- 2.4 m total length,
- CW, Li target

**LENS**, Indiana Univ., USA:
- p, 13 MeV, 25 mA.
- 1.8% duty factor, $W_b = 6$ kW, Be target


Under Construction.

In Operation.
High-Power Targets

Examples:
Lithium-Targets

- 4 kW, 14 mm beam $\rightarrow$ 2.6 kW/cm$^2$ $\rightarrow$ > 100 kW/cm$^3$.
- Lithium melting point $\approx$ 180°C.

FRANZ: solid lithium layer

SARAF: liquid lithium target (windowless setup)

Designed for 4 kW (14 mm beam size).

Successfully commissioned with $W_b = 2.3$ kW.


M. Paul et al., J. Radioanal. Nucl. Chem., 12.03.2015.
Flexible Time Structures

- CW (or high duty cycle): high average flux (activation measurements, BNCT). Can lead to challenging cooling scenarios.
- Short pulses: allow TOF, pulsed neutron imaging.
- Special case (FRANZ): short pulses (high peak intensity) with repetition rate so high that ion source and RFQ-DTL have to be operated in DC/CW.
Frankfurt Neutron Source FRANZ

<table>
<thead>
<tr>
<th>Mode</th>
<th>Neutron Flux</th>
<th>Measurement Description</th>
<th>Energy</th>
<th>Current</th>
<th>Pulse Duration</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Activation Mode</td>
<td>high average</td>
<td>measurement of the <em>integrated</em> n-capture cross sections</td>
<td>p, 2 MeV</td>
<td>2 mA</td>
<td></td>
<td>cw operation</td>
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<tr>
<td>Compressor Mode</td>
<td>high (peak)</td>
<td><em>energy-dependent</em> measurements of n-capture cross sections (using TOF)</td>
<td>p, 2 MeV</td>
<td>50 mA</td>
<td>1 ns, 250 kHz</td>
<td>(at the target)</td>
</tr>
</tbody>
</table>
Frankfurt Neutron Source FRANZ

- Arc-discharge driven ion source.
- Proton current: 50 mA (240 mA).
- Current density: 480 mA/cm².
- DC operation.
- Proton fraction > 90 %.
- \( \varepsilon_{\text{rms}, \text{norm}} < 0.08 \text{ mm}\cdot \text{mrad.} \)
- Beam energy: 120 keV.
Frankfurt Neutron Source FRANZ

Low Energy Beam Transport (LEBT) Section

- 4 Solenoids.
- Chopper.
- SC comp. (Sec. 1).
- No SC comp. (Sec. 2, pulsed).
- Installed and commissioned with 14 keV He$^+$ beam.

Faraday Cup 1

HV Pulse Generator

Aperture: $r = 50$ mm

$L = 3.7$ m
Frankfurt Neutron Source FRANZ

Chopping parameters
- $p$, 50 mA, 120 keV.
- Pulse length: 50 ns..350 ns.
- Rep. rate: 250 kHz.
Frankfurt Neutron Source FRANZ

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Beam-Separation:
O. Payir, IPAC'15, THPF023

\[
\int (\vec{F}_{\text{elec}} + \vec{F}_{\text{mag}}) \, dz = 0
\]

Pulsed Beam

DC Beam

Electric Deflector

\( V_{\text{defl}} = 12 \text{ kV} \)
Frankfurt Neutron Source FRANZ

Beam Pulse Measurements, 
\( \text{He}^+, 14 \text{ keV} \)

\( r_{\text{aperture}} = 50 \text{ mm} \)

\( \text{I}_{\text{dipole}} = 40.0 \text{ A} \)

\( f_{\text{rep}} = 257 \text{ kHz} \)
Frankfurt Neutron Source FRANZ

2 MeV Linac Section

- Total length: 2.4 m.
- $f_{rf} = 175$ MHz.
- 4-rod RFQ manufactured.
  Awaiting delivery.
- IH cavity to be copper plated.
- Coupling allows operation with single power amplifier.
- CW operated.
- Thermal losses.

H. Podlech, A. Schempp
M. Heilmann, U. Ratzinger
Frankfurt Neutron Source FRANZ

**RFQ Prototype Module**

- **RF Power Test**
  - 30 kW → 75 kW/m ($t \approx 200$ h).
  - 45 kW → 115 kW/m ($t \approx h$) → 94 kV.
  - RFQ design specs: 59 kW/m (50 mA).

Milled cooling channels covered with 3 mm thick copper plating.

Manufactured by NTG company

Brazed silver tuning plates.
Frankfurt Neutron Source FRANZ

Medium Energy Beam Transport (MEBT) Section

2 external QP triplets:
- Aperture: 30–38–30 mm.
- \( \frac{1}{r} \int B \, dz : 2.1–3.0–2.1 \, \text{T.} \)

RT CH rebuncher cavity:
- 5 gaps.
- Energy variation \( \Delta W_b = \pm 0.2 \, \text{MeV} \).
- \( f_{\text{rf}} = 175 \, \text{MHz.} \)
Frankfurt Neutron Source FRANZ

• Mobley-type bunch compressor, extended for high beam intensity.
• Electric kicker:
  • $f = 2.5$ MHz.
• Magnetic ion guiding system.
• Multiaperture rebuncher.
• Final focus rebuncher:
  • 6 gaps, 11.5 kW.
FRANZ is currently under construction at Frankfurt University:

- Deliver neutrons for nuclear astrophysics and material sciences.
- Accelerator test bench.
- Education of students in accelerator physics.

Physics Building, Goethe-Universität Frankfurt
Conclusion

• Small-scale accelerator-driven neutron sources can provide intense neutron beams at modest sizes and costs.

• The neutron energy range of keV to MeV is especially suited for nuclear astrophysics and BNCT.

• Challenges are: compact, high-intensity facilities with high-power targets and flexible time structures.

• FRANZ, under construction at Frankfurt University, is based on a 2 MeV, 50 mA proton driver, which allows operation from cw (2 mA) to short, 1 ns pulses at 250 kHz.
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Thank you for your attention!