A neutron facility at the INFN-LNL

Luca Silvestrin et al.
University of Padova

Bisello D., Maggiore M., Mastinu P., Porras I., Prete G., Silvestrin L. and Wyss J.
Outline

- Introduction
- NEPIR facility
  - Quasi-monoenergetic neutron facility
  - White spectrum neutron facility
- Atmospheric neutron emulator
Practical general-purpose neutron facilities are of two types:

1. **research reactors (fission reactions)**
2. **accelerator-driven sources** (non-fission nuclear reactions)
   - Large High-energy accelerator spallation sources
   - Compact low energy accelerators (non-spallation sources)

- Reactor sources play an essential role in materials characterization and other research purposes, **but some are going into closure** (Berlin; Orphee;…).
- Present and future high-energy spallation sources (ISIS at RAL; ESS;…), in spite of their high neutron yields and sophisticated instrumentation **achievable at great costs (expensive)**, they will barely fulfill the demands of the large neutron user community for materials research, let alone of other emerging important fields and disciplines.
Neutrons at Legnaro

Compact Accelerator Driven Neutron Sources (CANS) have shown promising capabilities in bridging the capacity insufficiency and the expanse of cross-disciplinary neutron applications.

- **NEutron and Proton IRradiation (NEPIR) complex.** UNDER DEVELOPMENT

  **NEPIR** is driven by the high power 30-70 MeV proton cyclotron ($I_{\text{max}} = 750$ uA) of the SPES project and consists of 3 subsystems:

  I. **QMN**: delivers quasi mono-energetic neutrons in the 20-70 MeV range
  II. **ANEM**: delivers atmospheric-like neutrons in the 1-70 MeV range
  III. **PROTON**: a direct proton (35-70 MeV) irradiation line (not this talk)

- **Legnaro Slow Neutron Source (LSNS)** FUTURE DEVELOPMENT

  **LSNS** encompasses state-of-the-art **Accelerator-driven, Brilliant, and Compact Neutron Sources (ABC NS)** and cross-disciplinary R&D. It delivers cold, thermal, and epithermal neutrons.
NEPIR overview

NEPIR

Fast neutrons \( (E_n > 1 \text{ MeV}) \)

- Three subsystems: \textbf{QMN, ANEM} and \textbf{PROTON}

- Originally conceived to study of \textit{radiation damage effects in electronic devices and systems} induced by:
  - flight-altitude and sea-level \textit{atmospheric neutrons}
  - solar \textit{protons}

- They will be also used to perform:
  - physics cross-section measurements,
  - biological samples irradiation,
  - shielding performance evaluation,
  - material degradation studies,
  - ...
Radiation effects

Ionizing radiation can interfere with the proper operation of electronic devices, causing temporary unwanted effects (soft errors) or permanent failures (hard errors).

Neutrons in cosmic-ray air-showers are a widening problem for industry:

- Aviation
- Automotive
- Trains
- Information technology and Infrastructure
- Medical (e.g. pace makers,...)
Qantas Flight 72 (QF72) was a scheduled flight from Singapore [...] to Perth [...] on 7 October 2008 that made an emergency landing [...] following an inflight accident featuring a pair of sudden uncommanded pitch-down manoeuvres that resulted in serious injuries to many of the occupants.

One of the aircraft’s three air data inertial reference units (ADIRU 1) exhibited a data-spike failure mode, during which it transmitted a significant amount of incorrect data on air data parameters to other aircraft systems...

Australian Transport Safety Beureau
Aviation Occurrence Investigation Report
AO-2008-070

“Radiation induced single events could be happening on everyone’s PC, but instead everybody curses Microsoft.”
Paul Dodd, Sandia National Laboratories
Radiation effects on electronics

If a neutron (proton) is fast enough...

a Single Event Effect (SEE) may occur (it depends on where it strikes)

Reference cross-section for “Soft Errors” such as SEU upset in digital electronics:

\[ \sigma_{\text{SEU}} = 10^{-14} \text{ cm}^2/\text{bit}, \]

\[ N_{\text{bits per device}} = 4 \times 10^6 \]
SPARE project

The neutron facility is currently financed by SPARE (Space Radiation Shielding)

SPARE is a project involving ASI, INFN and Centro Fermi. The goal is to perform a test campaign to investigate the effectiveness of active and passive shielding materials for the human activity on Mars, using the proton beam facility at TIFPA (Trento Institute for Fundamental Physics Applications) with $E_p = 70\text{-}228 \text{ MeV}$ and fast neutron beams at the LNL-NEPIR facility (under development) $E_p = 30\text{-}70 \text{ MeV}$.

We have designed two versions:

1) true QMN
2) pseudo QMN

The choice will depend on how the funds will be shared (under negotiation). Additional funds will be necessary to provide QMN beams.
Neutrons on Mars and Moon

The galactic cosmic rays environment on the lunar surface is shown at solar minimum (dashed lines) and solar maximum (solid line). Z=0 corresponds to neutrons, which can be up to hundredths of MeV.

The energetic (E > 1 MeV) neutron flux on earth is \(21 \times 10^6 \text{ n cm}^{-2} \text{ s}^{-1}\); for comparison; on the surface of the Moon it’s 3 orders or magnitude higher, as on the surface of the Moon where the spectrum is harder.

Mars surface neutron environment with 16 g/cm² CO₂ overhead and various surface material compositions.
Galactic cosmic rays are the dominant source of dose in a deep space mission, estimated to be around 1.8 mSv/day.

Comparison between dose and dose equivalents for neutrons and charged particles in four different Space Shuttle missions at 28.5° inclination in LEO.

Neutron dose (measured by nuclear emulsion) can account for 13-38% of the dose due to charged particles (measured by TLD-100 detectors).


Neutron energy spectrum measured by Mars Science Laboratory mission in deep space during the transit to Mars

Quasi Mono-energetic Neutron (QMN) reference fields allow one to study energy dependent neutron interaction mechanisms with matter, be it electronic, detector, dosimeter material, or living tissue...

In the context of SPARE, the QMN beam to be developed at NEPIR (LNL, 30-70 MeV protons) will be used to perform bench mark shielding measurements for spacecraft and planetary bases.

Log-log plot of the relationship between the neutron energy and the equivalent dose delivered by a neutron beam.

It is particularly complicated in the MeV to tens of MeV energy rage, where the local maximum is located.

This energy interval is accessible at the LNL neutron facility.
(Fast) Quasi Monoenergetic Neutrons

Forward ($\theta = 0^\circ$) QMN energy spectra beams for different proton beam energies on a thin (non beam-stopping) Lithium target

[TIARA facility, Japan].

Performance of different QMN sources (from Lithium) beams around the world.

<table>
<thead>
<tr>
<th>LAB</th>
<th>Energy of the protons (MeV)</th>
<th>Distance (m) of target to the test point</th>
<th>Mono-energetic neutron (peak) flux at the test point</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIARA (Japan)</td>
<td>40-90</td>
<td>12.9</td>
<td>$\sim 3.5-5 \times 10^3 \text{ n cm}^{-2} \text{ s}^{-1}$ for max 1-3 $\mu$A</td>
</tr>
<tr>
<td>CYRIC (Japan)</td>
<td>14-80</td>
<td>1.2</td>
<td>$10^6 \text{ n cm}^{-2}$ for 3 $\mu$A</td>
</tr>
<tr>
<td>RCNP (Japan)</td>
<td>100-400</td>
<td>10</td>
<td>$10^4 \text{ n cm}^{-2} \text{ s}^{-1}$ for 1 $\mu$A</td>
</tr>
<tr>
<td>ANITA (Sweden)</td>
<td>25-200</td>
<td>3.73</td>
<td>$\sim 3 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ for max 5-10 $\mu$A</td>
</tr>
<tr>
<td>NFS (France)</td>
<td>1-40</td>
<td>5</td>
<td>$\sim 8 \times 10^7 \text{ n cm}^{-2} \text{ s}^{-1}$ for 50 $\mu$A, 40 MeV</td>
</tr>
<tr>
<td>iTHEMBA (South Africa)</td>
<td>25-200</td>
<td>8</td>
<td>$1-1.5 \times 10^4 \text{ n cm}^{-2} \text{ s}^{-1}$ for typical 3 $\mu$A</td>
</tr>
<tr>
<td>QMN (LNL) <strong>PROPOSED</strong></td>
<td>30-70</td>
<td>3</td>
<td>$\sim 2.6 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ for 10 $\mu$A, 70 MeV</td>
</tr>
</tbody>
</table>
- Multi-disciplinary interest

- Energy dependent neutron-induced effects
  (e.g. measure the cross-section vs energy curve)

- Quasi ideal to study energy dependence
  - not 100% mono-energetic
  - strong angular dependence can be used to subtract away the wrong energy neutrons

QMN concept:
- Thin (few mm) lithium or beryllium target;
- Bending magnet to deflect emerging proton towards a beam dump;
- Collimator.
The “good” truly mono-energetic neutrons are produced mainly in the direction of the proton beam (forward, $\theta = 0$); wrong-energy neutrons are not as directional.

Kamata S., Itoga T., Unno Y., Baba M. (CYRIC ANNUAL REPORT 2005)

Wrong energy tail correction

- The corrected 0° peak with Li is sharper and closer to the proton beam energy.
- 30° subtraction works for both Li and Be with 70 MeV protons.

E_{proton} = 70 MeV
Correction of 0° data using 30° data.

\[ \phi_0^\text{corr}(E) = \phi_0(E) - A\phi_{30}(E) \]
The favorite material as QMN target is Li, only if the heat generated by the energy deposited by the beam is efficiently evacuated. When more than few tens of watts are deposited, a Be target is a simpler solution, at the price of a long cooling time of the activated material (also due to impurities).

<table>
<thead>
<tr>
<th></th>
<th>Li</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>180</td>
<td>1287°C</td>
</tr>
<tr>
<td>Thermal conduct.</td>
<td>85</td>
<td>190 W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Machining</td>
<td>easier</td>
<td>difficult</td>
</tr>
<tr>
<td>Reactivity to air</td>
<td>higher</td>
<td>lower</td>
</tr>
<tr>
<td>Toxicity</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Cost</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Neutron yield</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Neutron energy distribution</td>
<td>narrower</td>
<td>larger</td>
</tr>
<tr>
<td>Residual activity decay</td>
<td>shorter</td>
<td>longer</td>
</tr>
<tr>
<td>Suffers swelling from implanted H</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
Wrong-energy tail correction

The number of neutron-induced effects due to forward going neutrons can be corrected by subtracting the number of effects at angles (typically in the 15°-30° range).

• flexibility: adjustable angles
• but challenging to design magnet/target system

RIKEN-like movable collimator
true QMN at NEPIR

- layout in SPES building
- layout detailed
- table of costs
NEPIR experimental hall

Completed SPES infrastructure

NEPIR

SPES lab underground level floor plan

SPES

Radioisotope R&D and production

Existing (empty) NEPIR experimental hall
NEPIR: QMN layout
NEPIR: QMN layout (detail)
### NEPIR: QMN system cost

#### Fixed cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (k€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Services (electricity, water cooling, compr. air, conditioning...)</td>
<td>61</td>
</tr>
<tr>
<td>Access control system</td>
<td>18.3</td>
</tr>
</tbody>
</table>

#### QMN beam hardware

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (k€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum system and control</td>
<td>48.8</td>
</tr>
<tr>
<td>Concrete bunker</td>
<td>85.4</td>
</tr>
<tr>
<td>2 quadrupoles</td>
<td>195.2</td>
</tr>
<tr>
<td>QMN target system</td>
<td>61</td>
</tr>
<tr>
<td>QMN bending magnet (deflecting to beam dump)</td>
<td>152.5</td>
</tr>
<tr>
<td>QMN beam dump</td>
<td>18.3</td>
</tr>
<tr>
<td>Activated air management system (bunker depressuration)</td>
<td>61</td>
</tr>
<tr>
<td>Beam diagnostics for QMN (F.cup, wire monitor, control)</td>
<td>24.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>725.9</strong></td>
</tr>
</tbody>
</table>

Not included: manpower and proton energy degrader (30 -> 20 MeV)
pseudo-QMN

- layout
- thick Be white neutron spectra
- pseudo-QMN spectra
- thermal mechanical details of thick target
- shielding calculations
- table of costs
Layout of the NEPIR Phase 0 facility: a thick Be (28 mm) white spectrum source will exploit the shielding of the cyclotron hall to minimize the construction of additional shielding. The maximum proton current will be 1 µA. The direct proton beam line will be completed in a second moment.
**NEPIR: Thick Be white neutron spectra at different proton energies**

**Be 27 mm, different proton energies**

Neutron spectra (simulated with MCNP) at test point for different energies of the impinging proton beam.

**Comparison of the neutron spectra generated by 70 MeV protons and 60 MeV protons (rescaled by a factor 1.15).**

Maximum flux at closest test point: $3 \times 10^6$ N/cm$^2$ /s, with 1 µA of 70 MeV protons.

The difference between neutron spectra at different energies returns a quasi-rectangular neutron energy distribution with controllable width, down to few MeV.
NEPIR: thick Be target ANSYS calculations

Power = 70W
Be $T_{\text{max}} = 199^\circ$C
Be melting point: 1287°C.

Air cooling:
$v = 5$ m/s
$T = 20^\circ$C
NEPIR: thick Be target cooling fins performance

ANSYS CFX results for a target provided of cooling fins with different orientations.

Maximum Temperature = 138°C

ANSYS static structural result: total deformation due to thermal dilatation: 0.14 mm

Maximum Temperature = 127°C
The beam-stopping target is a Be core, 28 mm thick, with an aluminum cladding, located inside the conduit between the cyclotron hall and hall A9. It is provided of a forced-air cooling system.
Prompt ambient equivalent dose rate [µSv/h] delivered by thick (28 mm) Be target with a proton beam current of 1 µA.

The dose delivered to the cyclotron hall is one of the factor driving the choice of the target position.

The air activation in hall A9 limits the proton beam current to 1.5 µA when the full length of the beam path is used.

The target is located inside the conduit between the cyclotron hall and hall A9 (exact position to be determined)

Equivalent dose: in beam: ~10^5 µSv/h far from beam: several µSv/h
The construction could start in 2019, beam characterization could be completed by 2020, first beam to users by the end of 2020 or in 2021.
**Atmospheric Neutron EMulator**

**ANEM**

Neutrons in cosmic ray air-showers are a widening problem for Industry:
- Aviation
- Automotive
- Trains
- Information technology and Infrastructure
- Medical (e.g. pace makers,...)

“Radiation induced single events could be happening on everyone’s PC, but instead everybody curses Microsoft.”

*Paul Dodd, Sandia National Laboratories*
Energy distribution of fast (E>1MeV) neutrons at sea level

Data points by Gordon (2004), sea level, New York city, outdoors, mid-level Solar activity
JEDEC fit 1989 dashed
JEDEC fit 2006 continuous

\[ \Phi_n(E>1\text{ MeV}) = 21 \text{ n cm}^{-2} \text{ hr}^{-1} (*) \]

Of these:
- 42% are in 1-10 MeV range
- 47% are in 1-20 MeV range
- 65% are in 1-65 MeV range

(**) At flight altitudes the flux shape is similar, but \( \sim 300 \) times more intense.

The standard reference spectrum used by the JEDEC Solid State Technology Association, an independent semiconductor engineering trade organization and standardization body.

Typical value for SEU
\[ \sigma_{\text{Plateau}} = 10^{-14} \text{ cm}^2/\text{bit} \]
gives a low SEU rate
\( \sim 32 \text{ SEU} / (\text{month} \cdot 64 \text{ GByte}) \)

Boring! I need to speed these tests up... I want an accelerator!

(*) At flight altitudes the flux shape is similar, but \( \sim 300 \) times more intense.
The neutron differential energy spectra at accelerator electronic test facilities used for accelerated neutron SEE testing. The **JEDEC reference spectrum** is the black curve multiplied by an *acceleration factor* $F = 10^9$.

Using SPES 70 MeV protons, $I_{\text{proton}} \sim 10 \, \mu\text{A}$ ($P<1\,\text{kW}$)
A novel rotating, composite, high power target made of thick Be and W. A W disk and a Be circular sector rotate on a common water cooled hub and alternatively intercept the beam. The effective atmospheric-like neutron spectrum in the 1-65 MeV range is composed directly, without the use of moderators.

The target is designed to tolerate a maximum current $I_{\text{beam}} = 30 \, \mu\text{A (2.1 kW)}$, delivering at a distance of 6 m, a flux of neutrons ($E = 1\text{-}65 \, \text{MeV range}$) $\sim 10^9$ times the natural one, comparable with the highest factor to be used at Chip-IR facility.

(*) The Be sector does not stop the protons (to avoid damage); most of the protons pass through without causing nuclear reactions. The emerging low energy protons are stopped by the W disk.
The combination of 20% Be spectrum and 80% W spectrum yields the best fit of the atmospheric spectrum, without use of moderation.

The delivered **neutron flux is** $1.7 \times 10^6$ cm$^{-2}$ s$^{-1}$ (at 3 m for a 1 µA proton current), corresponding to an acceleration factor of $3 \times 10^8$. 

![Neutron flux graph](image-url)
CONCLUSION

- The **basic design** of the NEPIR facility, its beam-optics, and different neutron production target systems are defined; shielding calculations are nearly completed;

- A design of a **Phase-0 version** of the facility, with a white spectrum target that can be exploited for pseudo-QMN analysis was developed. The funding of the LNL work-package of the SPARE project is sufficient for this solution;

- The design of a more expensive **true-QMN** is in advanced stage, but present funds are not sufficient. Discussions within the SPARE collaboration are under way to evaluate benefit-cost ratio;

- An **ANEM prototype** exists, with an aluminum test disk and an electron gun system (under commissioning) for thermal tests to be completed in the next months.
The end

Thank you for your attention

Extra slides follow
Extra slides
QMN alternative layout (detail)
A vertical magnet is used to deflect the exiting proton beam towards a beam dump inside the slanted conduit.

A small bunker isolates the QMN target from the cyclotron hall.
High current QMN

Main limitation comes from the power sustainable from the target. R6D needs to improve the cooling system.

Avevo fatto dei calcoli ansys e dovresti avere qualche figura da mettere.