HEALTH RISKS FROM EXPOSURE TO FAST NEUTRONS

Prof. Marco Durante
Risk from neutrons

- Risk from exposure to fission spectrum neutrons has been extensively studied in the 60’s at nuclear reactors using animal models and epidemiology data.
- It is fair to say that it is the worst radiation type in terms of late effects.
Late risks: carcinogeensis


Dose rates: 4.2 rad/min to 552 rad/min
“how much” or when”?

Pulmonary Tumors in B6CF₁ mice
(Fry et al., Env. Int. 1, (1972))

Mortality Rate/10,000 Mice/Day

Controls
80 rad
(3.3x24 fract.)
240 rad
(10x24 fract.)
80 rad
(acute)
Neutron quality factor

\[ H_T = \sum w_R D_{T,R} \]

\[ E = \sum w_T H_T \]
Radiotherapy and SMN

- Cancer survivors represent about 3.5% of US population
- Second primary malignancies in this high-risk group accounts for about 16% of all cancers
- Three possible causes: Continuing lifestyle; Genetic predisposition; treatment of the primary cancer (SMN)

CCSS study, St. Jude et al. 2008-2015
Retrospective cohort of 14,000 survivors of childhood cancer diagnosed between 1970 and 1986
Fast neutrons: second cancers in radiotherapy

Application of new radiation treatment modalities

IMRT
Substantial increase in beam-on time

Hadron therapy
Neutron production

Increased cancer cure rates are

Increased number of secondary
Neutron spectra in radiotherapy

- Quasi-elastic peak (particle therapy)
- Evaporation peak (high-energy X-ray therapy)

18 MV X-rays, 5x5 cm² field, BDS
Direction: GT, Energy: 18 MV
Field size: 5x5 cm²

- Highest neutron fluence and mean energy measured infield at the surface
- All out-of-field spectra peak at 1 MeV
- Most of the neutrons are produced in the accelerator head rather than in water

Neutrons are the major contributors to the equivalent dose measured outside the field at the surface, but negligible at 10 cm depth.

Neutrons produced by charged particles

- Highest production of slow neutrons for photons
- Passive delivery enhances the production of slow neutrons compared to scanned beams
- Scanned carbon ions produce the lowest amount of low-energy neutrons

Secondary Malignant Neoplasms (SMN) in particle therapy

Comparison of relative radiation dose distribution with the corresponding relative risk distribution for radiogenic second cancer incidence and mortality. This 9-year old girl received craniospinal irradiation for medulloblastoma using passively scattered proton beams. The color scale illustrates the difference for absorbed dose, incidence and mortality cancer risk in different organs.

Newhauser & Durante, 
Neutrons in space: LEO

- Dose contribution: 5-15%
- Dose equivalent contribution: 20-50%
- Spectra by Bonner balls (ISS) or nuclear emulsions (Mir)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Altitude (km)</th>
<th>Neutron dose rate (μGy/day)</th>
<th>Charged particle dose rate (μGy/day)</th>
<th>Neutron equivalent dose rate (μSv/day)</th>
<th>Charged particle equivalent dose rate (μSv/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-55</td>
<td>302</td>
<td>5.9</td>
<td>57.2</td>
<td>52.0</td>
<td>120.1</td>
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<tr>
<td>STS-57</td>
<td>470</td>
<td>25.3</td>
<td>461.9</td>
<td>220.0</td>
<td>859.4</td>
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<tr>
<td>STS-65</td>
<td>306</td>
<td>11.0</td>
<td>75.2</td>
<td>95.0</td>
<td>157.8</td>
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<tr>
<td>STS-94</td>
<td>296</td>
<td>3.7</td>
<td>101.5</td>
<td>30.8</td>
<td>213.9</td>
</tr>
</tbody>
</table>
Neutrons in space: MSL

### Energy Coverage

- **p,He**
- **ions (Li-O)**
- **ions (Mg-Fe)**
- **neutrons**
- **γ-rays**
- **electrons**
- **positrons**

### Radiation Assessment Detector
Mars Science Laboratory

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<table>
<thead>
<tr>
<th>Condition</th>
<th>GCR dose rate (mGy/day)</th>
<th>GCR dose-equivalent rate (mSv/day)</th>
<th>Inspiration Mars (Sv)</th>
<th>Mars sortie (Sv)</th>
<th>Mars base (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSL cruise (Zeitlin et al., 2013)</td>
<td>0.46</td>
<td>1.84</td>
<td>0.92</td>
<td>0.7</td>
<td>0.98</td>
</tr>
<tr>
<td>MSL on Mars (Hassler et al., 2014)</td>
<td>0.21</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neutrons in RAD

- Stopping Ion (accepted)
- Neutron (accepted)
- Ion (rejected)
- γ-ray (accepted)
- Recoil proton
- Neutron (accepted)

RAD Shielding in Cruise Configuration

Depth [g/cm²] aluminum equivalent

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
Neutrons in deep space

Dose rate and dose equivalent rate for the calculated neutron spectrum. The measurement covers an energy range of 12–436 MeV, the simulation extends this range to 0.1–1000 MeV.

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
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<tr>
<td>Dose equivalent rate</td>
<td>19 ± 5 μSv/day</td>
<td>30 ± 10 μSv/day</td>
</tr>
<tr>
<td>Dose rate</td>
<td>3.8 ± 1.2 μGy/day</td>
<td>6 ± 2 μGy/day</td>
</tr>
</tbody>
</table>

Charged particle dose-rate 1840 μSv/day

Koehler et al., Life Sci. Space Res. 2015
Neutrons on Mars

Dose equivalent rate $= 61 \pm 10 \mu\text{Sv/d}$

$Doserate : 14 \pm 3 \mu\text{Gy/d}$

Charged particle dose-rate $640 \mu\text{Sv/day}$

Koehler et al., J. Geophys. Res. 2014
There is greater concern about high-energy neutron fields owing to the increasing number of high-energy accelerators in research and medicine and the special consideration given to the occupational exposure to cosmic radiation. In order to study the physics of neutron interactions in these applications, in particular concerning dosimetry, radiation protection monitoring of workplaces, and radiation effects in electronics, particularly those used in aircraft and in spacecraft, well-characterized neutron fields for high energies are needed.

- Louvain, Belgium: closed
- Uppsala, Sweden: closed
- NPI, Czech Republic: max 30 MeV
- NFS, Ganil, France: under construction, max 40 MeV

QMN beams with energies above 40 MeV will be available only in South Africa and Japan, with none in Europe.
A QMN FN facility at the TIFPA facility
Sala sperimentale

Laboratorio multifunzionale
Isochronous cyclotron

235 MeV max proton energy

300nA beam current

Typical efficiency: 55%

Conventional magnet coil: 1.7-2.2T (fixed field)

RF frequency: 106 MHz (fixed frequency)

Approx weight: 220 tons

Diameter: 4.3m
$^{7}$Li(p,n)$^{7}$Be TOTAL REACTION CROSS SECTION

$\ln \sigma = -1.13 \ln E_p + 7.05$

QMN neutron energy spectra measured at iThemba, South Africa
Possible configurations in TIFPA-Trento

Proton beam bent in the second line after the Li target, e.g. CYRIC, Japan

Proton beam in a carbon disc after the Li target, e.g. NPI, Czech Republic
Conclusions

• Fission-spectrum neutrons have very well characterized biological properties, and high REB for late effects
• Fast neutrons are less effective, but poorly studied
• They are very important for protection at accelerators, patients of particle therapy, and space travel
• At the moment there are no facilities for QMN FN in Europe
• A project has been launched at TIFPA in Trento
Thank you very much!