Neutron spectroscopy for Boron Neutron Capture Therapy Beams Characterization

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on behalf of Enter_BNCT collaboration
BNCT is a radiation therapy based on the capture of thermal neutrons in B-10 atoms selectively accumulated in tumor cells.
Boron Neutron Capture Therapy

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Neutron Beams for BNCT

- Epithermal neutron beams generated by accelerator based neutron sources or by nuclear reactors through customized beam shaping assemblies.
- The neutron energy spectrum is continuous and its shape determines the depth of maximum efficacy in the tissue.
- Instruments to measure the neutron dose and the neutron fluence with high precision are demanded (full spectrum coverage over about 8 order of magnitude).

INFN developed NCT-WES and NCT-ACS for the beam characterization and QA.
NCT-WES

Neutron Capture Therapy Wide Energy Spectrometer
NCT Wide Energy Spectrometer

Single moderator, directional, real time, neutron spectrometer for beam characterization and periodical QA

MAIN CHARACTERISTICS:

- **Bonner Spheres concept** but single exposure
Bonner Spheres Spectrometer: main aspects

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- Covers thermal to GeV energy range
- Isotropic response
- Simple operation
- Very accurate → the fluence in large energy intervals can be determined with <5% unc.
- Detector can be changed to match the field in terms of intensity and photon component
- Resolving power is limited by the shape of the response functions

- Sequential irradiations – time consuming – unsuited for real time monitor

Solved by single moderator spectrometer
All the detectors work simultaneously

The response function depends on the position inside the moderator
Single moderator, directional, real time, neutron spectrometer for beam characterization and periodical QA

MAIN CHARACTERISTICS:

- 0.01 eV-10 MeV energy sensitivity range
- Cylindrical collimator for minimizing the room scattered component
- 6 neutron sensitive silicon detectors simultaneously read by a 6 channel DAQ system
- Weight 40 kg, length 41.5 cm, external diameter 36 cm.
NCT Wide Energy Spectrometer

TNPD – thermal neutron pulse detectors

1-cm² Si-diode covered by 30 μm $^6$LiF

Slightly biased to improve noise gamma rejection

Custom multi-detector analog board (charge preamp. + shaper amp.)

Digital elaboration using commercial digitizer and laptop
The energy spectrum is obtained by measuring thermal neutrons at 6 different depths. MCNP6 simulations are used to calculate the Response Matrix and optimize the geometry to obtain the best response in the epithermal energy range.
1. Every inner detector calibrated in the thermal neutron reference field of HOTNES (moderated Am-B source @ LNF-ENEA Frascati)

\[ \varepsilon_{TNPD} = \frac{\dot{N}_{\text{Experiment}}}{\dot{N}_{6\text{Li}(n,\alpha)^3H}} = (23.8 \pm 0.4)\% \]

2. NCT-WES test at the AmBe reference neutron field at PoliMi  Response matrix validation
3. Response matrix validation at monoenergetic neutron beams at NPL (UK)

\[ R_{\text{exp}} = \frac{C_{\text{tot}}}{N_{\text{tot}}} - \frac{C_{\text{cone}}}{N_{\text{cone}}}, \]

- \( C_{\text{tot}}, C_{\text{cone}} \) counts without and with the shadow cone
- \( N_{\text{tot}}, N_{\text{cone}} \) monoenergetic neutrons emitted by the target as if they were isotropically distributed, without and with the shadow cone.

\[ \frac{R_{\text{i, sim}}}{R_{\text{i, exp}}} @ 841.9 \text{ keV} \]

| P1 | 1.03 ± 0.04 |
| P2 | 1.00 ± 0.04 |
| P3 | 1.04 ± 0.04 |
| P4 | 0.98 ± 0.04 |
| P5 | 1.04 ± 0.04 |
| P6 | 0.99 ± 0.04 |

- Accuracy of the response matrix
- Minimal energy and detector dependance (Distribution of all the ratios within 4%, average 1.002±0.008)

Neutron beams obtained by a 3.5 MV Van De Graaf proton accelerator on 7Li or Tritium target

71.5 keV, 144.2 keV, 565.1 keV, 841.9 keV, 1200.4 keV

Low scatter irradiation room at NPL. NCT-WES exposed at 0° with the shadow cone.

“Measuring the near-target neutron field of a D–D fusion facility with the novel NCT-WES spectrometer»
R. Bedogni et al.
NCT-ACS

Neutron Capture Therapy Activation Compact Spectrometer
NCT Activation Neutron Spectrometer

Small, passive detector for in phantom measurement of the neutron field with spectrometric capability.

Based on activation foils $\rightarrow$ $n,\gamma$ absorption resonances in the epithermal range

Different elements show resonances at different energies $\rightarrow$ quantitative analysis of the activation gives information about the neutron energy through an unfolding procedure.

Phase 1: Foil irradiation with neutrons.

Phase 2: Gamma analysis with a HPGe detector.

<table>
<thead>
<tr>
<th>Au</th>
<th>$n$</th>
</tr>
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Graph: Cross section (barns) vs. Energy (MeV)

- Total
- Absorption
- Elastic
- Gamma production

NCT-ACS
NCT ACS geometry

Elements selection criteria:

- Resonance energy
- $t_{1/2}$ of the activated nucleus
- Energy and B.R. of the $\gamma$ decay
- Decay chain
- $\gamma$ spectrum complexity
- Cross section for n-capture
- Toxicity

Small moderator to improve the response curves shapes

Cadmium cover to suppress the response in the thermal range

Without moderation -> sharp peaks -> unsuited for unfolding

With moderation

Credits to Ettore Mafucci
Gamma activation analysis is performed with an **HPGe detector**

Energy and efficiency calibration performed using **calibrated sources** (\(^{152}\text{Eu},^{60}\text{Co},^{137}\text{Cs},^{133}\text{Ba},^{22}\text{Na}\)).

Efficiency function  
\[ \ln \varepsilon = \sum_{j=0}^{n} a_j (\ln E)^j \quad n=3. \]

![Efficiency graph](image)

\[ \chi^2 / \text{ndf} = 5.222 / 13 \]

\[
\begin{align*}
p0 & = 15.07 \pm 0.1386 \\
p1 & = -8.929 \pm 0.03091 \\
p2 & = 1.39 \pm 0.004478 \\
p3 & = -0.07918 \pm 0.0004804
\end{align*}
\]

Measurements positions:
1. \(2.0 \pm 0.1 \text{ mm (at contact)}\)
2. \(10.0 \pm 0.1 \text{ cm (at distance)}\)

Thickness: \(30 - 500 \mu\text{m}\)

Diameter: \(10 - 12.5 \text{ mm}\)

Sources placed at 10 cm from the detector face in order to minimize the error induced by the finite dimension of the foils.

The activity of each element + response matrix

Unfolding code

Neutron energy spectrum reconstruction

Credits to Ettore Mafucci
NCT ACS analysis

Test @ the 18 MV Linac based epithermal neutron source in Torino [1]

Comparison with a calibrated Bonner Sphere System neutron spectrometry

Conclusions

Two neutron spectrometers have been developed to fulfill the BNCT beam quality assurance.

NCT-WES allows real time measurements of neutron beam spectra with a single exposure and with good rejection of the room-scattered component. Accuracy below 5%

NCT-ACS is a passive device, its small dimensions and isotropical response allow its use for in phantom measurements.

Both instruments have been succesfully tested in different neutron fields and have prooved to be able to give accurate results.
\[ \varepsilon_{contact}^{Ge} = \varepsilon_{10cm}^{Ge} \times F_{geom} \]

- \( \varepsilon_{10cm}^{Ge} \) is the saturation activity measured at 10 cm.
- \( F_{geom} \) is the ratio between the saturation activity measured at contact and at 10 cm.

The assumption is that at 10 cm the point source like approximation is good enough.

**Measurements positions:**
1. \( 2.0 \pm 0.1 \) mm (at contact)
2. \( 10.0 \pm 0.1 \) cm (at distance)
NCT Wide Energy Spectrometer

- a: polyethylene collimator
- b: polyethylene moderator block containing the neutron detectors

Dimension:
- Length 41.5 cm
- External diameter 36 cm
- Inner collimator diam 12 cm
- Weight 40 kg

Dedicated electronic and Labview acquisition software

Borated rubber to shield from thermal neutrons