Use of TEPCs for characterising BNCT Beams

Stuart Green

Mark Gainey (PhD, 1999-2002), Helen Howard (MSc 2003), Cecile Wojnecki (PhD 1998 -2002)
The diagram illustrates an interaction involving neutrons, boron, lithium, and gamma radiation. Incident epithermal neutrons react with boron-10 ($^{10}\text{B}$) to produce boron-11 ($^{11}\text{B}^+$) and an alpha particle ($\alpha$) with an energy of 1.47 MeV ($E_\alpha = 1.47 \text{ MeV}$). The reaction time is approximately $10^{-12}$ seconds ($t \sim 10^{-12} \text{s}$). Following the reaction, lithium-7 ($^7\text{Li}$) is produced with a lower energy of 0.84 MeV ($E_{^7\text{Li}} = 0.84 \text{ MeV}$). The gamma radiation ($\gamma$) is emitted with an energy of 0.48 MeV ($E_\gamma = 0.48 \text{ MeV}$) in 94% of the cases (94%).
The Medical Physics Building in Birmingham

Dynamitron

Cyclotron vault

Li target, Beam moderator / shield

Protons

Neutrons
The beam moderator / shield

- scanned proton beam
- shield
- graphite reflector
- FLUENTAL Moderator / shifter
- Li target
- lead filter
- heavy water cooling circuit
The actual treatment facility

- Proton beam-tube
- Heavy water reservoir
- FLUENTAL™ moderator
- Li-polythene delimiter / shield
- Heavy water inlet
- To pumps / chiller

Neutron source is $> 1 \times 10^{12} \text{ s}^{-1}$
Dose components

In agreement with IAEA TECDOC-1223

- Photon dose $D_g$
- Neutron dose $D_n$
- Nitrogen dose $D_p$
- Boron dose $D_B$

The standard dosimetric formalism uses these physical dose components with each one combined with a biological weighting factor (related to RBE) to form a weighted dose (units are still Gy)
Dose components in the Birmingham Beam

Assuming $^{10}$B at 15 µg/g, N at 2.2% and “usual” RBE/CBE factors
Dosimetry in BNCT

- EU working group has produced recommendations, defining methods and standard reference conditions
- Standard Reference Dosimetry - use of twin ionisation chamber technique
- Disadvantage of this technique - uncertainty for neutron dose varies up to $\pm 40\%$ at 95\% C.L.
- Secondary method - TEPCs
Exradin (above) and Far West Mg(Ar) chambers with caps used to produce charged particle equilibrium free-in-air
Formalism for ion chamber response

\[ N_{D,W,u} Q_u = h_u D_g + k_u D_n + k'_u \phi_0 \]

\[ N_{D,W,t} Q_t = h_t D_g + k_t D_n + k'_t \phi_0 \]

The formalism makes explicit the separation of the signal due to thermal neutrons events on the response of the chambers.
Formalism for ion chamber response

\[ N_{D,W,u} \ Q_u = h_u \ D_g + k_u \ D_n + k'_u \ \phi_0 \]

\[ N_{D,W,t} \ Q_t = h_t \ D_g + k_t \ D_n + k'_t \ \phi_0 \]

From photon calibration and M/C simulation

From M/C calculation

From thermal fluence calibration
Gas flow system and check-source
Ionisation chamber with $^6\text{Li}$ cap in the centre of the BITNIF facility (LFR Petten)
Problems with the ionisation chamber method

• **Complexity**
  – a wide range of calibration fields are needed
  – Detailed Monte Carlo studies are needed to interpret each measurement

• **Uncertainties**
  – Solution of the simultaneous equations inevitably leads to the subtraction of 2 very similar numbers
  – Uncertainty at shallow depths estimated to be more than +/- 30 % at 95% CL
  – Slight instabilities in chambers easily lead to reporting of negative neutron doses at depths in excess of 5 cm
TEPC Microdosimetry

- TEPC Microdosimetry is concerned with the energy imparted to a material in a single ionising event.
- Data is measured as a spectrum of pulse heights from each individual event in the detector.
- Recoil protons and other particles which result from neutron interaction produce large pulses in the detector.
- Recoil electrons resulting from photon interactions produce relatively small pulses in the detector.
Processed detector response in an epithermal neutron beam (FIR-1, Helsinki)
A preliminary in-phantom dosimetry intercomparison using TEPCs and ICs performed at the FiR 1 reactor in Finland.


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4Department of Radiology, Helsinki University Hospital, Helsinki, Finland, and
5Radiation and Nuclear Safety Authority, STUK, Helsinki, Finland.
Detectors ....

- 0.5" diameter spherical single wire TEPC, one commercial and one constructed at Birmingham University
- 2 µm simulated site diameter with propane TEG
- Detectors filled in Birmingham and transported by courier to Helsinki
- Pre-amplifiers carried from Birmingham to Helsinki
- Standard nuclear electronics used from the Helsinki group
Neutron component of the TEPC spectra at 2 depths
Dosimetry Formalisms

**Photons**

\[ D^b_{\gamma} = D^g_{\gamma} \cdot S_{gA150} \cdot \left( \frac{\mu_{en}}{\rho} \right)^b_{A150} \]

**Neutrons**

\[ D^b_n = D^g_n \cdot S_{gA150} \cdot K^b_{A150} \]
## Correction Factors

<table>
<thead>
<tr>
<th>Correction</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\mu_{en}/\rho)$ brain to A150 at 2.2 MeV</td>
<td>$1.034 \pm 0.007$</td>
<td>Gainey (2002)</td>
</tr>
<tr>
<td>Kerma brain to A150</td>
<td>$0.693 \pm 0.003$</td>
<td>Gainey (2002)</td>
</tr>
<tr>
<td>$S_{A150}$ to TEG (electrons)</td>
<td>0.971</td>
<td>Gainey (2002)</td>
</tr>
<tr>
<td>$S_{A150}$ to TEG (protons)</td>
<td>0.975</td>
<td>Burmeister (1999)</td>
</tr>
<tr>
<td>$S_{A150}$ to TEG (alphas)</td>
<td>0.977</td>
<td>Burmeister (1999)</td>
</tr>
<tr>
<td>W-value elects to protons</td>
<td>0.96 ± 0.01</td>
<td>Bronic (1997)</td>
</tr>
<tr>
<td>W-value alphas to protons</td>
<td>0.99 ± 0.01</td>
<td>Bronic (1997)</td>
</tr>
<tr>
<td>Source of error</td>
<td>Probability distribution</td>
<td>divisor</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>--------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>$N_c$ beam</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>Positional accuracy</td>
<td>rectangular</td>
<td>$\sqrt{3}$</td>
</tr>
<tr>
<td>Scaling $10\mu A \rightarrow 2mA$</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>Proton edge estimation</td>
<td>rectangular</td>
<td>$\sqrt{3}$</td>
</tr>
<tr>
<td>Proton edge energy</td>
<td>rectangular</td>
<td>$\sqrt{3}$</td>
</tr>
<tr>
<td>Gamma subtraction</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>W-value</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>Mass of gas in cavity</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>Measured charge</td>
<td>rectangular</td>
<td>$\sqrt{3}$</td>
</tr>
<tr>
<td>Perturbation by detector</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>$h_i$</td>
<td>normal</td>
<td>1</td>
</tr>
<tr>
<td>Total (expanded)</td>
<td>normal</td>
<td></td>
</tr>
</tbody>
</table>

1 Aro, A.C. Microdosimetry Relevant to Neutron and Proton Cancer Therapy up to 62MeV, Ph.D. Thesis, Birmingham University, 1992.
3 ICRU36, Microdosimetry, Bethesda, 1983.
Neutron dose as a function of depth, Epithermal FIR-1 beam in Helsinki
Results for the BNCT beam in Helsinki

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Neutron brain kerma</th>
<th>Photon brain kerma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TEPC/MCNP</td>
<td>TEPC/IC</td>
</tr>
<tr>
<td>32</td>
<td>0.98 ± 0.16</td>
<td>1.15 ± 0.28</td>
</tr>
<tr>
<td>50</td>
<td>1.02 ± 0.17</td>
<td>0.98 ± 0.23</td>
</tr>
<tr>
<td>75</td>
<td>1.03 ± 0.17</td>
<td>0.99 ± 0.24</td>
</tr>
<tr>
<td>125</td>
<td>0.98 ± 0.17</td>
<td>1.80 ± 0.43</td>
</tr>
</tbody>
</table>
Reference photon dosimetry

<table>
<thead>
<tr>
<th>Nuclide (Energy)</th>
<th>True Air Kerma (µGy/hr)</th>
<th>Measured Air-kerma (µGy/hr)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{137}$Cs (660 keV)</td>
<td>1160 ± 50</td>
<td>1020 ± 190</td>
<td>0.88 ± 0.17</td>
</tr>
<tr>
<td>$^{241}$Am (60 keV)</td>
<td>54.6 ± 2.2</td>
<td>53.2 ± 6.5</td>
<td>0.97 ± 0.13</td>
</tr>
</tbody>
</table>

All uncertainties at the 95% CL
Mini TEPC Microdosimeter

• Disadvantage of the TEPC currently being used - limited to low intensity neutron beam.

• Mini TEPC avoids the problem of pulse pile-up by reducing the active volume

• Designed by a former PhD student Mark Gainey construction needs to be completed
Mini Microdosimeter
In-phantom characterisation studies at the Birmingham Accelerator Generated epIthermal Neutron Source (BAGINS) BNCT facility

Chris Culbertson, Stuart Green, Anna Mason, David Picton, Gareth Baugh, Richard Hugtenburg, Zaizhe Yin, Malcolm Scott, John Nelson
In-phantom dosimetry

Leads to beam monitor chambers

Ionisation chamber

Reference water phantom (40 x 40 x 20 cm)

12 cm beam aperture
Independent Dosimetry validation in the Birmingham Beam (Helen Howard MSc)

![Graph showing Physical Dose in A150](image)

Graph legend:
- **TEPC - total neutrons**
- **TEPC - photons**
- **Ion chamber + foils neutrons**
- **Ion chamber photons**
TEPC Work - what’s next?

• Complete construction and testing of miniature detector
• Obtain funding for some kind of beam inter-comparison (as has been performed for neutron therapy beams)
• Work towards a beam quality specification for epithermal beams for BNCT
TEPCs - Not just for dosimetry?

Data from a previous generation (90 degree D₂O moderated) epithermal beam in Birmingham
Biological weighting function – derivations of an RBE value for epithermal neutron beams

Function taken from:
Summary

• TEPCs offer a route to lower measurement uncertainty for neutron dose measurement in epithermal neutron beams
• Measurements are relatively simple and straightforward
• Miniature detectors are necessary for measurements at full therapy beam powers
• More work to do on accuracy of gamma dose determination
BNCT beam dosimetry – what’s next?

• We have a number of excellent review documents (eg from IAEA and EU group)
• We have an ongoing (and expanding) programme of intercomparisons thanks to leadership of the MIT group
• Following the EU recommendations, an intercomparison of thermal calibration facilities is needed
• We should be working towards an ICRU report of beam dosimetry for BNCT
# Estimated Treatment Times

<table>
<thead>
<tr>
<th>Beam</th>
<th>Boron (µg/g)</th>
<th>Weighted Dose (Gy)*</th>
<th>Total time (1 field)</th>
<th>Approx time (2 fields)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 2003 (1mA)</td>
<td>15</td>
<td>13.5</td>
<td>240</td>
<td>430</td>
</tr>
<tr>
<td>Aug 2004 (1.5 mA)</td>
<td>15</td>
<td>13.5</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>Dec 2003 (1mA)</td>
<td>24</td>
<td>13.5</td>
<td>190</td>
<td>340</td>
</tr>
<tr>
<td>Aug 2004 (1.5 mA)</td>
<td>24</td>
<td>13.5</td>
<td>110</td>
<td>200</td>
</tr>
</tbody>
</table>

*Dose is assumed to be prescribed at 3 cm deep*
In air measurements – neutron fluence

![Graph showing normalized 235-U fission counts vs. off-axis position (cm).]
Measurements compared with MCNP (Physical doses)

![Graph showing physical dose in Gy/MU vs. depth in cm compared with MCNP calculations. The graph includes data points for Dg, N 2.2%, and fast n. The MCNP calculations are represented by solid lines, while the data points are shown with markers.]
Photons - Mass energy absorption coefficients

![Graph showing mass energy absorption coefficients for different materials.](image_url)
Neutron kerma factors

- Brain
- Lung
- Liver
Kerma Correction Factors

Kerma Correction Factor using MCNP (Full Geometry)

Depth (mm)

Kerma Correction Factor
Gas Filling Rig

- Propane based TE gas cylinder
- Detector attached here
- Vacuum Gauge
- Rotary Pump
- Pressure Gauge
- Diffusion Pump