Activation Products in Proton Therapy

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Topics

• General considerations
• Determination of activation cross sections
• Beam collimator activation
• Long-lived activation products in biologically relevant elements
• Formation of short-lived $\beta^+$ emitters in human tissue
• Conclusions
General Considerations

- For therapy purposes, well collimated proton beams are needed.
- Proton energy is tailored between 70 and 250 MeV, depending on the application.
- In proton therapy atomic and molecular data are of great significance.
- Nuclear interactions are of lesser importance, except for cases where high energy secondary particles are emitted.
- Data for the formation of activation products are not of paramount importance; however, they are needed in several special contexts.
Determination of Activation Cross Sections in the Medium Energy Range

**Experimental Method**

- Irradiation of target material with protons at a low current. Very often a stack of thin samples is irradiated (*stacked-foil technique*).
- Calculation of proton energy effective in each sample
- Determination of proton flux via a monitor reaction (or via a Faraday cup)
- Determination of absolute activity of the product nuclide, non-destructively or after chemical separation
- Calculation of cross section
- Construction of excitation function
**Irradiation Facilities**

Several types of cyclotrons and accelerators are needed to cover the full energy range.

The Jülich group used following machines:

- compact cyclotron ($\leq 21$ MeV);
- injector of COSY ($\leq 45$ MeV);
- accelerators at PSI ($\leq 72$ MeV), Uppsala ($\leq 180$ MeV), iThemba LABS ($\leq 200$ MeV) and Saclay ($\leq 350$ MeV)
Nuclear Model Calculations

- Hauser-Feshbach and precompound formalism successfully applied up to 50 MeV

  *Commonly used codes*: GNASH, STAPRE, EMPIRE II

- Hybrid exciton model commonly used in higher energy region

  *Common code*: ALICE-IPPE

- Direct interactions needed to be included

- Complex particle emission extremely difficult to treat
Activation Cross Section Needs

• Estimation of collimator activation in proton therapy facilities

• Estimation of long-lived activation products in biologically relevant elements
  - formation of $^7\text{Be}$
  - formation of $^{22,24}\text{Na}$ and other medium mass products

• Formation of short-lived $\beta^+$ emitters in human tissue
Activation of Beam Collimators

• Proton therapy demands high quality beams

• Tailoring of energy and homogenisation of intensity achieved through collimators

• Activation of collimators is of some concern

• Commonly used collimators include titanium, brass, tungsten, etc.
Results for a Pure Element as Target
(Easily detectable products)

Example: $^{\text{nat}}\text{Cu}(p,x)^{55,56,58}\text{Co}$ processes

- Model calculations reproduce experimental data well up to $E_p \leq 120$ MeV
Results for a Pure Element as Target
(Difficult to detect product)

Example: $^{\text{nat}}\text{Ti}(p,x)^{45}\text{Ca}$

- Good agreement between experiment and theory over the whole energy range

![Graph showing $^{\text{nat}}\text{Ti}(p,x)^{45}\text{Ca}$ cross section as a function of proton energy.](image)
Results for an Alloy as Target

Example: Formation of $^{52,54}\text{Mn}$ from brass

- Model calculation reproduces experimental data with partial success up to proton energies of about 120 MeV.
Activation of Brass Collimator

**Assumptions**
- 200 MeV, 400 nA p beam
- Periodical running sequence
- Two patients treated on one day of the week

- Estimated $^{54}$Mn activity/year: 37.5 MBq
- Dose rate (at 1m): 4.8 $\mu$Sv/h

Proper shielding of therapy facilities is mandatory
Long-Lived Activation Products in Biologically Relevant Elements

- Biologically relevant elements include H, C, N, O, F, Na, Mg, Si, P, S, Cl, Ca, Fe etc.

- Longer-lived activation products formed during proton therapy may include $^7$Be ($T_{1/2} = 53$ d), $^{22}$Na ($T_{1/2} = 2.6$ a), $^{24}$Na ($T_{1/2} = 15.0$ h) and several other medium mass products, like $^{42}$K ($T_{1/2} = 12.4$ h), $^{43}$K ($T_{1/2} = 22.2$ h), $^{51}$Cr ($T_{1/2} = 27.7$ d), $^{52}$Mn ($T_{1/2} = 5.6$ d), $^{54}$Mn ($T_{1/2} = 312$ d), $^{55}$Co ($T_{1/2} = 17.5$ h), etc.

- $^7$Be formation in interactions of protons with light elements C, N, O, F and Na involves both $^7$Be-emission (as a complex particle) and residual nucleus formation (after emission of several nucleons and $\alpha$-particles). For heavier target elements, emission of complex particle $^7$Be is more probable.

- $^{22,24}$Na and heavier mass radioactive products are formed as residual nuclei
Systematics of Excitation Functions of (p,\(^7\)Be) Reactions

- Probability of \(^7\)Be emission decreases with increasing mass of the target nucleus
Formation of $^{22,24}$Na in the Interactions of Protons with $^{\text{nat}}$Cl

- Cross sections for the formation of $^{22,24}$Na are relatively small (2 – 5 mb).
- Theory reproduces formation cross section with varying degree of success.
Formation of Short-lived $\beta^+$ Emitters in Human Tissue

Interactions of protons with constituents of human tissue generate short-lived $\beta^+$ emitters like $^{11}\text{C}$ ($T_{1/2} = 20$ min), $^{13}\text{N}$ ($T_{1/2} = 10$ min), $^{14}\text{O}$ ($T_{1/2} = 1.15$ min), $^{15}\text{O}$ ($T_{1/2} = 2$ min), $^{18}\text{F}$ ($T_{1/2} = 110$ min), etc.

**Examples of contributing nuclear reactions**

- $^{12}\text{C}(p,\text{pn})^{11}\text{C}$
- $^{14}\text{N}(p,\alpha)^{11}\text{C}$
- $^{14}\text{N}(p,\text{pn})^{13}\text{N}$
- $^{16}\text{O}(p,\alpha)^{13}\text{N}$
- $^{14}\text{N}(p,n)^{14}\text{O}$
- $^{15}\text{N}(p,n)^{15}\text{O}$
- $^{18}\text{O}(p,n)^{18}\text{F}$
- $^{16}\text{O}(p,\text{pn})^{15}\text{O}$

**Significance of production data**

a) Estimation of extra dose due to activation products
b) PET investigation of the patient after proton therapy (utilising the $^{11}\text{C}$ formed in the tissue); localises dose distribution in the treated area
Formation of Short-lived $\beta^+$ Emitters
(Protons on human tissue)

Example: $^{11}\text{C}$ formation

- Improved data base > 50 MeV
Estimated Activity in Human Tissue and Bone as a Result of Proton Therapy

**Assumption:** 200 MeV proton, 2 nA, 2 min irradiation

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (MBq)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Muscle tissue</td>
<td>Adipose tissue</td>
</tr>
<tr>
<td><strong>11C</strong></td>
<td>6.5</td>
<td>19.2</td>
</tr>
<tr>
<td><strong>13N</strong></td>
<td>3.9</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>15O</strong></td>
<td>2.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Total activity of $\beta^+$ emitters: 10 – 25 MBq
$^7$Be activity: 40 kBq
$^{22,24}$Na activity (in bone): < 250 Bq
Conclusions

• Activation of beam collimators at proton therapy facilities is of some concern regarding the therapy personnel.

• Formation of long-lived radioactive products in tissue and bone can be regarded as negligible.

• Formation of short-lived $\beta^+$ emitters is of some significance. Total activity (10 – 25 MBq) is sufficient for dose localisation via PET studies; the extra radiation dose from $\beta^+$ emitters is, however, negligible (< 1 %).