Detecting nuclear reaction products from markers as a range verification technique in proton therapy

Presented by Eva Kasanda
Advantages of Proton Therapy

- Protons deposit the majority of their energy at the end of their trajectory.
- Less radiation is delivered to healthy tissue compared to conventional therapy.
Proton Therapy at TRIUMF

TRIUMF hosts a 500 MeV cyclotron and is the only Canadian proton therapy institution

A dose as low as 5 Gy significantly increases risk of second malignancy

Photon Plan (IMRT)      Proton plan (same patient)

Dose-Monitoring and Range Verification

Range Verification

Range precision of proton therapy dependent on the accuracy of proton stopping powers in tissue

Dose Monitoring

\( \gamma \), proton and neutron flux all contribute to total dose to patient

Expected range uncertainties:

- Brain (10cm) -- 0.14cm
- Prostate (15cm) -- 0.33cm

Markers & Contrast Agents

Contrast agents in Medical Imaging Modalities

Tissue PET-activation for range verification in proton therapy

Marker PET-activation for range verification in proton therapy
Using prompt-spectroscopy to measure range

Characteristic peak
Approaches to $\gamma$-detection

**Prompt gamma rays:**
- measured when beam is online

**$\beta$-delayed gamma rays:**
- measured between beam pulses or after treatment

Fusion-evaporation

Radioactive decay
Time structure of Beam

Gamma-ray energy (MeV)

Time (s)

Beam On (785 ms)
Beam Off (1000 ms)

10^{10} protons
5mm target
1\% ^{58}\text{Ni}
Range-dependence of $^{58}$Ni reactions

77 MeV beam, 1% concentration of $^{58}$Ni in target, 20s measurement period

81 MeV beam, 1% concentration of $^{58}$Ni in target, 20s measurement period
Long-term Range Dependence

77 MeV beam, 1% concentration of $^{58}\text{Ni}$ in target, 1hr measurement period

81 MeV beam, 1% concentration of $^{58}\text{Ni}$ in target, 1hr measurement period
Energy Spectra for different beam ranges

**77 MeV beam**
- 1377 keV
- 1448 keV
- 1453 keV

**81 MeV beam**
- 1377 keV
- 1453 keV
- 1448 keV
Experimental Setup at TRIUMF proton treatment facility

- Experiment proposal M1780 approved at TRIUMF:
  - Test different contrast agents and concentrations
  - Compare to simulation
  - Determine expected SNR

70 MeV Proton Beam

Cyclotron

LaBr$_3$ scintillators

CAEN DT5730 Digitizer

Computer
Acknowledgements

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Building a Target & Mount

PMMA
LaBr$_3$(Ce) detectors
Sample

Side View (bisection)

Top View

Detectors need to be mounted to target holder too

Proton beam path

*actual dimensions still need to be figured out

Appropriate thickness to stop 100 MeV beam in target
Range verification in Proton Therapy

\[
\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \frac{n z^2}{\beta^2} \left( \frac{e^2}{4\pi \epsilon_0} \right)^2 \left[ \ln \frac{2m_e c^2 \beta^2}{I (1 - \beta^2)} - \beta^2 \right]
\]


Energy Spectra for different beam ranges

### 77 MeV beam

![Graph showing energy spectra for 77 MeV beam]

- **Gamma-ray energy (MeV)**: 1448 keV + 1453 keV
- **Counts**

### 81 MeV beam

![Graph showing energy spectra for 81 MeV beam]

- **Gamma-ray energy (MeV)**: 1448 keV + 1453 keV
- **Counts**
Adding a realistic detector to the mix

Counts

Gamma-ray energy (MeV)

1448 keV
+ 1453 keV

Counts

Gamma-ray energy (MeV)

1.2 1.25 1.3 1.35 1.4 1.45 1.5 1.55 1.6

Counts

Gamma-ray energy (MeV)

1.2 1.25 1.3 1.35 1.4 1.45 1.5 1.55 1.6

77 MeV beam

81 MeV beam
Geant4 Simulation Results

- Energy distribution of protons against depth in tissue.
- 10,000 events
Fusion-evaporation Reactions

\[ ^{98}\text{Tc} + p^+ \rightarrow ^{97}\text{Ru}^* + 2n \]

Cross-section of \(^{98}\text{Tc}\) fusion-evaporation reactions against proton energy

- \((p,n)\)
- \((p,2n)\)
- \((p,3n)\)
- \((p,4n)\)

Proton Energy (MeV)

Cross-section (mbar)

- 2545.5 keV
- 1845.7 keV
- 1199.1 keV
- 421.5 keV
- 421.55 keV
- 699.77 keV
- 646.47 keV
- 777.44 keV
- 421.5 keV

0.0 keV

tumor