Measurements of secondary particle production induced by particle therapy ion beams impinging on a PMMA phantom

Particle therapy (PT)

- In PT accelerated light ions (Z ≤ 8) are used for the treatment of tumors (p, $^{12}$C)
- Advantages of PT with respect to conventional Radiotherapy (with photons):
  - Highly localized dose deposition (Bragg Peak)
  - Higher biological efficiency (RBE)
  - Treatment of highly radiation resistant tumors, sparing surrounding organs at risk (OAR)

- Due to the highly localized dose deposition in PT a high precision monitoring is needed
- So far, we are still lacking a standard on-line monitoring procedure widespread in clinical use
The online monitoring challenge

• **On-line monitoring: not an easy task!**
  - Beam is stopped inside the patient (BP)
  - Monitor has to provide fast feedback to act on the beam control and prevent damage to OARs

• **Possible solution:** exploit the secondaries emitted in the nuclear interaction processes btw ion beam and the target nuclei
  - possibility to correlate the emission point of secondary particles with the dose release and BP position!

• **Achievable resolution** depends on:
  - Abundance of secondaries production
  - interaction inside the patient
  - detection efficiency (limited by external constraints such as the integration within the treatment room…)

Beyond p and $^{12}$C there’s a **growing interest in other “heavy” ions (4He, 16O) beam applications:** an improved characterization of the secondaries production for these beams is becoming crucial for their deployment in treatment centers
Three type of secondary particles have been exploited until now:

- **Prompt-\( \gamma \)** (comes from fragments nuclear de-excitation)
- **PET-\( \gamma \)** (comes from \( \beta^+ \) emitters fragments)
- **Charged fragments** (mainly \(^1\)H, \(^2\)H, \(^3\)H. The heavier ions are absorbed in patient body/PMMA target)

For each type of secondary particle is necessary to:

- correlate the emission point with the dose release and the BP position
- compute the production fluxes

In 2014 we performed an experiment @ HIT facility (Heidelberg Ion-Beam Therapy Center) in order to measure secondary particles produced in the interaction of \( \text{He}, \text{C and O beams} \) (with therapeutical energies) **against a thick PMMA target**

The HIT experimental setup

- Collected several millions of collisions with different beam energies, different geometrical configurations, and fixed distance btw BP and PMMA exit window.

- A MC simulation of the full setup has been developed with FLUKA for efficiencies and solid angle studies.
Different PMMA blocks have been assembled (for different beam energies) in order to have a target ensuring:

- a fixed BP position in our experimental reference frame (z=0 with the beam along the z axis)
- a fixed distance btw BP and PMMA exit window, to ease the systematics treatment for the fragmentation studies

The PET monitoring system was full functional only for He beams

The data analysis is still ongoing

In the following I’ll show only prompt-γ emission spectra, raw fluxes and preliminary secondary particles emission profiles

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MeV/u)</th>
<th>PMMA (cm)</th>
<th>Config</th>
<th>#ions (x 10^8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90° [60°]</td>
</tr>
<tr>
<td>He</td>
<td>102</td>
<td>7.65</td>
<td>90°, 60°</td>
<td>28.8 [33.2]</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>10</td>
<td>&quot;</td>
<td>32.4 [32.2]</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>12.65</td>
<td>&quot;</td>
<td>32.3 [31.9]</td>
</tr>
<tr>
<td>O</td>
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<td>23.9 [15.4]</td>
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<tr>
<td></td>
<td>260</td>
<td>10</td>
<td>&quot;</td>
<td>12.5 [12.3]</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>12.65</td>
<td>&quot;</td>
<td>29.9 [18.3]</td>
</tr>
<tr>
<td>C</td>
<td>120</td>
<td>12.65</td>
<td>90°</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>160</td>
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<td>&quot;</td>
<td>9.9</td>
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<td>180</td>
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<td>&quot;</td>
<td>6.4</td>
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<tr>
<td></td>
<td>220</td>
<td>&quot;</td>
<td>&quot;</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Prompt-\(\gamma\) production

• Prompt \(\gamma\) are mainly produced by the fragments de-excitations and are selected using \(E\) vs “ToF” (time of flight computed as \(t_{\text{LYSO}} - t_{\text{SC}}\))

• \(N_\gamma\) is computed from an unbinned likelihood fit to the time pull distribution in \(E_{\text{LYSO}}\) slices:
  • the background is modeled using the sum of a flat component (from LYSO internal radiation) and a peaking one, on the right (mainly due to neutrons)
Detected prompt-$\gamma$ spectra

- Prompt $\gamma$ production was observed for all the beams
- Emission spectra consistent with what already measured with LYSO detector @ LNS, GSI
- Broad peaks: convolution of prompt-$\gamma$ from different isotopes
- Emission spectra for 60° and 90° for He and O beams have been compared, normalizing them to have the same area.
Prompt $\gamma$ production was observed for all the beams.

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Broad peaks: convolution of prompt-$\gamma$ from different isotopes.

Emission spectra for 60° and 90° for He and O beams have been compared, normalizing them to have the same area.

For prompt $\gamma$ produced by $^{16}$O beam, we observe an asymmetry that is related to the prompt $\gamma$ production in the projectile fragmentation (and thus affected by the projectile boost).

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The PET $\gamma$ emission point is reconstructed only for helium beam.

PET $\gamma$ are identified requiring E around the 511 keV peak and $\Delta t < 3\sigma(t)$ for off spill events.

Still missing the $\varepsilon$ corrections.
• Started with analysis of He beams (plots are shown for 102 MeV/u beam).
• Proton, deuteron and triton bands are clearly visible for He fragmentation at all beam energies, with non negligible contribution at large angles
• The energy calibration of BGO detectors has been performed with p beams
• Nice agreement of E vs ToF distributions is observed with the predictions from Fluka MC simulation

![Graph showing charged fragments at small angles](image-url)
Charged fragments - large angles

- Tracks reconstructed by the DCH
  - Detector alignment done with aluminum table fixed positions (± 1mm)
  - DCH center aligned with fixed BP positions ($X_{\text{PMMA}} = 0$, ~1.5 cm before exit window)
  - $\Omega \sim 6 \cdot 10^{-5}$ sr, $\varepsilon_{\text{det}} > 90\%$
  - DCH trk resolution @ emission point ~ 1mm

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ToF (ns)
20
−
0
20
40
(MeV)
LYSO
10
20
30
40
50
60
70
80

(θ) = 0º
θ = 10º
θ = 30º

BGOa
BGOb
BGOc
STS2c
STS2b
STS2a

DCH
LYSO
LTS
PMMA
Rn
Rs
SC
STS1c
STS1b
STS1a

φ = 90º
φ = 60°

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preliminary data
He beam 90°
Mostly p,d,t
preliminary data
12C beam 90°
Mostly p,d,t

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p,d,t
• A non negligible production of charged particles at large angles is observed for all beam types
• The emission shape is correlated to the beam entrance window and BP position as already measured with $^{12}\text{C}$
• $\phi = dN_{\text{all}}/(N_{\text{ions}} \, d\Omega)$

<table>
<thead>
<tr>
<th>Beam type/E</th>
<th>$\phi , 90^\circ , (10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>He 102</td>
<td>0.6</td>
</tr>
<tr>
<td>He 125</td>
<td>0.7</td>
</tr>
<tr>
<td>He 145</td>
<td>1</td>
</tr>
<tr>
<td>C 160</td>
<td>1</td>
</tr>
<tr>
<td>C 180</td>
<td>2</td>
</tr>
<tr>
<td>C 220</td>
<td>3</td>
</tr>
<tr>
<td>O 210</td>
<td>3</td>
</tr>
<tr>
<td>O 260</td>
<td>5</td>
</tr>
<tr>
<td>O 300</td>
<td>10</td>
</tr>
</tbody>
</table>
Comparison of charged measurement at 90°

Very preliminary charged yields comparison at 90° for different energy and ion beams btw HIT data and previous data acquisition campaigns @ GSI and LNS of our group.
Conclusions

• The study of secondary particles production from He, C and O beams impinging on a thick PMMA target is well advanced! With the few millions of events collected at the HIT facility we already observed:

  ➡ A significant production of charged particles for all beam types. Results obtained for $^{12}$C beam are in agreement with what already published and confirm the feasibility of a dose monitor based on the charged particles detection!

  ➡ A significant forward fragmentation of $^4$He beams (p, d, t)

  ➡ A significant prompt-$\gamma$ production, with a spectra that has the same properties of what already observed in previous experiments.

    ➡ The contribution from projectile fragments de-excitation has been observed using the $^{16}$O beam.

  ➡ PET-$\gamma$ emission profile exploiting the He beam