Towards feasibility study of Positronium yield in proton beam therapy

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on behalf of the J-PET Collaboration

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Abstract

Proton beam therapy is a quickly emerging modality of radiation treatment. Its advantages over the conventional methods - finite range, maximal energy deposition at the end of the range and low energy deposition elsewhere - provide more conformal dose distribution over the tumor, save surrounding tissues and make the therapy more comfortable for the patient. To make an efficient use of those advantages one needs to develop a beam range monitoring system. Since the possible solution is utilizing the PET system for monitoring purposes, another possibility emerges [1,2,3]. The J-PET system enables positronium life-time measurements in PET imaging for diagnostics [4,5,6]. The same information about positronium life-time can be obtained also during proton beam therapy. However, this information is more difficult to acquire due to the high background coming from prompt gamma radiation, various isotopes that emit positrons and other particles and the medium that affects the life-time. Developing the methods for enabling positronium studies in proton beam therapy is crucial for determination of hypoxia level in the tissues, especially in the tumor region. Hypoxic tissues are more resistant to radiation therapy than normoxic tissues. Hence, determining the oxygenation level of tumor and surrounding tissues would enhance the effectiveness of the therapy [7,8]. We present estimation of β^+ - emitting isotope production rates during irradiation together with positronium yield and efficiency of the positronium signal registration with the J-PET system in dual-head configuration.

Production of β^+ emitters

Proton beam, traversing through the medium, induces nuclear reactions. That leads to the formation of various isotopes- in some cases β^+-emitters. In the first step we want to estimate the amount of produced isotopes.
We use a simple formula that gives the numbers of certain isotopes produced in one reaction chain in a small path (dx). The formula is as follows:

$$N_{C,O} = \Phi(x) \cdot S \cdot \rho_{C,O} \cdot \sigma(E(x)) \cdot dx$$

First component is the proton flux - $\Phi(x)$. This parameter gives information of the number of protons that form the beam. Essentially it is the number of protons that pass through a surface in a time unit.

S - is a spot size. It is a cross-section of the beam when it enters the medium.

$\rho_{C,O}$ - this is the molecular density of the medium. In this work we want to estimate the production ratios in the PMMA material. The density of the PMMA is $1.18\ \frac{g}{cm^3}$ and its chemical formula is the following:

$(C_5H_8O_2)_n$. We obtain the molar density from the formula: $\rho_M = \rho_{PMMA}[\frac{g}{cm^3}] \cdot \frac{N_A[\frac{1}{mol}]}{M[\frac{g}{mol}]}$, where N_A is the Avogadro number and M is the molecular mass.

Next component - $\sigma(E(x))$ is the cross-section for a certain nuclear reaction chain. Those cross-sections where calculated by prof. Kadenko using the Talys 2.0 software. The models take into account several reaction chains and calculate them separately as well as the total cross-section, but calculate them point by point. We extrapolate those calculations and make a curve fit to obtain the function $\sigma(E)$.

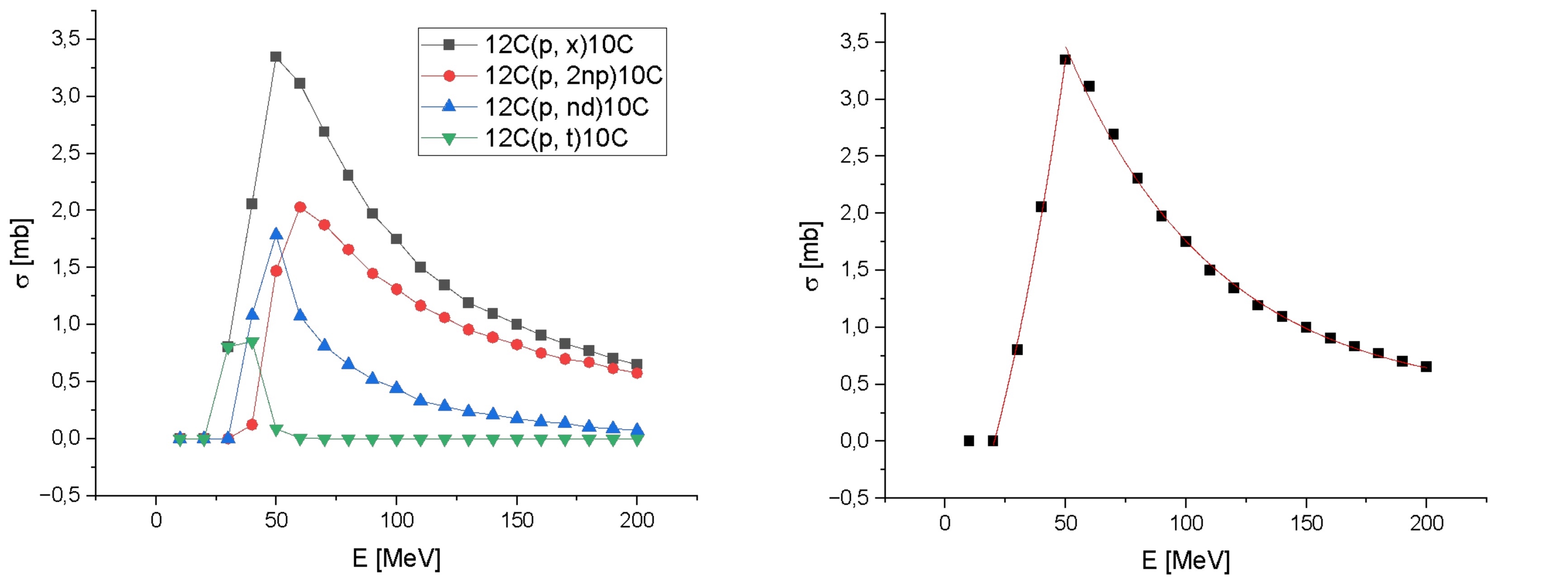

Fig. 1.: On the left we present the cross-sections for reaction chains leading to ^{10}C production from ^{12}C and a total cross-section. On the right we present the extrapolation with the fitting (red lines).

Calculations of the proton beam range and the energy function $E(x)$ were performed using Bethe-Bloch formula and using a simplified analytical solution following Grimes et al. [8].

To obtain the final results we performed the calculations in each of the regions of the thickness dx and added up the production numbers. We did it iteratively using Mathematica software. For calculation we used the parameters that were used during the irradiation of the PMMA with proton beam and J-PET was in use - see Tab1. Results are presented in Tab2.

Parameter	Value
Proton current	28 nA
Flux	$1.7 \cdot 10^{11}$ 1/s/cm^3
Total number of protons	$4.67 \cdot 10^{13}$
Spot	0.75 cm^3
dx	0.01 mm
Molecular density of PMMA	$7.1 \cdot 10^{21}$ 1/cm^3

Tab.1.: List of the used parameters.

Isotope	Yield
^{10}C	$2.87 \cdot 10^8$
^{11}C	$3.88 \cdot 10^9$
^{14}O	$1.11 \cdot 10^8$
^{15}O	$1.24 \cdot 10^9$

Tab.2.: Results of the yields of the isotopes.

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Positronium signal estimation

1. Positronium and positronium life-time

Positronium - metastable bound state of positron and electron - forms with about 40% ratio. This means that the values in Tab2. for each isotope have to be multiplied by factor 0,4 to obtain the positronium yield. The ultimate goal is to calculate the life-time of positronium in PMMA. To make it possible we need isotopes that shortly after the emission of positron, emit also (within ps) a gamma quantum, called prompt gamma. Those isotopes are ^{10}C and ^{14}O, which in almost 100% of the cases emit this additional prompt gamma. The rest of the analysis is mainly focused on those isotopes - Tab3.

Isotope	Half-life	Production	Positronium
^{10}C	19.29 s	$2.87 \cdot 10^8$	$1.148 \cdot 10^8$
^{14}O	70.61 s	$1.11 \cdot 10^8$	$0.444 \cdot 10^8$

Tab 3.: Number of expected positronium events for ^{14}O and ^{10}C isotopes.

2. Detector geometry

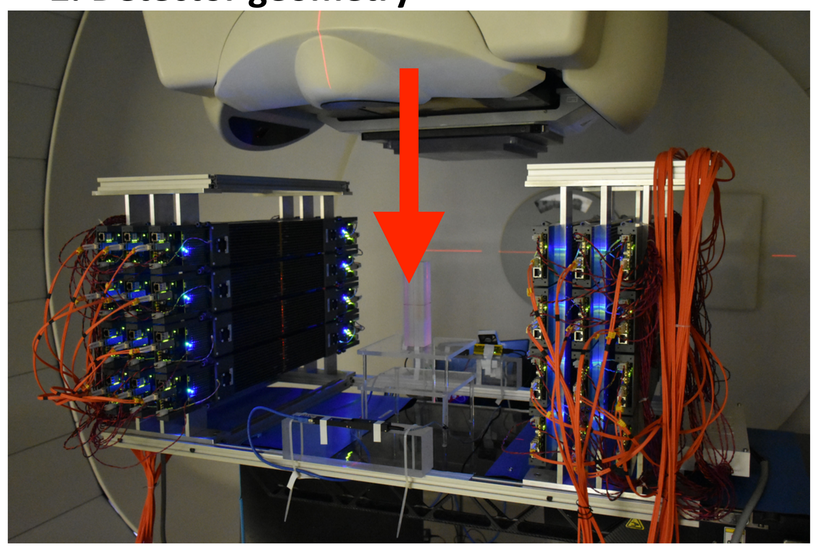

Fig. 1.: Experimental setup used during the experiment in CCB. The red arrow marks the direction of the beam.

Dual-head configuration of the J-PET system consist of 24 modules - each of the modules is build out of 13 plastic scintillators. Modules are arranged into three layers of 4 modules in each head. This configuration covers 21% of a total solid angle. This means that, if prompt gamma is emitted isotropically, it has 21% chance to hit the detector. The same applies to an annihilation gamma. Taking that into account we obtain that about 4,5% of all emitted prompt and annihilation gammas will hit the detector.

3. Energy deposition

J-PET detector consists 312 organic scintillators. Those scintillators are the compound type BC-404. They consists of carbon and hydrogen with the H:C ratio 1,1. Gamma quanta passing through the scintillator can undergo the Compton scattering - only that way they can deposit energy and be registered. To calculate the probability of the energy deposition one needs to calculate the attenuation coefficient for the scintillator's material. The function $\mu(E)$ is shown in the Fig.2. The amount of the energy deposited by the gamma is determined by the Klein-Nishina formula - Fig.3.

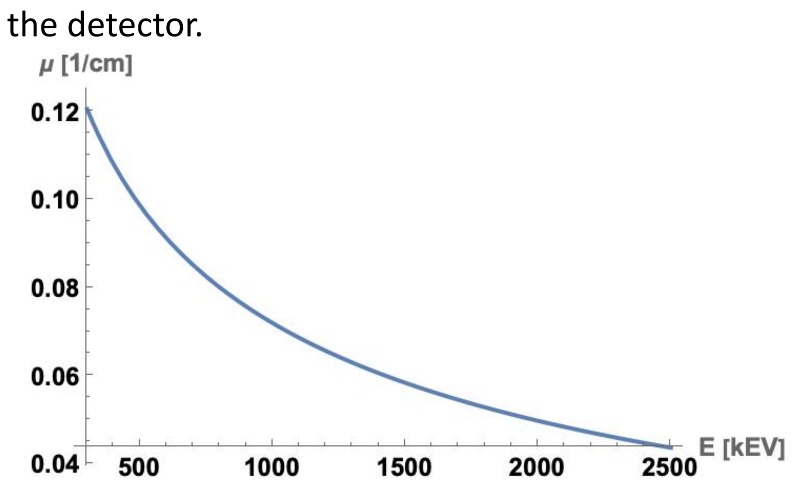

Fig. 2.: Plot showing the dependance of the attenuation coefficient and the energy of a gamma quantum.

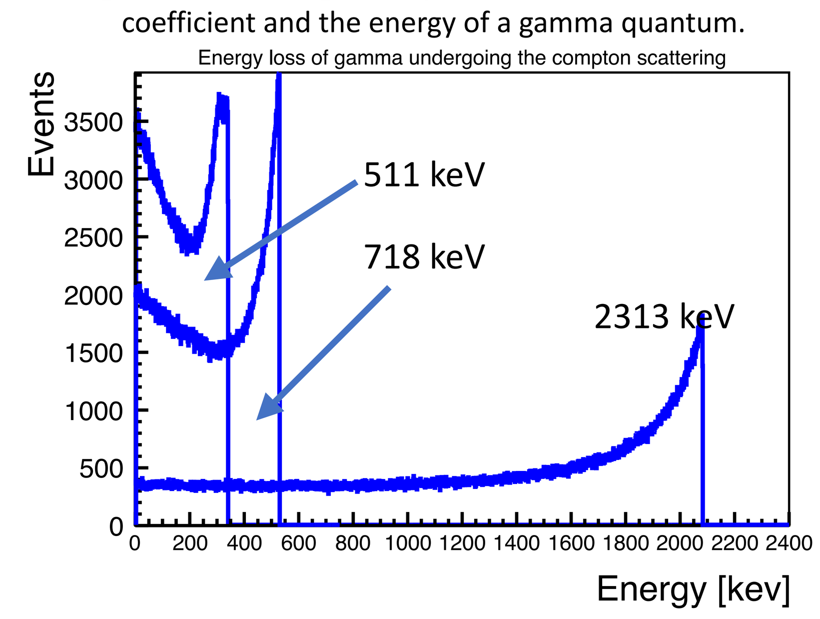

Fig. 3.: Plot showing the results of Klein-Nishina formula for gamma quanta of energies: 511, 718 and 2313 keV.

4. Efficiency

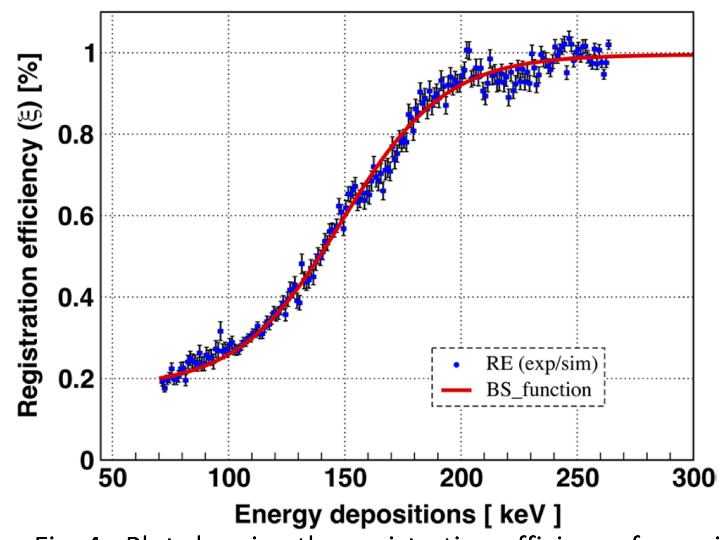

Fig. 4.: Plot showing the registration efficiency for various energy depositions for the J-PET detector. [9]

Once the energy is deposited in the strip of the detector it has some probability of being registered. This probability is dependent on the energy deposited in the strip. Fig.4. is showing a function describing this probability [9].

5. Results

Isotope	Annihilation pair + prompt	One 511 scattered	Prompt taken as annihilation
^{10}C	19 364	65 948	$4.78 \cdot 10^6$
^{14}O	5 567	21 531	$2.03 \cdot 10^5$

Tab.4..: Table showing final results of estimation of number of true positronium signal (according to our criteria), number of events when one annihilation scattered and number of events when prompt gamma deposited less energy and was mistaken with annihilation gamma.

Summary

In this work we attempt to estimate the possible signal registration of positronium events during proton beam therapy monitoring. We found that in the experiment conducted with the proton pencil beam, using our selection criteria, we should be able to observe approximately 25 thousands of positronium events. Additionally, there is a possibility to increase this number by the events where prompt or one annihilation gamma deposited less energy, but were registered. This in principal should allow us to calculate the life-times. Further work requires simulations studies that are already ongoing and, later, thorough data analysis and its interpretation.

References

1. Parodi K., Yamaya T., Moskal P. Experience and new prospects of PET imaging for ion beam therapy monitoring. Z. Med. Phys. 33 (2023) 22-34.
2. Durante, M., Loeffler, J. Charged particles in radiation oncology. Nat Rev Clin Oncol 7 (2010) 37–43.
3. Graeff C., Volz L., Durante M. Emerging technologies for cancer therapy using accelerated particles. Progress in Particle and Nuclear Physics 131, (2023) 104046.
4. Moskal P., et al. Positronium image of the human brain in vivo. Sci. Adv.10, (2024) eadp2840
5. Moskal P., et al. Feasibility study of the positronium imaging with the J-PET tomograph. Physics in Medicine and Biology, 64(5) (2019) 055017.
6. Moskal P., et al. Positronium imaging with the novel multiphoton PET scanner. Science Advances, 7(42) (2021).
7. P. Moskal and E.Ł. Stępień. Positronium as a biomarker of hypoxia. Bio-Algorithms and Med-Systems 17(4) (2021) 311-319.
8. Moskal P., Jasińska, B., Stępień, E.Ł. et al. Positronium in medicine and biology. Nat Rev Phys 1 (2019) 527–529
9. Grimes et al. An approximate analytical solution of the Bethe equation for charged particles in the radiotherapeutic energy range. *Sci Rep* **7**,
10. Sharma, S., Baran, J., Chug, N. *et al.* Efficiency determination of J-PET: first plastic scintillators-based PET scanner. *EJNMMI Phys* **10**, 28 (2023).