Charged and Neutral Particles Production from 80 MeV/u ^{12}C ion beam on a PMMA target

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Abstract

We have measured the properties of the secondary particles produced in the interaction of carbon ion beams with homogeneous targets, in order to reconstruct the profile of the dose delivered in an hadrontherapy treatment. Our measurements have been done with a 80 MeV/u fully stripped carbon ion beam at the INFN Laboratori Nazionali del Sud (LNS), Catania, with a Poly-methyl methacrylate target (PMMA).Both the neutral and the charged component of the secondaries have been measured, the neutral component including prompt photons and β^+-annihilation photons (γ-PET).

1 Introduction

Protons and carbon ion beams are presently used to treat many different solid cancers [1, 2] and several new centers based on hadron accelerators are operational or under construction [3, 4]. The main advantage of this technique, in comparison to the standard radiotherapy with X-ray beams, is the better localization of the irradiation dose in the tumor affected region sparing healthy tissues and possible surrounding organs at risk. This feature can be achieved because the heavy charged particles loose most of the energy at end of their range, the Bragg peak, in comparison to the exponentially decreasing energy release of the X-ray beam. New dose monitoring techniques need to be developed and introduced into clinical use, to meet the improved capability of hadrontherapy to match the dose release with the cancer position. The R&D effort should be then focused to develop novel imaging methods to monitor, preferably in real time, the 3-dimensional distribution of the radiation dose effectively delivered during hadrontherapy. This holds true especially for treatments using carbon ion beams since the dose profile is very sensitive to anatomical changes and minor patients' positioning uncertainties. Conventional methods for the assessment of patients' positioning used in all X-ray based radiation therapy, where a non-negligible fraction of the treatment beam is transmitted through the patient, cannot be used to pursue this task due to the different physics underlying.

We report on the measured properties of the secondary particles produced in the interaction of a 80 MeV/u fully stripped carbon ion beam at the INFN Laboratori Nazionali del Sud (LNS), Catania, with a Poly-methyl methacrylate target (PMMA). Both the neutral and the charged component of the secondaries have been measured, the neutral component including prompt photons and β^+-annihilation photons (γ-PET).

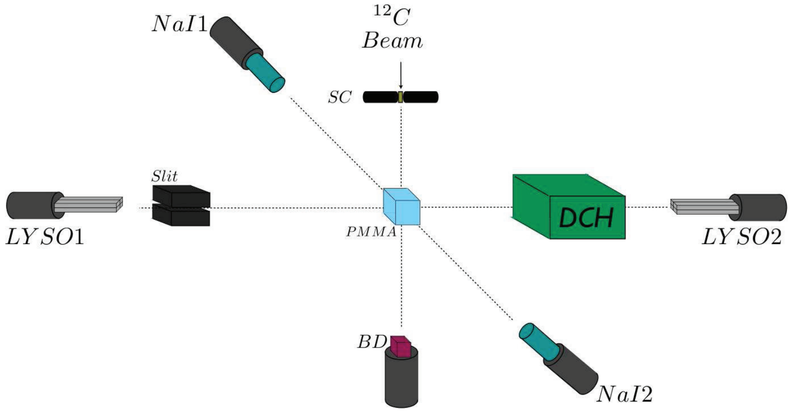

Fig. 1: Schematic view of the experimental setup; for prompt photon the acquisition is triggered by the Start Counter in coincidence with the LYSO, while for the γ-PET the NaI crystals are required.

2 Experimental setup

The experimental setup at LNS is shown in Fig. 1: a $4 \times 4 \times 4$ cm^3 PMMA target is placed on a fully stripped ^{12}C ion beam. The beam rate, ranging from hundred kHz to ~ 2 MHz, was monitored with a 1.1 mm thin scintillator on the beam line read-out with two photomultiplier tubes (PMT) (Hamamatsu 10583) put in coincidence (Start Counter) and placed at 17 cm from the PMMA.
A pair of cylindrical Thallium-doped sodium iodide crystals NaI(Tl) (r = 2.5 cm and h = 5 cm) was placed at 45° (225°) with respect to the beam line, at 20 cm from the PMMA. The scintillation light of the two crystals was detected by two Scionix V 14-EI PMTs triggered in coincidence within a time window of 80 ns.
An array of 4 LYSO crystals, each measuring 1.5x1.5x12 cm^3, was placed at 90° with respect to the beam line, at 74 cm from the PMMA center. The scintillation light of the crystals was detected with a PMT (EMI 9814B).
A 21 cm long drift chamber (DCH) was placed at 51 cm from the PMMA center, along the flight line connecting the PMMA to the LYSO crystals. We have chosen the configuration at 90° with respect to the beam line to maximize the sensitivity to the Bragg peak position along the beam.

3 Prompt photons measurement

Photons are detected by the LYSO calorimeter, and selected from charged particles by requiring no signal in the DCH. Prompt photons are discriminated by measuring the time difference between the beam impact on the Start Counter and the photon detection consistent with a particle emitted instantaneously and traveling at the speed of light.

We measured the energy spectrum, Fig. 2(left), and rate of prompt photons with a time resolution of 300 ps for photons with energies above 3 MeV, allowing for a much stronger neutron background rejection with respect to previous measurements [5]. The fit of the peak gives a fraction of $f_{^{12}\mathrm{C}}$ = (13.9±0.6)% for prompt photons over carbon ions at 4.44 MeV. Fig. 2(right) shows the data distribution compared to the MonteCarlo simulation from GATE [7] with G4QMDReaction for ions' inelastic process and ^{12}C-PMMA interactions, folded with detector response. The spectra, normalized to the number of incident carbons, show the level of agreement between data and MonteCarlo simulation: both the normalization and the fraction of E=4.44 MeV photons require further investigation.

The rate of photons per carbon ions triggered (N_C) $\mathrm{F}_{\mathrm{prompt}} = (3.04 \pm 0.01_{\mathrm{stat}} \pm 0.20_{\mathrm{sys}}) \times 10^{-6}$ has

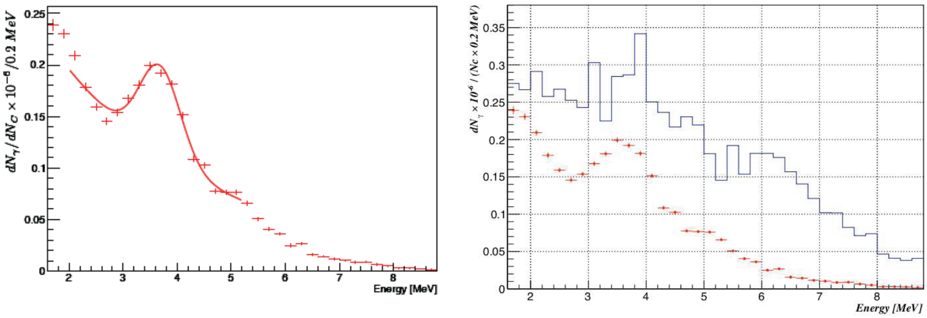

Fig. 2: (Left) Measured prompt photons spectrum obtained with the LYSO detector. The fit of the peak gives a fraction of $f_{^{12}\mathrm{C}}$ = (13.9±0.6)% for prompt photons over carbon ions at 4.44 MeV. (Right) Data-MC comparison of the prompt photons energy spectrum, normalized to the number of incident carbon ions.

been measured together with the differential production rate $dN_\gamma/(dN_\mathrm{C}d\Omega)(E > 2MeV, \theta = 90°)$ = (2.92±0.19)×10^{-2} sr^{-1} [6].

4 γ-PET measurement

NaI crystals have been used to detect the $\gamma-$PET signals, the collinear 511 keV photons produced by positrons annihilation from β^+ emitters. The rate of β^+ decays and the isotopic composition of the emitters has been measured as a function of time both during irradiation and in the intervals in between. The time dependence of the emission during the irradiation results from two main contributions: (i) the creation of new emitters induced by the passage of the carbon ions in the PMMA, and (ii) the decay of the previously created ones. When the irradiation time is comparable to the decay time of the emitters, the relation between the β^+ decays and dose rate is non-trivial. With the acquired data we have demonstrated the possibility to estimate the number of impinging carbon ions from the number of observed $\gamma-$PET. We measured the ratio between the number of activated ^{11}C and ^{13}N to be A_C/A_N = 16.6±2.7 and a number of (10.3±0.7)×10^{-3} generated ^{11}C ions, per impinging carbon ion, undergoing β^+ decay [8].

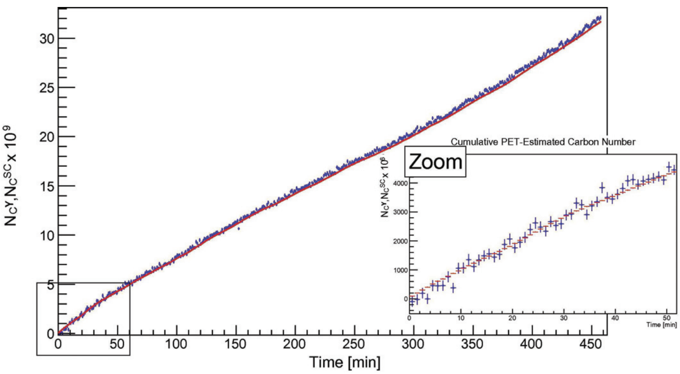

Fig. 3: Cumulative distribution of the number of carbon ion measured with the Start Counter, N_C (magenta dashed data), compared to the number of ions estimated by the measurements of γ-PET, N_C^γ (blue dot points). The plot on the right is a zoom of the first 50 min of acquisition.

With these data we also validated a model to describe the activated nuclei β^+ decay during the irradiation. Figure 3 shows the cumulative distribution of the number of ions estimated by the measurements of γ-PET, N_C^γ, blue dot points, compared to the cumulative number of carbon ions measured with the Start Counter N_C , magenta dashed data. A good agreement is visible, also at times comparable with the lifetimes of the decaying isotopes.

Finally we measured the mean position of the β^+ emission to be $D_{\beta+}$ = (5.3±1.1) mm from the beam entrance face of the PMMA, to be compared to the FLUKA simulated Bragg peak position D_{Bragg} = (11.0±0.5) mm. The D_{Bragg} value is confirmed from the direct observation of the PMMA deterioration after data taking, visible as a light yellow band and shown in Fig.12 of Ref [8]. All this information can be used as a benchmark for the β^+ emitters MonteCarlo simulation of hadrontherapy.

5 Charged particles

Charged secondary particles, produced at 90° with respect to the beam axis, have been tracked with the DCH, while their energy and time of flight has been measured by means of the LYSO scintillator. Secondary protons have been identified exploiting the energy and time of flight information (ToF), Figure 4 and their emission region has been reconstructed backtracking from the drift chamber to the target. In order to evaluate the setup acceptance and efficiency, and to optimize the particle identification analysis a detailed simulation has been developed using the FLUKA software release 2011.2 [10, 11]. The interaction of a sample of 10^9 carbon ions with 80 MeV/u, equivalent to 10^3 s of data taking at the typical 1 MHz rate of beam, has been simulated.

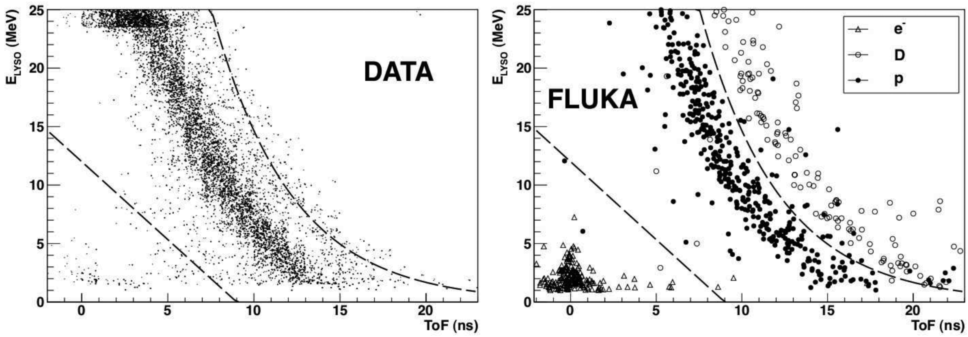

Fig. 4: Distribution of the detected energy in the LYSO crystals as a function of the Time of Flight: Data (Left) and FLUKA Simulation (Right).

The existence of a correlation between the reconstructed production region of secondary protons ($\bar{x}_{\rm PMMA}$) and the Bragg peak position ($x_{\rm Bragg}$) has been observed, performing a position scan of the PMMA target (Figure 5). The expected position of the Bragg peak has been obtained with the FLUKA simulation and its value confirmed from visual inspection of the PMMA deterioration after data taking, as mentioned above. A proton kinetic energy at emission time $E_{\rm kin}^{\rm Prod} > 83$ MeV has been required to account for the crossing of some centimeters of patient's tissue when using these secondary particles for monitoring purposes. The FLUKA simulation has been used to relate the detected proton kinetic energy to $E_{\rm kin}^{\rm Prod}$.

The achievable accuracy on the Bragg peak determination exploting this procedure has been estimated to be in the submillimeter range, using the described setup and selecting secondary protons with kinetic energy at emission $E_{\rm kin}^{\rm Prod} > 83$ MeV. The obtained accuracy on the position of the released dose should be regarded as an indication of the achievable accuracy for possible applications of this technique

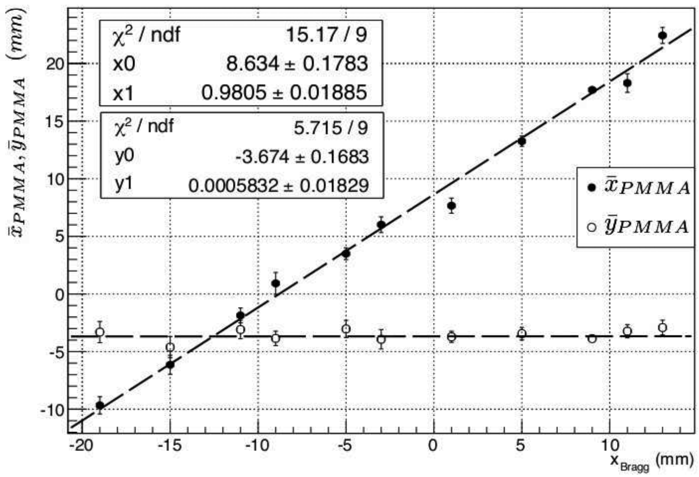

Fig. 5: Reconstructed peak position of the secondary proton emission distribution $\bar{x}_{\rm PMMA}$,$\bar{y}_{\rm PMMA}$ as a function of the expected Bragg Peak position $x_{\rm Bragg}$, with $\mathrm{E}_{\rm kin}^{\rm Prod} > 83$ MeV.

to monitor the Bragg peak position in hadrontherapy treatment.

We measured the differential production rate for protons with $\mathrm{E}_{\rm kin}^{\rm Prod} > 83$ MeV and emitted at 90° with respect to the beam line: $dN_{\rm P}/(dN_{\rm C}d\Omega)(E_{\rm kin}^{\rm Prod} > 83\ {\rm MeV}, \theta = 90°) = (2.69 \pm 0.08_{\rm stat} \pm 0.12_{\rm sys}) \times 10^{-4} sr^{-1}$ [9].

6 Conclusions

The measurement of the fluxes of the secondary particles produced by the hadron beam is of fundamental importance in the design of any dose monitoring device and is eagerly needed to tune Monte Carlo simulations.

Charged and Neutral Particles Production from the 80 MeV/u fully stripped carbon ion beam on a PMMA target at the INFN Laboratori Nazionali del Sud (LNS), Catania, provided us with several results.

With prompt photons we measured: energy spectrum, rate and differential production rate per triggered carbon ion and at 90° with respect to the beam line.

With γ-PET we validated a model to describe the activated nuclei β^+-decay during the irradiation, we estimated the number of carbon ions from the number of observed γ-PET, we measured the ratio between the number of activated ^{11}C and ^{13}N and the average position of β^+ emitters in the PMMA.

With secondary protons we observed the existence of a correlation between the reconstructed production region of these secondaries and the Bragg peak position. The achievable accuracy on the Bragg peak determination exploiting the proton signal has been estimated to be in the submillimeter range. The differential production rate per triggered carbon ion and at 90° with respect to the beam line has been also measured.

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