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Spectroscopic study of prompt-gamma emission for range verification in proton therapy

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ABSTRACT

We present the results of an investigation of the prompt-gamma emission from an interaction of a proton beam with phantom materials. Measurements were conducted with a novel setup allowing the precise selection of the investigated depth in the phantom, featuring three different materials composed of carbon, oxygen and hydrogen. We studied two beam energies of 70.54 and 130.87 MeV and two detection angles: 90° and 120°. The results are presented in form of profiles of the prompt-gamma yield as a function of depth. In the analysis we focused on the transitions with the largest cross sections: $^{12}C_{4.44\rightarrow g.s.}$ and $^{16}O_{6.13\rightarrow g.s.}$. We compare the profiles obtained under various irradiation conditions, with emphasis on the shape of the distal fall-off. The results are also compared to calculations including different cross-section models. They are in agreement with the model exploiting published cross-section data, but the comparison with the TALYS model shows discrepancies.

1. Introduction

Proton therapy is a rapidly emerging technique for tumour treatment that has been exploited and optimized for over half of a century. The well-defined location of the Bragg peak and steep distal fall-off of the dose deposition potentially offer the possibility to completely spare the healthy tissue behind the tumour and also largely the tissue upstream of it. Currently, an accuracy of the beam range *in vivo* of about $4.6\% + 1.2$ mm [1,2] is achievable. For this reason it is necessary to apply safety margins of the same order during treatment. The values of safety margins for deeply located tumours can exceed 10 mm. Consequently, for a large group of patients with tumours located close to critical organs the potential of the proton therapy is not fully exploited. Development of methods for *in vivo* monitoring of the dose distribution would allow to reduce currently used safety margins and provide better control of beam direction, leading to better conformity and consequently improved treatment.

Two main options for proton range monitoring are being currently developed by several groups all over the world: *positron emission tomography* (PET) and *prompt-gamma imaging* (PGI). PET allows registration of the distribution of β^+ emitters created in the course of irradiation. Typically the PET scans are performed in a different room and thus serve as a tool for post-irradiation control rather than for on-line monitoring (for a review see [3]).

The PGI method has a potential to become an *in vivo* and *in situ* monitoring tool. NuPECC in the report *Nuclear Physics for Medicine* [1] lists PGI among the most promising options. Protons traversing the tissue during irradiation produce a variety of gamma quanta. There is both a continuum and lines stemming from deexcitation of nuclei after they have been excited by impinging protons. The continuum part is not easily accessible, since the registered spectrum contains background due to neutrons. To some extent the neutrons can be eliminated using the time-of-flight technique (see *e.g.* [4]), but the discrete transitions form a more distinct signal. Experimental investigation of the correlation between the gamma yield and the depth in a phantom with respect to the Bragg

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peak position was initiated by Min et al. in 2006 [5,6], followed by many other groups [7–12]. Various experimental techniques were exploited for gamma detection for PGI, including the Compton camera solution (see *e.g.* [10,13–15]). A conceptually much simpler approach with a single high-efficiency collimated gamma detector with an active Compton shield and time-of-flight for neutron/gamma discrimination has been recently shown to be a promising alternative [11,16]. Also, results of commissioning of a PGI knife-edge shaped slit camera in clinical application has been reported in 2016 by Richter et al. [17].

Along with the experimental effort, a lot of attention has been paid to study the potential of the PGI technique in simulations of proton therapy [14,18–24]. Recently, promising results were reported of Monte-Carlo studies investigating the option of therapy monitoring using PGI in proton-boron fusion therapy [25] and boron neutron capture therapy [26]. In certain cases, *e.g.* in the work of Le Foulher et al. [27], large differences were found when comparing simulation results with experimental data, or in comparison of results obtained from various simulation engines [28]. This calls for extension of the existing experimental database, which would allow to better describe the processes useful for PGI as well as background reactions in the simulation codes.

The objective of our work was to study with high precision the depth profiles of gamma emission from phantoms irradiated with proton beams, with particular attention to the region of the Bragg peak, in order to understand the main dependences related to incident beam energy, chemical composition of the target and detection angle. Measurements were performed for three materials consisting of hydrogen, carbon and oxygen atoms in various relative fractions, at beam energies of 70.54 MeV and 130.87 MeV and detection angles of 90° and 120°. For one of the settings, an additional measurement was performed with a ripple filter[1] inserted into the beam line. The analysis is focused on the transitions: $^{12}C_{4.44\rightarrow g.s.}$ and $^{16}O_{6.13\rightarrow g.s.}$, where 'g.s.' denotes ground state. They can be easily identified in the spectra due to their large cross sections. We construct depth profiles of the gamma yield for each measurement conditions and compare them with model calculations using TALYS – a software package for simulation of nuclear reactions [29]. We present also a comparison of our data with calculations based on cross sections available in the literature.

2. Experiment

2.1. Experimental setup

The experiment was performed at the Heidelberg Ion-Beam Therapy Center (HIT) using a proton beam accelerated by a synchrotron to 70.54 or 130.87 MeV kinetic energy. The beam leaving the nozzle at the end of the ion pipe impinged onto a phantom consisting of two main parts, as depicted in Fig. 1. The more upstream part, located 37 cm downstream of the nozzle, consisted of two wedge-shaped blocks located on a moving platform allowing to slide one of the wedges along the other one, thus changing the thickness of the material in the beam path. The wedges had a form of right-angled prisms, with the acute angle of 36°, the opposite cathetus of 12 cm length and the height of the prism of 5 cm. Downstream of the wedge part, at a distance of 59.5 cm from the exit window of the nozzle, a so-called thin slice of the same material was located. Its lateral dimensions were $5 \times 5\ \mathrm{cm}^2$, while the thickness was 1 or 2 mm for different materials and is listed in Table 1, together with the relevant properties. The spectroscopic detector was directed to the thin slice. The situation can be compared to that with a standard block-shaped phantom and a detector collimated to observe only a certain part of it, with the main difference that in our experimental setup the upstream part of the block is separated spatially to eliminate background stemming from it, and the donwstream part is removed completely for the same reason. In addition, the split-up of the phantom allows for measuring the angular distribution of the prompt-gamma radiation stemming from the thin slice. The target setup allowed to control changes of target thickness with an accuracy of a few microns. However, the procedure of calibration of the target moving system involved a change of the wedge position. This could potentially lead to a spurious offset in the measured target thickness, common for the whole measurement series. The effect would manifest as a shift of all series points up to 0.5 mm along the phantom thickness axis.

For gamma detection we used a High-Purity Germanium (HPGe) detector in combination with an active Compton shield (ACS) made of scintillation detectors. The detector efficiency for registration of gammas with energies of 4.44 and 6.13 MeV was determined in a Monte-Carlo simulation as 3.9% and 2.5%, respectively (details in Section 4). The use of the ACS allowed the acquisition of cleaner spectra, but lead to a peak reduction of 16% and 23% for the two investigated transitions, which was determined experimentally under beam-time conditions by removing the anti-coincidence condition in the data acquisition system. Apart from the ACS, additional passive shielding was provided by encapsulating the detector in a lead sarcophagus. The detector was mounted on a movable platform allowing us to set the detection angle, the thin slice being in the center of rotation. The setting of the detection angle, just like the target thickness, were controlled remotely. The solid angle covered by the detector was $4.5 \cdot 10^{-3}$ sr.

For absolute normalization the Beam Current Monitor (BCM) was used in the form of a telescope consisting of four plastic scintillators. The setup was placed very close to the beam exit nozzle and registered protons scattered on the nozzle, thus enabling relative beam intensity monitoring independently of the target thickness. The BCM rate was translated into the beam intensity to provide an absolute normalization in several calibration runs based on the measurements of the EtherCAT system using the beam profile monitors inside of the nozzle. Beam intensity of $3.2 \cdot 10^9\ \mathrm{s}^{-1}$ was used.

2.2. Performed measurements

All performed measurements were divided into series, meaning registration of a set of prompt-gamma spectra collected at the same experimental conditions, but with different setting of the phantom thickness. Typically, a single measurement was taken with ca. 10^{11} protons leaving the beam nozzle to ensure statistical uncertainties of the data on the percent level. We registered nine series, each with different experimental conditions. They are specified in Table 2. Hereinafter we refer to the lower energy as '70 MeV' and the larger one as '130 MeV'.

Apart from the regular run series, measurements aiming at the study of the background were performed: for each of the series we registered spectra at various phantom thicknesses, but in the absence of the phantom part in form of the thin slice. Such measurements allowed to determine which part of the registered prompt-gamma spectrum stems from other sources than the thin slice, *e.g.* the wedges (despite shielding) and the surrounding air. It is worthwhile to note that our setup did not allow for discrimination between prompt gammas and neutrons produced in the beam interaction with the phantom. Thus, the continuum part of the spectra contains in fact both contributions and for this reason was skipped in the analysis.

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[1] Ripple filter is an optional beamline component used to widen a Bragg peak.

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