PROCEEDINGS OF SCIENCE

Monte Carlo Study of Prompt Gamma Emission in ^{12}C(p, p'γ)^{12}C Nuclear Reactions close to a Bragg Peak

---

M. Abuladze ,[a,b,*] **R. Hatzel,**[c] **J. Kasper,**[c] **R. Shanidze**[a,b] **and A. Stahl**[c]

[a]*Faculty of Physics, Ivane Javakhishvili Tbilisi State University,*
I. Chavchavadze str. 1, Tbilisi, Georgia
[b]*Kutaisi International University*
Youth Avenue, 5/7, Kutaisi, Georgia
[c]*Physics Institute III B, RWTH Aachen University,*
Otto-Blumenthal-Straße 18 , Aachen, Germany

E-mail: `mariam.abuladze@kiu.edu.ge`

Proton therapy is a high-quality radiation therapy which uses a proton beam to irradiate cancer tissue. The advantage of this type of treatment is a highly conformal dose deposition due to the presence of the Bragg peak. It is often required to irradiate the tumor volume with a precision better than 1 - 2 mm, which means that proton therapy needs not only precise treatment planning but also monitoring and proton range verification during the treatment. One way to monitor the proton range is Prompt Gamma Imaging (PGI) which means to detect gamma rays produced by the excitation of the target nuclei by incident protons.

In this work, the results of the Geant4 simulation (version 10.6.3.) of interactions of protons with a carbon target are presented. This includes the study of 4.4 MeV and 9.6 MeV line properties, as multiple differences were observed between simulation and experiment, one of which is a double peak for the C^{12}(p, p'γ 4.44)C^{12} spectral line. The shortcomings of the current physical models in Geant4 in describing the shape and intensity of the 4.4 MeV and 9.6 MeV gamma lines will be discussed.

RDP online PhD school and workshop "Aspects of Symmetry"(Regio2021),
8-12 November 2021
Online

---

[*] Speaker

PoS(Regio2021)033

1. Introduction

Cancer is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020 [1], thus investigating modern ways of cancer treatment has paramount importance. Proton therapy is a high-quality radiation therapy which uses proton beam to irradiate cancer tissue. The main advantage of this type of radiotherapy is a highly conformal dose deposition due to the presence of the Bragg Peak. It provides a maximum dose deposition in the area of cancer tissue while healthy tissues receive only a marginal dose [2]. In order to provide precision better than 1-2 mm live monitoring of a Bragg Peak with PGI (Prompt Gamma Imaging) seems to be among the most promising approaches [3, 4].

Monte Carlo simulations are increasingly used in medical physics and one of the widely applied Monte Carlo toolkit is the Geant4 software. This Monte Carlo toolkit provides models for simulations of low-energy proton interaction with matter including inelastic nuclear reactions making it possible to simulate the prompt gamma-ray emission [5]. The purpose of this work is to describe the drawbacks of the models currently implemented in this software in describing the prompt gamma emission while carbon phantom is irradiated with protons.

2. Physics Motivation

Different processes take place while a proton beam is passing through matter, one of which are nuclear reactions which account for prompt gamma emission while the particle deexcites at the second stage of the reaction [6, 7]. Although, nuclear reactions do not play an important role in proton beam stopping in matter, the Prompt Gammas resulting from these reactions still correlate with the position of a Bragg Peak in matter as it was observed in the experiment [8]. Therefore, the motivation for declaring PGI as the most effective way to monitor Bragg Peak is the nuclear reactions taking place in the same time scale needed for a projectile to travel through the nucleus, (between 10^{-23} and 10^{-22} seconds) [9] some of which are listed below:

- Inelastic Scattering: The projectile leaves the nucleus in an excited state. The timescale of the deexcitation depends on the half-life $t_{1/2}$ of the excited state and can be prompt if $t_{1/2} < 1$ ns.

  $$^{12}C + p \rightarrow p' +^{12} C^*$$

- Stripping: Parts of the projectile are transferred to the target nucleus. The target nucleus usually remains in an excited state. Not so important in our case.

  $$^{12}C + p \rightarrow {}^{13}N^*$$

- Kick-off: The projectile remains in the nucleus but another nucleon leaves the nucleus. This reaction can be distinguished from inelastic scattering only if the projectile and emitted nucleus are not identical.

  $$^{12}C + p \rightarrow n +^{12} N^*$$

- Pick-up: The projectile takes a nucleon from the target nucleus.

  $$^{12}C + p \rightarrow d +^{11} C^*$$

The inelastic scatterings are the most important for prompt gamma emission among the ones listed above, while proton beam interacts with carbon thus the energy of protons for which proton-carbon inelastic scattering cross section peaks [10, 11] is considered. Unlike this reaction the rest of listed ones involve change in nuclei which might be more energy dependent, thus have less efficiency. The angular distribution of the direct reaction products shows typically the maximum in beam direction due to conservation of energy-momentum four-vector.

3. Geant4 Simulation

The Geant4 software (Version 10.6.3) was used to perform simulations of gamma rays, emitted during proton interaction with a carbon target, using reference physics model QGSP_BIC_HP_EMZ, which is usually used in proton therapy simulations [5]. The state-of-the-art of this work is Geant4 project created at the Physics Institute III B, RWTH Aachen University, which describes the experiment conducted at the Heidelberg Ion-Beam Therapy Center.

3.1 Simulation Setup

The simulation setup consists of a beam energy degrader and a thin slice made of carbon, with their relative thicknesses of 35.56 mm and 2.0 mm. The thickness of the degrader was changing by 2.0 mm steps in the different cases of simulations ranging from 16.00 mm to 40.00 mm. The geometry of simulation setup is shown in Figure1.

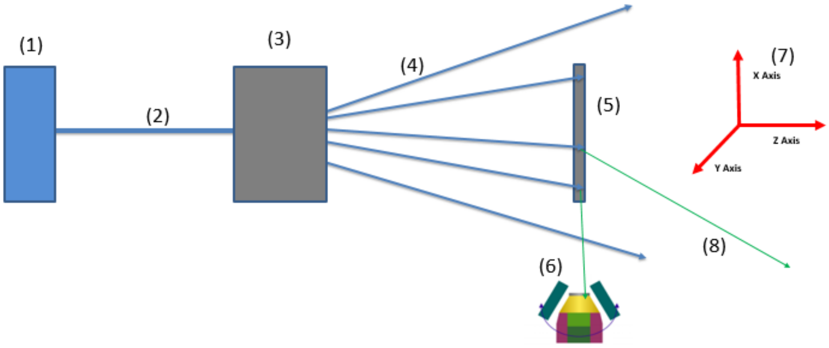


Figure 1: (1) The beam source, (2) the proton beam, (3) a carbon degrader, (4) proton beam after going through the degrader, (5) a thin slice, (6) a device detecting Prompt gammas, (7) naming of coordinate axes, (8) Prompt gammas emitted after de-excitement of carbons.

3.2 Proton Beam Parameters

The proton beam ejected from the beam source is initially a parallel beam with a mean energy of 88.97 MeV with standard deviation of 0.2 MeV which losses its energy and diverges when it goes through the degrader. Hence, the energy of a proton beam interacting with the thin slice is regulated by the degrader before interacting with the thin slice so that prompt gamma energy spectra can be calculated at each step by 2 mm interval before reaching the Bragg peak.

4. Results and Discussion

The work is intended to investigate features of prompt gammas as it was implemented in Geant4 software in order to describe the drawbacks of this software to describe the nuclear reactions responsible for prompt gamma emission. More precisely, the angular distributions and shapes of the prompt gamma 4.4 MeV and 9.63 MeV lines were investigated. While simulating prompt gammas emitted towards different angles relative to a beam direction, two effects were important: the angular distribution of the products of carbon de-excitement, which influences the number of gammas emitted in a particular direction and kinematic Doppler effect which influences the beam shape. The cases which illustrate how these effects are implemented in Geant4 Software is shown in the following Chapter.

4.1 Prompt Gamma Spectrum detected from six different Angles

As the products of direct nuclear reactions normally show the peak in a beam direction, the angular distributions of prompt gammas ware tested with Geant4 software. The energy spectrum of prompt gammas emitted through six different cylindrically symmetrical regions on the surface of sphere, in the center of which the thin slice is located, was recorded. Each of these regions cover the 30^o of azimuth angle.

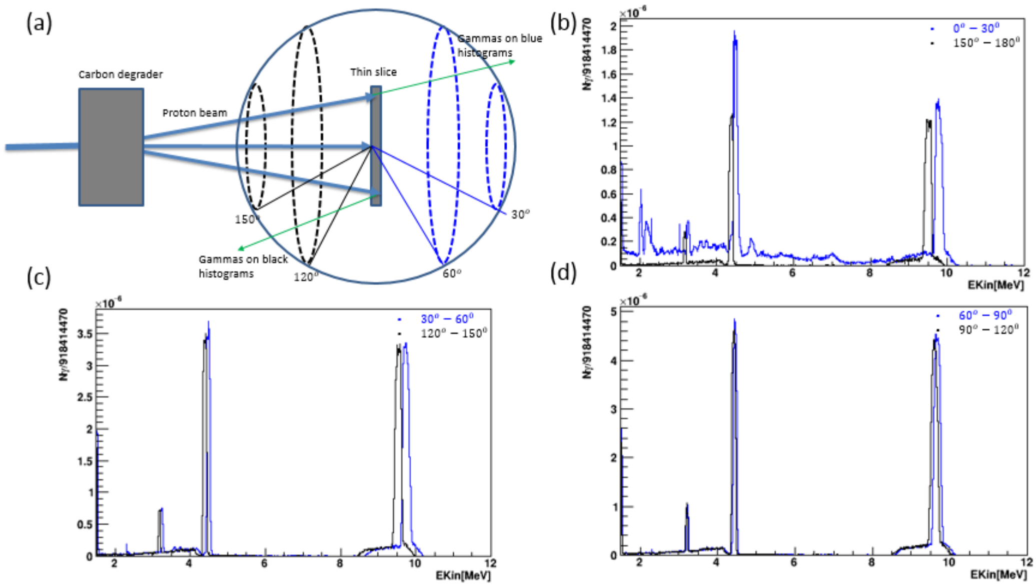
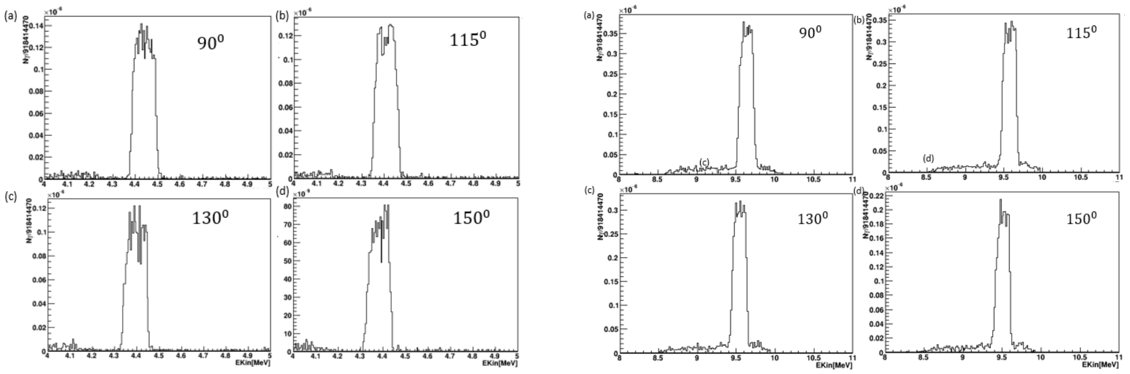


Figure 2: (a) The figure shows gamma detection setup. The gammas crossing the surface enclosed by Blue and Black circles are shown on figure (c). The figures (b), (c) and (d) illustrate the normalized spectrum of gamma particles emitted through the oppositely arranged angles, there the number of protons in a beam is $9.1 * 10^8$. The Blue histogram on figure (b) shows the gammas emitted by angles between 0^o and 30^o and Black one shows the same for the angles between 150^o and 180^o. The same is shown on figures (c) and (d) for another two couples of angle ranges.

Though nuclear reaction products are normally peaks in the beam direction, according to the current Geant4 model more gammas are emitted perpendicularly to the beams initial direction, which is more significant for 9.6 MeV gamma peak. Small difference between peaks on blue and black histograms were considered to be caused by kinematic effects.

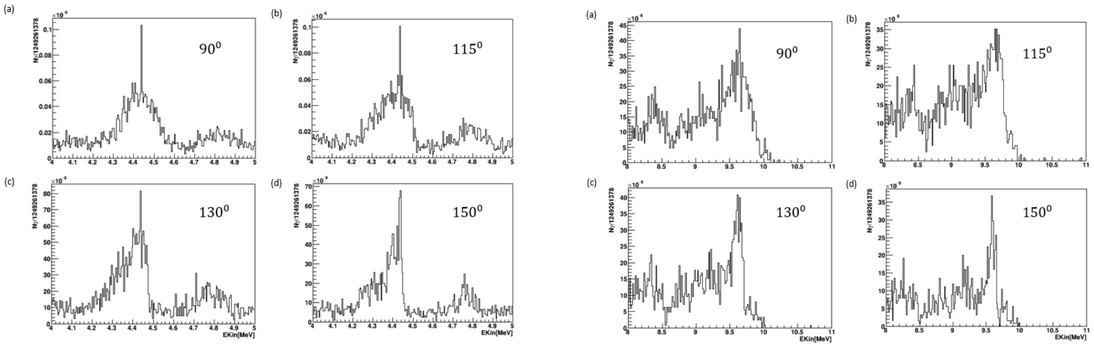
4.2 4.4 MeV and 9.64 MeV Gamma line shapes

As it is shown in Figure1 the detector covers just a little part of the solid angle, of the sphere which is crossed by prompt gammas in Figure 2. So taking the detectors geometry and acceptance into account is crucial in order to see the effects not visible for a large detection angle as it was in Chapter 4.1. In the configuration described in Chapter 3.1 the detector covers just the 0.018° azimuth angle of the circle the diameter of which coincides with the proton beam. However, cylindrical symmetry of emitted Prompt Gammas while proton beam is flowing along Z axis was used to increase gamma registration efficiency on simulations, this might not be the case on the experiment.



(a) 4.4 MeV line **(b)** 9.6 MeV line

Figure 3: 4.4MeV and 9.64 MeV gamma lines detected from different angles, then degraded proton beam mean energy is 17.56 MeV



(a) 4.4 MeV line **(b)** 9.6 MeV line

Figure 4: 4.4MeV and 9.64 MeV gamma lines detected from different angle for 63.22 MeV initial kinetic energy of proton beam.

As it is displayed on Figure 3, the effects of Doppler broadening and magnetic sub-levels of the excited state of carbon is not visible neither for 4.4 MeV nor for 9.6 MeV Gamma line, unlike the experiment on which these effects was observed for 4.4 MeV gamma line Figure 5, when kinetic energy of the degraded proton beam was 17.56 MeV [8]. Although 9.6 MeV line state refers to 3^- excited carbon state for which the same effects might be also important, there is no experimental results for this line to refer to.

The effects of kinematic Doppler broadening is more important for higher energies of impinging proton beam, so 4.4 MeV line was diverged in case of the proton beam energy of 63.22 MeV for simulated histograms Figure 4. Although, this effect diverges the 4.4 MeV Peak in 0.2 MeV interval considering the experimental results Figure 5 for lower energies impinging protons, the same scale of divergence is maintained for simulated one Figure 3 without considering the errors of measurements [8] . Another flaw of the software models lies in the sharp line existing right at 4.4 MeV bin which goes up much faster than the background of the spectrum while the number of events increases and this may not be related to radioactive decays implemented in Geant4 physics list.

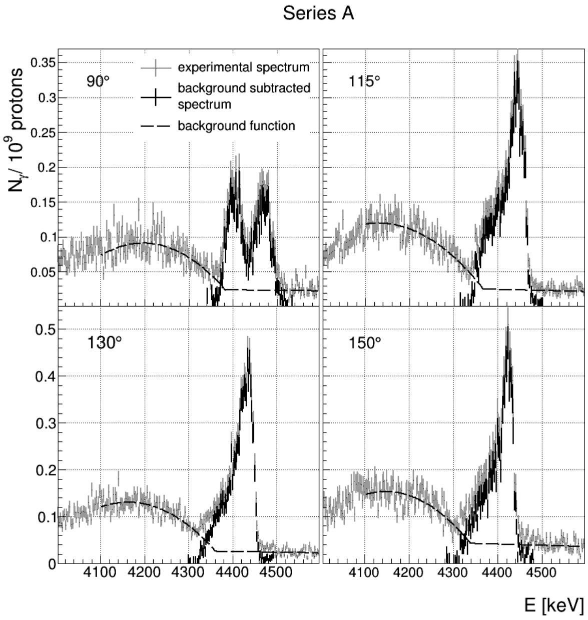


Figure 5: Experimental 4.4MeV carbon lines as measured and after background subtraction.The experimental data has been plotted in gray, the background subtracted spectrum has been plotted in black, and a dashed line is the fitted background function. Gamma spectra were recorded from the thin target with the use of a HPGe detector with an active Compton shield. The detector was placed on a movable platform (Figure 1 and Figure 2(a)), which allowed for remote control of its angular position. The thin target was the center of rotation. Additionally, a passive shield in the form of a lead sarcophagus for the detector was provided [8].

5. Conclusion

This work was intended to investigate to what extent the Geant4 model QGSP_BIC_HP_EMZ describes the process of prompt gamma emission in carbon-proton interactions close to a Bragg peak. Multiple peaks observed in the experiments are not visible neither for 4.4 MeV nor for 9.6 MeV lines in the simulations. In addition, sharp peak emerged in simulated prompt gamma energy distributions for energy of protons up to 50 MeV at exactly 4.4 MeV detected from different angles. The origin of this peak is not clear and it is subject of further investigations.

References

[1] https://www.who.int/news-room/fact-sheets/detail/cancer

[2] Min, C.H., Kim, C.H., Youn, M.Y. and Kim, J.W. (2006) *Prompt Gamma Measurements for Locating the Dose Falloff Region in the Proton Therapy. Applied Physics Letters*, *89* **Article ID:** 183517.

[3] Pinto, M., et al. (2015) *Absolute Prompt-Gamma Yield Measurements for Ion Beam Therapy Monitoring. Physics in Medicine and Biology*, *60* 565-594 .

[4] J.M.Verburg and J.Seco. *Proton range verification through prompt gamma-ray spectroscopy.* Phys Med Biol, 59 (23) (2014)

[5] https://geant4.web.cern.ch

[6] G. Musiol at all, Kern- und Teilchenphysik. Verlag Harri Deutsch, 1995.

[7] H. Enge, *Introduction to nuclear physics. Addison-Wesley series in physics*, Addison-Wesley Pub. Co., 1966.

[8] K.Rusiecka at all, *Shape of the Spectral Line And Gamma Angular Distribution of the 12C(p, p'γ4.44)12C Reaction* Received Feburuary 14, 2018; Accepted July 17, 2018, Katowice, Poland.

[9] K. Bethge at all, Springer Berlin Heidelberg, 2008.

[10] L. Kelleter *Spectroscopic Study of Prompt Gamma Emission for Online Range Verification in Proton Therapy* Master Thesis, Physics Institute III B, RWTH Aachen University, March 2016, Aachen, Germany.

[11] F. L. Lang and C. W. Werntz, *Cross section for production of the 15.10-MeV and other astrophysically signi*
cant gamma-ray lines through excitation and spallation of 12C and 16O with protons," Physical Review C, vol. 35, pp. 1214, 1227, 1987.

[12] Min, C.H. at all, *Prompt Gamma Measurements for Locating the Dose Falloff Region in the Proton Therapy*, *Applied Physics Letters, 89, rticle ID:* 183517, 2006.

[13] Moteabbed, M. *Monte Carlo Patient Study on the Comparison of Prompt Gamma and PET Imaging for Range Verification in Proton Therapy*, *Physics in Medicine and Biology, 56,* 1063-1082, 2011.

[14] Wrońska, A.at all, *Prompt-gamma emission in GEANT4 revisited and confronted with experiment*. *Physica Medica, 88,* 250–261, 2021.