COMPARISON OF VARIOUS MODELS OF MONTE CARLO GEANT 4 CODE IN SIMULATIONS OF PROMPT GAMMA PRODUCTION*

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(Received January 17, 2017)

In this paper, results of simulations of the gamma-ray production in reactions with 70 MeV protons in a target of PMMA are presented. The data obtained by means of two versions of Geant 4 software, 9.3 and 10.01, have shown significant differences in the gamma-ray spectra. The comparison between the calculated spectra and the measured ones has been carried out. The tested versions do not give satisfactory agreement with the experimental result. The reason of the performed verification was the planned application of this simulation toolkit for the preparation of *in vivo* dosimetry based on the prompt gamma-ray measurements for the proton therapy.

DOI:10.5506/APhysPolB.48.675

1. Introduction

Monte Carlo simulations are increasingly used in medical physics. Particularly, they are very useful for the development of innovative techniques of contemporary radiotherapy. One of the widely applied Monte Carlo toolkit is the Geant 4 software. This Monte Carlo toolkit [1] provides models for

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 28–September 4, 2016.

simulations of low-energy proton inelastic nuclear reactions making it possible to calculate the prompt gamma-ray spectra. The purpose of this work was verification of two Geant 4 versions (9.3 and 10.01) in the range of the prompt gamma-ray production in reactions with 70 MeV protons in a target of poly(methyl methacrylate) (PMMA). The reason of the performed test was the planned application of the Geant 4 code for the preparation of *in vivo* dosimetry based on the prompt gamma-ray measurements for the proton therapy.

2. Methods

2.1. Experimental data

The measurements were performed using the 70 MeV proton beam delivered by the PROTEUS C-235 cyclotron. The target was made of PMMA with the density of 1.19 g/cm^3 and with the thickness of 36 mm which is enough to observe the Bragg peak. The Bragg peak position was at 34.7 mm from a surface of the target. The gamma-ray spectra were measured by means of the High-Purity Germanium detector (HPGe) with an anti-Compton shield set at 60° relative to the beam axis. The detailed description of the experiment is included in [2].

2.2. Geant 4

Geant 4 is used to simulate interactions of particles as they traverse through the matter. The presented work is based on the use of Geant 4.9.3 (2009) and 10.01 (2015). Geant 4 provides physical models that we used for simulations of proton interactions inside the human tissue equivalent material *i.e.* PMMA. In this work, there were used models: QGSP_BIC provided in the version 9.3 and QGSP_BIC_EMY provided in the 10.01 version [3]. Both models consist of components related to different energy range. The QGSP (Quark–Gluon String Precompound) includes the basic physics with the quark–gluon string model for high energy interactions of protons, neutrons, pions, kaons and nuclei. The BIC model (Binary Cascade) generates the final state for hadron inelastic scattering by simulating the intra-nuclear cascade. This model reproduces detailed proton and neutron cross-section data in the region below 10 GeV [1].

2.3. Simulations

The parameters of the simulated proton beam hitting the target were the same as for the experimental beam. The spatial proton distribution on the target surface was implemented in strict accordance with the terms of the proton beam used in the experiment. The spatial beam distribution in the direction perpendicular to the target surface was modelled with a 2d-Gaussian distribution with $\sigma_x = 2.6$ mm and $\sigma_y = 0.7$ mm. In order to get the best agreement with the experiment, the response of the HPGe detector was simulated keeping the whole geometry of the experimental system, including the position of the detector and the target relative to the proton beam as well as the dimensions of the target and the detector, *etc.*

3. Results and discussion

The particularly significant lines for the *in vivo* dosimetry in proton therapy come from the transitions: $^{16}O_{6.13\to gs}$ and $^{12}C_{4.44\to gs}$ (Fig. 1). In the spectrum calculated by means of Geant 4.9.3 with the models implemented from QGSP_BIC, the lines at 4.44 MeV and at 6.13 MeV are clearly visible,

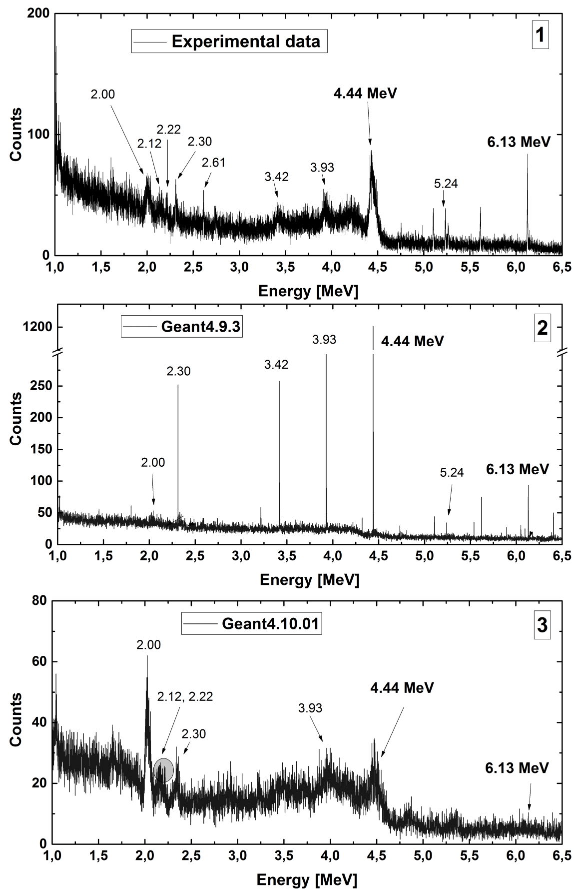

Fig. 1. The spectrum of gamma rays produced within the PMMA target with the thickness of 36 mm: (1) measured with the use of the High-Purity Germanium detector (experimental data: GammaCCB experiment — June 2014), (2) obtained in the simulation with the use of Geant 4.9.3, (3) obtained in the simulation with the use of Geant 4.10.01. Binning is 0.4 keV per bin.

but their proportions as well as the shape of the peaks are different from the experimental ones (Fig. 1 (2)). Geant 4.10.01 with the models implemented from QGSP_BIC_EMY provides the clear line at 4.44 MeV. The line at 6.13 MeV is hardly visible within the background radiation (Fig. 1 (3)). We observe the broadening of spectral lines. Basing on the comparison between the calculated gamma-rays spectra and the measured data (Fig.1 (1)), one can observe certain improvement of the newer Geant 4 version with respect to the 9.3 one. Table I provides relative areas A_x under all peaks identified in the spectra. All areas were related to the 4.44 MeV peak. Additionally, values of FWHM were determined and included in Table I. The obtained results suggest that simulations still require modifications to obtain better agreement with the experiment.

TABLE I

Summary of the identified gamma lines: E [MeV] — energy of the identified peak, A_x — the ratios of net areas of the area under the 4.44 MeV peak relative to the identified peaks, FWHM of the peaks. Reactions: ^{a} $^{12}C(p,p'n\gamma)^{11}C$, ^{b} second escape peak 4.44 MeV, ^{c} single escape peak 4.44 MeV, ^{d} $^{12}C(p,p'\gamma)^{12}C$, ^{e} $^{15}O(p,pp'\gamma)^{15}O$, ^{f} $^{16}O(p,p'\gamma)^{16}O$.

	Experimental data		Geant 4.9.3		Geant 4.10.1	
E [MeV]	A_x	FWHM [keV]	A_x	FWHM [keV]	A_x	FWHM [keV]
2.00^{a}	1.41	120	—	—	1.04	61
2.30	2.35	95	0.60	1	1.87	126
3.42^{b}	1.64	205	0.88	2	—	—
3.93^{c}	1.45	155	0.98	3	1.33	171
4.44^{d}	1.00	91	1.00	4	1.00	218
5.24^{e}	15.54	8	4.63	18	—	—
6.13^{f}	9.45	6	5.41	1	—	—

4. Conclusions

Our study has shown that the Geant 4 simulation toolkit gives a possibility of the Monte Carlo simulation of prompt gamma rays in the proton beam mode. However, the tested versions of this software do not give expected results for spectral lines. Optimization of the code focusing on proton hadronic inelastic models and cross sections is needed.

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