COMPARISON OF THE RESULTS OF DIFFERENT ELECTROMAGNETIC PROCESS MODELS IN GEANT4 FOR THE MODELING OF THE RESPONSE OF THE POINT–LIKE GAMMA–RADIATION SOURCE DETECTION UNIT

Malykhina T.V.

Kharkiv National University, Kharkiv, Ukraine

1. Problem formulation. The search for sources of penetrating radiation is very important for the development of facilities for locating radioactive sources that emerged from various technogenic catastrophes and radiation accidents. The relevance of finding a source of the penetrative radiation became apparent after the Chernobyl accident which resulted in the distribution of fuel fragments over a large territory. The detection of their location was a priority task during cleaning the contaminated areas.

2. A brief review of literature. Attempts to create models of relatively inexpensive devices for determining the direction to the radiation source were made earlier. The method for determining the direction on the plane with a variable thickness absorber (with the thickness of not greater than 2 cm) was considered by many authors and a circular absorber with two detectors was used [1, 2]. However, data obtained from experiments with models of the developed devices did not allow to make a conclusion about the uniqueness of the direction to the source even in a planar form. The prototype of device for determining the direction to point sources of gamma radiation is presented in Ref. [3]. A series of experiments was carried out for identifying the possibility of determining the direction of the radiation source. The isotope Cs–137, i.e. gamma–quanta of energy 661 keV, situated within 0,8 m from geometrical center of the absorber was used as a radioactive source. The measurements were carried out at 20^{o} step-type rotation of the absorber in three dimensions. The direction of the source of gamma radiation is offered for determining by the ratio of intensities of penetrating radiation measured by first and second detectors [3]. Computer simulation of the response of detector blocks was carried out in Ref. 4. Modeling was conducted using the program written on the C++ language, which uses the Geant4 toolkit [5, 6] and was created specifically for this task.

The purpose of this work is to analyze the results of two methods the Geant4 simulation of the device for location a point-like source of gamma radiation. This work is topical because it is necessary to choose the appropriate model of physical processes, scope, etc. at modeling the interaction of radiation with matter.

3. The Geant4–simulation of the detector block. There are various toolkits based on the Monte–Carlo method developed for the interaction process simulation between the radiation and the matter. Each toolkit has its own area of usage and also its own limitations. Geant4 is a toolkit for the simulation of the passage of particles through matter and fields. It includes a complete range of functionality including tracking, geometry, physics models and hits. The physics processes offered cover a comprehensive range, including electromagnetic, hadronic and optical processes, a large set of long-lived particles, materials and elements, over a wide energy range. Geant4 was used to develop two programs for two ways of modeling of the passage of gamma rays through the detector block of the device. Geometrical parameters of the device model were set according to geometrical parameters of the device prototype. Block diagram of detector setup is shown in Fig. 1. Detector block is an aluminum ball S0, its diameter is 50 mm. There are two CdTe detectors D1 and D2 inside the S0, each of which is cube with edge 5 mm, and detector D2 is located in a spherical cavity S1 of radius 15 mm.

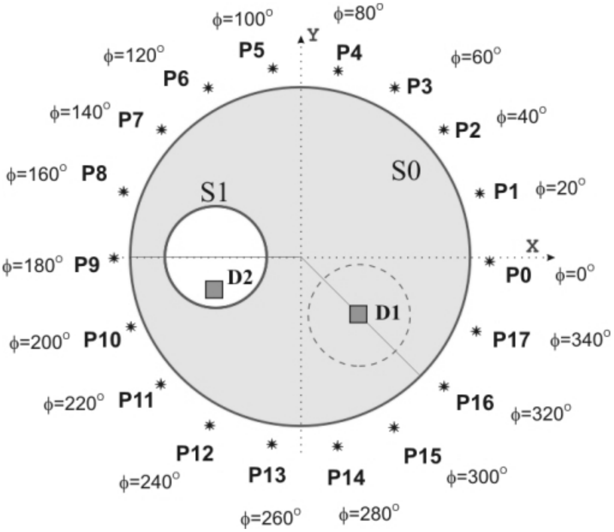

Fig.1. Scheme of the detector block.

Points P0 – P17 are locations of gamma radiation sources during each series of simulations. Parameters of the detector block are described in details in the Ref. [4]. The task of determining the direction of the arrival of gamma rays may be solved by calculating the difference between fluxes of gamma rays in detectors D1 and D2. The difference in fluxes results from the fact that gamma quanta pass different paths in the medium before being absorbed in the detectors (see Fig. 1). The experiment with a model of the device was described in the Ref. [3]. An isotope Cs–137, i.e., gamma-quanta with energy 661 keV was used as a source of gamma radiation. Therefore low-energy models of electromagnetic processes were selected for simulations.

It is possible to use two different models for the description of low energy electromagnetic processes (Geant4.9.4, December 2010) to simulate the passage of gamma rays through matter. These models are called “Livermore” and “Penelope” [6]. The model name "Livermore" comes from the name of the Livermore city, USA. This model uses a tabular data from E. Lawrence Livermore National Laboratory [7]. The model name "Penelope" – an acronym derived from the name of the simulation toolkit Penelope (PENetration and Energy LOss of Positrons and Electrons in matter) [8].

It is known that gamma-quanta with an energy of 661 keV in passing through a substance undergo Compton effect, photoelectric effect [9]. Classes from the Geant4 toolkit necessary for modeling Compton scattering and photoelectric effect were used in developing computer programs to simulate the passage of gamma rays through the detector block device. Thus, G4LivermoreComptonModel and G4LivermorePhotoElectricModel classes were used in the program based on the model of "Livermore", G4PenelopeComptonModel and G4PenelopePhotoElectricModel classes were used in the program, based on the model of "Penelope". List of classes from the Geant4 toolkit that used for the first and second modeling methods are given in Table 1.

Table 1. Geant4 classes which used for description electromagnetic processes

The “*Livermore*” model	The “*Penelope*” model
Compton scattering	
G4LivermoreComptonModel	G4PenelopeComptonModel
Photoelectric effect	
G4LivermorePhotoElectricModel	G4PenelopePhotoElectricModel

4. Description of used electromagnetic processes.

4.1. Compton scattering . Compton scattering cross section calculations performed by the empirical formula [6] when using the "Livermore" model

$$\sigma(Z, E_\gamma) = P_1(Z)\cdot\frac{\log(1+2X)}{X} + \frac{P_2(Z)+P_3(Z)\cdot X + P_4(Z)\cdot X^2}{1+aX+bX^2+cX^3} \tag{1}$$

where Z – atomic number of a matter, E_γ – energy of gamma quanta, $X = E_\gamma / m_e c^2$, m_e – electron mass, $P_i(Z) = Z(d_i + e_i Z + f_i Z^2)$. Selection of empirical parameters a, b, c, d_i, e_i, f_i was carried out by the experimental points in the interval $1 \le Z \le 100$ [6].

The accuracy of Compton scattering cross section depends on the energy of incident gamma quanta

$$\frac{\Delta\sigma}{\sigma} = \begin{cases} \approx 10\% & 10\ \text{кеВ} \le E_\gamma \le 20\ \text{кеВ} \\ \le 5\% & E_\gamma > 20\ \text{кеВ} \end{cases} \tag{2}$$

The length of a free path $\lambda(E_\gamma)$ of gamma-quantum with energy E_γ before the Compton interaction is determined by the formula

$$\lambda(E_\gamma) = (\sum_i n_{ati}\cdot\sigma_i(E_\gamma))^{-1}, \tag{3}$$

where n_{ati} is number of atoms per unit volume of the ith element of the material.

A full cross section of Compton scattering is determined from the analytical parameterization when using the "Penelope" model. The formula (1) is used for gamma ray energies are higher than 5 MeV. For $E < 5$ MeV a more parameterization is used, which takes into account atomic binding effects and Doppler broadening.

$$\sigma(E) = 2\pi \int_{-1}^{1} \frac{r_e^2}{2} \frac{E_C^2}{E^2} \left(\frac{E_C}{E} + \frac{E}{E_C} - \sin^2\theta \right) \times \sum_{\text{shells}} f_i \Theta(E - U_i) n_i(p_z^{\max}) d(\cos\theta) \qquad (4)$$

where r_e – classical radius of the electron, θ – scattering angle, E_C – Compton energy that calculated by formula:

$$E_C = \frac{E}{1 + (E/(m_e c^2)) \cdot (1 - \cos\theta)} \qquad (5)$$

f_i – number of electrons in the i^th atomic shell, m_e – electron mass, U_i – ionization energy of the i^th atomic shell, Θ – Heaviside step function, $p_z^{\max}$ – highest possible value of p_z (projection of the initial momentum of the electron in the direction of the scattering angle):

$$p_z^{\max} = \frac{E(E - U_i)(1 - \cos\theta) - m_e c^2 U_i}{c \cdot \sqrt{2E(E - U_i)(1 - \cos\theta) + U_i^2}} \qquad (6)$$

The integration of (4) is performed numerically using the 20-point Gaussian method [6].

4.2. Photoelectric effect. Tabular data from LLNL (E. Lawrence Livermore National Laboratory) used in modeling low-energy electromagnetic processes with the use of any of the models being considered. A full cross section for photoelectric effects of gamma-quantum with energy E is determined by interpolation [6]:

$$\log(\sigma(E)) = \frac{\log(\sigma_1)\log(E_2 / E) + \log(\sigma_2)\log(E / E_1)}{\log(E_2 / E_1)} \qquad (7)$$

where E_1 and E_2 are respectively the closest lower and higher energy for which data σ_1 and σ_2 are available.

5. Results of simulations. Simulation of gamma rays passing through the detector block device was carried out using two models of low energy electromagnetic processes. Spectra of the absorbed energy in the detector D2, were calculated in two ways and are shown on Fig. 2. The number of primary gamma rays with energies 661 keV is the same for two ways of modeling and is equal 10^8. The source of gamma rays is located at coordinates $\theta = 90°$, $\varphi = 180°$ (see Fig. 1), radiation is modeled uniformly in 4π.

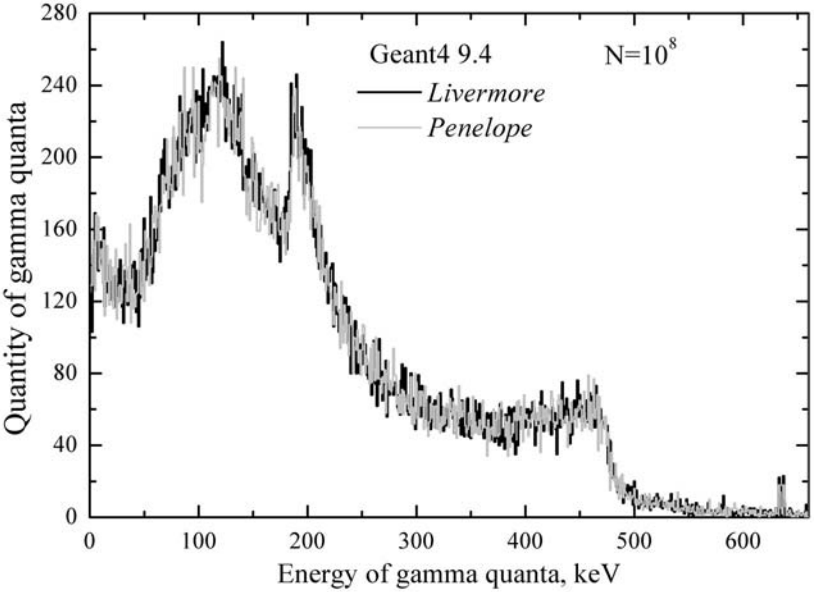

Fig. 2. Simulated spectra of the absorbed energy.

Spectra obtained using two different models are almost identical, as can be seen from Fig. 2. Both programs were developed to work at interactive and batch modes. The interactive mode uses OpenGL library and is designed mainly for visualization of the model of detector unit for a visual representation of a mutual arrangement of elements and observation of trajectories of primary gamma rays and secondary particles and so on. Batch mode is designed to simulate a large number of events. All results are stored in text files for further statistical processing.

The calculations described above were conducted in batch mode on a computer with Windows7 operating system. This computer has the following configuration: Intel Core i7 2600K quad-core CPU with a frequency of 3.7 GHz, 1667 DDR3 RAM of 8 GB and so on. The program, based on the "Livermore" model was running for about 35 minutes, and the program based on the "Penelope" model run 50 minutes, i.e., requires more time due to more cumbersome calculations.

Two series of simulations for the same quantity ($N_{events} = 10^8$) of primary gamma rays were conducted for the first model of electromagnetic processes ("Livermore") and for the second model ("Penelope").

Modeling was conducted at the location of gamma radiation source as shown in Fig.1. Polar angle $\theta = 90°$, azimuth angle φ was varied from –40° to 320°. The energy of gamma quanta was equal to 661 keV. Simulation results and their comparison with experimental data [3] are shown in Fig. 3.

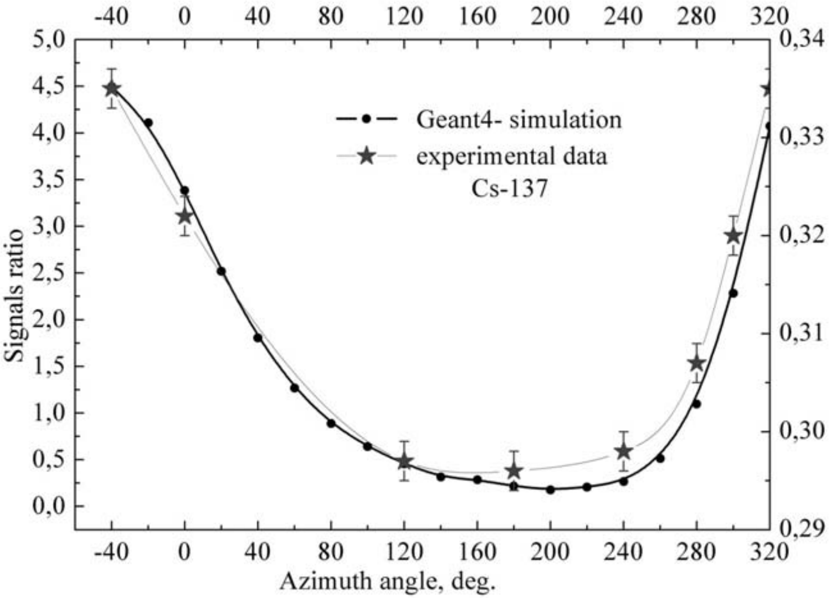

Fig. 3. The value of the signals ratio in the detectors

Simulated coefficients of signals ratio in the detectors are identical for different ways of modeling (see Fig. 3) and are comparable with the results of the experiment [3].

6. Conclusions. Simulation results show that there are differences only within the statistical error in this energy range. However, the program based on the "Penelope" model demanded more time for simulation due to more cumbersome calculations.

As a result the conclusion of the applicability of both models of electromagnetic processes in Geant4 can be made but it is more preferable to use "Livermore" model.

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