Simulation of Gamma Rays Attenuation Through Matters Using the Monte Carlo Program

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Abstract. This research focuses on simulation of the radiation attenuation using a Monte Carlo program called GEANT4. In the simulation, properties and geometries of the shielding system including thickness and element of the shielding material can be varied. The radiation in gamma rays regime is considered to be emitted from a Cs-137 radioactive source. The number of gamma photons at specific energy of 661.7 keV is calculated to compare the ability of radiation attenuation for different shielding materials with variable thickness. In addition, the experimental investigation was performed for three materials, which are lead, aluminum and iron, by using a NaI(Tl) scintillation detector. Then, the XCOM database were calculated to compare the results with the simulation. Both XCOM and simulation data as well as the experimental results are agreed well to the theoretical suggestion. Consequently, the results from Monte Carlo simulation using GEANT4 can be used to design the radiation shielding system for radioactive laboratories, particle accelerator institutes, radiotherapy area in hospitals, nuclear power plants, etc.

1. Introduction

The high-energy radiation like gamma rays or x-rays can be dangerous for people who work with the radiation sources such as nuclear power plants, medical radiotherapy centers and particle accelerator laboratories. These radiations can cause cancer or brutally diseases. Thus, the proper radiation shielding with sufficient radiation attenuation is very important to protect people and environment from the harmful radiation. There are many researches, which were studied to find the radiation attenuation capability of elements or compounds [1].

The radiation attenuation is an intrinsic property of materials, which can be explained by the exponential decay equation as

$$\frac{I}{I_0} = e^{-\mu x}, \tag{1}$$

where I and I_0 are the initial and the attenuated intensity of photons, respectively. The quantity x is the thickness of material and μ is the linear attenuation coefficient. Typically, the linear attenuation coefficient has a unit of cm^{-1}. However, it can be defined as the mass attenuation coefficient μ/ρ in a unit of cm^2g^{-1}. The attenuation of the radiation in the material depends on the interaction of photons with atoms, electrons or molecules in matter including coherent scattering, Compton scattering, photoelectric effect and pair production [2, 3].

This research studies on the radiation attenuation by using gamma rays with energy of 661.7 keV, which is produced from a standard Cs-137 radioactive source, to find the linear attenuation coefficient of three materials i.e. lead (Pb), aluminum (Al) and iron (Fe). We used a NaI(Tl) scintillation detector to measure the number of photons after the gamma rays penetrating the material. Then, simulation with the same geometry and setup parameters was conducted with the computer program called GEANT4. The linear attenuation coefficients obtained from the experiments and the simulation are compared with the data base from the XCOM calculation [4].

GEANT4 is a simulation toolkit using Monte Carlo method for tracking particles and analysing the tracked particles through materials in the considered system, which is desired with corresponding physics and geometry by the user [5]. This simulation program is based on the object-oriented coding with C++ programming language. It has separated classes of coding essentially for geometry construction, physics lists and particle generation. GEANT4 can be used for various elementary particles i.e. electrons, photons, protons, neutrons, ions or high energy particles in energy range from 250 eV to TeV. The simulation can be conducted with various physics and phenomena including electromagnetic, hadronic and optical processes [6]. Simulation results obtained from this program were reported in many publications. As an example, it was used to simulate the attenuation of gamma rays through scintillation detectors [7], which shows that the result from the experiment is comparable to the simulation data obtained from program GEANT4. This example research confirms that the results from GEANT4 simulation can be used for approximating the mass attenuation coefficient in various materials and photon energies. Thus, we chose to use this program in our research to investigate the radiation attenuation property of Pb, Al and Fe with different considered system from the above mentioned reference.

2. Experimental investigation

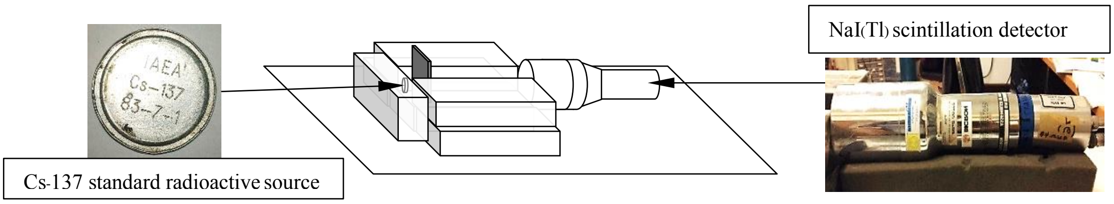

Figure 1. The lead chamber includes a Cs-137 standard radioactive source, a metal shielding plate (gray plate) and a NaI(Tl) scintillation detector.

In our experimental setup (as shown in fig.1) consists of a holder for a disk-like shape Cs-137 standard source, a lead chamber, a shielding plate and a NaI(Tl) scintillation detector. The lead chamber was constructed from six lead bricks with dimensions of 10x20x50 cm^3 to collimate the isotropically 661.7 keV gamma rays produced from the Cs-137 standard source to directly hit the detector with straight-like beam shape. The rectangular metal shielding plates were placed between the radiation source and the detector. Then, the amount of gamma rays was measured by the NaI(Tl) scintillation detector, which uses a photomultiplier tube to detect scintillated photons from the interaction between gamma rays and the NaI(Tl) crystal [3]. The shielding plates used in this experiment are made of lead, aluminum and iron with the density of 11.350, 7.874 and 2.699 g/cm^3 [1], respectively. The thickness of the shielding was adjusted by varying the number of plates placing inside the lead chamber. For each thickness, the gamma photons were counted by the detector for the life time of 200 seconds.

As an example, we present the experimental results of the calibrated energy spectra of gamma rays after passing through the lead plates with different thicknesses in fig. 2. Each energy spectrum has a dominant peak of gamma rays at 661.7 keV and a small peak at 30.1 keV. Furthermore, there are Compton effect spectral lines between the two peaks. As shown in the figure, the amount of gamma rays decreases when the thickness of the lead shielding increases. Considering the 661.7 keV peak, the decrease rates of gamma rays passing through the lead (Pb), aluminum (Al) and iron (Fe) plates are shown in fig. 3.

The results in fig. 3 show that amount of gamma rays is attenuated with exponential decay following the relationship suggested in Eq. (1). Thus, the linear attenuation coefficient (μ) can be obtained from the exponential fitting curves. As a result, the linear attenuation coefficients of aluminum, iron and lead are 0.180, 0.513 and 1.004 cm^{-1}, respectively. This concludes that lead has the better radiation attenuation property than iron and aluminum, respectively.

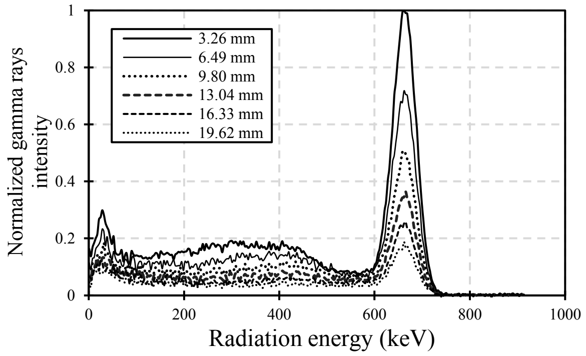

Figure 2. Energy spectra of the gamma photons produced from the Cs-137 standard source detected by the NaI(Tl) scintillation detector after the radiation passing through different thicknesses of the lead plates.

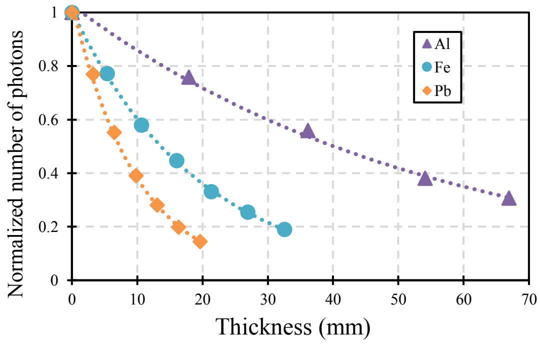

Figure 3. Normalized number of gamma photons at specific energy of 661.7 keV after the radiation passing through different thicknesses of Al, Fe and Pb shielding plates.

3. Simulation with GEANT4 program

The Monte Carlo simulation with program GEANT4 was performed by using the geometry as shown in fig. 4. This geometry is the same as the one we used in the experiment. The simulation processes are described in steps as followed. Firstly, the system was constructed in the UserDetectorConstruction class to be consisted of the lead chamber, the shielding material, and the NaI(Tl) scintillation detector. Then, related physics and phenomena were set in the UserPhysicLists class. In this research, we used the package called 'QBBC' including the EmStandardPhysics, which covers all interactions between photons and matter as mentioned in the introduction. Furthermore, the particle generation was set in the PrimaryGerneratorAction class to determine type, energy, direction and distribution of particles. In our case, the particles were set to be gamma photons with energy of 661.7 keV. The uniform distribution was used in both transverse and longitudinal directions. The beam of gamma photons was injected along the z-axis through the metal plate to the detector.

In terms of analysis, the values of interested parameters can be obtained from the UserScoreWriter class by meshing the material and recording the interested quantities after the particles passing through each mesh. In our case, the number of gamma photons at specific energy of 661.7 keV was recorded along the 20 cm of lead chamber with the resolution of 50 meshes per centimeter.

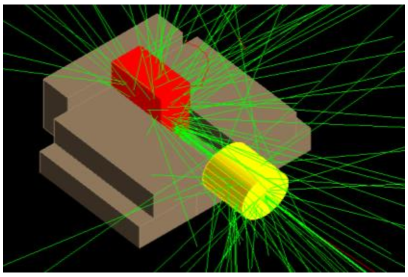

Figure 4. The system for GEANT4 simulation and visualized geometry with scattered photon trajectories.

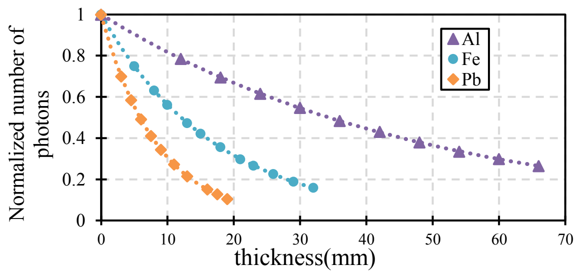

Figure 5. Simulation results using program GEANT4 with 100,000 incident gamma photons for specific energy of 661.7 keV.

The simulation results using 100,000 incident gamma photons with energy of 661.7 keV are shown in fig. 5. All graphs in fig. 5 have exponential decay curves as described in Eq. (1). The simulated linear attenuation coefficients of aluminum, iron and lead are 0.202, 0.574 and 1.183 cm^{-1}, respectively. These values are comparable to the values from the experiments with the deviation errors of 10.8%, 11.2% and 15.1%, respectively. The large discrepancy can be due to the different of geometry between the simulation and experimental setups. In simulation we used the homogeneous metal shielding with desired thickness but in the experiment we used several metal plates to vary the material thickness. In addition, the shielding plates using in the experiment seemed to be contaminated by metal oxides and might not pure materials. This can be observed from the color of the plates. While we used pure shielding materials in all simulations.

Moreover, the simulation to obtain the number of photons for every meshes was done in order to compare the simulated linear attenuation coefficient values with the XCOM database calculation [4]. The results in Table 1 show that the linear attenuation coefficients obtained from GEANT4 simulation are agree well to the calculated values obtained from the XCOM database. Thus, it is clearly that the simulation with GEANT4 can be used to desire and model the proper radiation attenuation system.

Table 1. Comparison of linear attenuation coefficients (*μ*) obtained from GEANT4 simulation and XCOM database calculation**.**

Material	μ from XCOM (cm^{-1})	μ from GEANT4 (cm^{-1})	Deviation error (%)
Iron	0.579	0.577	0.3
Lead	1.250	1.200	4.4
Aluminum	0.202	0.203	0.7

4. Conclusion

The attenuation efficiencies of lead (Pb), aluminium (Al) and iron (Fe) were experimentally and numerically investigated. The study results show that lead is the best shielding material with the linear attenuation coefficient of about 1.2 cm^{-1} and aluminium is the worst one. The estimated ratio of the linear attenuation coefficients for Pb: Fe: Al is 6: 3: 1. Furthermore, the simulated linear attenuation coefficients from GEANT4 calculation are comparable to the values from experiments and XCOM database, which are also agree well to the theoretical suggestion. Therefore, the Monte Carlo based program GEANT4 is suitable to simulate the radiation attenuation behavior of materials and to obtain the mass attenuation coefficients of pure elements or composite materials. Furthermore, it can be well used for modelling with flexible geometry and proper physics to design the suitable system for radiation attenuation.

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