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Application of GATE/GEANT 4 code in investigation of gamma shielding effectiveness of glass materials

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Abstract. GATE/GEANT4 code-based Monte Carlo simulations have been conducted and validated for the purpose of studying the mass attenuation coefficient of xR_mO_n: (100-x) SiO_2 glass systems (where R_mO_n are Bi_2O_3, PbO and BaO, with $30 \leq x \leq 70$ % by weight) at 662 keV. The results came in agreement with the ones previously obtained through WinXcom program. Consistency between simulation and experimental results is confirmed by using χ^2 test. The obtained results suggest the validity of using GATE for estimation of mass attenuation for different material compositions at different energies. This specific study recommends GATE simulation code as a suitable tool to investigate materials in the field of radiation shielding as an alternative to the experimental method.

1. Introduction

Mass attenuation coefficient is considered the most important characterization parameter of gamma-ray's interaction with a certain medium. This coefficient depends on the overall collective effects of the three main interaction mechanisms of a photon with matter – photoelectric absorption, Compton scattering and pair production [1].

There are two possible ways for determining the attenuation parameters of certain photon energy with certain material; one is the direct experimentation and the other is through modeling. As a matter of fact, determining experimental constants through experimentation is a difficult lengthy process, due to the necessity of employing high levels of accuracy customized upon the certain geometries of physical and mechanical parameters of the subject under experiment, such as collimation requirement for gamma source and detector in attenuation experiment. All of which could be avoided through modeling, mainly because of the high degrees of flexibility it provides, along with the ease of use. Consequently, using the right simulation tool with the right input data could be extremely useful as a pre-experiment step, or even for expanding the picture by adding results of different introduced modifications, like changing incident photon energies or the composition of the penetrated material.

For long time, we have witnessed the launch of different codes for particle transport. Like GEANT4, HZETERN, FLUKA, MULASSIS, SHIELDOSE2, MCNPX and SRIM. Researchers have been known to utilize these codes in shielding applications as to study the different materials attenuation properties [2–4].

One of the widely and most frequently used code of these is GEANT4 (GEometry ANd Tracking 4) which is an object-oriented Monte-Carlo based code for simulation of passage of particles transport through matter [5]. Being object-oriented based, it utilizes the notion of classes and objects. The user derives classes to describe the detector geometry, primary particle generator and chose the physics processes models. The physics processes can be any of the electromagnetic, decay or hadronic physics adapted to the materials in use and the experimental data or parameterizations. In most of the physics processes models, included is photoelectric effect, Rayleigh and Compton scattering, pair production, ionization, positron annihilation, synchrotron and transition radiation, Bremsstrahlung, Auger electrons emission, scintillation and fluorescence, absorption, reflection, refraction, and Cherenkov effect.

GATE (Geant4 Application for Tomographic Emission) is a Monte Carlo simulation platform built to make use of a set of well-validated physics components in GEANT4; like physics models, efficient visualization utilities and geometry modeling. The Open GATE collaboration introduced GATE as an advanced open source software that is useful for radiotherapy and medical imaging via numerical simulations. Up till now, GATE supports tomographic emission simulation, optical imaging and computed tomography along with radiotherapy experiments for dose calculations [6–10]. In the present study, GATE is used for calculating mass attenuation coefficients of three different glass samples. Comparison between the simulation and experimental results will be presented, using the previously measured mass attenuation coefficients of these glasses [11]. GATE code's validation is achieved here through comparison between the simulation results and the experimental values, as well as the theoretical values obtained by WinXcom program at 662 keV.

2. Materials and Methods

Three glass systems of the form xR_mO_n:(100-x) SiO2 were investigated for the composition range of x from 30 to 70 (weight %), where R_mO_n is the dopant, in either Bi2O3; PbO or BaO. These glass systems were previously prepared and experimentally measured for gamma attenuation parameters at 0.662 MeV [11].

2.1. Simulation setup and Geometry.

The simulation code considered a parallel beam of a collimated mono-energetic gamma-rays, attenuated in the glass materials which were characterized by the atomic composition. As shown in figure 1. the simulation set-up consists of an energetic photon beam, obtained by a point source of gamma photons, impinging on a slab of the studied material. The activity of the source is represented by the used number of events (10^6) during the simulation process. Two collimators are used; one for the point source while one for the detector.

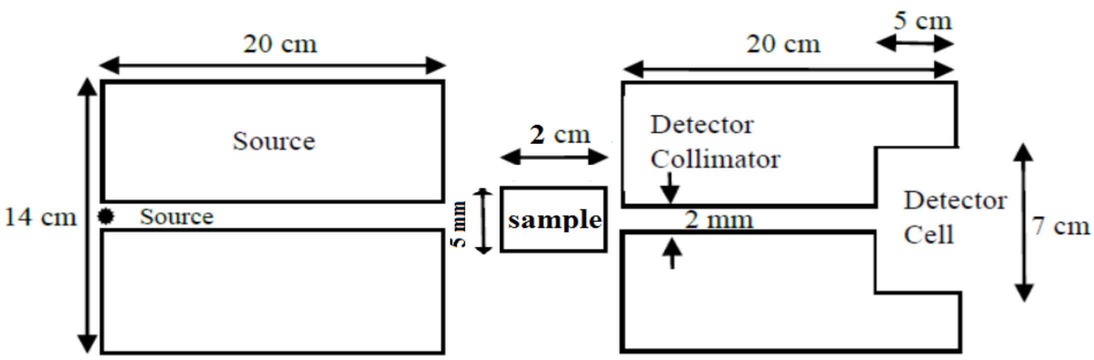

Figure 1. Simulation geometry setup.

The two collimators separated by 16 cm and are made of two lead cylinders of 14 cm outer diameter and of 20 cm length. The collimators inner diameters are of 2mm. The investigated samples have a cylinder shape of 5 mm diameter and 20 mm length. The world of the simulation setup has 5x5x5 m dimensions while the daughter has 3x3x3 m. The transmitted beam of photons is estimated for different thicknesses of each sample (1-10 cm).

The mass attenuation coefficients of the studied glasses were determined by the transmission method, according to Lambert-Beer's law.

$$I = I_0 e^{-\mu_m \rho x} \quad (1)$$

where I_0 and I are the incident and transmitted intensities of gamma photons, respectively. μ_m, x, ρ are the mass attenuation coefficient, the thickness (cm) and the mass density (g/cm^3) of the glass material respectively.

Attenuation of photons is calculated by simulating all relevant physical processes and interactions, before and after introducing the samples in the beam. Photon interactions used in the simulation include photoelectric effect, Compton scattering, pair production and Rayleigh scattering, while electrons interactions include Bremsstrahlung radiation, multiple scattering and ionization.

3. Results and Discussion

Figures 2-4 depict the results obtained from GATE 7.2, WinXcom, as well as the experimental results, of total mass attenuation coefficients for the selected glasses at 662 keV. The simulation results of the mass attenuation coefficients obtained from GATE are in satisfactory agreement with the experimental results. This agreement is quantified by using χ^2 test (χ^2 ranged from 0.018 to 0.096, at 0.05 significant level and $\chi^2_{critical} = 9.488$). The observed general discrepancy between the experimental and GATE values could be attributed to the various sources of experimental errors, and to non-stoichiometry of glass formula ratio after melting at high temperature. The large deviation observed at specific points could be attributed as well to the experimental errors. On the other hand, the obtained GATE results, when compared with the corresponding mass attenuation coefficient and theoretical calculations made by WinXcom shows very noticeable and promising agreement.

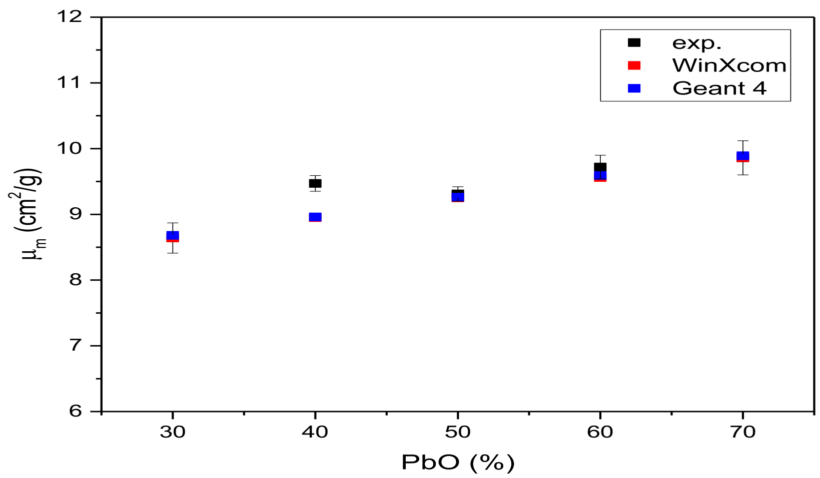

Figure 2. Mass attenuation coefficients of xPbO:(100-x) SiO2 glasses at 662 keV.

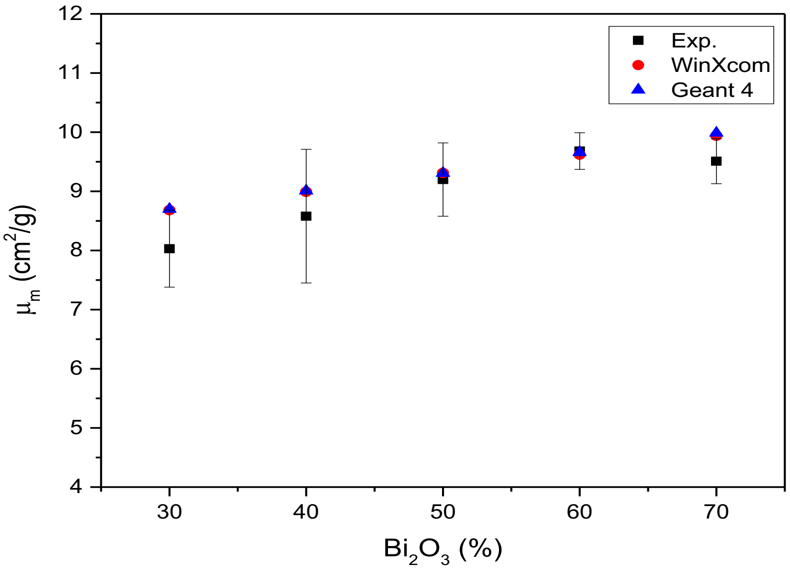

Figure 3. Mass attenuation coefficients of xBi_2O_3:(100-x) SiO2 glasses at 662 keV.

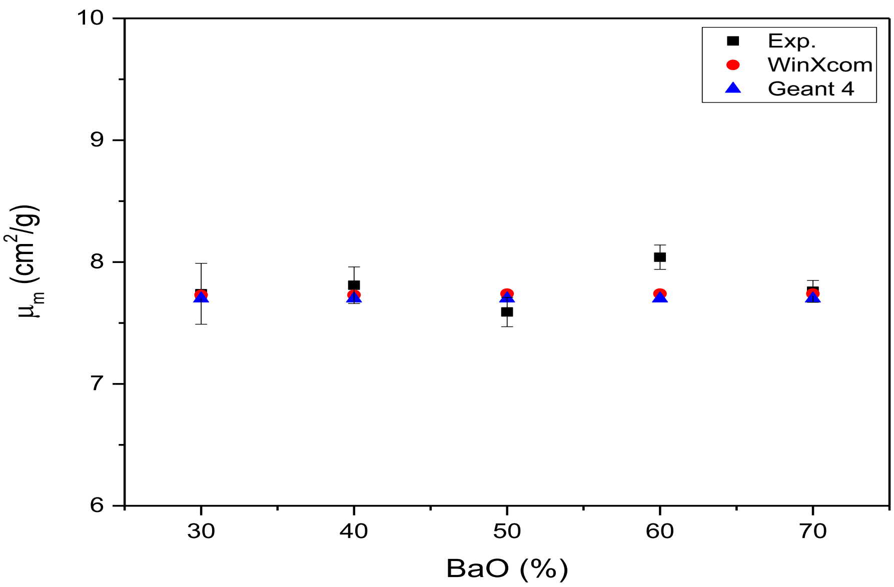

Figure 4. Mass attenuation coefficients of xBaO:(100-x) SiO2 glasses at 662 keV.

The attenuation coefficients for partial interactions due to photoelectric effect and Compton scattering are shown in table 1 and table 2. From tables 1 and 2, it is found that GATE simulation results for both photoelectric effect and Compton Scattering highly match those obtained by WinXcom program, while in general, the mass attenuation coefficients values simulated using GATE are slightly higher than those of WinXcom program for Compton scattering. On the contrary, WinXcom results come in higher values in the photoelectric effect interaction than GATE's.

Table 1. Photoelectric effect mass attenuation coefficient.

Photoelectric effect mass attenuation coefficient (cm^2/g)								
PbO %	WinXcom	Gate	BaO %	WinXcom	Gate	Bi_2O_3 %	WinXcom	Gat e
30	1.21	1.25	30	0.32	0.31	30	1.23	1.22
40	1.61	1.61	40	0.43	0.42	40	1.63	1.63
50	2.01	2.01	50	0.54	0.53	50	2.04	2.03
60	2.42	2.41	60	0.64	0.63	60	2.44	2.43
70	2.82	2.80	70	0.75	0.74	70	2.85	2.82

With regarding the energy dependence of material attenuation, the variations of the mass attenuation coefficient of 50PbO:50SiO2 glass composition at several photon energies in range from 0.238 to 2.615 MeV is presented in figure 5.

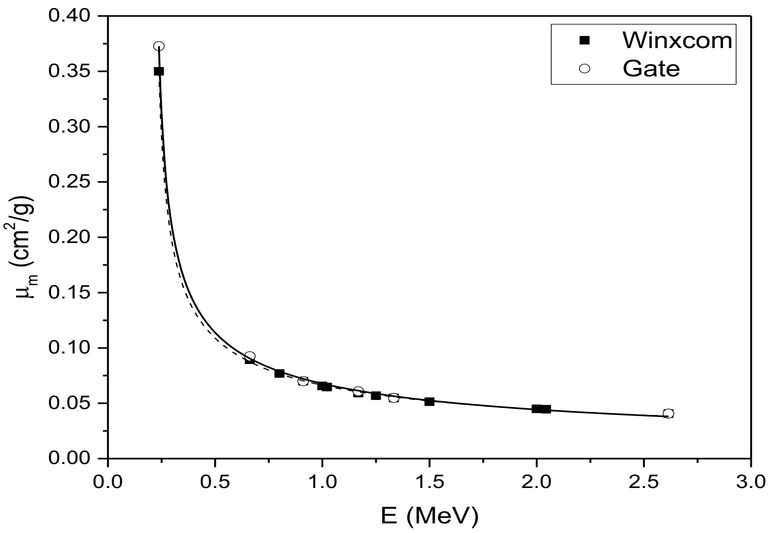

Figure 5. Variation of Mass attenuation coefficient with incident photon energy for $50PbO{:}50SiO_2$ glasses.

It is seen that the μ_m values of this glass composite are very large (~0.35 cm^{-1}) in the photoelectric absorption region and reduces gradually to become almost constant (~0.05 cm^{-1}) in the Compton scattering region (~1 to 2.615 MeV). Also from figure 5. agreement between the WinXcom data and those by Gate simulation is verified.

4. Conclusion

GATE simulation code is found to be able to successfully simulate attenuation of gamma ray radiation through a variety of material composition, at different photon energies. The mass attenuation coefficients of three different types of glassy materials at 661.6 keV photon energy were easily obtained. The simulated data was compared with those obtained experimentally and theoretically by WinXcom program. The results showed that the calculated values of mass attenuation coefficients of the investigated samples are in good agreement with the experimental values. On the other hand, the data of GATE and WinXcom came very close to each other. The partial gamma photon interaction results of GATE are in good agreement with those calculated via WinXcom. The variation of the mass attenuation coefficient with the incident photon energy is also simulated and validated. Hence, the present study suggests that GATE simulation is suitable to be used as an alternative approved method to the experimentation in the field of radiation shielding.

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