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Application of Monte Carlo Method for Gamma ray Attenuation Properties of Lead Zinc Borate Glasses

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Abstract

This work aims to introduce an useful computational model, based in Monte Carlo simulation, which can be used in practical application, and this paper presents values determined using a Monte Carlo algorithm for linear attenuation coefficient of lead zinc borate glasses with different percentages of PbO. The simulation results have been verified with predictions from the XCOM program in the studied energy region from 1 keV to 2000 keV and experimental results. Thus, this verification indicated that this research method can be followed to determine the interaction and attenuation of gamma rays with the several energies in different materials. Also, the values of mean free path and the half-value layer were calculated using the values of the linear attenuation coefficient. The dependence of these radiation shielding parameters on the energy of impinging gamma ray and the ratio of substances changes has been examined.

Keywords: Monte Carlo, gamma ray, attenuation, glass, shielding

1. INTRODUCTION

Monte Carlo method has for long been accepted as the most precise method for all the calculations that require the information of the probability distribution of responses of uncertain systems to uncertain inputs [1]. By the Monte Carlo technique, the works on particles' transport in materails can be performed successfully, with the knowledge of the elementary collision processes of particles. Monte Carlo method enables the simulation of particle transport processes with a physical reality. In these simulations, the traced particle is emitted according to distributions that describe the source. It travels in a path that determined by a probability distribution depending on the total interaction cross section and arrives to the site of a collision. According to the corresponding differential cross section, it scatters into another direction by an another energy. This process is continued until the particle is absorbed in slowing down material or leaves the geometry under consideration. Interested physical quantities can be achieved by calculations that use the average over a set of Monte Carlo particle histories. The statistical uncertainties of the calculations using simulation outputs depend on the number of simulated particle histories [2].

Monte Carlo simulation is the most reliable way to predict the effects of a gamma ray beam. Because fast computers are available, many codes have been developed that allow a detailed simulation of the passage of radiation through matter and provide information about attenuation of it in matter [3]. Moreover, it is very flexible, there is virtually no limit to the analysis. It can generally be easily extended and developed as required [4].

The linear attenuation coefficient is one of the important characteristics that need to be studied and determined prior to using a material in radiation applications since the accurate

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attenuation coefficient values of materials are a very essential parameter in nuclear and radiation physics, radiation dosimetry, spectrometry, biological, medical, agricultural, environmental and industrial [5]. It qualifies the diffusion and penetration of gamma radiation in matter and represents the probability per unit path length of gamma radiation that the gamma ray will have an interaction with absorber atom. It is the basic parameter to acquire several other parameters related to dosimetry and shielding, such as mass-energy absorption coefficient, molecular, atomic and electronic cross-sections, effective atomic numbers, electron densities, half-value layer and tenth-value layer thickness for shielding effectiveness [6].

Monte Carlo technique that considered as a powerful and reliable computational tool, was used in many studies regarding the characterization of several shielding materials [7-12]. In the present work, a computer simulation program based on Monte Carlo method was written to be as virtual experimental system, instead of the real experimental system, concerning evaluation of attenuation properties for studied glass materials.

2. MATERIALS AND METHOD

In this paper, shielding properties of lead zinc borate glasses (ZnO-PbO-B2O3) have been investigated by Monte Carlo technique. Chemical compositions and densities of studied glass samples [13] are shown in Table 1. Increasing the lead oxide (PbO) content of glass sample causes the increase in glass density as it is clear from this table.

Table 1. Chemical compositions of the studied glass samples

Sample No	Compositions (wt %)			Density
	B_2O_3	ZnO	PbO	(g cm^{-3})
1	70	10	20	3.675
2	50	10	40	5.088
3	25	25	50	5.917
4	30	10	60	6.212
5	25	5	70	6.650

Simulations for determination of gamma ray shielding properties of the samples were performed for gamma ray energies of 80, 356, 662, 1173 and 1332 keV. Outcomes of the simulation code were used to calculate the values of linear attenuation coefficient, half-value layer and mean free path, three of shielding properties, for the investigated samples. The equation below which is based on the Lambert–Beer law was used to calculate the linear attenuation coefficients (μ) of the samples.

$$\mu = \frac{1}{t_s} ln\left(\frac{I_0}{I}\right) \qquad (1)$$

where I_0 and I are the intensities of incident and transmitted gamma rays, respectively, and t_s is thickness of the attenuating sample. The transmitted gamma ray intensity was the outcome of the code. 1×10^7 gamma rays at points in the collimated beam were impinged on the glass sample and followed in this target. Tracking the gamma rays and attenuation of them in the target was detailed in our previous study [14]. In our algorithm, the free path length of each incident gamma ray is sampled according to an exponential distribution. Therefore, the cross sections of attenuating materials were derived from the XCOM program from NIST [15] and the relation given in Eq. (2) for fitting was written into the code for the calculation of cross sections (CS) for photoelectric effect and Compton scattering of glass samples for the energy range 10–2000 keV.

$$CS = exp(a + bx + cx^2 + dx^3 + ex^4) \qquad (2)$$

where x is the natural logarithm of the gamma ray energy and "a", "b", "c", "d" and "e" are the parameters for fitting photoelectric effect and Compton scattering cross sections. These parameters are acquired separately for each of glass samples.

In algorithm, gamma rays that arrive the detector are counted and this value is defined as the transmitted intensity (I) of gamma rays. The slope of a linear fit of ln(I_0/I) versus thickness of sample target (see Fig. 1) is obtained and this value of slope is utilized in Eq. (1).

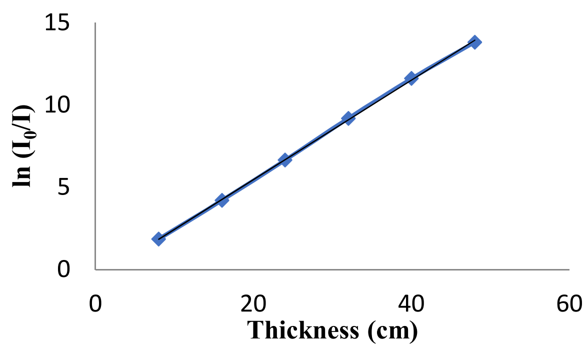

Figure 1. Plot of ln (I_0/I) versus attenuator material thickness (for Sample 3, %50 PbO, and 1332 keV gamma rays)

By using the linear attenuation coefficients achieved by the results from Monte Carlo simulations, half-value layer values were obtained for all samples by using the Eq. (3).

$$HVL = \frac{0.693}{\mu} \quad (3)$$

On the other hand, mean free path (MFP) values were calculated by the following relation that relates to linear attenuation coefficient:

$$MFP = \frac{1}{\mu} \quad (4)$$

3. RESULTS AND DISCUSSION

In this paper, we present a calculation method based on Monte Carlo algorithm to evaluate gamma ray attenuation properties of materials. Simulations were carried out using collimated beam of gamma rays with five different energies, 80, 356, 662, 1173 and 1332 keV.

The results for linear attenuation coefficient of glass samples obtained by simulation outputs have been successfully verified with experimental results [13] and theoretical ones [15]. The current calculated results and the published ones, experimental [13] and theoretical [15], are in good agreement as it is clear from Table 2. Small deviations observed between simulation results and literature values for all glass samples can be due to the experimental errors or utilization of fit function of cross-sections for glass samples in the written code.

Table 2. The linear attenuation coefficients of glass samples with different weight fraction of PbO at different gamma ray energies

Energy		Linear attenuation coefficients (cm^{-1})				
		Sample 1 (%20 PbO)	Sample 2 (%40 PbO)	Sample 3 (%50 PbO)	Sample 4 (%60 PbO)	Sample 5 (%70 PbO)
80 keV	Monte Carlo	2.0390	4.8298	7.1207	7.9735	9.4431
	Experiment	---	---	---	---	---
	XCOM	2.0830	4.7334	7.0176	8.0383	9.6492
356 keV	Monte Carlo	0.4587	0.8346	1.0377	1.1957	1.3793
	Experiment	---	---	---	---	---
	XCOM	0.4876	0.8516	1.0942	1.2551	1.4589
662 keV	Monte Carlo	0.2938	0.4375	0.5212	0.5531	0.6452
	Experiment	0.3072	0.4536	0.5399	0.5918	0.6582
	XCOM	0.2985	0.4426	0.5297	0.5762	0.6369
1173 keV	Monte Carlo	0.2097	0.2928	0.3336	0.3631	0.3912
	Experiment	0.2161	0.3082	0.3616	0.3850	0.4274
	XCOM	0.2127	0.2970	0.3449	0.3657	0.3939
1332 keV	Monte Carlo	0.1957	0.2732	0.3021	0.3379	0.3612
	Experiment	0.2049	0.2845	0.3283	0.3468	0.3787
	XCOM	0.1983	0.2754	0.3191	0.3374	0.3625

It is clear from Table 2 that the linear attenuation coefficient increases with the increasing density of the glass samples for both gamma ray energies.

Half-value layer (HVL) and mean free path (MFP) thicknesses of studied samples were calculated as being parameters for helping to quantify both the penetrating capability of gamma rays and the penetration through specified objects and plotted against the lead oxide content of them for the studied gamma ray energies in Figures 2 and 3. When HVL values are known, the penetration through other thicknesses can be easily determined.

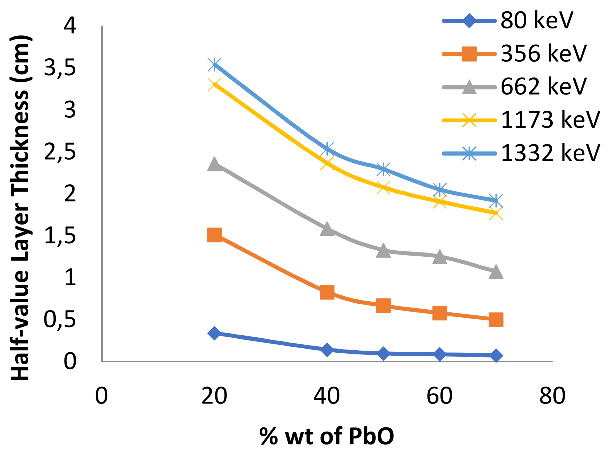

Figure 2. The half-value layer of glass samples versus lead oxide content for different gamma ray energies

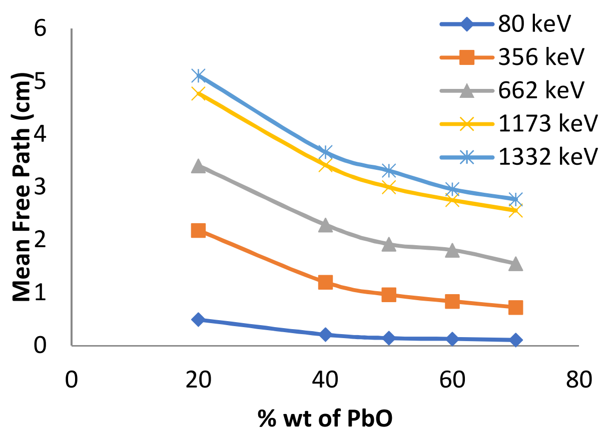

Figure 3. The mean free path of glass samples versus lead oxide content for different gamma ray energies

In Figures 2 and 3, both the half-value layer and the mean free path increase with the increase in the energy of gamma rays and decrease with increasing the lead oxide content, as an expected result.

All the calculations performed in the paper are required for the researchers who work with gamma radiation. Obtained quantities describe the shielding effectiveness of studied samples. Since the choice of shielding material and determination of thickness of shielding material are dependent on incident gamma ray energy, we present each quantity depending on the energy.

4. CONCLUSIONS

The aim of this study has been to provide a computational tool that would perform calculations of important physical quantities for gamma ray attenuation. Designed program simulates gamma ray interactions in matter. Linear attenuation coefficient, HVL and MFP values for glasses with different composition and densities were calculated for energies of 80, 356, 662, 1173 and 1332 keV. It can be concluded from this work that the effect of gamma rays can be minimized by increasing material density, indirectly reducing the materials' HVL and TVL thickness. On the other hand, the values of linear attenuation coefficient (μ) decrease with increasing gamma ray energy but the mean free path and half-value layer increase with increase in the energy of gamma rays. Observed good agreement among Monte Carlo simulation, XCOM program and experimental data indicates that the algorithm may be employed to make calculations for characterization of several shielding materials.

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