The comparative study of the radiation shielding of $PbO-Li_2O-B_2O_3$ glass system by using FLUKA to XCOM and experimental data

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Abstract. We had investigated the efficacy of FLUKA Monte Carlo code for the gamma radiation shielding parameter calculation of $(60-x)\,PbO-x\,Li_2O-40\,B_2O_3$ glasses (where $0 \leq x \leq 25$ mol%) at photon energies, 356, 662, 1173, and 1332 keV. Then we compared the mass attenuation coefficients, mean free path, effective atomic number, and electron density to standard XCOM data and experimental results from recently published work. We found that simulated and calculated results agreed well with those published results, for which the maximum relative deviation is less than 1.5 % for all the glass samples.

1. Introduction

During the past decade, there has been growing interest in the area of radiation shielding materials due to their applications in various fields such as radiation protection, hadron therapy, and nuclear power plants, etc. [1, 2]. Concretes are among the most commonly used radiation shielding materials against ionizing radiations because of their high density and easy to shape for any construction [3]. However, there are many disadvantages of concrete material, for example, it is not transparent to visible light, aggregates expansion, and forms crack, etc. [4–6]. One alternative shielding material is glass, due to its radiation protection compared to concretes of the same width and high optical transparency. Also, their properties can be to modified by changing other compounds [7–9].

Previously, different types of glasses have been studied by many researchers [8–13]. In the present article, $PbO-Li_2O-B_2O_3$ glass has been considered since lead-oxide (PbO) is known for their excellent infrared transmission, large density, and high refractive index [14]. In the process of glass formation, lead-oxide does not form oxide a network by itself, so the other glass such as silicate, phosphate, and borate are required. Borate (B_2O_3) is one of the most commonly used as an oxide network former because of its high glass forming ability, low thermal expansion, and high stability when added with alkali metal oxide (i.e., Li_2O, Na_2O, K_2O) [15]. Recently, the radiation shielding properties of the present glasses have been theoretically studied by using Monte Carlo (MC) simulation, provided in FLUKA program [16–18]. MC in FLUKA is coded in FORTRAN language for simulations of transport and interaction of electrons, neutrons, photons, all the corresponding antiparticles and heavy ions in matter [19]. Furthermore, theoretical

values of attenuation coefficients of the different elements and compounds were also studied by applying mixture rule using XCOM program [20]. Thus, this has encouraged us to be interested in radiation shielding properties of the selected glass studied by both techniques.

The goal of this work is to study the efficacy of FLUKA to investigate the $\gamma-$ray shielding parameter of $PbO-Li_2O-B_2O_3$ glass system by calculating mass attenuation coefficients, mean free path, effective atomic number, and electron density at energies, 356, 662, 1173, and 1332 keV. The obtained results are compared with the values calculated by using XCOM program and previous experiments. Mean free path values for the selected glasses also have been compared with standard shielding concretes.

2. Materials and methods

2.1. Material specification of glass samples

The chemical composition, chemical formula, mass density, and thickness of the (60−x) PbO−x Li_2O−40 B_2O_3; where x = 0, 5, 10, 15, 20 and 25 mol% glass system were taken from Kumar [21] (see table 1).

Table 1. Chemical composition, chemical formula, mass density, and thickness of glass samples.

Glass Sample	Composition (mol%) PbO	Li_2O	B_2O_3	Chemical Formula	Density (g/cm^3)	Thickness (cm)
G1	60	0	40	$Pb_3B_4O_9$	6.306	0.741
G2	55	5	40	$Pb_{11}B_{16}Li_2O_{36}$	6.144	0.712
G3	50	10	40	$Pb_5B_8Li_2O_{18}$	5.786	0.648
G4	45	15	40	$Pb_9B_{16}Li_6O_{36}$	5.553	0.659
G5	40	20	40	$Pb_2B_4Li_2O_9$	5.378	0.756
G6	35	25	40	$Pb_7B_{16}Li_{10}O_{36}$	5.138	0.684

2.2. Theoretical calculation

In this section, we conclude the theoretical relations used in the present article. The mass attenuation coefficients (μ_m) of the glass samples were determined by the transmission method according to Lambert-Beer's law [8, 21]:

$$\mu_m = \frac{\ln\left(\frac{I_0}{I}\right)}{\rho d} \tag{1}$$

where I_0 and I are incident and attenuated intensities of γ radiation, respectively, d is the thickness, and ρ is a density of the material. Moreover, theoretical values of μ_m obtained using the XCOM program for the selected glasses, based on mixture rule [20]:

$$\mu_m = \sum\nolimits_i w_i(\mu_m)_i \tag{2}$$

where w_i and $(\mu_m)_i$ (obtained directly from XCOM database) are the percentages by weight and μ_m of the ith constituent in the mixture material sample, respectively. Values of μ_m were then used to calculate the mean free path (λ), effective atomic number (Z_{eff}) and electron density (N_{el}). Details on theoretical calculation of these parameters can be found in various literature [17, 21].

2.3. FLUKA Simulation process

In this study, cylindrical geometries were employed in FLUKA code for modeling of glass samples. To measure the attenuation coefficients of the glass samples, the narrow beam transmission geometry depicted in figure 1 was simulated using radiation source as isotropic with collimated and monoenergetic $\gamma-$ray at energies, 356, 662, 1173 and 1332 keV for each calculation. In simulation setup, a radiation source, lead collimator, detector, and glass sample were located by considering the location points according to the narrow beam transmission geometry from experimental setup [21]. The isotropic source and detector were enclosed in a lead container with face aperture 2 cm. A cylindrical NaI detector [22], 7.62 cm in diameter and 7.62 cm in length, was 66 cm far from the radiation source. Three lead collimators with apertures 0.4, 0.6, and 0.2 cm, respectively, are shown in the figure 1. One collimator located in front of the radiation source and another one was in front of the detector. To get absorbed dose amounts in the detection region, USRTRACK estimator has been utilized. This type of estimator gives the average flux in a cell (detector volume) for each $\gamma-$ray emitted from the radiation source.

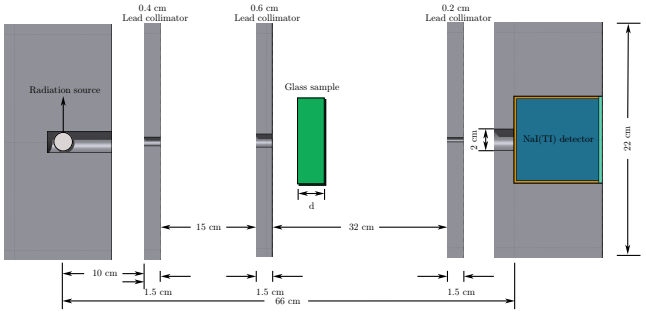

Figure 1. Total simulation geometry (sizes are not on scale).

3. Result and discussion

We found that the results agree very well with the experimental data and 10 million primary particles were used for the simulation with the statistical errors less than 0.3 %. In figure 2, the relative deviation (RD) values, the differences between simulated and calculated values of mass attenuation coefficients from both methods are in good agreement with experimental data, taken from Ref. [21]. The value of RD {(Theo.−Exp.)×100/Exp.} [4] ranges from 0.02% to

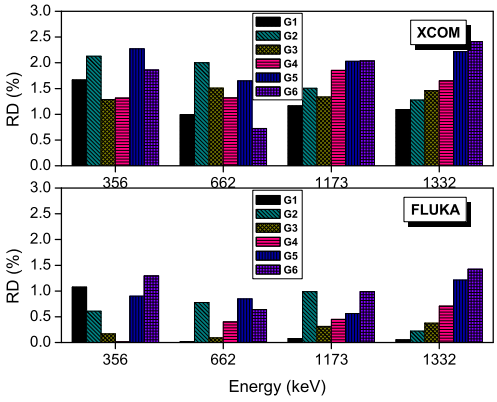

Figure 2. RD values between theoretical results with experimental data.

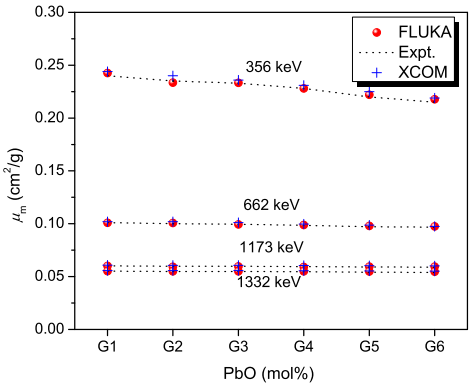

Figure 3. Variation of mass attenuation coefficients against PbO concentration.

1.43% and from 0.72% to 2.41% obtained from FLUKA and XCOM, respectively. The results from FLUKA obtained better agree with the experimental data compared to XCOM. However, the different values from both techniques could be due to nuclear data uncertainties, differences in the employed methods and databases, the geometry of the system for simulation, experimental conditions, and error in physical quantities (i.e., densities, thickness, and intensities of radiation source). The simulation and calculation values of the mass attenuation coefficients of the studied glasses are given in figure 3. It is clear that the decrease in mass attenuation coefficients with PbO contents may be due to the decrease in weight fraction of higher atomic number constituent (Pb) compared to other elements [10].

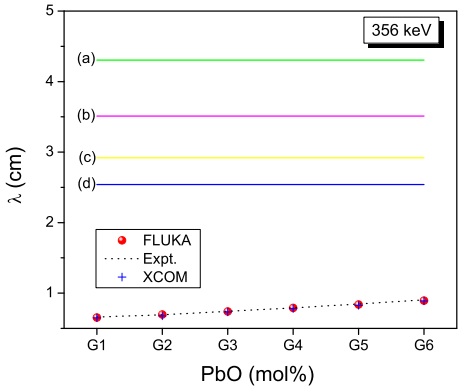

Figure 4. Comparison of mean free path in photon energy 356 keV.

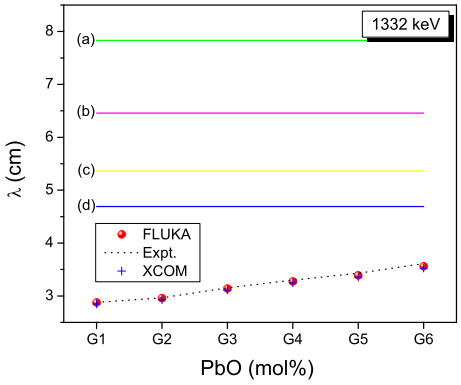

Figure 5. Comparison of mean free path in photon energy 1332 keV.

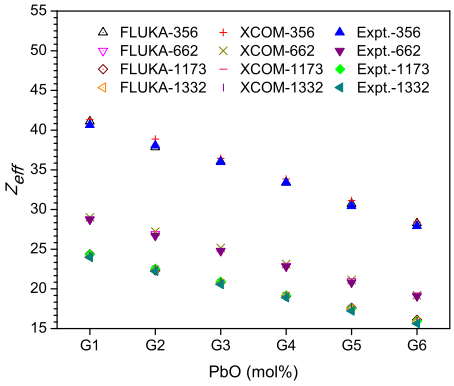

Figure 6. Variation of effective atomic numbers of glass samples.

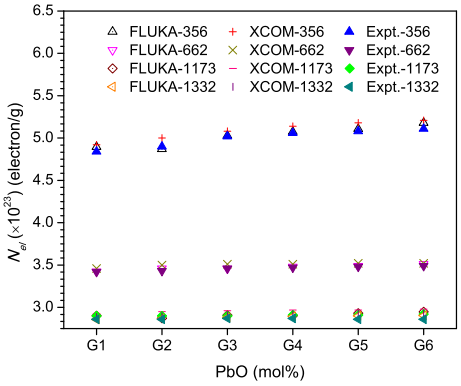

Figure 7. Variation of effective electron density of glass samples.

For shielding ability, lower values of the mean free path are desired. In this work, the mean free path values of $PbO-Li_2O-B_2O_3$ glasses have been compared to that of other standard shielding concretes (ordinary (a), ilmenite-limonite (b), ilmenite (c) and steel-scrap (d)) in photon energy 356 and 1332 keV [23]. It is clear from figure 4 and figure 5 that, the values of the mean free path for all selected glasses are lower than that of the common shielding concretes. Therefore,

it indicates that the shielding effectiveness of the studies glasses is better than the conventional concretes. Variation in effective atomic number and electron density of glass samples with different PbO contents at various photon energies are plotted and shown in figure 6 and figure 7, respectively. It is evident from figure 6 and figure 7 that the effective atomic number increases with a decrease in electron density and an increase in the concentration. It also found that effective atomic number and electron density decrease with an increase in incident photon energy. These values from two theoretical methods are in good agreement with experimental data.

4. Conclusion

In the present work, γ radiation shielding parameters of $PbO-Li_2O-B_2O_3$ glasses were investigated at different energies (356, 662, 1173, and 1332 keV) by using FLUKA and XCOM program. Mass attenuation coefficient values obtained from both methods are in good agreement with experimental data. The mean free path values of all glassy systems are lower than that of the standard shielding concretes. It was also found that the mass attenuation coefficient, effective atomic number, and electron density decrease with an increase of photon energy. Moreover, FLUKA MC code may be useful as an alternative method to the calculated γ shielding parameter for other glass systems which experiment cannot be set up.

Acknowledgments

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