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The comparative studies of gamma-ray shielding properties of the PbO–BaO–B_2O_3 glass system by using FLUKA code to XCOM program and accessible experimental data

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Abstract. We had performed computer simulations by using FLUKA for investigating the gamma-ray shielding properties of the xPbO–(50-x)BaO–50B_2O_3 glass systems for the 356, 662, 1173, and 1330 keV photons (gamma-rays) energies. Then we compared the results to XCOM and the previous experimental published data. We found that the results agree very well with the XCOM and the real data. Furthermore, we also found that the results from FLUKA are closer to the experimental data than the XCOM.

1. Introduction

There have been trying to develop the radiation shielding materials protecting people from various kinds of radiation such as the nuclear research reactors, nuclear power plants, cosmic rays from the outer space and also from the medical radioactive substances or sources and etc. In order to control and decrease the intensity of radiation to acceptable safety level to human, we need the appropriate shielding materials. The studying of different fundamental parameters which are related to shielding against harmful and dangerous radiations is very important [1–3].

Glasses changed properties by adding heavy metal oxide such as PbO are interesting for this study because they are high density and high refractive index. These qualities make them an essential material for the development of advanced optical communication and gamma radiation shielding materials [4].

Previously, experimental studies on the gamma-ray shielding properties of the xPbO–(50-x)BaO–50B_2O_3 glass systems (where $5 \leq x \leq 45$ mol%) at 356, 662, 1173, 1330 keV photons energies have been conducted [5]. The aim of this study is to apply FLUKA for investigating the gamma-ray shielding properties of this glass systems. Thus, the shielding parameters of them were measured by means of FLUKA code, which is a fully integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei in matters. The simulated results were compared with the reported experimental and XCOM results [5], which is a program or dataset for calculating X-ray and γ-ray attenuation coefficients of the different elements, compounds, and mixtures [6]. In addition, the gamma-ray shielding effectiveness has also been compared with the standard concretes in terms of their half value layer.

2. Methodologies

2.1. FLUKA simulation

Figure 1 is a visual representation of what the computer needs to model in order to agree with the earlier experimental setup [5] such as positions, dimensions, geometries, and materials.

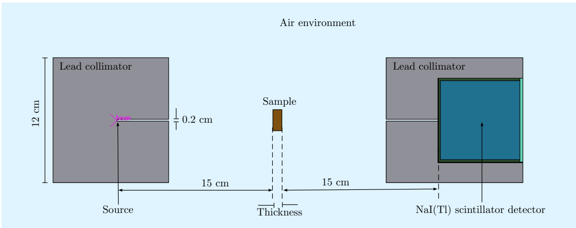

Figure 1. Cross-sectional geometry of total simulation model.

The simulation details consist of three main parts. Firstly, a beam source used for this model is a mono-energetic photon beam (aperture 0.2 cm dimension). The second is glass samples. The material specification of each glass samples listed in table 1 was added to be compound materials by COMPOUND card. In addition, the cylindrical geometries, 2.0 cm diameter and different thickness, were used for modeling all of the glass samples. Finally, a NaI scintillation detector (3 × 3 in) was enclosed by lead collimator made of a 13-cm-length lead cylinder, with 12 cm and 0.2 cm outer and inner diameter respectively. The materials and inner structure of the NaI detector were obtained from Mouhti *et al.* [7]. The computer simulations were run with 5 million number of primary histories.

The mass attenuation coefficients (μ_m) of the glass samples were determined by the transmission method ($\mu_m = \frac{1}{\rho t}\ln\left(\frac{I_0}{I}\right)$). In the simulation, I_0 and I represents the average particles flux values passed through the detector without shielding material and with shielding material, respectively, ρ and t are density and thickness of glass samples, respectively.

Table 1. Chemical composition, density, thickness, and weight fraction of atomic composition of the xPbO–(50-x)BaO–50B_2O_3 (where $5 \leq x \leq 45$ mol%) glass systems obtained from Issa [5].

Sample	Composition (mol%)			Density	Thickness	Element			
	PbO	BaO	B_2O_3	g/cm^3	cm	B	O	Ba	Pb
S1	5	45	50	4.318	0.523	0.15529	0.39526	0.40304	0.04642
S2	10	40	50	4.460	0.633	0.15529	0.39362	0.35826	0.09283
S3	15	35	50	4.602	0.752	0.15529	0.39199	0.31348	0.13925
S4	20	30	50	4.744	0.834	0.15529	0.39036	0.26870	0.18566
S5	25	25	50	4.886	0.912	0.15529	0.38872	0.22391	0.23208
S6	30	20	50	5.028	1.254	0.15529	0.38709	0.17913	0.27850
S7	35	15	50	5.170	1.321	0.15529	0.38546	0.13435	0.32491
S8	40	10	50	5.312	1.435	0.15529	0.38382	0.08957	0.37133
S9	45	5	50	5.454	1.511	0.15529	0.38219	0.04478	0.41774

2.2. XCOM program

XCOM is a software or dataset based on mixture rule ($(\mu_m)_{glass} = \sum_i^n w_i(\mu_m)_i$), where w_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of ith element in energy from 1 keV to 100 GeV. It requires input the weight fractions of the constituent elements listed in table 1 to calculate the μ_m values of the present glasses by using mixture rule. It does not need the experimental setup.

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3. Result and discussion

Mass attenuation coefficients (μ_m), mean free path (MFP), and half value layer (HVL) of the glass samples computed by FLUKA and XCOM for each photons energies are presented in table 2, as well as accessible experimental data [5]. Moreover, these μ_m values are compared with the experimental data by using RD = |theoretical − experimental| × 100/experimental.

Table 2. Comparison between the simulated (Fluka), calculated (Xcom), and experimental (Exp) results of mass attenuation coefficients, mean free path, and half value layer of the glass samples with different photons energies.

samples	E (keV)	μ_m (cm^2/g)			MFP (cm)			HVL (cm)		
		Fluka	Xcom	Exp	Fluka	Xcom	Exp	Fluka	Xcom	Exp
S1	356	0.1260	0.1265	0.1260	1.84	1.83	1.84	1.27	1.27	1.27
	662	0.0775	0.0780	0.0777	2.99	2.97	2.98	2.07	2.06	2.07
	1173	0.0555	0.0558	0.0552	4.17	4.15	4.20	2.89	2.88	2.91
	1330	0.0516	0.0520	0.0512	4.48	4.45	4.52	3.11	3.09	3.14
S2	356	0.1323	0.1331	0.1327	1.69	1.68	1.69	1.17	1.17	1.17
	662	0.0791	0.0795	0.0793	2.83	2.82	2.83	1.96	1.95	1.96
	1173	0.0558	0.0562	0.0557	4.02	3.99	4.03	2.78	2.77	2.79
	1330	0.0520	0.0524	0.0517	4.32	4.28	4.34	2.99	2.97	3.01
S3	356	0.1392	0.1397	0.1378	1.56	1.56	1.58	1.08	1.08	1.09
	662	0.0806	0.0810	0.0799	2.70	2.68	2.72	1.87	1.86	1.89
	1173	0.0561	0.0566	0.0559	3.87	3.84	3.89	2.68	2.66	2.69
	1330	0.0523	0.0527	0.0520	4.16	4.12	4.18	2.88	2.86	2.90
S4	356	0.1457	0.1463	0.1462	1.45	1.44	1.44	1.00	1.00	1.00
	662	0.0823	0.0826	0.0825	2.56	2.55	2.56	1.78	1.77	1.77
	1173	0.0565	0.0571	0.0565	3.73	3.69	3.73	2.58	2.56	2.59
	1330	0.0526	0.0530	0.0524	4.01	3.98	4.02	2.78	2.76	2.79
S5	356	0.1521	0.1529	0.1524	1.35	1.34	1.34	0.93	0.93	0.93
	662	0.0836	0.0841	0.0838	2.45	2.43	2.44	1.70	1.69	1.69
	1173	0.0570	0.0575	0.0568	3.59	3.56	3.60	2.49	2.47	2.50
	1330	0.0529	0.0534	0.0526	3.87	3.83	3.89	2.68	2.66	2.70
S6	356	0.1587	0.1595	0.1572	1.25	1.25	1.27	0.87	0.86	0.88
	662	0.0850	0.0856	0.0844	2.34	2.32	2.36	1.62	1.61	1.63
	1173	0.0574	0.0579	0.0571	3.46	3.43	3.48	2.40	2.38	2.41
	1330	0.0531	0.0537	0.0529	3.74	3.70	3.76	2.59	2.57	2.61
S7	356	0.1651	0.1661	0.1640	1.17	1.16	1.18	0.81	0.81	0.82
	662	0.0865	0.0871	0.0860	2.24	2.22	2.25	1.55	1.54	1.56
	1173	0.0578	0.0583	0.0576	3.35	3.32	3.36	2.32	2.30	2.33
	1330	0.0536	0.0540	0.0534	3.61	3.58	3.62	2.50	2.48	2.51
S8	356	0.1716	0.1727	0.1711	1.10	1.09	1.10	0.76	0.76	0.76
	662	0.0881	0.0886	0.0878	2.14	2.12	2.14	1.48	1.47	1.49
	1173	0.0582	0.0588	0.0582	3.24	3.20	3.23	2.24	2.22	2.24
	1330	0.0539	0.0544	0.0539	3.49	3.46	3.49	2.42	2.40	2.42
S9	356	0.1783	0.1793	0.1778	1.03	1.02	1.03	0.71	0.71	0.71
	662	0.0895	0.0901	0.0894	2.05	2.03	2.05	1.42	1.41	1.42
	1173	0.0586	0.0592	0.0587	3.13	3.10	3.12	2.17	2.15	2.17
	1330	0.0542	0.0547	0.0542	3.38	3.35	3.38	2.34	2.32	2.34

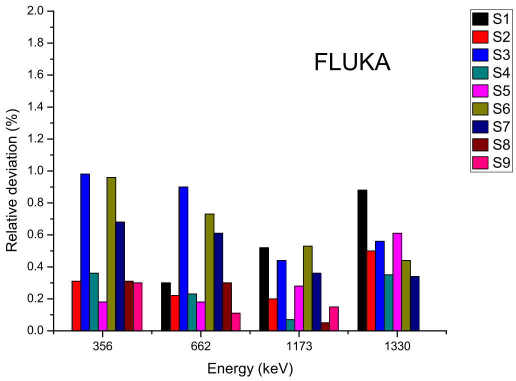

Figure 2. Relative different between FLUKA results and experimental data.

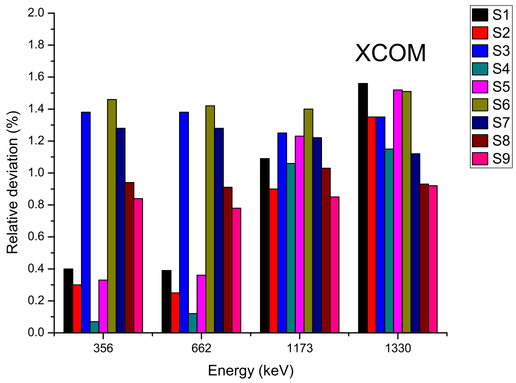

Figure 3. Relative different between XCOM results and experimental data.

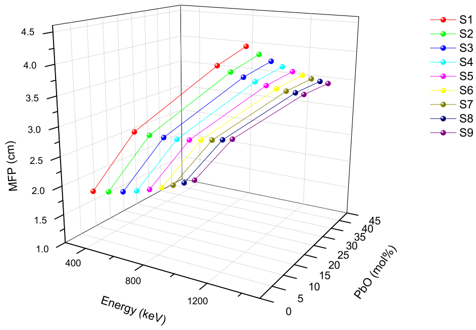

Figure 4. Variation of MFP with photons energies of glass systems.

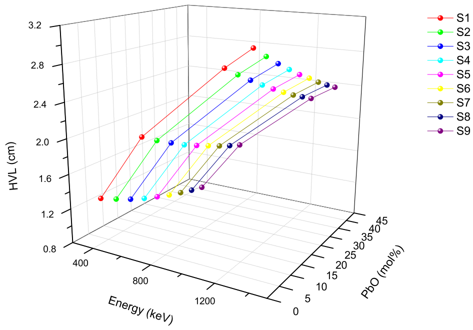

Figure 5. Variation of HVL with photons energies of glass systems.

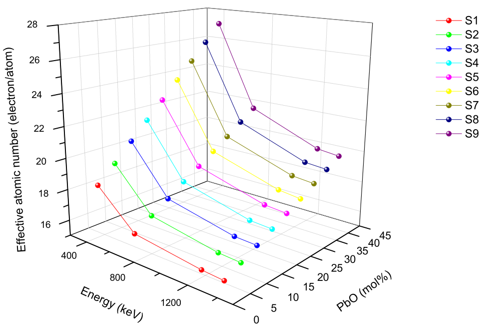

Figure 6. Variation of Z_{eff} with photons energies of glass systems.

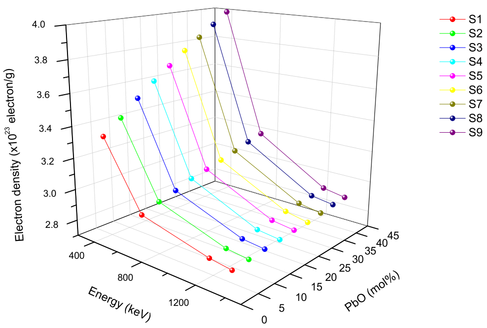

Figure 7. Variation of N_{eff} with photons energies of glass systems.

The relative different (RD) between FLUKA and XCOM results with experimental data of μ_m are shown in figure 2 and 3. There are values less than 0.98% for FLUKA and 1.56% for XCOM. It is clear that these results are good agreement with experimental data but the results from FLUKA are slightly closer to the experimental data than the XCOM. All simulation data obtained by FLUKA were reported with less than 0.1% statistical error. However, the end of the simulation process spends time so long about 14 hours, which are longer than XCOM.

The values of the mean free path (MFP) and half value layer (HVL) of samples are illustrated in figure 4 and 5, respectively. Both MFP and HVL decrease as lead oxide increase and increase as gamma-ray energies increase. The effective atomic number (Z_{eff}) and electron density (N_{eff}) of glass systems are shown in figure 6 and 7. It was found that the values of Z_{eff} and N_{eff} increase as mole percent of lead oxide increase and decrease as gamma-ray energies increase.

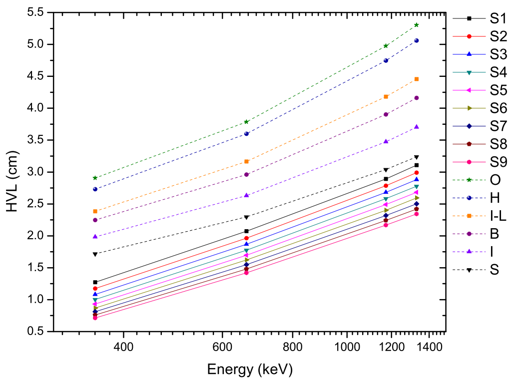

Figure 8. Comparison of the half value layer of glass samples with standard shielding concretes; Ordinary (O), Hematite-serpentine (H), Ilmenite-limonite (I-L), Basalt-magnetite (B), Ilmenite (I), and Stell-scarp (S).

The HVL values have been compared with HVL of the standard radiation shielding concretes obtained by Bashter [8] and shown in figure 8. We found that all glass samples are having the lower values of the HVL as compared to standard concretes. Therefore, the PbO-BaO-B_2O_3 glass is better radiation shielding materials than these standard concretes in the same thickness.

4. Conclusion

We have succeeded in investigating gamma-ray shielding properties of the PbO–BaO–B_2O_3 glass systems at the 356, 662, 1173, and 1330 keV photons energies by using FLUKA simulation. We found that the results from FLUKA are slightly closer to the experimental data than the XCOM but the finish simulation procedure spends time longer than XCOM. In addition, FLUKA may be used as a better alternative in the experiment to evaluate the gamma-ray shielding properties for other glass systems.

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