Theoretical Evaluation of Radiation Shielding and Particle Interaction Features of ZnO.B₂O₃ and ZnO.P₂O₅ Glass Systems Doped with PbO Nanoparticles

E.O. Echeweozo¹, M. S. Ali^{2,*}, G.C. Nwigwe¹, M. Nady³, Ehab M. Attalla⁴, Samy El Sherkawy³, M. Saleh⁵, A. M. Abdelmonem⁵

¹ Department of Industrial Physics, David Umahi Federal University of Health Science Uburu, Ebonyi State, Nigeria.

² African Institute for Mathematical Sciences, B. P. 1418 Mbour, Thies Region, Senegal.

³ Physics Department, Faculty of Science, Sohag University, Sohag 82524, Egypt.

⁴ Department of Radiotherapy & Nuclear Medicine, National Cancer Institute, Cairo University, Cairo, Egypt.

⁵ Reactor Physics Department, Nuclear Research Centre, Egyptian Atomic Energy Authority (EAEA), Egypt.

*Email: mohamed.s.g.ali@aims-senegal.org

Received: 5th September 2024, **Revised:** 3rd January 2025, **Accepted:** 8th January 2025 **Published online:** 30th March 2025

Abstract: This study examined the ability of two series of ternary phosphate and borate glass systems, with the compositions $Pb0.Zn0.B_2O_3$ and $Pb0.Zn0.P_2O_5$, to reduce the intensity of neutron, gamma radiation, and charged particles. The study methodically manipulated the amount of nanoscale PbO in each glass sample, leading to densities that ranged from 3.675 to 6.650 g.cm^-3 for borate glasses and 3.177 to 4.845 g.cm-3 for phosphate glasses. The Phy-X/PSD program was utilized to compute nine parameters related to gamma ray shielding. The SRIM Monte Carlo algorithm was used to calculate the ranges of H+, He2+, Au+, and C4+ ions at specific energies ranging from 0.01 to 20 MeV. The ESTAR NIST software was used to calculate the Total Stopping Power (TSP) and range (R) values for electron interactions at specific electron energies ranging from 0.01 to 1000 MeV. The Fast Neutron Removal Cross-Section (FNRCS) at 4.5 MeV and the macroscopic effective removal cross-section (MRCs) were estimated using Phy-X/PSD and MRCsC software, respectively. The findings revealed that the shielding capabilities of these two glass systems were predominantly affected by their chemical composition and densities. Significantly, the addition of 70% PbO in borate glass systems and 50% PbO in phosphate glass systems greatly improved their capacity to protect against gamma radiation, neutrons, electrons, and charged ions. This work offers significant insights into the potential of these two glass systems for applications that demand efficient radiation shielding, such as in the fields of nuclear medicine, radiation treatment, and spacecraft architecture. The results indicate that by adjusting the PbO concentration and glass composition, the effectiveness of their shielding may be optimized for certain uses.

Keywords: Glass shielding; phosphate and borate glasses; lead oxide; FNRCS; Phy-X/PSD; SRIM; ESTAR.

1. Introduction

The growing utilization of glass in radiation shielding applications, specifically in medical treatment, nuclear engineering, agricultural, and industrial industries, has emphasized the necessity to comprehend and assess the shielding capabilities of these materials. This worry arises from the inherent radiological dangers linked to the interaction between radiation and glass [1].

When radiation comes into contact with something, its strength decreases as it travels through the substance. Hence, it is important to ascertain the attenuation characteristics of any shielding material in order to choose the most efficient material for a particular use. Historically, concrete and lead have been preferred materials for radiation attenuation because of their strong structure and efficient shielding properties [2, 3]. Nevertheless, the variability of water content in concrete and the intrinsic lack of transparency in lead create errors when calculating their shielding parameters, which restricts their employment in situations where transparency is crucial [4, 5]. The rising need for radiation protection in many applications, especially in medical radiotherapy, has resulted in a burgeoning interest in modified glass materials that provide both efficient shielding and transparency. This is especially pertinent for medical equipment and buildings such as X-ray rooms, testing material laboratories, and specialty windows and doors, where visibility is of utmost importance [6, 7]. The desire for these altered glass materials is motivated by their distinctive amalgamation of qualities, which encompass exceptional optical traits, robust mechanical strength, and the capacity to integrate heavy metal oxides such as PbO, Bi_2O_3 , MoO_3 , and WO_3 with remarkable consistency. These metal oxides and doped glasses are often used in a variety of optical and shielding applications [8-12].

By including one or two of the following oxides - PbO, Bi_2O_3 , MoO_3 , WO_3 , TeO_2 , and GeO_2 into the basic glass materials, the stability of the glass matrix and its structural qualities may be greatly improved. An example of this is the

utilization of tellurite oxide and germanium oxide in a glass system, which can enhance thermal stability, chemical resistance, and mechanical resistivity. The inclusion of GeO_2 and other structural components enhances the transparency, melting point, chemical resistance, mechanical robustness, and operational temperature range of glass systems [13-17].

The glass systems doped with lead oxide (PbO) have shown remarkable properties such as strong chemical resistance, high density, high melting point, and good nonlinear optical susceptibility with high refractive indices and infrared transmission protection [18-20]. Glass networks can be either formed or modified by nanoscale PbO put into them, depending on the quantity of PbO [20]. The optical field, radiation shielding, and the temporary storage of radioactive waste are all potential uses for PbO doped glasses [18, 21]. Investigating the impact of changing the concentration of lead oxide (PbO) in glass systems on high-energy electromagnetic radiation such as X-rays, gamma rays, neutrons, and charged particles is crucial, taking into account all the important lead oxide properties in technologically modifying radiation protection materials. The evaluation of gamma radiation, charge particle, and neutron shielding properties of glass systems allows one to quantify the influence of PbO on these systems. A number of properties have been observed in systems of phosphate and borate glasses, including a low optical dispersion, a high thermal expansion coefficient, a low glass transition temperature, and a complex radiation absorption coefficient [22-24]. It will be easier to use borate and phosphate glass systems for radiation shielding if the effects of adding varying percentages of micro scale PbO to these glass systems are investigated. While it is true that some experimental investigations have assessed the shielding capacities of various glass systems, doing so involves risky and time-consuming computational procedures due to the massive amounts of data required. As a result, researchers were able to accurately calculate the radiation shielding parameter of glass samples using computer programs and codes, which saved time and ensured their safety. The use of these computer codes and algorithms was based on their proven track record of success in measuring a variety of radiation shielding properties over a broad spectrum of photon energies [27, 29, 30, 22, 31, 20].

The simulation and theoretical computation of radiation interaction factors are now being carried out with the assistance of several software applications and distinct codes. Phy-X/PSD, Win-XCOM [25-27], MCNCP codes [22], Py-MLBUF [28], and a number of other related applications are included in this category. For the purpose of providing an accurate estimation of the radiation shielding capabilities of the glass systems, particular shielding parameters are required. The linear attenuation coefficient (LAC), the mass attenuation coefficient (MAC), the half value layer (HVL), the mean free path (MFP), the effective atomic number (Zeff), and the effective electron density (Neff) are all examples of these characteristics.

As a result, the objective of this research is to investigate the ways in which the incorporation of different concentrations of nanoparticle PbO influences the characteristics of gamma radiation shielding, neutron and charged particle attenuation in

SOHAG JOURNAL OF SCIENCES

two series of ternary phosphate and borate glass systems (ZnO.P₂O₅ and ZnO.B₂O₃). Measurements of gamma radiation shielding parameters, fast neutron removal cross-section (FNRCS), proton (H⁺) and alpha (He⁺⁺) ion interactions, Au⁺ and C4⁺ ion interactions, range values, total stopping power of electrons during interactions, and macroscopic effective removal cross-section (MRCs) for fast neutrons at various photon energy levels will be carried out with the assistance of computer programs that are simple to use.

The selection of these two glass systems was made because of the great matrix stability, robust mechanical strength, and extraordinary transparency that each of them possesses. Because of these characteristics, these glass systems are ideal for a wide variety of structural designs that are often encountered in nuclear engineering technologies and radiation facilities [2, 3, 22].

2. Theoretical Background.

2.1. Gamma shielding parameters.

When gamma radiation passes through glass, it goes through three main processes: photoelectric absorption, Compton scattering, and pair formation [32]. The radiation shielding qualities of any material, particularly glass, are determined by the interactions that occur between the material and electromagnetic radiation. These interactions depend on factors such as the atomic number, density, and energy of the shielding material [33]. To examine the impact of PbO nanoparticle inclusion on the gamma radiation shielding characteristics of the two glass systems, it is necessary to assess many parameters related to gamma radiation shielding, including LAC (linear attenuation coefficient), MAC (mass attenuation coefficient), HVL (half-value layer), TVL (tenthvalue layer), MFP (mean free path), Zeff (effective atomic number), Neff (effective electron density), Ceff (effective atomic density), EBF (energy build-up factor), and others. The characteristics mentioned have been previously documented in many publications [34-40]. The G-P fitting approach was used to analyze the buildup factor (B), which accounts for the scattering impact of gamma radiation that is not accounted for in the Beer-Lambert equation [33, 41, 42].

2.2. Total stopping power (TSP) and CSDA range of charged particles

Charged particles have interactions when passing through a glass medium, resulting in energy loss and ultimately reducing the particle's speed to zero. As the charged particles gradually slow down, the ionization of the glass samples diminishes towards zero in the vicinity of Bragg's peak. This event is attributed to the depletion of the particle's kinetic energy. It is feasible to quantify both the Total Stopping Power (TSP) and the Continuous Slowing Down Approximation (CSDA) range of charged particles within the glass medium. The CSDA range [31] refers to the approximate average distance that a charged particle travels before coming to a stop. The relativistic Bethe's equation, denoted as equation 1 [43, 44], accurately reflects the phenomenon. The total scattering power (TSP) of a glass sample refers to the average energy loss per unit length that a charged particle experiences when passing through the sample

[37]. The Bethe–Bloch equation, as stated in Equation 1, calculates the total specific energy (TSP) of a charged particle by dividing the differential energy loss experienced by the particle in the glass sample by the corresponding differential particle path.

$$TSP = -\frac{dE}{dx} = \frac{4\pi e^4 Z^2 N Z}{(4\pi\epsilon_0)^2 M_e V^2} \left[In\left(\frac{2M_e V^2}{I}\right) - \ln(I - \beta^2) - \beta^2 \right] (1)$$

where V is the velocity of particle /electron $(\sqrt{2E/M})$, the variable " M_e " represents the mass of a particle or electron. "N" represents the number of atoms per unit volume. "Z" represents the number of particles or electrons in one atom. "I" represents the mean excitation or ionization potential of the glass sample. " β " represents the velocity of a particle or electron divided by the velocity of light. The CSDA range of electrons or charged particles may be determined by integrating the reciprocal of Equation 1, with the integration boundaries set from the starting energy to the stationary energy state of the particle [44, 45].

$$R = \int dx = \int_0^E \frac{dE}{dE/dx} = \int_0^v \frac{dx}{dv} dv$$
⁽²⁾

2.3. Total Macroscopic Cross-Section (ΣT)

The symbol Σ T represents the total probability of a neutron of a certain energy interacting with the atoms in a glass sample. This measurement is represented in units of cm⁻¹. Both the energy of the neutrons and the alignment of nuclei in the glass sample's atoms play a crucial role in establishing the shape of these interactions. The main interactions between the neutron and the glass sample are neutron capture, nuclear fission, elastic scattering, and inelastic scattering [**35**, **37**]. Consequently, enthalpy (Σ T) is the sum of the microscopic cross-sections for scattering interactions (σ_s) and absorption (σ_a) in each nucleus atom [**46**, **47**].

$$\Sigma_T = N(\sigma_a + \sigma_s) \tag{3}$$

N represents the number of nuclei per unit volume

In order to determine the value of ΣT for any neutron absorber, it is necessary to take into account the intensity of the neutron that is diminished due to absorption and scattering. This information is compared to the intensity of neutrons when there is no absorber involved. The Beer-Lambert equation will be utilized in order to determine the neutron attenuation caused by the glass absorber [48].

$$I_x = I_0 e^{-\Sigma_T x} \tag{4}$$

In this context, Ix and I0 denote the intensities of the neutrons that are entering the sample from the source without the glass sample and the neutrons that are traversing the sample via a specified thickness in cm, respectively.

2.4. Fast Neutron Effective Removal Cross Section (FNRCS)

By determining whether or not a neutron with fission energy or a fast neutron is capable of experiencing a first collision, the FNRCS is able to exclude it from the category of penetrating neutrons that do not suffer collisions. The unit of measurement is cm^{-1} . Similarly, the neutron with energy ranging from 2 to 12 MeV is the same. In order to assess it, Equation 5 [47] was utilized.

$$\Sigma_{R} = \sum_{i} \rho_{i} \left(\frac{\Sigma_{R}}{\rho} \right) i \tag{5}$$

The symbol ρ i represents the partial density in grams per cubic centimeter (g/cm³). The term $(\frac{\Sigma_R}{\rho})$ in centimeters squared per gram (cm²/g) denotes the mass removal cross-section of the ith constituent for a simple element. ρ_i is calculated by multiplying the weight fraction W_i of the ith sample by the density ρ_s of the sample, as given in Equation 6 [48, 38].

$$\rho_i = \rho_s W_i \tag{6}$$

3. Materials and method

The borate glass system is represented by the chemical formula $2xPbO.xZnO(1-3x)B_2O_3$, where x ranges from 0.1 to 0.26 mol %. On the other hand, the phosphate glass system is represented by the formula $xPbO_{1}(50-x)ZnO_{1}50P_{2}O_{5}$. where x can take the values of 10, 20, 30, 40, or 50 mol%. This study investigates the impact of varying nanoscale lead oxide (PbO) concentrations on the gamma radiation shielding properties of borate and phosphate glass systems. The investigation was conducted using the Phy-X/PSD software, and the results are presented in Table 1. The interactions between protons (H⁺) and alpha particles (He²⁺), as well as gold (Au) and carbon ions (C^{4+}) , were computed using the SRIM Monte Carlo algorithm at specified energies ranging from 0.01 to 20 MeV. The ESTAR NIST software was used to calculate the range and total stopping power values for electron interactions at various electron energies ranging from 0.01 to 1000 MeV. Additionally, the Phy-X/PSD program was used to compute the FNRCS at 4.5 MeV, and the MRCsC program was used to compute the MRCs for a wide range of energies of fast neutrons. These computer programs are adept at calculating and assessing ion interactions and radiation shielding characteristics within certain energy ranges [22, 27, 29, 30]. They are user-friendly and possess exceptional computational capabilities.

4. Results and Discussion

Table 1 presents the sample codes, chemical compositions, and densities of the two glass systems that have been assessed by experiments. Figures 1 to 24 depict graphical visualizations of the results accomplished for the radiation shielding capabilities of all glass specimens. These results were acquired at specific gamma energies ranging from 0.015 to 15 MeV. The findings were acquired with the Py-X/PSD computer program. The FNRCS, MRCS for fast neutrons, TSP, ion range (H⁺, He²⁺, Au⁺, and C⁴⁺), and electron range and interaction are crucial aspects for characterizing the shielding and interaction properties of any glass material. To establish radiation protection measures for nuclear and radiotherapy plants, it is essential to assess these attributes using user-friendly computer codes and algorithms. The data on shielding parameters may be found in Figures 25–33.

Table 1: Chemical composition of glasses (mol %)

S/N	S. Code	PbO	ZnO	B_2O_3	P_2O_5	Density	chemical composition
						(g.cm ⁻³)	
1	BZnPb20	20	10	70	0	3.675	$0.2PbO+0.1$ ZnO+ $0.7B_2O_3$
2	BZnPb40	40	10	50	0	5.088	$0.4PbO+0.1$ ZnO+ $0.5B_2O_3$
3	BZnPb50	50	25	25	0	5.917	$0.5PbO+0.25$ ZnO+ $0.25B_2O_3$
4	BZnPb60	60	10	30	0	6.212	$0.6PbO+0.1$ ZnO+ $0.3B_2O_3$
5	BZnPb70	70	5	25	0	6.650	$0.7PbO+0.05 ZnO+0.25B_2O_3$
6	PZnPb0	0	50	0	50	3.177	$0.5 ZnO + 0.5 P_2O_5$
7	PZnPb10	10	40	0	50	3.493	0.1PbO+0.4 ZnO+0.5 P ₂ O ₅
8	PZnPb20	20	30	0	50	4.121	0.2PbO+0.3 ZnO+0.5 P ₂ O ₅
9	PZnPb30	30	20	0	50	4.419	0.3PbO+0.2ZnO+0.5 P ₂ O ₅
10	PZnPB40	40	10	0	50	4.802	0.4 PbO+0.1 ZnO+0.5 P ₂ O ₅
11	PZnPb50	50	0	0	50	4.845	$0.5PbO+0.5 P_2O_5$

Table 2: Mass Attenuation Coefficient of investigated glass systems

Gamma Energy(MeV)	BZnPb20	BZnPb40	BZnPb50	BZnPb60	BZnPb70	PZnPb0	PZnPb10	PZnPb20	PZnPb30	PZnPb40	PZnPb50
0.02	19.53715	35.448	47.80763	51.35885	57.84622	16.43796	21.45725	26.47655	31.49584	36.51513	41.53443
0.08	0.635125	1.054443	1.345642	1.47376	1.656239	0.45053	0.605829	0.761128	0.916426	1.071725	1.227024
0.2	0.286997	0.450066	0.536655	0.613135	0.692986	0.139262	0.217427	0.295593	0.373758	0.451924	0.530089
0.5	0.099377	0.113538	0.120592	0.127699	0.134789	0.085698	0.092796	0.099895	0.106994	0.114092	0.121191
1	0.06368	0.065335	0.065868	0.06699	0.067915	0.061574	0.062598	0.063622	0.064645	0.065669	0.066693
1.5	0.050785	0.051098	0.051015	0.051411	0.051647	0.050124	0.05044	0.050756	0.051073	0.051389	0.051705
4	0.032591	0.034816	0.036382	0.037041	0.038002	0.032201	0.033012	0.033822	0.034632	0.035442	0.036252
6	0.028765	0.032368	0.035043	0.03597	0.03748	0.028391	0.02961	0.030828	0.032046	0.033265	0.034483
10	0.026389	0.031949	0.036194	0.037509	0.039801	0.026046	0.027849	0.029653	0.031457	0.033261	0.035064
15	0.026072	0.033343	0.038922	0.040614	0.043601	0.025647	0.027986	0.030326	0.032666	0.035005	0.037345

4.1. Mass attenuation coefficient (MAC)

To enhance clarity, the alterations in the MAC of borate and phosphate glass systems were depicted individually in Figures 1 to 3 and Figures 4 to 6, respectively, for gamma energies ranging from 0.02 to 15 MeV. The data shown in Table 2 was used to obtain these figures. Upon analyzing these deviations, it was found that the two glass systems had a comparable pattern in the areas of lower, intermediate, and higher gamma energy. The curves shown in Figures 1 through 6 clearly demonstrate that both glass systems are not only highly successful in blocking low-energy gamma radiation, but they are also extremely effective in providing protection against intermediate and high-energy gamma radiation. The experiment's findings indicate that there is a decrease in gamma interaction when the photon energy in these glass systems is raised. It is worth mentioning that the higher MAC values seen in borate and phosphate glassware systems were a result of the strong gamma interaction associated with the photoelectric effect. The primary interaction mechanism that takes place at lower energy levels is this interaction effect. As the photon's energy grows, the probability of the photoelectric effect occurring diminishes. This is done to counterbalance the occurrence of Compton scattering, which is observed at the intermediate energy level. The exceptional shielding properties of BZnPb₇₀ and PZnPb₅₀ glasses are evident from their greatest

MAC values of 76.23 cm2/g and 55.07 cm2/g, respectively, at 0.015 MeV, which surpass those of other samples at the same energy level. The assumption is correlated with the higher values of density, molar mass, and effective atomic weight seen in the assortment of glass specimens. BZnPb70 and PZnPb50.

4.2. High value layer

The fluctuations in HVL with gamma energy were illustrated in Figures 7 and 8, respectively, for both of the glass systems. When the variance was examined in further detail, it was discovered that lower gamma radiation energies revealed the values of HVL that were quite near to one another for all of the glass samples. When the photon energy was raised, it was noticed that the value of HVL rose. This was due to the fact that the chance of radiation contacts in the glass sample decreased when the photon energy was increased. The values of HVL that were measured at lower energies were shown to be lower in Figures 7 and 8. According to the interpretation, there is a greater chance of radiation contact in glass samples when there is a shorter distance between subsequent gamma radiation interactions [39, 50]. This substantiates the fact that the incorporation of PbO into these glass systems resulted in an improvement in the gamma attenuation and shielding capabilities of these glass samples when subjected to lower gamma energy. glass samples for testing.

80 70 BZnPb20 60 BZnPb40 BZnPb50 50 MAC (cm²/g) BZnPb60 40 BZnPb70 30 20 10 0 0.10 0.12 0.14 0.16 0.00 0.02 0.04 0.06 0.08 Lower Energy level (MeV)

Figure 1: The dependence of MAC on E_{γ} (Photoelectric effect)



Figure 2: The dependence of MAC on E_{γ} (Compton interaction)



Figure 3: The dependence of MAC on E_{γ} (Pair-production)

Figure 4: The dependence of MAC on E_{γ} (Photoelectric effect)

Figure 5: The dependence of MAC on Ey (Compton interaction)

Figure 6: The dependence of MAC on Ey (Pair-production)

Figure 7: Variation of HVL for BZnPb (20-70) with Ey

Figure 8: Variation of HVL for PZnPb (0-50) with Ey

SOHAG JOURNAL OF SCIENCES

4.3. Mean free path

The disparities between the MFP values and the photon energies in each and every borate and phosphate glass system were graphically shown in Figures 9 and 10. A comparison may be made between the dependency of photon energy on MFP values and the dependence of photon energies on HVL based on these figures. MFP values are inversely related to LAC values for each of the glass samples. This holds true for all of the samples collected. As a result, the material with the highest MFP values was found to be BZnPb₂₀ and PZnPbO over the whole spectrum of photon energies, while the material with the lowest MFP values was found to be BZnPb₇₀ and PZnPb₅₀. In comparison to BZnPb₇₀ and PZnPb₅₀, this indicates that photon energy with a wide range of energies is able to travel through BZnPb20 and PZnPbO with far less difficulty. These results are consistent with the findings that were acquired from LAC and MAC investigations.

Figure 9: Variation of MFP for BZnPb (20-70) with Ey

Figure 10: Variation of MFP for PZnPb (0-50) with Ey

4.4. Effective electron density (N_{eff})

The number of electrons per unit mass of a sample is denoted by the symbol Neff. The glass sample's chemical compositions are the determining factor in this regard. Figure 11 and Figure 12 are graphical representations of the fluctuations of Neff with respect to gamma energies. According to the plots, the curves suddenly surged and then dropped dramatically about 0.015 - 1 MeV as a result of photoelectric absorption and Compton scattering [18]. One of the most important interaction processes that occur at lower

SOHAG JOURNAL OF SCIENCES

energies is photoelectric absorption. In spite of the fact that the photon energy was continuously increasing from 1 to 15 MeV, a marginal rise in the value of Neff was determined to have occurred. Additionally, it was found that the penetration of gamma rays did not hold any substantial weight. It was determined that this was due to the fact that the densities of the glass samples were very near to one another, as well as the fact that comparable materials predominated in the chemical composition of borate and phosphate glass systems [51, 52].

Figure 11: Variation of Neff for BZnPb (20-70) with Ey

Figure 12: Variation of Neff for PZnPb (0-50) with Ey

4.5. Effective atomic number (Z_{eff})

The inclusion of nanoscale PbO has led to a significant decrease in the variation of Zeff with gamma energy, as seen in Figures 13 and 14. These curves exhibit a sharp decline in the initial energy range of 0.08MeV to 0.5MeV due to the occurrence of photoelectric absorption. Nevertheless, there was a little rise in their numbers when the photon energy escalated from 0.5MeV to 15MeV due to the occurrence of Compton scattering and pair creation.

Therefore, it may be inferred that Zeff relies heavily on the dominant interaction process in each energy zone for the reasons indicated above. Based on the study conducted by several studies [20, 53], it has been shown that glass materials with a higher Zeff value had a greater ability to shield against radiation. Figures 13 and 14 demonstrate significant gamma radiation interaction processes for the material at specific photon energy levels [52]. Furthermore, Figures 13 and 14 illustrated that the Zeff of the BZnPb₂₀ and PZnPbO samples exhibited the lowest Zeff value compared to the other samples

under investigation. This scenario happened due to the low density and low effective atomic weight of the $BZnPb_{20}$ and PZnPbO glass materials.

Figure 13: Variation of Z_{eff} for BZnPb (20-70) with E_{γ}

Figure 14: Variation of Z_{eff} for PZnPb(0-50) with E_{γ}

4.6. Effective conductivity

The effective conductivity, often known as Ceff, is a quantity that is associated to the amount of energetic electrons or free electrons present in a material sample. As can be seen in Figures 15 and 16, the influence of nanoscale PbO on the Ceff values of the glass systems that were tested at various energies reveals a behavior that is comparable to that of Neff and Zeff. The creation of very compact glass systems is achieved by the incorporation of nanoscale lead oxide into the structure of glass as an intermediate product. PbO has a strong polarity of lead ions, which enables it to store and lower the energy of excited electrons, hence enhancing radiation shielding. This is a convincing indicator that PbO has this property. This is due to the presence of lead, which is a glass modifier that resides in the glass matrix and helps to strengthen the links that make up the glass structure while also preventing electron excitation [18]. In the event that photons bombard a glass material, causing a change in the amount of free electrons, the conductivity of the glass material will adapt in order to accommodate the energy of the photons. Photoelectric absorption is the impact that is most prominent when the energy level is low sufficient. However, as the energy of the photon is raised, a greater number of photons are emitted, which results in an increase in the number of electrons that are excited. In light of the fact that Ceff is a function of the number of collisions that occur between electrons and high-energy photons, the Ceff is proportional to the Neff.

SOHAG JOURNAL OF SCIENCES

Figure 15: Variation of C_{eff} for BZnPb (20-70) with E_{γ}

Figure 16: Variation of C_{eff} for PZnPb(0-50) with E_{γ}

4.7. Exposure buildup factor

The implications of nanoscale PbO insertion on the EBF of the glass systems that were examined are seen in Figures 17 and 18. According to the graphical representations, the EBF values of the two glassware systems were obtained at a variety of photon energy and at a variety of penetration depths (mfps). The computed EBF value grew as the amount of PbO in the compound increased. The compounds with the lowest EBF values were BZnPb₂₀ and PZnPb₀, while the compounds with the highest EBF values were obtained. Using samples of BZnPb₇₀ and $PZnPb_{50}$ material. Consequently, this demonstrates that the EBF values that were obtained rise as the proportion of PbO concentration increases. The rise in the atomic number of these glass samples is not unrelated to this phenomenon under consideration. It is essential to take note of the fact that the variations shown in EBF are comparable to the differences seen in EABF (refer to Figures 19 and, respectively). Therefore, it is possible to quickly link the factors that were responsible for differences in EBF and EABF.

When the penetration depth was changed from 1 to 40 mfp, the values of the estimated EBF gradually increased. As a result of the fact that certain gamma radiation accumulates at different depths inside the glass materials, the majority of gamma rays require a longer amount of time to travel through

SOHAG JOURNAL OF SCIENCES

Research Article

denser layers. In light of this, it may be deduced that the lowest values of EBF are achieved at the lowest penetration depths ever (1 mfp).

Figure 17: Variation of EBF for BZnPb20with Photon Energy

Figure 18: Variation of EBF for BZnPb70 with Photon Energy

Figure 19: Variation of EABF for BZnPb20 with Photon Energy

Figure 20: Variation of EABF for BZnPb70 with Photon Energy

Figure 21: Variation of LAC for BZnPb(20-70) with % PbO

Figure 22: Variation of LAC for PZnPb(0-50) with %PbO

4.8. PbO percentage variation and Density variation

The high density of lead (Pb) atoms resulted in a rise in the percentage concentration of lead oxide (PbO) in both glass systems. This, in turn, increased the density of the glass samples and subsequently enhanced their shielding capabilities. These findings are consistent with previous investigations documented in the literature [18, 55, 22, 44, 27, 41]. Examination The data shown in Figures 23 and 24 demonstrate that an increase in the concentration of PbO in each of the glass systems leads to a corresponding rise in the density of the glass samples. These findings indicate that increasing the percentage of PbO from 20 to 70 in the bromated glass system and from 0 to 50 in the phosphate system resulted in enhanced cross-linking within the main matrix chain. This was achieved by sharing oxygen and boron atoms in the case of the bromated glass system and oxygen and phosphor atoms in the case of the phosphate system through a covalent bonded configuration [54, 55, 56]. This implies that a larger quantity of PbO may occupy the empty areas within the glass structure, resulting in higher densities and, thus, enhanced radiation shielding properties of these glass composites.

4.9. Fast Neutron Effective Removal Cross-Section

The influence that the addition of nanoscale lead oxide had on the rapid neutron removal coefficient of borate and phosphate glass samples was illustrated in Figure 25. Generally speaking, the fast neutron removal coefficient of the two glass systems was rather high, particularly in borate glass samples, which offered the highest level of 0.16 cm⁻¹ from BZnpPb₄₀.

On the other hand, the phosphate glass samples exhibited lower values, with maximum values of 0.13 cm^{-1} from PZnPB₄₀. This demonstrates that BZnpPb₄₀ possesses superior and noteworthy neutron shielding properties, and it is recommended that it be implemented as a main neutron shielding layer with other fission neutron moderators, as suggested by Şakar et al. [27].

Figure 23: Variation of density for BZnPb(20-70) with % PbO

Figure 24: Variation of density for PZnPb(0-50) with %PbO

Figure 25: The calculated MRCS of investigated composites glass samples

4.10. Mean excitation energies of electrons dependence of on the density of the glass samples

Data shown in Figure 26 demonstrated a proportionate relationship between the density of the glass material and its mean excitation energy. When the electron energy remains constant, this demonstrates that there is a strong dependence between the average ionization energy of the electron and the density of the target material. The BZnPb₇₀ sample exhibited

SOHAG JOURNAL OF SCIENCES

the greatest values of I and ρ , which were measured to be 375.1 eV and 6.65 g/cm3, respectively. On the other hand, the PZnPb₅₀ sample exhibited the highest values of 275.6 eV and 4.85 g/cm3, respectively. The findings are consistent with experiments and theoretical investigations that have been conducted in the past and are available in a variety of literatures [37, 57].

Figure 26: The dependence of mean excitation energies of electrons on the density of the investigated samples

4.11. Charged ions range at different energies through the investigated glass samples

In the charged ion range, the doping of borate and phosphate glass systems with lead oxide (PbO) demonstrated a significant influence. H⁺ had the greatest range of all the charged ions that were taken into consideration, whereas Au⁺ displayed the least amount of range. The reason for this was that the ions under investigation had different atomic weights. When compared to heavy ions, less heavy ions are more mobile when the photon energy is the same to both types of ions. A visual summary of the findings may be found in Figure **31**, which shows that the ranges of charged particles increase with decreasing density of glass samples at increasing energy levels. Figures **27-30** also show this relationship. Figures **27** and **30** are quite similar to one another, which suggests that the features of the responses of gold ions, carbon ions, proton and helium ions, and gold ions are comparable throughout a broad energy range.

Figure 27: The calculated H⁺ ions range at different energies through the composites glass investigated samples

Figure 28: The calculated Au⁺ ions range at different energies through the composites glass investigated samples

Figure 29: The calculated C⁴⁺ ions range at different energies through the composites glass investigated samples

Figure 30: The calculated He⁺⁺ ions range at various energies through composites glass samples

Figure 31: The calculated ions range at various energies through the BZnPb20 investigated samples.

4.12.Total stopping power (TSP) and CSDA range of charged electrons

Energy of the electron is a factor that determines the TSP of the electron. The ionization potential of the glass samples is the single factor that determines the electron stopping power when the energy level is 0 eV. Figure **32** illustrates this phenomenon. Because of the high density of the sample in question, BZnPb₇₀ produced the largest total surface area (TSP) when the energy of the electron was raised. This is because it contains the greatest quantity of nanoscale lead oxide.

Based on the data shown in Figure **33**, the CSDA range of electrons in all of the samples demonstrated an exponential connection to the kinetic energy of the particles. Because of the decrease in density, the CSDA ranges of electrons rose exponentially. This occurred when the electron energy was larger than 15 MeV. Throughout the whole energy range, the PZnPB₂₀ compound was found to have the highest CSDA range. Earlier comments made by other researchers in [**18**] that a low-density sample offered a greater CSDA electron range are further supported by this evidence.

Figure 32: The calculated total stopping power of electrons through composites glass samples

Figure 33: The calculated CSDA range of electrons through composites glass samples

5. Conclusions

It was hypothetically explored how incorporating PbO into $PbO.ZnO.B_2O_3$ and $PbO.ZnO.P_2O_5$ glass systems affected certain ionizing radiation shielding properties. To find out how inserting PbO affected the two glass systems shielding capacities, we looked at the interaction parameters of this ionizing radiation. The interaction properties of two series of ternary phosphate and borate glass systems, $PbO.ZnO.B_2O_3$

and *PbO*.*ZnO*.*P*₂*O*₅, with charged ions such as proton (H⁺), alpha (He⁺⁺), Au⁺, and C⁴⁺, were theoretically calculated by varying the concentration of PbO in each glass. The densities of the bromated glasses ranged from 3.675 to 6.650g.cm⁻³, while those of the phosphate glasses were 3.177 to 4.845g.cm⁻³. This study's findings indicate that, in general, radiation and charged ion shielding capability (interactions) is maximized at lower gamma energies when PbO is added incrementally to phosphate systems (from 0% to 50%) and to borate glass systems (20% to 70%). That is to say, in both the phosphate glass system (PZnPb₅₀) and the borate glass system (BZnPb₇₀), the maximal shielding capability was demonstrated. Consequently, systems of phosphate and borate glass adjusted with a larger proportion of PbO are beneficial for shielding purposes.

CRediT authorship contribution statement:

E.O. Echeweozo: Authored the initial manuscript, conducted data analysis, and meticulously revised and edited the document to its final form. A. M. Abdelmonem: Developed the research concept and formulated the calculations. Expertise in data analysis, review, and editing. Skilled in investigation, methodology, supervision, validation, and visualization. Reviewed and polished the manuscript to its final version. G.C. Nwigwe: Carefully reviewed and polished the manuscript to its final form. The final manuscript has been reviewed and approved by all the authors.

Consent for publication: All author hereby give consent for the publication of this manuscript. Availability of data and materials: The data presented in this study are available on request from the corresponding author.

Competing interests: The authors declare that they have no known competing financial interests or personal interests that could have appeared to influence the work reported in this paper.

Acknowledgements:

The authors of this research project provided the sole funding for the study, without any financial support from external sources such as public, commercial, or non-profit organizations. The corresponding author would like to thank the authors for their interest and dedication to this research.

References

- [1] S. M. Saheb, R. Vijay, P. V. Rao, P. Ramesh, B. C. Chandrakala, P. S. Prasad, G. N. Raju, *Results Phys.*, 11 (2018) 780-786.
- [2] K. Singh, S. Singh, A. S. Dhaliwal, G. Singh, Appl. Radiat. Isot., 95 (2015) 174-179.
- [3] E. Echeweozo, D. Igwesi, Appl. Radiat. Isot., 176 (2021) 109908.
- [4] H. Singh, K. Singh, L. Gerward, H. S. Sahota, R. Nathuram, Nucl. Instrum. Methods Phys. Res. B, 207 (2003) 257-262.
- [5] N. Singh, K. J. Singh, K. Singh, H. Singh, Nucl. Instrum. Methods Phys. Res. B, 225 (2004) 305-309.
- [6] B. Aktas, S. Yalcin, K. Dogru, Z. Uzunoglu, D. Yilmaz, *Radiat. Phys. Chem.*, 156 (2019) 144-149.
- [7] P. Kaur, K. J. Singh, S. Thakur, P. Singh, B. S. Bajwa, Mol. Biomol. Spectrosc., 206 (2019) 367-377.
- [8] H. S. Gokce, D. Kocyiğit, Opt. Mater. (Amst.), 83 (2018) 233-240.
- [9] D. S. Da Silva, T. A. A. De Assumpcao, L. R. P. Kassab, C. B. De Araujo, J. Alloys Compd., 586 (2014) S516-S519.

- SOHAG JOURNAL OF SCIENCES
- [10] T. Hashimoto, H. Inukai, K. Matsumura, H. Nasu, A. Ishihara, Y. Nishio, Sens. Actuators B Chem., 257 (2018) 807-814.
- [11] B. C. Jamalaiah, J. Non-Cryst. Solids, 502 (2018) 54-61.
- [12] Y. Zhang, C. Lu, Y. Feng, L. Sun, Y. Ni, Z. Xu, Mater. Chem. Phys., 126 (2011) 786-790.
- [13] U. Hoppe, N. P. Wyckoff, R. K. Brow, M. Von Zimmermann, A. C. Hannon, J. Non-Cryst. Solids, 390 (2014) 59-69.
- [14] L. R. P. Kassab, D. K. Kumada, D. M. Da Silva, J. A. M. Garcia, J. Non-Cryst. Solids, 498 (2018) 395-400.
- [15] P. Yu, L. Su, J. Cheng, J. Xu, Infrared Phys. Technol., 74 (2016) 53-56
- [16] A. Jha, B. Richards, G. Jose, T. Teddy-Fernandez, P. Joshi, X. Jiang, J. Lousteau, Prog. Mater. Sci., 57 (2012) 1426-1491
- [17] A. Das, M. Goswami, M. Krishnan, Ceram. Int., 44 (2018) 13373-13380.
- [18] O. I. Sallam, A. M. Madbouly, F. M. Ezz-Eldin, J. Alloys Compd., 926 (2022) 166935.
- [19] R. S. Kaundal, S. Kaur, N. Singh, K. J. Singh, J. Phys. Chem. Solids, 71 (2011) 1191-1195.
- [20] G. P. Singh, J. Singh, P. Kaur, S. Kaur, D. Arora, R. Kaur, K. Kaur, D. P. Singh, J. Mater. Res. Technol., 9 (2020) 14425-14442.
- [21] N. A. Ghoneim, H. A. Elbatal, A. M. Abdelghany, I. S. Ali, J. Alloys Compd., 509 (2011) 6913-6919.
- [22] A. Kumar, M. I. Sayyed, M. Dong, X. Xu, J. Non-Cryst. Solids, 481 (2018) 604-607.
- [23] M. I. Sayyed, I. Saleem, Z. Y. Qashou, J. Khattari, J. Alloys Compd., 696 (2017) 632-638.
- [24] P. Limkitjaroenporn, J. Kaewkhao, P. Limsuwan, W. Chewpraditkul, J. Phys. Chem. Solids, 72 (2011) 245-251.
- [25] L. Gerward, N. Guilbert, K. B. Jensen, H. Levring, *Radiat. Phys. Chem.*, 60 (2001) 23-24.
- [26] L. Gerward, N. Guilbert, K. B. Jensen, H. Levring, *Radiat. Phys. Chem.*, 71 (2004) 653-654.
- [27] E. Şakar, O. F. Özpolat, B. Alım, M. I. Sayyed, M. Kurudirek, *Radiat. Phys. Chem.*, 166 (2020) 108496.
- [28] K. S. Mann, S. S. Mann, Ann. Nucl. Energy, 150 (2020) 107845.
- [29] M. J. Berger, J. S. Coursey, M. A. Zucker, J. Chang, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
- [30] H. S. Gökçe, O. Güngör, H. Yılmaz, Radiat. Phys. Chem., 185 (2021) 109519.
- [31] M. O. El-Ghossain, Int. J. Phys., 5 (2017) 92-98
- [32] E. O. Echeweozo, A. D. Asiegbu, E. L. Efurumibe, L. A. Nnanna, H. K. Idu, *Radiat. Phys. Eng.*, 2 (2021) 29-37.
- [33] J. W. Martin, Materials for Engineering, 3rd Ed. Elsevier, Oxford, 2006.
- [34] W. D. Callister, D. G. Rethwisch, Materials Science and Engineering: An Introduction, 9th Ed. Wiley, New York, 2013.
- [35] R. E. Smallman, A. H. W. Ngan, Modern Physical Metallurgy, 8th Ed. Elsevier, Oxford, 2014.
- [36] D. J. Green, J. S. Kang, J. B. Youngblood, J. Am. Ceram. Soc., 80 (1997) 1465-1473.
- [37] C. J. Brinker, G. W. Scherer, Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing. Academic Press, San Diego, 1990.
- [38] A. R. West, Solid State Chemistry and its Applications, 2nd Ed. Wiley, New York, 2014.
- [39] H. Kolaska, Fuel Processing Technology, 77-78 (2002) 5-20
- [40] H. H. Kung, Transition Metal Oxides: Surface Chemistry and Catalysis. Elsevier, Amsterdam, 1989.
- [41] R. J. D. Tilley, Understanding Solids: The Science of Materials, 2nd Ed. Wiley, New York, 2013.
- [42] A. M. Neville, Properties of Concrete, 5th Ed. Pearson, London, 2011.
- [43] F. P. Incropera, D. P. DeWitt, Fundamentals of Heat and Mass Transfer, 7th Ed. Wiley, New York, 2011.
- [44] J. Crank, The Mathematics of Diffusion, 2nd Ed. Oxford

University Press, Oxford, 1975.

- [45] D. R. Lide, CRC Handbook of Chemistry and Physics, 85th Ed. CRC Press, Boca Raton, 2004.
- [46] K. Binder, D. W. Heermann, Monte Carlo Simulation in Statistical Physics, 5th Ed. Springer, Berlin, 2010.
- [47] G. Kresse, J. Hafner, Phys. Rev. B, 47 (1993) 558-561.
- [48] M. P. Allen, D. J. Tildesley, Computer Simulation of Liquids, 2nd Ed. Oxford University Press, Oxford, 2017.
- [49] W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, Numerical Recipes: The Art of Scientific Computing, 3rd Ed. Cambridge University Press, New York, 2007.
- [50] J. N. Reddy, An Introduction to the Finite Element Method, 3rd Ed. McGraw-Hill, New York, 2006.
- [51] S. Timoshenko, Strength of Materials, 3rd Ed. Van Nostrand, New York, 1955.
- [52] G. E. Dieter, Mechanical Metallurgy, 3rd Ed. McGraw-Hill, New York, 1986.
- [53] D. Hull, T. W. Clyne, An Introduction to Composite Materials, 2nd Ed. Cambridge University Press, Cambridge, 1996.
- [54] H. K. D. H. Bhadeshia, R. W. K. Honeycombe, Steels: Microstructure and Properties, 4th Ed. Butterworth-Heinemann, Oxford, 2017.
- [55] K. M. Ralls, T. H. Courtney, J. Wulff, Introduction to Materials Science and Engineering. Wiley, New York, 1976.
- [56] R. M. Rose, L. A. Shepard, J. Wulff, The Structure and Properties of Materials, Vol. IV. Wiley, New York, 1966.
- [57] C. Kittel, Introduction to Solid State Physics, 8th Ed. Wiley, New York, 2004.