Gamma Ray and Neutron Shielding Properties of Lead Borate Glass Containing Sodium, Alumenium and Zinc Oxides

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Abstract

Lead borate doped with Na2O- Al2O3- ZnO glass composition has been prepared by means of melt quenching technique. The mass attenuation coefficients of the prepared glass samples have been determined in the photon energy range up to 2 MeV. Furthermore, the neutron removal cross sections have been calculated. The obtained results illustrate that the glass samples containing 40% mol lead oxide (PbO) have considered capability to be used as a proper shielding material in the nuclear domain. The experimental mass attenuation coefficients are compared with the corresponding theoretical calculations based on the Xcom program and fair agreement has been obtained.

Keywords
Lead Glass, Mass Attenuation Coefficients, Effective Atomic Number, Fast Neutron Removal Cross-section.

1. Introduction

The wide spread of nuclear applications in different fields may cause many health hazards to mankind. Accordingly, solutions for protection against irradiation effects are very necessary making use of variety of chemical composition such as alloys, rubber and glasses. Borat glasses doped with adequate heavy or light elements comprise a special class of hard composite that differ from most alternative materials such as rubber, steel and concrete [1-3]. Those alternative materials are at least relatively expensive and their preparation is also difficult. It is well known that the interaction of radiation (neutrons and gamma rays) with matter is related to its effective atomic number and density. Therefore, the target of the present study is to follow the behavior of the neutron and gamma radiation interactions with the new investigated xPbO- 10 Na2O- 10 Al2O3- 10 ZnO- (70-x) B2O3 glass matrix by measuring the shielding properties for fast neutrons in addition to gamma rays at different energies from 228 to 1500 keV.

2. Theoretical calculations

2.1. Total Mass Attenuation Coefficient and Half-Value Layer

A parallel beam of monoenergetic gamma rays is attenuated in any material according to Lambert-Beer law [4]

\[ I(x) = I_0 e^{-\mu x} \]  

(1)

Where \( I_0 \) is the initial intensity, \( I(x) \) is the photons that penetrate the distance \( x \) in the material and \( \mu \) is the total linear attenuation coefficient.

The mass attenuation coefficient \( \mu/p \) for any mixture of elements is calculated by [4]

\[ \frac{\mu}{p} = \sum_i w_i \left( \frac{\mu}{p} \right)_i \]  

(2)

Where \( \left( \frac{\mu}{p} \right)_i \) is the mass attenuation of the \( i \)th constituent and \( w_i \) is the weight fraction of the \( i \)th constituent.

The half value layer (HVL) which is the thickness of a material required to reduce the intensity of incident radiation to half of its value is inversely proportional to the linear attenuation coefficient via the following form [5]

\[ HVL = \ln 2/\mu(3) \]

2.2. Effective Atomic Number

The effective atomic number \( Z_{\text{eff}} \) of the glass that consisting of different elements is based on the total attenuation cross section for \( \gamma \)-ray interactions and it can be obtained by means of the following form [7, 8]

\[ Z_{\text{eff}} = N_A \sum_i \frac{w_i \lambda_i Z_i}{A_i} \]  

(4)

Where \( N_A \) is the Avogadro’s number, \( Z_i \) is the atomic number of the \( i \)th element; \( A_i \) and \( \lambda_i \) are the weights in grams and number of atoms of element \( i \) relative to the total number of atoms in the investigated material respectively.
2.3. Effective Removal Cross-Section for Fast Neutrons ($\Sigma R \text{ cm}^{-1}$)

The removal cross section or the neutron attenuation coefficient $\Sigma R$ for homogenous mixture may be calculated from the value $\Sigma R_p$ or $\Sigma R$ for various elements in the compounds or mixtures using the following formula \[9\]

$$\Sigma R = \sum_i \rho_i (\Sigma R_i / \rho_i)$$

where $W_i$ is the weight percentage, $\rho_i$ and $(\Sigma R_i / \rho_i)$ are the partial density and the fast neutron mass attenuation coefficient of the $i^{th}$ constituent, respectively.

3. Materials and Methods

3.1. Preparation of the Shielding Material

Glass with composition ($x$PbO- 10 Na$_2$O- 10 Al$_2$O$_3$- 10ZnO- (70- $x$) B$_2$O$_3$), $x= 0, 10, 20, 30, 40$ mole % are prepared using the melt quenching technique. After melting, glass batches are immediately poured onto a hot stainless steel mold at 300 °C and the prepared samples are annealed at an appropriate temperature 500 °C for a period of two hours.

3.2. The Mass Attenuation Coefficient

A narrow gamma ray collimated beam using the transmission method was used for mass attenuation measurements by using the hyper pure germanium (HPGe) detector with relative efficiency 30%. Samples were placed between the detector and the standard gamma point source. Photons emitted from $^{232}$Th and $^{40}$K radioactive point sources in the range from 0.2 to 2.0 MeV were used taking into consideration the gamma ray lines of energies 238.62, 583.1, 968.9 and 1461.2 keV.

4. Results and Discussions

4.1. The Mass Attenuation Coefficient and the Corresponding Half-Value Layer

The resulting experimental values of the mass attenuation coefficient are shown in figure (1) together with theoretical values, calculated by the WinXCom program. It is observed that there is good agreement between experiment and theory.
Fig. (1) Mass attenuation coefficient of the studied glass samples as a function of gamma ray energy.

The dependence of the HVL on both gamma ray energy and PbO content is shown in Table 1. From the table, it is clear that the HVL decreases with increasing the mole fractions of PbO in the present investigated glass system. This behavior is simply attributed to the densities of the glass system.

**Table (1): The half value layer (m) for the prepared glass samples**

<table>
<thead>
<tr>
<th>Gamma ray energy (keV)</th>
<th>Pb=0%</th>
<th>Pb=10%</th>
<th>Pb=20%</th>
<th>Pb=30%</th>
<th>Pb=40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>238.62</td>
<td>0.05528</td>
<td>0.05423</td>
<td>0.0534</td>
<td>0.05219</td>
<td>0.04494</td>
</tr>
<tr>
<td>583.1</td>
<td>0.03126</td>
<td>0.02607</td>
<td>0.02249</td>
<td>0.01802</td>
<td>0.01709</td>
</tr>
<tr>
<td>968.9</td>
<td>0.02699</td>
<td>0.02158</td>
<td>0.01856</td>
<td>0.01449</td>
<td>0.01364</td>
</tr>
<tr>
<td>1461.2</td>
<td>0.02199</td>
<td>0.01799</td>
<td>0.01532</td>
<td>0.01208</td>
<td>0.01114</td>
</tr>
</tbody>
</table>

4.2. The Effective Atomic Number

The effective atomic number ($Z_{eff}$) has been calculated theoretically. The data of $Z_{eff}$ for the present investigated glass samples are shown in figure (2). From the figure it is obviously clear that the effective atomic number decreases with energy increase.
Fig. (2) The effective atomic number of the glass samples as a function of the photon energy.

### 4.3. The Removal Cross-Section

It is evident that there are irregularities that are caused by sharp drops in the value of cross-section that occur at neutron numbers of 50, 82 and 126. These exceptionally low values of the cross-section correspond to usually large level spacings such as those for lead which has 126 neutrons. In our investigated glass matrix it is found that the removal cross-section increases with the increase of lead content as shown in figure (3) inspite of having large level spacings. Therefore, the obtained results suggested that the value of the total neutron cross-section is largely affected by lead content. It is very well known that boron plays the dominant contribution to the total cross-section only at thermal neutron energy.

Fig. (3) Neutron removal cross-section as a function of lead oxide contents.
Conclusion

New shielding glass samples \((x\text{PbO}-10\text{Na}_2\text{O}-10\text{Al}_2\text{O}_3-(70-x)\text{B}_2\text{O}_3)\) were prepared by melt-quenching technique. Mass attenuation coefficients, half value layer, effective atomic number, and fast neutron removal cross-section for the five prepared samples have been evaluated. A comparison of theoretical and experimental mass attenuation coefficients for glass samples has been undertaken. In general, the obtained results indicate that the present investigated glass matrix has high capability to be used as a proper shielding material in the nuclear domain.

References


