Calculation of The Radiation Shielding Parameters in Long Ranges of Photon Energy: Bismuth Sodium Borate Glass

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Abstract. The theoretical calculations on radiation shielding parameters of glass systems in the composition(80-x) B\textsubscript{2}O\textsubscript{3}: 20Na\textsubscript{2}O: xBi\textsubscript{2}O\textsubscript{3} (where x = 0,5,10,15 and 55 mol\%) were inquired into using the WinXCom program. The characteristics of radiation shielding parameters for the glass systems had been examined for the mass attenuation coefficients, the effective atomic number, and the electron density in the energy ranges of 1 keV to 100 GeV. These are the glass systems at the different compositions of bismuth which were found that depend upon the energy regions. The results demonstrate that the mass attenuation coefficients, the effective atomic number, and the electron density have the same trend which those values increase with the increasing of the different compositions of bismuth. At the low-energy region, the mass attenuation coefficients show the several discontinuous jumps of the energies which correspond to the photoelectric absorption edges. At the medium-energy region, the Compton scattering process is the main interaction in these energy ranges. In the high-energy regions, pair production becomes the main interaction process and tends to be constant over energy.

1. Introduction
Currently, lead has been widely utilized for the manufacturing of the radiation shielding materials. However, some essential materials are supposed to be imported with high expenses such as the radiation shielding glass, particularly for nuclear plants, hospitals and industrial research. On the other hand, lead is a hazardous material and has disadvantages in both its weight and lack of environmental friendliness. Generally, recent international research suggests developing the radiation shielding properties by adding elements to improve the shielding properties which are used to replace lead [1-11].

Bismuth (Bi) is playing on important role inradiation glass shielding and replacing lead (Pb) due to environmental toxicity of Pb and protectionism in world economy. In this work, the measurement the total mass attenuation coefficients of the candidate materials which used for radiation shielding glass development such as Bi\textsubscript{2}O\textsubscript{3} in borate glass system [7] which glasses is one of the suitable materials which can be used for radiation materials due to their high transparency in visible region. Among glass materials, the borate is the most popular as a glass forming material [12].

Glass materials are specifically preferred alternatives to concrete for their transparency to visible light and moreover its properties can be modified with composition and preparation techniques.
are promising materials in this regard. Several glasses have been developed for nuclear engineering applications because they accomplish the double task of allowing visibility while absorbing radiations like gamma-rays and neutrons. A good shielding glass should have high value of interaction cross-section and at the same time, irradiation effects on its mechanical and optical properties should be small [2].

In 1995, Hubble and Seltzer had continuously been evolving the WinXCom software [14] that can compute the mass attenuation coefficients (MAC) of the elements and compounds in the range of 1 keV to 20 keV of the energy by calculation from the mixture rule and can continually calculate the effective atomic numbers [16]. For convenience on comfortably working, Berger and Hubble continued developing the XCOM software for designing the DOS systems which were later developed Gerward as and adjustment from DOS into the Windows systems by being called WinXCom [16,17]. Moreover, they can estimate the total mass attenuation coefficients, partial attenuation interaction, total atomic cross-section, partial atomic cross-section that also include the photoelectric absorption attenuation coefficient, Compton scattering attenuation coefficient, pair production attenuation coefficient, and coherent scattering attenuation coefficient in the range of 1 keV to 100 GeV of the energy and those values have been used for theoretical values which are in good agreement for international publication [7-13, 14-17].

The objective of this work is to investigate the mass attenuation coefficients, the effective atomic number and the electron density of (80-x) B\textsubscript{2}O\textsubscript{3}: 20Na\textsubscript{2}O: xBi\textsubscript{2}O\textsubscript{3} (where x = 0,5,10,15 and 55 mol%) by using the WinXCom program.

2. Theory

**Gamma matters interaction**

Depending upon the interacting particle/field in the matter (electrons, nucleons, electric field surrounding nuclei/electrons or meson field surrounding nucleons) with which gamma photons are interacting and the result of that interaction (may be complete absorption, elastic/coherent scattering or inelastic/incoherent scattering); there are many processes by which gamma rays can interact with matter. Different combinations of interacting particle/field with resultant mechanism suggests twelve processes of photon interaction. However, on the basis of probability of occurrence, only three dominant photon interaction processes are discussed below

*Photoelectric absorption*

Gamma photon interacts with the electron (mostly from K shell) of the matter which results in the complete absorption of the photon. During the process, partial photon energy is consumed to overcome the binding energy of the electron and remaining is transferred to the freed electron as its kinetic energy. The threshold energy for this process to occur depends upon the binding energy of the electron in a particular shell. Cross-section for photoelectric effect strongly depends on atomic number of an element as Z\textsuperscript{4-5} and energy of gamma photons as E\textsuperscript{-3.5}. It is concluded that this photon interaction process is dominant for heavy elements (like lead and uranium) at lower photon energies [18].

*Compton scattering*

It is the process of inelastic/incoherent scattering of gamma photon while interacting with an electron (which is assumed to be free/weakly bound and at rest). As a result of this process, partial photon energy has been transferred to an electron and photon scattered with the rest of energy. Hence, this process results in only energy degradation of the gamma photon. The cross-section for Compton scattering process is least dependent on atomic number and slowly decreases with the increase in
gamma-rays energy. Hence, this process is dominant at intermediate photon energy for all elements [19].

**Pair production**

It is the process of complete absorption of gamma photon in the electric field of nuclei/electrons, which results in the formation of an electron-positron pair. The threshold value for this process to occur is 1.022MeV (which is equivalent to the sum of rest mass of an electron and positron). For gamma photon with higher energy, the excess energy is transferred as kinetic energy to electron–positron pair. This process is the best example for transformation of energy into mass. The cross-section for pair production in the electric field of a nucleus varies directly with atomic number as $Z^2$ and with photon energy as $\log(E)$. Hence, it is a dominant process for heavy elements at higher photon energies [20].

**Radiation shielding properties**

Materials to be used for gamma radiation shielding should have homogeneity of density and composition, and sufficient thickness to absorb the radiations to a safe level. It must have high atomic number. Mass attenuation coefficient ($\mu_m$), effective atomic number ($Z_{eff}$), and the electron density ($N_e$) are the basic quantities which determine the scattering and absorption of X-rays and gamma rays photons in matter.

**The mass attenuation coefficient**

Mass attenuation coefficient measures the number of photons interacted (may be scattered or absorbed) with the interacting material. The mass attenuation coefficient can be evaluated using Lambert-Beer’s law which states that when a narrow beam of mono-energetic gamma ray photons passes through matter, the probability of attenuation is proportional to the thickness ($x$) of the matter, the density ($\rho$) of the matter and the linear attenuation coefficient ($\mu$) of the matter. Mathematically, it is expressed as

$$I = I_0 e^{-\mu x}$$

The mass attenuation coefficient ($\mu_m$) values for the glass samples can be computed in the energy region from 1keV to 100GeV using WinXCom based on the mixture rule. The software package provides total as well as partial attenuation coefficients and cross sections for various interaction processes (Coherent, Incoherent (Compton scattering), photoelectric absorption, pair production in nuclear field and electric field).

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i \left( \frac{\mu_i}{\rho_i} \right)$$

where $\mu_i$, $\rho_i$ and $w_i$ are the attenuation coefficient, density and weight fraction of the $i^{th}$ constituent element respectively. It is the fundamental tool to derive many other parameters such as mass energy absorption coefficient, atomic cross-section, electronic cross-section, effective atomic number, electron density in these works.
The effective atomic number

The effective atomic number for a material composed of several elements cannot be expressed by a single number. It has to be weighed differently for each of the different processes by which gamma rays can interact with matter. The atomic cross-section can be obtained by dividing the molecular cross-section by the total number of formula units as follow:

\[
\sigma_{t,a} = \frac{\left(\mu_m\right)_{\text{glass}}}{N_A \sum_i (w_i / A_i)}
\]

The electronic cross-section can be calculated by the relation

\[
\sigma_{t,el} = \frac{1}{N_A} \sum_i f_i A_i \left(\frac{\mu_m}{Z_i}\right)_i
\]

where \(f_i\) is the fractional abundance of \(i^{th}\) element to the total number of atoms of all elements in glass, \(Z_i\) is the atomic number of the \(i^{th}\) element in the mixture. The effective atomic number can be computed by the relation

\[
Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}}
\]

The effective electron density

It is the number of electrons per unit mass of the interacting material. The higher the value of electron density, the better are the chances of photon interaction. The electron density \((N_e)\) is given by [21-23]

\[
N_e = \frac{\mu_m}{\sigma_{t,el}}
\]

3. Results and discussion

| Table 1. Photon energies (in keV) of absorption edges. |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Element   | Z  | M5   | M4   | M3   | M2   | M1 | L3  | L2   | L1  | K  |
| Na        | 11 |       |      |      |      |    |     |      |      | 1.072       |
| Bi        | 83 | 2.580 | 2.688| 3.177| 3.969| 3.999| 13.419| 15.711| 16.388| 90.526 |
In the present study, the basic radiation parameters of bismuth sodium borate glass systems, different composition of bismuth, were studies by the direct method over wide photon energy range from 1 keV to 100 GeV using WinXCom program. These parameters are the mass attenuation coefficients, the effective atomic number ($Z_{\text{eff}}$), and the electron density ($N_e$). The formula of bismuth sodium borate glass is $\text{B}_2\text{O}_3$: $20\text{Na}_2\text{O}: x\text{Bi}_2\text{O}_3$ (where $x = 0, 5, 10, 15$ and $55$ mol%). The curves of radiation parameters were readily calculated after determining the chemical composition experimentally. WinXCom program can be used for theoretical calculation of total and partial interaction if the chemical composition of compound or mixture is known. The calculated results are shown graphically in Fig. 1 shows the results of the total mass attenuation coefficients of bismuth sodium borate glasses for all bismuth compositions against the photon energy. It is seen from figure that different dominant interaction processes on different energy regions. There are three energy ranges relative to the partial processes: photoelectric absorption at low energies, incoherent (Compton) scattering at intermediate energies and pair production at high energies.

The variation of $Z_{\text{eff}}$ of photon energy for total interaction processes in all bismuth sodium borate glasses is shown in Fig. 2. It can be seen that the minimum value of $Z_{\text{eff}}$ is found around intermediate energies ($0.3 < E < 4$ MeV). For the incoherent (Compton) scattering process, the variation of $Z_{\text{eff}}$ with photon energy which can be seen that initially $Z_{\text{eff}}$ decreases with increasing energy, minima at 10 keV,
and then it increases with increasing energy up to 400 keV. Finally, it remains constant even with further increase in energy.

For the photoelectric absorption process, the variation of $Z_{\text{eff}}$ with photon energy. The behavior of $Z_{\text{eff}}$ with respect to energy shows discontinuous jumps in the low energy range ($E < 0.04$ MeV) and then it remains constant there after. The energy of these discontinuities corresponds to photoelectric absorption edges of sodium, and bismuth as shown in Table 1.

The photon energy for pair production in nuclear field is shown in the range of the energy from 1.25 to 10 MeV. The values of $Z_{\text{eff}}$ decrease rapidly and then slightly decrease with further increasing of photon energy.

The variation of $N_{\text{eff}}$ of bismuth borosilicate glasses with photon energy for total photon interaction is shown in Fig. 3. The total and partial interaction processes of $N_{\text{eff}}$ values. It is observed that $N_{\text{eff}}$ shows similar trends to $Z_{\text{eff}}$.

4. Conclusions

The present study gives the values for the gamma-rays mass attenuation coefficients, effective atomic numbers, and effective electron density of bismuth sodium borate glasses over a wide range of photon energies from 1 keV to 100 GeV. The results demonstrated that the mass attenuation coefficients, $Z_{\text{eff}}$ and $N_{\text{eff}}$ parameters are dependent on photon energy.

- At the low-energy region, the mass attenuation coefficients, $Z_{\text{eff}}$, and $N_{\text{eff}}$ show the several discontinuous jumps of the energies which correspond to the photoelectric absorption edges.
- At the medium-energy region, the Compton scattering process is the main interaction.
- In the high-energy regions, pair production becomes the main interaction process and tends to be constant over energy.

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