Gamma-ray, Neutron and Beta Radiation Shielding Properties of Bi$_2$O$_3$-Li$_2$O-MnO$_2$-B$_2$O$_3$ Glasses

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Abstract. Proper shielding from harmful ionizing radiations is a mandatory requirement in nuclear facilities owing to the harmful effects on radiation workers and general public in case of radiation exposure. The present work is aimed at the investigation of the shielding properties of the prepared glass system of chemical composition (83.5+x)Bi$_2$O$_3$-(0.6+x)Li$_2$O-0.1MnO$_2$-(15.8-2x)B$_2$O$_3$ (with x = 0, 0.7 and 1.4 wt.% coded as L5, L10 and L15 respectively), with respect to the Gamma-ray, Beta and fast neutron radiation. The Gamma-ray shielding property of the glass system was also compared with the most commonly used Barite concrete and commercially available shielding glass ‘RS 253 G18’. Also, the neutron shielding properties was compared with common neutron shielding materials including Graphite, Boron Carbide and Polyethylene grains. An attempt was made in this study to select a better shielding material than the compared standard shielding materials. It is inferred that L15 glass sample is the best shield material for Gamma-rays, fast neutrons and also, for Beta radiation in the high energy region due to Bremsstrahlung, while in low energy region glass, L5 is better for Beta shielding.

1. Introduction

Nowadays, usage of radiation in various fields including radiotherapy, security arrangement and nuclear power generation is increasing. The medical area is unimaginable without the PET (Positron Emission Tomography) scans, CT (Computerized Tomography) scans, Magnetic Resonance Imaging (MRI), Nuclear Medicine Imaging. The number of nuclear power plants is also increasing worldwide. But with its advent, high risk is involved to the health of radiation workers and general public in the events of radiation leakage, unwanted radiation exposure, and nuclear accidents.

Therefore, proper shielding from the hazardous ionizing radiations such as Gamma-rays, neutrons and Beta particles becomes a necessity in nuclear facilities. Gamma-rays are neutral and of indirectly ionizing nature. Therefore, a high atomic number (high Z element) and dense material is required to shield from Gamma-rays. These materials can be Lead, Concrete, Bismuth, Tungsten etc. Neutrons are uncharged and also, indirectly ionizing particles that require lighter materials (low Z elements) for shielding purposes such as hydrogen and hydrogen containing materials, for example water, polythene, paraffin wax etc. Beta radiation comprises of fast moving electrons which have high penetration power due to their small size and requires both light and heavy materials for shielding [1].

Therefore, in this work, a Bi$_3$O$_3$-Li$_2$O-MnO$_2$-B$_2$O$_3$ glass system containing a combination of high and low-Z elements is studied for shielding against Gamma-rays, Neutrons and Beta particles. The
The glassy structure of the prepared samples was verified by X-ray diffraction (XRD). And then, the gamma-ray shielding properties of the samples were studied in terms of Mass attenuation coefficient, half value layer and mean free path. The neutron shielding of the glass samples was studied by ‘fast neutron removal cross-section’. Finally, the Beta radiation property was studied from the mass stopping power. The present work can be very helpful in developing a new generation glass shielding material which has the ability to shield not only the gamma-rays but also the neutrons and beta radiations.

2. Experimental Details

The glass samples of the chemical composition (83.5+\(x\))Bi\(_2\)O\(_3\).\((0.6+x)\)Li\(_2\)O.0.1MnO\(_2\).\((15.8-2x)\)B\(_2\)O\(_3\) where, \(x = 0, 0.7\) and \(1.4\) wt.\%, (labelled as L5, L10 and L15, as shown in table 1) were prepared by the conventional melt quenching technique. Stoichiometric amounts of AR grade reagents Bi\(_2\)O\(_3\) (CDH, India, purity 99%), Li\(_2\)CO\(_3\) (CDH, India, purity 99.5%), MnO\(_2\) (Merck, Germany, purity \(\geq\) 95%) and H\(_3\)BO\(_3\) (CDH, India, purity 99.5%) were used as raw materials to prepare the glass samples. The reagents used were mixed thoroughly using pestle and mortar and then, melted in Porcelain crucibles at 850\(^\circ\)C for 40 minutes with periodic stirring until homogeneous mixture was obtained and then followed by quenching. At this stage, the sample was poured in a pre-heated copper plate and annealed at 250\(^\circ\)C for 30 minutes followed by slow cooling to room temperature in order to remove internal stress. Cylindrical shaped samples were obtained.

### Table 1. Chemical composition, density and molar volume of the prepared glasses.

| Sample Codes | Composition (in wt. %) | Density (g/cm\(^3\)) | Molar Volume (cm\(^3\)/mol) |
|--------------|------------------------|-----------------------|-----------------------------|
|              | Bi\(_2\)O\(_3\) | Li\(_2\)O | MnO\(_2\) | B\(_2\)O\(_3\) |              |
| L5           | 83.5                  | 0.6     | 0.1     | 15.8     | 5.35   | 43.62 |
| L10          | 84.2                  | 1.3     | 0.1     | 14.4     | 5.47   | 42.26 |
| L15          | 84.9                  | 2.0     | 0.1     | 13.0     | 5.61   | 40.89 |

Density of the samples was measured by employing Archimede’s principle and molar volume was also obtained from the density values. The glassy nature of the prepared samples was examined from XRD patterns (by using X-ray diffractometer model Shimadzu XRD-7000 Maxima).

The Gamma-ray shielding ability of the prepared glasses was measured experimentally (using narrow beam transmission method) and theoretically (using Hubbell and Seltzer database of photon attenuation with the help of XCOM program [2]) at 662 keV in terms of mass attenuation coefficient and half-value layer (HVL) parameters. It was also compared with commonly used barite concrete and commercial shielding glass RS 253 G18 [3] in nuclear reactors.

Furthermore, the mass attenuation coefficient (MAC), half-value layer (HVL) and mean free path (MFP) values were also computed in the photon energy range varying from 1 keV to 100 GeV (i.e. \(10^{-3}\)-\(10^{-5}\) MeV) using XCOM software. The neutron shielding properties were studied from the parameter, “fast neutron removal cross-section (\(\Sigma_R\) )”. And, it was also compared with some common neutron shielding materials namely Graphite, Boron Carbide and Polyethylene grains.

Finally, the speculated shielding behaviour of our synthesized samples from Beta radiation was also studied from the mass stopping power (MSP) values obtained with the help of ESTAR database for electron interaction [1]. The data obtained from the above studies is used to provide an insight for selecting a better shielding material.
3. Results and Discussion

From the analysis of the XRD patterns (figure 1), it can be observed that there is the absence of sharp peaks. A broad hump at ~28° can be seen which is characteristic of the amorphous or, in other words, glassy nature of the prepared samples.

![Figure 1. X-ray diffraction patterns of glass samples.](image)

A slight increase in the density of glass samples (from 5.35 to 5.61 g/cc) is observed (table 1) owing to the increase in weight percentage of heavier Bi₂O₃ at the expense of lighter B₂O₃ (table 1). Decrease in molar volume (from 43.62 to 40.89 cc/mol) indicates the decrease in free space in the glass network.

| Sample Codes | Mass Attenuation Coefficient \((\mu/\rho)\) (cm²/g) at 662 keV | Half Value Layer (HVL) (cm) (From XCOM) | Sample Codes | \(\Sigma_R\) (cm⁻¹) |
|--------------|------------------------------------------------|--------------------------------------|--------------|----------------|
| L5           | 0.1030                                        | 1.254                                | L5           | 0.101          |
| L10          | 0.1034                                        | 1.222                                | L10          | 0.102          |
| L15          | 0.1037                                        | 1.191                                | L15          | 0.104          |
| Barite       | -----                                         | 2.539                                | Graphite     | 0.077          |
| Concrete     | -----                                         | 3.634                                | Boron Carbide| 0.071          |
| RS 253 G18   | -----                                         |                                      | Polyethylene grains | 0.078          |

The Gamma-ray shielding parameters at 662 keV vary with composition (table 2) hereby, showing their compositional dependence. At 662 keV, the mass attenuation coefficient (MAC) increases from L5 to L15, while the half value layer (HVL) decreases resulting from the increase in the weight percentage of higher atomic number constituent (Bi₂O₃) in the glass system (table 1). The experimental and theoretical results are observed to be in close agreement (% difference is between
0.1 to 0.3%). Also, the MAC and HVL values of L5-L15 glass samples are better than barite concrete and RS 253 G18 commercial shielding glass.

![Figure 2. Mass attenuation coefficient of the glass samples.](image)

The mass attenuation coefficient (MAC) was also studied with varying photon energy (figure 2) which shows its compositional dependence. The peaks of the curve obtained are as a result of dominance of photoelectric absorption, Compton scattering and pair production processes in different energy regions [4]. Some sharp peaks are observed due to absorption edges of Bi (~ 90, 13-16, 2-4 keV) and Mn (~ 6.5 keV). Higher MAC value of L15 glass sample than L5 and L10 (see inset of figure 2), indicates that L15 is the best glass sample. So, a comparison of half value layer (HVL) and mean free path (MFP) of L15 glass sample in the energy region 1 keV - 100 GeV has been undertaken with commonly used barite concrete and commercial shielding glass RS 253 G18 [3]. Lesser is the HVL, better is the radiation shielding material in terms of thickness requirements.

![Figure 3. Comparison of HVL of L15, RS 253 G18 and BC.](image)

![Figure 4. Comparison of MFP of L15, RS 253 G18 and BC.](image)
It has been observed that HVL values of the glass system L15 are much lower than the barite concrete (BC) and RS 253 G18 glass (figure 3). Accordingly, the MFP values for L15 were also observed to lower than BC and RS 253 G18 (figure 4).

From the neutron shielding studies, it can be seen that the fast neutron removal cross-section ($\sum R$) values increase from L5 to L15 (table 2). It can be due to increasing content of Li in the glass system. Lithium contributes in the FNRC (fast neutron removal cross-section) value due to its lower mass and hence, higher mass removal cross-section for neutrons. Also from table 2, comparing the FNRC values of glasses L5, L10 and L15 with some common shielding materials as Graphite, Boron Carbide, Polyethylene grains [5], it can be seen that our prepared glass samples have higher neutron shielding ability than the compared materials.

The mass stopping power (MSP) of the prepared glasses L5 to L15 for electron interaction in the energy range 0.01 to 1000 MeV is shown in figure 5. MSP is lower in the low energy region and increases in high energy region with increasing energy of the incoming electrons. Another interesting point to make is that, in the low energy region, MSP of L5 is higher while MSP of L15 is higher in the high energy region. This can be due to Bremsstrahlung radiation.

4. Conclusions
The Bi$_2$O$_3$-Li$_2$O-MnO$_2$-B$_2$O$_3$ glasses were successfully prepared using melt-quenching technique. The amorphous nature of the glasses was confirmed. It can be concluded that L15 glass sample has higher values of density, mass attenuation coefficient and lower values of HVL and MFP as compared to the other prepared glasses L5 and L10 as well as the standard radiation shielding material barite concrete and RS 253 G18 commercial glass. Thus, L15 is a better absorber for Gamma rays and is also cost effective due to lesser thickness requirement for design of radiation shield from L15 glass composition. L15 glass sample also has higher value of effective removal cross section than L5 and L10 glasses and other compared neutron shielding materials. Glass L5 is better for Beta shielding in low energy region and L15 is better for Beta shielding in high energy region. In the light of results of radiation shielding parameters, it can be concluded that the prepared glasses possess good shielding properties and can be used potentially in nuclear radiation shielding applications.
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