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# Comparative half-value layer study of novel PbO-$B_2O_3$-CuO-CaO glasses versus previous reports

Vicram Setiawan[1*], K. Veeravelan[2], Ahmed Akouibaa[3], Heryanto Heryanto[1]

[1]Physics Department, Hasanuddin University, Makassar, 90425, Indonesia
[2]PG and Research Department of Chemistry, Bharathidasan University, Nagapattinam 611 102, India
[3]Laboratory of Solid Physics, Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, 30000, Morocco

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**Abstract**

This work assesses the gamma-ray shielding performance of newly fabricated glasses with diversified PbO and $B_2O_3$ content, while comparing the results with those of previously reported glasses. The half-value layer (HVL) of glass samples Pb45B35, Pb40B40, Pb35B45, and Pb30B50 were determined in order to ascertain their radiation-attenuating ability. Comparatively, fabricated glass samples Pb45B35 (0.50 cm), Pb40B40 (0.55 cm), and Pb35B45 (0.62 cm) had lower HVL values than the glass samples reported in previous studies, where Pb45B35 exhibited the superior performance in terms of gamma-ray shielding, resulting from the presence of high PbO content which enhances the attenuation power of the sample. The results showed that the study's fabricated glass samples outperformed all other previously reported glasses used in comparison in terms of the gamma-ray protection ability.

## 1. Introduction

Glass is prominent in the realm of technology, especially in terms of daily activities. It protects eyes from radiation, while also assisting in clear vision [1]. Glass enhances visual awareness in daily activities, enabling safe driving and clear reading. In particular, special glasses provide significant resistance to harmful radiation, shielding personnel and delicate equipment from potential harm. This makes the role of glasses crucial for the coexistence of industry and personal use in technological fields like radiation shielding [2,3].Glass continues to be a key component in a wide range of advancements, from optical fiber to the screens of electronic devices [4]. Glasses contribute to sharp vision and high resolution on television and smartphone screens, ensuring that consumers have the best possible visualization experience [5]. Similarly, in the optical fiber realm, they continue to be the fundamental materials used in the long-distance, low-loss transmission of light signals, leading to rapid network communication—a critical function in the current transfer of data and connections. Ionizing radiation continues to be fundamental in the medical, scientific, and industrial domains. It serves a variety of purposes, all of which are extremely important for bringing forth new advancements in these domains [6,7].

* Corresponding author:
E-mail address: vicramsetiawan2901@gmail.com
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Techniques employed in the medical field include image diagnostics in X-ray facilities and computed tomography (CT) scanning, which aid in the planning of treatment and the identification of various illnesses [8]. It is important to develop new radiation-shielding materials in order to protect humans from high-energy photons. In this regard, glasses are one of the materials that are used widely for this purpose [9]. Due to their many interesting features such as ease of fabrication, low cost, and non-toxicity, glass properties can be developed by mixing different metal oxides. In the literature, many glasses have been developed for radiation-shielding applications. Some of these show good attenuation performance when compared with other commercial glasses and traditional shielding materials [10–13]. One example is borate glass, selected due to the stability of the structure when exposed to radiation [14], and also the low production cost when using this material [15].When developing a new material for radiation shielding, it is useful to estimate the attenuation performance. This can be achieved by determining certain factors such as the linear attenuation coefficient (LAC) and half-value layer (HVL) [16–18]. The HVL is a useful parameter that provides information about the thickness of the material required to attenuate half of the incoming photons. The HVL has an inverse relation with the LAC, and depends on the composition and the density of the material, as well as the energy of the radiation. The determination of the HVL of any material is useful since this parameter helps in estimating its performance in shielding against photons [19–21]. In this work, we compared the

HVL for the xPbO-(80-x)$B_2O_3$-10CuO-10CaO glass system with other glasses reported in the literature at 0.356 MeV. This energy range can show the different damping properties of each material [22,23], making it ideal for standardized energies in testing and assessing the effectiveness of radiation shielding [24,25].

## 2. Materials and methods

Four borate glasses doped with different concentrations of PbO were prepared using the melt quenching method. The glasses had the general formula xPbO-(80-x)$B_2O_3$-10CuO-10CaO, (where x=30, 35, 40 and 45 mol%). High purity (>99.9%) $B_2O_3$, CuO, CaO, and PbO chemicals were utilized to perform the production process. Each glass sample had 20 g of mixed oxides, in accordance with the proposed composition presented in **Table 1**. The mixture was added in 50 mL alumina crucibles and heated in an electric furnace at 1100 ºC for 45 min. The melted glasses obtained were then put into stainless steel molds. To eliminate thermal stress and glass bubbles, the acquired samples were annealed at 400 ºC for 4 h. The HVL is the thickness of the glass needed to attenuate half of the incoming radiation, and can be derived for any sample from the Lambert–Beer law as follows in **Eq. 1**:

$$I = I_0 e^{-\mu x} \quad (1)$$

where I represents the transmitted photons after passing through the medium, and $I_0$ is the initial intensity of the photons. The HVL is the thickness at which the intensity is decreased by 50%. In other words:

$$\frac{I_0}{2} = I_0 e^{-\mu.HVL} \quad (2)$$

We can write **Eq. 2** as follows:

$$\frac{1}{2} = e^{-\mu.HVL} \quad (3)$$

In order to derive the HVL from the above equation, we take the In for both sides, namely:

$$In(\frac{1}{2}) = -\mu.HVL \quad (4)$$

Simplifying the above equation, we get:

$$HVL = \frac{In^{(2)}}{\mu} \quad (5)$$

In this work, we calculated the HVL for the prepared glasses at 0.356 MeV and compared the obtained results with other glasses reported in the literature. We selected this energy since it corresponds to the Ba-133 radioactive source. This source has many applications, and so it is useful to evaluate the HVL for the prepared glasses at a certain gamma radiation energy usually utilized in real applications.

## 3. Results and Discussion

**Table 1** shows the samples used in this study, containing a list of the densities of each sample, where a higher density value indicates a lower HVL value, thus indicating good shielding effectiveness against radiation [26,27]. Three out of the four glasses (Pb45B35, Pb40B40, and Pb35B45) have lower HVL values (0.50, 0.55, and 0.62 cm, respectively) than all of the glass samples studied by Limkitjaroenporna et al. [28], signifying superior shielding ability in these three glasses (see **Fig. 1**). The lower HVLs shown by the three glasses are due to the high mole percentage concentration of PbO, which greatly reduces the penetration depth of the radiation, resulting in improved attenuation power. The glass with an HVL value close to one of our samples (Pb35B45) is sample 55PbO+20$Na_2O$+25$B_2O_3$ with an HVL value of 0.63 cm. All the other glass samples studied by Limkitjaroenporna have higher HVLs, making them inferior radiation-shielding materials.

**Table 1.** The chemical composition of the prepared glasses.

| Glass code | PbO | $B_2O_3$ | CuO | CaO | Density ($g/cm^3$) |
|---|---|---|---|---|---|
| Pb30B50 | 30 | 50 | 10 | 10 | 5.054 |
| Pb35B45 | 35 | 45 | 10 | 10 | 5.4075 |
| Pb40B40 | 40 | 40 | 10 | 10 | 5.761 |
| Pb45B35 | 45 | 35 | 10 | 10 | 6.1145 |

The comparison of the HVLs shown by our current glasses and those obtained by Singhn et al.[29] is illustrated in **Fig. 2**. Clearly, two of our glass samples (Pb30B50 and Pb35B45) have HVLs higher than all the HVLs shown by their glasses. Two of their glasses (70PbO+20$SiO_2$+10$Al_2O_3$ and 50$Bi_2O_3$+40$SiO_2$+10$Al_2O_3$) show HVLs (0.498 and 0.511 cm, respectively) very close to that of glass sample Pb45B35 (0.50 cm), and therefore the three glasses have similar attenuation ability.Their poorest radiation-shielding glass (50PbO+40$SiO_2$+10$Al_2O_3$) with an HVL of 0.58 cm has a better shielding ability than two of our glasses, resulting from the lower concentration of PbO in the two samples (Pb30B50 and Pb35B45) (30% and 35%, respectively).Two glass samples, 50$Bi_2O_3$+20$B_2O_3$+15$SiO_2$+15$Na_2O$ and 40$Bi_2O_3$+30$B_2O_3$+15$SiO_2$+15$Na_2O$ from those studied by Kulwinder et al.[30] have the lowest HVLs of 0.430 and 0.475 cm, respectively, indicating the highest shielding capability. Our two best glass samples (Pb45B35 and Pb40B40) that have the highest mole percentage concentration of PbO (45% and 40%, respectively) show HVLs between that of sample 40$Bi_2O_3$+30$B_2O_3$+15$SiO_2$+15$Na_2O$ and sample 30$Bi_2O_3$+40$B_2O_3$+15$SiO_2$+15$Na_2O$, as shown in **Fig. 3**. The poorest glass in terms of radiation shielding is our glass sample Pb30B50, whose HVL value is the highest among all the compared glasses; this occurred due to it having the lowest PbO content in its chemical composition (30%). The glass sample with the highest HVL (1.49 cm) and the least shielding strength is sample 75$B_2O_3$+10$Na_2O$+10PbO+5$Fe_2O_3$ (see **Fig. 4**).

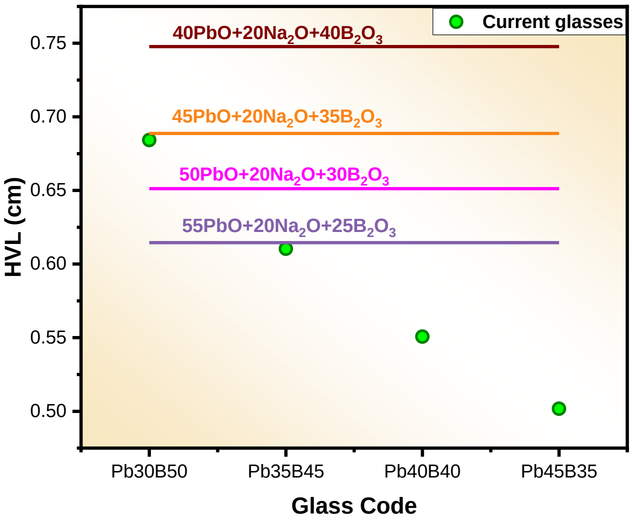


**Fig. 1.** A comparison chart of half-value layers (HVLs) between our current glasses and previous glasses studied by Limkitjaroenporna et al. (2011).

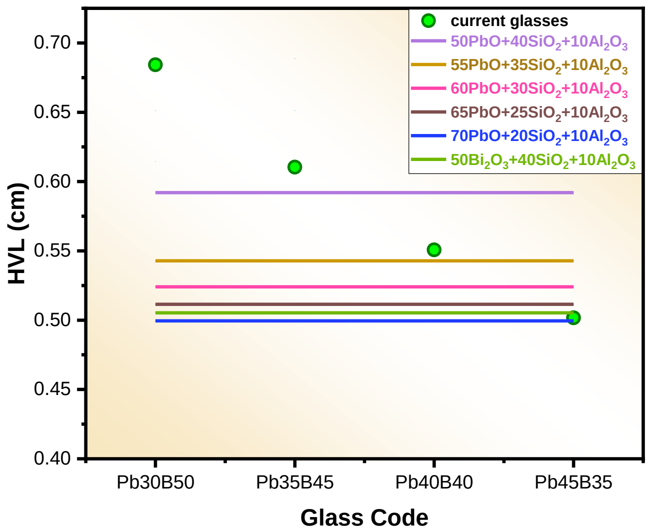


**Fig. 2.** A comparison chart of HVLs between our current glasses and previous glasses studied by Singhn et al. (2014).

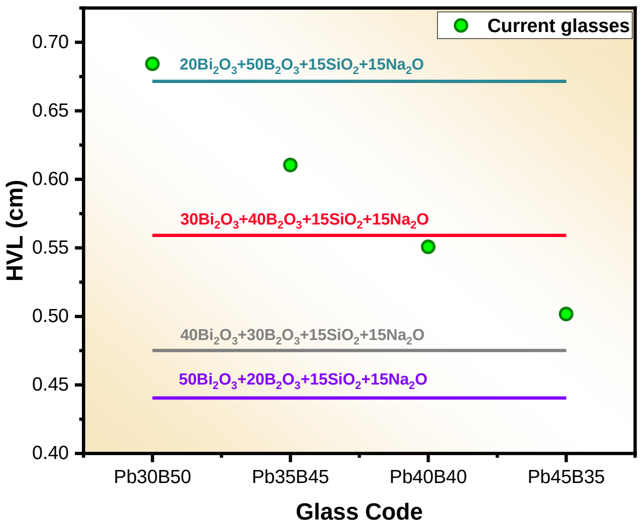


**Fig. 3.** A comparison chart of HVLs between our current glasses and previous glasses studied by Kulwinder et al. (2016).

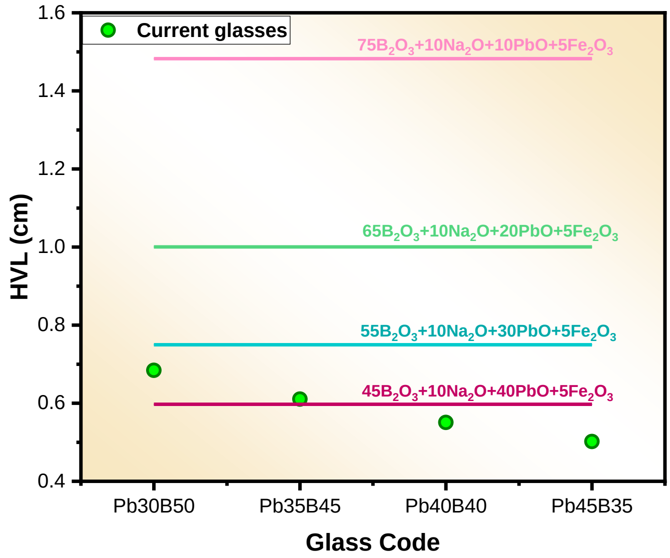


**Fig. 4.** A comparison chart of HVLs between our current glasses and previous glass samples studied by Sayyed et al. (2024).

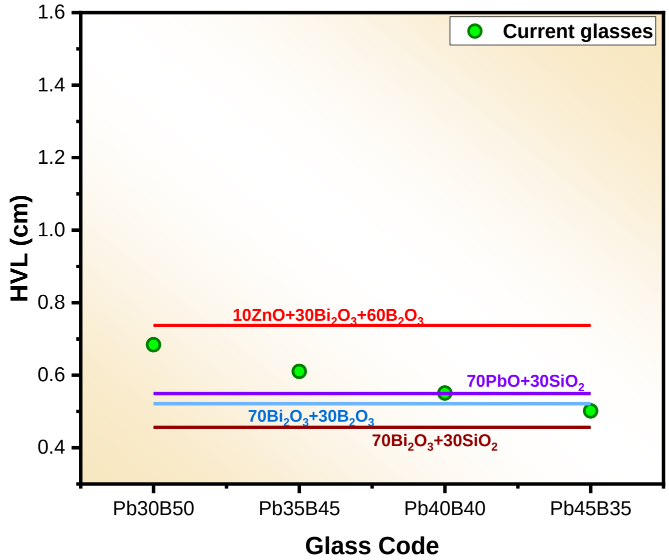


**Fig.5.** A comparison chart of HVLs between our current glasses and previous glass samples studied by Vishwanath et al. (2014).

Two other glass samples from Sayyed et al.[31] show HVLs higher than those of our glasses, sample $65B_2O_3+10Na_2O+20PbO+5Fe_2O_3$ and sample $55B_2O_3+10Na_2O+30PbO+5Fe_2O_3$, and thus a total of three glasses from their studies have lower attenuation ability than any of our glass samples. Our samples Pb45B35 and Pb40B40 have the lowest HVLs at 0.50 and 0.55 cm, respectively, and thus have greater attenuation ability than all the compared glasses, which resulted from the highest PbO content in sample Pb45B35 (45%) and sample Pb40B40 (40%).The best radiation-shielding glass among the compared glasses in **Fig. 5** is sample $70Bi_2O_3+30SiO_2$ studied by Vishwanath et al. [32], which has the lowest HVL of 0.45 cm, followed by our glass sample Pb45B35 with an HVL of 0.50 cm. Glass sample $70Bi_2O_3+30B_2O_3$ shows an HVL of 0.52 cm, which is very close to that of our sample Pb45B35, indicating a highly similar shielding ability. The poorest radiation-shielding glass material is sample $10ZnO+30Bi_2O_3+60B_2O_3$ that has the highest HVL value of around 0.74 cm, while sample $70PbO+30SiO_2$ has the same HVL as our glass sample Pb40B40 (0.55 cm), thus showing equal attenuation ability.Three of the four glasses (30PbO+10$Al_2O_3$+60$B_2O_3$, 35PbO+10$Al_2O_3$+55$B_2O_3$, and 40PbO+$Al_2O_3$+50$B_2O_3$) from Sandeep and Singh's[33] studies show very high HVLs (0.93, 0.81, and 0.725 cm, respectively) that are superior to any of our glass samples, making them the poorest shielding materials. The optimum shielding materials are three of our glass samples, Pb45B35, Pb40B40, and Pb35B45, having the lowest HVLs (0.50, 0.55, and 0.62 cm, respectively) due to their PbO content (45%, 40%, and 35%, respectively) (see **Fig. 6**).As shown in **Fig. 7**, our four glass samples (Pb45B35, Pb40B40, Pb35B45, and Pb30B50) have far lower HVLs (0.50, 0.55, 0.62, and 0.68 cm, respectively) than any of the glass samples studied by Aljawhara et al. [34], indicating that even our poorest attenuating glass material (Pb30B50) has superior shielding ability to their best glass sample (20PbO+20BaO+40$B_2O_3$+20ZnO, with a HVL value of approximately 0.93 cm). The HVLs of their studied glasses range from 0.93 to 1.05 cm, which is a far greater range than any of our studied glasses.

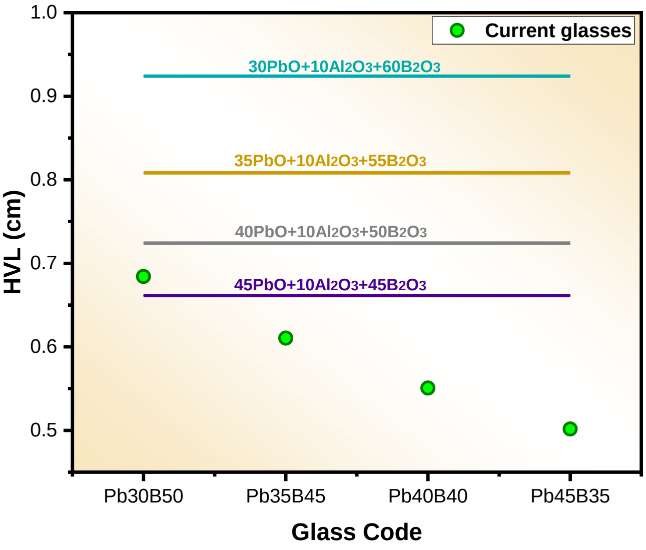


**Fig. 6.** A comparison chart of HVLs between our current glasses and those studied by Sandeep and Singh (2014).

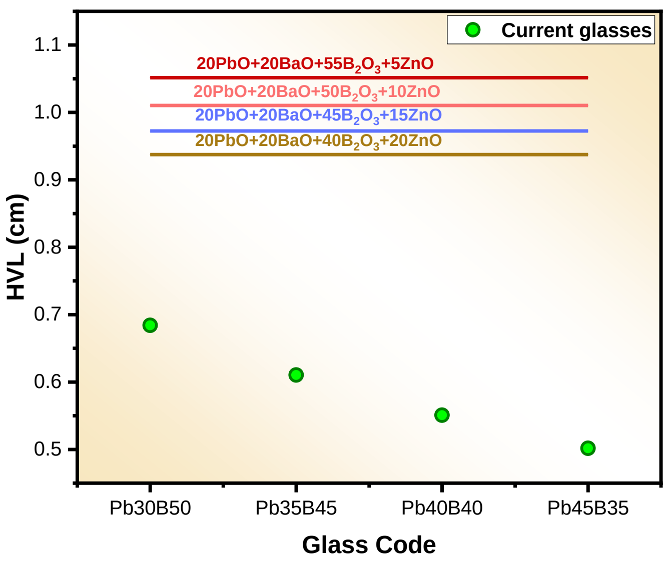


**Fig.7 .** A comparison chart of HVLs between our current glasses and previous glasses studied by Aljawhara et al. (2024).

## Conclusion

We fabricated four glass samples with fixed concentrations of CuO (10 mol%) and CaO (10 mol%), while varying the concentrations of $B_2O_3$ and PbO. The concentration of $B_2O_3$ was systematically reduced from 50 to 35 mol% in step 5, while the concentration of PbO was increased from 30 to 45 mol%, also in step 5, against that of $B_2O_3$. The aim of the work was to compare the radiation-shielding ability of our fabricated glasses with those of previously reported glasses from different authors. The study outcome revealed that our fabricated glass samples Pb45B35, Pb40B40, and Pb35B45 displayed reasonably lower HVL values of 0.50, 0.55, and 0.62 cm, respectively. Generally, our glass samples Pb45B35 and Pb40B40 had superior gamma-ray shielding performance when compared to previously reported works, which is as a result of the higher PbO concentration in our fabricated glasses. The results show that our glass samples outperformed all other previously reported glasses used in comparison, in terms of their gamma-ray protection ability.

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