Effective Atomic Number of Lead Sodium Borate Glass Systems at 662 keV

1Limkitjaroenporn, P., 1W. Chewpraditkul, 2J. Kaewkhao and 2S. Tuscharoen
1Department of Physics, Faculty of Science, Radiation Physics Laboratory,
King Mongkut’s University of Technology Thonburi, Bangkok 10140, Thailand
2Glass and Materials Science Research Unit, Faculty of Science and Technology,
Nakhon Pathom Rajabhat University, Nakorn Pathom, 73000, Thailand

Abstract: Mass attenuation coefficients of glass systems xPbO: 20Na₂O: (80-x)B₂O₃ (x = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 55% mol) were determined at 662 keV photon energy using gamma rays transmission method. The theoretical values of mass attenuation coefficients were calculated by WinXCom program. These coefficients were then used to determine the effective atomic numbers of glass samples. All shielding parameters were increased with increasing of PbO concentration. Our results have uncertainty less than 1% between experimental and theoretical values.

Key words: Lead sodium borate glass, mass attenuation coefficient, effective atomic number

INTRODUCTION

The study of absorption of gamma radiations in shielding materials has been important subject in the field of radiation physics and is potential useful in development of semi-empirical formulations of high accuracy (Singh et al., 2002).

In 1982 Hubbell published tables of mass attenuation coefficients and the mass energy absorption coefficients for 40 elements and 45 mixtures and compounds over energy range from 1 keV to 20 MeV. These tables, although widely used, should now be replaced by the Hubbell and Seltzer tabulation for all elements (Z = 1-92) and 48 additional substances for dosimetric interest (Singh et al., 2002).

Berger and Hubbell developed the theoretical tables and computer program (XCOM) for calculating attenuation coefficients for elements, compounds and mixtures for photon energies from 1 keV to 100 GeV (Singh et al., 2004; 2008). Recently, this well known and much used program was transformed to the Windows platform by Gerward et al. (2004) and the Windows version is being called WinXCom.

The parameter “effective atomic number” has a physical meaning and allows many characteristics of material to be visualized with a number. The effective atomic number (Z_{eff}) of composite material is defined as the ratio of total atomic cross-section to the total electronic cross-section (Cevik and Baltas, 2007; Singh et al., 2007).

Reports of attenuation coefficient and effective atomic number for any materials are published by several researchers (Singh et al., 1996; 2002; 2004; 2005; 2006; 2007 2008a; 2008b; Gerward et al. 2004; Cevik and Baltas, 2007; Kaewkhao et al., 2011; Baltas et al., 2007; Akkurt et al., 2004; Kaewkhao et al., 2008). In this study, we have measured the mass attenuation coefficients and the effective atomic numbers of lead sodium borate glass systems at 662 keV and then compare these parameters with theory using WinXCom program.

Theory: The mass attenuation coefficient is written as (Singh et al., 1996) Eq. 1:

$$\mu_a = \frac{\ln(I/I_0)}{\rho t}$$

(1)

Where:

\(\rho\) = The density of material (g cm\(^{-3}\))

\(I_0\) and I = The incident and transmitted intensities and t is the thickness of absorber (cm)

Theoretical values of the mass attenuation coefficients of mixture or compound have been calculated by WinXCom, base on mixture rule (Singh et al., 2002) Eq. 2:
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Fig. 1: Transmission experiment set up

\[ \mu_m = \sum_i w_i (\mu_{m_i}) \]  
(2)

Where:

- \( w_i \) = Weight fraction of element in alloy
- \( (\mu_{m_i}) \) = Mass attenuation coefficient for individual element in alloy

The value of mass attenuation coefficients can be used to determine the total atomic cross-section \( (\sigma_{t,a}) \) by the following relation (Singh et al., 2002) Eq. 3:

\[ \sigma_{t,a} = \frac{(\mu_{m})_{alloy}}{N_A \sum_i (w_i/A_i)} \]  
(3)

Where:

- \( N_A \) = Avogadro’s number
- \( A_i \) = Atomic weight of constituent element of alloy

Also the total electronic cross-section \( (\sigma_{t,el}) \) for the element is expressed by the following formula (Singh et al., 2002) Eq. 4:

\[ \sigma_{t,el} = \frac{1}{N_A} \sum_i f_i A_i (\mu_{m_i}) \]  
(4)

Where:

- \( f_i \) = The number of atoms of element i relative to the total number of atoms of all elements in alloy
- \( A_i \) = The atomic number of the \( i^{th} \) element in alloy

Total atomic cross-section and total electronic cross-section are related to effective atomic number \( (Z_{eff}) \) of the compound through the formula (Kaewkhao et al., 2008):

\[ Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \]  
(5)

MATERIALS AND METHODS

Sample preparation: The glass system \( x\text{PbO}: 20\text{Na}_2\text{O}:(80-x)\text{B}_2\text{O}_3 \) where \( x = 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 \) and \( 55 \) mol% were prepared by melt quenching technique at GMSRU, Nakhon Pathom Rajabhat University. Appropriate amounts of PbO, \( \text{Na}_2\text{CO}_3 \), \( \text{H}_3\text{BO}_3 \) of analytical reagent grade were mixed thoroughly. Each batch weighed about 30 g, was melted in high alumina porcelain crucibles by placing them in an electrical furnace. Dry oxygen was bubbled through melts at 850°C for 1 h. These melts were quenched at room temperature in air by pouring between the melt on a stainless steel plate and pressing with another stainless steel plate. The quench glasses were annealed at 450°C for 3 h for reduce thermal stress and cool down to room temperature. Density of glass samples were measured by Archimedes’ principle using distilled water as the liquid. The density is calculated according to the formula Eq. 6:

\[ \rho = \frac{w_A}{w_A - w_B} \]  
(6)

Where:

- \( w_A \) = The weight of the sample in air
- \( w_B \) = the weight of the sample in water and density of distill water is 1 g cm\(^{-3}\)

Transmission experimental detail: The block diagram of transmission experiment set up from previous our research (Kaewkhao et al., 2011) is shown in Fig. 1. The source and absorber system were mounted on composite of adjustable stands. With the help of a screw arrangement the platform having material was also made capable of movement in the transverse direction to the incident beam for proper alignment (In this experiment fix at 13 cm). The sample detector solid angle was <0.5 x 10\(^{-4}\) sr. The \( ^{137}\text{Cs} \) radioactive source of 15 mCi strength was obtained from Office of Atom for Peace (OAP), Thailand. The incident and transmitted gamma-rays intensities were determined for a fixed
preset time in each experiment by recording the corresponding counts, using the 2×2 NaI(Tl) detector (BICRON model 2M2/2) having an energy resolution of 10.2% at 662 keV, with CANNERRA PMT base model 802-5. The statistical uncertainty was kept below 0.3% by choosing the maximum counting time (fixed present time) so that 10⁵-10⁶ counts were recorded in the full energy peak (Singh et al., 2004). The dead time in this experiment was 0.73-1.37%. The pulse shaping time is 0.5 µsec. The optimum sample thickness was selected in this experiment, suggest from published literature (Creagh and Hubbell, 1987; 1990).

RESULTS AND DISCUSSION

The chemical compositions (mol %), densities and thickness of prepared glass samples are enlisted in Table 1.

The densities of glass sample increasing with PbO content were increase but not linearly were shown in Fig. 2, due to higher molecular weight of PbO compared to that of B₂O₃, therefore it is expected result.

The mass attenuation coefficients of glass samples as shown in Table 2 were evaluated from Incident (I₀) and transmitted (I) intensities and compare with theoretical values were calculated by WinXCom program.

It has been found that the mass attenuation coefficients were increase with increasing of PbO content in glass matrix, show that the shielding properties is better.

The statistical error in mass attenuation coefficient can be determined from combined errors in ray-sum, thickness and density (Kaewkhao et al., 2011). The experimental values of mass attenuation coefficient are good agreement with the theoretical values as shown in Fig. 3.

The effective atomic number (Z_eff) has been determined using Eq. 5. The calculation of Z_eff requires the mass attenuation coefficients of glass sample and their constituent elements. The data of effective atomic number for these glass samples are given in Table 3. Fig. 4 showed the good agreement between experimental values and theoretical values of effective atomic number. It has been found that the effective atomic numbers were increased with PbO content.

In the data of mass attenuation coefficients and effective atomic numbers have uncertainty between the experimental values and theoretical values less than 1% reflecting the good detection system setup of transmission experiment (Kaewkhao et al., 2011).

Table 1: Chemical compositions (mol%), densities and thickness of lead sodium borate glasses

| Composition (mol%) | Na₂O | B₂O₃ (80-x) | Thickness (cm) | Density (g cm⁻³) |
|--------------------|------|-------------|----------------|-----------------|
| 0                  | 20   | 80          | 1.04±0.01      | 2.20±0.01       |
| 5                  | 20   | 75          | 1.55±0.01      | 2.52±0.01       |
| 10                 | 20   | 70          | 1.45±0.01      | 2.90±0.01       |
| 15                 | 20   | 65          | 1.30±0.01      | 3.23±0.01       |
| 20                 | 20   | 60          | 1.24±0.01      | 3.55±0.01       |
| 25                 | 20   | 55          | 1.21±0.01      | 3.77±0.01       |
| 30                 | 20   | 50          | 1.05±0.01      | 3.93±0.03       |
| 35                 | 20   | 45          | 1.20±0.01      | 4.09±0.01       |
| 40                 | 20   | 40          | 1.11±0.01      | 4.23±0.01       |
| 45                 | 20   | 35          | 0.99±0.01      | 4.44±0.03       |
| 50                 | 20   | 30          | 0.98±0.01      | 4.56±0.01       |
| 55                 | 20   | 25          | 0.96±0.01      | 4.71±0.01       |

Table 2: The mass attenuation coefficients of PbO-Na₂O-B₂O₃ glass system

| x (mol%) | µₘₚₚₖ (x10⁻² cm² g⁻¹) | µₘₚₚₚ (x10⁻² cm² g⁻¹) |
|---------|----------------------|----------------------|
| 0       | 7.53                 | 7.5989±0.2328        |
| 5       | 8.01                 | 8.0399±0.8099        |
| 10      | 8.40                 | 8.4718±0.1853        |
| 15      | 8.72                 | 8.7484±0.1977        |
| 20      | 9.00                 | 9.0635±0.3401        |
| 25      | 9.23                 | 9.2969±0.0962        |
| 30      | 9.43                 | 9.3877±0.2562        |
| 35      | 9.61                 | 9.6396±0.5312        |
| 40      | 9.77                 | 9.7399±0.2347        |
| 45      | 9.91                 | 9.8994±0.1192        |
| 50      | 10.00                | 10.0275±0.4299       |
| 55      | 10.10                | 10.0490±0.0910       |

Fig. 2: The densities of PbO-Na₂O-B₂O₃ glass system with PbO contents
Fig. 3: Variation of mass attenuation coefficient values as a function of mol% of PbO.
Note: The line is theoretical value and point in this figure is experimental value

Fig. 4: Effective atomic number of PbO-Na$_2$O-B$_2$O$_3$ glass system.
Note: The line is theoretical value and point in this figure is experimental value

The mass attenuation coefficient and effective atomic number increase with concentration of PbO. From the increasing of these parameters, we obtained the photon interaction probability is increase with higher PbO content and lead to the transmission of gamma rays were decrease with increasing the amount of lead oxide.

CONCLUSION

In conclusion, we give values for gamma-ray mass attenuation coefficients and effective atomic numbers for the xPbO: 20Na$_2$O: (80-x) B$_2$O$_3$ glass system for photon energy 662 keV by transmission experiment. The results are good agreement with the theoretical values, calculated by WinXCom. All shielding parameter are increase with PbO content. Moreover, these results show that the potential of glass in radiation shielding materials.

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