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

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Abstract: Mass attenuation coefficients of glass systems xPbO: $20Na_2O$: $(80-x)B_2O_3$ (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 scattering and absorption of gamma radiations are related to the density and atomic number of element. In composite materials it is related to density and effective atomic number, knowledge of the mass attenuation coefficients is of prime importance. A single number therefore cannot represent the atomic number uniquely across the entire energy range, as the partial interaction cross-sections have different element number dependence (Singh *et al*., 2006).

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:

$$\mu_m = \frac{\ln(I_0/I)}{\rho t} \quad (1)$$

Where:
ρ = 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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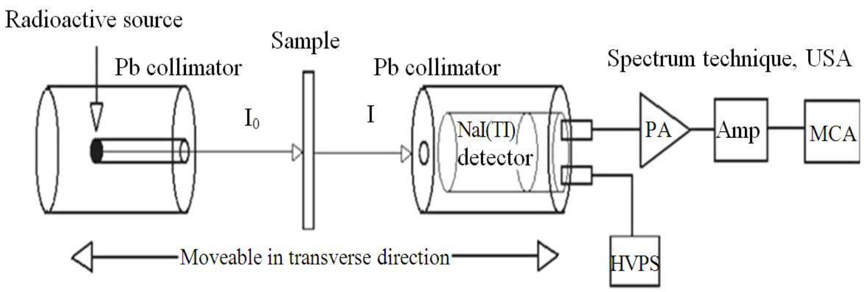

Fig. 1: Transmission experiment set up

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (2)$$

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:

$$\sigma_{t,a} = \frac{(\mu_m)_{alloy}}{N_A \sum_i^n (w_i/A_i)} \quad (3)$$

Where:

N_A = Avogradro'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:

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \quad (4)$$

Where:

f_i = The number of atoms of element i relative to the total number of atoms of all elements in alloy

Z_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):

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \quad (5)$$

MATERIALS AND METHODS

Sample preparation: The glass system xPbO: $20Na_2O$: $(80\text{-}x)B_2O_3$ where x = 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 55 mol% were prepare by melt quenching technique at GMSRU, Nakhon Pathom Rajabhat University. Appropriate amounts of PbO, Na_2CO_3, H_3BO_3 of analytical reagent grade were mixed thoroughly. Each batch weights about 30 g. was melt 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 anneal 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 distills water as the liquid. The density is calculated according to the formula Eq. 6:

$$\rho = \frac{w_A}{w_A - w_B} \quad (6)$$

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 $<0.5\times10^{-4}$ sr. The ^{137}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 uncertainly was kept below 0.3% by choosing the maximum counting time (fixed present time) so that 10^5-10^6 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 μ sec. 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 B_2O_3, therefore it is expected result.

The mass attenuation coefficients of glass samples as shown in Table 2 were evaluated from Incident (I_0) and transmitted (I) intensities and compare with theoretical values were calculated by WinXCom program.

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

Composition (mol%)				
PbO (x)	Na_2O	B_2O_3 (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	3.53±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 $PbO-Na_2O-B_2O_3$ glass system

x	$\mu_{m\,(th)}$ ($\times10^{-2}$ cm^2 g^{-1})	$\mu_{m\,(ex)}$ ($\times10^{-2}$ cm^2 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	9.6596±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

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 3: Effective atomic numbers of $PbO-Na_2O-B_2O_3$ glass system

x	$Z_{eff\,(th)}$	$Z_{eff\,(ex)}$
0	7.2133	7.2793
5	8.7476	8.7803
10	10.3569	10.4454
15	12.0433	12.0824
20	13.8338	13.9314
25	15.7052	15.8191
30	17.6829	17.6037
35	19.7849	19.8870
40	22.0143	21.9465
45	24.3745	24.3484
50	26.7889	26.8626
55	29.4154	29.2669

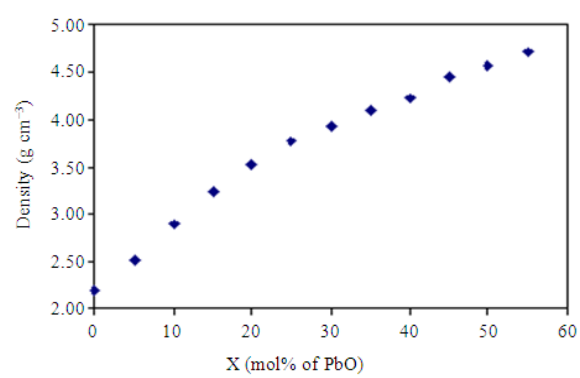

Fig. 2: The densities of $PbO-Na_2O-B_2O_3$ glass system with PbO contents

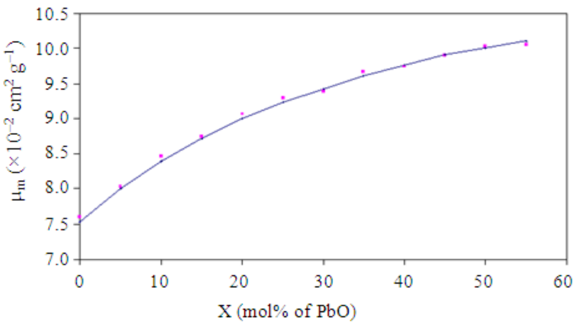

Fig. 3: Variation of mass attenuation coefficient values as a function of mol% of PbO.

Note: The line is theoretical value and point in this figure is experimental value

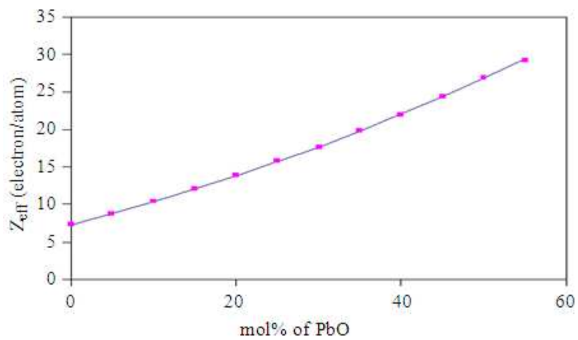

Fig. 4: Effective atomic number of PbO-Na_2O-B_2O_3 glass system.

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: $20Na_2O$: (80-x) B_2O_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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