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Gamma-Ray Shielding Parameters of Some Sodium-Borate Glasses Containing BaO and As_2O_3

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ABSTRACT

Some glass samples having the molecular composition [(70-X) mol % B_2O_3 + 10 mol % BaO + 20 mol % Na_2O + X mol % As_2O_3 where X = 0, 5, 10, 15 and 20] have been prepared by melting at 1200 ºc for two hours. They were thoroughly investigated from the gamma – ray attenuation parameters by applying both MCNP and Win X-Com programs. The applied gamma-ray energies were 661.7 keV (emitted from ^{137}Cs) and 1173.2 & 1332.5 keV (emitted from ^{60}Co). It was found that as As_2O_3 was gradually increased, the linear attenuation coefficients increased gradually, while the half value layer and mean free Path decreased. On the other hand, both linear and mass attenuation coefficients decreased and the half value layer and mean free Path increased as the energy of the incident γ-ray photon increased. Finally, it can be concluded that these glasses can be used as good γ-ray attenuators especially at low gamma-ray energies.

Keywords: Barium-Sodium-Borate Glasses, MCNP5, Win-XCom Programs, Gamma-Ray Shielding Glasses

I. INTRODUCTION

Pure borate glass are of little interest, while borate glasses containing various alkali cations appeared now of special scientific and technical importance. From another point of view, borate glasses doped heavy metals are considered also of high interest because of their widespread applications in various daily life fields. They can be used as layers for opto-electronic devices and as mechanical and thermal sensors as well as reflecting windows [1-3], in addition to their effects when used as gamma-ray shielding materials [4-5]. Among all these applications, the shielding parameters are of high interest now due to the spread using of different radio-active sources in different fields (such as medicine, industry, agriculture …etc.) [6-7].

However, a knowledge of gamma-ray attenuation parameters [such as linear attenuation coefficient, mass attenuation coefficient, half value layer and mean free path] is very important in the field of radiation protection and dosimetry. Accurate measurements and calculations of these parameters are required in order to design suitable shielding material for many scientific and industrial applications.

Therefore, in this article, gamma-ray attenuation parameters of some sodium-borate glasses containing constant amount of barium oxide and varying amounts of arsine trioxide – introduced at the expense of boron oxide will be thoroughly investigated.

II. THEORETICAL

It is of interest to exhibit a brief description about gamma-ray attenuation parameters of a solid material. The numerical values of these parameters can be used directly to decide the possibility of using a material as a suitable shield for a special radio-active source. The following parameters can be usually discussed:

i) The linear attenuation coefficient (μ, in cm) of a material is defined as the probability of radiation to interact with a material per unit path length. It represents an important parameter and its magnitude depends accurately on the incident photon energy, the mean atomic number (z) and the density (ρ) of such material [8].

ii) The mass attenuation coefficient (μ_m, in $cm^2.g^{-1}$) measures directly the effectiveness of a shielding material [9]. It can be calculated by applying the following equation,

$$\mu_m = \ln (I_0 / I) / \rho x \qquad (1)$$

where ρ is the density of material (g/cm^3), I_0 and I are the incident and transmitted γ-ray intensities, respectively, and x is the thickness of absorber (a material under study in cm).

Monte Carlo method can be used to duplicate theoretically a statistical process for the interaction of nuclear particles with materials and is particularly useful for complex problems that cannot be modeled by other computer codes. MCNP is a general-purpose Monte Carlo N–Particle code, and it can be used for neutron, photon, electron, or coupled neutron/photon/electron interaction, including the capability to calculate eigenvalues for critical systems [10].

Theoretical values for the total mass attenuation coefficient can be found in the tabulations prepared by Hubbell and Seltzer [11]. Many manual works can be saved by using suitable software. Berger and Hubbell [12], developed XCOM for calculating total mass absorption coefficients or photon interaction cross- sections for any element, compounds or mixtures at photon energies from 1 keV to 100 GeV. Recently, XCOM was transformed to the Windows platform by Gerward et al. [13], called WinX-Com.

Also, theoretical value of the total mass attenuation coefficients of mixture or compound has been calculated by Win-XCom, based on the mixture rule [11, 12], by applying the following equation,

$$\left(\frac{\mu}{\rho}\right)_m = \sum_i^n w_i \left(\frac{\mu}{\rho}\right)_m \qquad (2)$$

where $(\mu/\rho)_m$ is the total mass attenuation coefficient for the individual element in each component and w_i is the fractional weight of the element in each component. This rule is valid when the effects of molecular bindings are negligible.

iii) The following equation relates the half value layer (HVL) to the linear attenuation coefficient (μ):

$$HVL = 0.693/ \mu \qquad (3)$$

where HVL is the thickness of the attenuator that decreases the intensity of the incident photon to its half value (cm).

iv) The mean free path (cm) represents the average distance between two successive interactions of a photon with material, where the intensity of the incident photon beam is reduced by a factor of ($^1/_\mu$). It can be calculated using the value of linear attenuation coefficient μ (cm^{-1}) applying the following equation,

$$1\ MFP = \frac{1}{\mu} \qquad (4)$$

III. EXPERIMENTAL WORK

A glass system having the percentage molecular composition (70-x) mol % B_2O_3 + 10 mol % BaO + 20 mol % Na_2O + x mol % As_2O_3 (where x = 0, 5, 10, 15 and 20) has been prepared. The raw materials were mixed well in an agate morter, and were then transferred into porcelain crucibles. The batches were melted using an electric muffle furnace exacted at 1200 ºC for two hours. Melts were stirred several times during melting to ensure complete mixing and then, they were poured on a stainless steel molds at room temperature. The obtained samples were polished to obtain square samples of 2 x 2 cm and 3 mm in thickness.

XRD analysis was applied to check the glassy state of the prepared glasses, using Siemens D-500 diffractometer, outfitted with CuK_α radiation source

(λ =1.5406 A°). The scanning was performed at angles between 2 θ = 10 and 80° in steps of 0.02 degree.

The densities of the studied samples were measured at room temperature applying Archimed's technique using equation (5),

$$\rho_{exp} = (w_a / w_a - w_t) \rho_t \qquad (5)$$

where ρ_{exp} is the experimental density of a glass sample, w_a and w_t are the weights of a glass sample in air and in CCl_4 respectively and ρ_t is the density of the emersion liquid.

IV. RESULTS AND DISCUSSION

XRD was performed here to confirm the amorphous nature of the studied samples. Fig (1) represents the obtained XRD patterns of all samples, where broad humps around 2θ = 29 degree has been observed with no indication of any diffraction peaks in all glasses. Therefore, the glassy state of all the studied samples has been confirmed [14].

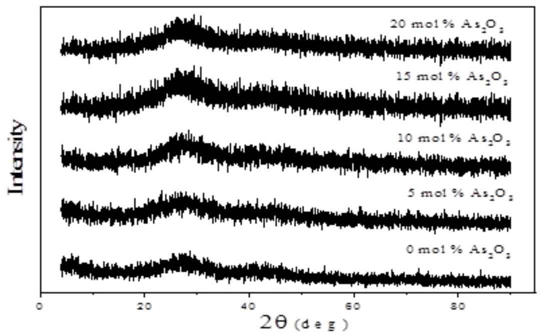

Figure 1. XRD patterns of all the studied glasses.

The obtained experimental density values of the investigated glasses are listed in Table (1).

Table 1. The experimental density values of the studied glasses as a function of As_2O_3.

As_2O_3 mol %	$(\rho)_{exp}$ (g/cm^3)
0	2.19
5	2.22
10	2.31
15	2.41
20	2.58

It can be seen that the density values increased gradually and linearly with the gradual increase of As_2O_3. This can be attributed to the high density value of As_2O_3 (3.74 g/cm^3) which is much greater than that of B_2O_3 (2.56 g/cm^3). Therefore, the density has to increase gradually and logically when As_2O_3 was gradually introduced replacing B_2O_3 [15].

The values of the linear attenuation coefficients obtained by applying both MCNP and Win X-Com programs for some low gamma-ray energies are plotted versus As_2O_3 concentration in Figure (2), (3) and (4) for the energy emitted from ^{137}Cs (661.7 keV) and ^{60}Co (1173.2 & 1332.5 keV) sources respectively.

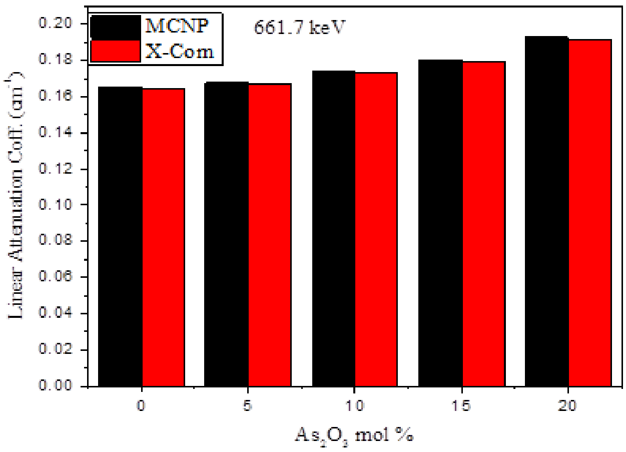

Figure 2. The variation of the linear attenuation coefficient of the studied glasses at 661.7 keV γ-rays energy versus As_2O_3 content.

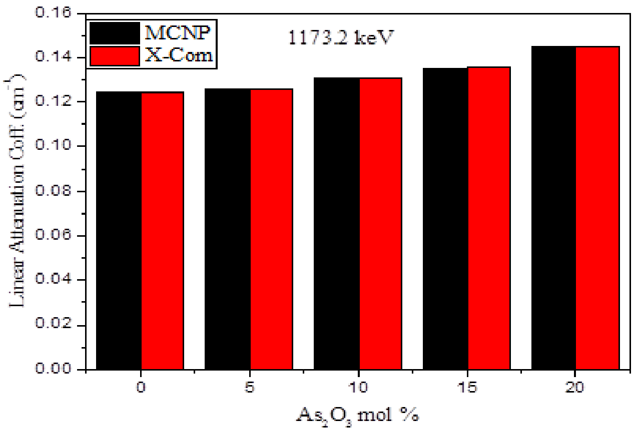

Figure 3. The variation of the linear attenuation coefficient for the studied glasses at 1173.2 keV γ-rays energy versus As_2O_3 content.

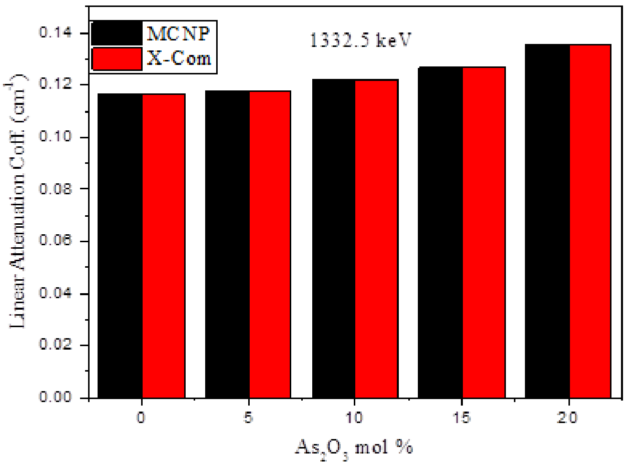

Figure 4. The variation of the linear attenuation coefficient of the studied glasses at 1332.5 keV γ-rays energy versus As_2O_3 content.

It is seen that the values of the linier attenuation coefficient obtained by either MCNP or Win X-Com programs for each sample at certain gamma-ray energy are approximately coincident.

Also, it can be shown that the linear attenuation coefficient for all glassy barriers increased as As_2O_3 was gradually increased. Therefor the maximum value of the effective γ-ray attenuation for different energies was observed for the sample containing 20 mol % As_2O_3 content which is an expected result.

The linear attenuation coefficients as a function of γ-ray energies for all samples (with different As_2O_3 concentrations) are shown in Figure(5), where it shows gradual decrease as gamma-ray energy was increased.

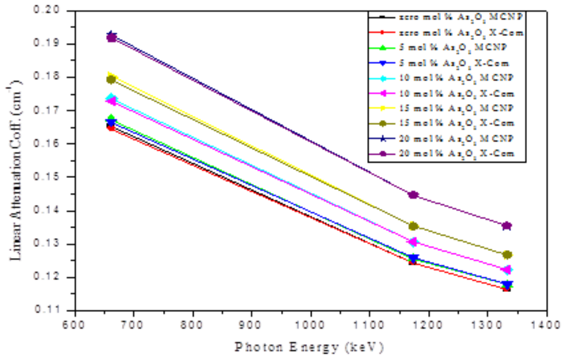

Figure 5. The variation of the linear attenuation coefficients as a function of γ-ray energies, for all samples.

It can be observed also that a sharp decrease in the linear attenuation coefficients takes place with the increase of gamma ray energy from 661.7 to 1150 keV. This may be due to the fact that, in this energy region the reaction between the glassy barriers and gamma ray is only due to the photoelectric effect. In the region of 1173.2-1332.5 keV, a slight decrease in the linear attenuation coefficients can also be observed which may be due to the fact that the reaction in this region is due to Compton scattering [16].

The values of the mass attenuation coefficients at different γ-ray energies were then calculated from equation (1) and were then plotted versus As_2O_3 content as shown in Figure(6) and all the obtained values are listed in Table (2).

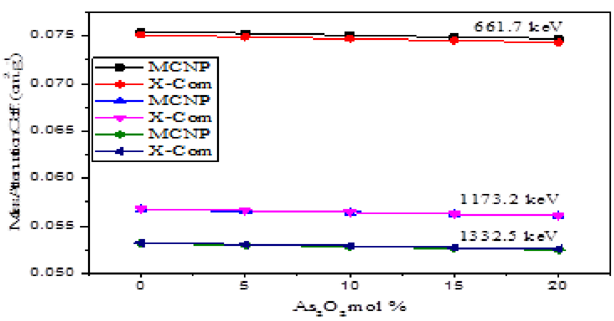

Figure 6. The variation of the mass attenuation coefficient values versus As_2O_3 content at all the applied γ-ray energies.

Table 2. The mass attenuation coefficient values of all the studied glasses at different γ-ray energies.

	μ_{mass} $(cm^2 . g^{-1})$					
Energy keV / As_2O_3 mol %	661.7 MCNP	661.7 X-com	1173.2 MCNP	1173.2 X-com	1332.5 MCNP	1332.5 X-com
0	0.0754	0.0751	0.0567	0.0568	0.0532	0.0532
5	0.0753	0.0749	0.0565	0.0566	0.0529	0.0531
10	0.0751	0.0747	0.0565	0.0564	0.0528	0.0529
15	0.0749	0.0745	0.0562	0.0563	0.0526	0.0527
20	0.0747	0.0743	0.0561	0.0561	0.0525	0.0526

It can be observed from this table that the mass attenuation coefficient exhibits slight gradual decrease as As_2O_3 was gradually increased. It shows also gradual decrease as γ-ray energy was increased and it can be stated that the studied glass sample exhibit poor gamma-ray attenuation at high photon energies [17].

The mass attenuation coefficients as a function of γ-ray energies for different As_2O_3 concentrations are represented in Figure (7).

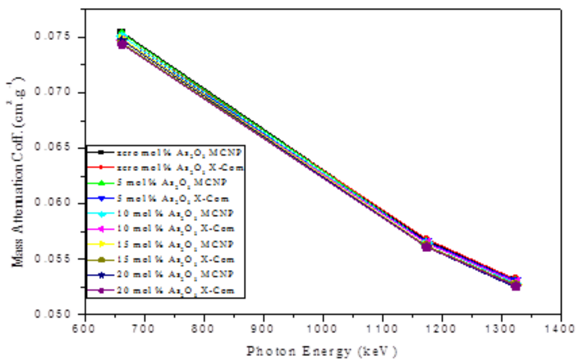

Figure 7. The variation of the mass attenuation coefficients as a function of γ-ray energies, for all the studied glasses.

The Half value layer (HVL) of the studied glasses was also calculated from equation (3), and plotted versus As_2O_3 content as shown in Figure(8). Also the obtained values are listed in Table (3).

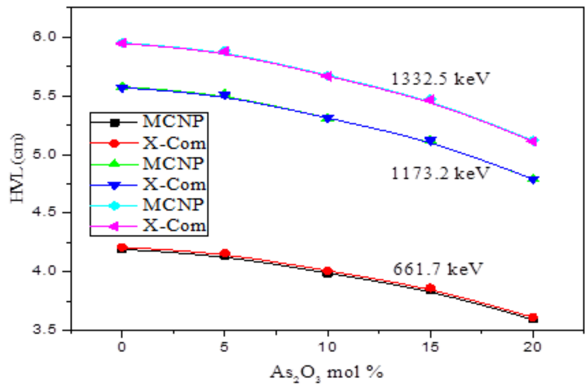

Figure 8. The variation of the HVL values of all glasses at different γ-ray energies.

Table 3. The half value layer (HVL) of all the studied samples at all the applied gamma-ray energies.

	HVL (cm)					
Energy (keV) / As_2O_3 mol %	661.7 MCNP	661.7 X-com	1173.2 MCNP	1173.2 X-com	1332.5 MCNP	1332.5 X-com
0	4.19	4.21	5.58	5.569	5.95	5.94
5	4.14	4.16	5.51	5.507	5.88	5.88
10	3.99	4.00	5.31	5.308	5.67	5.67
15	3.84	3.87	5.12	5.120	5.47	5.46
20	3.59	3.61	4.79	4.791	5.12	5.11

The calculated values of HVL exhibited in Table (3) shows a gradual decrease as As_2O_3 was increase. But they show gradual increase as the γ-ray energy was gradually increased. This was found in agreement with the data obtained by Ramadan et al. [18].

Also, the values of the mean free path (mfp) of all glasses were then calculated from equation (4), and they were then exhibited in Figure (9).

The values of the mass attenuation coefficients (μ_m) of some standard radiation shielding concretes were obtained by Bashter using win-xcom computer program [19, 20]. Then their values of the linear attenuation coefficients were calculated. The values of MFP of these concretes are found to be 5.57, 6.03 and 6.44 cm at 661.7, 1173.2 and 1332.5 keV γ-ray energies respectively. From Figure(9) it is observed that for the glass samples, having various concentration of As_2O_3, the value of mfp is found to be better than those of Ilmenite–limonite concrete only at 661.7 keV.

Therefore, it can be reported here that, because of the low mfp values, of the studied glasses, they appeared to be better radiation shielding materials than the standard shielding concretes, only at 661.7 keV gamma energy.

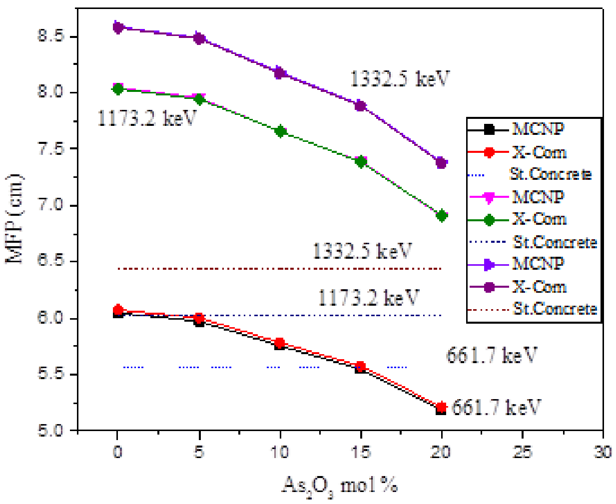

Figure 9.The variation of the MFP values of γ-ray emitted from ^{137}Cs and ^{60}Co radioactive source for different concentrations of As_2O_3 in comparison with the MFP values of Ilmenite–limonite concrete as a function of molar fraction of its modifier.

V. CONCLUSION

- ✓ All the prepared samples appeared by visual examination in a good glassy phase.
- ✓ All the obtained XRD patterns confirmed the amorphous nature and the randomness character of the studied samples.
- ✓ The experimental density for increased gradually and linearly with the gradual increase of As_2O_3.
- ✓ It can be concluded that the value of the linear attenuation coefficient increased as As_2O_3 was gradually increased, while it decreased with the increase of the γ-ray energy.
- ✓ The obtained HVL values showed a gradual decrease as As_2O_3 was increased while it shows gradual increase with the increase of γ-ray energy.
- ✓ The MFP showed a gradual decrease as As_2O_3 was increased while it shows gradual increase with the increase of γ-ray energy.
- ✓ It appeared from all γ-ray attenuation results that all the studied glasses can be used as efficient attenuator, especially at low γ-ray energies.

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