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Simulation of the Gamma Attenuation through Borate Glass Using Genat4

Shlair I. Mohammed **Ali H. Taqi** **Abdulahdi M. Ghalib**
Department of Physics/ College of Science/ University of Kirkuk

ABSTRACT

In this study, the protection parameters of the gamma-ray of Borate glass system containing $10Li_2O$. $10K_2O$. $20Na_2O$. xPbO. (60-x) B_2O_3 where x to be varied as 0, 10, 20, 30, 40, 50 and 60, were investigated using the Monte Carlo simulation code Geant4. The coefficients of attenuation were calculated using the Monte Carlo simulation code Geant4 as a function of the incident photon 0.0015 MeV and 15 MeV. The accuracy of the simulated results was tested by using the XCOM program. The Geant4 and XCOM results showed a reasonable agreement. The results of the attenuation parameters showed that the sample of higher PbO concentration absorbs a greater number of photons, therefore the attenuation coefficients are increased while the tenth-value layer (TVL) values are decreased due to the increase in PbO from 0 to 60%. The linear and mass attenuation coefficients decreased when the photon energy increase and many peaks are observed.

Keywords: Attenuation properties, glass shielded, attenuation coefficient, Geant4, XCOM.

INTRODUCTION

The impacts of various parameters on the mass attenuation coefficient of materials are discussed in many studies. Varied experimental and theoretical studies have been conducted on the effects of different factors on the mass attenuation coefficients of soil (Taqi *et al*., 2016), building materials (Najam *et al*., 2014; Najam *et al.*, 2016) and alloys (Taqi *et al*., 2020).

The glass has a set of features that make it useful and important in radiation shielding like, transparency, high homogeneity that can be attained and accepting a wide range of composition. The shielding properties can be modified by changing the chemical compositions (Kaewkhao and Limsuwan, 2010), or by adding other materials (Kaewkhao and Limsuwan, 2010; Mettam *et al*., 1999). The borates remain the most popular and is an excellent glass-forming material (Kaewjaeng *et al*., 2014; Mettam *et al*., 1999; Kirdsiri *et al*., 2009). Boric acid (B_2O_3) has a lower melting point with good transparency, high thermal stability, and high chemical durability (Kaewjaeng *et al*., 2014; Yasaka *et al*., 2014).

Shielding parameters have been studied for different types of glass samples such as $ZnO–PbO–B_2O_3$ glasses (Singh *et al*., 2003), $CaO–SrO–B_2O_3$ glasses (Singh *et al*., 2005). Lead strontium borate glasses (Kaundal *et al*., 2010), bismuth borosilicate glass (Chanthima and Kaewkhao, 2013), zinc bismuth borate glasses (Yasaka *et al*., 2014), Bismuth Borate Glasses (Kaundal, 2016), Bi_2O_3-B_2O_3-Na_2WO_4 Glasses (Dogra *et al*., 2017), Binary Oxide glasses (Kundal, 2017), Lead Bismuth Germanoborate Glasses (Ashok *et al*., 2018), (20+ x) PbO–10 BaO–10 Na_2O–10 MgO–(50- x) B_2O_3 glasses (Ashok *et al*., 2018), (30+x)PbO−10WO_3−10Na_2O−10MgO– (40-x)B_2O_3 glasses (Ashok *et al*., 2019), $Na_2O–CaO– P_2O_5–SiO_2$ bioactive glasses (Tekin *et al*., 2019) and lithium borotellurite glasses using Geant4 code (Kebaili *et al*., 2020).

The Monte Carlo simulation code Geant4 is one of the most important and common platform for the simulation of the passage of particles through matter (Al-Buriahi *et al*., 2019; Al-Buriahi; Rammah, 2019). The calculated values of the various elements and compounds were also studied using the XCOM program by applying the mixture rule (Gerward *et al*., 2004). The lead-oxide (PbO) is important in the process of creating glasses since it is famous for its excellent infrared transmission, high density, and the refractive index is high (Kaundal *et al*., 2010). The Borate (B_2O_3) is often used in preparing glass due to its high glass-forming capacity, low thermal expansion, and high stability when added with alkali metal oxides (i.e., Li_2O, Na_2O, K_2O) (Limkitjaroenpornn *et al*., 2011).

In the present work, the properties of radiation protection of the glass system: Li_2O-K_2O-Na_2O-PbO-B_2O_3 have been studied theoretically by using simulation Monte Carlo code Geant4 as a function of the incident photon 0.0015 MeV and 15 MeV, then the accuracy of the simulated results was tested by using the XCOM program.

MATERIALS AND METHODS

Geant4 is a simulating toolkit for the interaction of particles or radiation with matter (Grünwald, 2011). It is a C^{++} open-source code (Khalil, 2014). Monte Carlo simulations are predominating used for styling systems with high degrees of liberty in which other mathematical methods are not appropriate. The XCOM software is a web-based that calculates attenuation coefficients or scattering cross-section for elements, compounds and mixtures (Nulk, 2014). The calculated data can be given in the form of attenuation coefficients μ and total cross- sections attenuation coefficients as well as partial cross-sections of the following processes: incoherent and coherent scatterings, photoelectric absorption and pair production in the field of the atomic nucleus and electrons (Medhat *et al*., 2014)

In this work, the Borate glass systems in the form of 10Li_2O, 10K_2O, 20Na_2O, xPbO-(60-x) B_2O_3 were studied theoretically by using Monte Carlo simulation code Geant4 and XCOM program. Table (1), summarizes the labels, compositions of the samples with the density and it is clear that the density increases with PbO%. The density of investigated glass systems increases from 2.3724 to 5.0863 due to the increase of PbO concurrent with B_2O_3. Also, molar volume increases from 28.0625 to 31.2060 cm^3 mol^{-1} due to an increase of PbO concurrent with B_2O_3.

The computational calculations of the investigated samples are implemented by and Monte Carlo simulation code Geant4 and XCOM program and at the photon energies 0.0015MeV-15MeV. The shielding parameters of the prepared glasses were calculated as a function of the incident photon. In this study, we simulated the propagation of radiation through the investigated glass samples by Geant4 simulation code, where all the elements, materials and compounds were defined. The geometry is designed to determine the initial (I_0) and final intensity (I) of photons. To estimate the linear attenuation coefficient (μ_L) for each glass sample, we then used these numbers, according to Lambert-Beer law (Taqi and Khalil, 2017; Taqi *et al*., 2016).

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

Equation (1) can be expressed using the coefficient of mass attenuation $(\mu_m = \mu/\rho)$

$$I = I_0 e^{-\mu_m x\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The μ_m values of glass samples were calculated by mixture rule.

$$(\mu_m)_{composite} = \sum_i^n w_i (\mu_m)_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where w_i is the proportion by weight and $(\mu_m)_i$ is mass attenuation coefficient of the i^{th} element? Reducing the intensity of radiation to one-tenth of its original value is defined as the tenth value layer,

$$TVL = \frac{ln(10)}{\mu_L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Table 1: labels, concentrations, density and molar volume of the studied samples

sample	Li_2O	K_2O	Na_2O	B_2O_3	PbO	Density (gm cm^{-3})	molar volume (cm^3 mol^{-1})
S1	10	10	20	60	0	2.3724	28.06257
S2	10	10	20	50	10	3.0699	26.68933
S3	10	10	20	40	20	3.3904	28.69617
S4	10	10	20	30	30	3.8454	29.29459
S5	10	10	20	20	40	4.0063	31.95151
S6	10	10	20	10	50	4.4495	32.22053
S7	10	10	20	0	60	5.0863	31.20602

RESULTS AND DISCUSSIONS

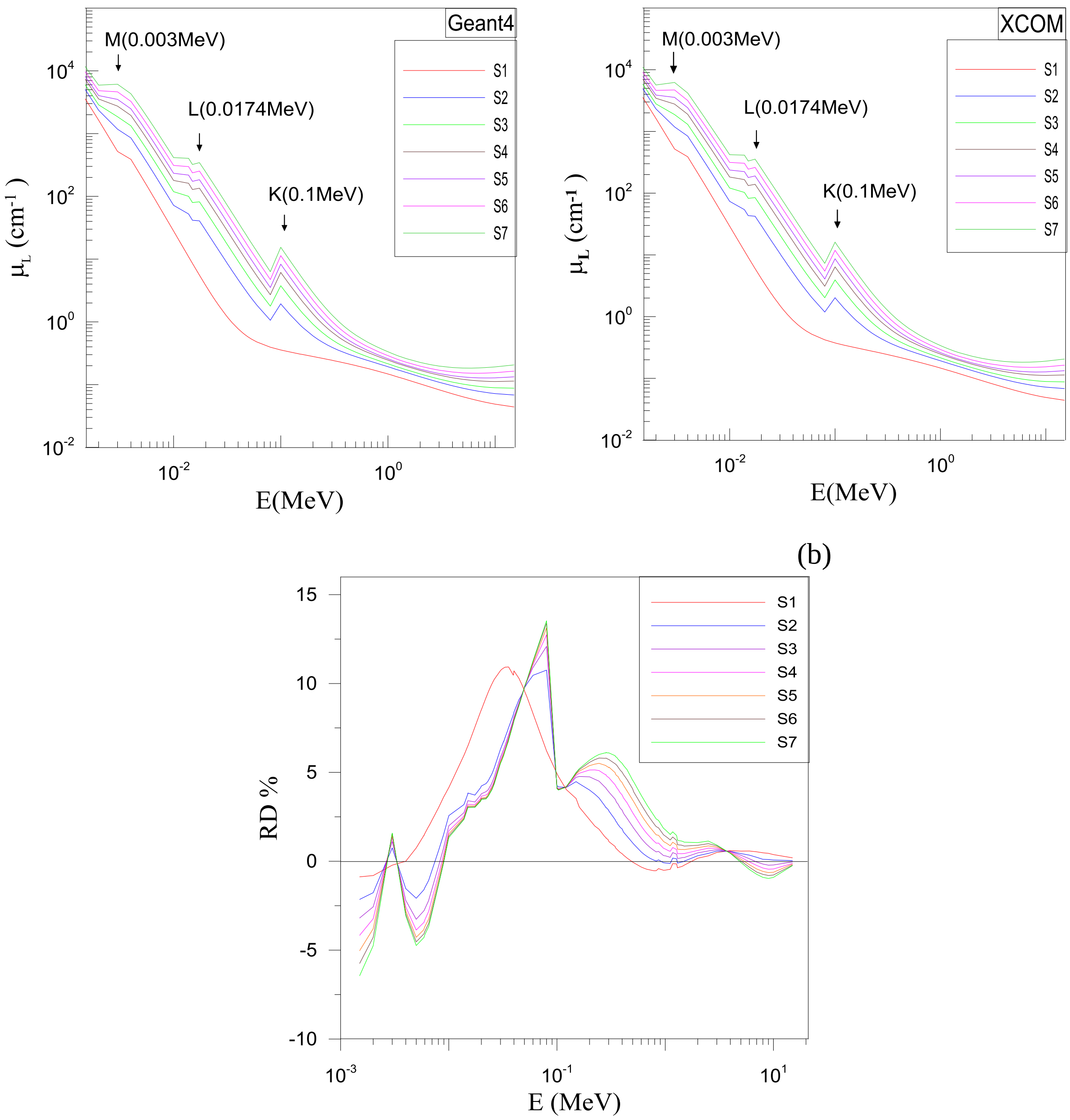
As shown in Fig. (1a and 1b) and Fig. (2a and 2b), the linear and the mass attenuation coefficients (μ_L and μ_m) decrease when the photon energy increase and many peaks are observed in the low photon energy region (< 100 keV) due to the K–, L– and M–photoelectric absorption edges, a high peak exists at 0.1 MeV owing to the K- absorption brink of (PbO) element. The sudden increases in the (μ_L and μ_m) values are due to photoelectric absorptions of the incident photons.

We determined the deviation between XCOM and Gean4 using,

$$RD\% = \left(\frac{(\mu_m)_{XCOM} - (\mu_m)_{Geant4}}{(\mu_m)_{XCOM}}\right) \times 100\% \ \ldots\ldots\ldots\ldots\ldots (5)$$

The deviations of the sample s1 varied from -0.044% to 10.920%, and from -0.244% to 11.265% for S7 as depicted in Fig. (1c) and Fig. (2c). The reported deviations show that the simulated values are in agreement with the XCOM this confirms the accuracy in the simulated values.

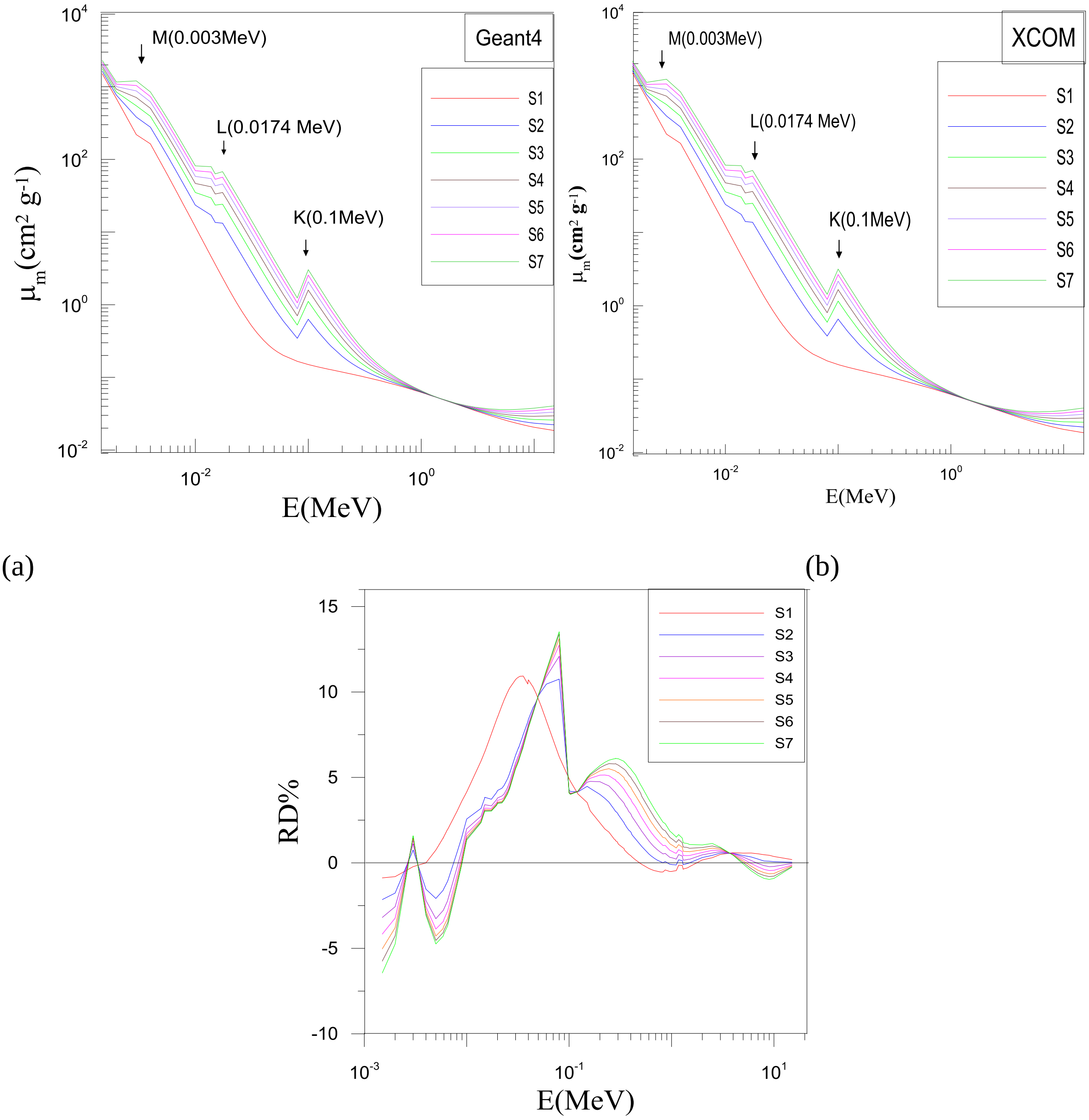
The total linear and mass attenuation coefficients with coherent scattering, respectively including the partial interactions: Photoelectric effect and Compton scattering are presented in Figs. (3 and 4), where the mass attenuation coefficients and TVL vs. energy and PbO concentration are illustrated in Figs. (5 and 6), respectively.



(b)

(c)

Fig. 1: Total linear attenuation coefficient μ_L of the investigated samples obtained by (a Geant4, b) XCOM, where c) outlines the RD% between XCOM and geant 4.



(a) (b)

(c)

Fig. 2: Total mass attenuation coefficient μ_m of the investigated samples obtained by (a Geant4, b) XCOM, where c) outlines the RD% between XCOM and geant 4.

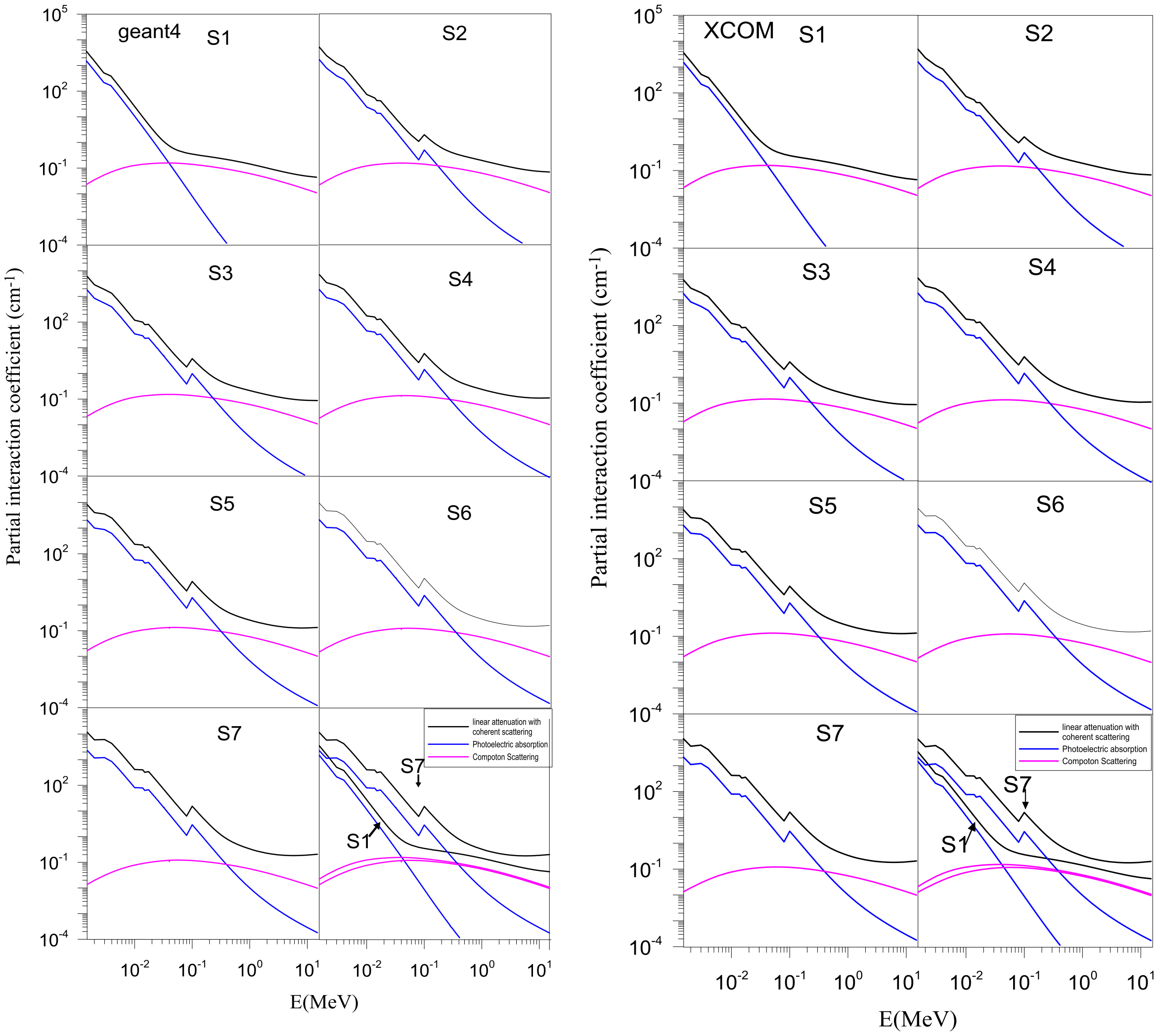


Fig. 3: Total and partial (photoelectric and Compton) linear attenuation coefficients calculated by Geant4 and XCOM.

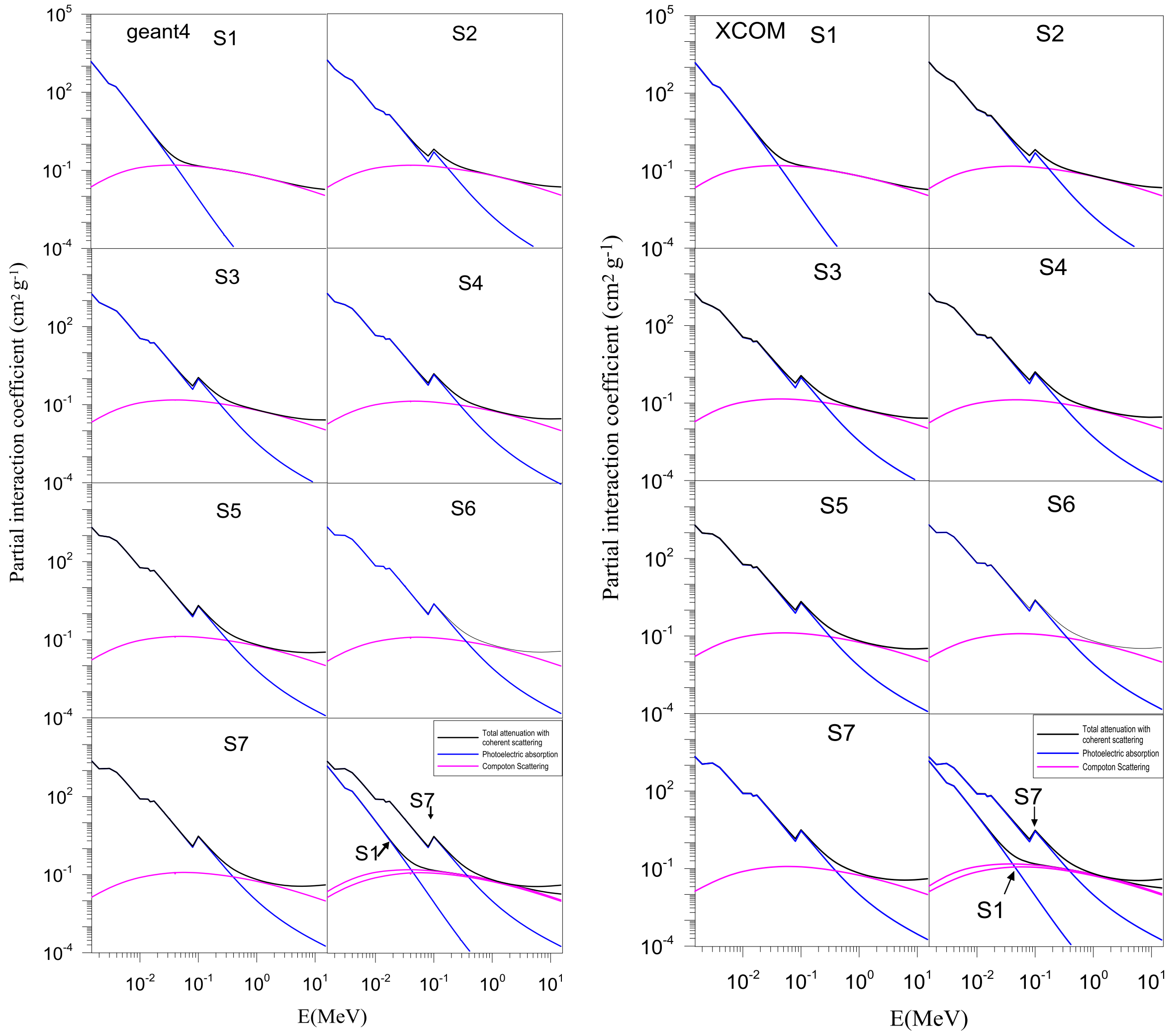


Fig. 4: Total and partial (photoelectric and Compton) mass attenuation coefficients calculated by Geant4 and XCOM.

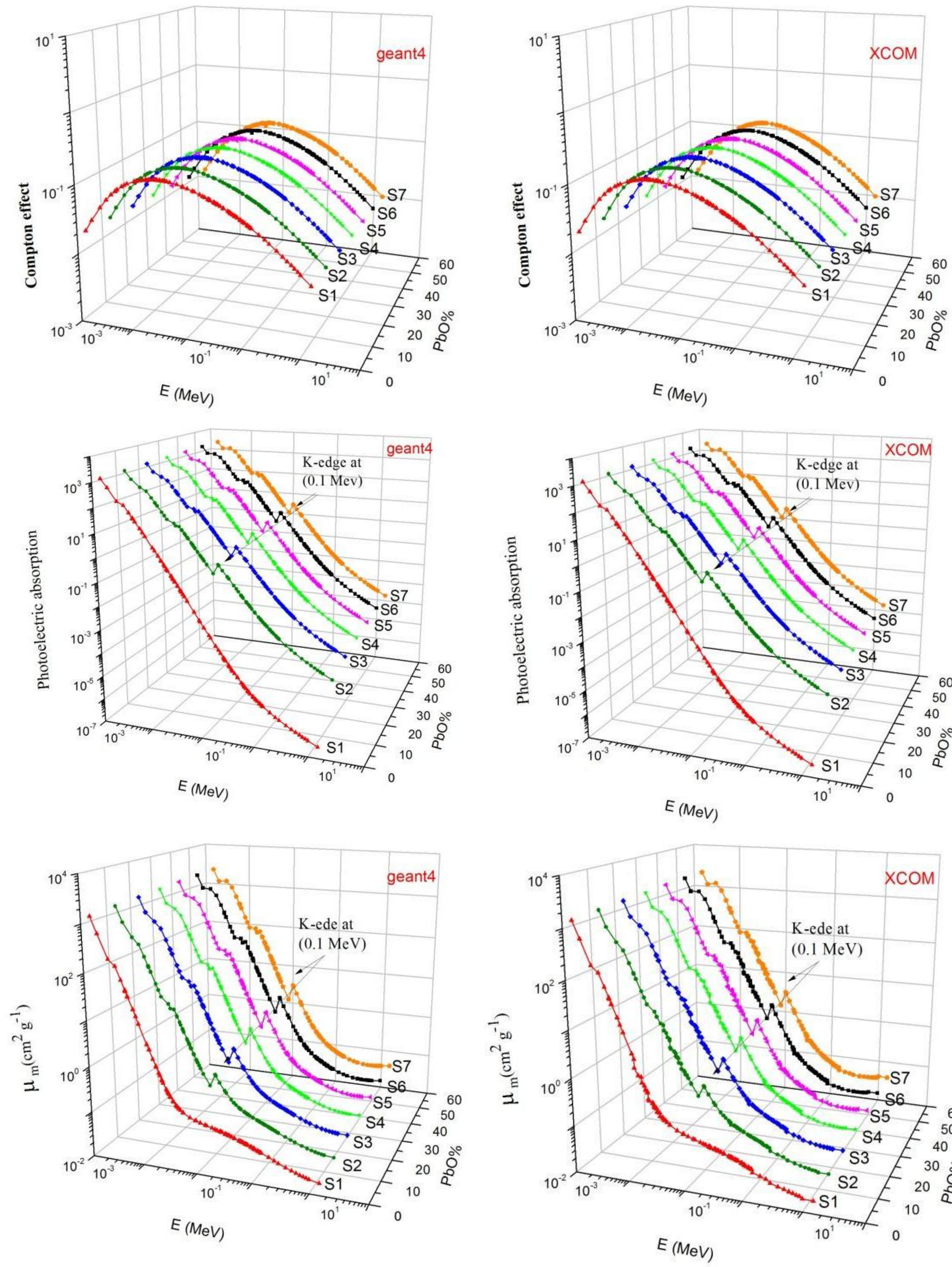


Fig. 5: Total and of partial (photoelectric and Compton) mass attenuation coefficients calculated by Geant4 and XCOM vs. energy and PbO concentration.

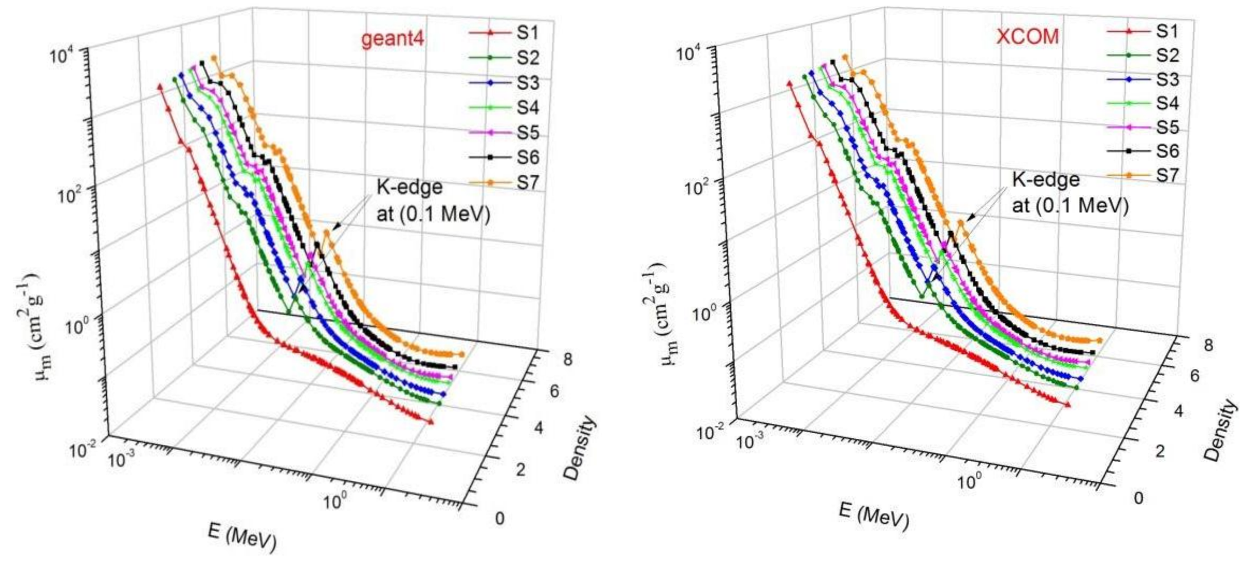
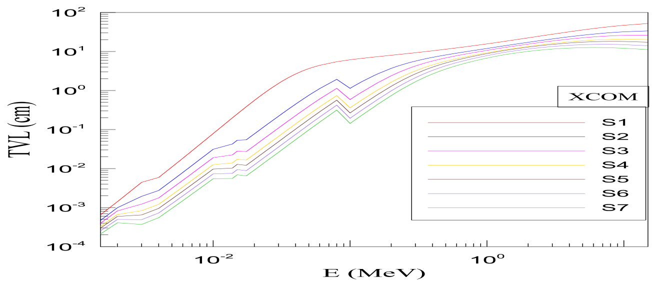
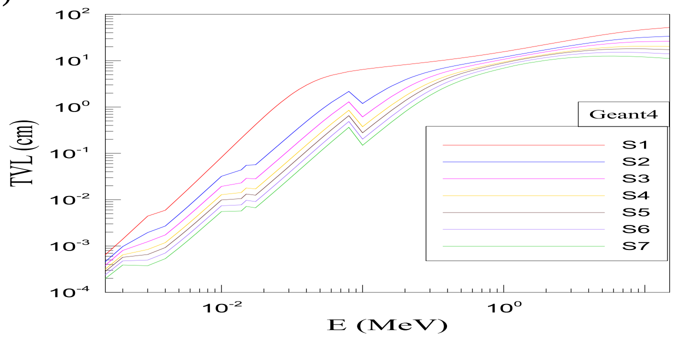


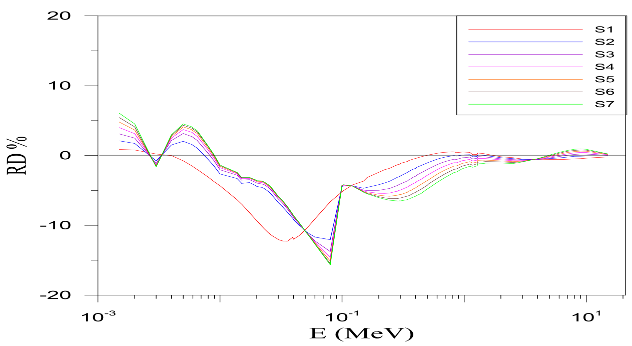
Fig. 6: Total mass attenuation coefficients calculated by Geant4 and XCOM vs. energy and density.



(a)



(b)



(c)

Fig. 7: The calculated tenth value layer (TVL) for the prepared samples obtained by a) Geant4, b) XCOM, where c) outlines the RD% between XCOM and geant4.

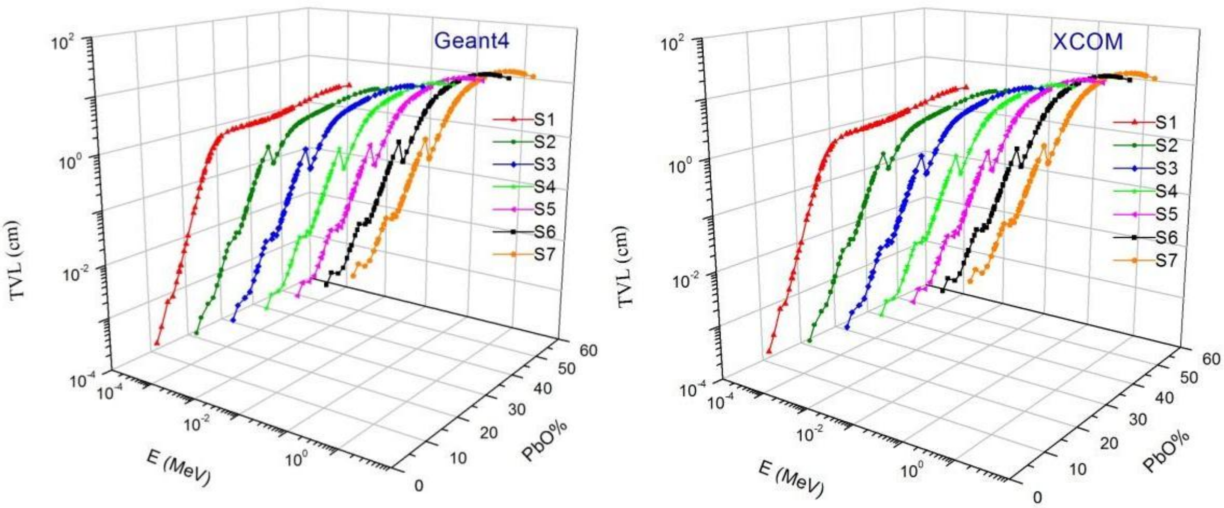


Fig. 8: Calculated tenth value layer (TVL) by Geant4 and XCOM vs. energy and PbO%

The variation of the attenuation coefficients for all the prepared glass samples versus photon energy depends on how the reaction photon of the prepared glass sample with the absorber. The photon reacts with the material in three methods, Pair Production at high energy, Compton scattering effect at intermediate energy, and photoelectric effect at low energy. Fig. (3 and 4), underline the total linear and mass attenuation coefficients with coherent scattering, respectively including the partial interactions: Photoelectric effect and Compton scattering. Fig. (5), illustrate the total and partial (photoelectric and Compton) mass attenuation coefficients XCOM vs. energy and PbO concentration, it appears that an increase in the PbO concentration causes an increase in the attenuation coefficients

Fig. (6) shows that an increase in the density leads to an increase in the attenuation coefficients, also the molar volume increased with an increase in the density and PbO concentration as noticed in (Table 1). The calculated tenth-value layer (TVL) values of the investigated glass samples by Geant4 and XCOM at the incident energy range (0.0015 MeV and 15 MeV) are illustrated in Fig. (7). It has been found that the TVL values are initially low and increase gradually with an increase in incident photon energy. Also, it is clear from Fig. (8) that the increase in the Pb% leads to a decrease in the TVL values, where it was found that at the first edge of sample S7 is lower than the edge of the sample S1. The reported deviations of TVL show that the simulated values are in agreement with the XCOM this confirms the accuracy in the simulated values.

CONCLUSION

The μ_L and μ_m for the present glasses ($10Li_2O$, 10K2O, $20Na_2O$, xPbO-(60-x) B_2O_3) were simulated using Geant4. The calculations were done at the energy range varying from 0.0015 MeV to 15 MeV. It was found that the attenuation properties increased with the increase in the Pb concentration of the investigated samples, therefore, the highest value of the μ_L and μ_m, and the lowest value of the TVL were found in the sample S7. The density of investigated glass systems increases from 2.3724 to 5.0863 gm cm^{-3} due to the increase of PbO concurrent with the decrease of B_2O_3. Also, molar volume increases from 28.0625 to 31.2060 cm^3 mol^{-1} due to an increase of PbO concurrent with the decrease of B_2O_3. Both density and molar volume exhibit monotonic increases with the x increasing. The Dev% between Geant4 and XCOM proof that the simulated values were in agreement with the XCOM this confirms the accuracy in the simulated values.

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محاكاة توهين كاما من خلال زجاج البورات باستخدام Geant4

الملخص

في هذه الدراسة، تم تحديد معاملات الوقاية protection parameters من اشعة كاما لنظام زجاج البورات Borate glass system المحتوي على $10\ Li_2O.\ 10K_2O.\ 20Na_2O.\ xPbO.\ (60\text{-}x)B_2O_3$ حيث x تتوعت كما يلي: 0 ، 10 ، 20 ، 30 ، 40 ، 50 و 60 باستخدام كود محاكاة مونت كارلو Monte Carlo simulation code Geant4. تم حساب معاملات التوهين attenuation coefficients باستخدام كود محاكاة مونت كارلو Geant4 كدالة لمدى طاقات الفوتون الساقط من 0.0015 MeV الى 15MeV. تم اختبار دقة نتائج المحاكاة باستخدام برنامج XCOM. أظهرت نتائج Geant4 وXCOM اتفاقًا معقولًا بين النموذجين. كذلك بينت نتائج معاملات التوهين أن العينة ذات التركيز الأعلى PbO تمتص عددًا أكبر من الفوتونات، وبالتالي تزداد معاملات التوهين بينما تنخفض قيم طبقة القيمة العاشرة (TVL tenth-value layer) بسبب الزيادة في PbO من 0 إلى 60٪. انخفضت معاملات التوهين الخطي والكتلي linear and mass attenuation coefficients عند زيادة طاقة الفوتون ولوحظ العديد من القمم.

الكلمات الدالة: خصائص التوهين، زجاج التدريع، معاملات التوهين، Geant4، XCOM .