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Simulation of the Gamma Absorption by Lead Bronze Alloys Using Geant4

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ABSTRACT

Shielding materials are extremely important in production or handling isotopes, nuclear reactors, accelerators, and medical centers, etc. The Monte Carlo simulation code Geant4 is one of the most important and common platforms for the simulation of the interaction of radiation with matter. Therefore, this paper is devoted to simulating the partial absorption of the gamma-ray by Lead bronze alloys (Pb, Sn, Cu) in different proportions using the Monte Carlo simulation code Geant4 from 1.5 keV to 15 MeV. The accuracy of the simulated results of the total and partial mass attenuation coefficients (μ_m) for the photoelectric effect, Compton Scattering and pair production, and tenth value layers (TVL) were evaluated by using the XCOM program. The agreements were good, but it depends on the energy of the incident photon. The mass attenuation coefficients decreased when the photon energy increased and many peaks are observed. The effect of adding Pb was clear, as the μ_m increases while the TVL decreases.

Keywords: Gamma absorption; Lead bronze alloys; attenuation coefficient; Geant4; XCOM.

INTRODUCTION

Gamma radiations refer to electromagnetic radiations of extremely high frequency or these are photons emitted as packets of energy, which travel at the speed of light. Gamma rays can be attenuated by materials, depending on the total mass along the path of the radiation, regardless of whether the material is of high or low density (Thukral, 2014). The radiation exposure risks are overcome by applying three main fundamental concepts shielding, distance and time. Attenuation coefficient is a quantity that characterizes how easily a material or medium can be penetrated by a beam of light, sound, particles, or other energy or matter. It describes the extent to which the intensity of an energy beam is reduced as it passes through a specific material (Thukral, 2014; El-Sawy and Amal, 2015).

Attenuation is the loss in intensity of any type of flow through a medium; it is an exponential function of the trajectory length through the median and is generally given by the Beer-Lambert law. The μ_L (cm^{-1}) is defined as the probability per unit length that gamma photon will undergo an interaction in the material (Ahmed *et al*., 2015).

There is an interest by researchers in studying the attenuation of different materials such as soil (Taqi *et al*., 2016), building materials (Najam *et al*., 2014; Najam *et al*., 2016) and others. In this work we will focused on the absorption of gamma by alloys, it has been conducted by many previous studies on the effects of different factors on the mass attenuation coefficients (Singh and Badiger, 2013; Narender *et al*., 2013; Singh and Badiger, 2014; Esfandiari *et al*., 2014; Singh *et al*., 2015; El-Kameesy *et al*., 2017; Kaur *et al*., 2017; Singh *et al*., 2018; Agar *et al*., 2018; Singh *et al*., 2019; Ekinci *et al*., 2019).

In this work, we have tried to simulate the partial absorption of gamma-ray by Lead Bronze alloys using Simulation code Geant4 at the energy range 0.0015 MeV to 15 MeV. To evaluate the results, the comparison of the simulation results with the XCOM program to be presented.

MATERIALS AND METHODS

XCOM is a web-based that calculates photon interaction mass attenuation coefficients (μ_m) or cross-section (σ) for elements, compounds and mixtures. Between 1987, 1999, Hubbell and Berger developed software called XCOM (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)

Geant4 is a toolkit for simulating the passage of particles through matter (Grünwald, 2011). It is an open source, in terms of the size and scope object-oriented simulation code written in C^{++} language (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 application fields involve high-energy physics, nuclear experiments, medical, accelerator and space physics (Briesmeister, 2000).

In this work, the simulation of the Lead Bronze alloys with different concentrations as presented in (Table 1) was implemented by the Monte Carlo simulation code Geant4 at the photon energies 1.5 keV - 15 MeV. The accuracy of the simulated results of the total and partial mass attenuation coefficients (μ_m) for the photoelectric effect, Compton Scattering and pair production, and tenth value layers (TVL) were tested by using XCOM program. In the simulation process, we defined the elements, materials and compounds. The geometry is designed to determine the initial (I_0) and the final number (I) of photons. μ_m depends on the thickness (*x*) and density (ρ) of the sample, and can be obtained according to, (Davisson, 1965; Taqi *et al*., 2016)

$$I = I_0 e^{-\mu_m \rho x} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (1)$$

The μ_m for any chemical compound or the mixture of elements can be calculated in terms of the weight fraction (w_i) by the mixture rule (Manohara and Hanagodimath, 2007).

$$\mu_m = \sum_i w_i \, (\mu_m)_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

The weight fraction of the i^{th} constituent element is given by,

$$w_i = \frac{n_i A_i}{\sum_j n_j A_j} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where A_i is the atomic weight and n_i is the number of formula units?

The thickness of a shielding sample required for attenuating a radiation beam to 10% of its radiation level is defined as Tenth Value Layer (TVL) and can be computed by in terms of the linear attenuations' coefficient μ_L (Biswas *et al.*, 2016),

$$\mathrm{TVL} = \frac{2.303}{\mu_L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Table 1: Elemental fractions of the investigated samples

Sample	Compounds	Sn %	Cu %	Pb %
1	Sn	100		
2	Cu		100	
3	Pb			100
4	Sn10Cu90	10	90	
5	Pb10Sn10Cu80	10	80	10
6	Pb20Sn10Cu70	10	70	20
7	Pb30Sn10Cu60	10	60	30
8	Pb40Sn10Cu50	10	50	40

RESULTS AND DISCUSSIONS

Fig. (1) illustrates the partial μ_m for the Compton scattering, photoelectric effect and, pair production calculated by Geant4 and XCOM. The μ_m of the photoelectric process decreases with increasing photon energy. Hence, the contribution of the photoelectric process can be seen in the lower part of the energy. The variation in $\mu_m$value for the Compton process vs. the energy of the incident photon is slow in comparison with that of the photoelectric process, therefore the Compton scattering process is dominant in the middle energy region. The μ_m of the pair production starts from 1.022 MeV and increases with photon energy increasing.

In Fig. (2a and 2b), it has been found that the total μ_m values dropped quickly with the increase in the incident photon energy up to 5.0 MeV, after that the values increase gradually with the increase in the incident photon energy. The largest value of the μ_m was for the sample (Pb40Sn10Cu50), it may be due to the higher atomic number of constituent elements. The smallest μ_m value was for the sample (Sn10 Cu90). Many peaks are observed in the low photon energy region due to photoelectric absorption edges of Pb, Sn, and Cu elements. The edges occurred at photon energy just above the electron binding energy of the shells. A high peak exists at 0.088 MeV owing to the K- absorption brink of (Pb) element.

The deviation between Geant4 and XCOM was less than 14%, where the lowest values for the lead, copper, and tin were 0.3549, 0.3639, and 0.2042, respectively and the highest values were 14, 16, and 8.968, respectively, as shown in Fig. (2c).

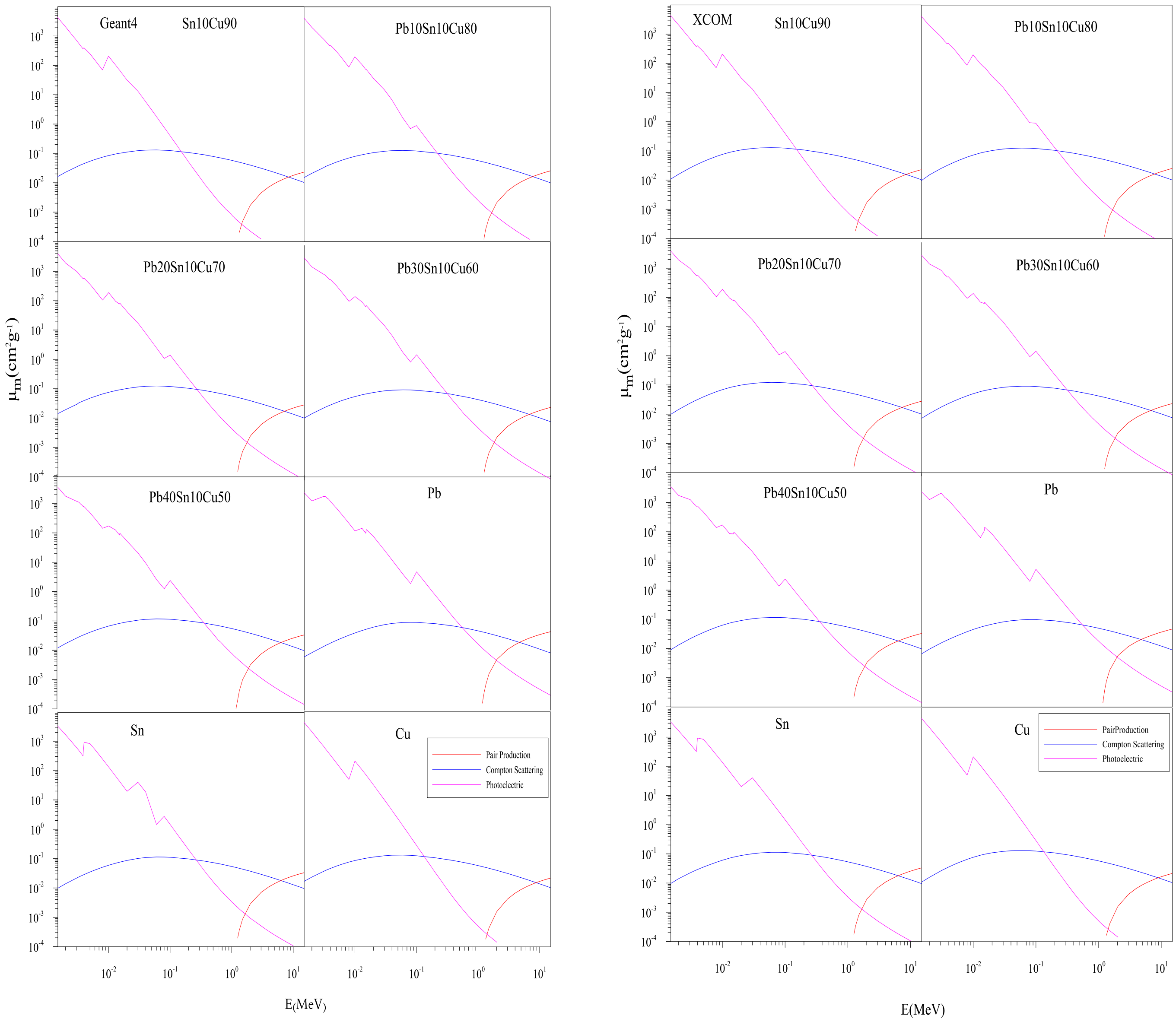


Fig.1: Partial μ_m for the Photoelectric, Compton scattering, and Pair production calculated by Geant4 and XCOM.

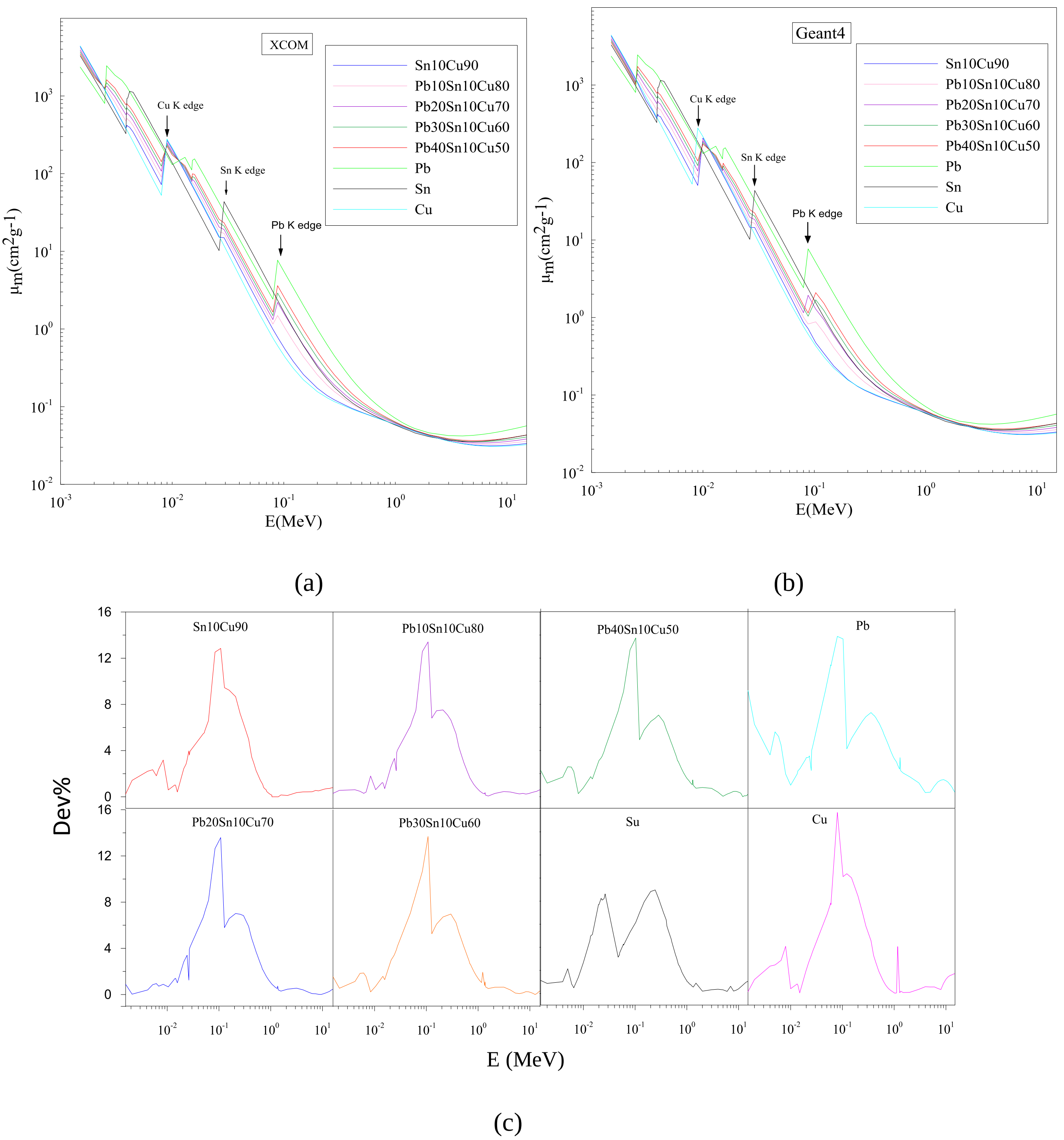


Fig. 2: Total μ_m of the investigated samples obtained by a) Geant4, b) XCOM, c) outlines the Dev % between geant4 and XCOM.

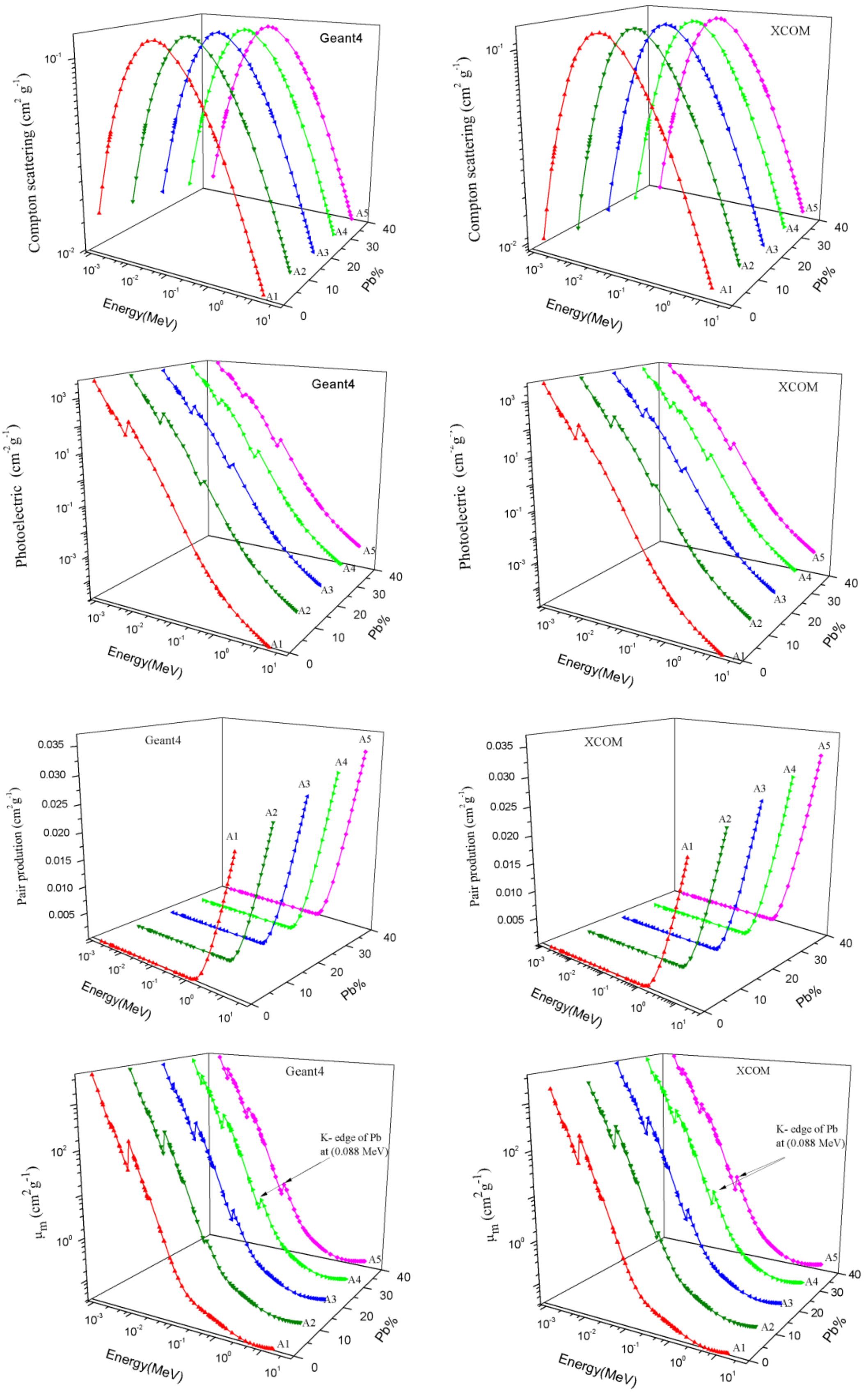
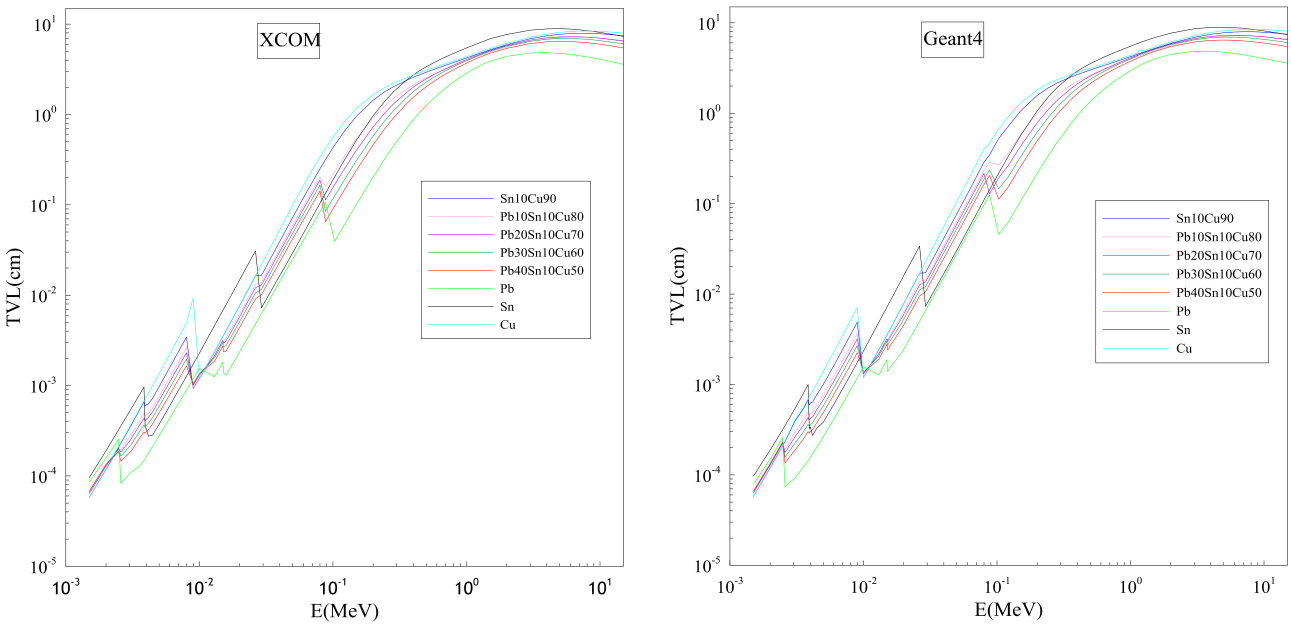
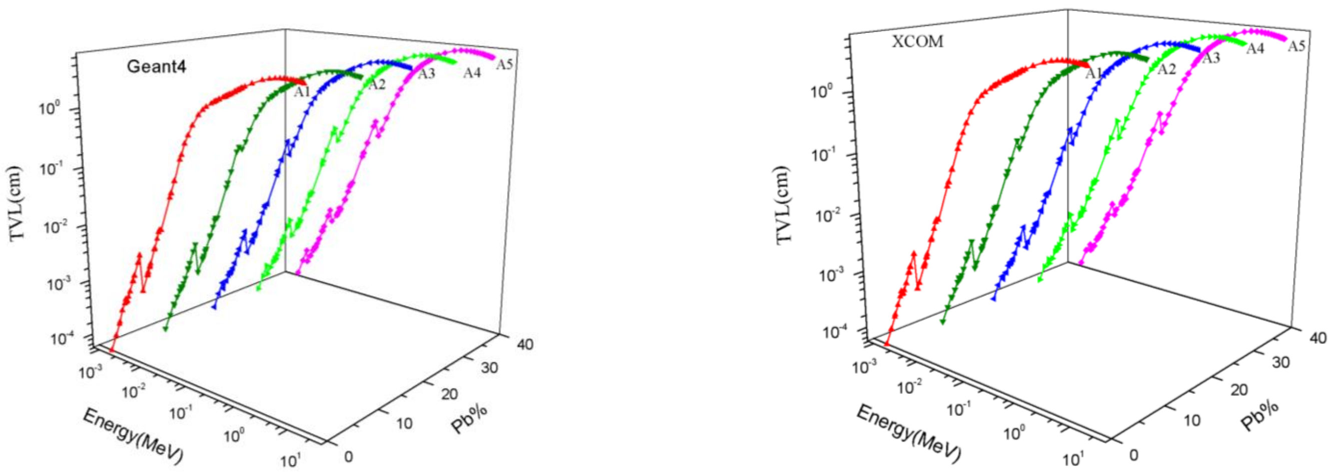


Fig. 3: partial (photoelectric, Compton, Pair) and total μ_m calculated by Geant4 and XCOM vs. energy and Pb concentration



(a) (b)

Fig. 4: The calculated tenth value layer (TVL) for the simulated samples obtained by (a Geant4, b) XCOM.



(a) (b)

Fig. 5: The simulated tenth value layer (TVL) by (a Geant4, b) XCOM vs. energy and Pb concentration.

Fig. (3) illustrate the partial (photoelectric, Compton scattering and Pair production) and total μ_m calculated by Geant4 and XCOM vs. energy and Pb concentration, it appears that an increase in the Pb concentration causes an increase in the attenuation coefficients.

The calculated tenth value layer (TVL) values of the simulated samples by Geant4 and XCOM at the incident energy range 1.5 keV-15 MeV are illustrated in Fig (4). It has been found that the TVL values are initially low and increase gradually with an increase in incident photon energy up to 5 MeV. Above 5 MeV, the rate of decrease of TVL is weak with the incident energies. The calculated TVL values by Geant4 and XCOM for the photon energy range (1.5 keV -15 MeV) with the lead ratio Pb% are shown in Fig. (5a and 5b), where the increase in the Pb% leads to a decrease in the TVL values, also it was found that at the first edge of sample Pb40Sn10Cu50 is lower than the edge of the sample (Sn10Cu90).

CONCLUSION

The partial and total μ_m of Lead Bronze alloys is simulated using Monte Carlo simulation code Geant4 form 1.5 keV to15 MeV, then tested by using XCOM program. It was found that the attenuation properties increased with the increase in the Pb concentration, therefore, the highest value of the μ_m, and the lowest value of the TVL was found in the sample Pb40Sn10Cu50, where the first edge this sample is lower than the edge of the sample Sn10Cu90. The good agreements between Geant4 and XCOM indicate that the simulation programs are useful to calculate the shielding parameters, particularly in cases where no experimental data exist.

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محاكاة امتصاص كاما بواسطة سبائك الرصاص البرونزية باستخدام Geant4

الملخص

تعتبر مواد الحماية من الاشعاع Shielding materials مهمة للغاية في إنتاج أو التعامل مع النظائر والمفاعلات النووية والمسرعات والمراكز الطبية وما إلى ذلك. يعد كود محاكاة مونت كارلو Monte Carlo simulation code Geant4 أحد أهم المنصات الشائعة لمحاكاة تفاعل الإشعاع مع المادة. لذلك، هذا البحث المقدم مخصص لمحاكاة الامتصاص الجزئي والكلي لأشعة كاما بواسطة سبائك الرصاص البرونزية Lead bronze alloys بنسب مختلفة من (Pb, Sn, Cu) وذلك باستخدام كود محاكاة مونت كارلو Geant4 لمدى الطاقات من 1.5 keV إلى 15 MeV. تم تقييم دقة النتائج لمعاملات التوهين الكتلي mass attenuation coefficients الكلي والجزئي (μ_m) للتأثير الكهروضوئي photoelectric effect وتشتت كومبتون Compton Scattering وإنتاج الزوج pair production اضافة الى tenth value layers (TVL) باستخدام برنامج XCOM. كانت التوافقات بين النموذجين جيدة، وتبين انها تعتمد على طاقة الفوتون الساقط. انخفضت معاملات التوهين الكتلي عندما زادت طاقة الفوتون ولوحظت العديد من القمم. كان تأثير إضافة الرصاص Pb واضحًا، حيث لوحظ ان قيمة μ_m تزداد بينما حدث انخفاض في قيمة TVL.

الكلمات الدالة: امتصاص كاما، سبائك الرصاص البرونزية، معامل التوهين، Geant4، XCOM.