The Nucleus **61**, No. 2 (2024) 63-68

www.thenucleuspak.org.pk

The Nucleus

ISSN 0029-5698 (Print)
ISSN 2306-6539 (Online)

Study of Linear Attenuation Coefficient and Buildup Factor of Some Metals at 662 keV and 1332 keV

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ABSTRACT

The nuclear shielding properties of some metals such as lead, copper, iron, aluminium, and carbon were studied using 3"×3"NaI(Tl) scintillation detector by the evaluation of shielding parameters such as the linear attenuation coefficient and gamma-ray buildup factor. The linear attenuation coefficient of lead is very high compared to the other materials used for the study. The buildup factors of these materials were observed to increase with the increase in the thickness of the material. The value of the buildup factor is found to be high at 662 keV and low at 1332 keV. Moreover, the buildup factors of lead were significantly higher than those of other materials investigated in this study.

Keywords: *Linear attenuation coefficient, Buildup factor, Gamma Energy, Compton scattering, NaI(Tl) scintillation detector.*

1. Introduction

The protective radiation shielding materials play an important role in reducing the effect of radiation exposure on people in the whereabouts of radiation in agriculture, medical fields and scientific fields such as the construction of nuclear reactors and research reactors for power generation [1]. The radiation shielding properties of the materials mainly depend on the radiation attenuation coefficient and buildup factor of radiation. The gamma-ray buildup factor measures the enhancement of radiation dose within a material due to multiple scattering and absorption events. It plays an important role in the process of radiation shielding and protection. It is also used as a correction factor in the calculation of the appropriate thickness of the shielding material for the gamma-ray sources [2].

The radiation shielding properties of different materials were evaluated using parameters such as energy absorption coefficients, mass attenuation coefficients and half-value layer. Moreover, Beer-Lambert's law was modified to account for the effect of secondary radiations that usually occur due to the buildup of photons from the collided part of the incident beam. According to this law, the intensity of the gamma-rays after passing through an absorber $I = I_0 e^{-\mu x}$, where I_0 is the initial intensity of the gamma-rays incident on the material of thickness x and μ is the linear attenuation coefficient, is under three conditions, which are (i) monochromatic radioactive source (ii) thin absorbing material (iii) narrow beam geometry. In case any of the three conditions has been violated, this law no longer holds. However, violation of this law can be maintained using the correction factor B, which is known as the buildup factor [3]. The modified equation is written as

$$\mathrm{I} = \mathrm{B I_0 e^{-\mu x}}$$

Where B stands for the buildup factors, namely Energy Absorption Buildup Factor (EABF) and Exposure Buildup Factor (EBF). The modification accounts for the secondary radiation effect that commonly occurs because of photon buildup from incident beam collection [4].

Buildup factors of different shielding materials were determined to make corrections for energy deposition in such materials. Hence buildup factors are crucial for accurately predicting radiation interactions within the material and designing effective radiation shielding and dosimetry systems [5]. Buildup factors can be evaluated by using several methods like geometric progression (GP) fitting method, invariant embedding method, Taylor's method, Berger's method, Monte Carlo method, moment method and Beer Lambert's formula etc. However, the buildup factor values obtained for the same shielding material and the same thickness of the material using different formulas are different. 6]. Yinghong Zuo et al. [6] have found that the buildup factor values for iron and lead materials using Taylor's formula and Berger's formula are different, but in both cases the buildup factor increases with the thickness of the material. They found that the buildup factor values for both lead and iron material using Taylor's formula is lower than Berger's formula and they found that the difference between buildup factor values using the two formulas are affected by the type of shielding material, gamma-ray energy, and the thickness of the material.

Danial Salehi et al. [7], estimate the energy buildup factor in iron using different methods of GP fitting method, invariant embedding, a simulation program written by the Monte Carlo method to calculate this factor and MCNP4C code in the energy range 0.1-10 MeV with penetration depths up to 25 mfp and the results are compared with the GP fitting method. It was found that the effect of coherent scattering is considerable for the gamma-ray energy up to about 0.2 MeV and the mean free path R≤ 8 mfp. The exposure buildup factor values decrease at higher penetration depths and energy. Pew Basu et al. [8], have shown the gamma-ray buildup factor values based on the Taylor form, the Berger form, GP fitting form and ANSI values increase with the penetration depth, whereas the trends are different in high Z material (lead)

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compared with the intermediate Z (iron) and low Z (concrete) materials and found that the buildup factor values become saturate at the higher thickness, but not in the case of iron or concrete. Y S Rammah et al. [9] studied the shielding features for three binary alloys series such as: (Pb-Sn), (Pb-Zn) and (Zn-Sn) and found that the energy buildup factor decreases with increased Sn and Zn concentrations for all selected alloys using MCNP-5 simulation code for the energy between 0.01 and 15 MeV. They concluded that these alloys can be used as effective gamma radiation shielding materials. Hiwa Mohammed Qadr et al. [10] calculated the gamma-ray buildup factor for aluminum, graphite and lead using NaI(Tl) detector, and were analyzed by the maestro program. It was found that the buildup factor decreases with the increase in the thickness of the material and depends entirely on the geometry of the experimental setup.

Murat Kurudirek [16] studied photon buildup factors in some dosimetric materials such as water, polystyrene, polymethyl methacrylate (PMMA), solid water (WT1), RW3 (Goettingen water 3), and ABS (acrylonitrile butadiene styrene), for MV X-rays and ^{60}Co gamma rays using G-P fitting formula for multi energetic sources which is helpful for therapy planning or shielding calculations. In all the cases the energy absorption buildup factor increases with the thickness of the material and decreases with the incident gamma-ray energy.

The penetrating power of gamma-rays is higher than alpha and beta radiations. Due to this it can easily pass through the human body and results in harmful effects. To avoid this highly dense and high atomic number materials are often used for protection from harmful gamma radiations. The traditionally used shielding material is lead because of its high density (11.34 kgm^{-3}) and high atomic number (82). However, the use of lead as a shielding material is avoided because of its disadvantages like toxicity, heaviness, and high production cost. Therefore, other materials such as copper, zinc, aluminium, iron, graphite, tin, carbon etc. are used to replace lead. Later, to get good attenuation results, composite materials, such as metal-metal composites, glass-metal composites, cement composites and polymer composites are used [17], [18]. In composite materials also lead is used as a prime material, as a filler with any matrix materials to get the required attenuation [19], [20].

The present study is an attempt to evaluate the linear attenuation coefficient using Beer-Lambert's law and hence the buildup factor using Berger's formula of some conventional shielding materials such as lead, copper, iron, aluminium and carbon at 662 keV and 1332 keV using 3″×3″ NaI(Tl) scintillation detector and to prove the radiation shielding properties depend on the atomic number and density of the materials.

2. Theory

2.1 Linear attenuation coefficient

When a gamma-ray beam of intensity I_0 passes through a target of thickness x under narrow beam geometry, the intensity of the transmitted beam is according to Beer-Lambert's law

$$I = I_0 e^{-\mu x} \tag{1}$$

Where "μ" is the linear attenuation coefficient, can be evaluated by the relation

$$\mu = \frac{1}{x} \ln\left(\frac{I_0}{I}\right) \tag{2}$$

In this study, "μ" is calculated from the slope of the graph $\ln\left(\frac{I_0}{I}\right)$ Vs the thickness "x" of the sample.

2.2 Buildup factor:

Whatever the photon source and the attenuating medium, the energy spectrum of the total photon fluence $\emptyset$(r, E) at some point of interest "r" may be divided into two components. The un-scattered component $\emptyset^0$(r, E) consists of those photons that have reached "r" from the source without experiencing any interactions in the attenuating medium. The scattered component $\dot{\emptyset}'$ (r, E) consists of source photons scattered one or more times, as well as secondary photons such as X-rays and annihilation gamma rays. Accordingly, the dose or detector response D(r) at the point of interest "r" may be divided into un-scattered (primary) and scattered (secondary) components D^0(r) and D^s (r). The buildup factor "B" is defined as the ratio of the total dose to the un-scattered dose, i.e.,

$$B(r) = \frac{D(r)}{D^0(r)} = 1 + \frac{D^s(r)}{D^0(r)} \tag{3}$$

The general form of Berger's formula is

$$B = 1 + \frac{(\mu x - 1)(1 - e^{-\mu x})}{\mu x} \tag{4}$$

Where "μ" is the linear attenuation coefficient, and "x" is the thickness of the sample. This formula can be more complex depending on the specific conditions, such as the type of material and the energy of the photons. Variants of the formula may include additional terms or correction factors to account for different scattering phenomena and material properties [10].

3. Experimental study

3.1 Materials

Experiments on gamma ray shielding properties of some metals were conducted using 3″×3″ NaI(Tl) detector with good geometrical arrangement at the Centre for Application of Radioisotope and Radiation Technology (CARRT), Mangalore University, Mangalore by using lead, copper, iron, aluminium and carbon slabs of dimension 10cm × 10 cm × 0.2 cm as radiation shielding materials at 662 keV (Cs^{137}) and 1332 keV (Co^{60}) gamma-ray energy.

3.2 Experimental setup

For the study of radiation shielding properties, such as linear attenuation coefficient "μ" and hence the buildup factor "B", a good geometrical arrangement was used by using collimators of size 8 mm and 2.5cm at the radioactive source assembly and detector assembly respectively. Fig. 1 is the schematic diagram of NaI(Tl) scintillation detector used for the study. The source assembly consists of seven cylindrical lead blocks of thickness 5 cm and outer diameter of 12 cm. Two of them with an inner diameter of 2.5 cm are used to place the radioactive source. Three of them are used to cover the back surface of the source to avoid the leakage of harmful radiation. To get a well-collimated beam of radiation, one of the lead blocks of diameter 8 mm is used as a collimator and one is used to cover the source when the experiment is not conducted.

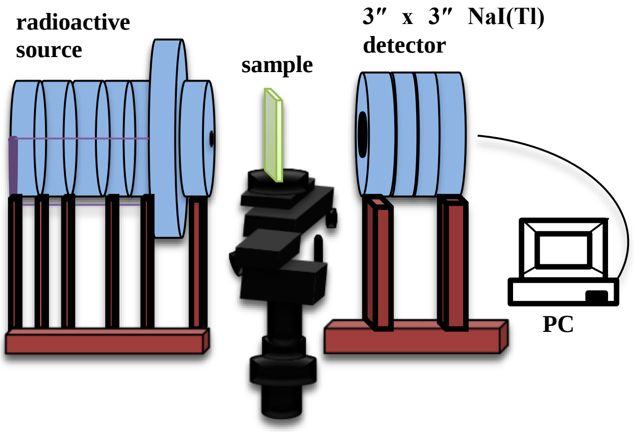

Fig. 1. Schematic diagram of NaI(Tl) detector

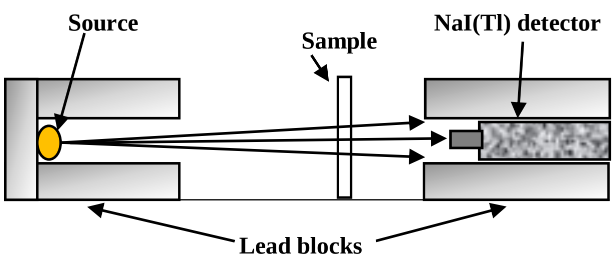

Fig.2. Bad geometry of the experimental set up

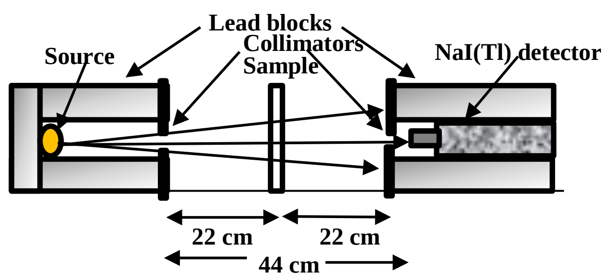

Fig. 3 Good geometry of the experimental set up.

The detector assembly is composed of five cylindrical lead rings of thickness 3.5 cm and an outer diameter of 16 cm. Four of them of inner diameter 9 cm are used to cover NaI(Tl) detector coupled with a photomultiplier tube, amplifier, and MCA, and one of them of inner diameter 2 cm is used as a collimator. The detector is connected to a PC with the Win TMCA 32 software package. The source collimator, the target, and the detector collimator are along the same line, representing the good geometry of the experimental setup [2]. Fig. 2 shows the bad geometry (without collimators), and Fig. 3 shows the good geometry (with collimators) of the experimental setup.

In the present study, some materials like lead, copper, iron, aluminium and carbon were taken in the form of rectangular sheets of dimension 10 cm × 10 cm × 0.2 cm as radiation shielding materials to investigate their shielding properties, such as the linear attenuation coefficient and hence the buildup factor at 662 keV and 1332 keV gamma energy. The sample is placed on the target stand with the support of a polyester slab, which is not a good absorber of radiation. Each measurement was taken for 2000 seconds with four trials to reduce the experimental error by 0.5.

4. Results and discussion

In the present study, the linear attenuation coefficient of some common shielding materials like lead, copper, iron, aluminium and carbon was evaluated by plotting the graph of $\ln \frac{I_0}{I}$ vs the thickness of the material according to the relation (2). The slope of the curve is equal to the linear attenuation coefficient of the absorber. The linear attenuation coefficient of the shielding material used for the study is entered in Table 1. It was observed that the value of μ depends on the density ρ and atomic number Z of the materials, according to the equation $\mu = \frac{\sigma N_A \rho Z}{M}$, where σ is the scattering cross-section per electron of the material, N_A is the Avogadro number, and M is the atomic weight of the material. As the density decreases, the linear attenuation coefficient "μ" decreases. Also, it was observed that the value of "μ" increases with the increase in the atomic number of the target material. Further, Fig. 4 shows clearly that the value of "μ" is high at a lower energy 662 keV, and low at higher energy 1332 keV, i.e., "μ" increases with the decrease in the gamma-ray energy [11].

These observations reveal that, among the radiation shielding materials used for the study, lead has good radiation shielding properties because of its high atomic number and density. Further study of the buildup factor of the shielding materials is necessary to prove the good geometrical arrangement, which is essential for the attenuation of high energy gamma radiations, and to decide the good shielding material.

Table 1: Linear attenuation coefficient "μ" of different radiation shielding materials

Radiation shielding material	Density kgm^{-3}	Atomic No. Z	Linear attenuation coefficient μ cm^{-1}	
			662 keV	1332 keV
Lead	11.34	82	0.6146±0.0059	0.3773±0.0041
Copper	8.94	29	0.3464±0.0102	0.2892±0.0047
Iron	7.85	26	0.3045±0.0084	0.2851±0.0142
aluminium	2.7	13	0.0927±0.0002	0.0796±0.0006
Carbon	2.26	6	0.0307±0.0002	0.0247±0.0002

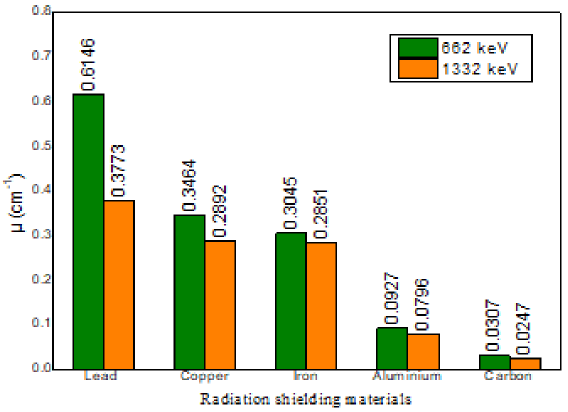

Fig.4 Linear attenuation coefficient values of lead, copper, iron, aluminium and carbon at 662 keV and 1332 keV gamma energies.

Fig. 5 shows the variation of buildup factor with the thickness of the shielding materials used for the study such as lead, copper, iron, aluminium and carbon. As the sample thickness increases, the buildup factor increases at both energies. This is primarily attributed to the increased interaction between gamma photons and the material. As the penetration depth increases, more Compton scattering events occur, leading to the generation of a larger number of lower-energy photons. At lower penetration depths, the pair production process is pre-dominated, resulting in an electron-positron pair, these particles may escape from the material or, after multiple collisions within the material, come to rest and further annihilate. With the increase in the penetration depth, the secondary gamma rays contribute to the rise in intensity of the primary gamma rays [12].

Fig. 6 shows the variation of buildup factor at 2, 4, and 6 cm thickness of the sample for 662 keV and 1332 keV gamma energy. It indicates that the buildup factor value is higher for lead, and it has a very low value for carbon. Since the Energy Buildup Factor values are directly proportional to $\frac{Z^{4-5}}{E^{3-4}}$. This shows that as the atomic number of the material increases, its buildup factor increases [12].

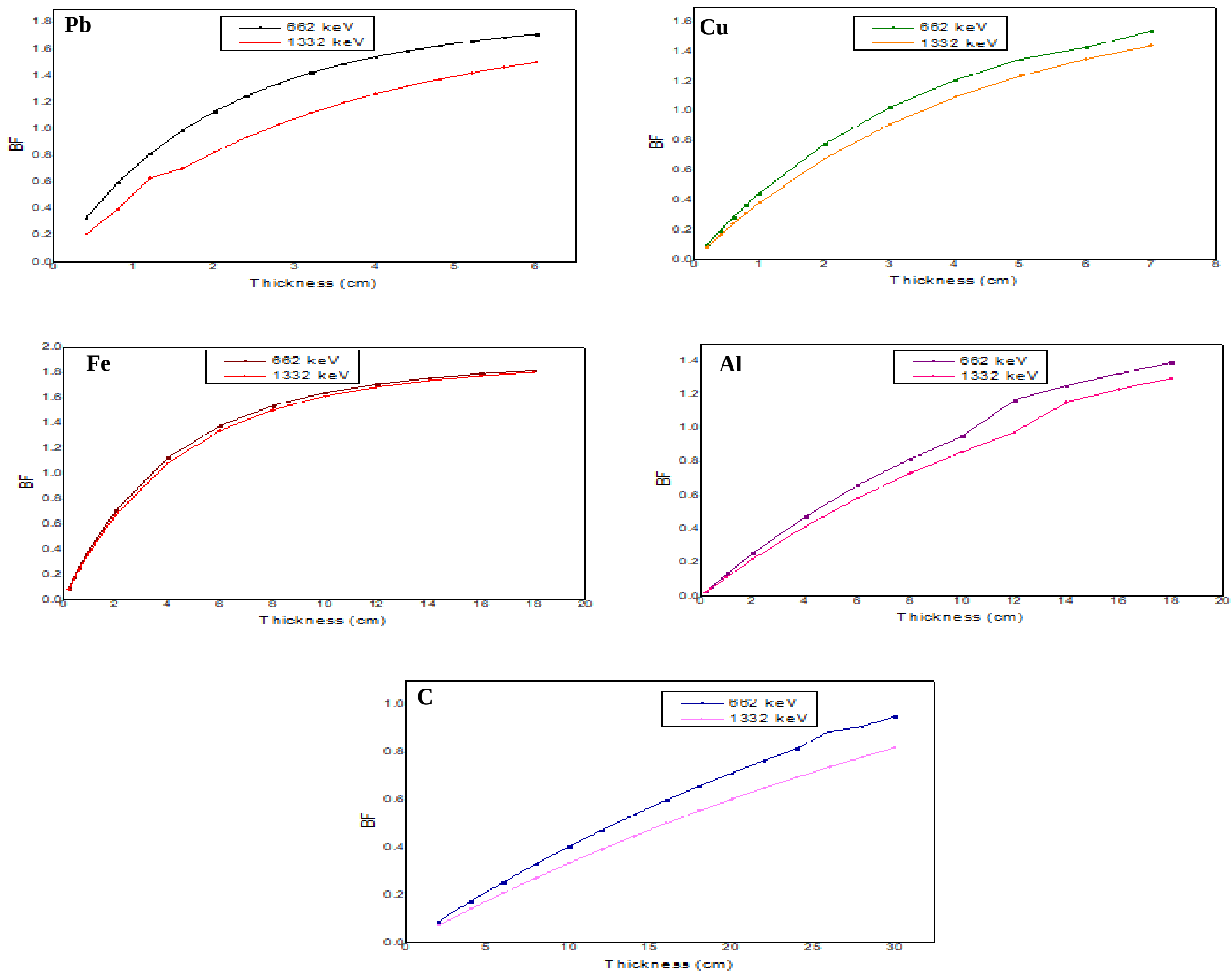

Fig.5: Variation of buildup factor with the thickness of (a) lead (b) copper (c) iron(d) aluminium and (e) carbon at 662 keV and 1332 keV of gamma radiations.

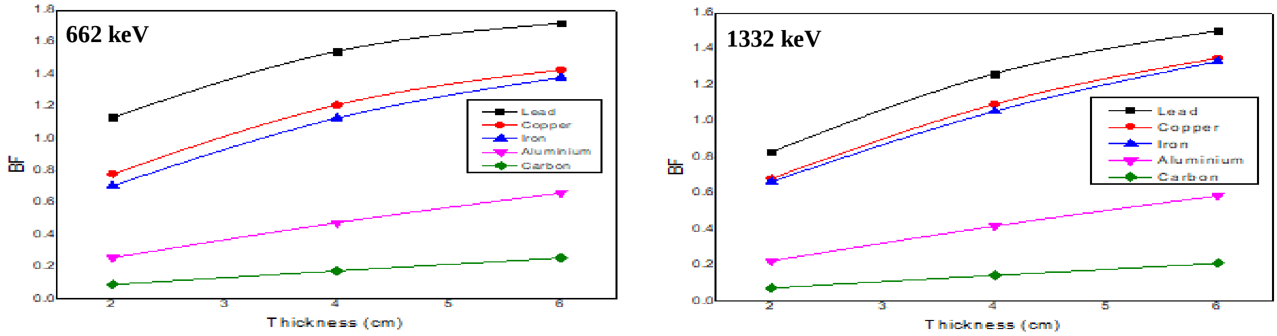

Fig. 6: Variation of buildup factor of lead, copper, iron, aluminium, and carbon at 662 keV and 1332 keV with the increased thickness of the material.

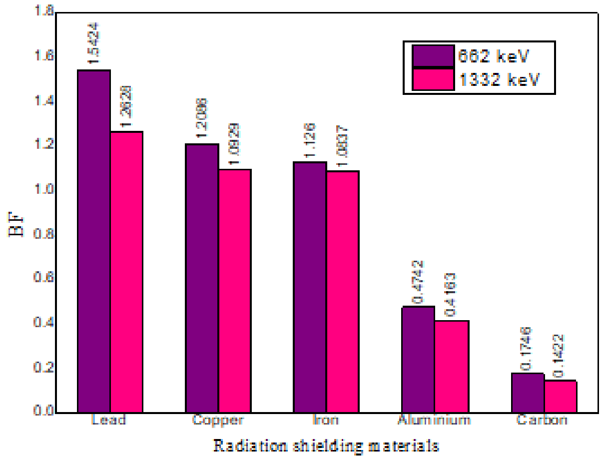

Fig. 7: Buildup factor at 4 cm thickness of different radiation shielding materials at 662 keV and 1332 keV.

Fig. 7 indicates the value of buildup factor is high at low energy (662 keV) and low at high energy (1332 keV) at 4 cm thickness of the radiation shielding materials. This is due to the fact that at the intermediate energy range of 0.15 -0.8 MeV, the buildup factor values are high for a given penetration depth due to the dominance of the Compton effect. This contributes to the degradation of photon energy and fails to remove a photon completely. Because of multiple scattering of photons, they exist for a longer time in a material, which leads to a higher value of the buildup factor. Further, at energies greater than 1MeV, the pair production process dominates over the Compton effect and hence the buildup factor values decrease at higher energies [12,13]. Also, it was observed that the value of buildup factor is nearly equal to unity, indicating the good geometry of the experimental setup. This is due to the dominance of absorption over the scattering of gamma photons [14,15].

5. Conclusion

The linear attenuation coefficient "μ" and the buildup factor "B" of some conventional shielding materials like lead, copper, iron, aluminium and carbon were evaluated at 662 keV and 1332 keV gamma radiations. It was found that both the values of "μ" and "B" increase with the increase in density and the atomic number of the material, and decrease with the increase in the energy of the gamma-rays. Further, it was found that 'B' increases with the thickness of the shielding material, and its value is nearly equal to unity, which indicates the good geometrical arrangement was used for the study. These results conclude that among the conventional shielding materials used for the study, lead is a good shielding material, whereas carbon has a feeble shielding ability, and hence it proves the shielding performance of the material depends on its atomic number and density.

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