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Effect of Bismuth Ratios on the Gamma Shielding Properties for NBR/Nano Silica Composites

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Abstract: The effect of the different ratios of bismuthon Nitrile Butadiene Rubber (NBR)/nano silica composite as shielding materials are studied in this study. And the study was carried on for gamma ray photon energies (0.3, 0.6, 1.25, 3 and 7) MeV obtained by (^{131}Ir, ^{60}Co and ^{137}Cs) radioactive sources by using MCNP5, WINXCOM and Matlab. The numerical simulation results showed that, the shielding properties (Linear and mass attenuation coefficients, Transmission factors, Half value layer and radiation protection efficiency) of the composite materials increase with increase in the bismuth ratio and decreases with increase in energy. Also the results show that, Half-value layer (HVL) decrease with increase in the Bismuth ratio and increase with increase in gamma photon energy. It is found that the optimum concentration of Bismuth is 60%. The results confirm that rubber composites loaded with bismuth can act as an excellent gamma radiation shielding materials.

Keywords: MCNP5, WINXCOM, Nano Silica, NBR, Bismuth

1. Introduction

Nowadays, it is an important issue to study radiation protection properties and new materials. This potential risk can be overcome by three main procedures: time, distance and shielding. The third has been allowing new materials usage and various investigations for better radiation protection. The shielding method is related to gamma ray energy and charge of related material [1]. By comparison with some other shielding materials used in radiation areas,

Gamma ray shielding performance could be achieved with composite materials comprising a polymer matrix filled with materials, So the field of gamma ray shielding, polymeric materials such as silicone rubber composites are going to replace the ordinary shielding materials (concrete shields and developed glass) because of their great properties (elasticity, light weight, durability) [2, 4]. Nowadays, silicone rubber is used in a large variety of applications because it has low density, large degree of flexibility, thermal resistance, radiation resistance... etc. [5]. Usually silicon rubbers to get flexible radiation protective materials and it are one of the matrix materials which have good elasticity properties [6]. It has relatively cheap production cost [7]. Nowadays, for shield designs, gamma ray was one of the main types of nuclear recently; there was a continuous demand for improved polymers for use as shielding materials [8-9].

In nuclear applications such as γ-radiation shields, Polymer nanocomposites have been gaining considerably attention both in academia and in industries, due to their outstanding mechanical properties such as high elastic stiffness and strength with a small concentration of nanomaterial. The other excellent properties of polymer nanocomposites are barrier resistance, flame retardancy, wear resistance, magnetic, electrical and optical properties. In nuclear applications such as γ-radiation shields, rubber nanocomposite are used in a large variety of applications because it has low density, large degree of flexibility, thermal resistance, radiation resistance... etc. [10]. Silica nanocomposites have been attracting some scientific interest as well due to the advantage of low cost of production and in the high performance features. Polymer silica nanocomposites had shown drastic enhancement in mechanical properties (modulus & tensile strength), thermal properties (heat resistance & flammability) and barrier properties [11]. Elham et al [11] studied the effect of NBR rubber as dispersion media to disperse the nanosilica in NBR matrix using conventional mixing techniques. They studied the effect of Nanosilica and high gamma radiation on mechanical and thermal properties of polymer nanocomposites. The dispersion of the silica nano particle in the rubber matrix was studied using scanning electron microscopy (SEM) and also by FTIR.

The MCNP (-4B or -4C) code has been popular in simulating radiation attenuation of various materials and aggregates. Using the MCNP code, Sharifi et al. [12] simulated shielding properties of some materials and compared the results with experimental results; Shirmardi et al. [13] studied attenuation properties of barite concretes and lead by comparing the simulation results with XCOM and experimental data; and Singh et al. investigated massattenuation coefficient for some polymers by using Monte Carlo method [14]. The MCNP-X code, and other codes, can be applied to predict the mass attenuation coefficients for different attenuator and energies and can be an alternative method for experimental method, due to their flexibility and convenience in defining geometry [15].

In this study, gamma shielding properties of five NBR/nanosilica composite [11] based material reinforcement with different ratios of bismuth (Bi) (0%, 20%, 40%and 60% w) have been studied. The samples are square shaped (3×3cm), in certain thicknesses from 1 to 7 cm. The shielding properties of the nanosilica rubber/Bismuth composite (linear Attenuation coefficient (μ) and total mass attenuation coefficient (μ/ρ)) have been evaluated using three radioactive point sources (^{131}Ir, ^{60}Co and ^{137}Cs) in the energy range (0.2 - 7 MeV). The simulation of radiation attenuation is performed using MCNP5, Win WINXCOM and Matlab.

Bismuth was selected as the reinforcement by looking into its potential properties such as high density, high melting point and low conductivity. Then, the gamma ray attenuation coefficients as a function of different gamma ray energies and filler concentrations were investigated.

2. Methodology

2.1. MCNP-5 Simulation Code

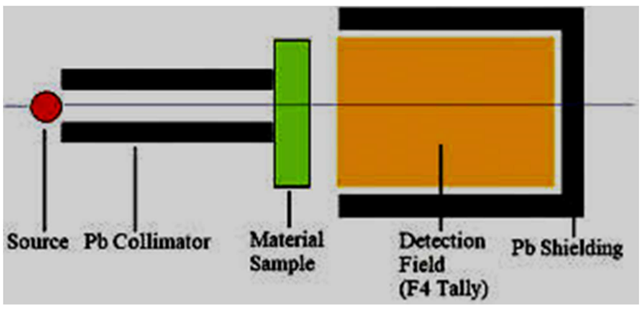


Figure 1. *(Color online) Schematic view of the MCNP-X simulation geometry.*

MCNP5 is a general code used for modeling interactions of radiations with materials and tracking all particles at all energies. Being fully three dimensional, it utilizes extended nuclear cross-sectional libraries and uses physics models for particle types [16]. Initially, we modeled the same geometric data as the experiment which the figure 1 shows schematically the modeled geometry for the simulation using MCNP5. The gamma rays are collimated by the lead shielding, attenuated by the sample of the NBR/nanosilica/Bismuth, collimated again and detected by the detector.

2.2. Validation of MCNP-5

To confirm a validation of modeled MCNP-5 simulation geometry, the mass attenuation coefficients for composite with ratios 20% w of bismuth were calculated at energy between (0.662 – 2.5) MeV. Figures 5 and 6 showed the results of compared between WINXCOM, MCNP5 software simulation and Matlab for silicon rubber/Bi and nanocomposite/Bi respectively. Win XCOM program is a user friendly calculation program and input parameter specifications are quite flexible and easy to access. In the Win Xcom program, firstly, shielding material types were defined by their elemental mass fractions.

3. Materials Specification

Elemental composition of NBR nanocomposite/Bi depends mainly on the mix proportions and chemical composition of the materials. By using WINXCOM to calculate the elemental atomic fraction as shown table 1 presents the atomic fraction of hydrogen, carbon, oxygen, silica and Bismuth with the total densities from ~1.7929 g/cm^3 to ~6.564 g/cm^3 defining the input materials in simulation

Table 1. *The elemental atomic fraction by weight of the nanocomposite / Bisamples.*

Element	Sample1	Sample2	Sample3	Sample4
	Bi=0	Bi=20%	Bi=40%	Bi=60%
H	0.039605	0.031684	0.023763	0.015842
C	0.283167	0.226534	0.169900	0.113267
N	0.110073	0.088058	0.066044	0.044029
O	0.12573	0.100586	0.075439	0.050293
Si	0.441423	0.353138	0.264854	0.176569
Bi	-----	*0.2*	*0.4*	*0.6*

3.1. Linear Attenuation Coefficient

Linear attenuation coefficient is the simplest parameter which is being used to measure experimentally the absorbing ability of any material for the incident radiation. It is defined as the probability of a gamma photon interacting with a material medium per unit path length Gamma rays interact primarily with atomic electrons. The linear attenuation coefficient [μ] of samples has been determined by the usual attenuation equation:

$$I = I_o\, e^{-\mu x} \quad (1)$$

Where I is the gamma ray intensity after the shield material, I_o is the gamma ray intensity before the shield material, μ is the attenuation coefficient factor and xis the thickness of the absorbing medium, for photons in an attenuating medium.

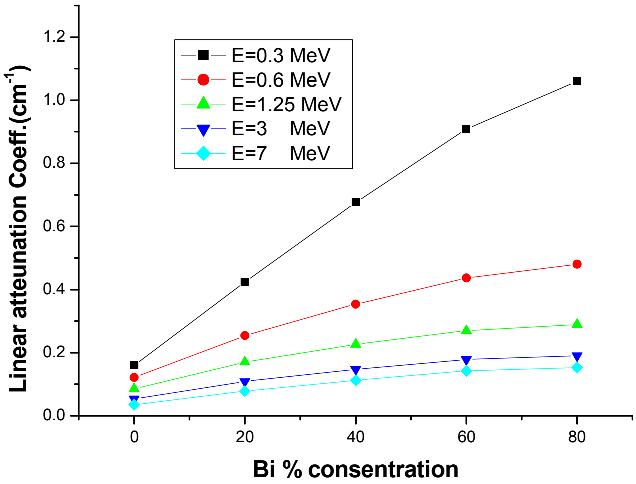


Figure 2. *Linear attenuation coefficent of nanocomposite with different ratios of Bismuth.*

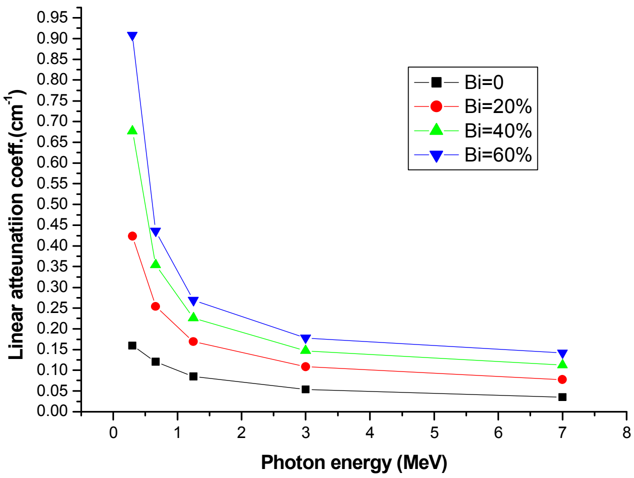


Figure 3. *Linear attenuation coefficent of nanocomposite/Bisamples versus Incident Photon Energy.*

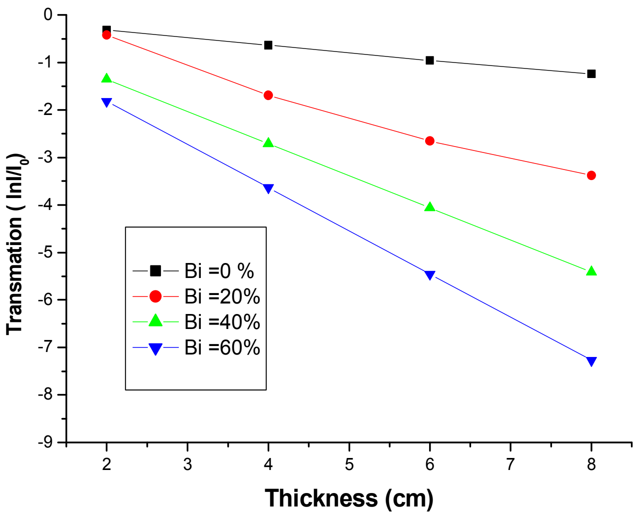


Figure 4. *The variation of Transimation of nanocomposite/Bi samples versus thickness at 0.33 MeV.*

Theoretical linear attenuation coefficients as a function of γ-ray energies for all samples are illustrated in Figures 2, 3 has been observed. Figure 2 shows the energy lines of gamma rays which emitted from 0.225 MeV-7 MeV it is observed that The linearattenuation coefficients increase linearly with increasing Bi content, Figure 3 shows that the linear attenuation coefficient decrease by increasing the energy of gamma rays for all composition under this investigation. The observed behavior of linear attenuation coefficients is attributed to the high atomic number of bismuth which leads tohigh absroption gamma ray. Figure 4 shows that the transimation of 0.33 MeV of gamma radiation is deacrasing linearty with increasing the thickness and also deacrasing with increasing Bi, concentration.

3.2. Mass Attenuation Coefficient

Mass attenuation coefficient is another shielding parameter which is essential to compare the shielding ability of various materials. It is defined as the probability of gamma photon interacting with the medium per unit mass of the absorber. It is independent of density and was obtained by dividing the linear attenuation coefficient with the density of the material. The mass attenuation coefficient [μ_m] determined by the equation:

$$\mu_m=\mu/\rho \ (cm^2/gm) \quad (2)$$

whereμ: linear attenuation coefficient and ρ: density of the material

Figures 5, 6 show the variation of mass attenuation cofficient of silicon rubber with 20% Bismuth andnanocomposite sample with 20% Bi versus Incident Photon Energy by WINXCOM, MCNP5 software simulation and Matlab respecively. And it is a goodagreement between all theoretical calculations has been observed at the energy range from 0.662 – 2.5 MeV.

Figure 7 shows the variation of mass attenuation coefficient nanocomposite sample with 20% Bi (as optimum ratio) versus Incident Photon Energy by WINXCOM, MCNP5 software simulation and Matlab.

The mass attenuation coefficients decrease with increasing gamma energies, and the MCNP-5 simulation results almost agree with the WINXCOM and Matlab results.

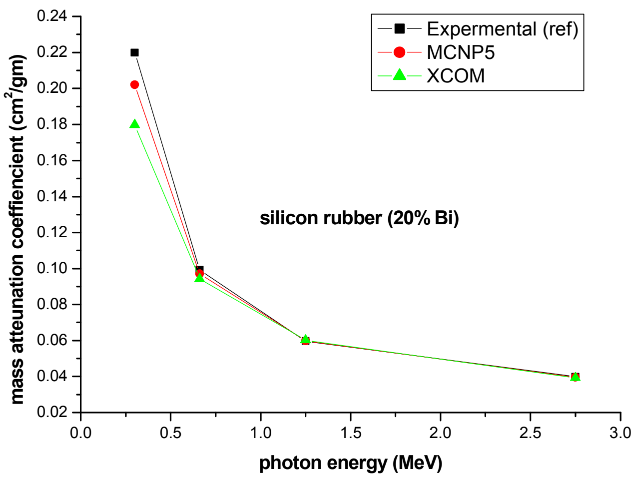


Figure 5. *Mass attenuation cofficient versus Incident Photon Energy of silicon rubber with 20% Bismuth.*

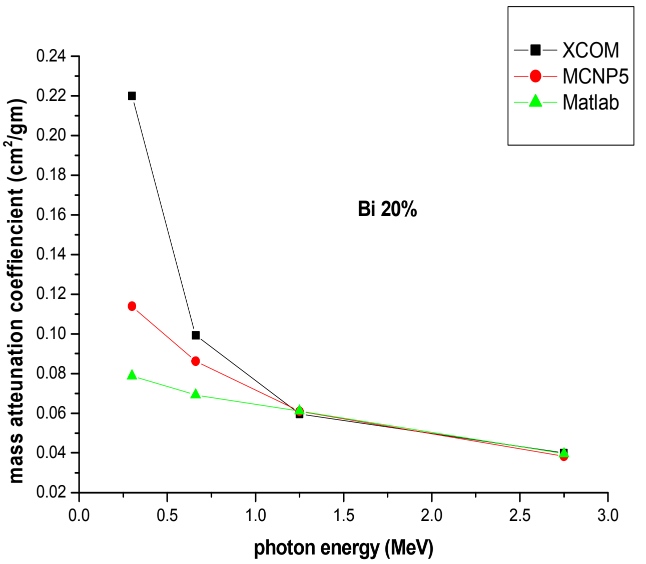


Figure 6. *Mass attenuation cofficient versus Incident Photon Energy of nanocomposite sample with 20% Bi.*

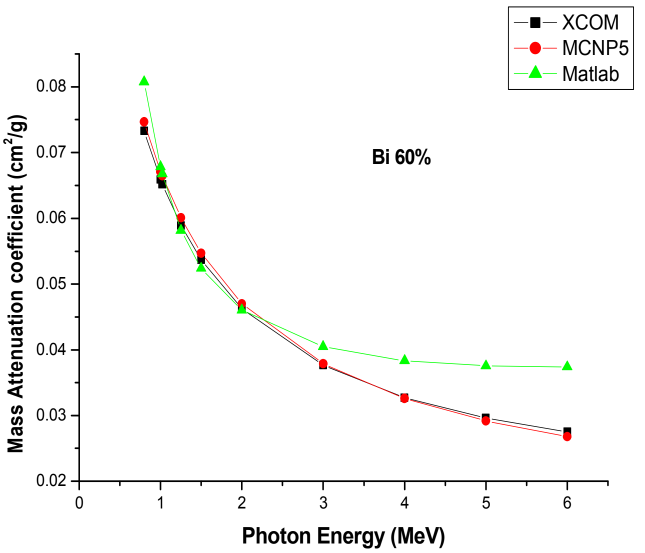
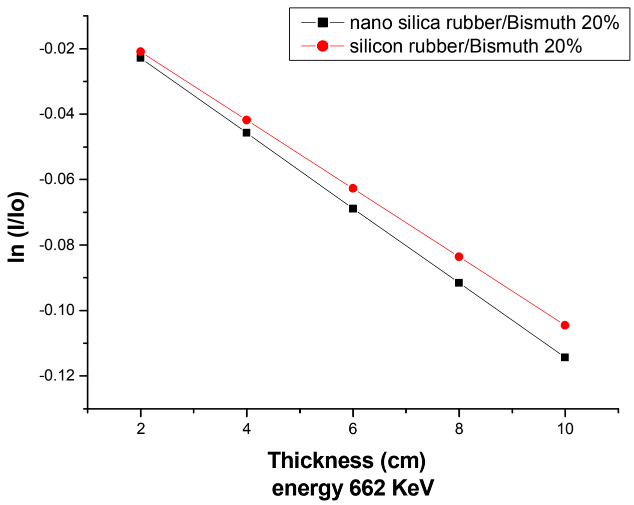


Figure 7. *Mass attenuation cofficient versus Incident Photon Energy of nanocompsite sample with Bismuth 60%.*

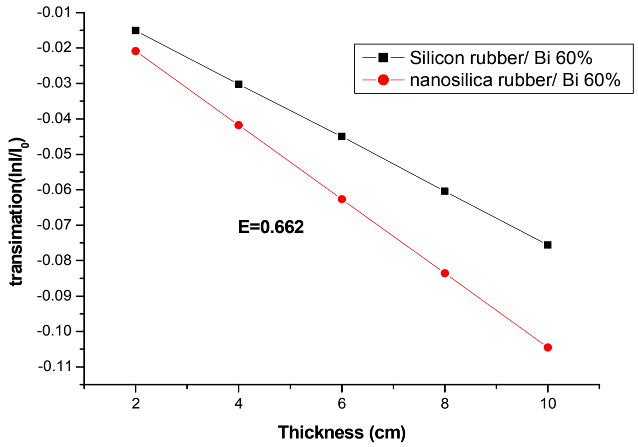
3.3. Transmission Factor

By using MCNP-5, we simulated the transmission factors for selected gamma rays (0.662 MeV) as a function of compositesthickness figure 8.

figure 8a, bshowthe comparison oftransimation factorby MCNP5 for nanocomposite/Bi and silicon rubber/Bi with 20% and 60%w Bismuth respectivly. figure 8a is observed that the transmitionfactorof nanosilica rubber/Bi 20% is better than silicon rubber. And the thickness of 4 cm of the proposed compound may reduce up to 10%. Also from figure 8b is observed that when the consentation of Bi is increasing thenanocopposite/Biis better asgamma shielding material thansilicon rubber/Bi composite. And 25% of 0.662 MeV gamma-rays in comparison with the same thickness of silicon rubber/Bi (60%). The best results have been observed at 60 wt. % of Bismuth.



(a)



(b)

Figure 8. *(a) Transimation of 0.66MeV gamma radiation by MCNP5 for nanocomposite rubberand silicon rubber; (b) Transimation factor for nanocomposite rubber and silicon rubber.*

3.4. Radiation Protection Efficiency (Rp)

The radiation protection efficiencies of the investigate samples of the material are Calculated by using the following equation:

$$Rp=(1-I/I_0)\times 100 \quad (3)$$

Figure 9 Shows a new radiation shielding composite material showed the best efficiency against Ir-131 (0.364 MeV average energy) and after that against Cs-137 (0.662 MeV average energy) and the last efficiency against Co-60 (1.25 MeV average energy), for the same distance. The shielding efficiencies of the entire composites showed big difference. Hence it is observed that the Bismuth Nano silica rubber composite is a more effective shield for the source Ir-131 has higher shielding gamma energy when compared with Cs-137 and Co-60 sources, so, it shows a weakness against high energy gamma rays because of secondary radiation.

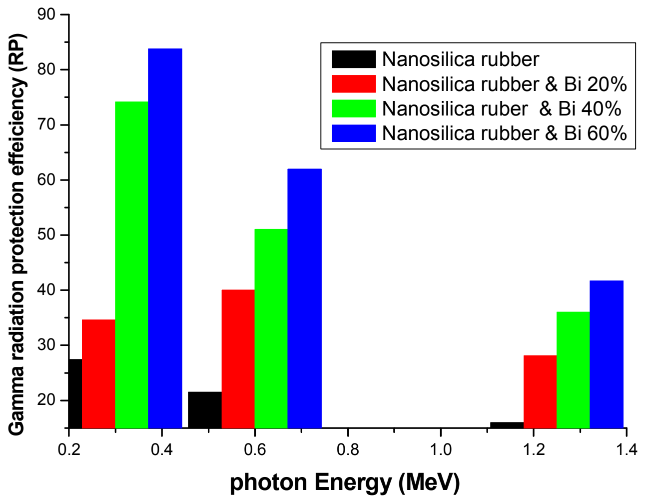


Figure 9. *Radiation Protection Efficiency versus Incident Photon Energy for nanocomposite/Bi samples.*

3.5. Half-value Layer (HVL)

It is useful to express the attenuation of gamma-ray in terms of another quantity which is the half-value layer (HVL). The HVL is the thickness, at which the transmitted intensity is 50% of the initial intensity. The HVL reflects the fact that energetic photons have a capability to penetrate the material as photon energy increases. The HVL for the present composite materials with different concentration of Bi can be calculated using the following equation:

$$HVL=\frac{\ln(2)}{\mu} \tag{4}$$

Where μ is the linear attenuation coefficient.

Figure 10 Shows that when, the concentration of Bi is increasing, the thickness is decreasing, and also when the energy is increasing the HVL is increasing.

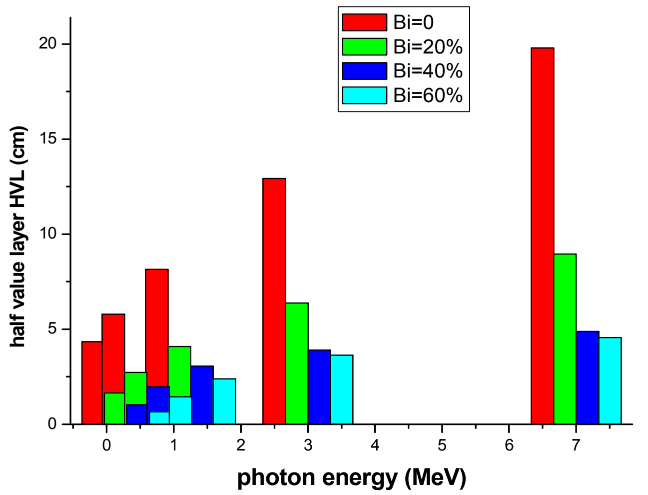


Figure 10. *Half value layer versus Incident Photon Energy for nanocomposites/Bi.*

The use of bismuth in the present composites has advantages. The effects of bismuth have been investigated by different groups. Ambikaet al. [17] the attenuation coefficient increases with increase in the filler wt% and decreases with increase in the gamma photon energy. El-Fiki et al. [18] reported that the bismuth silicone rubber can attenuate gamma ray and has a significant improvement in its mechanical properties and can replace lead that has high toxicity. Considering the bismuth's advantages on radiation protection, this study investigated the effect of bismuth on radiation attenuation properties of NBR/nanosilica composite, confirming that bismuth added to rubber composites, with enhanced radiation attenuation properties, are suitable material for gamma irradiation Shielding.

4. Conclusion

Linear and mass attenuation coefficients, Transmission factors, HVL for Nano silica rubber filled with bismuth content at different concentrations at the energy range from 0.662 – 2.5 MeV gamma ray energies were simulated and calculated using MCNP-5, Win Xcom and Matlab program. HVL results were found to decrease with increase in the Bismuth wt% and increase with increase in the gamma photon energy. It was found that, the nano silica rubber is better 10% -25% than silicon rubber foradding Bi filler to improve the shielding properties. So this study confirming that bismuth added to rubber composites are suitable material for gamma irradiation shielding and bismuth can replace lead that has high toxicity.

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