GAMMA-RAY ATTENUATION CHARACTERISTICS OF POLYPROPYLENE FILLED WITH NANO-SIZED AND BULK Bi_2O_3 AND CuO

Mona M. GOUDA [1], ***Mona SHEBLY*** [2], ***Khulud HABANJAR*** [2], ***Amro OBEID*** [2,3], ***Ramadan AWAD*** [1,4], ***and Mohamed S. BADAWI*** [1,5*]

[1] Physics Department, Faculty of Science, Alexandria University, Alexandria, Egypt
[2] Department of Physics, Faculty of Science, Beirut Arab University, Beirut, Lebanon
[3] Lebanese Atomic Energy Commission, National Council for Scientific Research, Beirut, Lebanon
[4] Department of Basic Sciences, Faculty of Computer Science and Artificial Intelligence, Pharos University in Alexandria, Alexandria, Egypt
[5] Faculty of Science, Alamein International University, Alamein City, Matrouh Governorate, Egypt

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Polypropylene was produced using compression molding and combined with bulk Bi_2O_3/CuO, and Bi_2O_3/CuO nanocomposites at various filler weight fractions (0 %, 5 %, 10 %, 15 %, and 20 %). Gamma-ray energies from four radioactive sources (241Am, 133Ba, ^{137}Cs, and ^{60}Co), ranging from 59.53 keV to 1332.5 keV, were used to evaluate the radiation attenuation capabilities of the new PP/Bi_2O_3/CuO polymer composite. Parameters such as the mass attenuation coefficients, total molecular cross-section, effective atomic cross-section, total electronic cross-section, electron density, effective atomic number, half-value layer, tenth value layer, and relaxation length were examined. The results underscored the significant influence of both the size and weight fraction of Bi_2O_3/CuO fillers on the gamma-ray shielding ability of the polypropylene composite, particularly at lower gamma-ray energy levels. Pure lead, a traditional and widely used shielding material, was used as a reference to assess the effectiveness of the polypropylene composite's half-value layer. Polypropylene composites incorporating nano-sized Bi_2O_3/CuO exhibited notable improvements in attenuation parameters, highlighting their potential for radiation protection and gamma-ray shielding applications.

Key words: polypropylene composite, Bi_2O_3/CuO nanocomposite, attenuation parameter, radiation protection

INTRODUCTION

Radiation in its various forms has become widespread, especially in essential daily applications such as industry and medicine. However, its constant use brings serious hazards, urging researchers to focus on developing and implementing effective radiation protection and shielding properties. Such hazards affect humans and the environment alike, depending on the time, distance, and protection from the radiation source [1]. However, it is undeniable that the benefits of radiation outweigh the risks, especially when used safely and shielded appropriately. The more protected people are from radiation through appropriate shielding material, the more benefits we could gain from radiation, including gamma rays, and the lower the health and environmental risks will become. Hence, researchers have designed shields that can absorb high energy to protect humans from these hazardous radiations depending on their chemical and physical [2], structural and nuclear properties, and the characteristics of the radiation affecting them.

Lead, a metal with high density and atomic number, has been the most common material used for attenuating higher quantities of generated gamma rays. However, it makes for a rather impractical shielding material as it is toxic[3], heavyweight, chemically unstable, and has limited mechanical properties. Therefore, there is a growing trend towards replacing traditional fillers with inorganic micro- and nano-filler-reinforced polymer composites, such as epoxy, polyethylene, polyester, and polyimide. These composites offer a safer, more cost-effective, lighter, and more flexible alternative. Additionally, they are chemically stable and possess beneficial physical and radiation properties. They also have high plasticity and are easily shapeable during the reinforcement process, which involves combining them with high-density materials due to their low atomic number. Due to these reasons, oxides, including bismuth oxide and copper oxide, are generally considered better shielding material against gamma rays than lead [3]. Micro and nano-fillers can be created using various metal oxides, such as PbO, Bi_2O_3, and WO_3. These metal oxides' high density al-

* Corresponding author, e-mail: ms241178@hotmail.com

lows the polymer composite to significantly improve its radiation shielding ability by offering uniform dispersion and a larger surface/volume ratio of the filler at the nanoscale [4-8].

Several nanocomposite materials/polymers have been developed and improved by researchers such as Kunzel and Okuno [9] investigated polymeric resin incorporating copper oxide (CuO) particles at 5 %, 10 %, and 30 % in both micro- and nano-sizes. The findings indicated that the effectiveness of the CuO-resin composites was higher with nano-sized particles compared to micro-sized particles. Additionally, during another research study, high-density polyethylene (HDPE) was blended with micro and nano-sized cadmium oxide particles to reduce photon beams with energies between 59.53 keV and 1408.01 keV. The researcher's findings suggested that incorporating nanoscale-reinforced HDPE improved the overall shielding effectiveness, especially at lower photon energies [10]. A study by Alyaa H.[11] examined the effectiveness of a nanocomposite material, consisting of ultra-high molecular weight reinforced with varying concentrations of Bi_2O_3, in shielding against gamma radiation. The findings indicated that the shielding capabilities of the synthesized composites improved as the bismuth oxide concentration increased. It was observed that the polymer containing 2.0 % Bi_2O_3 demonstrated higher efficiency in attenuating photons.

Another promising and effective shielding material is polypropylene (PP), a well-known thermoplastic [12] polymer with applications in various fields, such as plastic packaging, medicine, and electrical industries. One of the main reasons for its wide use is that polypropylene is a hydrocarbon polymer- as it consists substantially of carbon atoms, it is capable of effectively mitigating the effects of radiation. Moreover, polypropylene has excellent tensile strength and temperature resistance [13-16], making it a favorable choice for experiments. Overall, the capabilities and efficiency of polymer nanocomposites are dependent on various factors including filler type, the filler weight fraction to the matrix, the conditions set, and the synthesis procedure. This research project aims to design new composite materials by choosing PP as a matrix due to its high-pressure resistance and superior mechanical properties, where Bi_2O_3 and CuO bulk and nano-composites were selected as a filler with different weight fractions (0 %, 5 %, 10 %, 15 %, 20%) micro and nanocomposite due to their potential properties such as ability in their potential properties, including their high melting point and the ability to be turned into fine powder. The compression molding technique was used to create the polymer composites, while the mechanical ball mill approach was used to prepare the nanocomposite. At gamma-ray energies of 59.53 keV, 356.01 keV, 661.66 keV, 1173.23 keV, and 1332.5 keV, the radiation attenuation parameters of the PP/(Bi_2O_3/CuO) composite were examined to assess the impact of (Bi_2O_3/CuO) fillers' size and weight fraction on the easily and inexpensively made polymer nanocomposite materials. The outcome of this investigation will not only demonstrate the potential for these new composite materials to be further developed for radiation shielding applications. It will also provide valuable prospects for creating new, safe, and effective gamma-ray protective PP nanocomposites.

EXPERIMENTAL

Materials

A commercial sample of polypropylene was obtained from Egyptian Propylene and Polypropylene Company under the trade name (FM525J) with a density of 0.9 gcm^{-3} and a Melt Flow Index (MFI) of 3 g per 10 min was used as a matrix in this study. Microparticles of bismuth oxide were collected from Sigma Aldrich, Spain in powder form (purum 98 %) with a molecular weight (MW) of 465.96 $gmol^{-1}$ and a density of 8.9 gcm^{-3} . In addition, copper oxide (cupric oxide) was obtained by the same company- Sigma Aldrich, China- as a powder (<10 μm and purity 98 %). It has a density of 6.31 gcm^{-3} and an MW of 79.55 $gmol^{-1}$. Both Bi_2O_3 and CuO were used without further purification.

Bi_2O_3 and CuO nanocomposite preparations

To start the preparation method of Bi_2O_3 or CuO, A mechanical method designated by a high energy planetary ball mill (Retch, PM 100) was used in a dry state for 60 min with the following conditions: the ball to powder weight ratio was 10:1 and the milling speed was set at 400 (revolutions per minute), where the milling was stopped for 1 min every 20 min to cool down the system. The sizes obtained for Bi_2O_3 and CuO were 74.30 nm and 14.30 nm, respectively.

Bi_2O_3 -CuO bulk /nanoparticle mixture preparations

To ensure homogeneity for both bulk and nano-mixtures, commercial or the obtained nano Bi_2O_3 (70 %) and CuO (30 %) were used. They dispersed in pure ethanol under stirring for around 60 minutes. The solvent was evaporated at 60 °C during stirring.

Polymer composite synthesis

The compression molding process was used to create PP composites with filler weight fractions of 0 %, 5 %, 10 %, 15 %, and 20 % of (Bi_2O_3/CuO) Bulk (B) and (Bi_2O_3/CuO) NP(N). The categories, names, and descriptions of the samples are displayed in tab 1. After weighing, the PP pellets were added to XK400 two-roll

Table 1. Category, name, and descriptions of samples

Category	Name	Descriptions
PP	PP	Polymer without reinforcement
Polymer Composites of pure Composites (Bi_2O_3/CuO) as received	5 wt % (Bi_2O_3/CuO) Bulk(B)	PP filled with 5 wt % of (Bi_2O_3/CuO) Bulk(B)
	10 wt % (Bi_2O_3/CuO) Bulk(B)	PP filled with 10 wt % of (Bi_2O_3/CuO) Bulk(B)
	15 wt % (Bi_2O_3/CuO) Bulk(B)	PP filled with 15 wt % of (Bi_2O_3/CuO) Bulk(B)
	20 wt % (Bi_2O_3/CuO) Bulk(B)	PP filled with 20 wt % of (Bi_2O_3/CuO) Bulk(B)
Polymer Composites of Composites (Bi_2O_3/CuO) milled for 60 min	5 wt % (Bi_2O_3/CuO) NP(N)	PP filled with 5 wt % of (Bi_2O_3/CuO) NP(N)
	10 wt % (Bi_2O_3/CuO) NP(N)	PP filled with 10 wt % of (Bi_2O_3/CuO) NP(N)
	15 wt % (Bi_2O_3/CuO) NP(N)	PP filled with 15 wt % of (Bi_2O_3/CuO) NP(N)
	20 wt % (Bi_2O_3/CuO) NP(N)	PP filled with 20 wt % of (Bi_2O_3/CuO) NP(N)

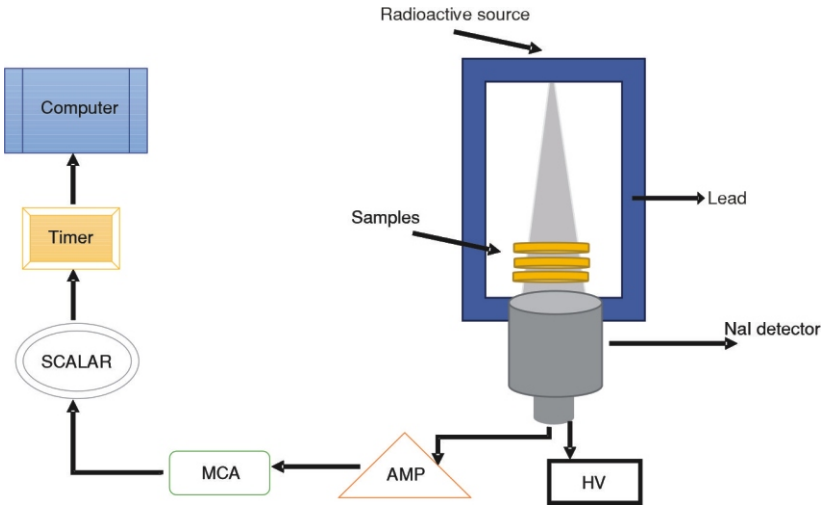

Figure 1. The experimental work's illustration setup

mill mixers. The mixer was then set to 40 rpm and heated for 15 minutes at a temperature of 190 °C. To prevent clumping, specific volumes of either (Bi_2O_3/CuO) Bulk(B) or (Bi_2O_3/CuO) NP(N) were introduced to the mixing chamber. Once the polymer matrix was fully melted, the prepared samples were shaken after ten minutes to ensure thorough and even mixing. The samples, along with a Teflon layer, were placed in a rectangular stainless-steel mold measuring 25 cm × 25 cm × 0.3 cm to achieve a smooth surface. Subsequently, a 10-minute hot press was conducted at 8 MPa and 190 °C. The pressure was then gradually increased to 15 MPa for 10 minutes. The formed composite sample was then progressively cooled with water at a rate of 20 °C per minute until it reached room temperature. Thus, a pure PP sample was produced without adding (Bi_2O_3/CuO). Each prepared sheet was then divided into five disk samples, each with a diameter of 8.3 cm, to examine their gamma radiation shielding properties.

Measurements of gamma-ray attenuation coefficients

Gamma-ray attenuation measurements were conducted at Alexandria University's Radiation Physics laboratory. Figure 1 outlines the setup using a scintillation NaI detector [17]. The gamma-ray spectrometry system includes a high voltage (HV) power supply for detector operation, a preamplifier to reduce noise and shape the pulse induced by fluctuations, and an amplifier to enhance the signal, sometimes over 1000 times. Additionally, a timer is connected to the scalar to record pulses, ensuring optimal time interval control and management. These components interface with ISO 9001 Genie 2000 software for analysis. Radioactive sources (^{241}Am, ^{133}Ba, ^{137}Cs, and ^{60}Co) were procured from the Physical-Technical Federal Institute (PTB) in Braunschweig and Berlin and measured at a 75 cm axial distance from the detector's front surface. Table 2 illustrates the emitted energies that specify the sources [18-21].

The sample was positioned on a holder between the source and the detector, and the gamma-ray generated during experimental measurements was added. This repeated process involved sequentially adding five different thicknesses of the sample with the same composite, and then the detected spectra were analyzed using Genie2000 software. The net area beneath each characteristic peak was highlighted and measured to determine the count rate (N). To ensure statistical reliability with less than 1 % uncertainty, the acquisition time was adjusted until at least 20000 counts were registered beneath the full-energy peak. Sources were placed far from the detector surface to mitigate counting rate, dead time, and pile-up effects.

Table 2. Photon energy of the used radioactive sources

Radioactive sources	Photon energy [keV]
^{241}Am	59.53
^{133}Ba	356.01
^{137}Cs	661.66
^{60}Co	1173.23
	1332.5

The best-fitting analysis of the plotted slope representing the linear relationship between ln [N] and the thickness of the disc specimens x (cm) was determined. The linear attenuation coefficient μ [cm^{-1}] [22] of each composite sample was then calculated

$$\mu \quad \frac{1}{x} \ln \frac{N_0}{N_x} \tag{1}$$

N_x and N_0 are the detector count rates with and without the composite sample.

Accurate measurements of the apparent density ρ of the prepared composite samples were performed using a calibrated balance (precision of 0.1 mg) and applying the following equations based on Archimedes' technique [23]

$$\rho \quad \frac{a}{a \quad w \quad b} \rho_w \tag{2}$$

where a is the apparent mass of the specimen weighed in the air without wire, b – the apparent mass of the specimen completely submerged in water and the wire partially submerged in water, is the apparent mass of the wire partially submerged in water, and ρ_w – the density of water (1.00 gcm^{-3}).

Dividing μ by the measured density of the composite sample ρ yields the value of mass attenuation coefficient μ_m (cm^{2}g^{-1}) by using the following equation [24, 25]

$$\mu_m \quad \frac{\mu}{\rho} \tag{3}$$

The theoretical values of the mass attenuation coefficients of the mixture or composite have been investigated by NIST XCOM standard reference databases and were used to obtain the theoretical values of the mass attenuation coefficients of the mixture or composite based on the mixture rule. The contribution of each element to the total interaction of the gamma-ray photon was taken into assumption. The following equation is then used to acquire the total mass attenuation coefficient [26]

$$\mu_m \quad \sum_i w_i (\mu_m)_i \tag{4}$$

where wi and $(\mu_m)_i$ represent the weight fraction and the mass attenuation coefficient of the constituent elements of the composite, respectively.

The equation used to determine the weight fraction is as follows

$$w_i \quad \frac{n_i A_i}{\sum_i n_i A_i} \tag{5}$$

where A_i and n_i are the atomic weight and the number of formula units of the it^{h} constituent element of the composite, respectively.

The values of the calculated theoretical density of the composite samples were calculated by [27]

$$\rho_T \quad \frac{100}{m_{\text{matrix}} / \rho_m \quad m_{\text{filler}} / \rho_f} \tag{6}$$

where m_{matrix} is the wt % of PP, m_{filler} – the wt % of Bi_2O_3/CuO, ρ_m – the density of PP, and ρ_f – the density of Bi_2O_3/CuO.

The obtained experimental values of the mass attenuation coefficient μ_m were compared to the theoretical values acquired using the NIST XCOM database.

The following equations are used to calculate the total molecular cross-section σ_{mol} (cm^2 per molecule) and the total atomic cross-section σ_{atm} (cm^2 per atom) [28]

$$\sigma_{\text{mol}} \quad \frac{(\mu_m)}{N_A} \sum_i n_i A_i \tag{7}$$

$$\sigma_{\text{atm}} \quad \frac{(\mu_m)_{\text{mix}}}{N_A \sum_i \frac{w_i}{A_i}} \quad \frac{\sigma_{\text{mol}}}{\sum_i n_i} \tag{8}$$

where N_A is the Avogadro constant (6.022 1367(36) × 10^{23} mol^{-1}).

The total electronic cross-section σ_{el} (cm^2 per electron) is obtained by

$$\sigma_{\text{el}} \quad \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} \frac{\mu}{\rho}_i \tag{9}$$

where Z_i is the atomic number of each element and f_i – the number of atoms relative to the total number of atoms of all elements in the mixture.

The effective atomic number Z_{eff} is related to σ_{atm} and σ_{el} as follows [29]

$$Z_{\text{eff}} \quad \frac{\sigma_{\text{atm}}}{\sigma_{\text{el}}} \tag{10}$$

The effective electron density N_{eff} (electrons per g × 10^{22}) is defined as the number of electrons per unit mass and obtained from [30]

$$N_{\text{eff}} \quad \frac{N_A}{\sum_i n_i A_i} Z_{\text{eff}} \sum_i n_i \tag{11}$$

The half-value layer (HVL) is defined as the thickness of a material needed to reduce the intensity of the incident radiation to half of its original value. The tenth-value layer (TVL) is the thickness required to reduce the intensity to one-tenth of its original value [31]. They are calculated using the following equations

$$HVL \quad \frac{\ln 2}{\mu} \quad \frac{0.693}{\mu} \tag{12}$$

$$TVL \quad \frac{\ln 10}{\mu} \quad \frac{2.3026}{\mu} \tag{13}$$

The relaxation length, also known as the mean free path and defined as the average distance traveled by a gamma photon [31] during different collisions with the medium's atoms, can also be used to understand the shielding feature of a material. The measurement was conducted utilizing relation

$$\lambda \quad \frac{1}{\mu} \tag{14}$$

where μ is the coefficient of linear attenuation coefficient.

RESULTS AND DISCUSSION

Linear attenuation coefficient (μ)

The linear attenuation coefficient (LAC) is a basic parameter used to experimentally measure the absorptive capacity of any material for incoming radiation. It is described as the probability of photon interaction by one physical process or another per unit distance [32]. The values obtained from experimentation, the calculated values μ using NIST XCOM databases, and the density values of PP, PP/(Bi_2O_3/CuO) Bulk(B), and PP/(Bi_2O_3/CuO) NP(N) composites at 59.53 keV, 356.01 keV, 661.66 keV, 1173.23 keV, and 1332.5 keV are compiled and displayed in tab. 3.

The primary interaction of gamma rays occurs with atomic electrons. Consequently, the linear attenuation coefficient is directly linked to the electron density, which is in turn proportional to the bulk density ρ of the absorbing material. The density of the polypropylene sample is 0.9277 gcm^{-3}, while the bulk composites range from 0.9692 to 1.1183 gcm^{-3} and the nanocomposites range from 0.9958 to 1.1507 gcm^{-3}. Increasing the weight percentage of the reinforcing material leads to a higher linear attenuation coefficient of the composites, attributable to their greater density. Conversely, the linear attenuation coefficient decreases with higher energy levels, as shown in tab. 3.

Mass attenuation coefficient μ_m

The mass attenuation coefficient (MAC) is a constant that is commonly used to evaluate how effective various materials are at absorbing and shielding from radiation. The concept can be described as the probability of the gamma photon interacting with the medium per unit mass of the absorber [32]. The value is not influenced by density and was calculated by dividing the linear attenuation coefficient by the material's density by using eq. 3. Table 4 summarizes the theoretically calculated values using NIST XCOM databases, experimentally obtained values, and experimentally values of PP,

Table 3. Density, linear attenuation coefficients, and theoretical values were measured using an XCOM database for pure PP, PP/Bi_2O_3/CuO(B), and Bi_2O_3/CuO(NP) composites

Sample	Energy [kev]	Linear attenuation coefficient μ			Density ρ [gcm^{-3}]	
		Bi_2O_3/CuO Nano	Bi_2O_3/CuO_3 Bulk(B)	X-COM	Bi_2O_3/CuO Nano	Bi_2O_3/CuO_3 Bulk(B)
Pure PP(0 wt %)	59.53	0.1770		0.1751	0.9277	
	356.01	0.1039		0.1055		
	661.66	0.0810		0.0816		
	1173.23	0.0624		0.0622		
	1332.5	0.0582		0.0582		
5 wt %(PP\Bi_2O_3/CuO)	59.53	0.3908	0.3434	0.3901	0.9958	0.9692
	356.01	0.1300	0.1151	0.1209		
	661.66	0.0937	0.0852	0.0888		
	1173.23	0.0692	0.0644	0.0674		
	1332.5	0.0646	0.0611	0.0630		
10 wt % (PP\Bi_2O_3/CuO)	59.53	0.6028	0.5211	0.6230	1.0412	1.0109
	356.01	0.1407	0.1233	0.1371		
	661.66	0.0996	0.0894	0.0963		
	1173.23	0.0727	0.0668	0.0728		
	1332.5	0.0669	0.0628	0.0679		
15 wt % (PP\Bi_2O_3/CuO)	59.53	0.8431	0.7075	0.7148	1.1047	1.0614
	356.01	0.1581	0.1362	0.1358		
	661.66	0.1073	0.0939	0.0943		
	1173.23	0.0773	0.0698	0.0698		
	1332.5	0.0706	0.0653	0.0652		
20 wt % (PP\Bi_2O_3/CuO)	59.53	1.1040	0.9268	0.9338	1.1507	1.1183
	356.01	0.1725	0.1494	0.1483		
	661.66	0.1113	0.0990	0.0997		
	1173.23	0.0802	0.0728	0.0731		
	1332.5	0.0728	0.0680	0.0683		

Table 4. Measured values of mass attenuation coefficients, relative increase rate, theoretical values of mass attenuation coefficients, and discrepancy for PP and PP composites

Sample	Energy [keV]	Mass attenuation coefficient [cm^2g^{-1}]				
		PP			XCOM	[%]
Pure PP (0 %)	59.53	0.1908			0.1888	1.053
	356.01	0.1120			0.1138	1.587
	661.66	0.0873			0.08802	0.807
	1173.23	0.0673			0.06708	0.270
	1332.5	0.0627			0.06283	0.153
Sample	Energy [keV]	Bi_2O_3/CuO_3 Bulk(B)	Bi_2O_3/CuO Nano	δ [%]	XCOM	[%]
5 wt % (PP/Bi_2O_3/CuO)	59.53	0.3543	0.3925	10.761	0.3504	1.120
	356.01	0.1188	0.1306	9.926	0.1185	0.221
	661.66	0.0879	0.0941	7.036	0.0883	0.441
	1173.23	0.0664	0.0695	4.581	0.0666	0.302
	1332.5	0.0630	0.0649	2.902	0.0623	1.048
10 wt % (PP/Bi_2O_3/CuO)	59.53	0.5155	0.5789	12.304	0.512	0.684
	356.01	0.1220	0.1351	10.783	0.1232	0.994
	661.66	0.0884	0.0957	8.159	0.0885	0.170
	1173.23	0.0661	0.0698	5.657	0.0662	0.223
	1332.5	0.0621	0.0643	3.421	0.0619	0.283
15 wt % (PP/Bi_2O_3/CuO)	59.53	0.6666	0.7632	14.490	0.6735	1.027
	356.01	0.1283	0.1431	11.524	0.128	0.253
	661.66	0.0885	0.0971	9.786	0.0888	0.451
	1173.23	0.0658	0.0700	6.399	0.0658	0.071
	1332.5	0.0615	0.0639	3.874	0.0615	0.022
20 wt % (PP/Bi_2O_3/CuO)	59.53	0.8287	0.9594	15.769	0.8351	0.762
	356.01	0.1336	0.1499	12.214	0.1327	0.672
	661.66	0.0885	0.0967	9.262	0.0891	0.712
	1173.23	0.0650	0.0697	7.066	0.0653	0.433
	1332.5	0.0608	0.0633	4.047	0.0610	0.434

PP/(Bi_2O_3/CuO) Bulk(B), and PP/(Bi_2O_3/CuO) NP(N) composites at 59.53 keV, 356.01 keV, 661.66 keV, 1173.23 keV, and 1332.5 keV. The table also presents the percentage discrepancy between experimental and theoretical values for PP composites, and the comparative rate of increase between the values of (Bi_2O_3/CuO) NP(N) and (Bi_2O_3/CuO) Bulk(B) composites by using the following eq. [33]

$$\delta \quad \frac{\mu_{\text{nano}} \quad \mu_{\text{bulk}}}{\mu_{\text{bulk}}} \; 100\,[\%] \qquad (15)$$

The PP/Bi_2O_3/CuO NP(N) composite showed higher values than its counterparts, as shown in tab. 4. This difference is primarily due to a greater concentration of Bi_2O_3/CuO fillers per gram in Bi_2O_3/CuO NP compared to bulk Bi_2O_3/CuO fillers. The discrepancy % values in the table indicate a close agreement between the experimentally measured and theoretically calculated values of μ_m for all PP composites, affirming the precise calibration of the measurement setup. The relative increase rate of δ % values suggests that the mass attenuation coefficient values of PP/Bi_2O_3/ CuO NP(N) composite are higher compared to PP/Bi_2O_3/CuO Bulk(B) composite at the same Bi_2O_3/CuO wt % and same investigated gamma-ray energy; the high surface-to-volume ratio of nanocomposite heightens the likelihood of gamma-ray interaction with the absorbing composite samples. Typically, densely packed atoms within the polymer matrix effectively attenuate the primary gamma-ray beam by increasing the probability of photon scattering processes [18]. Conversely, the PP/Bi_2O_3/CuO NP(N) composite demonstrates better gamma-ray absorption capabilities. Therefore, it holds potential as a better gamma-ray shielding material compared to PP/Bi_2O_3/CuO Bulk(B) composites across the entire range of studied gamma-ray energies.

Tables 3 and 4 also show that LAC and MAC are significantly affected by both the incident energies of gamma rays and the chemical composition of the PP composites. It experiences a significant decrease between the gamma-ray energies of 59.53 keV and 356.01 keV. Conversely, it demonstrates an increase as the weight fraction of Bi_2O_3/CuO in the PP composites rises, indicating a direct relationship. In this range of photon energies, the primary interaction with the composite samples is attributed to the photoelectric effect [27]. This is because the photoelectric effect was increased at high atomic numbers and low energies, and decreased with increasing -ray energy [28]. This explains the sharp decrease and the enhanced photon absorption capacity with increased Bi_2O_3/CuO filler content. The values of MAC and LAC decrease less significantly when the energy exceeds 661.66 keV due to the rising occurrence of Compton scattering [28] at intermediate energies that are relative to the atomic

number to the atomic weight ratio (Z/M) and pair production interaction at energies greater than 1173.2 keV. The primary interaction depends on the quantity of unattached electrons per unit of mass, rather than on Z, which diminishes the significance of the Bi_2O_3/ CuO filler in the procedure. Additionally, the concentrations of support material and the density of the nanocomposite were raised, leading to an improvement in the shielding properties for both kinds of samples.

Molecular and atomic cross-section

Table 5 presents the experimentally measured and theoretically calculated values of the total molecular cross-section σ_{mol} and the effective atomic cross-section σ_{atm} for PP and its composites. The results show a correlation between the incident gamma-ray energies and the chemical composition of the PP composites. The values of σ_{mol} and σ_{atm} exhibit a pattern similar to μ and μ_m, wherein they sharply decrease between gamma-ray energies of 59.53 keV and 356.01 keV and then slightly decrease within the energy range from 661.66 keV to 1332.5 keV.

The σ_{mol} and σ_{atml} increased as the Bi_2O_3/CuO filler weight fraction increased for all PP composites and decreased with increasing energy. Moreover, PP/Bi_2O_3/CuO NP(N) composites show the greatest values of σ_{mol} and σ_{atm} compared to PP/Bi_2O_3/CuO Bulk(B) composites when retaining Bi_2O_3/CuO weight fraction and energy value.

The experimental determination of the mass attenuation coefficients for the main composite elements of PP is challenging due to their low atomic number. The parameters σ_{el}, Z_{eff}, and N_{eff} are obtained using eqs. (7-11) and exhibit similar behavior across different gamma-ray energies. These parameters are influenced by both the low gamma-ray energies of the incident and the chemical composition of the PP composites. The values of σ_{el}, Z_{eff}, and N_{eff} demonstrate an increase as the weight fraction of Bi_2O_3/CuO in the PP composites increases within the gamma-ray energy range of 59.53 keV to 356.01 keV. This is attributed to the predominant impact of the photoelectric effects with Z^{4-5} dependence [31] on the total interaction with the composite samples. Within the energy range of gamma rays from 661.66 keV to 1332.5 keV, $\sigma_{el,}$ Z_{eff} and N_{eff} maintain relatively constant values across all energies. This trend persists with an increase in the mass fraction of the filler Bi_2O_3/CuO due to the predominance of Compton scattering [20]. Hence, the elevated atomic number of bismuth and copper, compared to other elements in the PP composite, along with the increase in molecular weight due to the higher wt %, does not significantly impact the PP composites'

Table 5. Total molecular cross-section and the effective atomic cross-section for PP and PP composites at various filler wt. % and different energies

Sample	Energy [keV]	Total molecular cross-section σ_{mol} 10^{-24} (cm^2 per/molecule)			Effective atomic cross-section σ_{atm} 10^{-24} (cm^2 per atom)		
		PP	XCOM		PP		XCOM
0 wt % (PP/Bi_2O_3/CuO)	59.53	0.130	0.131		1.452		1.465
	356.01	7.674	7.950		0.894		0.883
	661.66	5.983	6.150		0.681		0.683
	1173.23	4.609	4.687		0.525		0.520
	1332.5	4.299	4.390		0.492		0.487
Sample	Energy [keV]	Bi_2O_3/CuO Bulk(B)	Bi_2O_3/CuO Nano	XCOM	Bi_2O_3/CuO Bulk(B)	Bi_2O_3/CuO Nano	XCOM
5 wt % (PP/Bi_2O_3/CuO)	59.53	0.259	0.287	0.294	2.834	3.139	3.472
	356.01	8.700	9.563	9.138	0.950	1.044	1.076
	661.66	6.440	6.893	6.716	0.703	0.752	0.790
	1173.23	4.867	5.090	5.097	0.531	0.555	0.600
	1332.5	4.618	4.752	4.763	0.504	0.518	0.560
10 wt % (PP/Bi_2O_3/CuO)	59.53	0.396	0.445	0.474	4.257	4.781	5.090
	356.01	9.389	0.104	0.104	1.007	1.116	1.120
	661.66	6.808	7.363	7.340	0.730	0.790	0.787
	1173.23	5.087	5.374	5.549	0.545	0.576	0.595
	1332.5	4.782	4.946	5.174	0.513	0.530	0.555
15 wt % (PP/Bi_2O_3/CuO)	59.53	0.540	0.618	0.546	5.697	6.522	5.756
	356.01	0.104	1.16	0.103	1.096	1.223	1.093
	661.66	7.175	7.877	7.207	0.759	0.830	0.759
	1173.23	5.333	5.675	5.337	0.562	0.598	0.562
	1332.5	4.989	5.183	4.989	0.525	0.546	0.525
20 wt % (PP/Bi_2O_3/CuO)	59.53	0.710	0.822	0.715	7.348	8.506	7.404
	356.01	0.114	0.128	0.113	1.184	1.329	1.176
	661.66	7.586	8.288	7.640	0.784	0.857	0.790
	1173.23	5.578	5.972	5.602	0.577	0.617	0.579
	1332.5	5.210	5.421	5.234	0.539	0.560	0.541

ability to attenuate gamma radiation. This observation aligns with the experimental results for the mass attenuation coefficient.

HVL and TVL Values

The design of effective radiation shielding, based on LAC calculations, heavily relies on the half-value layer (HVL) and tenth-value layer (TVL). The HVL indicates the thickness of the radiation shielding material needed to reduce the radiation level to 50 % of its initial value [30], while the TVL represents the thickness required to reduce the radiation to one-tenth of its original intensity [31]. Equations 12 and 13 are used to calculate the HVL and TVL, respectively. According to the findings depicted in figs. 2(a-b), the HVL values of the tested composites show a significant decrease compared to pure PP, particularly at lower energies and higher filler concentrations. This leads to enhanced shielding properties of the composites compared to pure PP. As photon energy increases, the HVL values also increase, requiring more thickness of absorbing material to reduce the intensity of the incident radiation, thus reducing its strength, and penetrating deeper into the material. The TVL diminishes as the percentage of filler weight rises and increases with higher energy levels, as illustrated in figs. 3(a-b).

Relaxation length

The ability of a material to shield can be explained by its relaxation length, also known as the mean free path. This length refers to the average distance a gamma photon travels before colliding with at-

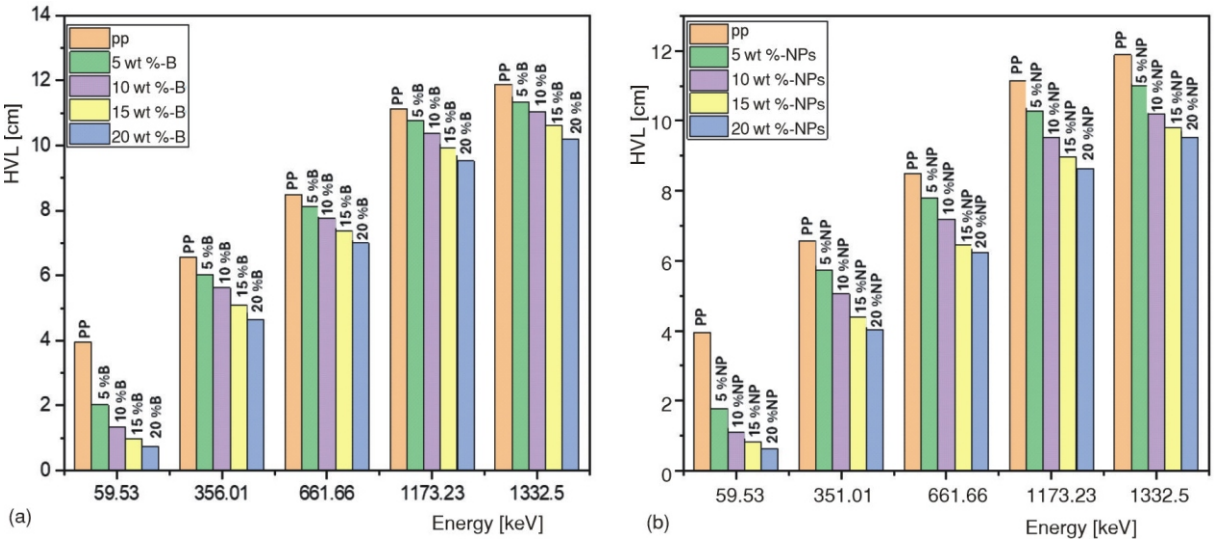

Figure 2. Comparison of HVL thickness and gamma-ray energy for the (a) Bi_2O_3/CuO Bulk(B) composites and (b) Bi_2O_3/CuO Nano (NP) composites

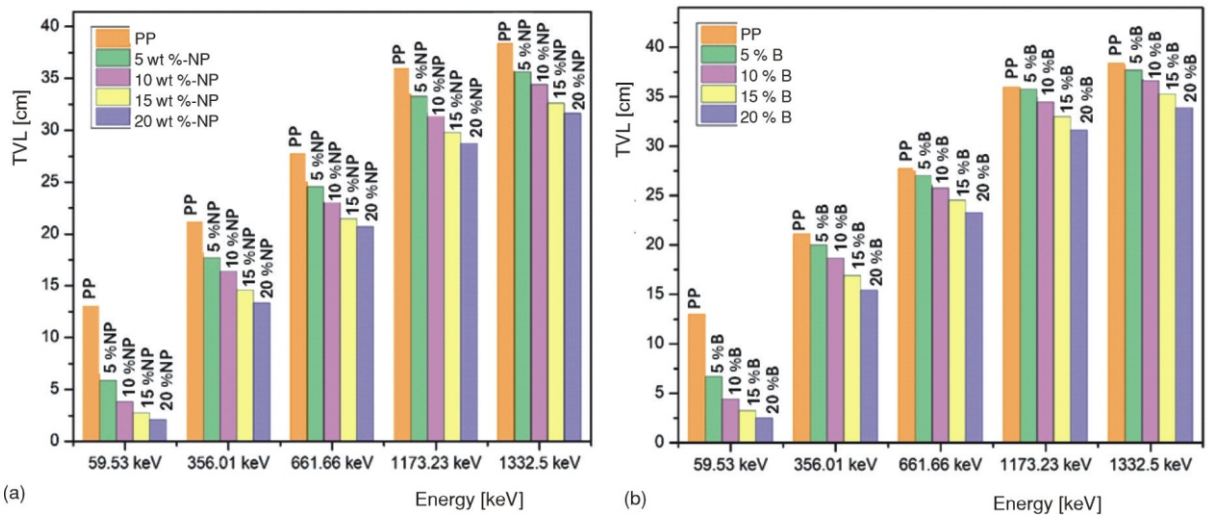

Figure 3. The polymer composites' TVL thickness concerning the filler % weight (a) Bi_2O_3/CuO Nano (NP) composites and (b) Bi_2O_3/CuO Bulk(B) composites

oms in the medium. It was determined using eq. (14), and the outcome is depicted in fig. 4. The equation indicates that the relaxation length depends on the LAC, with a higher LAC value corresponding to a shorter relaxation length. The graph shows that declines as the filler weight percentage increases, but rises as gamma energy increases. Low-energy photons dissipate their energy over a limited distance, whereas high-energy photons require a greater distance to dissipate their energy. This indicates that the shielding property of a material improves as its relaxation length decreases. The values of LAC for a nano composite containing 20 wt % varied from 1.1040 cm^{-1} at 59.53 keV to 0.0728 cm^{-1} at 1332.5 keV. At the same energy levels, the HVL ranged from 0.74 cm to 10.19 cm when compared to the bulk and other nano-composite samples. This indicates that the optimal shielding parameters were achieved when PP was reinforced with a nanocomposite containing 20 wt %.

As a result, the HVL values for the composite sample with 20 wt % were selected for comparison with pure lead (Pb) due to its outstanding radiation performance. Table 7 displays the HVL ratio of the PP composite with a 20% weight fraction of Bi_2O_3/CuO compared to pure lead across the gamma-ray energy range of 59.53 keV to 1332.5 keV, demonstrating the effectiveness of the investigated PP composites as materials for shielding against radiation. The equivalence at 59.53 keV between 7.47 mm of 20 wt % nano Bi_2O_3/CuO composite and 0.13 mm of lead shield is 56.65 times the thickness of lead. However, at a higher energy of 1332.5 keV, 101.93 mm of this composite is only 9.08 times the thickness of lead, which is equivalent to 11.21 mm of lead. Therefore, this lightweight nanocomposite shows promise as an absorber for

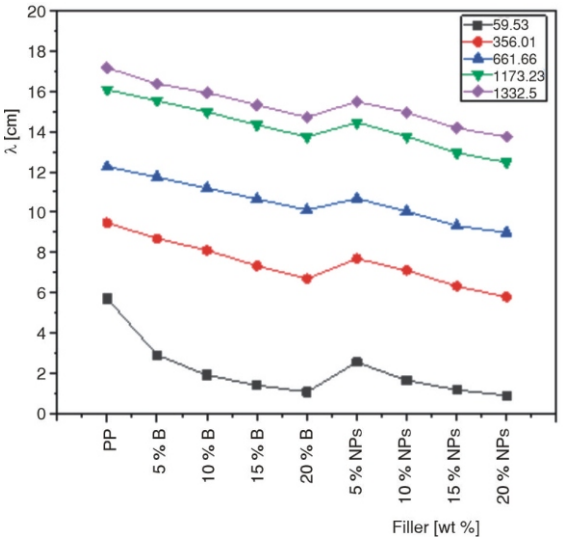

Figure 4. The polymer composites' relaxation length changes based on the filler's weight percentage

Table 6. Total electronic cross-section σ_{el}, effective atomic number Z_{eff}, and electron density N_{eff} for PP and PP composites at various filler wt % and different energies

Sample	Energy [keV]	σ_{el} (cm^2/electron)	Z_{eff}	N_{eff} 10^{23} (electrons /g)
		Theoretical		
0 wt % (PP/Bi_2O_3/CuO)	59.53	0.5471	2.6788	3.4502
	356.01	0.3314	2.6653	3.4328
	661.66	0.2562	2.6666	3.4345
	1173.23	0.1953	2.6664	3.4342
	1332.5	0.1829	2.6667	3.4346
	Energy [keV]	**Bi_2O_3/CuO Bulk(B)**	**Bi_2O_3/CuO Bulk(B)**	**Bi_2O_3/CuO Bulk(B)**
5 wt % (PP/Bi_2O_3/CuO)	59.53	0.6199	5.6005	6.4930
	356.01	0.3352	3.2093	3.7207
	661.66	0.2577	3.0682	3.5571
	1173.23	0.1961	3.0590	3.5464
	1332.5	0.1837	3.0525	3.5390
10 wt % (PP/Bi_2O_3/CuO)	59.53	0.7001	7.2701	8.8022
	356.01	0.3394	3.3017	3.9975
	661.66	0.2593	3.0362	3.6761
	1173.23	0.1971	3.0196	3.6560
	1332.5	0.1846	3.0071	3.6408
15 wt % (PP/Bi_2O_3/CuO)	59.53	0.7306	7.8775	9.2169
	356.01	0.3377	3.2383	3.7889
	661.66	0.2576	2.9477	3.4489
	1173.23	0.1954	2.8774	3.3666
	1332.5	0.1830	2.8719	3.3601
20 wt % (PP/Bi_2O_3/CuO)	59.53	0.8057	9.1894	10.363
	356.01	0.3402	3.4574	3.8993
	661.66	0.2582	3.0610	3.4522
	1173.23	0.1955	2.9650	3.3439
	1332.5	0.1831	2.9572	3.3352

Table 7. The HVL outcomes for the 20 wt % nanocomposite sample compared with those for pure lead (Pb), and the ratio between them was calculated

Energy [keV]	HVL		HVLcomposite \HVL$_{Pb}$
	Pure lead (Pb)	PP/Bi_2O_3/CuO Nano 20 wt %	
59.53	0.0132	0.74789	56.65833
356.01	0.2299	4.63953	20.18064
661.66	0.5901	7.00148	11.8649
1173.23	1.0254	9.5212	9.285352
1332.5	1.1218	10.1933	9.086557

gamma rays and could serve as an alternative to lead shielding.

CONCLUSION

The Bi_2O_3/CuO (70 %/30 % weight fraction) micro-and nanocomposite with different weight percentages (0 %, 5 %, 10 %, 15 %, and 20 %) reinforced into PP samples have been thoroughly investigated for their potential use in radiation attenuation. Tests on the effectiveness of gamma-ray protection against various energy sources revealed a good agreement between the experimental data and NIST-XCOM data. When adding the Bi_2O_3/CuO weight fraction to the PP composite at low gamma energies, the mass attenuation coefficients , total molecular cross-section , and effective atomic cross-section all increased. Notably, for all gamma-ray energies, there is a significant improvement in the nanocomposite NP(N) compared to the Bulk(B) composites. This enhancement is attributed to the high electron density from the amplification of the nano-filler in the polymer matrix, which increases the likelihood of gamma-ray interaction within the nanocomposites. Conversely, increasing the weight fraction of Bi_2O_3/CuO in the composites at low energies increases the total electronic cross-section, the effective atomic number, and the electron density. However, at high energies, no significant variation is observed, and increasing the weight fraction of Bi_2O_3/CuO in the composites decreases the half-value layer(HVL), tenth-value layer (TVL), and relaxation length ?. These findings are particularly noteworthy at low energies. The results of shielding parameters demonstrate that for all tested energies, PP reinforced with nano Bi_2O_3/CuO provides superior attenuation compared to PP reinforced with micro Bi_2O_3/CuO. Ultimately, the composite with 20 wt % (PP/Bi_2O_3/CuO) NP showed excellent shielding qualities, suggesting that it could be a good alternative for radiation shielding.

AUTHORS' CONTRIBUTIONS

M. M. Gouda: Writing-review & editing, visualization, Methodology, Data curation. M. Shebly and A. Obeid: Writing-original draft, Visualization, Methodology, Formal analysis. K. Habanjar: Writing-original draft, Visualization, Preparing Samples. R. Awad and M. S. Badawi: Writing-review & editing, supervision, conceptualization.

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ORCID NO

M. M. Gouda: 0000-0002-0182-6512
M. Shebly: 0009-0006-7029-8297
K. Habanjar: 0000-0002-7437-0288
A. Obeid:0000-0001-6181-5068
R. Awad: 0000-0001-9193-4092
M. S. Badawi: 0000-0002-4919-856X

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**Мона М. ГОУДА, Мона ШЕБЛИ, Кулуд ХАБАНЦАР,
Амро ОБЕИД, Рамадан АВАД, Мохамед С. БАДАВИ**

КАРАКТЕРИСТИКЕ СЛАБЉЕЊА ГАМА ЗРАЧЕЊА ПОЛИПРОПИЛЕНОМ ИСПУЊЕНИМ У МАСИ НАНОВЕЛИЧИНАМА Bi_2O_3 И CuO

Полипропилен је произведен компресијским пресовањем и комбинован са нанокомпозитима Bi_2O_3/CuO и Bi_2O_3/CuO са различитим тежинским фракцијама примеса (0 %, 5 %, 10 %, 15 % и 20 %). Енергије гама зрачења из четири радиоактивна извора (^{241}Am, ^{133}Ba, ^{137}Cs и ^{60}Co), у распону од 59.53 keV до 1332.5 keV, коришћене су за процену способности слабљења зрачења новог композитног полимера PP/Bi_2O_3/CuO. Испитани су параметри: масени коефицијенти слабљења, укупан молекулски пресек, ефективни атомски пресек, укупан електронски пресек, електронска густина, ефективни атомски број, вредности слоја полуслабљења и слоја десетоструког слабљења и дужина релаксације. Резултати су указали на значајан утицај величине и масеног удела Bi_2O_3/CuO примеса на способност заштите од гама зрачења полипропиленског композита, посебно на нижим нивоима енергије гама зрака. Чисто олово, традиционални и широко употребљаван заштитни материјал, коришћен је као референца за процену ефикасности слоја полуслабљења полипропиленског композита. Полипропиленски композити који садрже нановеличине Bi_2O_3/CuO показали су значајна побољшања параметара слабљења, наглашавајући њихов потенцијал за примену у заштити од гама зрачења.

Кључне речи: полипропиленски композит, Bi_2O_3/CuO нанокомпозит, параметар слабљења, заштита од зрачења