STUDY OF SOME GAMMA RAY ATTENUATION PARAMETERS FOR NEW SHIELDING MATERIALS COMPOSED OF NANO ZnO BLENDED WITH HIGH DENSITY POLYETHYLENE

by

Zainab ALSAYED [1*], ***Mohamed S. BADAWI*** [1], ***Ramadan AWAD*** [1], ***Abouzeid A. THABET*** [2], ***and Ahmed M. EL-KHATIB*** [3]

[1]Department of Physics, Faculty of Science, Beirut Arab University, Beirut, Lebanon
[2]Department of Medical Equipment Technology, Faculty of Allied Medical Sciences, Pharos University in Alexandria, Alexandria, Egypt
[3]Physics Department, Faculty of Science, Alexandria University, Alexandria, Egypt

Scientific paper
https://doi.org/10.2298/NTRP190718033A

The extensive utilization of radiation is rapidly developing worldwide involving abundant fields like medical, industrial, research, and nuclear facilities. This makes the need for studying radiation shielding materials and their properties more urgent than ever. In the present study, bulk and nano ZnO were mixed by the same ratio each time (10, 20, 30, and 40 wt.%), with high-density polyethylene as a polymer matrix and characterized by X-ray diffraction. The results confirmed the good dispersion of bulk and nano ZnO particles within the polymer matrix. The prepared composite samples were used in different thicknesses as gamma ray shielding materials, and the heaviness was calculated and compared to lead. Using HPGe detector at specific energies (59.53, 356.01, 661.66, 1173.33, and 1332.50 keV) for different radioactive point sources (^{241}Am, ^{133}Ba, ^{137}Cs, and ^{60}Co), the mass attenuation coefficient for the samples was measured experimentally. Depending upon the obtained values, the linear attenuation coefficient, half-value layer, tenth value layer, heaviness and relaxation length were estimated. Using the XCOM database, the values of linear attenuation coefficient, mass attenuation coefficient, and other parameters were calculated theoretically for the bulk ZnO blended with high-density polyethylene. The obtained results were compared to the experimental values for nano and bulk ZnO blended with high density polyethylene. The radiation shielding behavior of nano ZnO blended with high density polyethylene was found to be more promising and efficient for radiation protection against gamma ray.

Key words: nano ZnO, bulk ZnO, high-density polyethylene, composite sample, mass attenuation coefficient, radiation shielding material

INTRODUCTION

Radiation is always considered as a serious threat in nuclear power, medical, high energy research, agricultural, and industrial facilities [1-6]. Restraining radiation, hindering its physical, biological harm to human health and the environment, is becoming the main concern to ensure human safety. According to the type of radiation used, including neutrons, gamma rays, and X-rays, the effects of radiation can be determined based on the degree of interaction of radiation beams with the shielding material involved. The principle of radiation shielding is mainly based on how the elemental properties constituting the shielding material can attenuate the radiation beam by reducing its effects. When choosing and designing appropriate radiation shielding material, it is recommended to have enough background, knowledge about its structural, physical, and nuclear properties. Furthermore, the most important properties to determine the effectiveness of a material, as a radiation barrier, are linear attenuation coefficient, μ, mass attenuation coefficient, μ_m, half-value layer (HVL), tenth-value layer (TVL), relaxation length, λ, and heaviness. Many studies have attempted to evaluate the shielding effectiveness of various materials by determining the values of the most important shielding parameters [7, 8]. Nowadays, the field of radiation shielding is oriented towards manufacturing new materials such as composite polymers and enhancing their properties against gamma radiation [9]. Their competent properties like lightness, low cost, softness, stability, and elasticity make them beneficial alternatives compared to lead in the attenuating radiation [10]. Many studies investi-

* Corresponding author; e-mail: zka295@student.bau.edu.lb

gated the use of various polymers as a basic matrix with different metal or metal oxide fillers. Aycik and Belgin *et al*. [11] inspected linear low-density polyethylene (LLD-PE) by varying the amounts of powdered fillers PbO and WO_3 as shielding materials against ionizing radiation. They found that for higher filler loadings, good attenuation performance against gamma radiation was achieved. Mortazavi *et al*. [12] designed a neutron shield composed of high-density polyethylene with boron nanoparticles as a filler, they concluded that borated high-density polyethylene (HDPE) was more effective in shielding than raw HDPE. Afshar *et al*. [13] developed HDPE composite loaded with W, MoS_2 and B_4C to study their radiation attenuation capability. The 45 wt.% HDPE/W composite fraction demonstrated a good attenuation of radiation compared to HDPE/Pb, HDPE/B_4C and HDPE/W composites. Mahmoud *et al*. [14], fabricated, characterized nano and micro lead oxide with different weight fractions that were dispersed in high density polyethylene. They concluded that the attenuation coefficients increased with the increase of PbO content and the radiation parameters (HVL, TVL, and λ) for HDPE/PbO nanocomposites revealed better performance in radiation shielding.

This study is intended for developing new, low cost, and light radiation shielding materials starting from HDPE and ZnO as a filler. Different fractions (10, 20, 30, and 40 wt. %) of bulk and nano ZnO particles were added identically to the HDPE matrix. The linear and mass attenuation coefficients in addition to other parameters such as HVL, TVL, λ, and heaviness were calculated and compared to HDPE. Both bulk and nano ZnO particles were chosen to enhance the attenuation properties of the composites, whereas the HDPE polymer was used as a matrix to reduce the heaviness of the composites and provide their easy manufacturing and formability.

THEORETICAL BACKGROUND

Calculation of total mass attenuation coefficient, linear attenuation coefficient, density, and discrepancy

Better shielding properties against gamma ray photons are obtained by the ZnO nanoparticles, which are highly dispersed within the polymer matrix. Their high electron density increases the probability of interaction with gamma rays. The linear attenuation coefficient μ [cm^{-1}] of the absorber was calculated according to the following eq. [15]

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

where N_0 is the detector count rate without the polymer target, N_x – the count rate with the polymer target, and x [cm] the thickness of the absorber.

The mass attenuation coefficient μ_m [cm^2g^{-1}] is a widely used quantity in radiation calculations, representing the effectiveness of the absorber in radiation shielding and is obtained by the following equation

$$\mu \quad \mu_m\rho \tag{2}$$

The total mass attenuation coefficient, ($\mu\rho$ $_{\text{compound/mixture}}$ for any chemical compound or mixture of elements, is given by the mixture rule [16]

$$\frac{\mu}{\rho} \quad {}_i\, w_i(\mu_m) \tag{3}$$

where w_i represents the weight fraction defined as

$$w_i \quad \frac{n_i A_i}{{}_i\, n_i A_i} \tag{4}$$

where A_i is the atomic weight of the sample and ni is the number of formula units.

The total linear attenuation coefficient of the compound can be derived as follows

$$\mu_{\text{compound}} \quad \frac{\mu}{\rho}_{\text{compound}}\rho \tag{5}$$

where ρ is the apparent density of the sample determined by the Archimedes technique. To calculate the average density of the composite samples based on ASTM D 792-91 (ASTM, 1997) [17], three organic liquids (toluene, chlorobenzene, and ethanol) and an electrical balance with a calibrated pan (Analytical balance, GR200, Japan) were used. After determining their weights the composites' densities were calculated using the equation

$$\rho_{\text{exp}} \quad \frac{A}{A\ B}\ \rho_L \tag{6}$$

where ρ_{exp} is the experimental density of the composite, A – the weight of the composite in air, B – the weight of the composite in the organic liquid, and ρ_L – the density of the organic liquid

Using the relation below, the theoretical values of ρ for the composites were calculated and compared to the experimental *vs*.

$$\rho_T \quad \frac{1}{\frac{M}{\rho_m}\ \frac{F}{\rho_f}} \tag{7}$$

where ρ_T is the theoretical density of the composite, M [%] – the mass of the matrix, ρ_m – the density of the matrix, F [%] – the mass of the filler, ρ_f – the density of the filler.

The discrepancy Δ% values between μ of nanocomposites and bulk composites are calculated according to the following equation

$$\Delta \quad \frac{\mu_{(\text{nanocomp})}\quad \mu_{(\text{bulkcomp})}}{\mu_{(\text{nanocomp})}}\ 100\,[\%] \tag{8}$$

Calculation of HVL, TVL, heaviness and relaxation length

The HVL is defined as the thickness of an absorber reducing the radiation level by a factor of 2, *i.e.* to half of its initial level and is determined by the following equation

$$HVL \quad \frac{\ln 2}{\mu} \tag{9}$$

Correspondingly, TVL is defined as the thickness of an absorber needed to reduce the radiation beam to one-tenth of its initial value and is calculated by

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

where λ is defined as the average distance between two successive interactions. It is also known as photon mean free path, which is determined by the equation

$$\lambda \quad \frac{1}{\mu} \tag{11}$$

By assigning lead as standard and normalized to 100 % the heaviness of HDPE/ ZnO composites was calculated using the equation

$$\text{Heaviness} \quad \frac{\text{Density of composite}}{\text{Density of lead}} \; 100[\%] \tag{12}$$

MATERIALS AND METHODS

Materials

Bulk ZnO (Molar weight 81.39 $gmol^{-1}$, purity 98-100.5 %) was used without further purification. $ZnCl_2$ (Mw 136.3 $gmol^{-1}$, purity >99 %) and NaOH (Mw 40 $gmol^{-1}$, purity >96 %) used in the synthesis of ZnO nanoparticles were supplied by Sigma Aldrich. HDPE supplied with a density of 960 kgm^{-3} and melt flow index (MFI) about 0.05 g/10 min was dried at 90 °C ground by a mechanical grinder (HRPM-13, Jiangsu, China) and crushed into pellets was chosen as a base polymer matrix.

The ZnO nanoparticles synthesis

Using the co-precipitation method, ZnO nanoparticles were synthesized from 1M $ZnCl_2$ and distilled water as precursors. After dissolving 30 g of $ZnCl_2$ in distilled water, the solution was mixed at a constant stirring rate for 30 minutes. Then 4M NaOH was added dropwise to the stirred solution to adjust the pH = 13. Later, the solution was submitted to the constant stirring at 80 ºC for 2 hours. Then it was washed several times with hot distilled water to settle the pH = 7 and then dried at 100 ºC for 18 hours. The established powder was calcined afterward at 550 ºC for 5 hours to obtain ZnO nanoparticles, which were ball-milled with a ratio of 1:5 (powder: balls) at 250 rounds per minute for 10 minutes.

Polymer composites fabrication

The HDPE composites with 10, 20, 30, and 40 wt.% of ZnO filler were synthesized by a compression molding technique. The HDPE was melted in a roll mixer (XK400, Shandong, China) for 10 minutes. The appropriate fractions of either bulk or nano ZnO particles were added with continuously mixing for 15 minutes. After that, the mixture was agitated well to obtain a homogeneous mixture distributed uniformly within the polymer matrix. The obtained specimens were removed from the mixer after milling process and then spilled into rectangular stainless-steel mold of dimensions (25 cm × 25 cm × 0.3 cm) and smoothed between two layers of thermal teflon. This was followed by hot pressing using a hydraulic press of 20 MPa at 170 °C for 15 minutes. Under compression, the obtained samples were cooled by water at 20 °C min^{-1}. The prepared composites with 10, 20, 30, and 40 wt. % ZnO filler were cut into disc specimens of 8.5 cm diameter for the subsequent radiation shielding test.

The X-ray diffraction

The crystallite size of the obtained samples was determined using X-ray diffraction (Model: D8 FOCUS BRUKER), employing Cu-k_α radiation (λ = 0.154 nm) in a range 10° 2θ 70°.

Gamma rays acquisition and analysis

Using a multi-channel analyzer (MCA) the experimental gamma ray measurements were determined in the Radiation Physics laboratory (RPL), Faculty of Science, Alexandria University, Alexandria-Egypt. The most intense peaks in the spectra were observed and treated by using ISO 9001 Genie 2000 data acquisition and analysis software by Canberra. Four radioactive point sources were used for the calibration process ^{241}Am, ^{133}Ba, ^{137}Cs, and ^{60}Co. Statistical uncertainties >1 % were achieved by increasing the acquisition time. By exploiting automatic peak search and peak area calculations, the acquired spectra by the MCA of gamma rays were processed. To execute the needed calculations, the peak areas, real-time, starting time, and live time were entered into charts for each spectrum. As shown in fig. 1, the gamma ray spectrometry is acquired by the HPGe detector that is connected to MCA. The obtained spectrum from MCA is analyzed using the Canberra software so that a very narrow beam can be acquired while neglecting the effect of detector dead time [18]. The detector was enclosed with lead blocks to reduce the background.

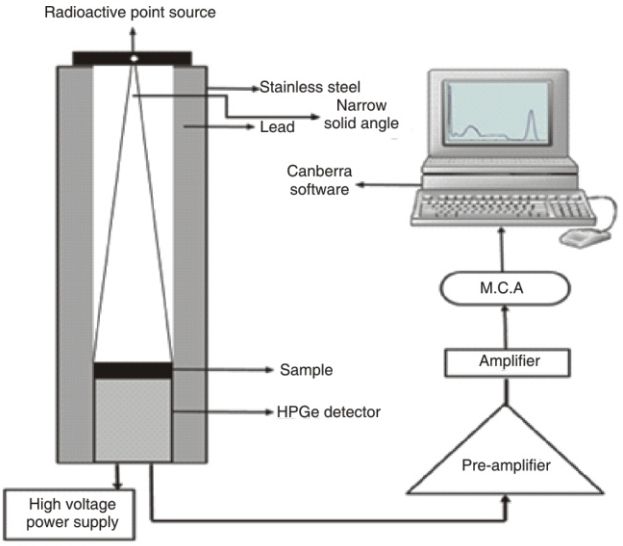

Figure 1. Diagram of measurement set-up using the HPGe detector

By estimating the transmission of gamma rays through the samples using five different thicknesses (2 mm, 4 mm, 6 mm, 8 mm, and 10 mm) the linear attenuation coefficient μ [cm^{-1}] and the mass attenuation coefficient μ_m [cm^{-2}g^{-1}] of polymer composites were determined using the XCom software. The experimental attenuation results were measured and compared to the calculated theoretical results. The four radioactive point sources (^{241}Am, ^{133}Ba, ^{137}Cs, and ^{60}Co) were chosen to emit (59.53, 356.01, 661.66, 1173.33, and 1332.50 keV) and these sources were purchased from Physikalisch-Technische Bundesanstalt in Braunschweig and Berlin. Using a well- calibrated high purity germanium cylindrical detector (HPGe) (Model GC1520) with relative efficiency 15 % and energy range (50 keV-10 MeV). The count rate (N) was calculated from the net areas under the spectral lines 59.53, 356.01, 661.66, 1173.33, and 1332.50 keV. A linear plot of ln *N vs*. *x* (thickness) of each sample was provided to obtain the best fit for μ [cm^{-1}].

RESULTS AND DISCUSSION

The X-rays diffraction

Figures 2(a)-2(d) illustrate the XRD patterns of HDPE, ZnO nanoparticles, HDPE/ ZnO nano-co mposites and HDPE/ bulk ZnO composites, respectively. As shown in fig. 2(a), HDPE possesses an orthorhombic, hexagonal crystal structure with reflection planes (110), (200), and (020). An intensive peak is displayed at 2θ = 21.61º, followed by other small peaks at 24.02 º and 30.04 º, having interplanar spacing at 4.11, 3.7, and 2.97 Å (1 Å = 10^{-10} m), respectively [19]. Figure 2(b) displays the planes (100), (002), (101), (102), (110), (103), (200) and (112) corresponding to hexagonal (wurtzite) structure of ZnO nanoparticles of average crystallite size 27 nm estimated by Rietveld method using MAUD program fitting [20]. Three major strong peaks at 2θ = 31.86 º, 34.52 º and 35.74 º, appear and the sharpness of the peaks depicts the high degree of crystallinity of the oxide.

In fig. 2(c), 10 wt.%, 20 wt.%, 30 % and 40 wt.% XRD patterns of HDPE/ZnO nanocomposites are displayed. The sharp peaks of these composites illustrate the presence of amorphous crystallite structure. All displayed patterns form a conjunction between peaks of HDPE and ZnO nanoparticles, with a change in intensity and peak width, while the peak position remains the same in the range. The identified peaks of ZnO nanoparticles are detected at 2θ = 32.38º, 34.88 º, and 36.86 º. For low wt.% of ZnO nanoparticles, the planes (110) and (200) corresponding to the HDPE remain unchanged indicating that the chemical and crystallite structure of HDPE matrix has not changed. As the filler concentration increases the HDPE peaks are attenuated and become weaker for 30 and 40 wt.% of ZnO nanoparticles. This illustrates the good dispersion of ZnO nanoparticles into the polymer matrix. Figure 2(d) displays the analogous behavior of XRD patterns for HDPE/ bulk ZnO composites.

Measurement of gamma ray attenuation parameters with different energies

Experimentally, the gamma ray attenuation was measured with and without the polymer sample. The density of the sample is an important parameter in the attenuation process, where for heavy atoms more interactions with photons can occur per unit length of a sample. It is more convenient and precise to use the mass attenuation coefficient μ_m [cm^{2}g^{-1}] to define the attenuation behaviour of a given sample. Table 1 illustrates the values of the measured linear attenuation coefficient μ [cm^{-1}], theoretical μ [cm^{-1}] calculated from XCOM program, measured density ρ, discrepancy % between the measured and the theoretical values

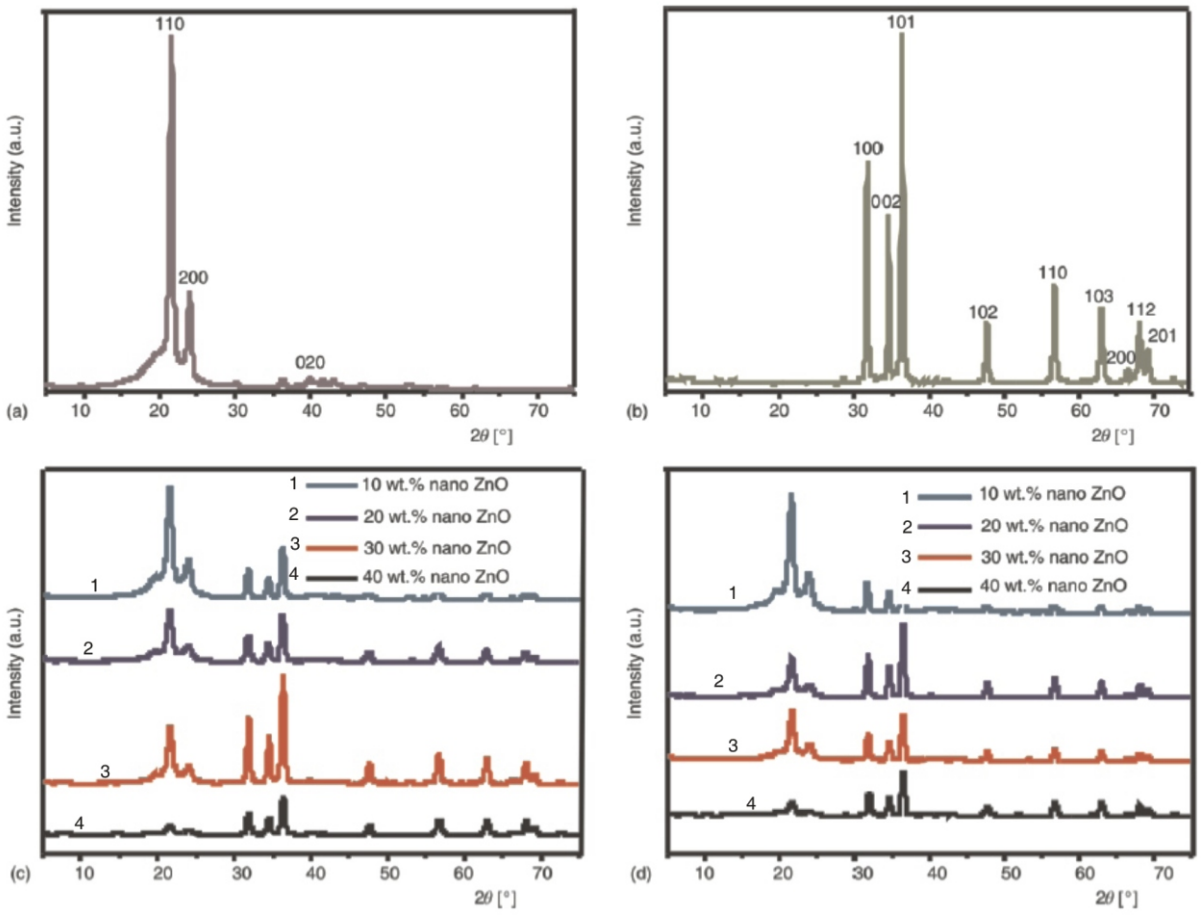

Figure 2. The XRD patterns of (a) HDPE, (b) ZnO nanoparticles, (c) HDPE/ ZnO nanocomposites, and (d) HDPE/ bulk ZnO composites, respectively

of μ and the mass attenuation coefficient μ_m [cm^2g^{-1}] for HDPE, 10, 20, 30, and 40 wt. % of HDPE/bulk composites at 59.53, 356.01, 661.66, 1173.25, and 1332.50 keV, respectively. It is clear, from the results prevailed by tab. 1 that the measured values of ρ increase with the increase of bulk ZnO content. This is attributed to the dispersion of HDPE with the bulk ZnO having a higher density (ρ = 5.61 gcm^{-3}) compared to HDPE, which consequently increases the packing density of the composite. The ligands attached to bulk ZnO particles influence their interaction with the HDPE matrix, thus affecting the particle behavior and spatial distribution [21]. The data listed in tab. 1 confirm that the increase in ZnO bulk content increases the magnitude of μ in all wt.% of the composite samples at all energy ranges.

Table 2 illustrates the experimental values of linear attenuation coefficient μ [cm^{-1}], mass attenuation coefficient μ_m [cm^2g^{-1}], and density ρ [gcm^{-3}] for HDPE, HDPE/ZnO nanoparticles and HDPE/ bulk ZnO composites at energies 59.53, 356.01, 661.66, 1173.33, and 1332.50 keV, respectively. The linear and mass attenuation coefficients for the samples decrease as the photon energy increases. This behavior is related to the ability of the composite to attenuate radiation and its permeability. For the same wt.% the linear and mass attenuation coefficients are higher for the ZnO nanoparticles filled composite compared to the bulk ZnO composite. This indicates that ZnO nanoparticles are better than bulk ZnO in shielding performance.

Figures 3(a)-3(b) display the variation of linear attenuation coefficient μ [cm^{-1}] values of HDPE and the bulk and nano ZnO composites *vs*. photon energies, respectively. For all the selected composite materials, the variety of μ with the incident photon energy is almost the same. Two main energy regions could be characterized: the low energy region, $E < 0.4$ MeV where μ decreases sharply and high energy region, $E_\gamma > 0.4$ MeV, where μ decreases slightly. These regions are attributed to the photon absorption mechanisms for different photon energies [22]. By increasing the gamma ray energy the interaction cross-sections are decreased. At low energies, the photoelectric effect is dominant, whereas the Compton scattering overlaps with the photoelectric effect within the energy range (100 keV to 1.33 MeV). But above this range of energy pair production is significantly higher [23]. There is only complete absorption of the incident gamma photons in case of the photoelectric effect, rather than Compton scattering and pair-production where photons are not completely absorbed. The discrepancy

Table 1. The ZnO wt.%, the measured values of density, linear, mass attenuation coefficients, and the theoretical values estimated by the XCOM program of HDPE and HDPE/ZnO bulk composites at 59.53, 356.01, 661.66, 1173.25, and 1332.50 keV

Sample	Energy [keV]	Linear attenuation coefficient [cm^{-1}]		Δ [%]	Density of composites [gcm^{-3}]	Mass attenuation coefficient [cm^2g^{-1}]
		Measured	XCOM			
HDPE	59.53	0.174	0.167	3.898	0.887	0.196
	356.01	0.103	0.101	2.042		0.116
	661.66	0.08	0.078	2.459		0.090
	1173.23	0.062	0.060	4.189		0.070
	1332.50	0.058	0.056	4.044		0.065
10 wt.% Bulk ZnO composite	59.53	0.331	0.321	2.969	1.041	0.318
	356.01	0.112	0.117	–4.200		0.108
	661.66	0.0886	0.090	–1.681		0.085
	1173.23	0.0704	0.069	2.578		0.068
	1332.50	0.064	0.064	–0.453		0.061
20 wt.% bulk ZnO composite	59.53	0.502	0.473	6.109	1.104	0.455
	356.01	0.124	0.122	1.455		0.112
	661.66	0.096	0.094	2.265		0.087
	1173.23	0.074	0.071	3.577		0.067
	1332.50	0.068	0.067	1.589		0.062
30 wt.% bulk ZnO composite	59.53	0.713	0.675	5.593	1.231	0.579
	356.01	0.132	0.134	–1.785		0.107
	661.66	0.102	0.103	–0.824		0.083
	1173.23	0.08	0.078	2.278		0.065
	1332.50	0.075	0.073	2.327		0.061
40 wt.% bulk ZnO composite	59.53	0.902	0.857	5.277	1.282	0.703
	356.01	0.142	0.138	2.935		0.111
	661.66	0.107	0.105	1.743		0.083
	1173.23	0.084	0.080	5.101		0.065
	1332.50	0.078	0.075	4.134		0.061

Table 2. The HDPE/ ZnO composites filler wt.%, density, [ρ], discrepancy Δ%, linear and mass attenuation coefficients at different energies

Sample	Energy [keV]	Linear attenuation coefficient [cm^{-1}]		Δ [%]	Density of ZnO NPs composites [gcm^{-3}]	Mass attenuation coefficient of ZnO NPs [cm^2g^{-1}]
		ZnO NPs composites	Bulk ZnO composites			
10 wt.%	59.53	0.422	0.331	21.563	1.063	0.397
	356.01	0.118	0.112	5.084		0.111
	661.66	0.096	0.0886	7.708		0.090
	1173.23	0.077	0.0704	8.571		0.072
	1332.50	0.071	0.064	9.859		0.067
20 wt.%	59.53	0.516	0.502	2.713	1.067	0.483
	356.01	0.134	0.124	7.462		0.126
	661.66	0.104	0.096	7.692		0.097
	1173.23	0.082	0.074	9.756		0.077
	1332.50	0.074	0.068	8.108		0.069
30 wt.%	59.53	0.71	0.713	–0.422	1.116	0.636
	356.01	0.137	0.132	3.649		0.123
	661.66	0.111	0.102	8.108		0.099
	1173.23	0.087	0.08	8.0459		0.078
	1332.50	0.081	0.075	7.407		0.073
40 wt.%	59.53	0.945	0.902	4.550	1.224	0.772
	356.01	0.152	0.142	6.578		0.124
	661.66	0.121	0.107	11.570		0.099
	1173.23	0.094	0.084	10.638		0.077
	1332.50	0.086	0.078	9.302		0.070

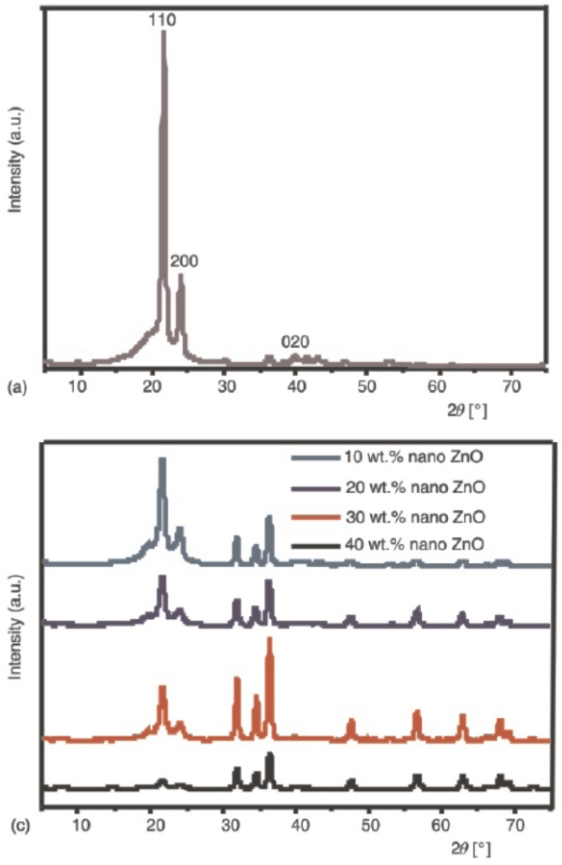

Figure 3. Linear attenuation coefficients of HDPE with (a) bulk and (b) nano ZnO composites *vs.* energy

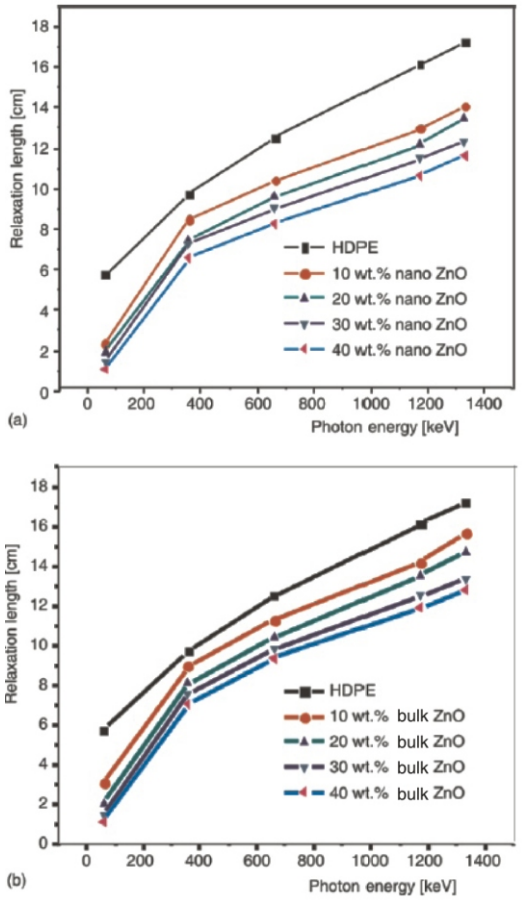

Figure 4. Relaxation length of HDPE with (a) nano ZnO and (b) bulk ZnO composite materials *vs.* photon energy

values Δ% listed in tab. 1, confirm the close agreement between the measured linear attenuation coefficients and XCOM data results.

The μ_m depends on both the incident photon energy and filler wt.%; μ_m increases when filler wt.% increases, but decreases with the increase of incident photon energy. This may be ascribed to the increase of ZnO content within the polymer matrix and the good dispersion of the filler within HDPE. For all investigated gamma ray energies, a significant increase is observed in μ and μ_m values for the composites filled with ZnO for the same wt.%. The probability of interaction between the composite samples and the photon beam is enhanced due to the high electron density and high surface area of ZnO nanoparticles that are uniformly distributed within the polymer matrix. So it is confirmed that both composites containing bulk ZnO and ZnO nanoparticles improve HDPE as a shielding material, but the better attenuation performance is credited to the composites containing ZnO nanoparticles.

The relaxation length, λ, is calculated and listed in tabs. 3 and 4 for all the composite samples at the photon energies 59.53, 356.01, 661.66, 1173.25, and 1332.50 keV, respectively. It represents the average distance between two successive interactions so that the shielding properties of the fabricated samples can be compared easily. Better shielding properties of the materials are attained by those having less relaxation length. Figures 4(a)-4(b) show the variation of the relaxation length, λ, with photon energies for the HDPE/ZnO composite samples. It is obvious that at the lower energy range photons can lose their energy at a shorter distance, whereas the high energy photons need a longer distance. Also, from both figs. 5 and 6, it can be noticed that the samples with high ZnO wt.% show the shorter relaxation length, which confirms their performance in gamma ray attenuation shielding over the energy range 59.53, 356.01, 661.66, 1173.25, and 1332.50 keV, respectively.

Two important parameters must be considered when designing a new shielding material, HVL and TVL. Figures 5 and 6 show the changes of HVL and TVL values with the wt.% of ZnO content at energy 1173.23 keV. Both HVL and TVL values decrease with the increase in ZnO wt.% content. Also, the variation of HVL and TVL for all samples are elucidated in tabs. 3 and 4. These values are useful for selecting the best radiation shielding sample that has a higher content of ZnO nanoparticles.

The heaviness percentage of HDPE with bulk and nano ZnO composites was calculated compared to lead as a standard (100 %) as illustrated in fig. 7. The heaviness percentage of 40 wt.% sample is 9.8 % for nano ZnO and 10.8 % for bulk ZnO. The values obtained confirm that the obtained HDPE/ZnO composites are much lighter compared to lead. In addition to

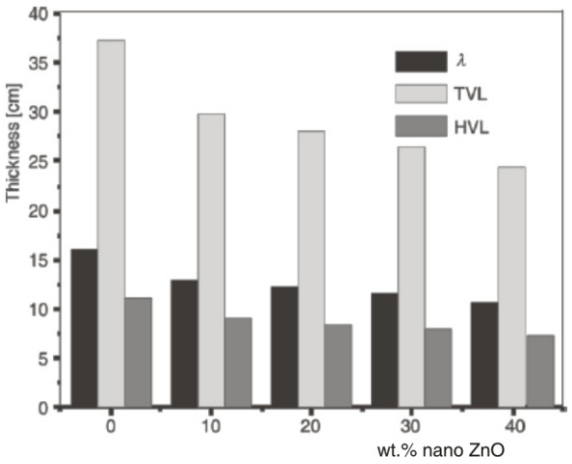

Figure 5. The HVL, TVL, and λ values of HDPE/ZnO nanocomposites measured at energy 1173.23 keV

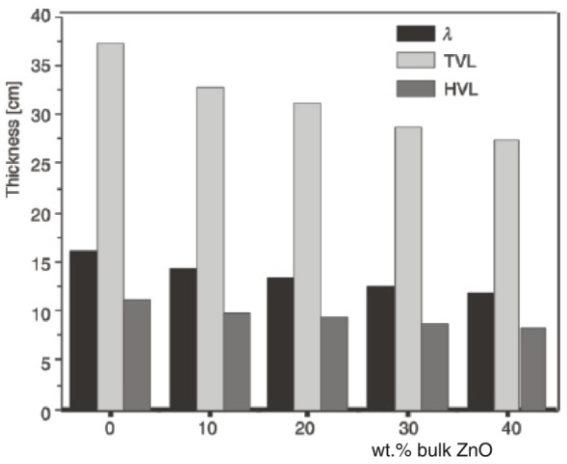

Figure 6. The HVL, TVL, and λ values of HDPE/bulk ZnO composites measured at energy 1173.23 keV

Table 3. The experimental values of HVL, TVL, and λ of HDPE and HDPE/ZnO nanocomposites

Sample	Energy [keV]	HVL [cm]	TVL [cm]	λ [cm]
HDPE	59.53	3.984	13.233	5.747
	356.01	6.730	22.355	9.709
	661.66	8.664	28.782	12.500
	1173.23	11.180	37.138	16.129
	1332.5	11.951	39.700	17.241
10 wt.% nano	59.53	1.643	5.456	2.370
	356.01	5.874	19.513	8.475
	661.66	7.220	23.985	10.417
	1173.23	9.002	29.904	12.987
	1332.5	9.763	32.431	14.085
20 wt.% nano	59.53	1.343	4.462	1.938
	356.01	5.173	17.183	7.463
	661.66	6.665	22.140	9.615
	1173.23	8.453	28.080	12.195
	1332.5	9.367	31.116	13.514
30 wt.% nano	59.53	0.976	3.243	1.408
	356.01	5.059	16.807	7.299
	661.66	6.245	20.744	9.009
	1173.23	7.967	26.466	11.494
	1332.5	8.557	28.427	12.346
40 wt.% nano	59.53	0.733	2.437	1.058
	356.01	4.560	15.149	6.579
	661.66	5.728	19.030	8.264
	1173.23	7.374	24.496	10.638
	1332.5	8.060	26.774	11.628
	661.66	6.796	22.574	9.804
	1173.23	8.664	28.782	12.500
	1332.5	9.242	30.701	13.333

their high performance in radiation shielding, these composites are flexible and non-toxic.

CONCLUSION

New light and considerably low-cost materials for gamma ray radiation shielding were successfully fabricated from HDPE and ZnO as a filler. XRD results confirm the crystallinity of ZnO nanoparticles of average crystallite size 27 nm, which is well dispersed within HDPE. The values of linear and mass attenuation coefficients decrease with the increase in photon energies but increase with ZnO filler content. Heaviness, half-value layer, and tenth-value layer decrease with the increase in ZnO filler concentration. The re-

Table 4. The experimental values of HVL, TVL, and λ of HDPE and HDPE/ZnO bulk composites

Sample	Energy [keV]	HVL [cm]	TVL [cm]	λ [cm]
HDPE	59.53	3.984	13.233	5.747
	356.01	6.730	22.355	9.709
	661.66	8.664	28.782	12.500
	1173.23	11.180	37.138	16.129
	1332.5	11.951	39.700	17.241
10 wt.% bulk	59.53	2.094	6.956	3.021
	356.01	6.189	20.559	8.929
	661.66	7.823	25.989	11.287
	1173.23	9.846	32.707	14.205
	1332.5	10.830	35.978	15.625
20 wt.% bulk	59.53	1.381	4.587	1.992
	356.01	5.590	18.569	8.065
	661.66	7.220	23.985	10.417
	1173.23	9.367	31.116	13.514
	1332.5	10.193	33.862	14.706
30 wt.% bulk	59.53	0.972	3.229	1.403
	356.01	5.251	17.444	7.576
	661.66	6.796	22.574	9.804
	1173.23	8.664	28.782	12.500
	1332.5	9.242	30.701	13.333
40 wt.% bulk	59.53	0.768	2.553	1.109
	356.01	4.881	16.215	7.042
	661.66	6.478	21.519	9.346
	1173.23	8.252	27.412	11.905
	1332.5	8.887	29.520	12.821

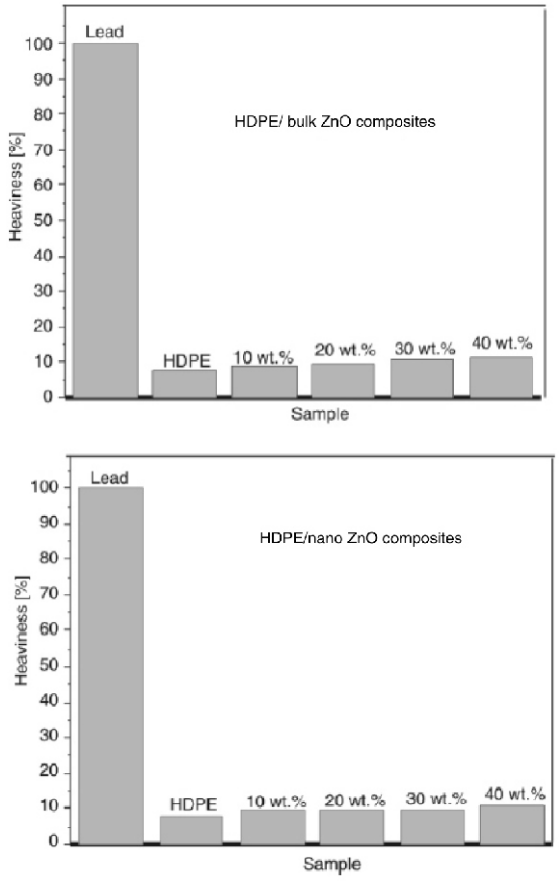

Figure 7. Heaviness percentage values of different HDPE and HDPE/ZnO composite radiation absorbers compared to lead as a standard (100%)

laxation length increases with photon energies but decreases with ZnO wt.%. The composites containing ZnO nanoparticles as a filler show superior performance in radiation shielding for all investigated energies. The ZnO nanoparticles were involved in increasing the interaction probability with gamma rays by effectively increasing the electron density. The fabricated HDPE/ZnO composites are lighter compared to lead, easily manufactured, non-toxic, and highly recommended for manufacturing comfortable, professional outfits for all staff working in radiation facilities and around radiation-based equipment.

ACKNOWLEGMENT

This work was done in the frame of the scientific collaboration between the Physics Department, Faculty of Science, Beirut Arab University, Beirut, Lebanon and the Physics Department, Faculty of Science, Alexandria University, Alexandria, Egypt. National Council for Scientific Research (CNRS), Beirut, Lebanon.

AUTHORS' CONTRIBUTIONS

Experimental part was performed by Z. Alsayed and A. A. Thabet. Theoretical analysis and writing were carried out by M. S. Badawi, R. Awad, A. M. El-Khatib and Z. Alsayed. All authors discussed and

analyzed the results. The figures were arranged by M. S. Badawi and Z. Alsayed.

REFERENCES

[1] Pires, L., Medhat, M., Different Methods of Mass Attenuation Coefficient Evaluation: Influences in the Measurement of Some Soil Physical Properties, *Appl. Radiat. Isot., 111* (2016), Feb., pp. 66-74
[2] Manohara, S., *et al*., On the Effective Atomic Number and Electron Density: A Comprehensive Set of Formulas for all Types of Materials and Energies Above 1 keV, *Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At., 266* (2008), July, pp. 3906-3912
[3] Gowda, S., *et al*., Photon Mass Attenuation Coefficients, Effective Atomic Numbers and Electron Densities of Some Thermos Luminescent Dosimetric Compounds, *J. Phys., 63* (2004), 3, pp. 529-541
[4] Otto, B., Gur, A., Determination of Mass Attenuation Coefficients of Concretes Containing Tincal Concentrator Waste, *Int. J. Phys. Sci., 7* (2012), 44, pp. 5861-5864
[5] Biswas, R., *et al*., Calculation of gamma ray Attenuation Parameters for locally Developed Shielding Material: Polyboron, *J. Radiat. Res. Appl. Sci., 9* (2016), 1, pp. 26-34
[6] Gounhalli, S. G., *et al*., Studies on Mass Attenuation Coefficient, Effective Atomic Numbers and Electron Densities of Some Narcotic Drugs in the Energy Range 1 keV to 100 GeV, *IOSR J. Appl. Phys., 2* (2012), 4, pp. 40-48
[7] Akkurt, I., *et al*., Photon Attenuation Coefficients of Concrete Includes Barite in Different Rate, *Ann. Nucl. Energy., 37* (2010), 7, pp. 910-914
[8] Elkhayatt, A. M., Radiation Shielding of Concretes Containing Different Lime/Silica Ratios, *Ann. Nucl. Energy, 37* (2010), 7, pp. 991-995
[9] Kucuk, N., *et al*., Mass Attenuation Coefficients, Effective Atomic Numbers and Effective Electron Densities for Some Polymers, *Radiat. Protect. Dosim., 153* (2013), 1, pp. 127-134
[10] Bhosale, R. R., *et al*., Radiation Shielding and Gamma Ray Attenuation Properties of Some Polymers, *Nucl Technol Radiat, 32* (2017), 3, pp. 288-293
[11] Aycik, G. A., Belgin, E. E., Effect of Polymer Matrix Type on Electromagnetic Radiation Shielding Performances of PbO Reinforced / Polyethylene, Isophytalic Polyester and Bisphenol A Vinylester Based Composites, *IJCCE., 3* (2018), ISSN: 2367-9042
[12] Mortazavi, S.M.J., *et al*., Design and Fabrication of High Density Borated Polyethylene Nanocomposites as a Neutron Shield, *Int. J. Radiat. Res, 14* (2016), 4, pp. 379-383
[13] Afshar, M., *et al*., Radiation Attenuation Capability and Flow Characteristics of HDPE Composite Loaded with W, MoS_2, and B_4C, *Polym. Compos,* (2017), Jan., pp. 149-158
[14] Mahmoud, M. E., *et al*., Fabrication, Characterization and Gamma Rays Shielding Properties of Nano and Micro Lead Oxide-Dispersed-High Density Polyethylene Composites, *Radiat. Phys. Chem., 145* (2018), Apr., pp. 160-173
[15] Harish, V., *et al*., Lead Oxides Filled Isophthalic Resin Polymer Composites for Gamma Radiation Shielding Applications, *Ind. J. Pure Appl. Phys., 50* (2012), Nov., 847-850
[16] Elmahroug, Y., *et al*., Calculation of Gamma and Neutron Shielding Parameters for Some Materials Polyethylene-Based, *Inter. J. Phys. Res. (IJPR), 3* (2013), 1, pp. 33-40
[17] ***, ASTM., Standard Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement (D 792-91). Vol. 08.01 (1997) ASTM: Annual Book of ASTM Standards, West Conshohocken
[18] El-Khatib, A. M., *et al*., Full-Energy Peak Efficiency of an NaI(Tl) Detector with Coincidence Summing Correction Showing the Effect of the Source-To-Detector Distance, *Chin. J. Phys., 55* (2017), 2, pp. 478-489
[19] Waddon, A., *et al.*, Nanostructured Polyethylene-POSS copolymers: Control of Crystallization and Aggregation, *Nano Lett., 2* (2002), 10, pp. 1149-1155
[20] Manikandan, A., *et al*., Optical and Magnetic Properties of Mg-Doped $ZnFe_2O_4$ Nanoparticles Prepared by Rapid Microwave Combustion Method, *J. Magn. Magn. Mater., 64* (2013), Dec., pp. 118-131
[21] Balazs, A. C., *et al.*, Nanoparticle Polymer Composites: Where Two Small Worlds Meet, *Science, 314* (2006), Nov., pp. 1107-1110
[22] Hubbell, J. H., Photon Mass Attenuation and Energy Absorption Coefficients from 1 keV to 20 MeV, *Int. J. Appl. Radiat. Isot., 33* (1982), 11, pp. 1269-1290
[23] Evans, R. D., 1955, *The Atomic Nucleus*, Tata McGraw-Hill Inc., New York

Received on July 18, 2019
Accepted on September 9, 2019

**Заинаб АЛСАЈЕД, Мохамед С. БАДАВИ, Рамадан АВАД,
Абузеуд А. ТАБЕТ, Ахмед М. ЕЛКАТИБ**

ИСТРАЖИВАЊЕ ПАРАМЕТАРА СЛАБЉЕЊА ГАМА ЗРАЧЕЊА НОВИХ ЗАШТИТНИХ МАТЕРИЈАЛА САСТАВЉЕНИХ ОД НАНО ZnO ПОМЕШАНОГ С ПОЛИЕТИЛЕНОМ ВИСОКЕ ГУСТИНЕ

Екстензивна употреба зрачења брзо се шири светом, укључујући обимне области попут медицинских, индустријских, истраживачких и нуклеарних постројења. Због тога је потреба за проучавањем материјала за заштиту од зрачења и њихових својстава хитнија него икад. У овом раду основна подлога и нано ZnO мешани су сваки пут у истом односу (10-40 масених процената), са полиетиленом високе густине као полимер матриксом и окарактерисани су дифракцијом рендгенских зрака. Резултати су потврдили добру дисперзију основних и нано ZnO честица унутар полимерне матрице. Припремљени композитни узорци коришћени су са различитим дебљинама као гама заштитни материјал, а њихова јачина израчуната је и упоређена са оловом. Коришћењем HPGe детектора експериментално је измерен масени коефицијент слабљења узорака при специфичним енергијама (59.53, 356.01, 661.66, 1173.33, и 1332.50 keV) различитих радиоактивних тачкастих извора (^{241}Am, ^{133}Ba, ^{137}Cs, и ^{60}Co). У зависности од добијених вредности процењени су линеарни коефицијент слабљења, дебљина полуслабљења, дебљина слабљења десет пута, коефицијент тежине и дужина релаксације. Користећи XCOM базу података, теоријски су израчунате вредности коефицијента линераног слабљења, масеног коефицијента слабљења и други параметри за основни ZnO помешан са полиетиленом високе густине. Добијени резултати упоређени су са експерименталним вредностима. Показало се да је заштита од зрачења нано ZnO помешаног са полиетиленом високе густине перспективнија и ефикаснија за гама зрачење.

Кључне речи: нано ZnO, основни ZnO, полиетилен високе густине, композитни узорак, масени коефицијент слабљења, материјал за заштиту од зрачења