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Gamma Radiation Shielding Properties of High-Density Polyethylene

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خواص الحماية من أشعة جاما للبولي إيثيلين عالي الكثافة

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Abstract:
In this study, the linear attenuation coefficients LAC, half-value layer HVL, tenth-value layer TVL, and mean free path MFP of high-density polyethylene HDPE samples were measured at 511, 661.7, 1173, 1274, and 1333 keV gamma energies using a NaI(Tl) spectrometer. The gamma-rays were obtained from 22Na, 137Cs, and 60Co sources. The highest value for LAC was 1.41 cm^{-1} at 511 keV. Conversely, the lowest values for HVL, TVL, and MFP were recorded at the same energy. The results indicated that the linear attenuation coefficient of the HDPE samples was inversely proportional to gamma energies. Conversely, HVL, TVL, and MFP were directly proportional to gamma energies. Consequently, this study concluded that HDPE samples were suitable as shielding material for gamma radiation.

Keywords: Gamma-ray radiation, high-density polyethylene, linear attenuation.

الملخص
في هذه الدراسة، تم قياس معاملات التوهين الخطي LAC، وHVL نصف القيمة، وTVL عُشر القيمة، ومتوسط المسار الحر MFP لعينات البولي إيثيلين عالي الكثافة HDPE عند طاقات غاما 511، و661.7، و1173، و1274، و1333 keV باستخدام مطياف NaI(Tl). تم الحصول على أشعة غاما من مصادر Na22، وCs137، وCo60. بلغت أعلى قيمة لـ LAC 1.41cm-1 عند kev511 . في المقابل، سُجلت أدنى قيم لـ HVL، وTVL، وMFP عند نفس الطاقة. أشارت النتائج إلى أن معامل التوهين الخطي لعينات البولي إيثيلين عالي الكثافة يتناسب عكسياً مع طاقات غاما. في المقابل، كانت HVL، وTVL، وMFP متناسبة طردياً مع طاقات غاما. وبناءً على ذلك، خلصت هذه الدراسة إلى أن عينات البولي إيثيلين عالي الكثافة (HDPE) مناسبة كمواد واقية من أشعة غاما.

الكلمات المفتاحية: إشعاع أشعة جاما، البولي إيثيلين عالي الكثافة، معامل التوهين الخطي.

Introduction

The widespread application of radiation across various industrial, medical, and agricultural sectors necessitates effective shielding solutions to mitigate its potential hazards to human health [1]. Accordingly, utilizing appropriate shielding materials remains the most effective strategy to ensure safety in radiation-related applications [2, 3]. Traditional shielding materials, such as lead, are often heavy and challenging to handle [4]. This has spurred a focus on developing alternative, lightweight, and easily moldable materials, with polymers emerging as an attractive option for radiation shielding [5]. Synthetic polymers, including linear low-density polyethylene (LLDPE), medium-density polyethylene (MDPE), and high-density polyethylene (HDPE), are widely used in plastics and fibers due to their low cost and controllable properties [6, 7]. For radiation shielding, polymers can be used in two main ways: either by creating polymer composites with high atomic number elements like lead or bismuth to enhance absorption [8], or by using them in their pure form. While research on polymerbased shielding is ongoing [9], their potential is significant as they can be customized for specific applications [10, 11]. Previous studies have investigated the attenuation properties of HDPE at specific gamma-ray energies [12, 13]. Building on this prior work, the current study aims to comprehensively investigate the effect of a broader range of gamma-ray energies from standard sources on HDPE's shielding performance, including its linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (mfp).

Material and methods

Sample preparation

Samples were produced by hot-pressing raw HDPE material into a steel mold (10 cm diameter) to achieve various thicknesses ranging from 1 to 2 cm. The raw material was first weighed using a sensitive scale, then melted at 280 °C for 30 minutes in a three-zone tube furnace (HZS and TVS models). The mold was immediately transferred to a hydraulic press and subjected to a pressure of 5-9 bar to form the final sample shape. The samples were then left to cool in the air, as shown in Fig. 1.

(a). Carbolite furnaces.

(b). Pressure machine.

(c). Prepared HDPE sample.

Figure 1. (a), (b) and (c) are steps of preparation of HDPE samples.

Measurement of attenuation coefficients

The linear attenuation coefficients (LAC) of the samples were measured using a gamma counting spectrometer with a "1.5×1.5" NaI(Tl) scintillation detector. The gamma-rays were obtained from standard sources: ^{60}Co (1173 and 1332 keV), ^{137}Cs (661.7 keV), and ^{22}Na (511 and 1274 keV). The detector was placed at a separation distance of 5 cm from the sample. An integrated spectroscopic system, controlled by a personal computer, provided power to the detector and acquired the gamma spectra. The experimental setup is illustrated in a schematic diagram (refer to Fig. 2). All radiation shielding parameters were calculated using the equations listed in Table 1.

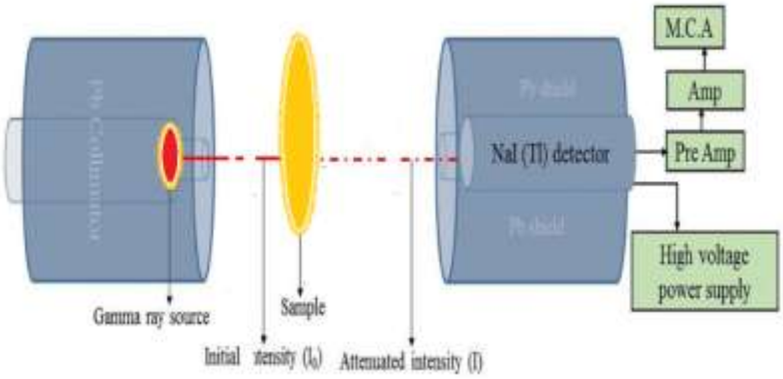

Figure 2. Schematic of the gamma ray attenuation experiments.

Table 1. Calculation equations of radiation shielding factors for the HDPE samples.

Radiation shielding parameter	Equation	Units	References
Linear attenuation coefficient	$I = I_0\, e^{-LCA\, x}$	cm^{-1}	[14,15]
Mean free path	$MFP = \frac{1}{LAC}$	*cm*	[16]
Half value layer	$HVT = \frac{\ln 2}{LAC} = \frac{0.693}{LAC}$	*cm*	[17]
Tenth value layer	$TVT = \frac{\ln 10}{LAC} = \frac{2.301}{LAC}$	*cm*	[18]

Where I_0, I and x refer to the non-attenuated gamma ray photon, attenuated gamma ray photon and HDPE sample material thickness.

Results and discussion

The linear attenuation coefficient (LAC) values for energies ranging from 511 keV to 1332 keV are presented in Table 2 and Fig. 3. The data show that the gamma-ray attenuation properties of the HDPE samples were effective across the studied energy interval. It can be clearly observed that attenuating gamma rays becomes more challenging at higher energies compared to lower energies.

Table 2. Linear attenuation coefficient (cm^{-1}) of different energies (keV)

x cm	LAC				
	511	661.7	1173	1274	1332
2	1.41	1.25	0.70	0.42	0.33
4	0.73	0.61	0.40	0.21	0.19
6	0.56	0.46	0.30	0.16	0.15
8	0.45	0.36	0.26	0.13	0.12
10	0.41	0.30	0.23	0.11	0.09
12	0.35	0.27	0.21	0.10	0.08
14	0.31	0.23	0.18	0.09	0.07

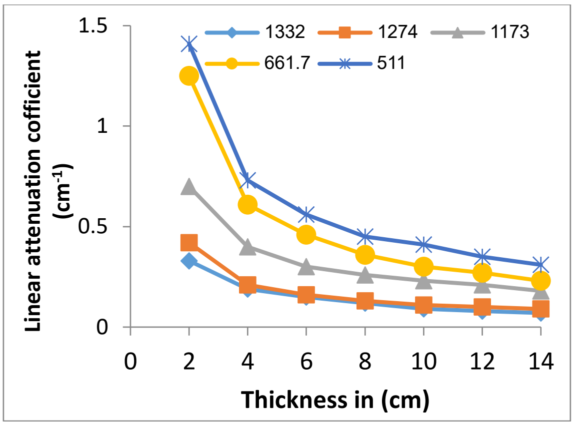

Figure 3. The linear attenuation coefficients in cm^{-1} with thickness in cm at different energies in keV.

The calculated mean free path (MFP), half-value layer (HVL), and tenth-value layer (TVL) of the high-density polyethylene (HDPE) samples are the primary indicators of gamma shielding effectiveness. Lower values for these parameters signify a more effective shield. As presented in Tables 3, 4, and 5 and Figures 4, 5, and 6, the MFP, HVL, and TVL values demonstrate the thickness required to attenuate gamma-ray radiation. It was observed that these values increase steadily with increasing gamma-ray energy from 511 keV to 1332 keV. The study concluded that the MFP, HVL, and TVL values are strongly correlated, and that the gamma-ray shielding effectiveness of HDPE increases with greater thickness. All obtained values are consistent with previously published data [8].

Table 3. Mean free path (cm) of different energies (keV)

x cm	*MFP*				
	511	661.7	1173	1274	1332
2	0.71	0.80	1.43	2.63	2.98
4	1.40	1.65	2.50	4.76	5.12
6	1.77	2.16	3.30	6.25	6.57
8	2.22	2.78	3.82	7.7	8.60
10	2.45	3.31	4.29	9.09	10.61
12	2.81	3.73	4.80	10	11.94
14	3.18	4.28	5.43	11.11	13.50

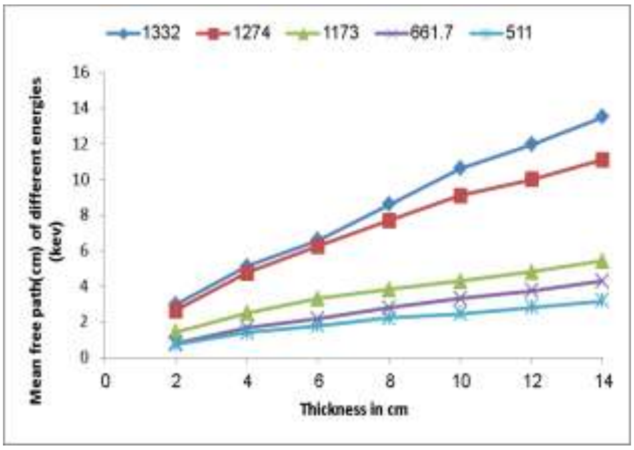

Figure 4. The Mean free path with the thickness for different energies.

Table 4. The half-value thickness (cm) of different energies (keV)

x cm	$X_{1/2}$				
	511	661.7	1173	1274	1332
2	0.49	0.55	0.99	1.824	2.07
4	0.95	1.14	1.73	3.3	3.55
6	1.23	1.49	2.29	4.33	4.56
8	1.54	1.93	2.64	5.33	5.96
10	1.69	2.30	2.97	6.3	7.35
12	1.95	2.59	3.32	6.93	8.28
14	2.21	2.97	3.76	7.7	9.36

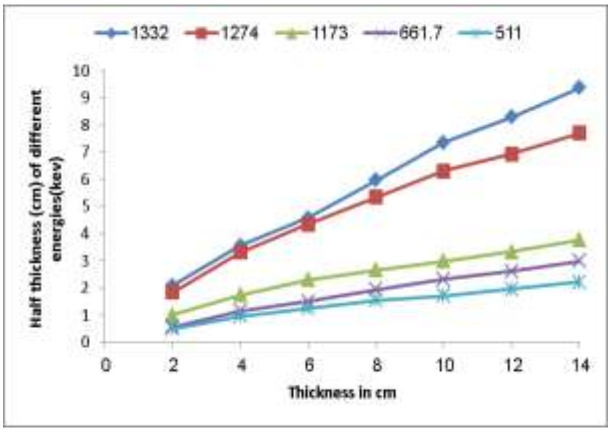

Figure 5. The half-value thickness with the thickness at different energies.

Table 5. Tenth value thickness(cm) of different energies (keV)

x cm	$X_{1/10}$				
	511	661.7	1173	1274	1332
2	1.63	1.84	3.30	6.06	6.87
4	3.17	3.79	5.75	10.96	11.79
6	4.07	4.96	7.60	14.39	15.13
8	5.11	6.40	8.79	17.71	19.80
10	5.63	7.63	9.87	20.93	24.43
12	6.48	8.60	11.04	23.03	27.50
14	7.33	9.85	12.50	25.58	31.08

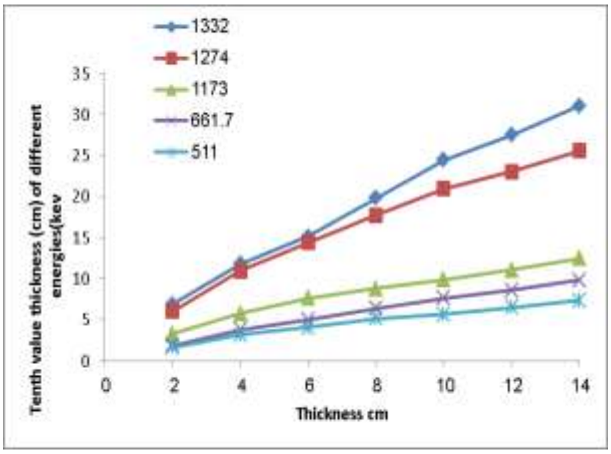

Figure 6. The tenth value thickness with the thickness at different energies.

Conclusion

Gamma-ray shielding properties were measured using a NaI(Tl) scintillation detector for energies ranging from 511 keV to 1332 keV, with ^{137}Cs, ^{22}Na, and ^{60}Co as radiation sources. The linear attenuation coefficient (LAC) was found to be highest at 511 keV and lowest at 1332 keV. This demonstrates that the LAC decreases as the gamma-ray energy increases. Conversely, the mean free path (MFP), half-value layer (HVL), and tenth-value layer (TVL) all increase with increasing gamma-ray energy. These results are valuable for designing radiation shielding applications, and this study's findings can serve as a foundation for future experimental work.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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