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Imam Mohammed Ibn Saud Islamic University

College of Sciences

Department of Physics

Investigation of Radiation Attenuation Properties in Polymer-Based Materials for Shielding Applications

A graduation project submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Science in Applied Physics

Prepared by :

Fahed Al-Anzi

Supervisor:

Dr. Mohammad Marashdeh

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The project's success and final outcome necessitate significant effort and guidance from a wide range of individuals. I am grateful for the help and guidance I received during this project, with only a small amount coming from Allah. Additionally, I would like to express my gratitude to my supervisor and guide, Dr. Mohammad Wassef Marashdeh, who was instrumental in initiating and supervising the project. I diligently work on every step of the project, and Dr. Marashdeh guides me to gather the necessary information to achieve the best possible outcome for the advertisement. He also extends his sincere thanks for the encouraging support and guidance from all faculty members in the Physics Department. I would like to thank my parents, siblings, and friends for their encouragement and support beyond measure.

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Investigation of Radiation Attenuation Properties in Polymer-Based Materials for Shielding Applications

ABSTRACT

This study investigates the radiation shielding properties of various polymer materials by analyzing key attenuation parameters, including the mass attenuation coefficient (μ/ρ), linear attenuation coefficient (μ), mean free path (MFP), and half-value layer (HVL). The polymers examined—such as PVC, PTFE, HDPE, and PDMS—were evaluated over a photon energy range of 10 keV to 3 MeV using the EpiXS program. The results indicate significant variations in shielding efficiency based on material composition and density, with PVC and PTFE demonstrating superior radiation attenuation, particularly at lower photon energies where the photoelectric effect is dominant. At 10 keV, PVC exhibited the highest mass attenuation coefficient (33.439 cm^2/g) and the lowest HVL (0.01 cm), making it the most effective material for low-energy photon shielding, while PTFE also showed strong performance with an HVL of 0.05 cm. In contrast, HDPE had a significantly lower attenuation capacity, with an HVL of 0.35 cm at 10 keV, highlighting its limited shielding efficiency. At 3 MeV, PTFE had the highest HVL (22.27 cm), followed by HDPE (18.07 cm) and PVC (13.27 cm), confirming the reduced effectiveness of polymer shielding at high photon energies. These findings emphasize the importance of selecting materials based on specific radiation energy levels, with PVC and PTFE proving to be the most effective for medical and industrial shielding applications. Future studies should explore the integration of high-Z additives to enhance polymer-based shielding performance across broader energy ranges.

دراسة خصائص التوهين الإشعاعي في المواد القائمة على البوليمر لتطبيقات الحماية

الملخص

تبحث هذه الدراسة في خصائص الحماية من الإشعاع لمواد البوليمر المختلفة من خلال تحليل معلمات التوهين الرئيسية، بما في ذلك معامل التوهين الكتلي(μ/ρ) ، ومعامل التوهين الخطي(μ) ، ومتوسط المسار الحر(MFP) ، ونصف طبقة القيمة (HVL) .تم تقييم البوليمرات التي تم فحصها - مثل PVC و PTFEو HDPEو - PDMSعلى مدى نطاق طاقة الفوتون من 10 كيلو فولت إلى 3 ميجا فولت باستخدام برنامجEpiXS ، تشير النتائج إلى اختلافات كبيرة في كفاءة الحماية الاشعاعية بناءً على تركيبة المادة وكثافتها، حيث أظهر PVC و PTFEتوهينًا إشعاعيًا متفوقًا، خاصة عند طاقات الفوتون المنخفضة حيث يكون التأثير الكهروضوئي هو السائد. عند 10 كيلو فولت، أظهر بولي كلوريد الفينيل أعلى معامل توهين كتلي (33.439 سم^2/جم) وأقل قيمة0.01) HVL سم)، مما يجعله المادة الأكثر فعالية للحماية من الفوتونات منخفضة الطاقة، بينما أظهر بولي تترافلورو إيثيلين أيضًا أداءً قويًا بقيمة HVL تبلغ 0.05 سم. في المقابل، كان لدى بولي إيثيلين عالي الكثافة قدرة توهين أقل بكثير، مع قيمة HVL تبلغ 0.35 سم عند 10 كيلو فولت، مما يسلط الضوء على كفاءته المحدودة في الحماية. ومع زيادة طاقة الفوتون، عند 3 ميجا فولت، كان لدى بولي تترافلورو إيثيلين أعلى قيمة22.27) HVL سم)، يليه بولي إيثيلين عالي الكثافة (18.07 سم) وبولي فينيل كلوريد (13.27 سم)، مما يؤكد انخفاض فعالية الحماية البوليمرية عند طاقات الفوتون العالية. تؤكد هذه النتائج على أهمية اختيار المواد بناءً على مستويات طاقة إشعاعية محددة، حيث أثبتت مادة PVC و PTFEأنها الأكثر فعالية لتطبيقات الحماية الطبية والصناعية. يجب أن تستكشف الدراسات المستقبلية دمج الإضافات عالية Z لتعزيز أداء الحماية القائمة على البوليمر عبر نطاقات طاقة أوسع.

CHAPTER 1
INTRODUCTION

1.1 Introduction

Radiation is present all around us, originating from natural and artificial sources. Natural sources include cosmic rays, terrestrial radionuclides, and radon gas, while human-made sources are used in medical imaging, nuclear power, and industrial applications. While low levels of radiation may not be harmful, prolonged or high-energy exposure can cause tissue damage, cellular mutations, and increased cancer risks [1]. Thus, radiation protection is crucial in fields like healthcare, nuclear energy, and aerospace.

Effective shielding mitigates radiation's harmful effects by reducing its intensity through attenuation, where materials absorb or scatter radiation. Materials vary in their attenuation capacities based on density, atomic number, and thickness. Lead (Pb) has long been preferred for its high density and excellent attenuation properties [2]. However, lead's weight and toxicity make it impractical for applications requiring lightweight, flexible, or environmentally friendly solutions, such as personal protective gear or portable shields. These limitations highlight the need for alternative, efficient, and eco-friendly materials.

Polymers have emerged as promising alternatives to traditional lead-based shielding. These organic compounds consist of repeating molecular units and offer unique properties such as lightweight, flexibility, and non-toxicity. Their versatility allows for a wide range of densities, physical properties, and mechanical characteristics [3]. Polymers can also be engineered to enhance their radiation attenuation by incorporating additives or composites with heavy metal oxides, bismuth, or tungsten. These enhancements improve shielding efficiency while maintaining the benefits of low weight and easy processing [4].

The main goal of this study is to find out how well polymer materials work as radiation shields by looking at their mass and linear attenuation coefficients over a wide range of energies. The mass attenuation coefficient (μ/ρ) shows how dense a material is, which lets you compare different materials. The linear attenuation coefficient (μ) shows how much radiation intensity is lost per unit thickness. In this study, polymer samples will be tested with radiation energies ranging from 10 keV to 3 MeV. This includes low- to high-energy radiation used in nuclear energy, medical imaging, and industrial radiography. The goal is to identify polymers that effectively block radiation while being lightweight, safe, and environmentally sustainable.

This study is valuable as it explores innovative, sustainable approaches to radiation shielding, focusing on safe, lightweight, and versatile materials. By studying the attenuation properties of polymers, the research aims to facilitate the development of shielding solutions suitable for various applications, such as protective gear, portable shields, and eco-friendly alternatives to traditional materials. These advancements could enhance safety and sustainability across multiple industries reliant on radiation protection.

1.2 Objectives

The aim of this study is to investigate the radiation properties of different polymer samples. The specific objectives of the study are as follows:

1- To calculate the linear and mass attenuation coefficients of various polymer samples across a broad photon energy range of 10 keV to 3 MeV, using the EpiXS program, to determine their effectiveness in radiation shielding.

2- To calculate the mean free path (MFP) of the polymer samples within the photon energy range of 10 keV to 3 MeV, providing insights into their shielding thickness requirements and attenuation capacity.

3- To determine the half-value layer (HVL) of the polymer samples across photon energies of 10 keV to 3 MeV.

1.3 Structure of Report

Chapter 1 introduces the concept of radiation shielding properties in polymers and highlights the importance of using the EpiXS program to evaluate these properties. The objectives of this report are also outlined. Chapter 2 provides the theoretical background on radiation interactions with matter and explains the formulas and units used for calculating linear and mass attenuation coefficients, mean free path (MFP), and half-value layer (HVL). In addition, Chapter 3 covers the materials and methods used in this study. It describes the polymer samples, the simulation process with the EpiXS program, and the methodology for determining the attenuation properties. Examples are included to clarify the steps. In addition, Chapter 4 presents the results of the study, including the attenuation properties of polymer samples across the photon energy range of 10 keV to 3 MeV. It discusses the calculated linear and mass attenuation coefficients, MFP, and HVL for each sample, and their relevance to radiation shielding applications. Finally, Chapter 5 concludes the report by summarizing the findings, emphasizing the potential of polymers as alternatives to traditional shielding materials, and suggesting directions for future research.

CHAPTER 2
THEORETICAL BACKGROUND

2.1 X-ray and Gamma ray

X-ray analysis and diagnostics have been extensively researched disciplines in science and engineering since the advent of X-rays in 1895. It continues to be the primary application area for X-rays in medical diagnostics, notwithstanding the growing variety of X-ray modalities. A diverse array of assessment methodologies, including those used in medical, analysis, security, and industrial quality assurance [5]. Roentgen noticed that X-rays are produced when an electron stream strikes a target. During collisions with atomic electrons, the electrons mostly lose their energy, resulting in the ionization and excitation of atoms. X-ray photons may be significantly deflected near atomic nuclei when irradiated, resulting in energy loss. X-rays are classified into two categories: characteristic X-rays and bremsstrahlung X-rays [5].

2.2 Interaction of photon with matter

Since photons have no electrical charge, they do not gradually lose energy when they interact with matter. The main ways that photon energy gets into a material are through photoelectric absorption, Compton scattering, and pair production.

2.2.1 Photoelectric Effect

The photoelectric effect occurs when a photon interacts with an electron that is tightly bonded to an atom. When a photon interacts with an absorbing atom, the atom emits a high-energy photoelectron from one of its bound shells, and the photon is completely annihilated in the process [5]. The unbound electrons do not participate in the interaction; it alone impacts the atom in its whole. The most robust K-shell or shells of an atom may function as a source of photoelectrons for sufficiently powerful gamma rays.

The interaction also generates an ionized absorption atom with a vacancy in one of its bonding shells. An ambient free electron is swiftly attracted into the gap, and/or electrons from alternative atomic shells are displaced into the gap. Thus, it is feasible to generate one or more distinctive X-ray photons. An external free electron is rapidly attracted into the gap, and/or electrons from other atomic shells are displaced into the gap. Thus, it is feasible to generate one or more distinctive X-ray photons [6].

2.2.2 Compton Effect (Compton scattering)

The Compton effect is the result of an energetic photon's interaction with an absorber's loosely bound orbital electron. Theoretical investigations of the Compton effect are based on the idea that the photon interacts with a free, still electron. An electron known as the Compton (recoil) electron is expelled from the atom with kinetic energy, and a photon known as the scattered photon is created with energy that is lower than the incident photon energy [5].

2.2.3 Pair production

Energy-wise, the effect of pair production is possible if the energy of the gamma ray is more than 1.02 MeV, which is twice the energy of an electron at rest.

The possibility for pair production is low at gamma-ray energies that are only a few hundred keV over this limit. However, as the energy rises into the MeV region, this interaction mechanism starts to dominate. The interaction causes the gamma-ray photon to vanish and be exchanged by an electron-positron pair, which must take place in the nucleus's Coulomb field. The kinetic energy distributed by the positron and electron receives any extra energy over the 1.02 MeV required to produce the pair. Because the positron will eventually vanish after slowing down in the absorption medium, two annihilation photons will be created as a consequence of the process [7]. The sensitivity of gamma ray detectors is significantly influenced by the subsequent destiny of this annihilation energy [7].

2.4 Attenuation Coefficients

Any beam of gamma-photons experiences attenuation by photoelectric absorption, Compton scattering, and pair production when a material of a certain thickness is being traversed. Based on the Beer-Lambert law [7],

$$I = I_o \, e^{-\mu x} \qquad (2.1)$$

Where x the thickness of the sample as measured in (cm), I and I_o It estimates beam intensity after traveling through a thickness, and initial intensity, μ is the linear attenuation coefficient as measured in (cm^{-1}) [7].

The density-independent mass attenuation coefficient (μ_m or μ/ρ) is a coefficient which more precisely describes a certain material as measured in ($cm^2\ g^{-1}$) , is given by:

$$\mu_m = \mu/\rho = \sum_i (\mu/\rho)_i\, w_i \qquad (2.2)$$

where $(\mu/\rho)_i$ is the mass attenuation coefficient of constituent element i^{th} , and w_i is the weight fraction of constituent element i^{th}.

2.5 Half-value layer (HVL)

The half-value layer (HVL) is the thickness or layer of a shield or absorption that reduces the intensity of radiation by 50%of its initial intensity as measured in (cm) [7]. represented by the following relationships:

$$HVL= \frac{Ln(2)}{\mu} \qquad (2.3)$$

Furthermore, the average distance between two consecutive gamma photon interactions is indicated by the term mean free path (MFP) as measured in (cm) [7], the equation is:

$$MFP = {}^{1}/_{\mu} \qquad (2.4)$$

CHAPTER 3
MATERIALS AND METHODS

3.1 Materials

This study investigates the radiation shielding properties of various polymer samples. The selected polymers vary in chemical composition, density, and structure, making them suitable for evaluating attenuation characteristics. Table 3.1 presents the polymer materials analyzed in this study, along with their elemental compositions and density ranges.

Table 3.1: List of Polymer Samples Used in This Study [8].

Abbreviation	Full Name	Element Composition	Density (g/cm³)
BTHC	Butyryl-trihexyl-citrate	$C_{20}H_{34}O_7$	1.02
DINCH	Di-iso-nonyl-1,2-cyclohexanedicarboxylate	$C_{24}H_{42}O_4$	0.98
HDI	Hexamethylene diisocyanate	$C_6H_{12}N_2O_2$	1.05
HDPE	High-Density Polyethylene	C_2H_4	0.95
IPDI	Isophorone diisocyanate	$C_{12}H_{18}N_2O_2$	1.05
PAN	Poly(acrylonitrile)	C_3H_3N	1.24
PDMS	Poly(dimethylsiloxane)	$Si(CH_3)_2O$	1.02
PEPA	Polyester Polymer Alloy	$C_2H_5O_2P$	1.15
PES	Polyether Sulfone	$C_{12}H_8O_3S$	1.24
PMP	Poly(methylpentene)	$C_8H_{13}N_2O_5P$	0.83
PTFE	Poly(tetrafluoroethylene)	C_2F_4	2.20
PVC	Poly(vinyl chloride)	C_2H_3Cl	1.40
PVDF	Poly(vinylidene fluoride)	$C_2H_2F_2$	1.75

These polymers were selected due to their widespread applications in various industries, including medical, aerospace, and industrial shielding, as well as their structural and chemical diversity. These polymers exhibit a range of densities from 0.83 g/cm³ to 2.2 g/cm³, and their elemental compositions vary, affecting their interaction with radiation.

3.2 Methodology

This study employs the EpiXS program [9], a well-established tool for photon interaction cross-section calculations, to analyze the attenuation properties of various polymer samples. EpiXS enables researchers to estimate key radiation attenuation parameters, including the mass attenuation coefficient (μ/ρ), across a broad photon energy range (10 keV to 3 MeV). By using EpiXS, a more efficient and standardized approach to evaluating radiation shielding materials is achieved.

To determine the mass attenuation coefficients and other shielding parameters, the EpiXS program was used in a stepwise manner, as follows:

1. **Input Preparation**
   - The polymer's elemental composition and density were entered into the EpiXS database.
   - The photon energy range (10 keV to 3 MeV) was selected for simulation, as shown in Figure 3.1

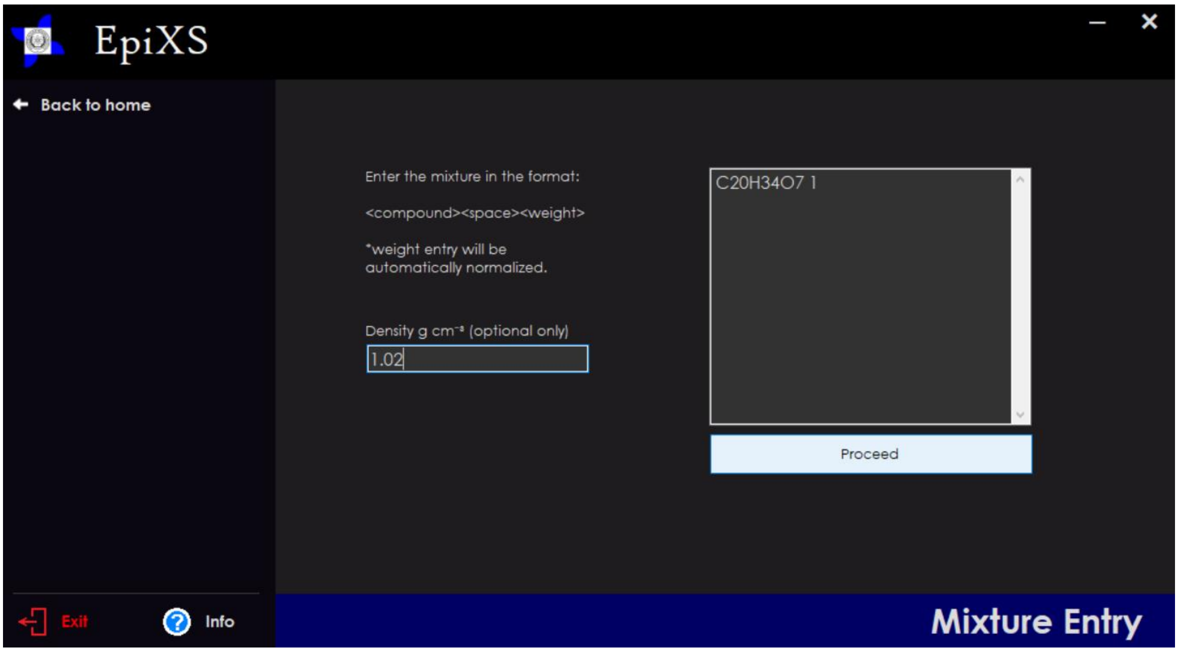

Figure 3.1 EpiXS Program interface for entering the composition of the polymer samples

2. **Calculation of Mass Attenuation Coefficient (μ/ρ)**
    - EpiXS computes the mass attenuation coefficient based on photon interaction cross-sections, considering photoelectric absorption, Compton scattering, and pair production effects.
    - The mass attenuation coefficient is obtained by normalizing the linear attenuation coefficient with the material's density as shown in the Figure 3.2.

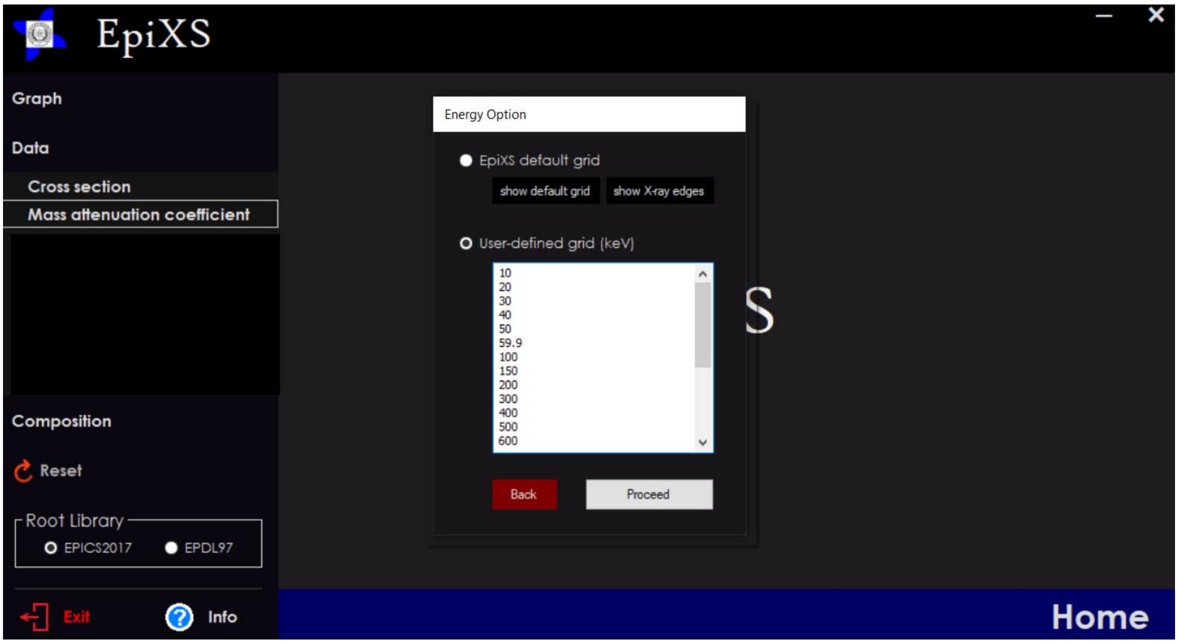

Figure 3.2 EpiXS Program interface for entering the energy (keV) of the polymer samples

3.3 Data Analysis and Interoperation

The results obtained from EpiXS simulations were analyzed to compare attenuation properties across different polymer samples. By evaluating mass attenuation coefficients, linear attenuation coefficients, MFP, and HVL, the study identified materials with superior radiation shielding potential. The polymers exhibiting higher attenuation coefficients and lower MFP and HVL values were considered more effective for radiation shielding applications.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Linear Attenuation Coefficient (μ) Measurement

The linear attenuation coefficient (μ) describes the probability of photon interaction per unit path length and depends on both material composition and density. Materials with higher atomic numbers and densities typically exhibit larger μ values, making them more effective for radiation shielding. The linear attenuation coefficient values further support these findings, as shown in Figure 4.1. At 10 keV, PVC demonstrates the highest linear attenuation coefficient of 46.815 cm^{-1}, while HDPE has the lowest at 1.986 cm^{-1}, highlighting the influence of material density on attenuation properties (Table 4.1). As photon energy increases, the attenuation coefficients decrease due to reduced interaction probabilities, particularly when Compton scattering becomes the dominant mechanism. PTFE and PVC maintain relatively higher μ values even at energies above 1 MeV, reinforcing their effectiveness as shielding materials against high-energy radiation.

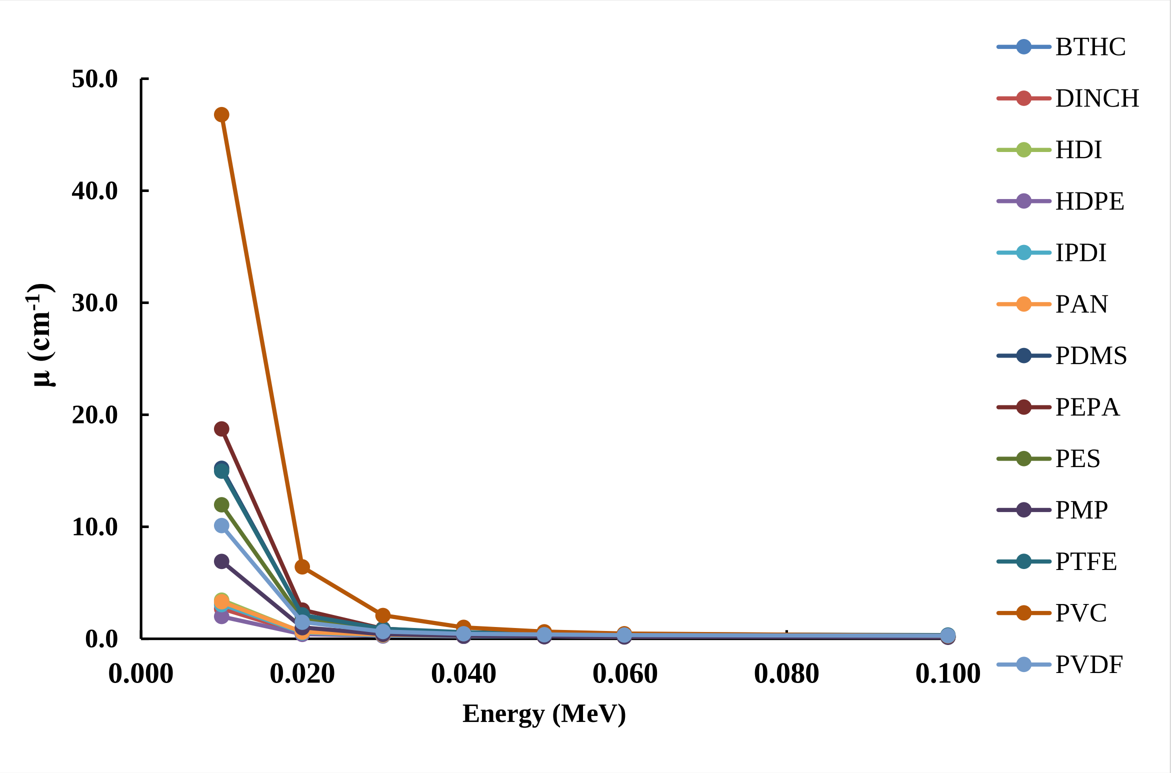

Figure 4.1 Linear attenuation coefficient (μ) of polymer samples over energies from 0.01 MeV to 0.1 MeV.

Table 4.1: Linear attenuation coefficient of the polymer samples used in this study within energies from 10 keV to 0.3 MeV

Energy (MeV)	BTHC	DINCH	HDI	HDPE	IPDI	PAN	PDMS	PEPA	PES	PMP	PTFE	PVC	PVDF
0.010	3.30	2.69	3.46	1.99	3.06	3.30	15.23	18.75	11.97	6.92	14.98	46.81	10.11
0.020	0.57	0.49	0.59	0.41	0.55	0.60	2.10	2.58	1.73	1.00	2.13	6.42	1.49
0.030	0.31	0.28	0.32	0.26	0.30	0.34	0.75	0.91	0.67	0.40	0.89	2.09	0.65
0.040	0.24	0.23	0.25	0.22	0.24	0.27	0.43	0.50	0.41	0.26	0.58	1.02	0.45
0.050	0.21	0.20	0.22	0.20	0.21	0.25	0.31	0.35	0.31	0.20	0.47	0.64	0.37
0.060	0.20	0.19	0.20	0.19	0.20	0.23	0.25	0.29	0.27	0.18	0.41	0.47	0.33
0.100	0.17	0.16	0.17	0.16	0.17	0.20	0.18	0.20	0.20	0.14	0.33	0.26	0.27
0.150	0.15	0.15	0.15	0.15	0.15	0.18	0.15	0.17	0.18	0.12	0.29	0.21	0.24
0.200	0.14	0.13	0.14	0.13	0.14	0.16	0.14	0.15	0.16	0.11	0.26	0.18	0.22
0.300	0.12	0.12	0.12	0.12	0.12	0.14	0.12	0.13	0.14	0.09	0.23	0.16	0.19
0.400	0.11	0.10	0.11	0.10	0.11	0.12	0.11	0.11	0.12	0.08	0.20	0.14	0.17
0.500	0.10	0.09	0.10	0.09	0.10	0.11	0.10	0.10	0.11	0.08	0.18	0.13	0.15
0.600	0.09	0.09	0.09	0.09	0.09	0.11	0.09	0.10	0.10	0.07	0.17	0.12	0.14
0.662	0.09	0.08	0.09	0.08	0.09	0.10	0.09	0.09	0.10	0.07	0.16	0.11	0.14
0.800	0.08	0.08	0.08	0.08	0.08	0.09	0.08	0.08	0.09	0.06	0.15	0.10	0.12
1.000	0.07	0.07	0.07	0.07	0.07	0.08	0.07	0.08	0.08	0.06	0.13	0.09	0.11
1.173	0.07	0.06	0.07	0.06	0.07	0.08	0.06	0.07	0.08	0.05	0.12	0.08	0.10
1.332	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.07	0.07	0.05	0.12	0.08	0.10
1.500	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.05	0.11	0.07	0.09
2.000	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.06	0.04	0.09	0.06	0.08
2.500	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.05	0.03	0.08	0.06	0.07
3.000	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.03	0.08	0.05	0.06

4.2 Mass Attenuation Coefficient (μ/ρ)

The mass attenuation coefficient (μ/ρ) is a key parameter in evaluating a material's ability to attenuate radiation, quantifying how effectively a material absorbs or scatters incoming photons per unit mass. Higher values indicate superior shielding properties, particularly at low photon energies where the photoelectric effect dominates. The mass attenuation coefficient values for different polymer samples were calculated over a range of photon energies (10 keV to 3 MeV). The results indicate that at lower photon energies (10 keV), Poly(vinyl chloride) (PVC) exhibits the highest attenuation coefficient of 33.439 cm²/g, followed by Poly(dimethylsiloxane) (PDMS) at 14.928 cm²/g, while the lowest value is observed for HDPE at 2.090 cm²/g as shown in Table 4.2. The decrease in mass attenuation coefficient with increasing energy is attributed to the dominance of Compton scattering over photoelectric absorption at higher photon energies. Since PVC has a higher atomic number due to the presence of chlorine, it demonstrates superior attenuation at lower energies where photoelectric absorption is the dominant interaction mechanism.

Table 4.2: Mass attenuation coefficient of the polymer samples used in this study within energies from 10 keV to 0.3 MeV

Energy (MeV)	BTHC	DINCH	HDI	HDPE	IPDI	PAN	PDMS	PEPA	PES	PMP	PTFE	PVC	PVDF
0.010	3.24	2.74	3.30	2.09	2.92	2.66	14.93	16.31	9.65	8.34	6.81	33.44	5.78
0.020	0.56	0.50	0.56	0.43	0.52	0.49	2.05	2.24	1.39	1.21	0.97	4.59	0.85
0.030	0.30	0.29	0.30	0.27	0.29	0.28	0.74	0.79	0.54	0.49	0.40	1.49	0.37
0.040	0.23	0.23	0.23	0.23	0.23	0.22	0.42	0.44	0.33	0.31	0.27	0.73	0.26
0.050	0.21	0.21	0.21	0.21	0.20	0.20	0.30	0.31	0.25	0.24	0.21	0.46	0.21
0.060	0.19	0.19	0.19	0.20	0.19	0.19	0.25	0.25	0.22	0.21	0.19	0.33	0.19
0.100	0.17	0.17	0.16	0.17	0.16	0.16	0.18	0.17	0.16	0.16	0.15	0.19	0.15
0.150	0.15	0.15	0.15	0.15	0.15	0.14	0.15	0.15	0.14	0.14	0.13	0.15	0.14
0.200	0.13	0.14	0.13	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.13	0.12
0.300	0.12	0.12	0.12	0.12	0.12	0.11	0.12	0.11	0.11	0.11	0.10	0.11	0.11
0.400	0.10	0.11	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10
0.500	0.09	0.10	0.09	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.09
0.600	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08
0.662	0.08	0.09	0.08	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.08	0.08
0.800	0.08	0.08	0.08	0.08	0.08	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07
1.000	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.06
1.173	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
1.332	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.05
1.500	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.05
2.000	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.04
2.500	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
3.000	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04

4.3 Mean Free Path (MFP)

The mean free path (MFP) represents the average distance a photon travels before interacting with a material, with a lower MFP indicating a higher probability of interaction and, consequently, greater radiation shielding efficiency. The MFP values, as shown in Figure 4.2, reveal that PVC and PTFE exhibit the lowest MFP values at low photon energies (0.021 cm and 0.067 cm, respectively, at 10 keV), indicating superior attenuation properties. In contrast, HDPE and PMP have higher MFP values (0.504 cm and 0.144 cm at 10 keV), suggesting lower photon attenuation efficiency (Figure 4.2). As photon energy increases, the

MFP also increases, implying that photons penetrate deeper before interacting, which reduces the overall shielding effectiveness of these materials at higher energies.

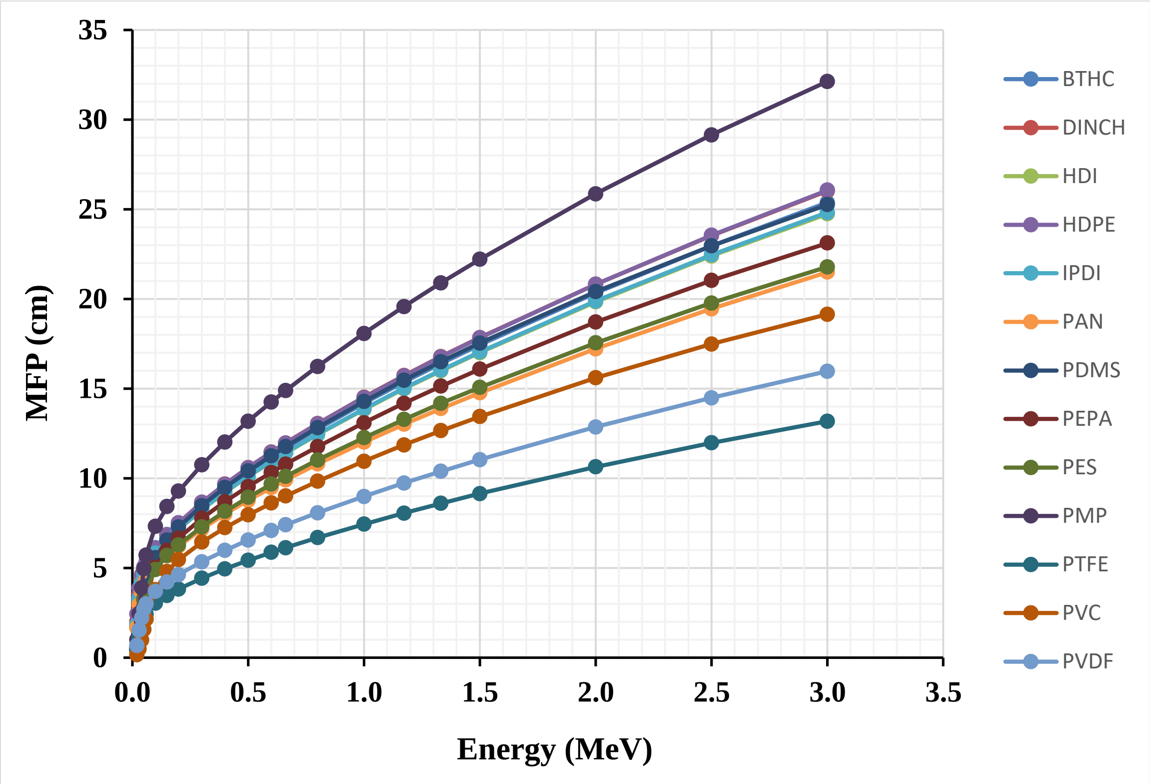

Figure 4.2: Mean free path (MFP) of polymer samples over energies from 0.01 MeV to 0.3 MeV.

4.4 Half-Value Layer (HVL)

The half-value layer (HVL) results demonstrate significant variation in radiation attenuation capabilities among different polymer samples across photon energies ranging from 10 keV to 3 MeV. At low energies (10 keV), PVC exhibits the lowest HVL (0.01 cm), followed by PTFE (0.05 cm), PDMS (0.05 cm), and PEPA (0.04 cm), indicating their superior shielding efficiency due to strong photoelectric absorption as shown in Table 4.3. In contrast, HDPE has a much higher HVL (0.35 cm), reflecting its lower attenuation capability. As energy increases, HVL values rise across all materials due to the transition from photoelectric absorption to Compton scattering. At 100 keV, PVC's HVL increases to 2.62 cm, while PTFE remains lower at 2.10 cm, reinforcing its superior attenuation properties. Meanwhile, HDPE reaches 4.24 cm, highlighting its reduced shielding effectiveness.

Table 4.3: Half-Value Layer (HVL) of the polymer samples used in this study within energies from 10 keV to 0.3 MeV

Energy (MeV)	BTHC	DINCH	HDI	HDPE	IPDI	PAN	PDMS	PEPA	PES	PMP	PTFE	PVC	PVDF
0.010	0.21	0.26	0.20	0.35	0.23	0.21	0.05	0.04	0.06	0.10	0.05	0.01	0.07
0.020	1.22	1.40	1.17	1.69	1.27	1.15	0.33	0.27	0.40	0.69	0.33	0.11	0.47
0.030	2.26	2.46	2.19	2.69	2.29	2.03	0.92	0.76	1.03	1.71	0.78	0.33	1.06
0.040	2.89	3.06	2.81	3.21	2.88	2.53	1.63	1.38	1.69	2.70	1.19	0.68	1.54
0.050	3.27	3.41	3.18	3.50	3.23	2.82	2.26	1.96	2.21	3.44	1.48	1.08	1.86
0.060	3.52	3.64	3.42	3.70	3.46	3.01	2.75	2.43	2.59	3.96	1.67	1.48	2.08
0.100	4.12	4.23	4.01	4.24	4.03	3.50	3.86	3.50	3.41	5.07	2.10	2.62	2.56
0.150	4.64	4.75	4.52	4.76	4.54	3.93	4.55	4.15	3.95	5.84	2.41	3.33	2.92
0.200	5.08	5.20	4.96	5.21	4.97	4.31	5.05	4.62	4.36	6.43	2.65	3.78	3.21
0.300	5.86	6.00	5.72	6.00	5.73	4.96	5.87	5.38	5.05	7.45	3.07	4.46	3.71
0.400	6.55	6.70	6.39	6.70	6.40	5.55	6.57	6.03	5.65	8.33	3.43	5.02	4.14
0.500	7.17	7.34	7.00	7.34	7.01	6.08	7.21	6.61	6.20	9.13	3.76	5.52	4.54
0.600	7.76	7.94	7.57	7.94	7.58	6.57	7.80	7.15	6.70	9.88	4.07	5.97	4.91
0.662	8.10	8.29	7.90	8.29	7.92	6.86	8.15	7.48	7.00	10.32	4.25	6.24	5.13
0.800	8.83	9.04	8.62	9.04	8.64	7.48	8.89	8.15	7.64	11.25	4.64	6.81	5.60
1.000	9.83	10.06	9.59	10.05	9.61	8.33	9.89	9.07	8.50	12.52	5.16	7.59	6.23
1.173	10.64	10.90	10.39	10.89	10.41	9.02	10.72	9.83	9.21	13.57	5.59	8.22	6.75
1.332	11.36	11.63	11.09	11.63	11.11	9.63	11.44	10.49	9.83	14.48	5.96	8.77	7.20
1.500	12.08	12.37	11.79	12.36	11.81	10.23	12.16	11.15	10.44	15.39	6.34	9.32	7.65
2.000	14.09	14.43	13.74	14.43	13.78	11.93	14.14	12.96	12.16	17.92	7.37	10.81	8.91
2.500	15.91	16.31	15.52	16.32	15.56	13.48	15.91	14.58	13.70	20.20	8.30	12.12	10.04
3.000	17.59	18.03	17.15	18.07	17.20	14.90	17.51	16.02	15.10	22.27	9.13	13.27	11.07

A comparative analysis of Figure 4.2 at 0.1 MeV and 0.6 MeV further supports these findings. At 0.1 MeV, PTFE and PVC maintain the lowest HVL values, indicating strong attenuation, whereas HDPE and PMP exhibit significantly higher values, demonstrating weaker shielding performance. At 0.6 MeV, a noticeable increase in HVL occurs for all materials, with PTFE still maintaining relatively lower values compared to other polymers. However, HDPE and PMP show substantial increases in HVL, confirming their reduced effectiveness at higher photon energies. At 3 MeV, the HVL values increase even further, with PTFE reaching 22.27 cm, HDPE 18.07 cm, and PVC 13.27 cm, emphasizing the growing influence of Compton scattering at high energies (Table 4.3). Despite this, PVC and PTFE maintain relatively better shielding performance across energy ranges, making them ideal for medical and industrial shielding applications. Conversely, HDPE and PMP, with higher HVL values, are less suitable for high-radiation environments but may still be useful in lightweight shielding solutions where minimal attenuation is acceptable. These results highlight the necessity of material selection based on specific radiation energy levels to optimize shielding effectiveness.

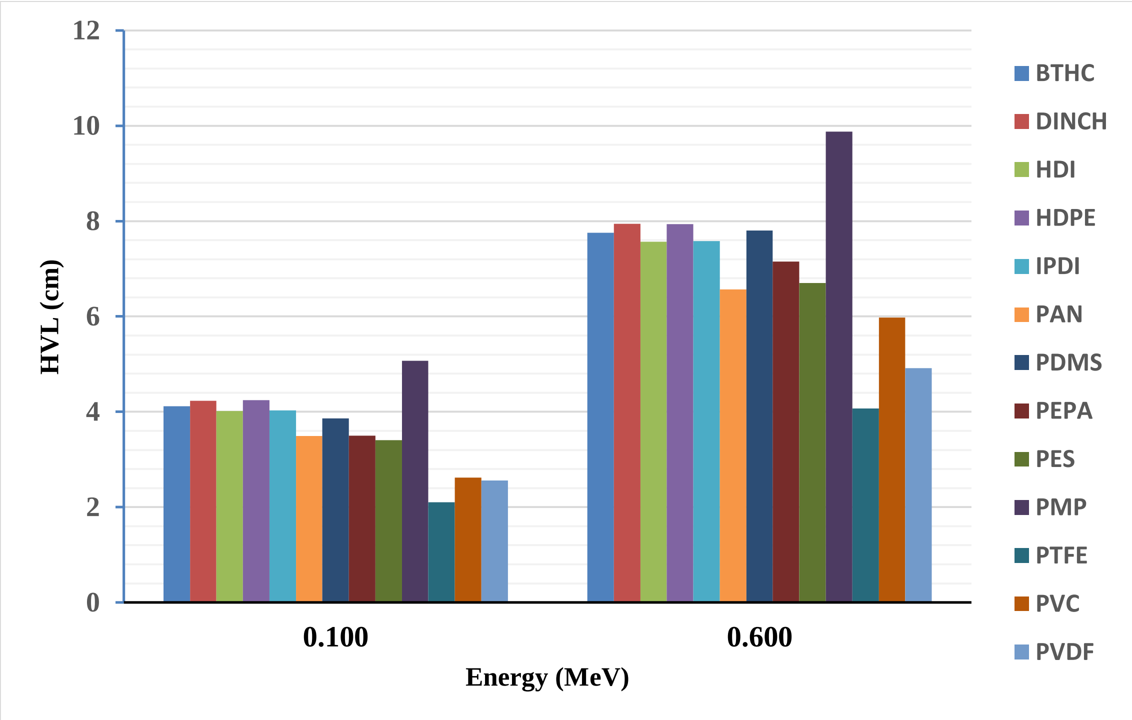

Figure 4.3: Half-Value Layer (HVL) of polymer samples at 0.1 and 0.6 MeV.

CHAPTER 5
CONCLUSION

This study evaluated the radiation shielding properties of various polymer materials by analyzing key parameters, including mass attenuation coefficient (μ/ρ), linear attenuation coefficient (μ), mean free path (MFP), and half-value layer (HVL). The results demonstrate that PVC and PTFE provide superior shielding, particularly at low photon energies, due to their higher attenuation coefficients and lower MFP and HVL values. At 10 keV, PVC exhibited the highest mass attenuation coefficient (33.439 cm^2/g) and linear attenuation coefficient (46.815 cm^{-1}), with an effective atomic number of 16.054. PTFE also showed strong performance with a mass attenuation coefficient of 21.643 cm^2/g.

In contrast, HDPE and PMP had significantly lower shielding efficiency. At 10 keV, HDPE had the lowest mass attenuation coefficient (2.090 cm^2/g), indicating limited photon interaction capability. The MFP and HVL results further confirmed that PVC and PTFE effectively reduce photon penetration. At 10 keV, PVC had the lowest MFP (0.021 cm) and HVL (0.015 cm), making it highly efficient in attenuating radiation. However, at higher energies (3 MeV), the effectiveness of all materials decreased due to the dominance of Compton scattering, with PVC's HVL increasing to 9.134 cm and PTFE's to 22.269 cm.

These findings highlight the importance of material selection based on energy-dependent shielding performance. PVC, with its chlorine content, is particularly effective for low-energy photon attenuation, making it suitable for medical and industrial shielding applications. PTFE, with its higher density, performs well across a broader energy range. HDPE and PMP, while not ideal for high-radiation environments, may still be viable for lightweight shielding applications. Future research should explore polymer composites with high-Z additives to enhance radiation attenuation, particularly at higher photon energies.

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