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Comparative Study of Lead Iodide-Polymethyl Methacrylate Polymer Composites and Polyvinyl Alcohol as a X-ray Shielding Material

Priti Rana[1], Meenakshi[1] and Kulvinder Singh[2]

[1]Department of Physics, Baba Mastnath University, Asthal Bohr, Rohtak, Haryana, India
[2]Department of Physics, Deen Dayal Upadhyaya College, University of Delhi, New Delhi, India

Abstract

X-rays are becoming increasingly important in various fields such as medical diagnosis, cancer treatment, nuclear energy, airport and railway security scanners, and food preservation processes. However, exposure to X-rays can pose significant health risks to individuals working with or around these facilities. Medical professionals, operators, and researchers need effective protection from the harmful effects of high-energy ionizing radiation like X-rays and gamma rays. One of the primary methods of protection is radiation shielding, which involves creating a barrier that blocks or reduces radiation through mechanisms like photoemission and scattering. This shielding is essential for ensuring the safety of those exposed to radiation regularly. Protective clothing and shielding materials, such as lead glasses and rubberized lead sheets, are commonly used. However, heavy materials like lead sheets are gradually being replaced by lightweight alternatives, such as polymer-based sheets. In recent advancements, lead compounds have been integrated with polymers to create lighter and more efficient shielding materials. In this study, lead iodide was incorporated into various polymer composites to assess their effectiveness in blocking X-rays. These polymer composite sheets were produced using a solution-based method and tested under soft X-ray exposure (30 KeV–60 KeV) at room temperature. The results showed that these composite sheets provided varying levels of X-ray absorption, comparable to traditional lead-based shielding materials, but with the added benefits of reduced weight and easier handling.

Keywords: *X-rays, Shielding material, Polymer composite material, Lead iodide.*

Introduction

X-rays play a crucial role in diverse fields such as medicine, industry, biology, agriculture, and environmental sciences. However, exposure to X-rays can harm human cells, causing skin burns, hair loss, and an increased risk of cancer. Hence, proper shielding materials are essential to protect individuals from the harmful effects of X-rays. Radiation shielding is one of the most effective methods of protection, creating a barrier between the radiation source and the user. This barrier absorbs or scatters radiation through photoemission and scattering processes [1].

Lead is widely used as a shielding material because of its high density, atomic number, and attenuation coefficient, making it highly effective against X-rays. Products like lead aprons are frequently used during medical procedures to provide protection. However, the heavy weight of lead-based protective gear can lead to physical strain, such as back pain, especially during prolonged use. Additionally, lead's toxicity poses environmental challenges, and its disposal can create ecological hazards. Its low melting point also increases the risk during emergencies, such as fires. To address these issues, extensive research has been conducted on alternative materials and methods for X-ray shielding. These includes Lead and Lead-Based Composites in which traditional lead shielding has been modified to improve flexibility and reduce lead content. Composites like lead-acrylic and lead-rubber maintain shielding efficiency while being more user-friendly. Further, Bismuth-Based Materials has gained attention as a safer alternative to lead due to its lower toxicity. Compounds like bismuth oxide and bismuth sulphate have demonstrated promising X-ray attenuation properties. Later on, Concrete and Barite Concrete are used in medical and industrial facilities. Research focuses on optimizing their composition and thickness for effective shielding. In the same way, Polymeric materials such as polyvinyl chloride (PVC), polyethylene, and polyurethane have been studied for radiation protection [2,3]. Adding fillers like lead or bismuth to polymers enhances their shielding abilities while reducing weight. After that, the researcher switches to glass and glass composites which are popular in radiology for their transparency and shielding properties. Studies aim to refine their composition and thickness for maximum effectiveness. Later on, Lead-Free Composites like tin, tungsten, and rare earth-based composites are being explored. These materials provide comparable shielding capabilities without the downsides of lead.

Currently, nanoparticle-based materials innovations like gold nanoparticles have been investigated for medical applications, such as targeted cancer therapies, to enhance X-ray attenuation. Recent research focuses on developing lightweight protective materials using composite polymers. This study compares shielding properties of light polymer sheets mixed with lead iodide. These materials are evaluated based on parameters like mass attenuation coefficient, X-ray absorption efficiency, effective atomic number, and density. Replacing heavy glass sheets with polymer composites significantly reduces weight, making them more practical for various applications [4,5].

Lead iodide is preferred over metallic lead due to its stability and effective shielding properties. The attenuation capability of these materials, expressed by their linear and mass attenuation coefficients, depends on factors such as X-ray energy, atomic number, and density. Accurate attenuation coefficient values are crucial for applications in nuclear physics, radiation dosimetry, radiography, crystallography, and other scientific fields [6].

This research highlights the potential of lead-polymer composites as effective, lightweight, and environmentally safer alternatives to traditional lead-based shielding materials.

Experimental Details

Various experimental techniques were employed to prepare and analyze samples of lead iodide and its composites with polymethyl methacrylate (PMMA) and polyvinyl alcohol (PVA). The current study includes the following key processes:

- Fabrication of composite samples
- X-ray switching studies
- Measurement of the mass attenuation coefficient

Fabrication of Samples

Lead iodide of analytical reagent (AR) grade was procured commercially and used as the starting material. Polymer composites of lead iodide were fabricated using a solution-based method at room temperature. The process involved dissolving lead iodide and a polymer in an appropriate solvent such as chloroform. Two polymers were selected as the base materials for this study

1. Polymethyl methacrylate (PMMA)
2. Polyvinyl alcohol (PVA)

Preparation Process

Polymer sheets were broken into small pieces for easier processing. Precise amounts of lead iodide and polymer granules were weighed using a single-pan weighing machine with a least count of 0.01 g. The exact quantities were recorded for consistency.

The preparation process involved the following steps:

1. A clean and dry beaker was taken, rinsed thoroughly with chloroform.
2. For PMMA composites, polymer granules were placed in the beaker, and chloroform (Fisher Scientific, India, with 99% purity) was added as the solvent. For PVA composites, normal water was used as the solvent.
3. The mixture was stirred thoroughly using a magnetic stirrer to dissolve the polymer completely.
4. Lead iodide in fine particulate form was blended into the polymer solution.
5. The final composite solution was cast into sheets using the slow evaporation technique, allowing the solvent to evaporate gradually and form solid sheets.

This method produced thin and uniform composite sheets, suitable for further testing and analysis. The process is illustrated schematically in Fig. 1.

This approach ensures that the lead iodide is evenly distributed within the polymer matrix, allowing the composite sheets to be effectively tested for their X-ray attenuation properties and other characteristics.

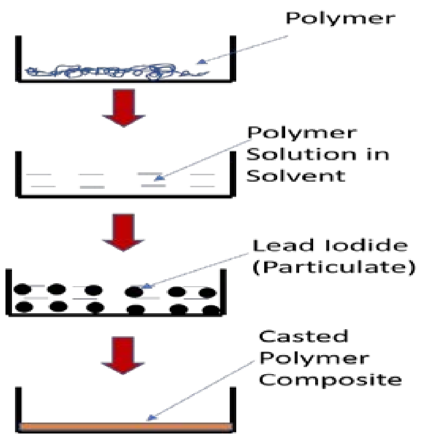

Figure 1: Development of polymer composite using solution methods

The casted polymer composites of lead iodide, prepared at room temperature, were allowed to dry in a vibration-free environment. The mixture was left undisturbed for several days to ensure complete drying. This process resulted in the formation of fine, thin, and uniform layers of lead iodide embedded within the polymer matrices [7,8].

Results and discussion

The prepared composite sheets of PMMA and PVA were then subjected to soft X-rays with energies up to 60 KeV at room temperature. After passing through the composite sheets, the radiation was detected using a lead iodide (PbI_2) sensor for precise measurement. The experimental setup for this process is depicted in Fig. 2.

This approach allowed for an effective evaluation of the X-ray shielding properties of the prepared polymer composite sheets, enabling further analysis of their performance under controlled conditions.

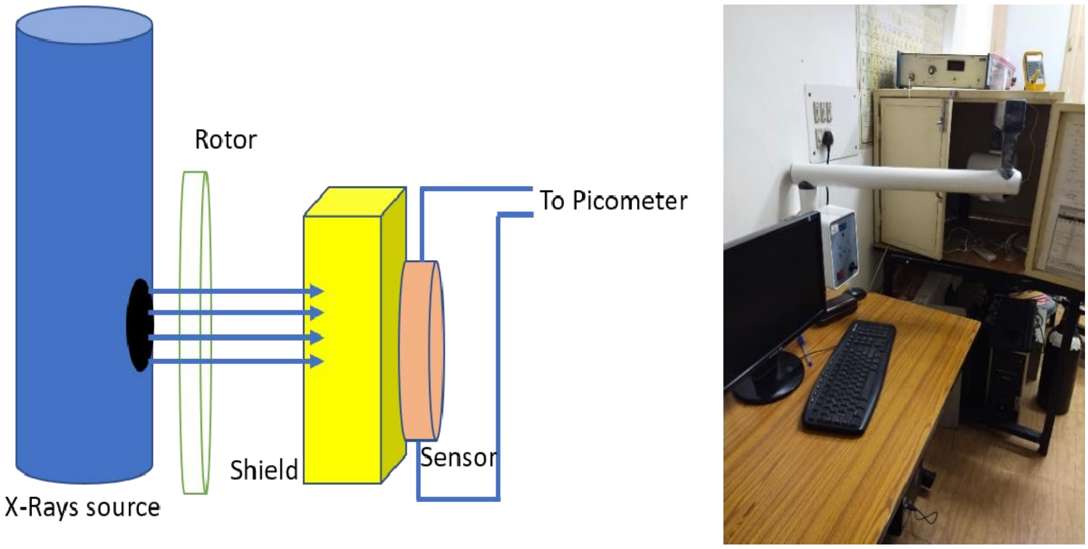

Figure 2: Set-up for X-ray absorption

X-rays were generated using a copper-target X-ray tube operating at a voltage range of 30–60 kV with a maximum current of 10 mA. The samples were placed perpendicularly in the path of the X-ray beam. To vary the thickness of the material, additional sheets were stacked one by one.

The intensity of the X-rays passing through the samples was measured using a detector positioned behind the sheets. The detector current, directly proportional to the X-ray intensity, was recorded. The difference between the photoelectric current (I_p) and the dark current (I_d) was measured and plotted against the sample thickness for both PMMA and PVA composites, as shown in Fig. 3. The data for these plots is presented in Table 1 (PVA) and Table 2 (PMMA).

This method enabled a detailed analysis of how the thickness of the polymer composite sheets influenced their ability to attenuate X-rays, providing critical insights into their shielding efficiency.

Table 1: Sample of Lead Iodide with PVA

Sr. No.	Thickness (in mm)	Photo Current-Dark Current $10e^{-10}$
1.	0	38.1
2.	0.71	27
3.	1.16	21.8
4.	2.366	14.8
5.	3.056	8.76
6.	4.106	6.18
7.	4.816	4.87

Table 2: Sample of Lead Iodide with PMMA

Sr. No.	Thickness (in mm)	Photo Current-Dark Current $10e^{-10}$
1.	0	9.07
2.	0.40	6.0625
3.	0.62	3.6161
4.	0.98	3.1828
5.	1.34	2.2521

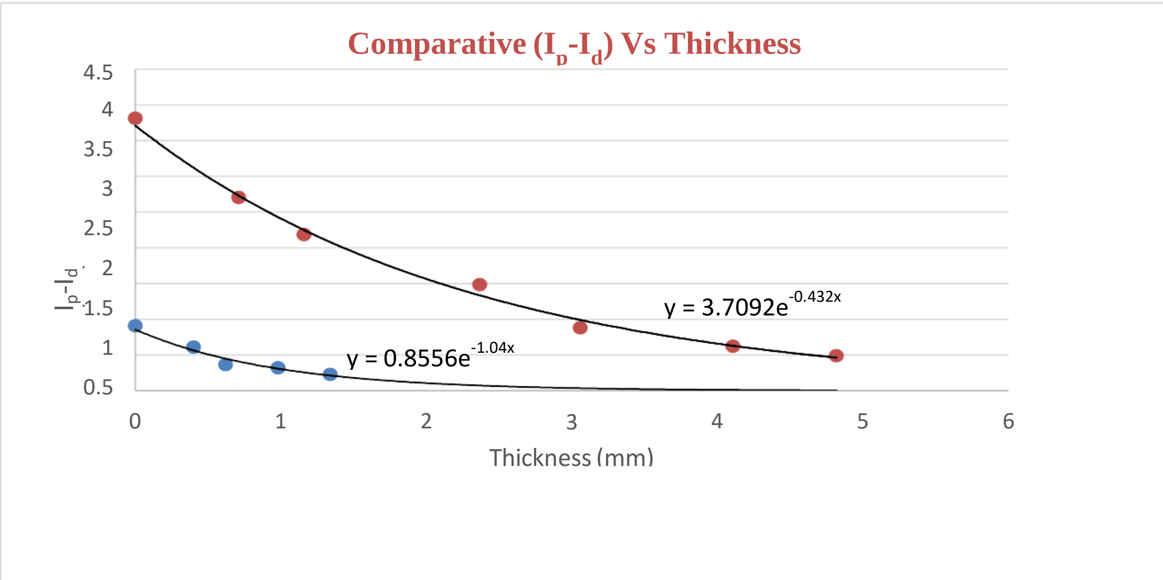

Figure 3: Difference in photocurrent I_p and dark current I_d Vs thickness

The mass attenuation coefficient for the samples was calculated using Beer-Lambert's law. For the lead iodide composite with PMMA, the mass attenuation coefficient was determined to be **7.58 cm²/g**, while for the lead iodide composite with PVA, it was found to be **17.94 cm²/g [9,10]**.

These results indicate that the PVA-based composite exhibits higher attenuation capabilities compared to the PMMA-based composite, showcasing its superior performance in reducing X-ray intensity. This difference highlights the impact of the polymer matrix on the shielding efficiency of the lead iodide composites.

Conclusion

PMMA (Poly(methyl methacrylate)) and PVA (Polyvinyl alcohol) exhibit distinct differences that affect their suitability as shielding materials. PMMA is synthesized from acrylic acid and has a rigid molecular structure, which enhances its interactions with ionizing radiation while PVA, derived from vinyl acetate, has a different chemical structure, influencing its radiation shielding and other properties. PMMA effectively attenuates ionizing radiation like X-rays and gamma rays due to its high electron density, which helps reduce penetration but PVA, with lower electron density, offers relatively less attenuation, though it still provides a moderate level of shielding. PMMA is highly transparent to visible light, making it ideal for applications where visibility is essential, such as protective barriers in medical settings although PVA is also transparent but not to the same extent as PMMA, with its clarity varying depending on additives and formulation. PMMA tends to be more expensive than PVA, which may affect its cost-effectiveness for certain applications. PMMA is less resistant to some organic solvents and chemicals, which can degrade its structure but PVA exhibits better chemical compatibility and can withstand a wider range of chemicals. PMMA is easy to machine, mold, and fabricate, making it suitable for creating custom shapes and designs further PVA is also moldable but more flexible, which can limit its use in rigid structural designs. PMMA is water-resistant, eliminating the need for additional protective coatings and PVA, being water-soluble, requires proper covering for protection when used in environments with moisture. PVA is biodegradable under specific conditions, making it environmentally friendly but PMMA is not biodegradable, which could be a concern in sustainability-focused applications. The densities of lead iodide composites with PMMA and PVA are similar at 1.27 g/cc and 1.29 g/cc, respectively. However, PMMA's higher atomic number contributes to better radiation shielding. PMMA is rigid and durable, offering structural integrity for shielding applications while PVA is more flexible, which can be advantageous in applications requiring pliability but may compromise its structural strength. The water-resistant nature of PMMA composites with lead iodide makes them more robust and eliminates the need for additional protective coverings. In contrast, PVA composites with lead iodide require proper coatings due to their water-soluble nature. PVA composites with lead iodide demonstrated excellent attenuation properties, absorbing up to 69% more X-rays compared to conventional lead shielding materials. These sheets are also lightweight, making them a promising alternative for X-ray shielding applications. Overall, both materials have unique strengths, but the choice depends on the specific requirements of the shielding application, such as water resistance, cost, and environmental impact.

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