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ORIGINAL

Experimental determination of radiation absorption coefficients for gamma radiation in various metals using the Na-I script detector system

Determinación experimental de los coeficientes de absorción de radiación gamma en varios metales utilizando el sistema detector de script Na-I

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ABSTRACT

Introduction: the radiation absorption coefficient (μ) is a critical parameter for accurately calculating safe shielding requirements against radiation exposure. This coefficient is influenced by the type and energy of the radiation, as well as the nature and density of the shielding material. Determining this value for candidate materials is essential for safety protection applications.
Method: this study focused on experimentally determining the linear absorption coefficient (μ) of three common shielding materials: copper (Cu), lead (Pb), and aluminum (Al). The measurements were conducted using gamma radiation emitted from Cesium-137 (Cs-137) and Cobalt-60 (Co-60) radioactive sources. Na-I scintillation detector counting system was employed to measure the attenuation of the gamma rays as they passed through the material samples.
Results: the experimental results for the radiation absorption coefficients of copper, lead, and aluminum for the specified gamma energies were obtained. These measured values demonstrated consistency with previously published and documented results for the same materials and energy ranges.
Conclusions: the findings confirm the reliability of the experimental methodology and the importance of these determined absorption coefficients for designing effective radiation shielding. The established μ values for Cu, Pb, and Al can be confidently used in safety calculations against exposure to Cs-137 and Co-60 gamma radiation.

Keywords: Radiation Absorption Coefficient; Gamma Radiation; Na-I Scintillation Detector.

RESUMEN

Introducción: el coeficiente de absorción de radiación (μ) es un parámetro crítico para calcular con precisión los requisitos de blindaje seguro contra la exposición a la radiación. Este coeficiente se ve influenciado por el tipo y la energía de la radiación, así como por la naturaleza y la densidad del material de blindaje. Determinar este valor para los materiales candidatos es esencial para las aplicaciones de protección de seguridad.
Método: este estudio se centró en la determinación experimental del coeficiente de absorción lineal (μ) de tres materiales de blindaje comunes: cobre (Cu), plomo (Pb) y aluminio (Al). Las mediciones se realizaron utilizando radiación gamma emitida por fuentes radiactivas de cesio-137 (Cs-137) y cobalto-60 (Co-60). Se empleó un sistema de conteo con detector de centelleo de Na-I para medir la atenuación de los rayos gamma al atravesar las muestras de material.

Resultados: se obtuvieron los resultados experimentales de los coeficientes de absorción de radiación de cobre, plomo y aluminio para las energías gamma especificadas. Estos valores medidos demostraron consistencia con los resultados previamente publicados y documentados para los mismos materiales y rangos de energía.
Conclusiones: los hallazgos confirman la fiabilidad de la metodología experimental y la importancia de los coeficientes de absorción determinados para el diseño de un blindaje eficaz contra la radiación. Los valores μ establecidos para Cu, Pb y Al pueden utilizarse con seguridad en los cálculos de seguridad frente a la exposición a la radiación gamma de Cs-137 y Co-60.

Palabras clave: Coeficiente de Absorción de Radiación; Radiación Gamma; Detector de Centelleo de Na-I.

INTRODUCTION

When ionizing radiation, including alpha, beta, gamma, and X-rays, traverses' matter, a range of physical phenomena are initiated. The specific effects are contingent upon the energy and type of the radiation, as well as the elemental composition of the medium. Fundamentally, these interactions are characterized by the transfer of energy, which results in the excitation and ionization of the atoms comprising the material.[1,2]

Gamma rays are quanta of electromagnetic energy known as photons, which possess no electric charge and exhibit extremely short wavelengths, so when they pass through matter, gamma rays do not directly ionize matter. However, when photons interact with atoms of matter, they can knock out electrons or create electron-positron pairs, which are electrically charged particles that directly ionize matter and create other charged particles.[3,4] The basic interactions between photons and matter include: the photoelectric effect, Compton scattering (also known as non-coherent scattering) and the pair production effect. The intensity of an incident gamma ray beam decreases exponentially as it propagates through an absorbing medium. This phenomenon is called gamma radiation absorption in matter. The amount of radiation reduced depends on the quality of the radiation beam, the material, the density of the sample and the thickness of the sample through which the radiation beam passes.[5]

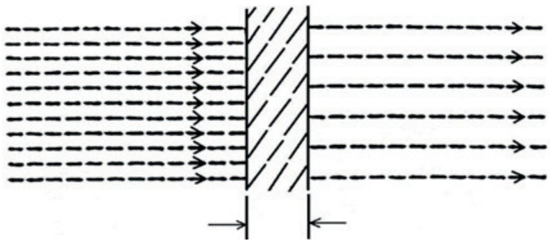

Figure 1. Radiation absorption process

To calculate the absorption of gamma radiation in matter, we use the formula:[6]

$$I = I_0 e^{-\mu x} \quad (1)$$

The equation describes the attenuation of radiation intensity, where I_0 is the incident intensity and I is the transmitted intensity after passing through a material of thickness x (cm). The linear absorption coefficient, μ, characterizes the material's attenuation properties.

As a result of the experiment, we can measure the decrease in the number of counts recorded by the system after radiation through the material instead of measuring the decrease in radiation intensity. Thus, we can use the formula to calculate the decrease in radiation according to the number of counts recorded when passing through the material as follows:[1]

$$N = N_0 e^{-\mu x} \quad (2)$$

$$\mu = -\frac{\ln\left(\frac{N}{N_0}\right)}{x} \quad (3)$$

In there:

N: Count recorded when there is shielding material between the source and the meter.

N_0: Count recorded when there is no shielding material between the source and the meter.

Thus, the experiment determines the count N, the count N_0 corresponding to metal materials with different thicknesses x. From there, the radiation absorption coefficient of the metal for gamma radiation can be calculated.

While the theoretical framework for gamma attenuation is well-established, with sophisticated computational models like XCOM providing highly accurate cross-section data for all elements [7] a persistent knowledge gap necessitates continued experimental validation. This gap arises primarily because real-world measurements often deviate from the idealized narrow-beam conditions assumed by theory. Specifically, practical laboratory setups, including those employing the commonly used NaI scintillation detector system, frequently operate in a semi-broad-beam geometry. This configuration allows scattered photons (primarily from Compton events) to reach the detector, leading to a measured attenuation coefficient that is lower than the theoretical value.[8,9] Review studies consistently emphasize that the specific characteristics of the detector, such as the moderate energy resolution of the NaI crystal, must be empirically characterized to accurately isolate photopeak events and quantify the contribution of scattering to the overall measurement uncertainty.[10] Furthermore, the fundamental exponential attenuation experiment serves as a cornerstone of radiation physics education and requires continuous, high-quality experimental validation to ensure reliable data for both routine instrument calibration and pedagogical reinforcement of theoretical concepts.[11,12] Therefore, a systematic study is required to bridge the gap between theoretical prediction and the practical measurements obtained using this widely utilized detector system.

The primary objective of this work is to conduct a detailed, systematic experimental determination of the linear attenuation coefficients of various metallic absorbers for key gamma energies from Cs- 137 and Co-60 using the NaI Scintillation Detector System. The novelty and main contribution of this research are threefold: it provides current and verified empirical data for common shielding materials measured under non-ideal, yet typical, laboratory conditions. This analysis explicitly addresses and characterizes the influence of the practical semi-broad-beam geometry and the inherent response of the NaI detector system. The research establishes a robust, optimized experimental protocol that can serve as a high-fidelity guide for accurate attenuation measurements, directly benefiting educational laboratories and routine calibration procedures in the field of radiation physics.

METHOD

Material for measuring absorption coefficient

Three distinct metal samples—Aluminum (Al), Copper (Cu), and Lead (Pb)—were utilized as attenuators. All samples were sourced with 99 % minimum purity, a crucial parameter for reliable comparison with theoretical attenuation coefficients. The characteristics of the attenuators were as follows:

Table 1. Material for measuring absorption coefficient

Material	Geometry	Nominal Diameter/ Edge Length	Thicknesses Used (x)	Purity
Aluminum (Al)	Circular Discs	3,00±0,01 cm	0; 2, 5,11,13 cm	99,99 %
Copper (Cu)	Square Sheets	8,00±0,01 cm	0; 0,5; 1,5; 2,2 cm	99,99 %
Lead (Pb)	Circular Discs	3,00±0,01 cm	0; 0,5; 1; 2; 3 cm	99,99 %

The thicknes was adjusted by stacking individual, precisely manufactured plates of known thickness (measured with a micrometer with ± 0,01 mm uncertainty).

The choice of geometry (circular for Al and Pb; square for Cu) was dictated by sample availability. However, all samples were ensured to be large enough to fully cover the entire active face of the detector crystal and shield the source area, thereby minimizing geometric errors and the contribution of photons scattered around the absorber edge.

Gamma radiation source

The experimental setup utilized two standard gamma radiation sources, Cesium-137 (Cs-137) and Cobalt–60 (Co-60), provided by the Institute of Nuclear Science and Technology, Vietnam Atomic Energy Institute. The Cs-137 source emits a principal gamma ray at 661,66 keV, while the Co-60 source emits two primary gamma rays at 1173,24 keV and 1332,50 keV.

Gamma energy measuring device

The gamma energy measurement was performed using a NaI Scintillation Detector System. The detector utilized a thallium-doped sodium iodide crystal, cylindrical in shape, with dimensions of 7,62 cm * 7,62 cm, manufactured by Canberra (USA).

The detector was connected to an OspreyTM digital tube base, which integrates all essential signal processing components: a high-voltage power supply (HVPS), a preamplifier, and a multi-channel analyzer (MCA). The OspreyTM base communicated with a control computer via a USB port. The gamma spectra were recorded and processed using the Genie2k software platform. The recorded count is proportional to the energy intensity of the radiation beam.

Counting procedure and background subtraction:

For each material and corresponding thickness, the measurement procedure was rigorously standardized to ensure statistical reliability. Each spectrum was acquired for a fixed live time of 600 seconds (10 minutes) to minimize uncertainties arising from statistical fluctuations. The initial measurement established the unattenuated count rate (N_0) in the full-energy peak by performing the measurement with no absorber (x=0). This baseline measurement was repeated three times, and the mean and standard deviation were calculated to establish the reference N_0. Subsequently, the attenuated count rate (N) was determined by repeating the measurement for each specific absorber thickness (x). To accurately isolate the source-specific radiation, a separate background spectrum (with the source removed and the experimental setup intact) was measured for an extended period of 1800 seconds (30 minutes) both prior to and after the main runs. This background component was automatically stripped from all acquired N and N_0 spectra using the Genie2k software, thereby ensuring that the recorded counts were purely attributable to the gamma sources.

RESULTS

The results of the sample measurements with shielding materials to determine the recorded counts of the source when absorbed by the shielding materials are shown in figure 2, figure 3 and figure 4.

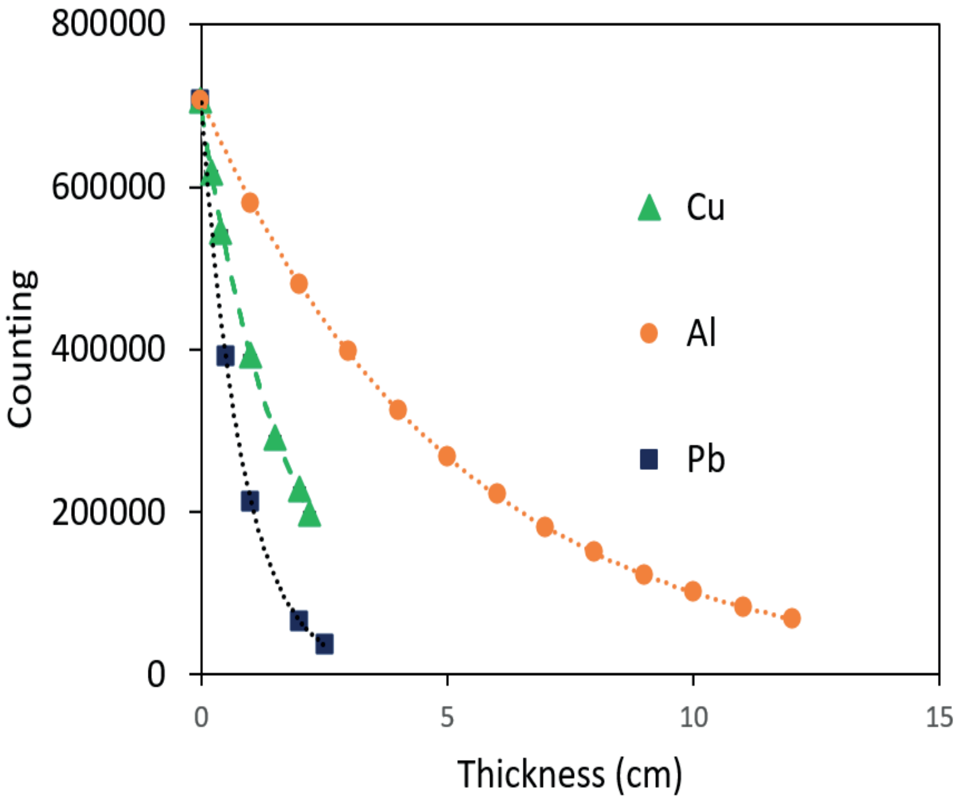

Figure 2. Count decay records the decrease in energy intensity of gamma radiation emitted from Cs-137 with thickness

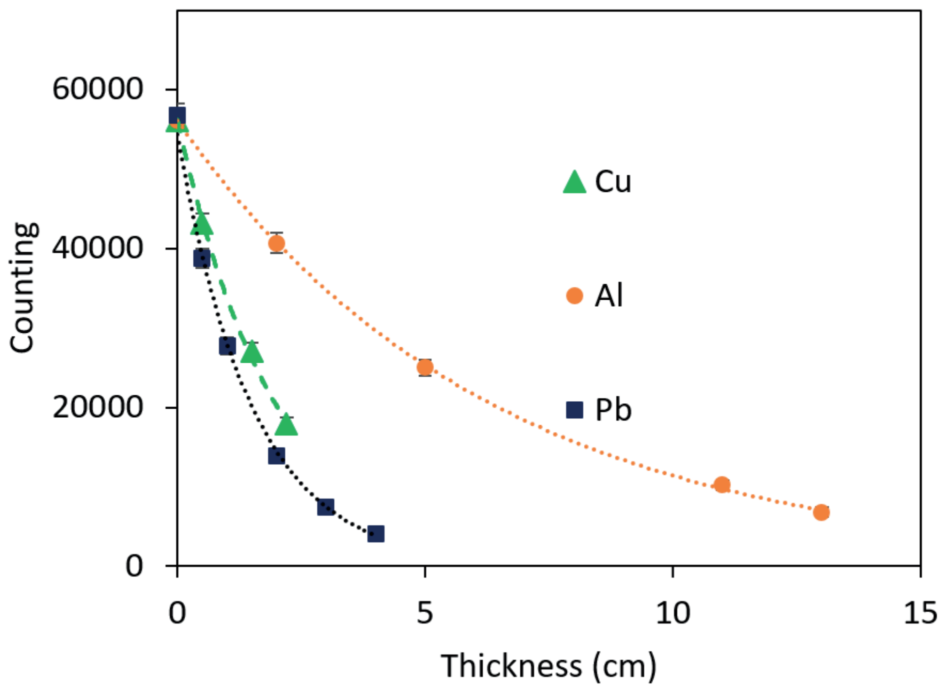

Figure 3. Count decay records the decrease in energy intensity of gamma radiation emitted from Co-60 (1173 keV)

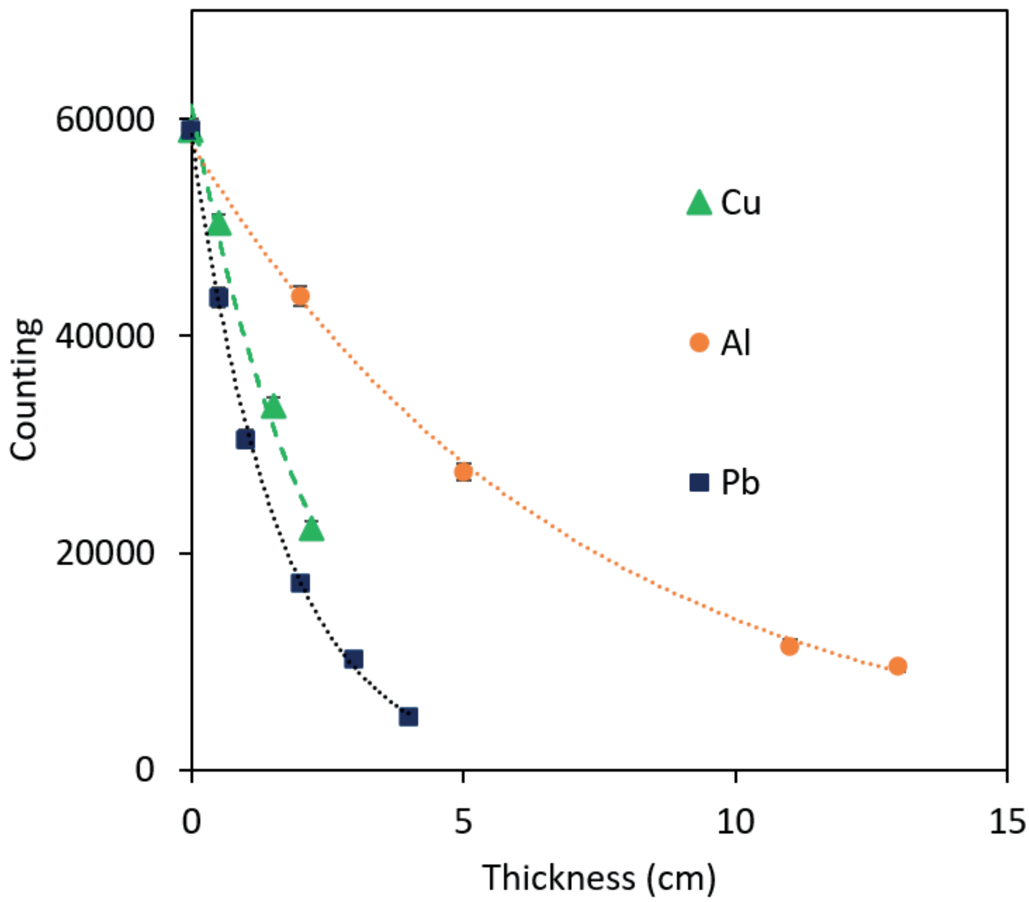

Figure 4. Count decay records the decrease in energy intensity of gamma radiation emitted from Co-60 (1332 keV)

Based on the results of the count attenuation recording the decrease in energy intensity of gamma radiation from Cs-137 and Co-60 sources, we calculate the radiation absorption coefficient of the materials according to the table below.

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Table 2. Radiation absorption coefficients of aluminium, copper and lead

Energy (keV)	Radiation absorption coefficient μ (1/cm)		
	Aluminum	Copper	Lead
661,66	0,195	0,566	1,179
1173	0,159	0,511	0,611
1332	0,143	0,439	0,609

Gamma radiation is high energy photons. Different materials absorb different amounts of it depending on the number of atoms in the material that can block it. Lead is very dense, meaning there are many atoms with many particles that can block it. Therefore, lead is very good at blocking gamma rays, better than less dense materials with lower atomic numbers (number of protons in their nuclei).[5,13]

The mass attenuation coefficients do not depend on the density of the absorber because the fundamental interactions can be expressed in terms of cross-sections per atom and when they are multiplied by the number of atoms per gram, we directly obtain the Mass attenuation coefficient. This study result is considered to be consistent with previous research results on mass attenuation coefficient of aluminium, copper and lead.[14]

Table 3. Experimental data on the mass attenuation coefficients of aluminum, copper, and lead

Energy (keV)	Mass attenuation coefficient (cm^2/g)		
	Aluminum	Copper	Lead
661,66	0,072	0,063	0,104
1173	0,059	0,057	0,054
1332	0,053	0,049	0,054

DISCUSION

The observed variations in the experimental μ as a function of both gamma-ray energy and the atomic number (Z) of the absorber are deeply rooted in the energy-dependent probabilities of the three dominant photon interaction processes: the photoelectric effect, Compton scattering, and pair production.

For all tested materials (Al, Cu, and Pb), a marked decrease in the attenuation coefficient was observed as the energy increased from 661,66 keV to 1332,50 keV. This energy regime falls predominantly within the Compton scattering region. The cross-section for Compton scattering is approximately inversely proportional to the photon energy (E), leading to higher penetrating power and thus a lower μ value as the energy increases. Furthermore, the attenuation values for the two Co-60 energies (1173,24 keV and 1332,5 keV) are closely grouped. This behavior confirms the theoretical prediction that the rate of change in the total attenuation cross-section is significantly reduced in the intermediate energy range, where Compton scattering reaches its maximum relative contribution before pair production becomes substantial.

The influence of the absorber's atomic number is most crucial for understanding the overall shielding efficiency. The experimental data clearly demonstrates that the atomic number Z is the decisive factor, but its impact is highly energy-dependent:

Low-to-intermediate energy (661,66 keV): At 661,66 keV, the linear attenuation coefficient for Lead (Z=82) is dramatically higher (approximately 6,7 times greater) than that of Aluminum (Z=13). This significant divergence confirms the strong dominance of the photoelectric effect at this energy. The photoelectric cross-section scales aggressively with the atomic number, making high Z materials vastly superior absorbers for medium-energy gamma rays.

High Energy (1332,50 keV) and Convergence: As the photon energy rises to 1332,50 keV, the attenuation coefficient ratio between Lead and Aluminum decreases significantly. This indicates a convergence of attenuation capabilities. At these higher energies, the photoelectric effect has diminished, and Compton scattering becomes the primary interaction mechanism for all three materials. Since the Compton cross-section is proportional to the electron density (number of electrons per gram), and the electron density is roughly constant (approx. 0,5) for most elements, the attenuation differences are less pronounced. Lead's remaining attenuation superiority stems primarily from its high mass density, which ensures a greater number of interaction sites per unit length.

CONCLUSION

Radiation absorption coefficients for three high purity materials aluminum, copper, and lead were measured with two Cs-137 and Co-60 sources using a Na-I scintillation detector. Lead showed the best radiation absorption ability at low energy levels, at high energy levels there was no clear difference between the absorption abilities of the three studied metals at high energy.

To enhance the precision and scope of these findings, future work should focus on two key areas. Firstly, methodological refinement is essential: subsequent studies must incorporate Monte Carlo simulations (e.g., MCNP or Geant4) to model the current experimental setup precisely, allowing for the calculation of a geometric correction factor that compensates for the known systematic error introduced by the semi-broad-beam geometry. Secondly, the scope of investigation must be expanded: this includes utilizing a higher-resolution detector, such as a High Purity Germanium (HPGe) detector, to minimize uncertainties in photopeak determination, and extending the energy range to include gamma rays below 100 keV (to fully map the photoelectric effect) and above 2 MeV to observe the onset of pair production, thereby providing a complete empirical characterization of all three primary photon interaction mechanisms.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Conceptualization: Doan Thi Ngoc Bich; Tran Thi Nhan.
Data curation: Tran Thi Nhan.
Formal analysis: Tran Thi Nhan, Doan Thi Ngoc Bich.
Research: Tran Thi Nhan.
Methodology: Doan Thi Ngoc Bich.
Project management: Doan Thi Ngoc Bich, Tran Thi Nhan.
Drafting - original draft: Doan Thi Ngoc Bich, Tran Thi Nhan.
Writing - proofreading and editing: Doan Thi Ngoc Bich, Tran Thi Nhan.