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Determination of the linear attenuation coefficients of aluminum, iron and lead for collimated 661.66 keV gamma rays using TCS-172 gamma scintillation survey meter

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Abstract. *The linear attenuation coefficients of aluminum (Al), iron (Fe), and lead (Pb) for 661.66 keV gamma rays were determined based on gamma dose rate measurements obtained using a handheld TCS-172 gamma scintillation survey meter. The gamma-ray beam, emitted from a Cs-137 radioisotope source, was collimated using a narrow-beam geometry to minimize scattering effects. The comparison of experimental results with simulation and published data demonstrated good agreement. The experiment was carried out at the Training Center of the Nuclear Research Institute in Da Lat, Vietnam.*

Keywords: Linear attenuation coefficient; 661.66 keV gamma rays; TCS-172 gamma scintillation survey meter.

Classification numbers: 07.85.Fv; 07.85.-m; 29.40.Mc.

1. Introduction

The linear attenuation coefficient represents the probability of interaction per unit distance in an absorbing medium [1]. The transmission method [2] has been widely used to determine the linear attenuation coefficients of various absorber materials, such as Al, Cu, Fe, and Pb, for gamma rays in the energy range from keV to MeV. Of these, Al and Cu are commonly use as filters in X-ray generators, while Fe and Pb are widely used as shielding materials for photon radiations (X-rays and gamma rays). Typically, a gamma spectrometer coupled with a NaI(Tl) scintillation detector is used to detect gamma-ray intensities before and after adding an absorber plate between a radioisotope source and the detector [2–4]. The advantage of the gamma spectrometer system is that once calibrated, the energy and intensity of the gamma rays (i.e., peak counts) can be accurately determined. In addition, many research and educational laboratories for nuclear radiation measurement, there are not only gamma spectrometers but also portable devices that attach the NaI(Tl) detector to measure the gamma dose rate. However, there have been very few studies using such handheld devices to determine the linear attenuation coefficients of absorber materials. In this work, we aim to measure the linear attenuation coefficients of Al, Fe and Pb materials for 661.66 keV gamma rays emitted by a Cs-137 source, using a TCS-172 gamma scintillation survey meter (GSSM) manufactured by Aloka Co., Ltd.

2. Experiment and data analysis

2.1. Experimental procedure

Our experimental setup consists of a Pb chamber, a disk-shaped standard radioactive source of Cs-137, a TCS-172 GSSM, a radioactive source tray, a detector tray, and four cylindrical-shaped Fe collimators to produce a collimated gamma-ray beam. In this experiment, six rectangular Al plates and three rectangular Pb plates provided by Oak Ridge, Tennessee-based Spectrum Techniques were used. In addition, we also used an uncalibrated Fe plate. The density and thickness parameters of the absorber plates are presented in Table 1 [5]. A sample stand was used to hold the Cs-137 source, the NaI(Tl) detector of the TCS-172 GSSM, the collimators, and the absorber plates during the experiment.

Table 1. Information of the absorbers [5].

Material	Al						Fe	Pb		
Name of sample	P	L	I	O	M	K	Z	T	S	R
Area density [mg/cm]^2	840	425	216	655	552	328	-	7367	3448	2066
Thickness [cm], x	0.318	0.160	0.081	0.254	0.203	0.127	0.510	0.635	0.318	0.163

Figure 1a shows the instruments used in our investigation to detect the gamma dose rate caused by the radioisotope source, while Fig. 1b illustrates the experimental setup employed to measure the gamma dose rate with the collimated gamma-ray beam emitted by the Cs-137 source. The sample stand, as well as the source and detector trays, were made of polyethylene.

There are two sets of Fe collimators with internal diameters of 0.5 cm and 0.3 cm, respectively. These are used to collimate the radiation beam emitted by the radioactive source, and when it reaches the detector. The Cs-137 source, with an initial activity of 106 kBq in July 2000, was provided by the Board of Radiation and Isotope Technology, India [6]. The TCS-172 GSSM system consists of a detector with a 25.4 mm $\times$ 25.4 mm NaI(Tl) scintillator and a conversion unit that transforms the detected gamma radiation into an equivalent dose rate [7]. In our laboratory, the unshielded background radiation was approximately 0.2 $\mu Sv/h$ for TCS-172 GSSM; however, utilizing a lead chamber to shield the NaI(Tl) detector of the TCS-172 GSSM reduced the radiation background to 0.03 μSv/h. Therefore, the entire system was placed in a Pb chamber for radiation shielding, as shown in Fig. 1a.

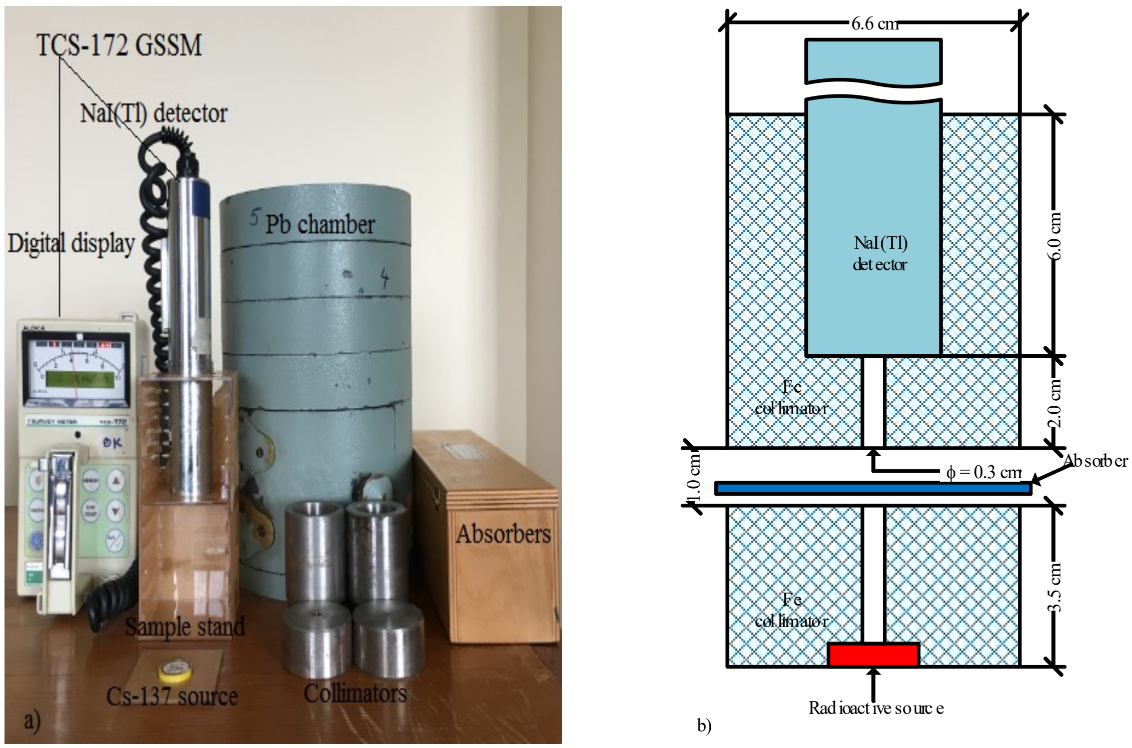

Fig. 1. Experimental setup for determining the linear attenuation coefficient: (a) Instruments used and (b) Arrangement of the experimental setup.

2.2. Data analysis

In previous experimental studies of the linear attenuation coefficient, gamma spectrometer measurements were often expressed in terms of radiation beam intensity. The relationship between the measured intensities before (I_0) and after (I) attenuation is stated as [2–4]:

$$I = I_0 \times e^{-\mu x}. \tag{1}$$

However, in this study we used the equivalent dose rate measuring device, where the unit is expressed in $\mu Sv/h$. The relationship between the equivalent dose rate and the characteristic parameters of a radiation source is given by the equation [8]:

$$\dot{H}_0 = \frac{0.576 \times A \times f \times E_\gamma \times \left(\frac{\mu_{en}}{\rho}\right)_{air}}{4\pi d^2}, \tag{2}$$

where $\dot{H}_0$ is the gamma dose rate in the absence of an absorber (μSv/h), A is the activity of the radioactive source (Bq), f is the gamma–ray emission probability, E_γ is the gamma–ray energy (MeV), $(\mu_{\text{en}}/\rho)_{\text{air}}$ is the mass energy absorption coefficient of air corresponding to gamma rays with energy E_γ (cm^2/g), and d is the distance from the radioactive source to the central point mark of the detector (cm).

We can easily see the linear relationship between the equivalent dose rate and the radiation intensity $I_0 = Af/(4\pi d^2)$. Accordingly, the gamma dose rate through absorbers of thickness x (μSv/h) [1] is calculated using the following formula:

$$\dot{H} = \dot{H}_0 \times e^{-\mu x} \tag{3}$$

where μ is the linear attenuation coefficient of the absorber (cm^{-1}), and x is the absorber thickness (cm). The relationship between the linear attenuation coefficient, absorber thickness, and gamma dose rates can be described by the following equation:

$$\mu = \frac{1}{x} \ln\left(\frac{\dot{H}_0}{\dot{H}}\right). \tag{4}$$

According to Ref. [9], the total error is the quadratic sum of partial errors; hence, the error of the linear attenuation coefficient in Eq. (2) can be expressed as:

$$\sigma_\mu = \frac{1}{x}\sqrt{\frac{\sigma_x^2 \ln\left(\frac{\dot{H}_0}{\dot{H}}\right)}{x^2} + \frac{\sigma_{\dot{H}_0}^2}{\dot{H}_0^2} + \frac{\sigma_{\dot{H}}^2}{\dot{H}^2}} \tag{5}$$

where σ_μ, σ_x, $\sigma_{\dot{H}_0}$ and σ_I are the errors of the linear attenuation, the absorber thickness and the gamma dose rate without absorber and through the absorber, respectively.

3. Results and discussion

3.1. Determination of the absorber thickness

In order to assess the uncertainty of absorber thickness, we used a vernier caliper to measure the thickness of each absorber plate, as listed in Table 1. The vernier caliper has the smallest division and uncertainty, responding to 0.02 mm and 0.03 mm. We found that the densities of several Al metal plates were practically comparable. Therefore, we combined Al plates of similar densities to increase the difference in radiation intensity between the cases with and without Al plates. This approach considerably reduces the uncertainty in calculating the linear attenuation coefficient. The measured thicknesses of the absorbers used in our investigation are presented in Table 2.

Table 2. Measured thickness of the absorbers used in our study.

Material	Al		Fe	Pb		
Name of sample	PLI	OMK	Z	T	S	R
Density [g/cm^3]	2.64	2.60	7.86	11.60	10.86	12.71
Thickness [cm], x	0.552 ±0.003	0.554 ±0.003	0.510 ±0.003	0.634 ±0.003	0.318 ±0.003	0.162 ±0.003

Note: PLI and OMK are combinations of individual plates P, L, I and O, M, K, respectively.

3.2. Determination of linear attenuation coefficient and its standard error

Although the absorbers used in this study were calibrated for thickness and density, their measured densities differed from those published in the literature. For example, the reports indicated that the densities of Al and Pb were 2.7 g/cm^3 and 11.35 g/cm^3, respectively. To determine gamma dose rates, we simulated the arrangement depicted in Fig. 1(b) using MCNP and a Pb absorber density of 11.6 g/cm^3. We then conducted experimental trials to verify the agreement between the measured gamma dose rates and the simulations. As a result, the normalization factor for the gamma dose rate in this study's simulation model was determined to be 1.49×10^9. The values of the gamma dose rate (produced only by the Cs–137 source) simulated using the MCNP code for air ($\dot{H}_0$), Al, Fe, and Pb using a collimator with an inner diameter of 0.5 cm are presented in Table 3.

Table 3. Simulated gamma dose rates with the collimator's inner diameter of 0.5 cm.

Gamma dose rate [μSv/h]						
$\dot{H}_0$	$\dot{H}$					
	PLI	OMK	Z	T	S	R
0.130 ±0.6%	0.116 ±0.6%	0.116 ±0.6%	0.098 ±0.6%	0.060 ±0.8%	0.089 ±0.7%	0.103 ±0.6%

Tables 4 and 5 show the measured results of the background and gamma dose rates in cases without and with the absorbers for collimators with inner diameters of 0.5 cm and 0.3 cm, respectively.

Table 4. Measured gamma dose rates with the collimator's inner diameter of 0.5 cm.

No.	Gamma dose rate [μSv/h]							
	$\dot{H}_{BGR.}$	$\dot{H}_0$	$\dot{H}$					
			PLI	OMK	Z	T	S	R
1	0.03	0.16	0.14	0.15	0.12	0.09	0.12	0.13
2	0.03	0.16	0.15	0.15	0.12	0.09	0.11	0.13
3	0.03	0.16	0.14	0.14	0.12	0.09	0.11	0.13
4	0.03	0.17	0.14	0.14	0.13	0.08	0.12	0.13
5	0.03	0.16	0.14	0.15	0.13	0.10	0.12	0.14
6	0.03	0.15	0.14	0.14	0.13	0.09	0.12	0.14
7	0.03	0.16	0.14	0.15	0.13	0.09	0.13	0.13
8	0.03	0.16	0.15	0.15	0.13	0.10	0.12	0.15
9	0.03	0.16	0.15	0.14	0.13	0.09	0.12	0.14
10	0.03	0.16	0.15	0.15	0.12	0.09	0.12	0.14

Note: $\dot{H}_{BGR.}$ in Tables 4 and 5 are the background gamma dose rates.

The values of the linear attenuation coefficients of Al, Fe, and Pb for 661.66 keV gamma rays are shown in Table 6. The simulation and experimental values of the linear attenuation coefficients were calculated from the incident ($\dot{H}_0$) and transmitted ($\dot{H}$) equivalent dose rates of 661.66 keV gamma rays.

Table 5. Measured gamma dose rates with the collimator's inner diameter of 0.3 cm.

No.	Gamma dose rate [μSv/h]							
	$\dot{H}_{BGR.}$	$\dot{H}_0$	$\dot{H}$					
			PLI	OMK	Z	T	S	R
1	0.03	0.11	0.09	0.10	0.08	0.06	0.07	0.09
2	0.03	0.10	0.10	0.09	0.09	0.07	0.08	0.09
3	0.03	0.11	0.10	0.10	0.09	0.07	0.07	0.10
4	0.03	0.11	0.10	0.10	0.08	0.07	0.08	0.09
5	0.03	0.11	0.10	0.09	0.08	0.06	0.08	0.09
6	0.03	0.11	0.09	0.10	0.08	0.06	0.09	0.10
7	0.03	0.10	0.09	0.09	0.09	0.07	0.09	0.09
8	0.03	0.10	0.09	0.10	0.08	0.06	0.08	0.09
9	0.03	0.10	0.10	0.10	0.08	0.07	0.08	0.09
10	0.03	0.10	0.10	0.10	0.08	0.07	0.08	0.09

Table 6. Linear attenuation coefficient was obtained from both the simulation and the experiment.

Diameter of collimator [cm]	Method	Linear attenuation coefficient [cm^-1]					
		PLI	OMK	Z	T	S	R
0.5	Sim.	0.195	0.202	0.556	1.218	1.165	1.379
	Exp.	0.238 ± 0.035	0.206 ± 0.034	0.595 ± 0.044	1.193 ± 0.053	1.192 ± 0.076	1.260 ± 0.128
0.3	Exp.	0.232 ± 0.073	0.204 ± 0.072	0.504 ± 0.062	1.158 ± 0.097	1.092 ± 0.146	1.175 ± 0.194

Note: Sim. and Exp. are the simulation and experiment, respectively.

The linear attenuation coefficients of three representative absorbers (Al, Fe, and Pb) are plotted in Fig. 2 for both simulation and experiment. The experimental values show good agreement with the simulated ones. It has been found that the linear attenuation coefficients were increased with increasing atomic number. These values are approximately equal to 0.2, 0.5, and 1.2 for Al (Z = 13), Fe (Z = 26), and Pb (Z = 82), respectively.

Our analysis also revealed that by employing a Cs-137 source with an active diameter of 6 mm and a total collimator length of 5.5 cm, we can determine the linear attenuation coefficient of Al and Pb with good accuracy for both inner diameters of 0.5 cm and 0.3 cm (Fig. 2). However, as the collimator's inner diameter decreases from 0.5 to 0.3 cm, the average value of the linear attenuation coefficients varies only quite slightly, by around 3% for Al and 8% for Pb, the uncertainties of the linear attenuation coefficients increase approximately twice, from 17% to 36% for Al and from 7% to 16% for Pb. The uncertainty increases due to the decrease in the radiation beam as the inner diameter of the collimator decreases. Therefore, to determine the attenuation coefficient of the absorbers with the above-mentioned devices, a collimator with an inner diameter of 0.5 cm should be used to produce a narrow beam.

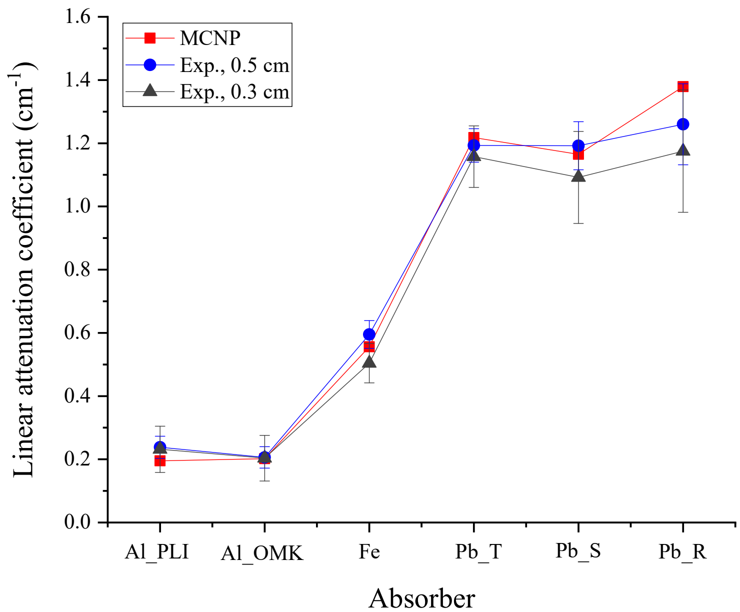

Fig. 2. Comparison of linear attenuation coefficients of Al, Fe, and Pb between experiment and simulation.

Table 7. Linear attenuation coefficients of Al, Fe, and Pb for 661.66 keV gamma rays, compared with previously published data.

Absorber	ρ [g/cm^3]	**Author**	μ [cm^{-1}]	**Year**
Al	2.64	This work	0.238 ± 0.035	2025
	2.60	This work	0.206 ± 0.034	2025
	2.7	Conner [2]	0.20077 ± 0.00068	1970
		Salavica [4]	0.2444	2016
		Martin [1]	0.2024	2006
Fe	7.86	This work	0.595 ± 0.044	2025
		Martin [1]	0.5821	2006
Pb	12.71	This work	1.26 ± 0.13	2025
	11.60	This work	1.19 ± 0.05	2025
	10.86	This work	1.19 ± 0.08	2025
	11.35	Conner [2]	1.2190 ± 0.0057	1970
		Buyuk [3]	1.0507 ± 0.0180	2014
		Salavica [4]	1.3382	2016
		Martin [1]	1.2419	2006

According to Ref. [1], the linear attenuation coefficients of 661.66 keV gamma rays are 0.2024 cm^{-1} for Al with a density of 2.7 g/cm³, 0.5821 cm^{-1} for Fe with a density of 7.86 g/cm³, and 1.2419 cm^{-1} for Pb with a density of 11.35 g/cm³. The comparison of our investigation results for the linear attenuation coefficients of Al, Fe, and Pb absorbers for 661.66 keV gamma rays with the previously published data is presented in Table 7.

4. Conclusion

The linear attenuation coefficients of aluminum, iron and lead absorbers for 661.66 keV gamma rays were estimated based on gamma dose rates measured with the TCS-172 GSSM. According to our findings, with the current activity of the Cs-137 source of approximately 60 kBq (03/2025), collimators with an inner diameter of 0.5 cm and a total length of about 5.5 cm are suitable for examining the linear attenuation coefficients of Al, Fe, and Pb. The study provides valuable nuclear data that can be applied to radiation shielding design, dosimetry calculations, and training activities at the Nuclear Research Institute in Dalat. Furthermore, the study demonstrates a practical experimental approach that could be extended to other absorbing materials and photon energies in future research.

Authors Contributions

The first draft of the manuscript was written by Pham Dang Quyet and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have declared that no competing interest exists.

Ethical approval

This study does not contain any studies with human or animal subjects performed by any of the authors.

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