Theoretical and Experimental Determination of Mass Attenuation Coefficient of Lead for Different Gamma Energies.

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Abstract

In this research work, mass attenuation coefficients of lead for different energies have been measured by experimental methods and compared with theoretical values. The mass attenuation coefficients of Lead for 511 keV , 662 keV, 1173 keV and 1332 keV from gamma sources is determined by using NaI(Tl) scintillation detector. Mass attenuation coefficients measured by experimental methods from this research work are compared to theoretical values from National Institute of Standards and Technology (NIST). The measured values are in agreement with their theoretical values but there is a small difference between experimental and the theoretical results and it has also been noticed that mass attenuation coefficient decreases when the gamma energy increases.

Keywords: mass attenuation coefficient, NaI(Tl) scintillation detector, National Institute of Standards and Technology (NIST)

Introduction

is one of the basic principles of radiation protection. In general, various materials have been used for the radiation shielding in different applications. The amount of shielding required depends on the type of radiation being shielded, the activity of the source, and the dose rate which is acceptable outside of the shielding material.

An effective shield will cause a large energy loss in a small penetration distance without emission of more hazardous radiation. However, other factors may also influence the choice of shielding materials such as, cost of the material, weight of the material, and how much space is available for the material. The effectiveness of the shielding material is determined by the interactions between the incident radiation and the atoms of the absorbing medium. The interactions which take place depend mainly upon the type of radiation, the energy of the radiation, and the atomic number of the absorbing medium (Klingberg,2009).

The study of absorption of gamma radiations in shielding materials has been an important subject in the field of radiation physics. In order to design the protective shielding around the nuclear reactor, accelerators and high radiation region, the knowledge of the attenuation in shielding materials is essential. Photon attenuation coefficient is an important parameter for characterizing the penetration of gamma rays in the materials. The absorption of gamma radiations is related to density and effective atomic numbers of material.

This research work is to determine the mass attenuation coefficients of Lead for 511 keV from ^{22}Na, 662 keV from ^{137}Cs and 1173 and 1332 keV from ^{60}Co gamma sources.

Detection system used to detect the radiation from gamma sources includes Model 4001A high voltage power supply, 3″ x 3″ NaI(Tl) scintillation detector

Shielding

associated with Model 296 photomultiplier tube, preamplifier, Model 671 amplifier and multichannel analyzer.

Throughout the experiment, operating voltage of 1000V is maintained and coarse gain and fine gain of the amplifier are set to 20 and 8.5 respectively. To analyze the measured spectra, Gamma Vision 32 software was used. As absorbing material, Lead sheets manufactured by Instruments for Measurement of Radioactivity, Radiation Counter Laboratories, INC, SKOKIE, ILLINOIS which are available on the Experimental Nuclear Physics Laboratory were used. In this research, five different thicknesses of Lead (2854 mg/cm^2, 5765 mg/cm^2, 8648 mg/cm^2, 11531 mg/cm^2 and 14414 mg/cm^2) were utilized to realize the various attenuations.

Theoretical background

Radioactivity was first discovered by Henri Becquerel in 1896. The phenomenon of spontaneous emission of heavy elements (Z > 82) is called natural radioactivity. The elements which exhibit this property are called radioactive elements. The atoms of radioactive elements emit radiations composed of three distinct kinds of rays, alpha, beta and gamma radiations. The number of atoms that break up at any instant is proportional to the number of atoms present at that instant. Let N be the number of atoms present in a particular radioelement at a given instant t. Then the rate of decrease $\frac{dN}{dt}$ is proportional to N.

$$\frac{dN}{dt} = -\lambda N \qquad (1)$$

where, λ is a constant known as the decay constant or disintegration constant of the radioactive element. It is defined as the ratio the amount of the substance which disintegrates in a unit time to the amount of substance present. The negative sign signifies that N is decreasing with time. If $N = N_0$ and $t = 0$, this equation can be integrated to give

$$N(t) = N_0 e^{-\lambda t} \quad (2)$$

where N_0 is initial number of radioactive nuclei at t = 0 and N(t) is number of radioactive nuclei at time t. This equation shows that the number of atoms of a given radioactive decreases exponentially with time.

Activity and half-life of a radioactive substance

Activity of any radioactive nuclei is the rate at which the nuclei of its constituent atoms decay.

$$A(t) = \lambda N(t) = A_0 e^{-\lambda t} \quad (3)$$

The unit of radioactivity is the Becquerel (Bq), which is defined as a decay rate of one disintegration per second (dps) or Curie (Ci) which was defined as a decay rate of 3.7×10^{10} dps.

Half-life of a radioactive substance is defined as the time for one half of the radioactive substance to disintegrate. The half-life can be written in terms of the decay constant.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \quad (4)$$

Half-life is inversely proportional to the decay constant. Half-life is different for different radioactive substances (G. F. Knoll, 1979).

Mass attenuation coefficient

When gamma radiation of intensity I_0 is incident on an absorber of thickness (x), the emerging intensity I transmitted by the absorber is given by the exponential expression

$$I = I_0 \; e^{-\mu x} \quad (5)$$

where μ is linear attenuation coefficient and it is the probability of a photon interaction per path length. Its unit is typically in cm^{-1}. The linear attenuation coefficient used in the photon attenuation equation is dependent on photon energy, chemical composition of the absorber (Z) and the physical density of the absorber. The linear attenuation coefficient will change depending on the physical density of the absorber. It is desirable to express the probability of an interaction as a function of the amount of absorber rather than the path length. This would be to represent the probability of an interaction by a value that is independent of density. This is done by dividing the linear attenuation coefficient by the physical density.

$$\mu_m = \frac{\mu}{\rho} \quad (6)$$

where μ_m is mass attenuation coefficient and ρ is physical density. When the units of linear attenuation coefficients are cm^{-1} and the units of physical density are mg/cm^3, the units of mass attenuation coefficient become cm^2/mg. To cancel out the units of μ_m thickness must have units of mg/cm^2. Thickness with these units is called density thickness and denoted by (d). Density thickness is a value equal to the product of the density of the absorbing material and its thickness (W. R. Leo, 1993).

The simplest method for determining the effectiveness of shielding material is the concepts of half value thickness ($d_{1/2}$). Half value thickness is defined as the amount of shielding material required to reduce the radiation intensity to one half of the unshielded value.

Experimental set-up

Detection system used to detect the radiation from gamma sources includes Model 4001A high voltage power supply, 3″x3″ NaI(Tl) scintillation detector associated with Model 296 photomultiplier tube, preamplifier, Model 671 amplifier and multichannel analyzer. The multichannel analyzer sorts all incoming electrical signals according to their amplitudes. Throughout the experiment, operating voltage of 1000V is maintained and coarse gain and fine gain of the amplifier are set to 20 and 8.5 respectively. To analyze the measured spectra, Gamma Vision 32 software was used.

Gamma sources and material used to shield the gamma ray

The energies of gamma rays used in this research are 511 keV from ^{22}Na, 662 keV from ^{137}Cs and 1173 and 1332 keV from ^{60}Co. Properties of these sources are described in Table 1. As absorbing materials, lead sheets manufactured by Instruments for Measurement of Radioactivity, Radiation Counter Laboratories, INC., SKOKIE ILLINOIS which are available on the Experimental Nuclear Physics Laboratory were used. In this research, five different thicknesses of lead (2854 mg/cm^2, 5765 mg/cm^2, 8648 mg/cm^2, 11531 mg/cm^2 and 14414 mg/cm^2) were utilized to realize the various attenuations. Since this study is concerned with finding the mass absorption coefficient of lead, the density thickness is used instead of the thickness of the material. The density thickness is the product of the thickness and density of the material. The known value of the density of Lead is 11.34 g/cm3.

Table 1. Properties of ^{22}Na, ^{137}Cs and ^{60}Co gamma sources

Gamma Sources	Gamma Energy (keV)	Activity (μCi) t_0 = March, 2002	Half Life (y)	Present Activity (μCi) t = March, 2020
^{22}Na	511	1	2.6	0.008
^{137}Cs	662	1	30.2	0.662
^{60}Co	1173, 1332	1	5.27	0.093

Experimental procedure

Before the acquisition of a gamma spectrum, the detector has to be calibrated to make sure that the peaks found in the spectrum belong to the correct energy. After calibrating the system, measurements were conducted. The procedure is to measure and record the net counts of detected gamma rays as a function of the various thicknesses of lead absorber that are placed between the source and the detector.

Firstly, only ^{22}Na source was placed at 8 cm from the detector and measured for 300 s. The measured spectrum was recorded. Then, a sheet of lead was inserted between the source and the detector and measured for 300 s without moving ^{22}Na source. Attenuated measured spectrum was also recorded. In the same way, rests of lead sheets were measured, recording the attenuated spectra. For each thickness, three-time measurements were performed. The same measurements for ^{137}Cs and ^{60}Co were also conducted.

Spectra of ^{22}Na, ^{137}Cs and ^{60}Co for various thicknesses of lead absorber can be seen in Figure 1. to Figure 3. The decreasing intensity of the peaks with increasing shielding thickness can be observed. The peaks are differently attenuated depending on the gamma energy. Net count of each spectrum can be obtained by adding the counts from left to right of region of interest (ROI) of photo peak and subtracting the background from total counts. Net counts for different gamma energies as a function of different thicknesses of Lead absorber are listed in Table 2. to Table 5.

Determination of half-value thickness

Net counts as a function of various thicknesses of lead absorbers for 511 keV from ^{22}Na, 662 keV from ^{137}Cs and 1173 and 1332 keV from ^{60}Co gamma sources are presented in Figure 4, Figure 5, Figure 6 and Figure 7 respectively. From the straight line curve, half value thicknesses were determined. Half value thicknesses of lead for various gamma energies are described in Table 6. Half value thickness of lead as a function of various gamma energies is shown in Figure 8. According to Figure 8, half value thickness increases as the gamma energy increases.

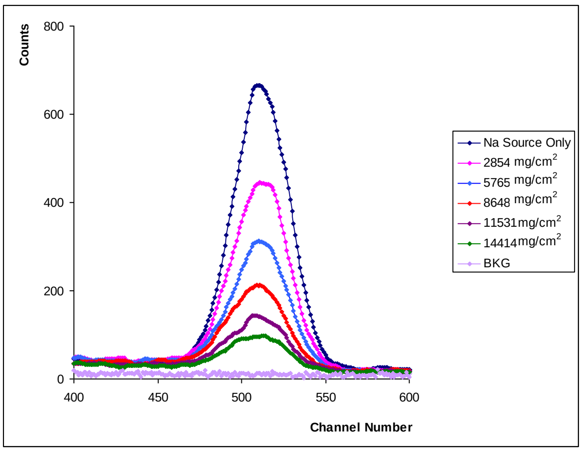

Figure 1. Spectra of ^{22}Na for various thicknesses of lead absorber

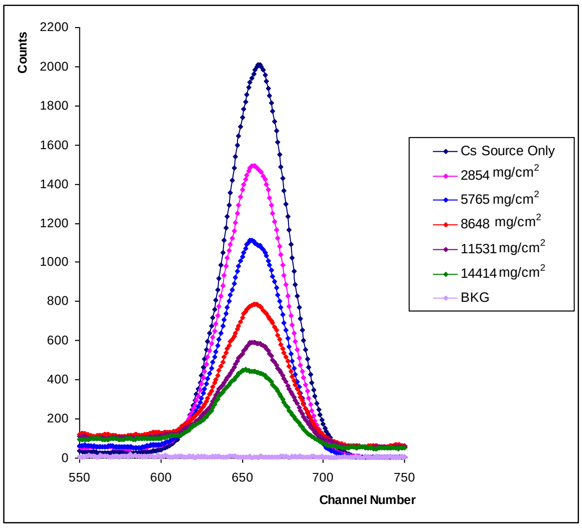

Figure 2. Spectra of ^{137}Cs for various thicknesses of lead absorber

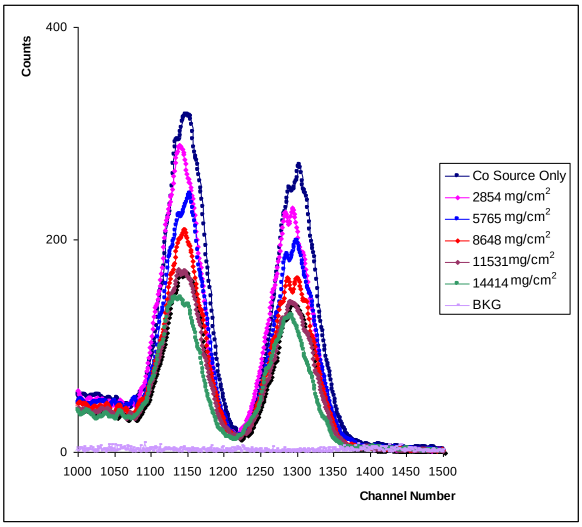

Figure 3. Spectra of ^{60}Co for various thicknesses of lead absorber

Table 2. Net counts of three-time measurements and average net counts of various thicknesses of lead absorber (for 511keV gamma energy)

Thickness (mg/cm^2)	Net Counts 1	Net Counts 2	Net Counts 3	Average Net Counts
Na Source	25568	25777	25541	25628.67±129.16
2854	16942	16816	17292	17016.67±246.62
5765	11313	11192	10501	11002.00±438.07
8648	6862	7695	7063	7206.66±434.68
11531	4710	4720	4544	4658.00±098.85
14414	2973	2777	3052	2934.00±141.58

Table 3. Net counts of three-time measurements and average net counts of various thicknesses of lead absorber (for 662 keV gamma energy)

Thickness (mg/cm^2)	Net Counts 1	Net Counts 2	Net Counts 3	Average Net Counts
Cs Source	84677	84432	85898	85002.33±785.23
2854	62807	63010	62662	62826.33±174.80
5765	45372	46489	46275	46045.33±592.85
8648	30408	29671	29902	29993.67±376.95
11531	21905	21626	21963	21831.33±180.17
14414	16373	16326	16628	16442.33±162.50

Table 4. Net counts of three-time measurements and average net counts of various thicknesses of lead absorber (for 1173 keV gamma energy)

Thickness (mg/cm^2)	Net Counts 1	Net Counts 2	Net Counts 3	Average Net Counts
Co Source Only	13748	13520	13066	13444.67±347.18
2854	10104	10763	10665	10510.67±355.57
5765	10060	9410	9507	9659.000±350.64
8648	7751	7621	7514	7628.667±118.68
11531	6512	6084	6351	6315.667±216.17
14414	5182	5469	4989	5213.333±241.52

Table 5. Net counts of three-time measurements and average net counts of various thicknesses of lead absorber (for 1332 keV gamma energy)

Thickness (mg/cm^2)	Net Counts 1	Net Counts 2	Net Counts 3	Average Net Counts
Co Source Only	10977	11066	11471	11171.33±263.30
2854	9247	8446	9051	8914.667±417.54
5765	8586	7815	8007	8136.000±401.36
8648	6437	6125	6997	6519.667±441.83
11531	5873	5612	5568	5684.333±164.86
14414	4260	4765	4691	4572.000±272.72

Determination of mass attenuation coefficient

After measuring the half value thicknesses, mass attenuation coefficients were calculated according to the half value thickness and mass attenuation coefficient relation. Mass attenuation coefficients of lead for different gamma energies are listed in Table 7. . Figure 9. indicates mass attenuation coefficient of Lead as a function of various gamma energies. According to Figure 9. , the mass attenuation coefficient decreases when the gamma energy increases.There is reciprocal relationship between the half value thickness and mass attenuation coefficient. Mass attenuation coefficients obtained from this research work are compared to their theoretical (accepted) values from National Institute of Standards and Technology. The measured values are in agreement with their respective theoretical (accepted) values.

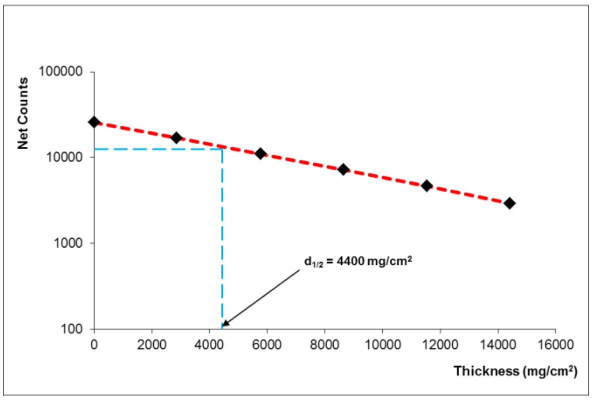

Figure 4. Net counts as a function of various thicknesses of lead absorber (for 511 keV)

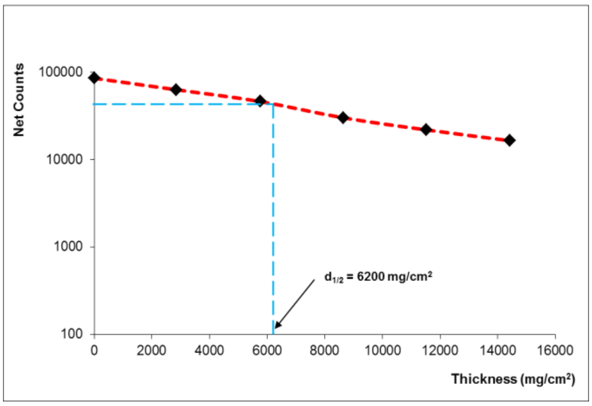

Figure 5. Net counts as a function of various thicknesses of lead absorber (for 662 keV)

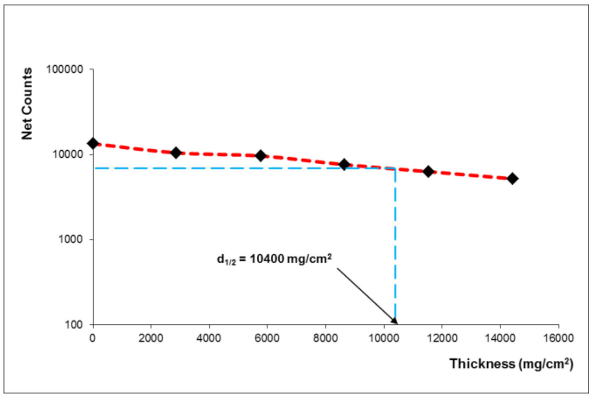

Figure 6. Net counts as a function of various thicknesses of lead absorber (for 1173 keV)

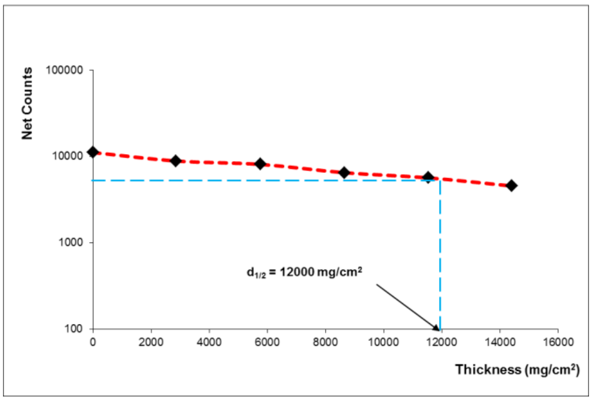

Figure 7. Net counts as a function of various thicknesses of lead absorber (for 1332 keV)

Table 6. Half value thicknesses of lead for different gamma energies

Gamma Source	Gamma Energy (keV)	Half Value Thickness (mg/cm^2)
^{22}Na	511	4400
^{137}Cs	662	6200
^{60}Co	1173	10400
^{60}Co	1332	12000

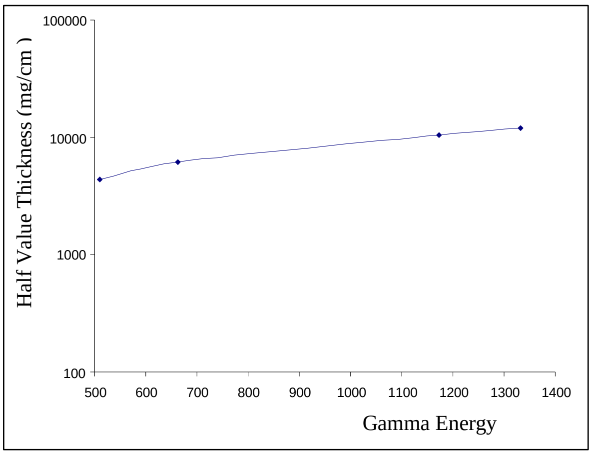

Figure 8. Half value thickness as a function of different gamma energies

Table 7. Comparison data of mass attenuation coefficients for different gamma energies

Energy (keV)	Mass Attenuation Coefficients (cm^2/g)	
	Theoretical (or) Accepted Value	Measured Value
511	0.156	0.157
662	0.110	0.112
1173	0.062	0.067
1332	0.056	0.058

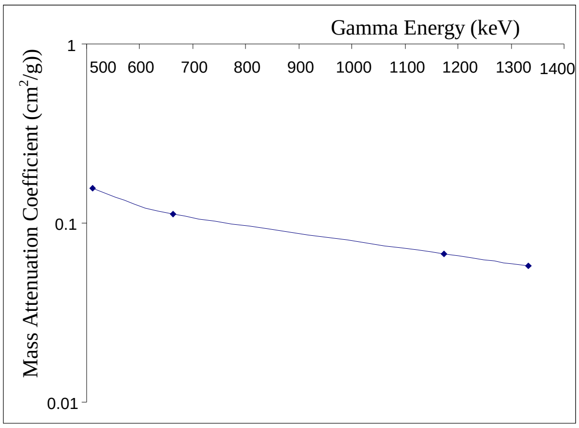

Figure 9. Mass attenuation coefficient of lead as a function of different gamma energies

Results and discussion

In this research work, mass attenuation coefficients of Lead for 511 keV from ^{22}Na, 662 keV from ^{137}Cs and 1173 and 1332 keV from ^{60}Co have been investigated. Mass attenuation coefficients measured by experimental methods from this research work are compared to theoretical values from National Institute of Standards and Technology (NIST) (J. H. Hubbell and S. M. Seltzer, 2010).

Conclusion

. The measured values are in agreement with their theoretical values but there is a small difference between experimental and the theoretical results and it . has also been noticed that mass attenuation coefficient decreases when the gamma energy increases.

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