Gamma Ray Spectroscopy of Co-60 Radioactive Source

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December 8, 2018

Abstract

In this experiment the energy spectra of gamma-rays, resulting from radioactivity of Co-60, was collected by means their interaction with the NaI(Th) detector. The resulting spectra was analyzed on the basis of known energy loss processes that occur inside the crystal. By adding multiple Pb sheets the attenuation coefficient of the absorbing material was determined and the geometric efficiency of the detector was also calculated.

1 Introduction

1.1 Gamma-Ray Interaction with Matter

Gamma-rays are electromagnetic rays produced in nuclear transitions. Gamma-rays when incident on a medium will lose energy through three different processes:

1. Photoelectric effect
2. Compton scattering
3. Pair production

Photoelectric effect

The process occurs for Gamma-ray (γ) photon energy less than 50 KeV. The incoming photon is absorbed by a K-shell electron. The electron is ejected from its orbit with energy:

$$E_\gamma - E_B, \tag{1}$$

where, E_γ is the energy of the incident photon and E_B is the binding energy of the electron. The nucleus absorbs the recoil momentum.

Photo-electric effect is important in gamma-ray spectroscopy since in results in the complete loss of photon energy inside the detector medium. A loss in energy by an amount equals to the binding energy of electron can be ignored.

Compton scattering Compton scattering dominates for energy range $100KeV \rightarrow 10MeV$. An incoming photon strikes an electron imparting some of it energy. A photon of reduced

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energy is scattered off at an angle θ from the incidence axis, with the remaining energy. The energy of the scattered photon ($E^{'} = h\nu^{'}$), and electron (E_e) can be derived using energy-momentum conservation laws to be:

$$\nu^{'} = \frac{h\nu}{1+\frac{h\nu}{m_o c^2}(1-cos\,\theta)} \quad \text{and} \tag{2}$$

$$E_e = \frac{h\nu}{1+\frac{m_o c^2}{h\nu}(1-cos\,\theta)^{-1}}\ , \tag{3}$$

where $h\nu$ is the incident photon energy and θ is the scattering angle.
Maximum energy transfer to the electron occurs at θ equals to 180 degrees . As in a head on collision, the reflected photon is scattered in a completely opposite direction and it's energy is not measured in the detector.

Pair production
Pair production occurs for minimum photon energy of 1.02 MeV as this equals the rest mass energy of an electron and a positron.The photon in the field of a nucleus produces an electron and positron, which carry away the excess photon energy as kinetic energy.

$$E_{pair} = h\nu - 2m_o c^2 \tag{4}$$

1.2 Decay Processes

Gamma-ray spectroscopy focuses in measuring high energy photons produced when nuclei in their excited states move to lower energy states by means of beta decay, inverse beta decay or electron capture, The excited state of Cobalt decays to a stable state of Nickel with a half life of 5.2 years, in a series of steps involving excited Nickel nuclei. The reaction occurring 99% of the time is as follows:

$$_{27}Co^{60} \rightarrow {}_{28}Ni^{60*} + \beta + \nu^{1} \tag{5}$$

$$_{28}Ni^{60*} \rightarrow {}_{28}Ni^{60*} + \gamma_{(1.173\,MeV)}{}^{2} \tag{6}$$

$$_{28}Ni^{60*} \rightarrow {}_{28}Ni^{60} + \gamma_{(1.332\,MeV)} \tag{7}$$

The net reaction is:

$$_{27}Co^{60} \rightarrow {}_{28}Ni^{60} + \gamma_{(1.332\,MeV)} + \gamma_{(1.173\,MeV)} \tag{8}$$

The aim of this experiment is to identify the two photon energies in eq.(8) using photoelectric effect.

Figure 1: 'Spectech Multichannel analyzer

Figure 3: REXON NAI 1.50PX1.50/2.0LV detector with cylindrical lead shielding and photo-multiplier tube. The detector is perched on a stand closed on three sides. The slots in the stand are used to vary the distance of the source from the detector. Source is placed in a tray on one of the level.

Figure 2: Co-60 source with half-life of 5.27 years and decay rate of 1 Ci (1Ci = 3.7×10^4 counts/s)

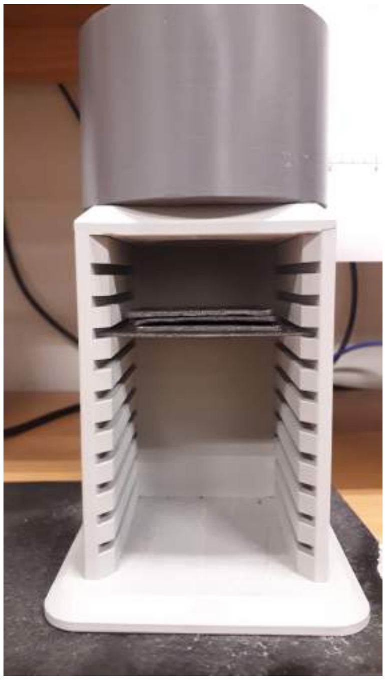

Figure 4: Lead sheets serve as photon absorbers in the mass attenuation coefficient test

2 Equipment & Method

The detector shown in Figure 1 is a Thallium-doped Sodium Iodide [NaI(Tl)] crystal. A gamma ray that enters the detector through it's glass window losses it's energy by means of processes mentioned in the previous section.Excitation and deexcitation of orbital electrons in the crystal produces photons that lie in the visible energy range.These photons are absorbed by the photocathode of the photomultiplier tube resulting in the emission of electrons. Thallium doping shifts the wavelength of photons into the sensitive range of the photo cathode thereby increasing its energy collection efficiency.Detectors working on this principle are called Scintillation detectors. The number of electrons produced is proportional to the energy of the original photon from our radiation source. The photomultiplier amplifies the electron current and converts it into a voltage signal to be analyzed by the 'Spectech' Multi-channel analyzer. The number of counts for each energy are obtained over a fixed time period and graphed. Photoelectric peaks are identified and with there help, a few less prominent peaks as well. A more detailed description of energy collection by the detector will be given in the next section. In this experiment, the Co-60 source was placed 3 cm below the detector as shown in Figure 1. Data was recorded for 750 s. This was followed by background measurements (without source) of 2 days. The software used for this purpose was Spectrum Techniques' STX Rate meter and USX-UCS30 (Universal Computer Spectrometer).

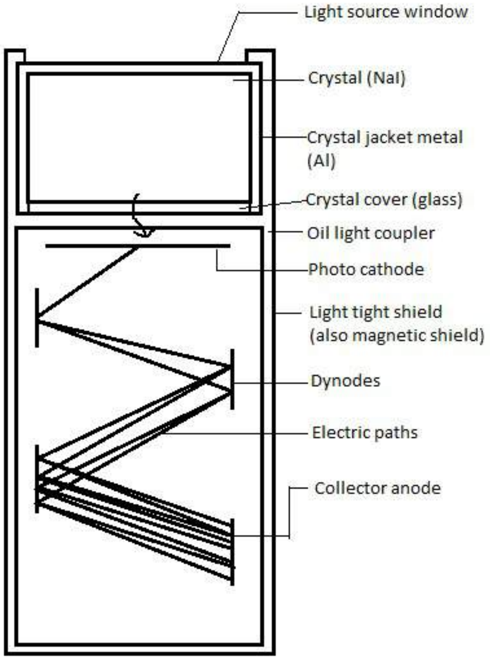

Figure 5: Example of a visible photon leaving the NaI Scintillation detector Crystal and being converted into a voltage by the Photomultiplier Tube

3 Results & Analysis

3.1 Photopeaks, Backscatter Peaks, Pair Production Peaks & Compton Edge

Ideally the photons entering the detector would give only two photopeaks at energies 1.17 MeV and 1.33 MeV pertaining to the decay processes in eq. 4. But the photons undergo various processes in the detector due to which we measure multiple peaks.

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[1] Ionization potential of Ni^* is 2.506 MeV

[2] Ionization potential of Ni^* is 1.332 MeV

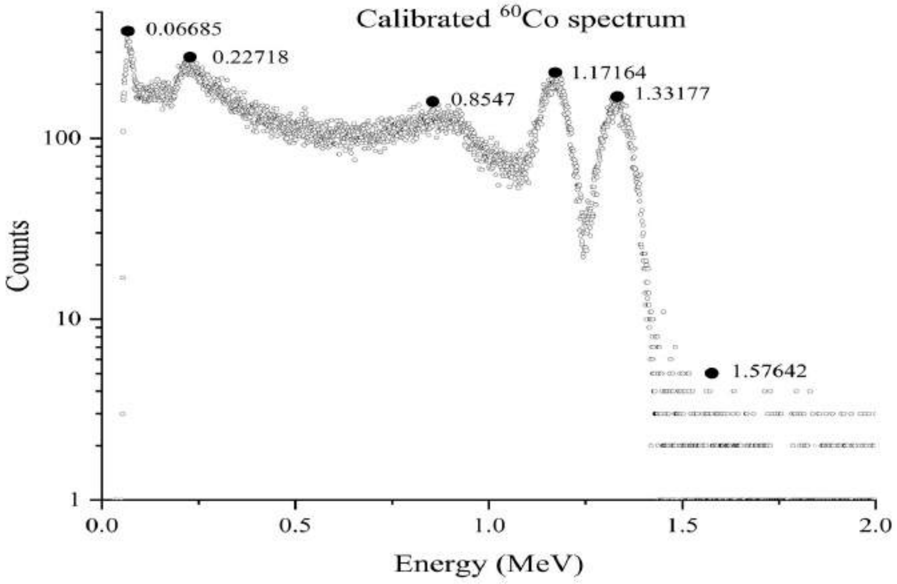

Figure 6: Count verses Energy spectrum of Co-60. The photo peaks of 1.1740 MeV, and 1.3325 Mev are first identified and the graph is calibrated accordingly. Compton scattering peak is evident at 0.8547 MeV. Backscatter peak of photon is at 0.22718. The peak at 0.0668 has originated from background radiations.

Expected E_γ MeV	**Experimental E_γ MeV**	**Percentage Error %**
1.174	1.172	0.26
1.333	1.332	0.15

Table 1: Experimental and expected values of photopeaks in the spectrum

Photoelectric Peaks

These pertain to the complete absorption of gamma rays by the orbital electron. The electron go on further to lose energy through ionization and excitation processes in the detector. Table 1 gives the values of photopeaks for Co-60.

Compton Scattering Edge

The energies of scattered photon and electron are given by eq.2 and eq.3 respectively. At large angles, the scattering cross section becomes independent of the angle and while the energy of the scattered electron gradually increases till it reaches a maximum value at 180 degrees angle of deflection.This leads to an almost flat count rate till E_{max} is reached, known as the Compton edge.

The Compton edge energy can be calculated for both photon energies (1.1740 MeV, 1.3325 MeV) using eq. 3 as in the table given below. The scattered photon leaves the detector

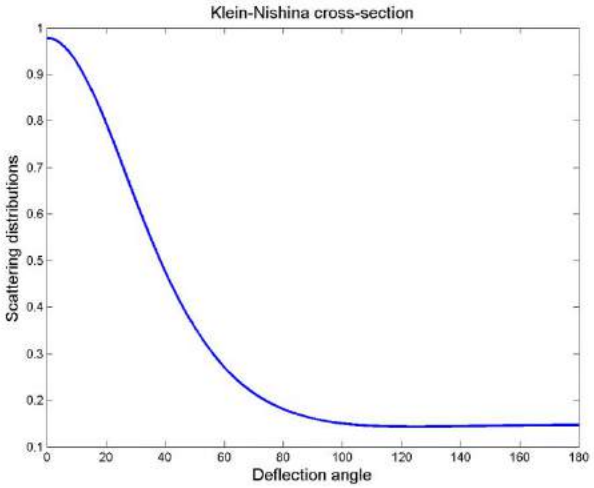

Figure 8: Compton scattering cross section w.r.t to deflection angle.[3]

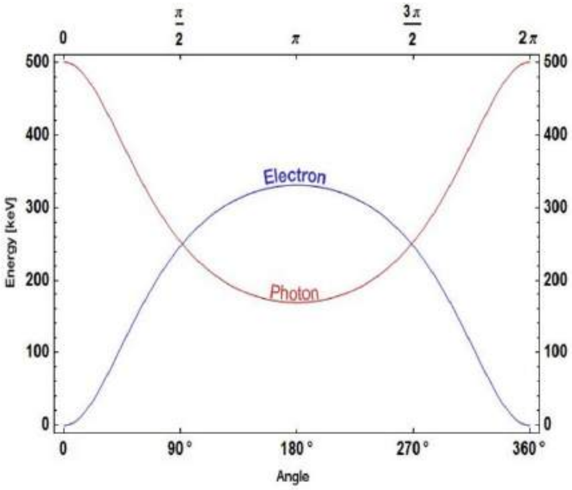

Figure 9: Energy of scattered particles w.r.t to angle of deflection[4]

Theoretical. E_γ **MeV**	**Calculated** E_{max} **MeV**
1.333	1.116
1.1743	0.960
Average (MeV)	1.038
Experimental value (MeV)	0.855
Percentage Error %	6.5

Table 2: Experimental and expected values of Compton edge in the spectrum

without depositing there energy inside the detector and therefore escape full detection. The electron on the other hand goes on to lose its energy in the detector through ionization and excitation processes. In a regular sized detector there is only 1 to 10 percent probability of Compton scattering, therefore multiple Compton scatterings are extremely rare.

An ideal gamma-ray energy spectrum with Compton scattering and photopeaks will look like Figure 8, where the gap $E_\gamma - E_{max}$ gives the energy of the scattered photon .

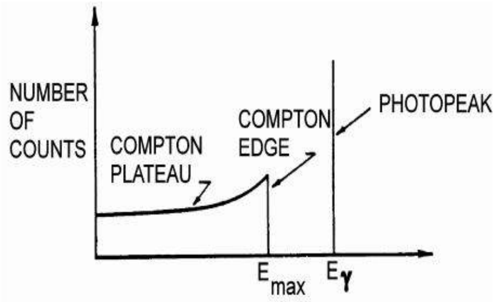

Figure 7: Idealization of gamma-ray spectrum showing Photo peak and Compton plateau[5]

Theoretical E_{gamma} MeV	**Calculated E'_{max} MeV**
1.174	0.210
1.335	0.214
Average (MeV)	0.212
Experimental value (MeV)	0.227
Percentage Error %	4.1

Table 3: Experimental and expected values of backscattered peaks in the spectrum

However, since the two Compton edges calculated are so close in energies, they merge to give one edge only, at 0.8547 MeV, as seen in Figure 5, pertaining to the average value of Compton edge calculated in Table 1.

Back Scattering Peak
Gamma-rays from the source hit the aluminum shielding around the NaI crystal and undergo, Compton Scattering. The scattered photons, or secondary photons, are deflected backwards into the detector. Since these photons carry energy less than the original Gamma-ray photons, they undergo Photoelectric effect in the NaI Crystal depositing all of their energy inside the detector. Since for scatterings occurring at angles greater than 120 degrees, the photon energy is almost constant, as shown in Figure 7, we get a mono-energetic voltage pulse at the photomultiplier output.
In Figure 5, the backscatter peak is at 0.22718 MeV. The theoretical calculation for backscatter peak is done using equation(2) by putting $\theta = 180$ degrees. Table 3 lists the energy values. A schematic diagram of backscattering processes is shown in Figure 10.

3.2 Background Spectrum

The Co-60 spectrum needs to be separated from the background by subtraction in order to gain the net counts. The analysis software subtracts the count rate of the background radiations, from the count rate for source+background, giving us the net counts for each energy channel. The net counts value is used to evaluate the total counts for an energy channel in our next experiments concerning mass attenuation coefficient. The spectrum is calibrated using the same two-point calibration obtained in the Co-60 spectrum. The peaks on the background spectrum was manually marked by identifying the energy channel with the highest counts. Peak energies are compared to know radiation energies in the atmosphere and difference computed.

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[3] Image taken from Presentation by Tony Hyun Kim 12/1/2008 `https://web.stanford.edu/~kimth/www-mit/8.13/Compton/_presentation/thk_compton.pdf`

[4] `http://www.student.nada.kth.se/~f93-jhu/phys_sim/compton/Compton.htm`

[5] Figure taken from Gamma Ray Spectroscopy report, University of Toronto `https://faraday.physics.utoronto.ca/IYearLab/gammaray.pdf`

[6] Figure taken from Gamma Ray Spectroscopy manual by Uzair Latif, Imran Yousaf. `https://www.physlab.org/wp-content/uploads/2016/04/GammaExp-min.pdf`

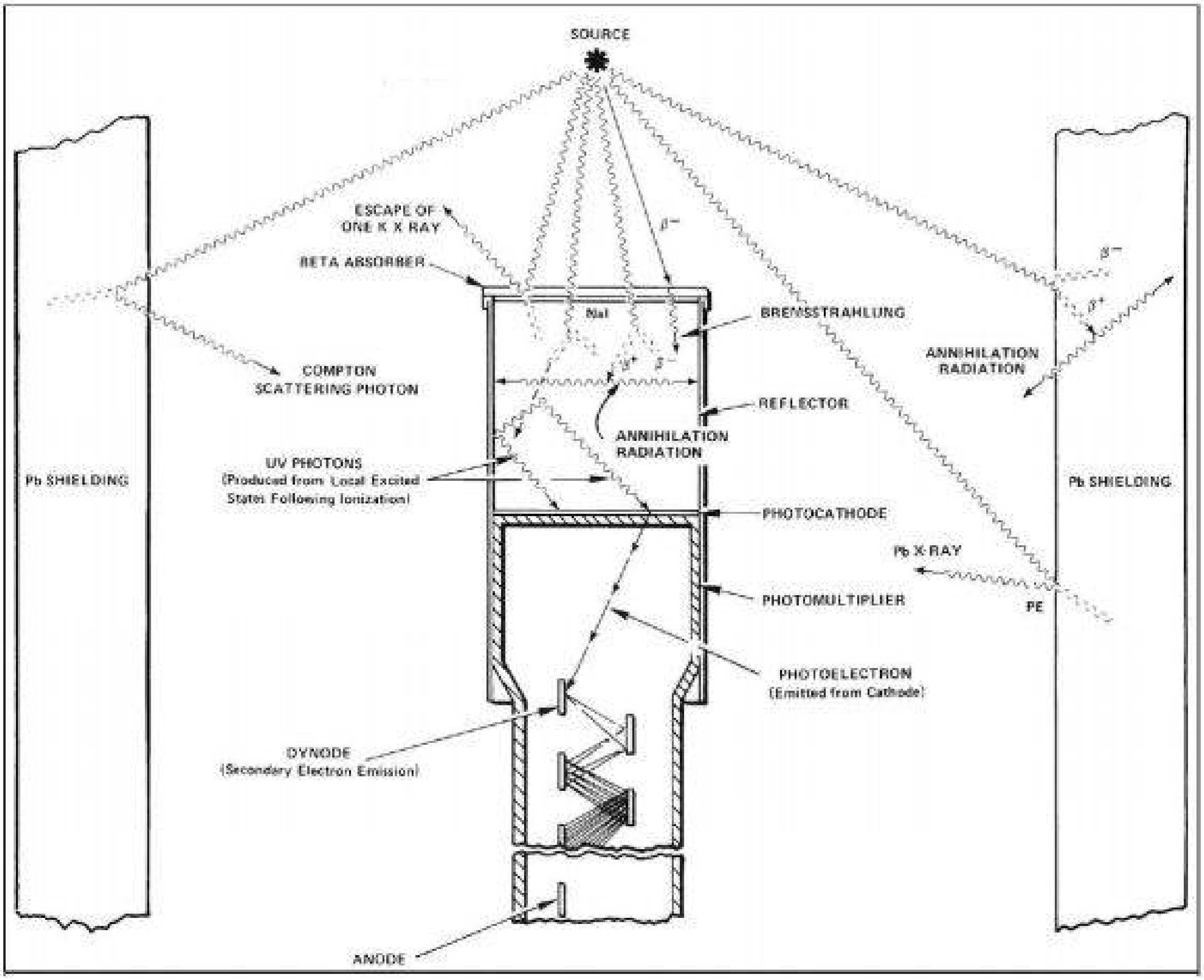


Figure 10: The structure of the Na I(Tl) Detector and various types of gamma-ray interactions occurring in the typical source-detector-shield configuration.[6]

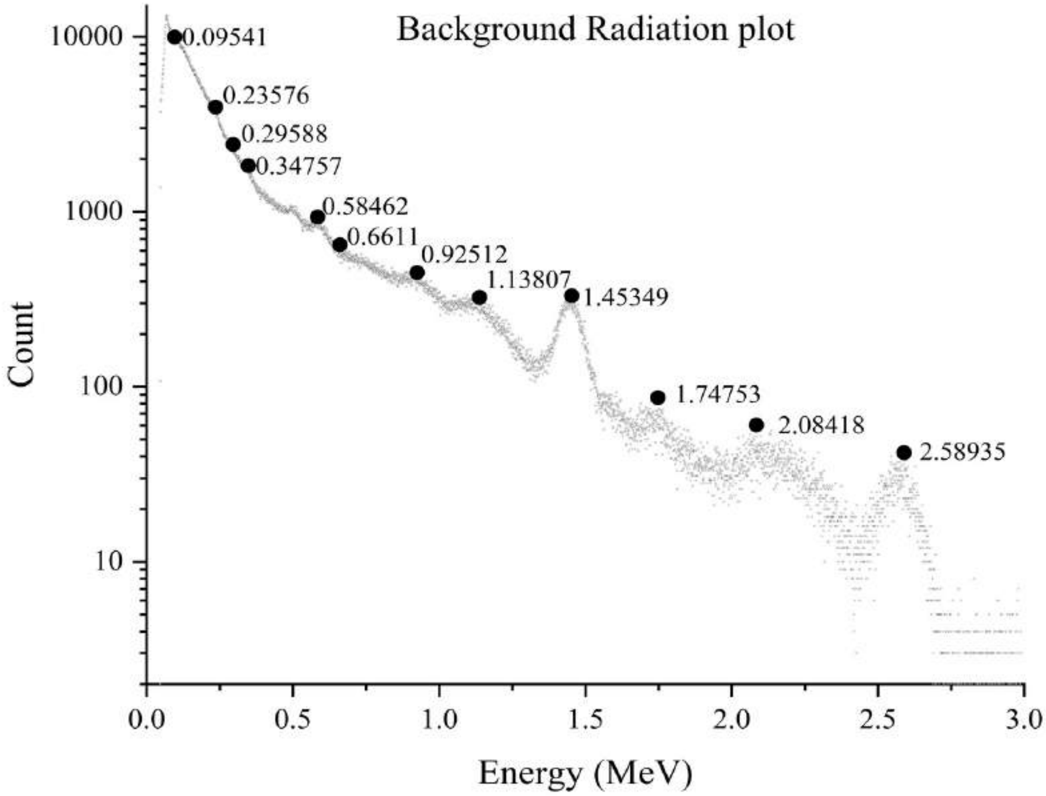
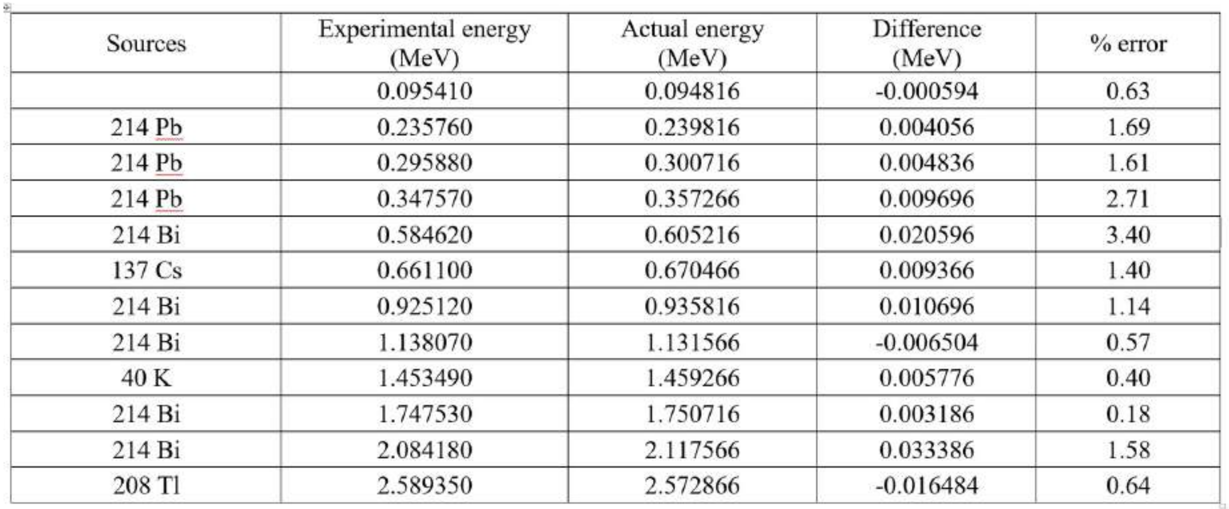


Figure 11: The background spectrum attained over 2 days with source removed.



Sources	Experimental energy (MeV)	Actual energy (MeV)	Difference (MeV)	% error
	0.095410	0.094816	-0.000594	0.63
214 Pb	0.235760	0.239816	0.004056	1.69
214 Pb	0.295880	0.300716	0.004836	1.61
214 Pb	0.347570	0.357266	0.009696	2.71
214 Bi	0.584620	0.605216	0.020596	3.40
137 Cs	0.661100	0.670466	0.009366	1.40
214 Bi	0.925120	0.935816	0.010696	1.14
214 Bi	1.138070	1.131566	-0.006504	0.57
40 K	1.453490	1.459266	0.005776	0.40
214 Bi	1.747530	1.750716	0.003186	0.18
214 Bi	2.084180	2.117566	0.033386	1.58
208 Tl	2.589350	2.572866	-0.016484	0.64

Figure 12: Background spectrum peaks and their theoretically and experimentally obtained values

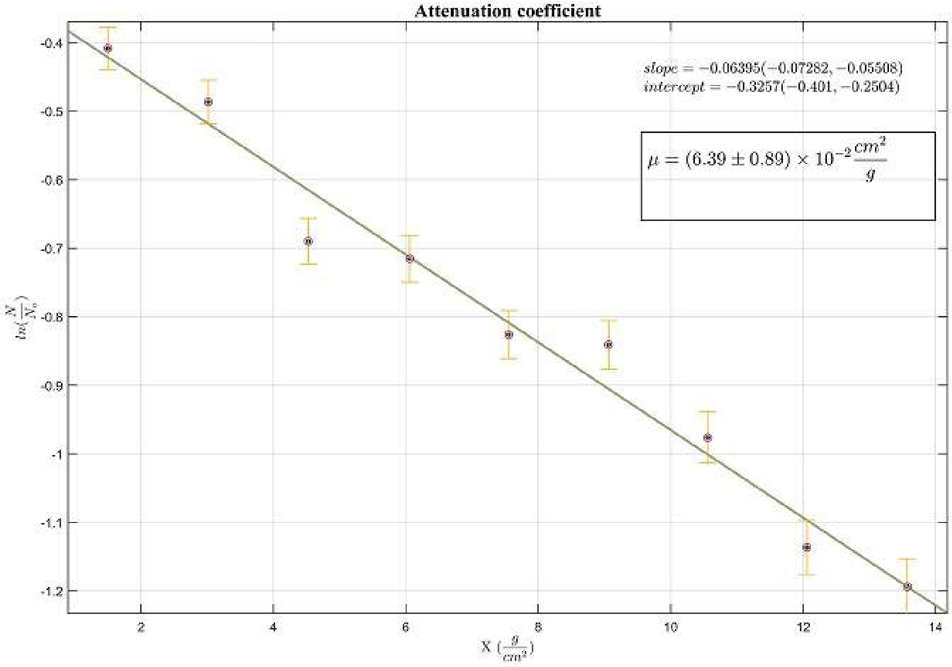


Figure 13: Logarithmic plot of N/N_o w.r.t mass of Pb per unit area.

4 Mass Attenuation Coefficient

4.1 Method

As gamma rays pass through the Pb sheets the number of photons are attenuated. With the source placed 3 cm below the detector, Pb sheets were piled over it in increasing order from 1 to 9. Each lead sheet was found to have an average thickness of 1.33 mm. The cumulative thickness of the sheets was measured at each turn and the number of counts plotted w.r.t thickness of absorbing sheets.
From to Beer Lambart Law:

$$I \;=\; I_o \, exp(-\mu \, x), \tag{9}$$

where, I_o (J/scm^2)is the incident intensity of photon beam, I(J/scm^2) is the intensity at at an arbitrary density thickness (cm^2/g) and μ is the mass absorption coefficient (g/cm). Multiplying the formula on both sides by the time period over which the data is collected we get:

$$N \;=\; N_o \, exp(-\mu \, x), \tag{10}$$

where N and N_o are the number of counts detected with and without shielding by Pb sheets.

5 Geometrical Efficiency

We measured the efficiency of the detector by placing radiation source at different distances from the detector and measured the counts for 3625 seconds. To calculate the efficiency, one

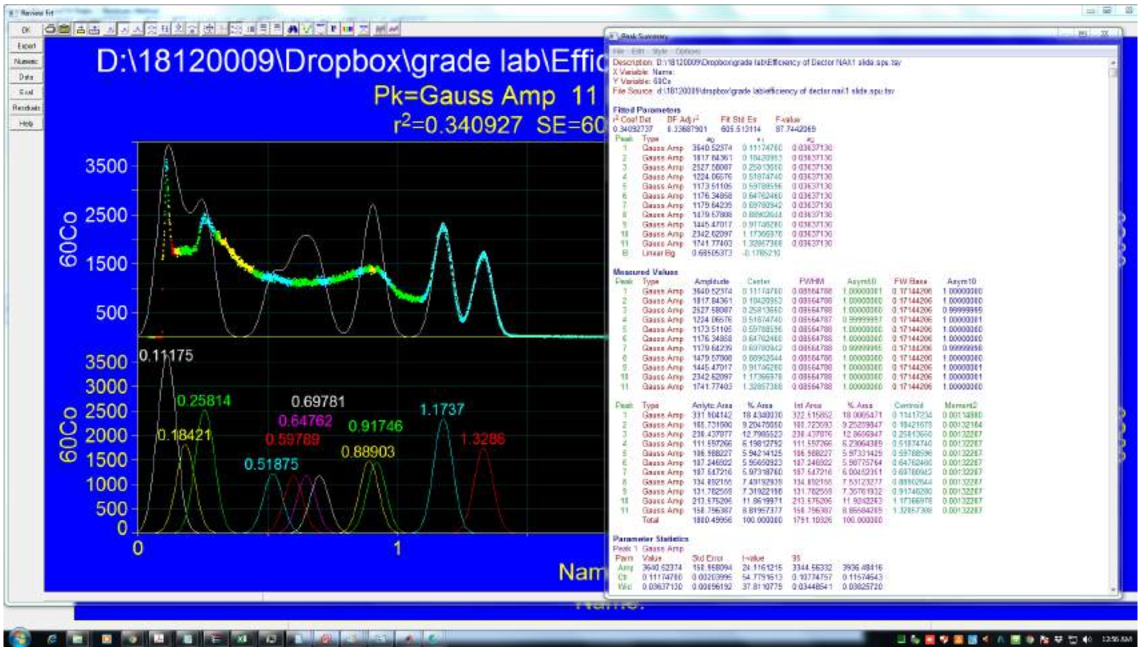


Figure 14: PeakFit software interface. Gaussian fits are applied to photopeaks, back scattering peaks and Compton edge and counts noted. Detector efficiency is calculated then, for these energies

first had to calculate the actual decay rate of the source. As the half life of Co is 1919.9 days (5.27 years) and the elapsed number of half lives amount to 1.74 ± 0.03 (calculated from the date of creation of source), the actual counts are given as,

$$N_{actual} = 11059.2 \pm 0.01 \ \frac{counts}{second}$$

Efficiency was measured from the formula given as:

$$\epsilon = \frac{N_{measured}}{N_{actual}} \tag{11}$$

Here, $N_{measured}$ is the counts detected, and N_{actual}, the decay rate of the source. We used two point calibration, point 1 at (1.174 MeV) and point 2 at (1.3325 MeV) for each of the runs for different distances (from 1 cm to 10 cm) of source from the detector. After this fitting software, PeakFit,[7] to calculate the counts for the different energies by Gaussian fitting as shown in Fig. 11. The geometric efficiency of the detector was seen to decrease with distance according to the relation:

$$y \propto \frac{1}{x},$$

where, x is the distance from the detector in centimeters.

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[7] PeakFit is an automated nonlinear peak separation and analysis software package for scientists performing spectroscopy, chromatography and electrophoresis.

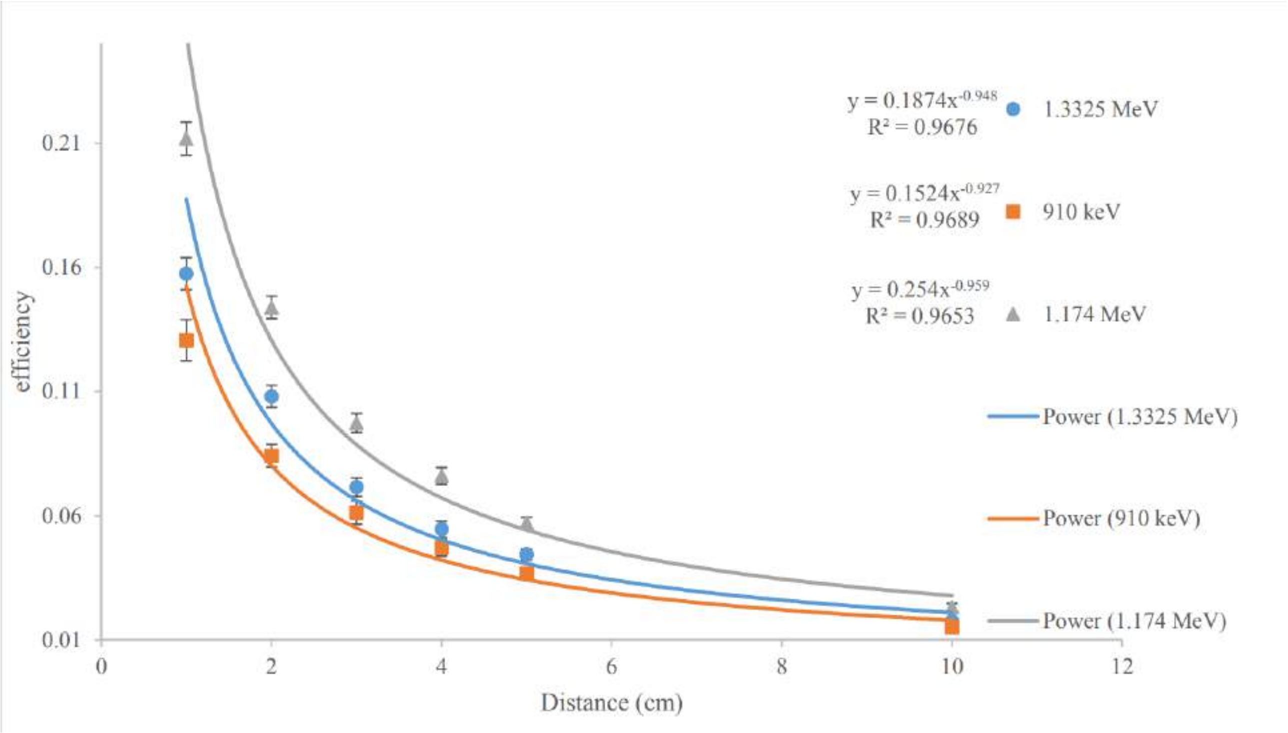

Figure 15: Efficiency vs distance of source from the detector.

6 Conclusion

The measurements were satisfactorily accurate with two point fitting to spectrum showing just 4.1% error in backscatter peak and 6.3% error in Compton edge. Peaks formed due to pair production processes were not seen as at photon energies 1.174 MeV & 1.3325 MeV, pair production cross section is very low. The detector's resolution power failed to distinguish the the back scatter peaks and Compton edges resulting from the two gamma-ray energies and we saw merged peaks at the desired points, giving us the combined counts from the two different gamma-rays. The geometric efficiency, found to decrease inversely with distance, differs from the inverse square law for detector efficiency. Lead was found to be $(6.4 \pm 0.9) cm^2/g$. The intent of the experiment was to become familiar with the equipment: Its energy resolution power and geometric efficiency.

Further Testings
Backscatter peak can be made to appear more prominent by adding further shielding around the detector. This way backscattering of gamma-rays of both energies will be seen clearly. It will also reduce background effects and the CO-60 spectrum will be observed better.

7 References

1. Glenn Knoll, Radiation Detection and Measurement, Third Edition, ISBN-13: 978-0471073383
2. Gamma Ray Spectroscopy by Kristin Howley `http://www.ucolick.org/~kirsten/undergradlabs/lab3.pdf`
3. GammaExp by Uzair Latif and Imran Younas`https://www.physlab.org/wp-content/uploads/2016/04/GammaExp-min.pdf`

8 Acknowledgements

This experiment and report would not have been completed without the invaluable input of Hassan Bukhari in data collection and computer analysis.