

Measurements of Gamma Ray Source Spectra with Germanium (Ge) Detector, Sodium Iodide (NaI(Tl)) Scintillation Detector using Multi-Channel Analyser (MCA)

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Abstract: This research investigates the basic properties of γ -rays using a high-resolution Germanium (Ge) detector, a Sodium Iodide (NaI(Tl)) Scintillation detector and Multi-Channel Analyser (MCA). These detectors are kept cold in operation and once the detector is switched on neither power supply nor the electronics setup are altered. In this experiment, we also determine linear attenuation coefficient for two different materials (Aluminium and Steel) by taking spectra and recording the count rate with varying thicknesses of these materials between the source and detector. Starting with five plates of our chosen materials, we took a spectrum until the 511.0 keV and 1274.6 keV photopeaks were clearly identified for a set time interval. We recorded the net number of counts (including the error) in each of these two peaks using the software which takes account of the large background under the peak. Also, recorded are the live time, real time and dead time. Dead time is the amount of time spent by the detector in a state where it could be missing events. Any detection system has a limit to the rate at which events can be registered and processed. In the case of a scintillation detector, if pulses from different photon interactions overlap significantly, only one light pulse will be measured by the photomultiplier tubes (pulse pile-up). The electronics also have a maximum rate at which they can process data, typically around 1 MHz.

I. Introduction

Gamma rays interact with matter by three main processes, the photo-electric effect, Compton scattering and pair production[6]. For the range of γ -ray sources used, Compton scattering is the most dominant process, since this process involves γ -rays scattering from electrons, the amount of scattering or attenuation strongly depend on the number of electrons in the material. Heavier materials, such as lead, are often used to shield γ -rays because they have a large atomic number and therefore, a greater density of electrons.

II. Aim & Objective

This work looks at the manner at which γ -rays interact with matter. The setup uses a high-resolution Germanium (Ge) detector, a Sodium Iodide (NaI(Tl)) Scintillation detector and a Multi-Channel Analyser (MCA). This research is an important tool in health physics and is effectively used to shield oneself from a radiation source. The work also investigates the attenuation of γ -rays in matter. The first part of this work focus on the radiation emitted from a ^{137}Cs source. The understanding of this work was made easy by studying the schematic nuclear decay charts to help understand the decays of the radioactive sources used.

III. Methodology & Result

A. The ^{137}Cs source

Place the ^{137}Cs source on the holder a few centimetres above the detector face and take a γ -ray decay spectrum of this source for approximately five minutes.

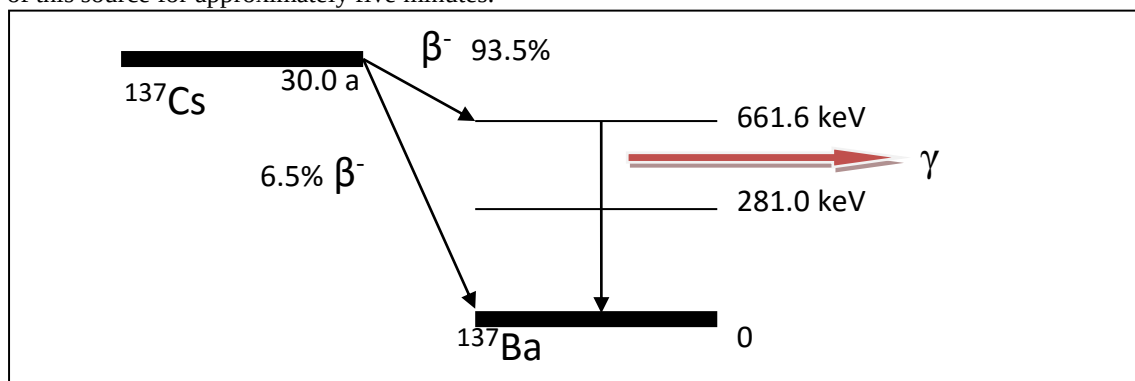


Figure 3.1.1: The decay scheme for ^{137}Cs isotope (including the β^- and internal γ -ray decays)

Caesium (^{137}Cs) nucleus will β^- decay to Barium (^{137}Ba) by changing a neutron to a proton. In this process an excited nuclear state is produced in ^{137}Ba . This excited nuclear state rapidly internally decays and emits a γ -ray transition of energy 661.6 keV. This is the γ -ray transition that was detected in this experiment. Information on ^{137}Cs , its production and decay was found in the Table of Isotopes[1], which lists the nuclear isotopes in order of increasing mass number. For each mass, the isotopes are listed in order of increasing atomic number, Z . The decay scheme for this isotope (including the β^- and internal γ -ray decays) is as shown in fig. 3.1. Note that, the 661.6 keV γ -ray originate from Ba-137 Nucleus, which is the excited nuclear state. Now in order to investigate the function of the gain of the amplifier and select a suitable range used, we placed the ^{137}Cs source on the holder a few cm above the detector face. The spectrum needs to include energies up to 2 MeV. The basic precautionary measure taken was that once chosen, this gain should not be moved for the rest of the practical[7]. The γ -ray spectrum was measured for approximately five minutes. In order to make a very rough calibration of channel number correspondence to energy, the approximate channel number of 661.6 keV peak in the spectrum is required, which was recorded as 401.40.

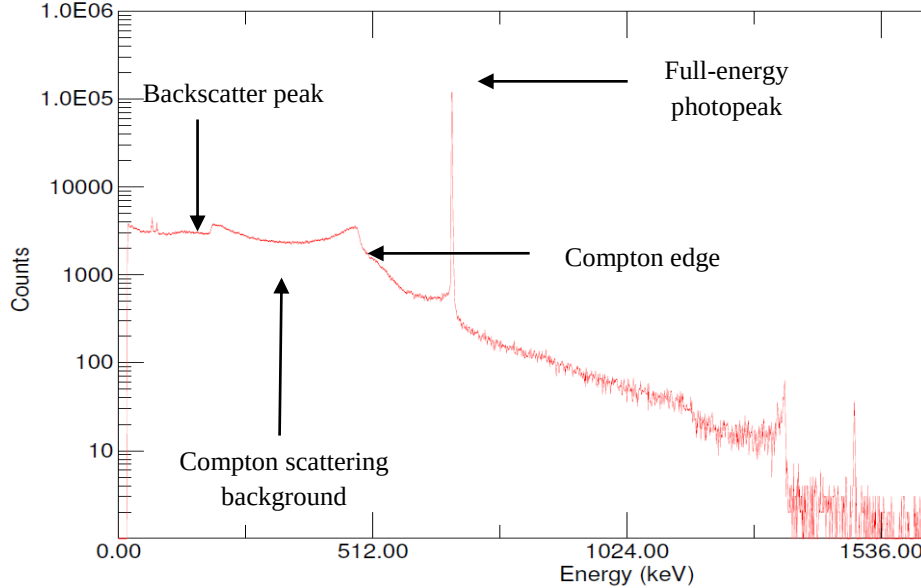


Figure 3.1.2: γ -ray spectrum of ^{137}Cs from a Ge detector

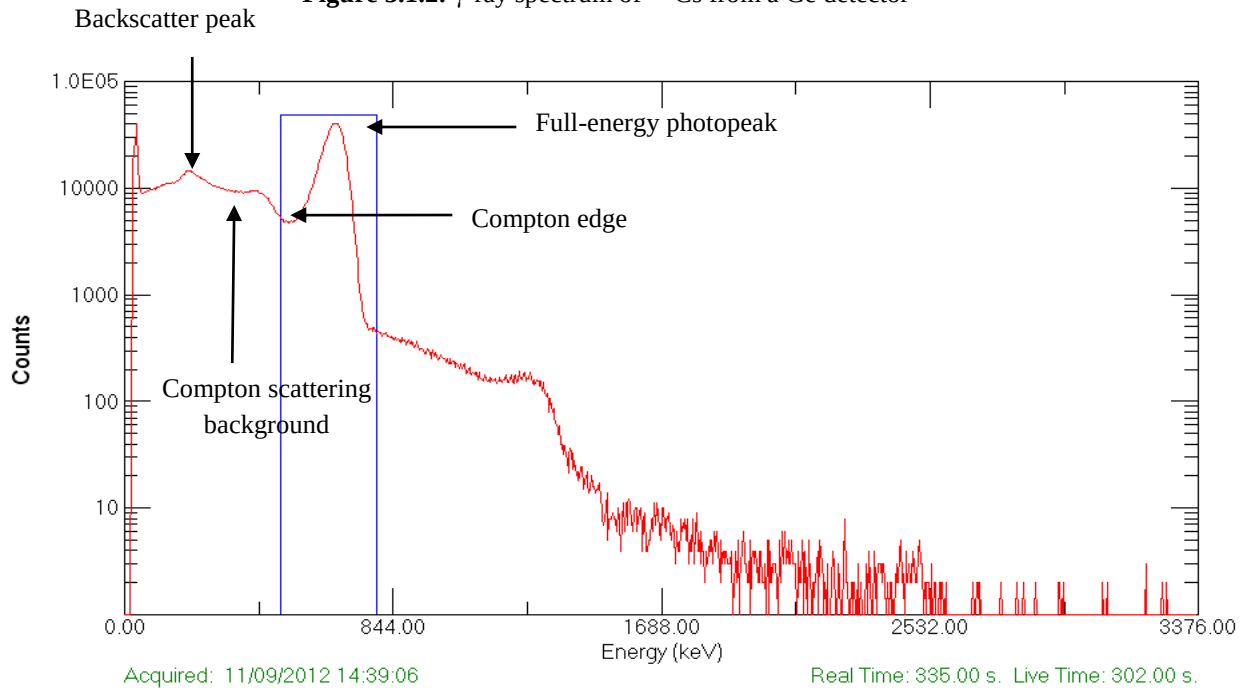


Figure 3.1.3: The spectrum of ^{137}Cs γ -ray source as measured with a NaI(Tl) scintillation detector.

From the decay schemes, one only expects to see a single peak in the spectrum corresponding to the 661.6 keV γ -ray transition. However, additional features are introduced into this spectrum as a consequence of detection processes.

(a) The full-energy photopeak is created by γ rays (in this case 661.6 keV) which transfer all their energy to electrons in the detector's crystal. This can occur in a single photoelectric conversion or by multiple Compton scatters prior to photoelectric absorption[3].

(b) The Compton background at lower intensity is due to Compton scatters where the scattered γ ray escapes without photoelectric absorption[3].

(c) The Compton edge; this is the upper limit to the Compton continuum/plateau/background and it is defined by the maximum energy of the recoil electrons – created when a photon scatters through 180° [3].

3.1.1 One-point Calibration

The MCA displays the γ -ray spectrum as a histogram of the number of counts versus channel number. In the following, we calibrated this channel number to energy using a known source. Since the decay of the ^{137}Cs source emits a γ -ray transition of energy 661.6 keV, a rough estimate of the calibration of the detector was gained.

We established the position (channel number) of this peak using the MCA software;

Channel number of 661.6 keV peak: **671.57**

Hence we calculated (energy / channel number) which gives the number of keV per channel:

$$\frac{661.6}{671.57} = 0.985 \text{ keV/channel}$$

3.1.2 Two-point Calibration

Replace the ^{137}Cs source with a ^{22}Na source and locate the positions of the 511.0 keV and 1274.6 keV peaks, using the information from the rough one-point calibration. (This assumes that the detector amplifier and MCA energy response is linear.)

Channel number of the 1274.6 keV peak: **1293.55** c.f. 1294.0 from rough calibration

Channel number of the 511.0 keV peak: **518.47** c.f. 518.8 from rough calibration

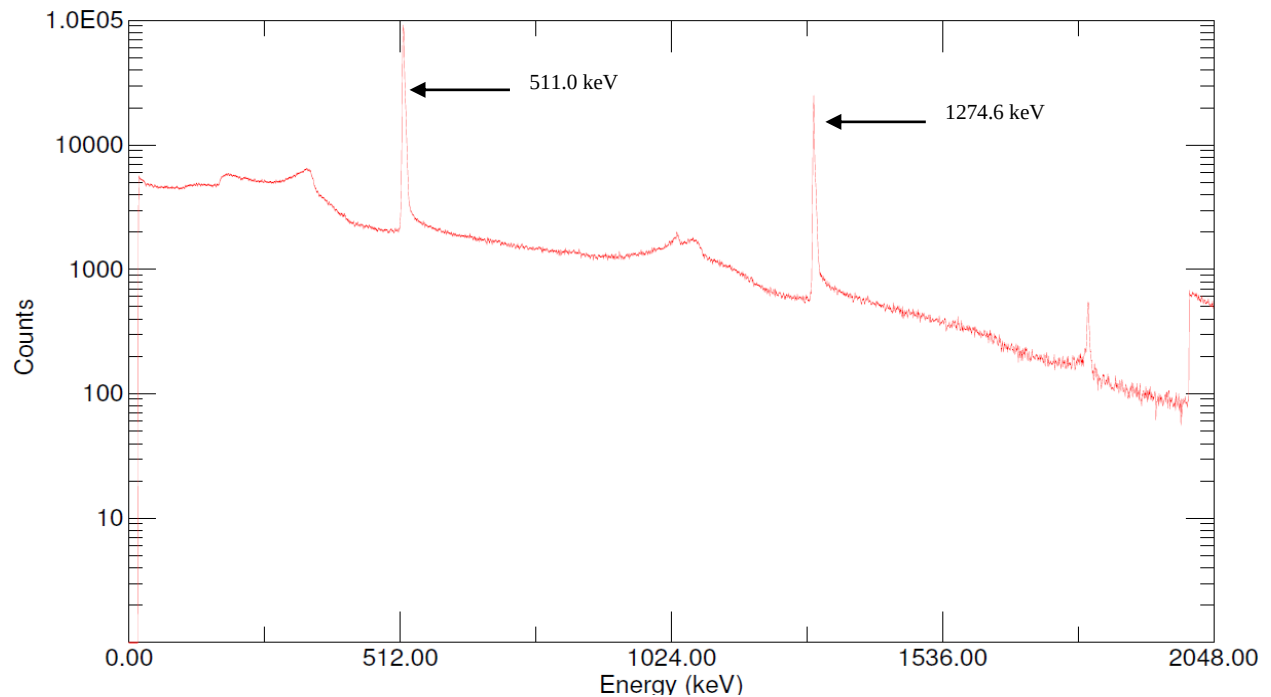


Figure 3.1.4: ^{22}Na γ -ray spectrum from a Ge detector

The spectrum can now be calibrated by performing a two point fit to the 661.6 keV and 1274.6 keV peaks positions. The gradient and intercept of the calibration can be found from the following;

$$\text{gradient} = \frac{(E_{1274.6} - E_{661.6})}{(C_{1274.6} - C_{661.6})} \text{ keV/channel};$$

where $E_{1274.6}$ is the energy of the 1274.6 keV transition, $E_{661.6}$ is the energy of the 661.6 keV transition, $C_{1274.6}$ is the channel number of the 1274.6 keV peak and $C_{661.6}$ is the channel number of the 661.6 keV peak.

The intercept is given by;

$$\text{intercept} = 1274.6 - \text{gradient} \times C_{1274.6} \text{ keV:}$$

From your data, work out the gradient and intercept in the box below

$$\text{gradient} = \frac{1274.6 - 661.6}{1293.55 - 671.57} = 0.986 \text{ keV/channel}$$

$$\begin{aligned} \text{intercept} &= 1274.6 - (0.986 \times 1293.55) = -0.274 \text{ keV} \\ \text{Gradient} &= \mathbf{0.986 \text{ keV/channel}} \\ \text{Intercept} &= \mathbf{-0.274 \text{ keV}} \end{aligned}$$

B. The ^{22}Na Source

The isotope ^{22}Na is unstable to β^+ decay. In this process it changes a proton into a neutron and produces a neutrino and a positron. Neutrinos are very difficult to detect, however, the emission of a positron will have indirect consequences for the spectrum which will be detected from this source[6].

In the same manner as for the ^{137}Cs , we use the Table of Isotopes to look up information about ^{22}Na , its production and decay. The decay scheme for this isotope (including the β^+ and internal γ -ray decays) is as shown in the box below.

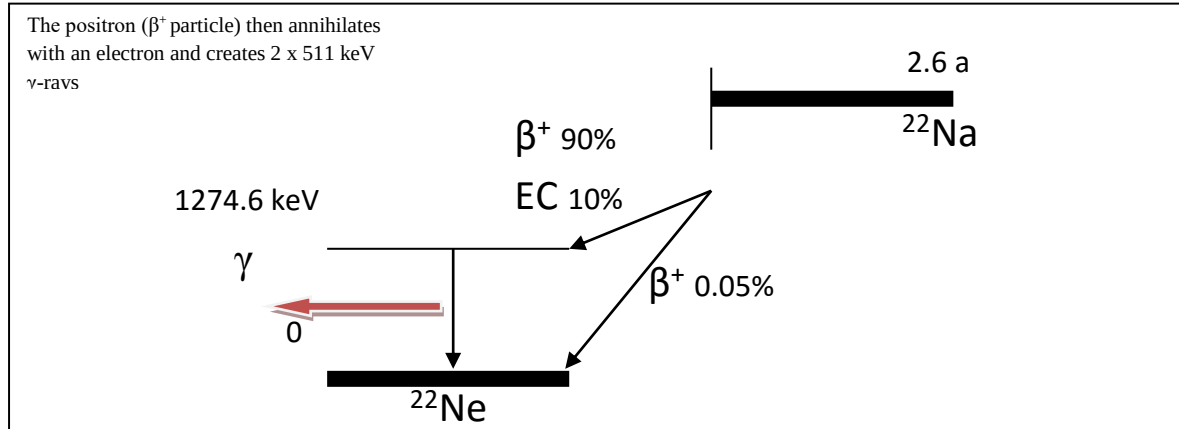


Figure 3.2.1: The decay scheme for ^{22}Na isotope (including the β^+ and internal γ -ray decays)

In this case we use the apparatus to collect a spectrum from the ^{22}Na source. Place the ^{22}Na source on the holder a few cm above the detector face. The γ -ray spectrum is measured for approximately ten minutes.

Place the ^{22}Na source on the plastic holder approximately 10-15cm above the detector face. Ensure that at least five thicknesses of the stopper medium (lead, aluminium, or steel) can be placed between the source and the detector. The height of the source is not changed during the experiment.

When the thickness of stopping material is varied, the intensity, I (counts/sec) for a given source will be reduced from the original intensity, I_0 (counts/sec) according to the formula;

$$I = I_0 \exp(-\mu x)$$

where x is the thickness of the material (cm) and μ is the linear attenuation coefficient (cm^{-1}). This coefficient describes how strongly matter attenuates the γ -rays[4]. In this experiment, we determine linear attenuation coefficient for different materials by taking spectra and recording the count rate with varying thicknesses of material between the source and detector.

Starting with five plates of our chosen material, take a spectrum until the 511.0 keV and 1274.6 keV photopeaks can clearly be identified for a set time interval. In the following tables, we recorded the net number of counts (including the error) in each of these two peaks using the software which takes account of the large background under the peak. Also, recorded is the live time, real time and dead time. Dead time is the amount of time spent by the detector in a state where it could be missing events.

Any detection system has a limit to the rate at which events can be registered and processed. In the case of a scintillation detector, if pulses from different photon interactions overlap significantly, only one light pulse will be measured by the photomultiplier tubes (pulse pile-up) [3]. The electronics also have a maximum rate at which they can process data, typically around 1 MHz.

From the recorded net counts, you can then calculate a count rate using the live time. Now repeat the measurements for various thicknesses of the material, again recording your results in the tables below.

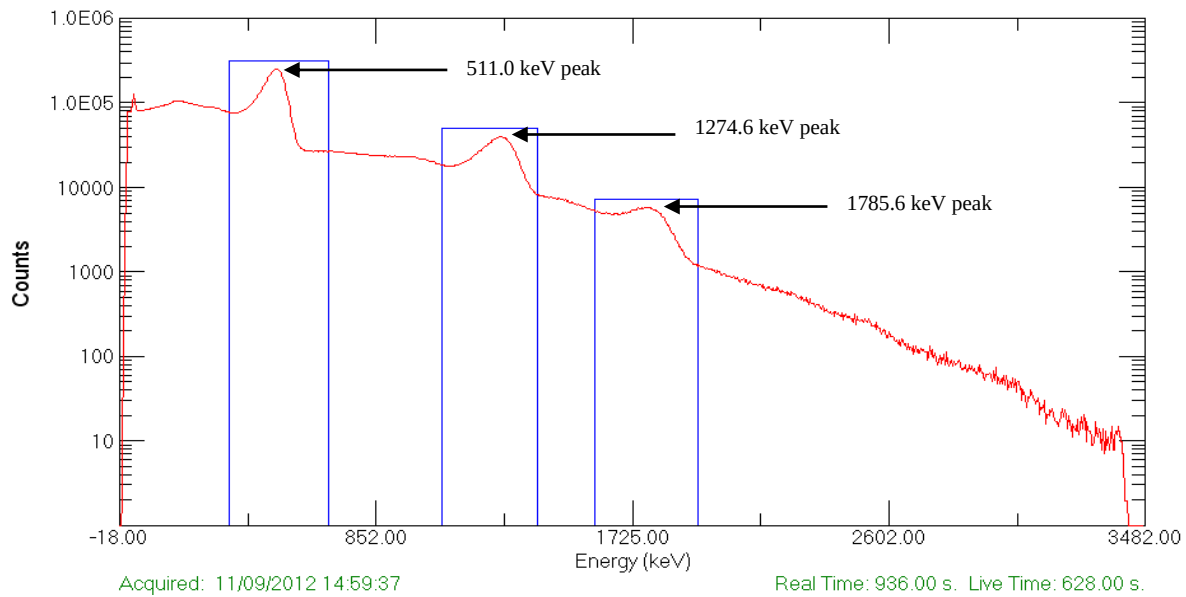


Figure 3.2.2: Spectrum showing three peaks and their approximate channels

This spectrum above contains three peaks and approximate channels has been determine because we know the approximate position of the 661.6 keV transition measured in the first part of this practical. From this knowledge we estimated the expected channel position of the 1274.6 keV transition as can be seen in the box below:

$$661.6 \text{ keV}/401.4 = 1274.6 \text{ keV}/\text{channel \#} \quad \text{Therefore}$$

$$\text{channel \#} = (1274.6 \text{ keV}/661.6 \text{ keV}) * 401.4 = 773.3$$

Now comparing the expected value with the actual channel position of the 1274.6 keV transition in the spectrum we found that

Actual position of 1274.6 keV in channel number: **760.02**

Using this information we were able to ascertain the energies of two other peaks observed in the spectrum. First by recording the channel positions of these peaks;

Channel number of additional peak 1: **311.79**

Channel number of additional peak 2: **1059.18**

Then the rough energies of these peaks were calculated as shown below;

Approximate Energy of additional peak 1: **513.90 keV**

Approximate Energy of additional peak 2: **1745.98 keV**

From our spectrum, we found two additional peaks, one at 511.0 keV and one at 1274.6+511.0 keV. The origin of these additional peaks are described in the box below;

Origin of 511.0 keV peak:

β^+ decay of ^{22}Na emits a positron.
This positron annihilates with an electron and creates 2 x 511.0 keV γ -ray photons.
This peak is created when a single 511.0 keV photon is detected.

Origin of 1785.6 keV peak:

When a 1274.6 keV photon (emitted during de-excitation of ^{22}Ne nucleus) is detected simultaneously with an annihilation photon.
The energy detected is the sum of both: $1274.6 + 511.0 = 1785.6 \text{ keV}$

Finally, we compare and contrast the properties of the NaI(Tl) detector in this section with those of the Germanium detector.

Energy resolution: the resolution of a Ge semiconductor detector is much greater than that of a NaI(Tl) scintillation detector.

The Ge detector needs to be cooled with liquid nitrogen whereas the NaI(Tl) detector can operate at room temperature.

Semiconductor detectors suffer from radiation damage since heavy particles can create imperfections in the crystal lattice by knocking atoms from their sites.

NaI(Tl) scintillation detector is more efficient at higher energies, the Ge detector is not efficient above 1 MeV energy.

C. Accurate Detector Calibration

We now perform a more accurate calibration such that the detector can be used to identify an unknown sample based on its emitted γ -ray spectrum.

Place the ^{152}Eu source a few centimetres from the detector face. Record a spectrum making sure that you can identify the 1408 keV γ -ray transition at the top end of the spectrum. All of the γ -rays emitted by this source are given in the Table of Isotopes along with their relative intensity (emission probability).

After identifying the 1408.01 keV γ -ray in our spectrum we find the accurate channel positions of the 121.78-, 244.69-, 344.28-, and 778.90 keV transitions and then use the MCA software to accurately calibrate the system. The MCA will perform a fit based on your results which should be accurate over the entire energy range. The channel positions were recorded in the table below.

E (keV)	Channel number
1408.01	1428.84
121.78	123.91
244.69	248.61
344.28	349.62
778.90	790.59
1085.83	1101.96
1112.09	1128.59
964.04	978.42
411	417.40
443.96	450.64

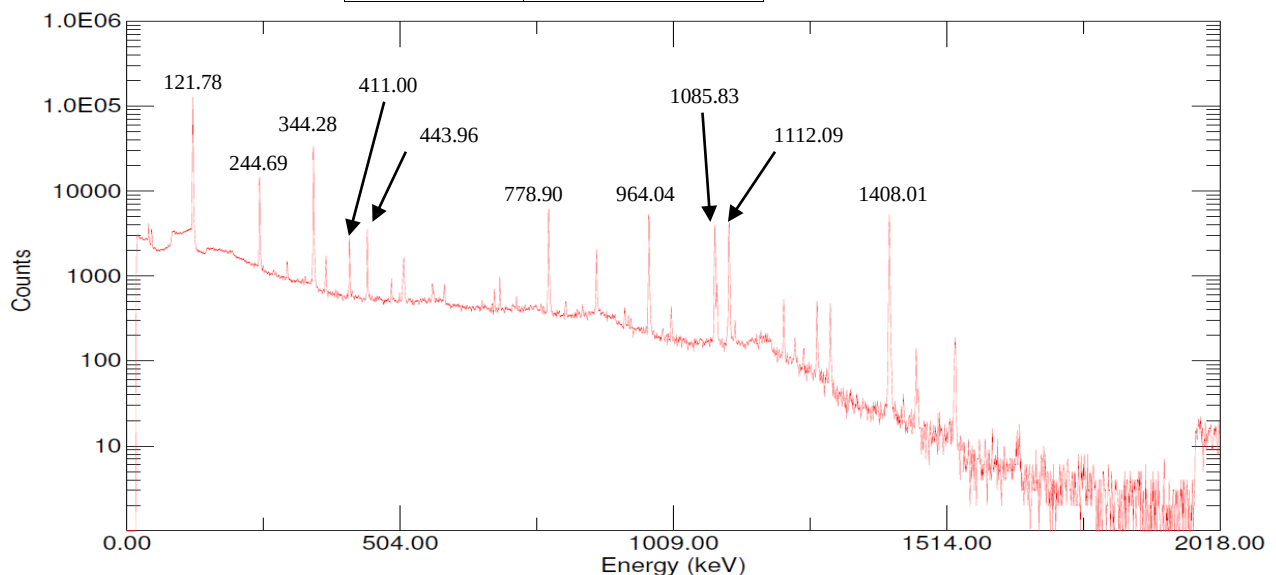


Figure 3.3.1:

Place the ^{137}Cs source back in front of the detector and verify that the energy calibration is correct by recording the energy of this peak.

Measured Energy ^{137}Cs : **661.65 keV** c.f. official value 661.6 keV

The energy of this peak should be 661.6 keV.

Place the ^{22}Na source back in front of the detector and verify that the energy calibration is correct by recording the energy of the two main peaks.

Measured Energy ^{22}Na Peak 1: **510.98 keV**

Measured Energy ^{22}Na Peak 2: **1274.54 keV**

The energy of these peaks should be 511.0 keV and 1274.6 keV.

D. Identification of Unknown Sources

D.1 Measurement of Background Spectrum

After obtaining the accurate calibration of the detector, we try to identify unknown γ -ray sources by analysing their spectrum. In doing this, we needed to account for the fact that there are various other radioactive sources in the laboratory and these might interfere with our measurements. One major source of background for γ -ray detectors is that due to ^{40}K , contained in the wooden benches and concrete walls. Using the Table of Isotopes, we found the important γ -ray energy associated with the decay of ^{40}K :

Expected energy of ^{40}K peak: **1460.726 keV**

In order that you do not misidentify your source, you need to take account of these background peaks. The easiest way to do this is to take a spectrum of the background which can be subtracted from the spectrum of the sample. The MCA software allows you to do this.

Take a spectrum of the background. Try to ensure there are no radioactive sources near your detector. As the background count rate is quite low, you will have to record your background spectrum for a minimum of 15 minutes in order for peaks in the spectrum to be clearly visible.

The MCA software includes a library of nuclides and their associated γ -rays. As you have accurately calibrated your detector, the software will suggest the source of the γ -ray peaks you see in your spectrum. We identified as many background peaks as we could and recorded them in the table below.

E (keV)	Likely natural source	Likely source from alternative library
511.00	Y-88 Yttrium†	Positron annihilation
609.39	Bi-214 Bismuth	
1274.49	Na-22 Sodium	
1460.80	K-40 Potassium	
1764.81	Bi-214 Bismuth	
1120.32	Bi-214 Bismuth	
911.15	I-133 Iodine*	Ac-228 Actinium @ 911.17 keV
352.07	Pb-214 Lead	
295.19	Pb-214 Lead	
583.17	Eu-154 Europium*	Tl-208 Thallium @ 583.19 keV

* Nuclide not expected in background, look to other library of nuclides

† Nuclide not expected, 511.0 keV γ -ray is actually created by positron annihilation (not accounted for in Maestro's library).

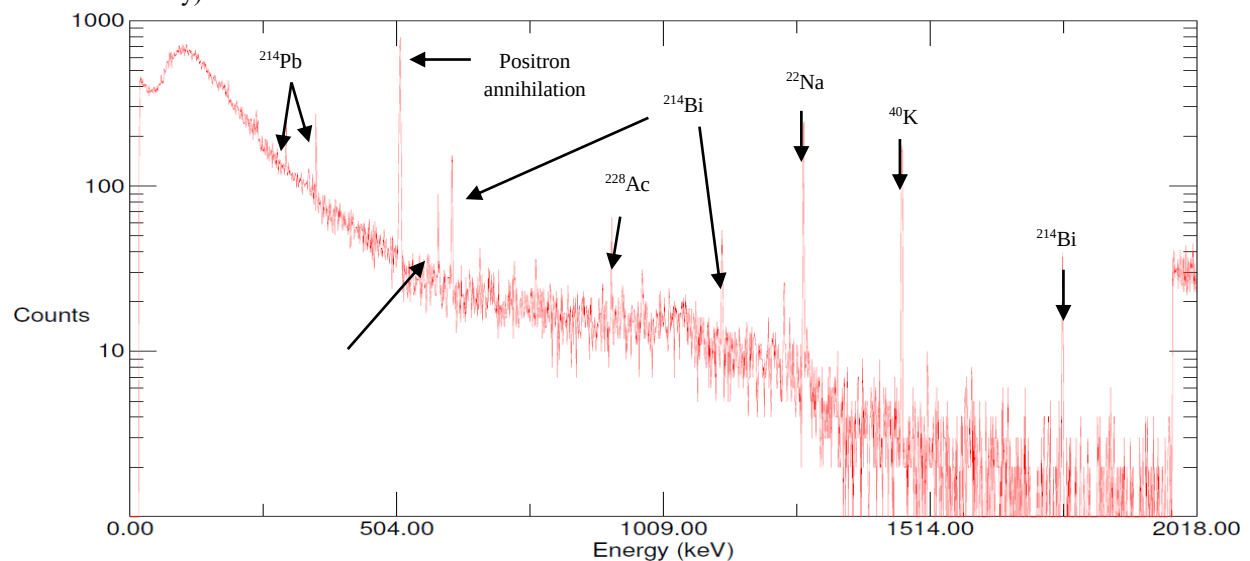


Figure 3.4.1: Background spectrum measured by a Ge detector

D.2 Unknown Source 1

Take a spectrum for a suitable length of time with your accurately-calibrated detector. Subtract your background spectrum, then record the energies of the γ -rays from the unknown source in the table below.

The use of MCA library or the Table of Isotopes was introduced to identify the isotopes present in the unknown source, based on the energies of the γ -rays observed. We also bear in mind there could be more than one isotope in the sample you have been given.

Observed E (keV)	Identification
186.06	Ra-226
241.92	La-140*
295.15	Pb-214
351.84	Pb-214
609.33	Bi-214
934.05	Bi-214
1120.32	Bi-214
1377.73	Bi-214

Perhaps Eu-152 from the source used in previous experiments?

Source 1 Identity: **U-238 decay chain**

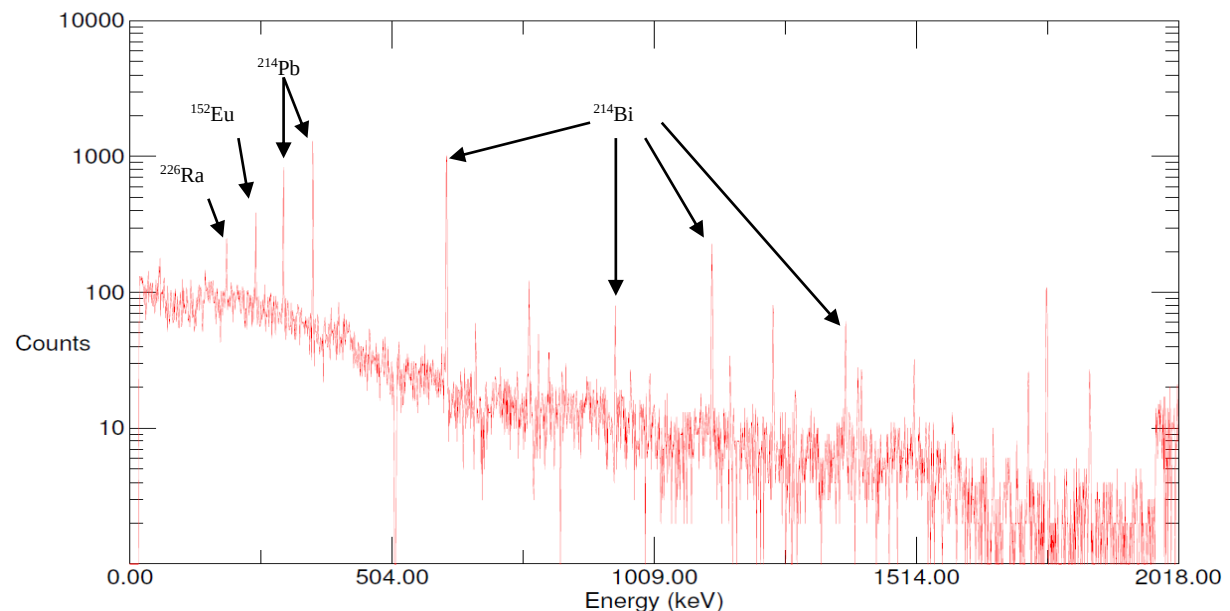


Figure 3.4.2: background subtracted spectrum of unknown source measured with Ge detector

D.3 Unknown Source 2

As before, take a spectrum for a suitable length of time, then subtract your background spectrum and record the energies of the γ -rays observed. In doing this, we were able to identify the source.

Observed E (keV)	Identification
80.89	Ba-133
276.47	Ba-133
302.95	Ba-133
356.11	Ba-133
383.87	Ba-133
436.80	Ba-140*
1173.48	Co-60
1332.74	Co-60

Actually Ba-133: combination of two lower energy photons detected simultaneously (80 + 356 = 436). This is not accounted for in Maestro's library.

Source 2 Identity: **Ba-133**

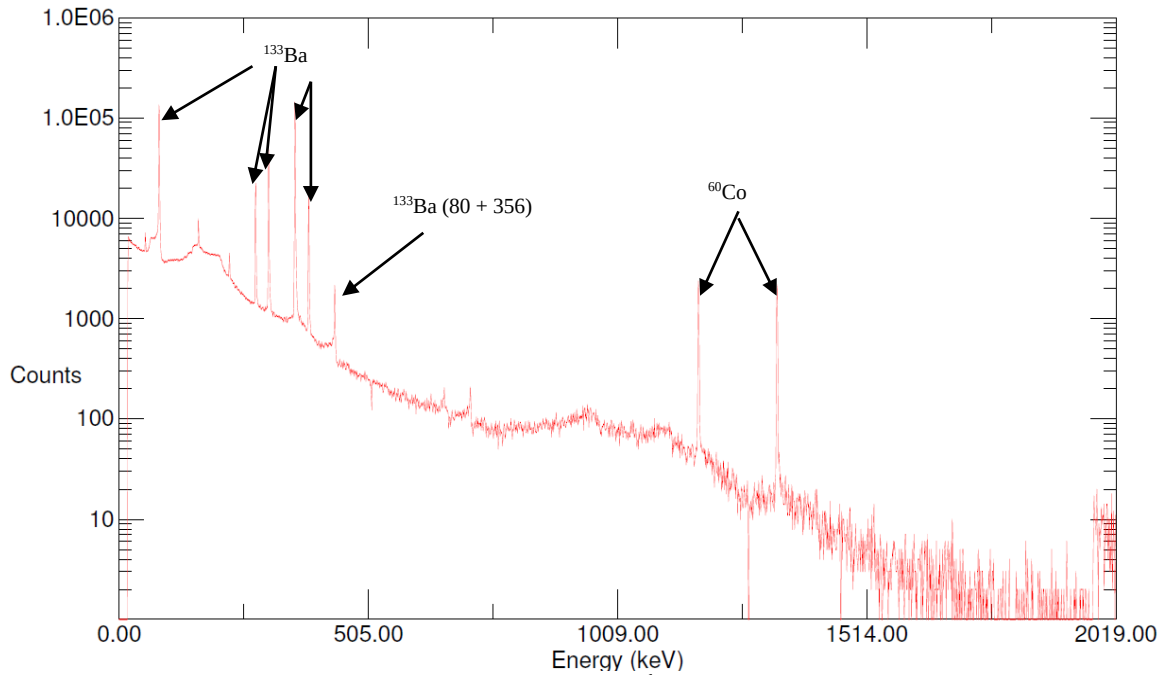


Figure 3.4.3: background subtracted spectrum of 2nd unknown source measured with Ge detector

D. Inverse-Square Law

The radiation dose from a source is expected to fall off inversely proportional to the square of the distance. This is a consequence of the solid angle effect and is an important factor for radiation dose estimation. We checked this effect using a ^{137}Cs source at various distances from the detector. We place the source at a series of distances away from the detector and take a spectrum at each distance. Then recorded the count rates for the ^{137}Cs peak as shown below.

Distance, r (cm)	Error (cm)	Net counts	Error	Live time (s)	Count rate (1/s)	Error (1/s)	1/(r ²)	log(1/r ²)
2.2	0.1	137076	446	120	1142.3	3.72	0.206612	-0.68485
4.3	0.1	56917	281	85.62	664.76	3.28	0.054083	-1.26694
6.6	0.1	25808	185	60	430.13	3.08	0.022957	-1.63909
10.9	0.1	13513	133	60	225.22	2.22	0.008417	-2.07485
15.4	0.1	8459	101	60	140.98	1.68	0.004217	-2.37504
19.7	0.1	34676	213	371.78	93.4	0.57	0.002577	-2.58893
22	0.1	6952	93	88.94	78.17	1.05	0.002066	-2.68485

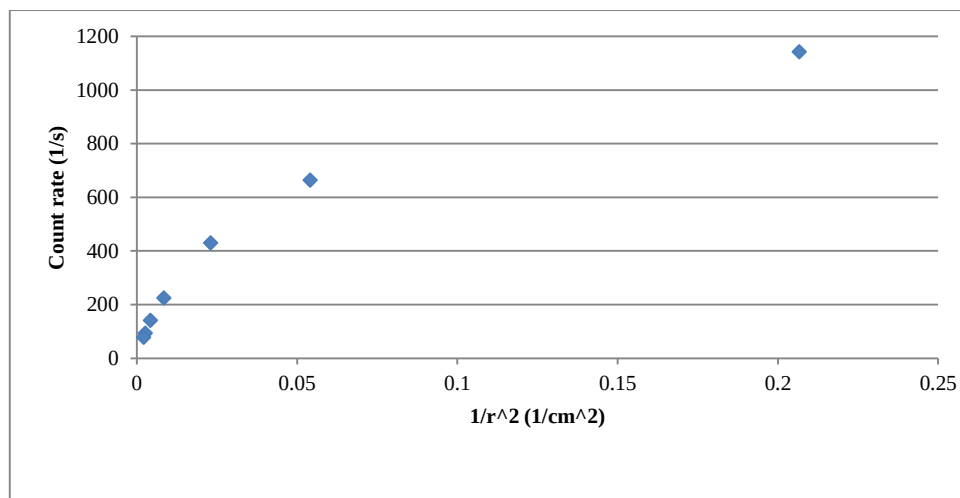


Figure 3.5.1: test of the inverse square law; how the intensity of a ^{137}Cs point source varies distance using a Ge detector

If the measurements exhibited the inverse square law, count rate would have a linear relationship with $1/r^2$. However, intensity actually appears to decline with $1/r^2$ in the form of a natural logarithm function: intensity is lower than expected at closest distances. The possible reasons for any differences from this expected behaviour could be due to the detector's dead time. At close distances, the high intensity of the source might cause the pulses from different photon interactions to overlap. These dead time losses become more significant with increasing count rates (shorter distances) and could be causing the ever-declining slope[5]. To test this hypothesis we re-plot the graph using only the four measurements taken at distances above 10cm (Figure 3.5.1)

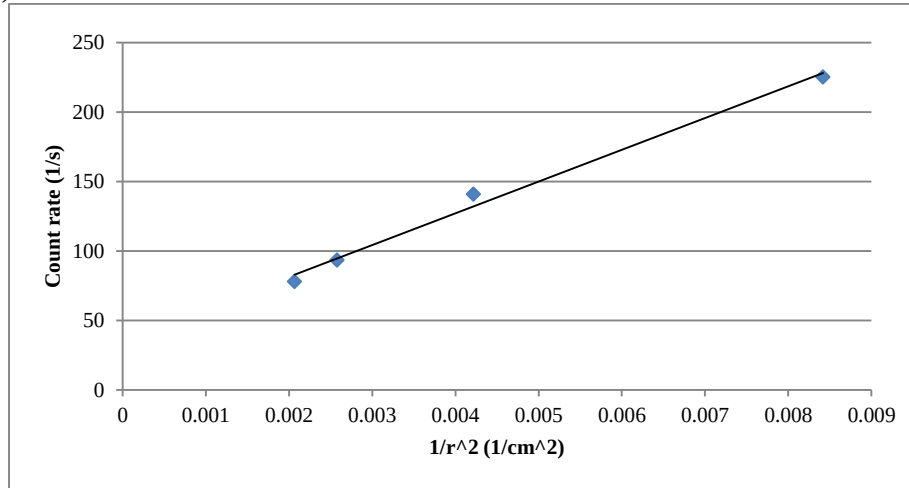


Figure 3.5.2: test of the inverse square law; using only source distances greater than 10cm to reduce the impact of detector dead time

From just four data points, the relationship at large distances appears to approximate a linear one, however more data points are needed at such distances to confirm a linear relationship and support the hypothesis that dead time losses are the cause.

E. Absorption of γ -rays by Matter

Using spreadsheet software (e.g. Microsoft Excel), we work out the natural log of intensity ($\ln$ [counts/sec]) and plot this against material thickness, x . We fit a straight line and extract the values of the intercept and gradient from the fit for both the 511.0 keV and 1274.6 keV peaks. The gradient is the negative of the linear attenuation coefficient μ for the material.

Material 1: Aluminium

Aluminium Thickness (cm)				511.0 keV peak					
				Counts	Error	Count rate (1/s)	Error (1/s)	$\ln(\text{intensity})$ (1/s)	Error
5.83	167.96	181.64	7.53	200,550	1827	1194.03	10.88	7.085	0.009
4.73	154.16	167.4	7.91	234091	1825	1518.49	11.84	7.325	0.008
3.57	159.78	174.42	8.39	331371	1934	2073.92	12.10	7.637	0.006
2.32	152.32	167.22	8.91	391723	1949	2571.71	12.80	7.852	0.005
1.16	160.02	176.44	9.31	536167	2035	3350.62	12.72	8.117	0.004
0	155.9	172.82	9.79	663019	2025	4252.85	12.99	8.355	0.003
Aluminium Thickness (cm)				1274.6 keV peak					
				Counts	Error	Count rate (1/s)	Error (1/s)	$\ln(\text{intensity})$ (1/s)	Error
5.83	167.96	181.64	7.53	82150	1005	489.10	5.98	6.193	0.012
4.73	154.16	167.4	7.91	87874	1007	570.02	6.53	6.346	0.011
3.57	159.78	174.42	8.39	106189	1098	664.60	6.87	6.499	0.010
2.32	152.32	167.22	8.91	121399	1116	797.00	7.33	6.681	0.009
1.16	160.02	176.44	9.31	150229	1210	938.81	7.56	6.845	0.008
0	155.9	172.82	9.79	172778	1217	1108.26	7.81	7.011	0.007

	511.0 keV peak	1274.6 keV peak
Intercept	8.3667	7.0074
Gradient (-μ)	-0.2174	-0.1403

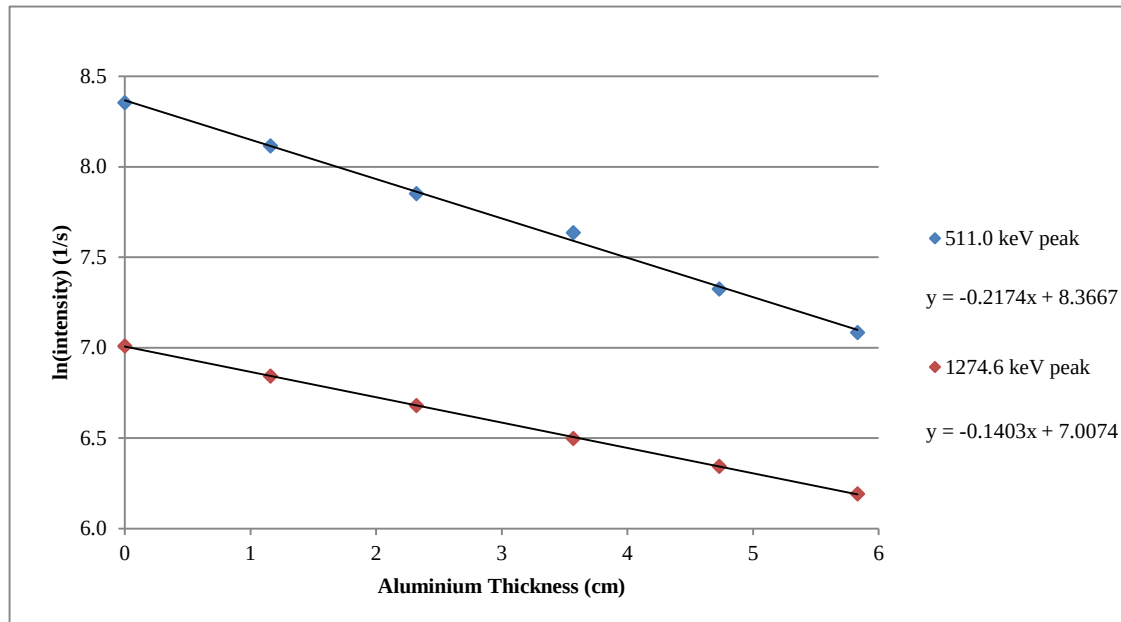


Figure 3.6.1 plots showing the attenuation of γ -rays through aluminium.

Material 2: Steel

				511.0 keV peak					
Steel Thickness (cm)	Live Time (s)	Real Time (s)	Dead Time (%)			Count rate (1/s)	Error (1/s)	ln(intensity) (1/s)	Error
				Counts	Error				
0.611	165.42	181.66	8.94	479,207	2060	2896.91	12.45	7.971	0.004
0.491	153.15	168.48	9.10	477017	1990	3114.70	12.99	8.044	0.004
0.368	160.76	177.2	9.28	539204	2056	3354.09	12.79	8.118	0.004
0.245	176.64	195.04	9.43	634299	2175	3590.91	12.31	8.186	0.003
0.123	164.64	182.12	9.60	640997	2091	3893.32	12.70	8.267	0.003
0	171.92	190.56	9.78	728487	2120	4237.36	12.33	8.352	0.003
				1274.6 keV peak					
Steel Thickness (cm)	Live Time (s)	Real Time (s)	Dead Time (%)			Count rate (1/s)	Error (1/s)	ln(intensity) (1/s)	Error
				Counts	Error				
0.611	165.42	181.66	8.94	141369	1202	854.61	7.27	6.751	0.009
0.491	153.15	168.48	9.10	138132	1159	901.94	7.57	6.805	0.008
0.368	160.76	177.2	9.28	152313	1204	947.46	7.49	6.854	0.008
0.245	176.64	195.04	9.43	175969	1278	996.20	7.24	6.904	0.007
0.123	164.64	182.12	9.60	172170	1245	1045.74	7.56	6.952	0.007
0	171.92	190.56	9.78	190589	1270	1108.59	7.39	7.011	0.007

	511.0 keV peak	1274.6 keV peak
Intercept	8.3452	7.0078
Gradient (-μ)	-0.6163	-0.4192

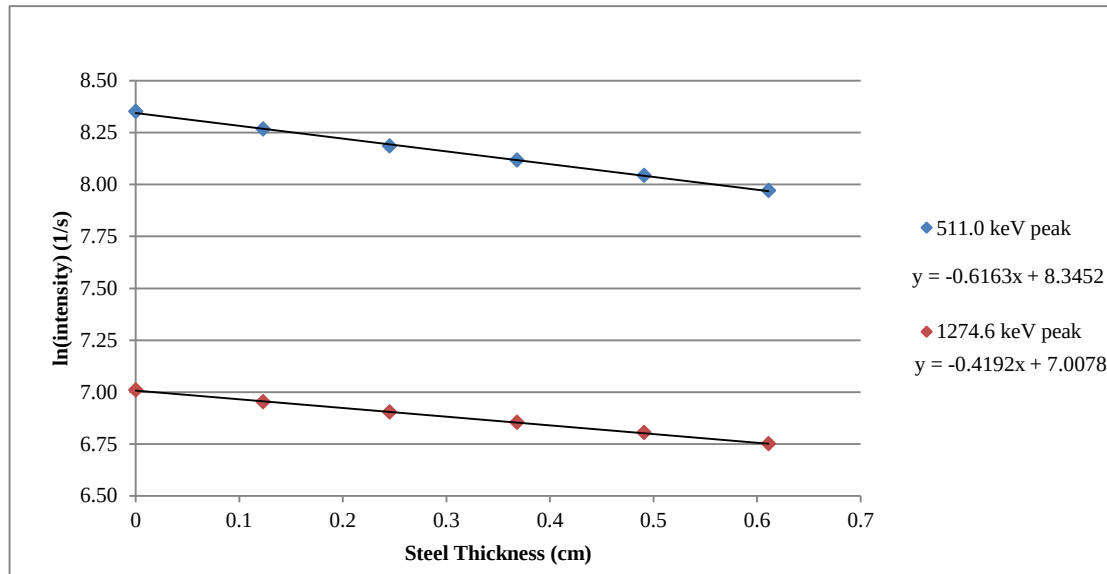


Figure 3.6.2: Plots showing the attenuation of γ -rays through steel

μ decreases with increasing γ -ray energy. This result is expected because higher energy photons are more penetrative[5]. The total cross-section has contributions from all three interaction processes: $\sigma = \sigma_{pe} + Z\sigma_c + \sigma_{pp}$ (Photoelectric, Compton scattering (for a single electron) and Pair production cross sections respectively). Generally σ_{pe} and σ_c are inversely proportional to photon energy, and σ_{pp} is proportional to photon energy (above activation energy). Therefore the total cross-section decreases with photon energy.

The linear attenuation coefficient is proportional to cross-section; $\mu = N\sigma$, therefore linear attenuation coefficient decreases with photon energy. (In this case the uncollimated source also contributes Compton-scattered γ -rays which otherwise would not reach the detector).

Shielding Calculation Based on Results

From our estimates of the linear attenuation coefficient, we calculated the thickness of shield made from Material 1 that would be required to reduce the intensity of a 1460 keV γ -ray source, by a factor of 1000.

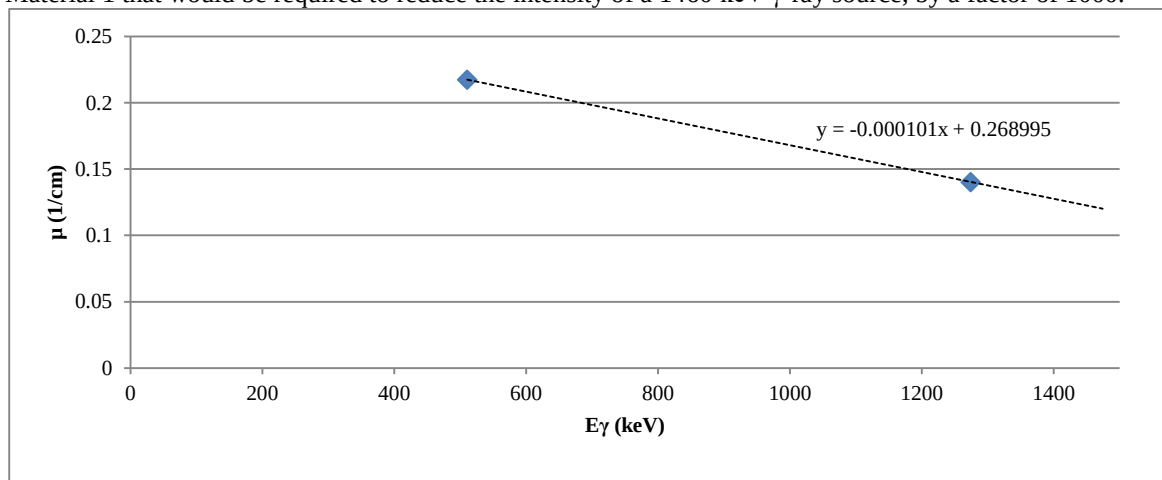


Figure 3.6.3: Plots showing the linear attenuation coefficient for aluminium as a function of photon energy

Assuming attenuation is linear with respect to γ -ray energies for aluminium, then the values of μ for the 511.0 keV and 1274.6 keV γ -rays as calculated above can be extrapolated to find a value for μ at higher energy (1460 keV).

Using the equation of the straight line above:

$$\mu = (-0.000101 \times 1460) + 0.268995$$

$$\mu = 0.1215$$

$$\text{Then } x = \ln(I/I_0)/-\mu$$

$$x = \ln\left(\frac{1}{1000}\right)/-0.1215 = 56.9 \text{ cm}$$

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