Gamma Ray Spectroscopy

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Contents

1 Abstract

In this experiment spectra were successfully produced for various radioactive sources using a spectrometer. These spectra were studied to find features including the backscatter peak, the Compton edge and the total energy peak.
It was estimated that there are 8 dynodes in the photomultiplier of the spectrometer, a value for resolution for the caesium-137 sample was found to be 0.1202. The efficiency for the spectrometer with the sodium-22 sample was found to be 25 percent and with the cobalt-60 sample to be 26 percent. A count rate for the KCl sample was found to be 0.16 Bq.

2 Introduction and Theory

The purpose of this experiment is to obtain spectra of various radioactive samples using a spectrometer, and to investigate the operation of the spectrometer and analyse the individual spectra themselves.

2.1 Radioactivity

Radioactivity is a property exhibited by certain types of matter of emitting energy and subatomic particles spontaneously [1].

Unstable nuclei emit radiation in the form of alpha, beta and gamma decay. Alpha decay generally occurs in nuclei which are too large to be stable. An alpha particle consists of 2 protons and 2 neutrons bound together (similar to a helium nucleus) with total spin zero [2].

Beta decay can be classified into three different types; Beta-minus decay, Beta-plus decay, and electron capture.
A beta minus particle is an electron and it is produced by a nucleus transforming into a proton, an electron and an antineutrino. The antineutrino is a neutral particle which accounts for the conservation of charge, energy and momentum in this process. The simple decay equation can be seen below;

$$n \rightarrow p^{+} + \beta^{-} + \bar{\nu}_{e} \tag{1}$$

Beta minus decay generally occurs when the proton to neutron ration of a nuclide is too large for stability [3].
Nuclides with too small of a neutron to proton ratio for stability tend to undergo beta-plus decay. A beta-plus particle is a positron and it is produced from the transformation of a proton to a neutron, a positron and an electron neutrino, as seen below;

$$p \rightarrow n + \beta^{+} + \nu_{e} \tag{2}$$

Electron capture occurs when an atom does not have enough energy for beta-plus decay. A neutrino is emitted which is formed alongside a neutron from the combination of a proton and an electron;

$$p + \beta^{+} \rightarrow n + \nu_{e} \tag{3}$$

These are three types of beta decay which occur inside the nucleus of an atom, however the decay equations are slightly different when dealing with decay occurring outside of the nucleus, where in general they follow the decay equation (1). (3) is also possible with the addition of energy e.g. from a collision [4].

Gamma decay occurs with the emission of gamma ray photons when an excited nucleus returns to its ground state. A nucleus may be in an excited state due to bombardment with high energy particles or by a radioactive transformation [5]. Gamma decay, unlike those seen previously, does not transform atomic structure. Gamma rays are high energy and massless packets of energy called photons [6].

2.2 Production and Detection of Gamma Rays

In this experiment, caesium-137, cobalt-60 and sodium-22 were the sources used to detect gamma decay. As before, gamma radiation occurs when an excited nucleus returns to its ground state. In this case, the nucleus is excited due to beta-plus decay. As discussed previously, beta plus decay occurs when the neutron to proton ratio is too high for the nucleus to be stable. Beta plus decay may occur in this case as the mass of the parent atom is at least 2 electron masses larger than that of the final atom [7].
Gamma rays do not ionise or excite molecules as they pass through materials, unlike alpha and beta particles. Therefore, they cannot be measure directly or as easily. However, gamma rays do interact with matter in specific ways which can be detected. These include Photoelectric Absorption, Compton Scattering, and Pair Production.

2.2.1 Photoelectric Absorption

The gamma ray photon disappears as it transfers its energy to one of the orbital electrons of an atom. This energy will far exceed the binding energy of the electron and therefore it will be ejected at high velocity [8]. The energy of the ejected electron is equal to the energy of the incident photon less the binding energy of the electron:

$$E_e = E_\gamma - E_b \tag{4}$$

However, the gamma ray energy can be determined directly from the total energy peak due to another electron generated by electron capture also undergoes photoelectric absorption.

A special case occurs in the case of cobalt-60 in which 2 gamma rays are emitted. In this case the total energy peak corresponds to the sum of the energies of the 2 photons.

2.2.2 Compton Scattering

Compton Scattering refers to the inelastic scattering of photons by free, charged particles [9]. In this case a gamma-ray photon is scattered by an electron. The energy of the scattered photon is equal to

$$h\nu^1 = \frac{h\nu}{[1 + h\nu\frac{(1-\cos\theta)}{m_0c^2}]} \tag{5}$$

Where hv is the energy of the incident photon, theta is the angle though which the photon is scattered, and m0 is the rest mass of the electron. This can be derived from the conservation of linear momentum and the conservation of total relativistic energy.
Task: Derive this formula.
The relativistic energy equation is:

$$E^2 = p^2c^2 + m_0c^4 \tag{6}$$

Where p is the linear momentum, E is the energy, m0 is the rest mass of the photon and c is the speed of the wave. However, the photon has zero rest mass therefore:

$$E = pc \tag{7}$$

One may then analyse the conservation of energy for the photon-electron system:

$$E_f + m_0c^2 = \tilde{E}_f + E \tag{8}$$

Where m0 is the rest mass of the electron Ef is the energy of the incident photon, E is the energy of the electron, and tilde Ef is the energy of the scattered photon. The left side of the equation is the energy of the system immediately before the collision and the right side of the equation is the energy of the system immediately after the collision. Rearranging to get:

$$[(E_f - \tilde{E}_f) + m_0c^2]^2 = E^2 \tag{9}$$

Divide both sides by c:

$$(\frac{E_f}{c} - \frac{\tilde{E}_f}{c})^2 + 2m_0c(p_f - \tilde{p}_f) = p^2 \tag{10}$$

Use the conservation of momentum equation:

$$\vec{p}_f = \vec{\tilde{p}}_f + \vec{p} \tag{11}$$

where pf is the momentum of the incident photon, tilde pf is the momentum of the scattered photon and p is the momentum of the electron. We rearrange this to get

$$(\vec{p}_f - \vec{\tilde{p}}_f)^2 = p^2 \tag{12}$$

and

$$(\vec{p}_f - \vec{\tilde{p}}_f)^2 = p_f^2 + \vec{\tilde{p}}_f{}^2 - 2\vec{p}_f \cdot \vec{\tilde{p}}_f \tag{13}$$

Using the formula for a scalar product of vectors:

$$\vec{p}_f \cdot \vec{\tilde{p}}_f = p_f \tilde{p}_f cos\theta \tag{14}$$

one can derive an equation relating the momentum and the scattering angle theta:

$$(p_f - \tilde{p_f})^2 + 2m_0c(p_f - \tilde{p_f}) = p_f^2 + \tilde{p_f}^2 - 2p_f\tilde{p}_f \cos\theta \tag{15}$$

which may be simplified to

$$\frac{1}{p_f} - \frac{1}{\tilde{p}_f} = \frac{1}{m_0c}(1 - \cos\theta) \tag{16}$$

From equation (7)

$$p_f = \frac{E_f}{c} \tag{17}$$

Therefore

$$\tilde{E}_f = \frac{E_f}{[1 + E_f\frac{(1-\cos\theta)}{m_0c^2}]} \tag{18}$$

If one lets the Energy equal to vh where h is Planck's constant then

$$hv^1 = \frac{hv}{[1 + hv\frac{(1-\cos\theta)}{m_0c^2}]} \tag{19}$$

Assuming the only variable is theta, when theta is at a minimum = 0, cos(theta) is at a maximum =1, (1-cos(theta)) is at a minimum =0, hv1 is at a maximum:

$$hv^1 = hv \tag{20}$$

When cos(theta) is at a minimum = 0 [due to theta = pi], (1-cos(theta)) is at a maximum = 1, which means hv1 is at a minimum:

$$hv^1 = \frac{hv}{[1 + \frac{hv}{m_0c^2}]} \tag{21}$$

2.2.3 Pair Production

If the gamma ray energy is more than twice the rest mast energy of an electron, instead of scattering, a gamma ray fired at matter will disappear and produce an electron and a positron. This is called Pair Production. The positron and electron have equal and opposite charge and therefore the system conserves charge. These particles will then slow down inside of the medium, annihilate each other, and the excess energy will be converted into two gamma ray photons. The photons travel at equal and opposite velocity and therefore conserve both energy and momentum. These have a total energy great than or equal to

$$2m_ec^2 = 1.022MeV \tag{22}$$

These effects are measured using the spectrometer, which is covered in the following section.

2.3 Spectroscopy

Spectroscopy is the study of the absorption and emission of light and other radiation by matter, as related to the dependence of these processes on the wavelength of the radiation. Spectroscopy also includes the study of the interactions between particles and their interactions as a function of their collision energy [10].

Spectroscopy is performed using a spectrometer. A spectrometer consists of three main parts; the scintillator, the photomultiplier and the multichannel analyser.
An electron passes through the scintillator, electron-hole pairs are created and they recombine here and emit photons. A small percentage of these photons eject an electron from the photocathode. These are multiplied in the photomultiplier with a voltage pulse of

$$V = \frac{Charge}{Capacitance} \tag{23}$$

and the height of the pulse is proportional to the energy E.

2.3.1 Resolution

Resolution is the minimum wavenumber, wavelength or frequency difference between two lines in a spectrum that can be distinguished [11]. Resolving power, R, is given by the transition wavenumber, wavelength or frequency, divided by the resolution [12]. The energy resolution is defined as

$$R = \frac{FWHM}{H_0} \tag{24}$$

Where FWHM is the full width at half maximum height of the peak and H0 is the peak position. For a Gaussian curve

$$FWHM = 2.35\sigma \tag{25}$$

and so

$$R = \frac{(2.35)\sigma}{H_0} \tag{26}$$

Approximately linear detectors give

$$\sigma = K\sqrt{N}, H_0 = KN \tag{27}$$

where K is a constant of proportionality and N is the number of photoelectrons emitted from the photocathode. Then

$$R = \frac{2.35}{\sqrt{N}} \tag{28}$$

Taking into account fluctuations in various quantities:

$$R = 2.35[\frac{1}{x}(1 + \frac{1-p)}{p} + \frac{1}{p(m-1)})]^{\frac{1}{2}} \tag{29}$$

Where x is the average number of photons produced by photoelectric absorption of gamma rays, which is approximately 40,000 in this experiment, p is the quantum efficiency of the photocathode, which is approximately 0.2 in this experiment and m is the average multiplication factor at a dynode, which is approximately 5 in this experiment.

2.4 Spectra

Spectra are plotted using MAESTRO II software which plots the number of pulses versus the channel number. This is a useful plot as the pulses are the counts and the channel number is related to pulse height, which as before, is proportional to the electron energy, which is related to the gamma ray energy.

2.4.1 Backscatter peak

A backscatter peak can be seen on the spectra, this appears as a small peak left of the total energy peak. This is due to a large percentage of gamma rays undergoing Compton scattering in the lead shield and deflect through a large angle of approximately 180º and absorbed into to scintillator. Subsequently a visible peak forms on the spectra.

2.4.2 Compton Edge

A small trough can be seen on the spectra and this feature is known as the Compton edge. This is due to electrons acquiring a maximum energy in Compton Scatting which from earlier was calculated to be:

$$E = hv \tag{30}$$

2.4.3 Broad Peaks

Even though the gamma rays that are produced in this experiment have well defined energy, the peaks in the spectra are relatively broad. This is mainly due to the statistical nature of the charge pulse Q. There are statistical fluctuations in Q due to fluctuations in; the number of visible photons produced by each gamma ray, the number of photons converted to electrons at the photocathode, the number of electrons reaching the anode. The broad peaks may also result from a variation in Voltage, non-uniformity of sensitivity from the cathode, and non-uniformity in the transparency of crystals in the scintillator.

3 Apparatus

The apparatus consists of a spectrometer (with a a scintillator, a photomultiplier and a multichannel analyser), and a PC with Maestro II software downloaded to produce, view and save spectra.

4 Experimental Method

4.1 Experiment 1

The objective of this section is to record and analyse the effect of changing the voltage in the photomultiplier on the spectrum.
1. The lab technician must place the Caesium-137 source into the spectrometer.
2. Spectra are to be obtained on the computer for varying photomultiplier voltages from 550V to 650V.
3. Using the CHN files created, the peak positions, and the full width at half height measurements are to be obtained to calculate the resolution for each voltage.

4.2 Experiment 2

The objectives of this section is to record and interpret spectra for our 3 samples, and to investigate the dependence of the resolution on the gamma ray energy.
1. As before, obtain spectra using the MAESTRO II program on the PC which is attached to the spectrometer with a photomultiplier voltage of 600V, for each of the 3 samples.
2. Using the reference image below (fig.1), identify the energies at which the total energy peaks occur.
3. Use Logarithmic scale to view smaller peaks.

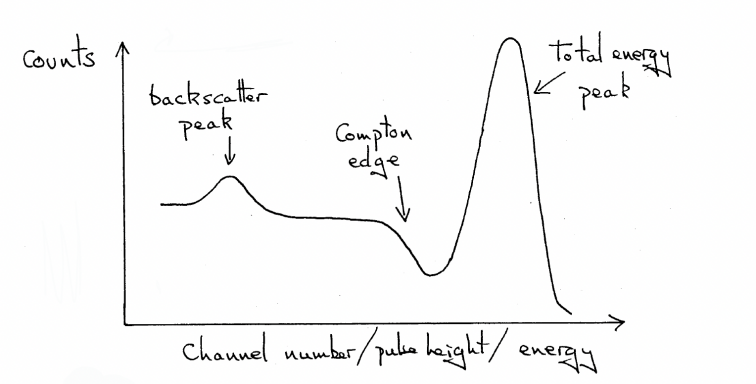

Figure 1: Reference Image for Identifying Peaks

4.3 Experiment 3

The objectives of this section are to measure the detection efficiency of the spectrometer, and to measure the activity of a sample of KCl.
1. Obtain a spectrum for the KCl sample as done previously with the other samples.
2. Use the spectrum to find the efficiency of the spectrometer at 511 keV.
3. Carry out the same process with cobalt-60 sample.
4. Measure the count rate of a sample of 3.625g of KCl using the same techniques. Allow the count to run over night and over more than 24 hours to obtain an accurate sample (see more in section 6.1:Improving Accuracy).

5 Results

5.1 Experiment 1

The image below is the spectrum obtained for Caesium-137.

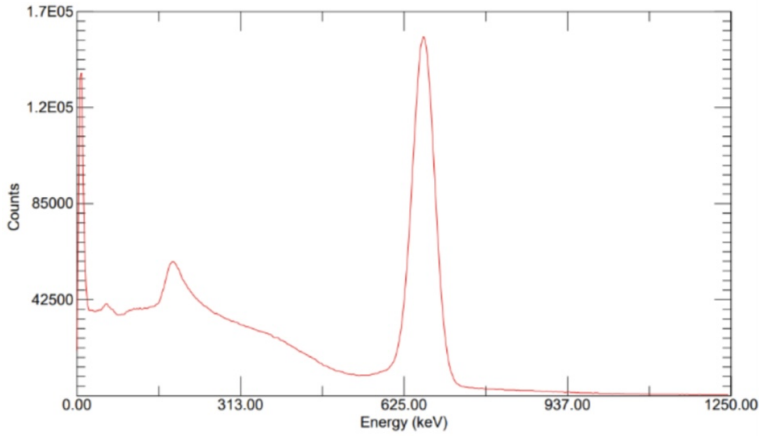

Figure 2: Spectrum of Caesium-137

The following image is a table of the data set obtained for Experiment 1 from the Caesium-137 source.

	Data Set for Caesium-137					
	PM voltage (V) ± 1	Peak Energy ± 1 (keV)	H0 ± 1	FWHM ±0.1	Resolution	dR
1	650	1272	455	80.7	0.177	0.0004
2	640	1120	404	75.5	0.187	0.0005
3	630	986	355	69.1	0.195	0.0006
4	620	867	313	61.8	0.197	0.0007
5	610	757	276	55.2	0.200	0.0008
6	600	663	245	49.3	0.201	0.0009
7	590	577	210	30	0.143	0.0008
8	580	500	184	35	0.190	0.0012
9	570	430	163	29	0.178	0.0014
10	560	371	141	27	0.191	0.0017
11	550	318	120	25	0.208	0.0019

Figure 3: Data for Caesium-137

The following image is a linear scale graph of H0, the position of the total energy peak, versus the photomultiplier voltage.

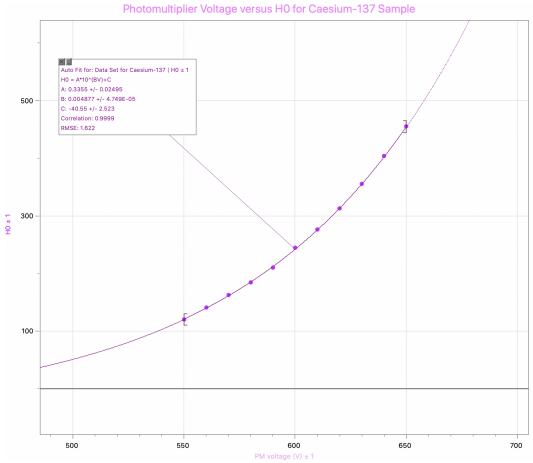

Figure 4: Graph of H0 vs. PMV for Caesium-137

The next image is a log-log plot of H0, the position of the total energy peak, versus the photomultiplier voltage.

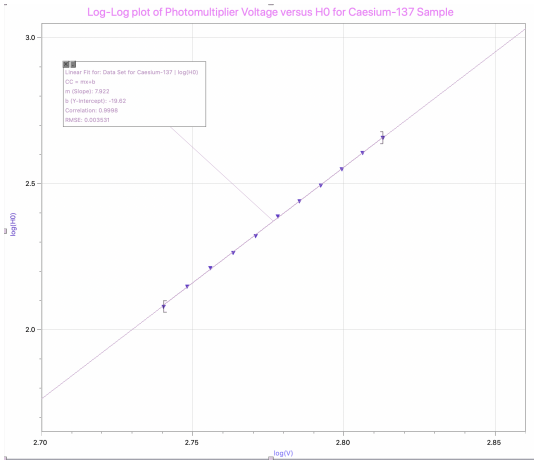

Figure 5: Log Plot of H0 vs. PMV for Caesium-137

It is a known formula that

$$H_0 \propto V^n \tag{31}$$

and we are asked to find if our data agrees with this equation and also to find n, the number of dynodes in the photomuliplier. As seen from the log-log plot of H0 and V, it follows a linear relationship. Therefore we may express these variables in a linear relationship as follows:

$$\log H_0 = n \log V + c \tag{32}$$

which, due to the indices' laws this proves true;

$$nlogx = logx^n \tag{33}$$

.
Looking at the slope of the line fit, we estimate n to be 7.992. Therefore a good estimate of 8 dynodes. We will now analyse the plots of the PM voltage and the FWHM of the peaks to investigate resolution. The following image is the graph of the PM voltage against the FWHM of the energy peaks.

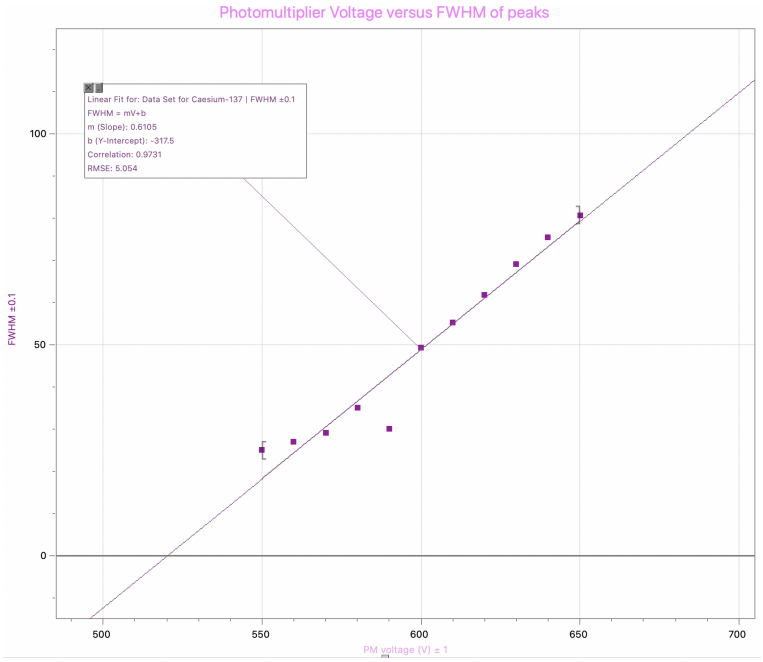

Figure 6: Plot of PMV vs FWHM for Caesium-137

The next image is the log-log plot of the PM voltage against the FWHM of the energy peaks.

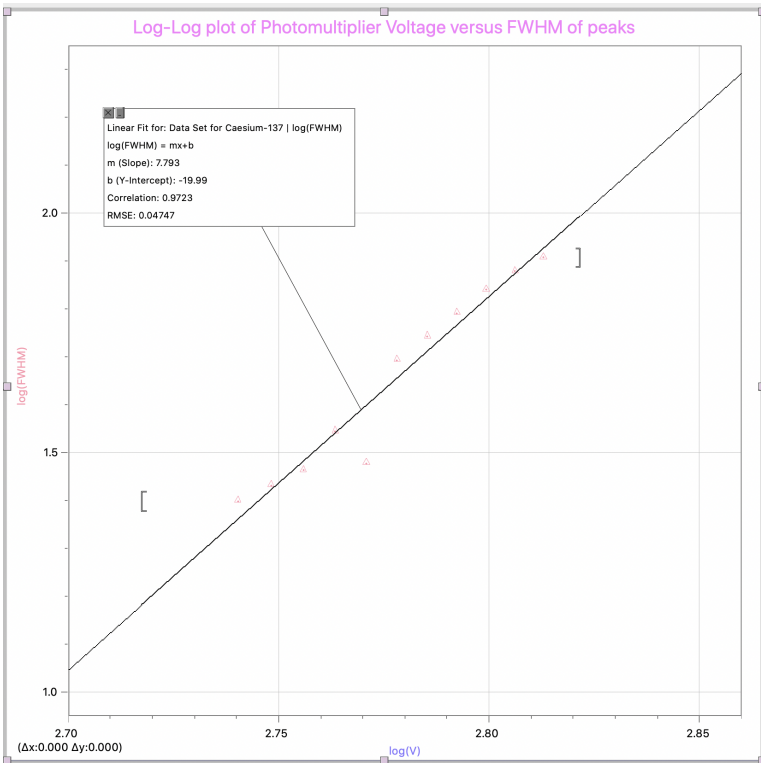

Figure 7: Log-Log Plot of PMV vs FWHM for Caesium-137

The theoretical value for R=0.1942. We want to experimentally find a value for R and compare them. The linear fit of the log log plot gives us a linear equation similar to the previous one:

$$log(FWHM) = plogV + c = 838 \tag{34}$$

Looking at the slope and the y-intercept on the graph we obtain the equation:

$$log(FWHM) = (7.793)logV - 19.99 \tag{35}$$

From the other graph we obtained the equation:

$$log(H_0) = (7.992)logV - 19.62 \tag{36}$$

Subbing in V=600 for each of these give us the following results:

$$log(FWHM) = 1.66 \tag{37}$$

therefore

$$FWHM = 45.71 \tag{38}$$

and

$$log(H_0) = 2.58 \tag{39}$$

therefore

$$H_0 = 380.19 \tag{40}$$

Using a formula from earlier, one can find the resolution:

$$R = \frac{FWHM}{H_0} \tag{41}$$

therefore

$$R = \frac{45.71}{380.19} = 0.1202 \tag{42}$$

The position H0 of the peak was found to be 380.19 and the full width at half height (FWHM) was found to be 45.71
One expects that for a fixed energy of the charged particle the pulse height is proportional to the voltage V raised to the power of the number of dynodes.

$$H_0 \propto V^n \tag{43}$$

.
The resolution was found to be 0.1202.
The Value for n found was estimated to be 8.
Question: How would one expect the FWHM and R to depend on V?

$$R = \frac{(2.35)\sigma}{H_0} \tag{44}$$

therefore

$$R \propto \frac{1}{H_0} \tag{45}$$

and

$$H_0 \propto V^n \tag{46}$$

therefore

$$R \propto \frac{1}{V^n} \tag{47}$$

Question: compare the heoretical estimate of R for V=600 and with the measured value. The value for R was measured to be 0.1202 The theoretical estimate for R was 0.1957. This is therefore a relatively inaccurate result obtained by experiment.

5.2 Experiment 2

5.2.1 Spectra

The following images are the spectra obtained by the experimental method for section 2:

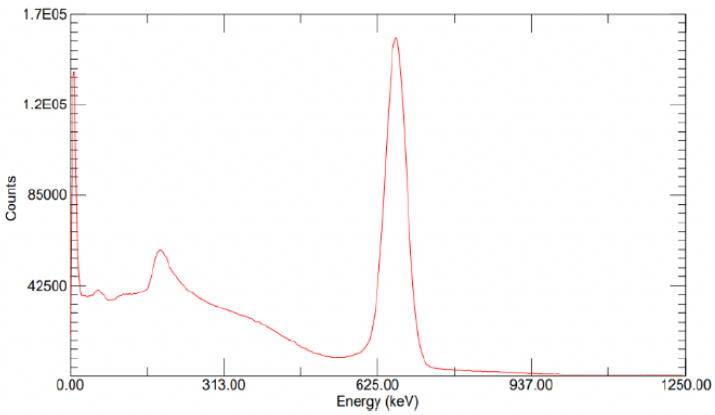

Figure 8: Spectrum of Caesium-137

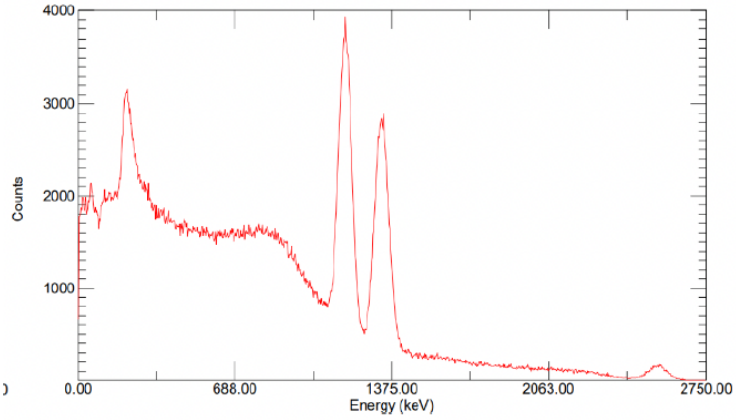

Figure 9: Spectrum of Cobalt-60

5.2.2 Data Sets

The following images are the analysed data sets collected for each of these radioactive sources:

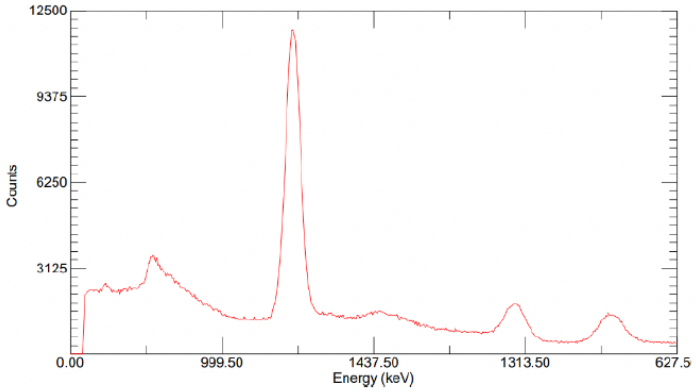

Figure 10: Spectrum of Sodium-22

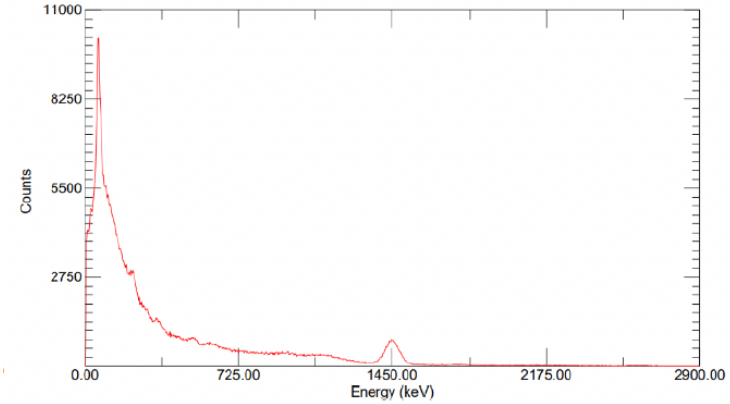

Figure 11: Spectrum of KCl

Cs-137	1st Peak
Measured Energy (keV)	662.00
Theoretical Estimate of energy (keV)	661.70
Calculated resolution	0.1942

Figure 12: Data for Caesium-137

Co-60	1st Peak	2nd Peak	Sum Peak
Energy(keV)	1170.8	1321	2491.8
H0	420.3	481.1	901.1
FWHM	5.74	5.28	11.02
Count Rate (c/s)	105	229.9	334.9
Theoretical Estimate of energy (keV)	1173	1333	2506
Resolution	0.0136	0.01910	0.0061

Figure 13: Data for Cobalt-60

Na-22	1st Peak	2nd Peak	3rd Peak	4th Peak	5th Peak
Energy (keV)	509.36	1046.85	1290.37	1826.30	2349.16
H0	188.42	376.7	462.01	649.74	832.9
FWHM	40.97	31.42	10.38	12.85	6.56
Count rate (c/s)	4405.13	549.7	406.62	94.32	16.7
Theoretical estimate of energy (keV)	511	1068	1274	1819	2364
Resolution	0.2174	0.0834	0.0225	0.0198	0.0079

Figure 14: Data for Sodium-22

KCl	1st Peak	2nd Peak
Energy (keV)	60.31	1447.85
H0	31.16	517.17
FWHM	18.04	16.89
Count rate (c/s)	2.17	0.16
Theoretical estimate of energy (keV)	73	1461
Resolution	0.5789	0.0327

Figure 15: Data for KCl

5.2.3 Decay Processes

It is necessary to understand the decay process for each nucleus before analysing any data. The following images are the decay processes for the samples:

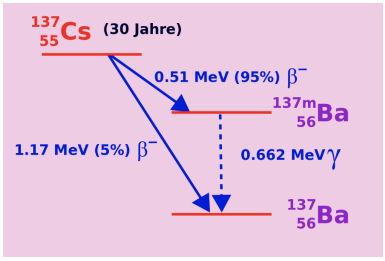

Figure 16: Decay scheme for Caesium-137

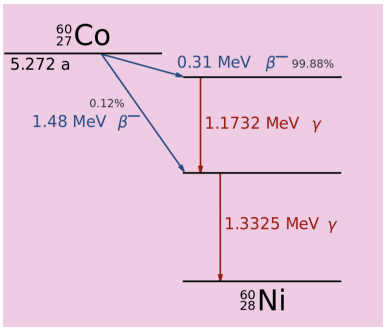

Figure 17: Decay scheme for Cobalt-60

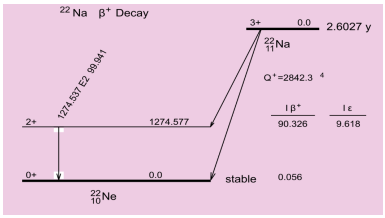

Figure 18: Decay scheme for Sodium-22

The data collected verifies the relation between resolution and H0:

$$R \propto \frac{1}{H0} \tag{48}$$

5.2.4 Caesium-137

In the spectrum, an energy peak of 662 keV is emitted. This occurs when the nucleus of the newly formed barium 137 atom is excited and subsequently returns to its ground state emitting a high energy gamma ray. This process can be seen in figure 16. A notable backscatter peak is seen at 210 keV and a compton edge is seen at 470 keV.

5.2.5 Cobalt-60

In the spectrum for Cobalt-60 sum peak can be seen at 2540 keV due to two gamma rays being involved in the absorption. At 205 keV there is a backscatter peak and at 1050 keV there is a Compton Edge.

5.2.6 Sodium-22

From the first peak pair production is apparent. Pair annihilation occurs at 511 keV. At 180 keV there is a backscatter peak and at 760 keV there is a Compton Edge.

5.2.7 KCl

At 1450 keV an energy peak is observed and at 30 keV a backscatter peak can be seen.
Due to the statistical nature of the processes by which the gamma ray photons produce a pulse, and the imperfect nature of the spectrometer, the peaks seen on the spectra are broad, even though the gamma rays produces have discrete and well defined energies.
The resolutions seen in the data tables above were found using the formula:

$$R = \frac{FWHM}{H_0} \tag{49}$$

Question: How do you expect R to vary with the peak energy?

$$R = \frac{FWHM}{H_0} \tag{50}$$

and

$$H_0 \propto E_{peak} \tag{51}$$

therefore

$$R \propto \frac{1}{E_{peak}} \tag{52}$$

Inversely proportional relationship, which implies a higher peak energy will result in lower resolution.
The results did match the expectation.

5.3 Experiment 3

The count rate for the sum peak is given by

$$A\varepsilon^2 \tag{53}$$

Where A is the activity and epsilon is the efficiency of detection in the total peak energy.
The data gave the following values for Sodium-22:

$$2A\varepsilon = 4405.13 \tag{54}$$

$$A\varepsilon^2 = 549.7 \tag{55}$$

$$\varepsilon = \frac{2 \times A\varepsilon^2}{2A\varepsilon} \tag{56}$$

Using the above formula and the results for sodium-22 the efficiency of the spectrometer at 511 keV was found to be 25 percent.
The data gave the following values for Cobalt-60:

$$2A\varepsilon = 105.1cps \tag{57}$$

$$A\varepsilon^2 = 13.69 \tag{58}$$

Using the above formula and the results for cobalt-60 the efficiency of the spectrometer was found to be 26 percent.
The half life of potassium-40 is 1.26 billion years. Beta-minus decay accounts for 89 percent of its decay and electron capture accounts for 11 percent of its decay. The abundance ratio of potassium 40 in potassium is 0.011 percent.
The mass of potassium-40 in the sample 0.0399 grams which is the equivalent of 6.011 times 10 rasied to the power of 20 atoms. Using the formula for activity to find the count rate:

$$A = N\frac{ln(2)}{\tau_{\frac{1}{2}}} \tag{59}$$

The count rate for 3.625g of KCl was found to be 0.16 Bq. This is not consistent with the theoretical estimate of 288.29 Bq for an efficiency of 25 percent (see more in section 6.1: Improving Accuracy).

6 Error Propagation

Using Gauss' law of error propogation for

$$R = \frac{FWHM}{H_0} \tag{60}$$

we get

$$\Delta R = \sqrt{(\frac{\partial R}{\partial (FWHM)}\Delta(FWHM))^2 + (\frac{\partial R}{\partial H_0}\Delta H_0)^2} \tag{61}$$

$$= \sqrt{(\frac{\Delta FWHM}{H_0})^2 + (\frac{-FWHM\Delta H_0}{H_0^2})^2} \tag{62}$$

$$= \sqrt{(\frac{\Delta FWHM}{H_O})^2 + (\frac{FWHM\Delta H_0}{H_0^2})^2} \tag{63}$$

6.1 Improving Accuracy

Some results found in this experiment were relatively inaccurate. However, when replicating this experiment, the experimenter should take note of the following suggestions as to improve the accuracy of results:
1. Due to the statistical nature of the processes by which the gamma ray produces charge pulse Q, a longer sampling time will increase the sample size and therefore the accuracy.
2. Performing this experiment in better shielding will result in less radiation noise which will improve accuracy.
3. One may practice methods of ensuring homogeneity of samples for example by vortexing prior to the experiment to improve the accuracy of results. Similar methods and testing can be done to ensure the homogeneity of the apparatus for example the crystals in the scintillator of the spectrometer.

7 Conclusion

During this experiment, Spectra were produced for various radioactive sources by producing gamma rays which were picked up in the spectrometer and reproduced on a computer. These spectra were analysed and plots were made to compare characteristics of the produced spectra and the theoretical estimates for those characteristics.
One example of a well fitting plot with the predicted value was the value found for energy of the total energy peaks in Cobalt. For example the experimental value for the energy of the first peak Cobalt was found to be 1170.8 and the theoretical estimate was 1173. One example of a failure of an experimental result to obtain a reasonably close value to a theoretical estimate was the resolution value in section 1. The experimental result gave a value of 0.1202 which is relatively small compared to the theoretical estimate of 0.1942.

8 Appendix

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