UNIVERSITY *of*
TASMANIA

Gamma-ray spectroscopy

May 12, 2021

Safety

This experiment involves the use of ionising radiation, specifically alpha, beta and gamma radiation. Alpha particles are highly ionising and therefore are unable to penetrate far through matter: they are typically brought to rest in a few centimetres of air. Beta particles are moderately-ionising (as compared to alpha particles) and have moderate penetrating power through matter: they are typically brought to rest in a few metres of air or a few millimeters of tissue. However, both alpha and beta-particle emitters are dangerous if inhaled, ingested, or if they enter a wound and care must be taken when handling them. Gamma radiation is a high-energy form of electromagnetic radiation and has a high penetrating power and therefore the impacts of gamma radiation can occur throughout the body. Prior to beginning the experiment, you will be provided with a radiation safety induction, but as a general set of guidelines:

- Only handle the radioactive sources when they are required and act reasonably to minimise exposure

- Ensure to sign out the source of radiation on the manifest when collecting the source, and sign it back in upon its return

- Wash your hands thoroughly with nonabrasive soap immediately after handling the source

This experiment also makes use of lead shielding, and care must be taken to avoid lead exposure. Lead is a highly toxic cumulative poison; however the risks posed by this experiment are minimal as interaction with the lead is not required. In any case, when working with lead it is recommended that you:

- Wash your hands and face thoroughly prior to eating or drinking after spending time in a lead-risk area

- Shower and wash hair as soon as possible after spending time in a lead-risk area

Gamma-ray spectroscopy

Summary

This experiment investigates the characteristic gamma-ray spectra produced by various radionuclides, and probes the different mechanisms by which gamma radiation interacts with matter.

Objectives and learning outcomes

- Mastery of the apparatus and signal conditioning to collect energy spectra
- Collection and interpretation of gamma-ray spectra
- Identification of an unknown source of radiation

Introduction

With research into radiation in its infancy at the turn of the 19th to 20th century, it was the experiments of Paul Villard that led to the discovery of gamma rays. Investigating the emissions from radium, he found that there were three distinct forms of radiation, each with a different power to penetrate material. The forms of radiation were named alpha, beta, and gamma in order of their ability to penetrate material, but unlike alpha and beta radiation, gamma radiation was not deflected by a magnetic field. Subsequent work would show that gamma rays are a form of high-energy electromagnetic radiation, with energies greater than $100\,\mathrm{keV}$ and distinct from X-rays due to their method of production: X-rays are produced by the decay of excited electronic states of an atom, whereas gamma rays are produced by the decay of excited nuclear states of an atom. The uses of gamma radiation are myriad, ranging from sterilisation of medical equipment, pasteurisation of foodstuffs to fuel gauges in aircraft, and medical and industrial imaging.

Gamma radiation

Gamma rays are produced when a nucleus in an excited state decays to a lower-energy nuclear state, in complete analogy with the decay of electronic states. Excited nuclear states are produced through nuclear fusion or other nuclear reactions, for example a radioactive nucleus decaying via the emission of an alpha or beta particle and the daughter nucleus is left in an excited state. The process is expressed as

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma. \tag{1}$$

where X^{*} denotes the excited state of the nucleus. The lifetime of excited nuclear states is typically very short, usually in the range of $10^{-10} - 10^{-12}\,\mathrm{s}$ which is commensurate with a large transition linewidth.

Interactions with matter

In atomic, nuclear, and particle physics, the scattering of particles is characterised by the cross section σ for a given process, which is the probability that a process will occur and is therefore related to the strength of the interaction. An intuitive application of the cross section is the description of attenuation of particles through a material of thickness dz, whereby the flux Φ will decrease as

$$\frac{d\Phi}{dz} = -n\sigma\Phi \tag{2}$$

where n is the number density of scattering sites. In the context of gamma radiation, it is more common to see the intensity as a function of z, $I(z)$, expressed and a function of the incident intensity I_0:

$$I(z) = I_0 e^{-n\sigma z}. \tag{3}$$

2

Importantly, to understand the scattering of radiation in materials, we must understand the mechanisms by which the radiation interacts with the material, which is encapsulated by the cross section σ. In the case of gamma radiation, there are three distinct processes through which the radiation interacts: the photoelectric effect, Compton scattering and pair production.

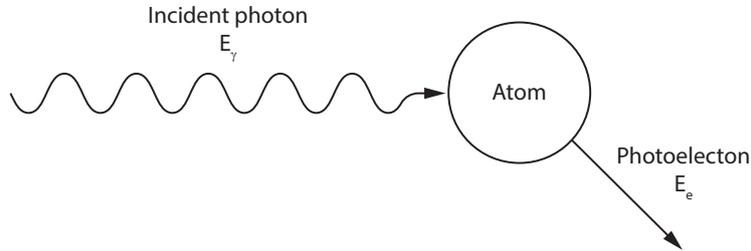I: The photoelectric effect

Figure 1: Photoelectric scattering of gamma radiation

When a gamma photon interacts with a bound electron, a transfer of energy from the photon to the electron is possible resulting in the emission of the electron from the parent atom. The energy of the photoelectron will be the energy of the gamma photon minus the binding energy, E_b. The cross section for the photoelectric effect goes as

$$\sigma \propto \frac{Z^n}{E^3} \tag{4}$$

but this is only approximate, as the exponent n takes a value between 4 and 5. Regardless of the exponent, it is clear that as the energy of the gamma ray decreases, the probability of scattering via the photoelectric effect increases rapidly. Indeed, photoelectric absorption is the predominant interaction for low-energy gamma rays.
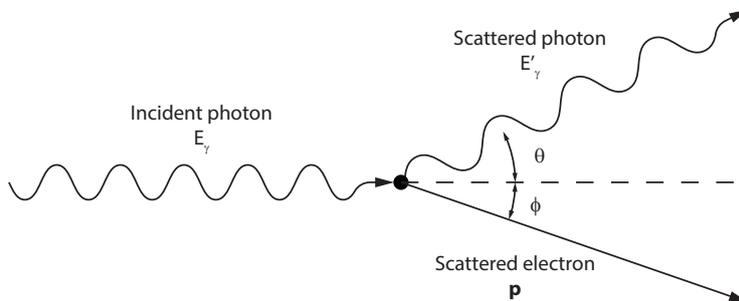
II: Compton scattering

Figure 2: Compton scattering of gamma radiation

When a gamma photon interacts with a free or weakly bound electron ($E_\gamma \gg E_b$) this can result in the partial transfer of energy to the electron. The conservation of energy and momentum dictates that only partial energy transfer can occur when the electron is not sufficiently tightly bound to allow the parent atom to absorb any recoil energy. Thus in a Compton scattering event, there is a frequency shift of the gamma photon with a commensurate momentum transfer to the scattered electron.

Exercise 1

Use conservation of energy and momentum to show that the energy of the scattered photon E'_γ is given by

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos(\theta))} \tag{5}$$

From equation 5, it is clear that the energy shift increases when $\frac{E}{mc^2}$ becomes large: for low-energy photons ($\frac{E}{mc^2} \ll 1$), the energy shit will be small and $E' \approx E$, whereas for $\frac{E}{mc^2} \gg 1$, E' is independent of E and $E' \approx mc^2$.

Exercise 2

At what angle is the scattered photon energy maximised? At what angle is the scattered photon energy minimised? Write expressions for the maximum and minimum photon energies $E'_{\gamma,max}$ and $E'_{\gamma,min}$ in terms of the incident energy E

One of the early triumphs of quantum field theory was to show that the differential cross section $\frac{d\sigma}{d\Omega}$ (where Ω is the solid angle) for Compton scattering is given by the Klein–Nishina formula

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \left(\frac{\hbar}{m_e c} \right)^2 \alpha^2 P(E_\gamma, \theta)^2 \left(P(E_\gamma, \theta) + P(E_\gamma, \theta)^{-1} - \sin^2(\theta) \right) \tag{6}$$

where α is the fine structure constant and $P(E_\gamma, \theta)$ is the ratio of incident and scattered photon energies

$$P(E_\gamma, \theta) = \frac{\lambda}{\lambda'} = \frac{1}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos(\theta))} \tag{7}$$
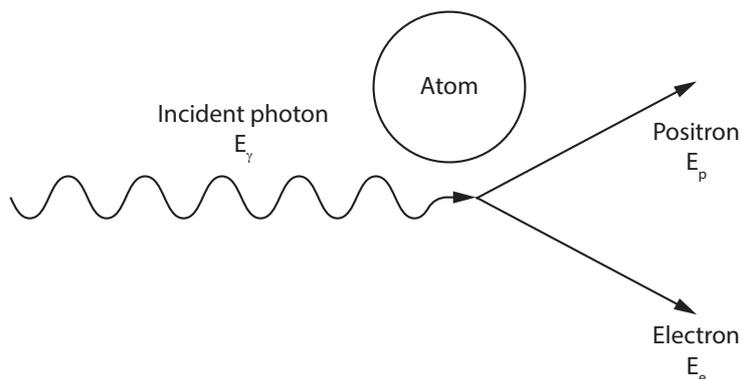
III: Pair production

Figure 3: Pair production from gamma radiation

When a gamma ray has an energy greater than twice the rest mass energy of the electron ($2 \times 0.511\,\text{MeV} = 1.022\,\text{MeV}$), it is possible for the energy of the photon to be converted into an electron-positron pair:

$$\gamma \rightarrow e^- + e^+. \tag{8}$$

In reality, this process must occur in proximity to a nucleus which receives a very small amount of recoil energy in order to satisfy conservation of momentum: an electron-positron pair cannot simultaneously satisfy the conservation of energy and momentum. If a photon has an energy of greater than $1.022\,\text{MeV}$, the excess energy is shared between the electron and positron in the form of kinetic energy. The cross section for pair production is considerably more complicated than those of the photoelectric effect of Compton scattering [**?**], but is of the form

$$\sigma(E_\gamma) = Z^2 \left(\frac{\hbar}{m_e c} \right)^2 \alpha^3 \ln(E_\gamma) \tag{9}$$

which dominates over all other processes in the limit of large E_γ.

4

Gamma ray detection

We have seen the ways in which gamma rays interact with matter, and thus can look at methods to detect their presence. The simplest form of detection is an ionisation chamber, however this does not provide any energy resolution. In order to resolve energy, there are broadly two categories of detector: semiconductor-based detectors and scintillation detectors. The former, which operates based on the detection of charge carriers generated in the semiconductor (usually germanium-based) by scattering of gamma rays provides superior energy resolution; however, they require cryogenic temperatures to operate. Scintillation is the process by which a material can fluoresce (or phosphoresce) in the presence of ionising radiation - the exact details of this process depends on the kind of scintillator - and when combined with highly-sensitive detection of the optical emission, said radiation can be detected and it is this technique we shall be using.

The Scintillator

The most common scintillation material for gamma ray detection (and the one we shall be using) is thallium doped sodium iodide, NaI(Tl). The doped crystal structure is necessary because in a pure crystal, the absorption of energy can elevate electrons from the valence band to the conduction band; however, the decay of the electron to the valence band is an inefficient process and decay is usually non-radiative. Moreover, the band gap energy is typically large resulting in the emission of photons outside the visible spectrum. By doping the crystal with trace amounts of an impurity, sites in the crystal lattice are created with a modified band gap structure and the impurity is chosen such that electron decay is the primary means of relaxation and the decay results in the emission of a visible photon. NaI(Tl) is widely used for a variety of reasons, but notably as the wavelength of light emission $(325 - 550\,\mathrm{nm})$ is convenient for use with photomultiplier tubes, the emission is largely independent of temperature, the crystal does not degrade with exposure to radiation and thallium provides a high atomic number necessary for efficient scattering. Unfortunately, it is highly hygroscopic, meaning that it will readily absorb moisture from the air and degrade and therefore must be hermetically sealed - meaning we cannot play with it, but given the toxicity of thallium, this is not necessarily a bad thing.

The photomultiplier

Following scintillation, visible photons are produced and can be detected; however, we essentially want to count individual photons which is no mean feat. Fortunately, an extremely sensitive photodetector exists for the purpose detecting light when intensities are extremely low: the photomultiplier tube. These vacuum tubes consist of a photocathode, several dynodes held at increasing voltages, and an anode. The principle of operation is high gain charge amplification of a photoelectron: an incident photon ejects an electron from the photocathode via the photoelectric effect, and this electron is accelerated towards the first dynode which upon impact with liberate many other electrons in a process known as secondary emission. These electrons are themselves accelerated towards the next dynode where the same process continues, resulting in an avalanche of charge which is ultimately collected at the anode.
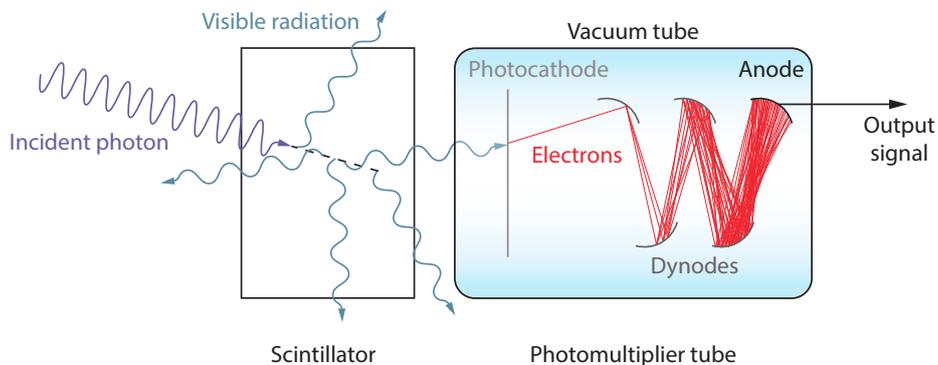

Figure 4: A schematic of gamma ray detection using a scintillator and photomultiplier tube

A schematic of the method for gamma ray detection is shown in figure 4. One of the most crucial aspects

of this detection system is the relationship between the energy of the incident radiation is related linearly to the amount of current measured at the anode of the photomultiplier tube, which means that if we analyse the amplitude of the detected pulses, we will have a path towards measuring energy spectra of gamma ray sources.

Sources of radiation

Up to this point, we have discussed what is gamma radiation and how it interacts, but not from where it comes. Gamma rays are emitted when the nucleus transitions from an excited state, and nuclei typically end up in an excited state through though radiative decay: the emission of either alpha or beta radiation, but the exact pathway will depend on the nuclide. Due to the quantised energy levels in the nucleus, in the same way we can identify atoms and molecules from their optical emission/absorption spectra, we can identify radionuclides from their the gamma-ray spectra. In this experiment we will be using multiple gamma ray sources and this section provides a brief introduction to these radionuclides.

Caesium-137

Caesium ($Z = 55$) is a highly reactive alkali metal, chemically similar to sodium and potassium. The only stable isotope is Cs-133; however the isotope Cs-137, which has a half-life of 30.17 years, is a common product of the nuclear fission of uranium-235 along with other fission reactions, notably the detonation of nuclear weapons. Caesium readily forms caesium hydroxide (similar to table salt) which is highly soluble in water and thus is very easily dispersed, which makes Cs-137 an extremely problematic environmental contaminant following nuclear disasters.

The decay of Cs-137 is shown in figure 5. The emission of beta radiation likely results in the production of a metastable state of barium-137, denoted as ^{137m}Ba, which subsequently decays to the (stable) ground state of barium-137 via the emission of a 0.6617 MeV gamma ray.
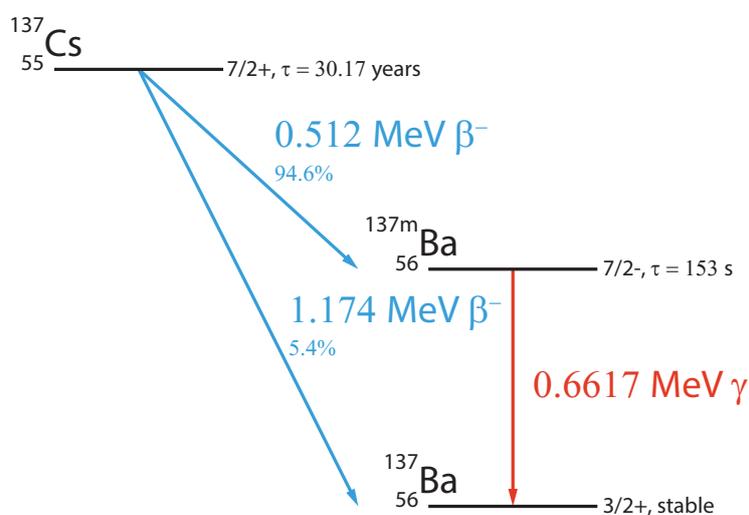

Figure 5: An energy-level diagram for the decay of caesium-137

Cobalt-60

Cobalt ($Z = 27$) is a weakly reactive transition metal, well-known for compounding into a distinctive blue pigment which has been used used to colour glass and ceramics for millennia. Co-60 is a synthetic isotope with a half-life of 5.27 years and is a high-intensity gamma-ray emitter, but unlike Cs, it is much more chemically inert facilitating containment. Consequently, Co-60 is used widely in industrial and medical applications and is typically produced by neutron bombardment of natural Co-59.

An energy-level diagram for the decay of Co-60 is shown in figure 6. The prominent decay channel is the

emission of beta radiation to a metastable state of Ni-60, which in turn decays in a two-photon process resulting in the emission of two gamma-ray photons with energies of 1.1732 MeV and 1.3325 MeV.
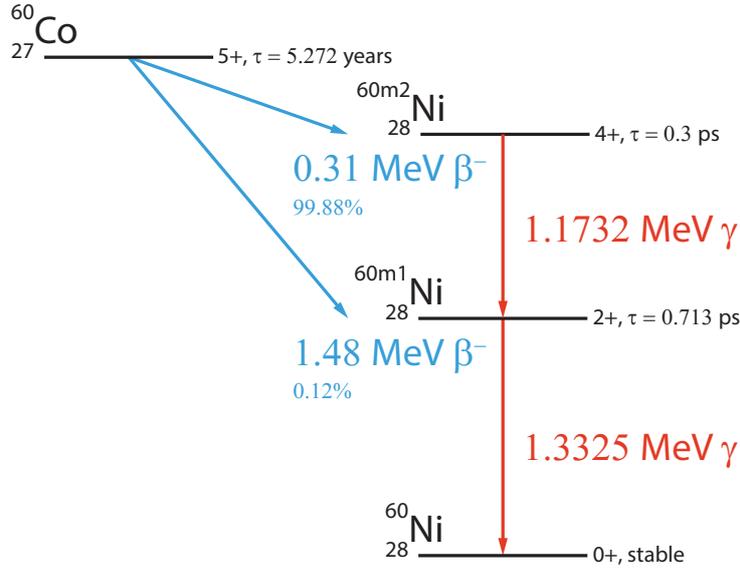

Figure 6: An energy-level diagram for the decay of cobalt-60

Apparatus

With the principles of gamma-ray detection outlined previously, what remains is to discuss the specific implementation of gamma-ray detection in our system. The goal of our apparatus is to facilitate measurement of a gamma-ray spectrum, which is done ultimately by analysing the voltages of pulses produced by the detector. The output signal of the detector is not suitable for direct analysis, so we must *condition* the signal to something more appropriate for analysis. In plain terms, we must amplify the signal with a suitable gain such that we maximise the dynamic range of our voltage pulse height analyser. An block diagram of the signal chain is shown in figure 7.
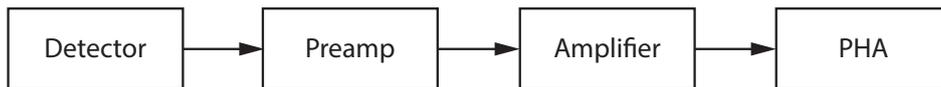

Figure 7: A block diagram showing the signal chain for collecting gamma spectra

A NaI(Tl) scintillator[1] is mated with a photomultiplier tube[2]. The top of the photomultiplier has two BNC connectors for the tube accelerating voltage (marked HV) and for the anode signal output (marked S). The signal is sent to a preamplifier[3] which serves as both a linear amplifier and a buffer, meaning that it has a large input impedance and thus requires only a small current to sense the input signal, and a small output impedance and thus when current is drawn there in minimal change in the output voltage. The preamp output is then amplified[4] and a pulse-height analysis of the signal is performed using an analogue-to-digital converter[5].

---

[1] Bicron model 3MW3P
[2] Bicron P-14
[3] Ortec model 113
[4] Ortec model 485
[5] Spectech UCS30

Pulse-height analysis

By design, the voltage of a detection event is proportional to the energy of the electron produced in the scintillator which is in turn related to the gamma ray energy. Therefore, by collecting a spectrum of the voltages from detection events in combination with an appropriate calibration between voltage and energy, we can produce an energy spectrum.

The collection of a voltage spectrum involves the use of an analogue-to-digital converter to digitise the signal from the detector: the analogue signal which is continuous in both time and voltage is converted to a signal that is discrete in both time and amplitude. An analogue-to-digital converter will have some voltage range over which it samples and a specific number of voltage steps into which this range is broken: in our case, the UCS30 samples the range of $0 - 8\,\text{V}$ with a resolution of $2^{10} = 1024$ bits. Pulse-height analysis involves recording the maximum value of the voltage over a given time interval and then producing a histogram of these events. For example, a signal with (analogue) amplitude between $0 - 0.008\,\text{V}$ would be placed into channel 0 and a signal with (analogue) amplitude between $7.992 - 8\,\text{V}$ would be placed in channel 1023. **It this therefore critical that the gain settings of the amplifier are set such that the amplitude of the pulse corresponding to the maximum gamma ray energy is less than** $8\,\text{V}$.

Gamma-ray spectroscopy

Having discussed both the theory and apparatus, it is time to collect some gamma-ray spectra. Our ultimate goal is to construct a gamma-ray spectrometer: a device in front of which we can place a radioactive sample of unknown composition and with the aid of tabulated energies for gamma-ray emissions, identify which radionuclides are present.

> The purpose of these notes is to facilitate your experiment, not to prescribe the processes. The experimental procedure will require you to tinker with the setup, and importantly make decisions about methods, settings and analyses that are appropriate for the desired outcome(s). Care and attention has been paid to ensure that you have the required resources to accomplish you goals; however some perseverance and critical thinking will be required.

Familiarisation

The first step to producing meaningful gamma-ray spectra is the characterisation and calibration of pulse-height analyser. In the first instance, we are going get a fell for the detection system and the signal conditioning electronics by collecting a Cs-137 source. Begin by retrieving the Cs-137 source, which should be removed from its storage container and placed below the scintillator and photomultiplier tube assembly. In order to detect gamma-ray interactions in the scintillator, the photomultiplier tube must first be biased.

1. Ensure that the high-voltage power supply[6] is connected to the high-voltage input on the photomultiplier (marked HV) and then increase the voltage to $900\,\text{V}$

Exercise 3

With gamma radiation entering the detector and a powered photomultiplier, one should be able to observe output pulses directly. Do this, and describe the pulse.

---

2. Connect the photomultiplier to the preamplifier and ensure that the capacitance is set to the minimum value

---
[6]Ortec model 456

3. Connect the preamp output to the amplifier and in turn connect the amplifier to both the pulse-height analyser and the oscilloscope

4. Adjust the gain settings on the amplifier such that all pulses from the detector will be measured by the pulse-height analyser

Spectra are acquired from the pulse-height analyser using the software USX.

5. In USX, select *mode → PHA - direct in* to bypass the preamplifier and amplifier internal to the UCS30

> **Exercise 4**
>
> Collect a Cs-137 spectrum and identify any prominent features.

You should now have a spectrum which at its core is a histogram of pulse-heights for detector events. The next step is to turn this spectrum into a histogram of the number of detected events as a function of gamma-ray energy.

> **Exercise 5**
>
> What is the maximum energy gamma-ray photon you expect to detect from all sources? From this, establish what voltage you would expect the pulses from the detector corresponding to the highest-energy gamma-ray photons from the decay of Cs-137. Is it better to underestimate or overestimate this voltage? Justify your answer.

6. Set the gain using the above criterion and record another Cs-137 spectrum

> **Exercise 6**
>
> Comment on the significance of the width of the photopeak: how narrow or broad do you expect the peak to be? What is the limiting factor in determining the peak width?

The width of features determines the energy resolution of the detection system; to quantify the width of a peak, the full width at half maximum is used. The fractional energy resolution (quoted in %) is then given as the ratio of the peak width ΔE to the peak energy E and is proportional to $1/\sqrt{E}$ for a Poisson process.

> **Exercise 7**
>
> Vary the supply voltage of the photomultiplier between $800-1000\,\mathrm{V}$ and determine the fractional energy resolution of the Cs-137 photopeak at each voltage. Is there a relationship between the resolution?

7. Set the photomultiplier voltage to achieve the best energy resolution, adjusting any gain settings as necessary. It is important the photomultiplier voltage remains constant for the rest of the experiment

The final step on the path to calibration, is to ensure that the calibration is valid over the range of energies for which we are interested and therefore, we want to collect a Co-60 spectrum.

8. Replace the Cs-137 source with the Co-60 source and collect an energy spectrum

The Cs-137 source is labelled with as having an activity of 39 kBq, whereas the Co-60 is much less than this. Consequently, you may find it more difficult to assess if your gain settings are correct by monitoring

the oscilloscope. In any case, your final gain settings should be determined by ensuring your spectra are appropriate. Once you are happy this is the case, you can move onto calibration; **however, take care not to adjust the gain settings at any point once set, otherwise you will invalidate your energy calibration**.

Calibration

The calibration of the pulse-height analyser bin number to gamma-ray energy is arguably the most important aspect of this experiment, as it allows one to convert from a largely meaningless voltage to physical quantities which can be predicted from first principle calculations.

> **Exercise 8**
>
> Explain how the spectrometer can be calibrated using the Cs-137 and Co-60 sources. Perform the calibration.

Energy spectra

With a valid calibration, it is now possible to produce gamma-ray energy spectra for Cs-137 and Co-60.

9. Record a background spectrum which should be subtracted from future radionuclide spectra

10. Collect spectra for both Cs-137 and Co-60

> **Exercise 9**
>
> Identify and explain all features of both spectra and find the energies of prominent features. Where possible, compare the observed energies to their predicted values.

> **Exercise 10**
>
> Plot the fractional energy resolution as a function of the photopeak energy. Does this follow the expected trend?

Identification of an unknown source

With a calibrated spectrometer, we can collect the energy spectrum of an unknown sample and use it as a kind of fingerprint for the radionuclides present in the sample.

11. Record a spectrum for the unknown sample

> **Exercise 11**
>
> Locate all photopeaks in the spectrum and attempt to identify the sample. You can find libraries of tabulated gamma ray data here[a] and here[b].
>
> ---
> [a] http://www.lnhb.fr/nuclear-data/module-lara/
> [b] http://nucleardata.nuclear.lu.se/toi/radSearch.asp