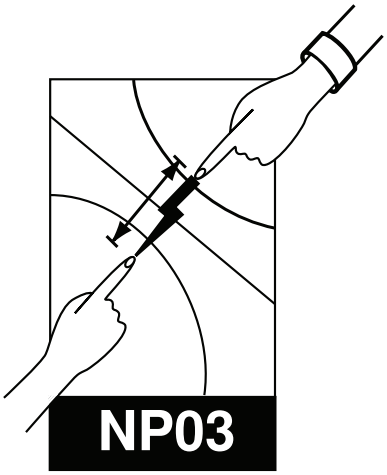
gamma-ray spectroscopy



GB October 2008

NP03

This experiment uses radioactive sources, which must be issued and returned to the Nuclear Physics Laboratory Radiation Safe.

1. Ask the Senior demonstrator to explain the procedure for signing sources out and in and handling of the source to be used including any special handling procedures described in 'Special Local Rules for this laboratory' and 'Local source handling procedure in the Teaching Laboratory' documents.
2. The sources you require are either sealed in a special container with a handle or sealed in small plastic containers. Hold the source by the handle if it has one, with the source pointing away from you or using the tongs provided. DO NOT try to open the containers or interfere with the sources in any other way.
3. Carry the source to and from the experiment in a safe manner, in the tray provided, avoiding contact to any other person. Under no circumstances are sources to be carried in pockets, bags etc.
4. Sources should either be in the store or being used in your apparatus. DO NOT leave sources on your bench or anywhere other than the store.
5. Do not sit close to source or let others sit close to source.
6. Do not lend your source to another group. First return the source to the store and let the other group sign them out.
7. Do not leave your apparatus unattended while using a source. Return it to the store.
8. If you have any questions, ask a demonstrator or technician.
9. If a source appears to have gone missing, let a demonstrator or Teaching Laboratory staff know immediately.

Do **not** switch the electronics rack on or off yourself. **Never** change the detector bias voltage.

If you are planning to carry out the mini-project on this experiment, you will need to write your own risk assessment, stating the hazards involved, and the control measures in place to avoid these risks, in your logbook BEFORE STARTING THE EXPERIMENT. Demonstrators will help you write the risk assessment once you have read the script through and looked at (but not touched) the apparatus.

▶ If you are not doing the mini-project, ask the demonstrator to see the risk assessment for this experiment and discuss it with them before you start the experiment.

▶ If you are doing the mini-project, discuss the risk assessment you have written with a demonstrator before starting the experiment.

1 Introduction

A reasonable definition of a gamma ray is that it is a photon, usually of high energy, which has not been generated by an atomic electron. All photons emitted when an excited state of an atomic nucleus relaxes to a lower energy state are called gammas; the two (or occasionally three) photons produced when a positron annihilates with an electron are gammas, and photons produced when a high energy electron is accelerated in the coulomb field of a nucleus may be called X-rays or gammas, depending on the context. The 6.24 keV photon emitted by the nucleus ^{181}W is called a gamma, the 6.4 keV photon emitted by the iron atom when an electron shifts from the L shell to a vacancy in the K shell is an X-ray.

Nuclei are complicated structures composed of protons and neutrons and most have a rich sequence of excited states (take a look at the Table of Isotopes). Essentially mono-energetic photons are emitted in transitions between these states. Excited states of nuclei are frequently produced by the weak interaction processes of electron emission, positron emission or Electron Capture by the parent nucleus, or by nuclear reactions (for example, neutron capture). The energy spectrum of the gammas reflects the structure of the excited states. This experiment is concerned with the spectra of gammas emitted by daughter nuclei, following weak interaction decays of their parents.

It is important to be clear NOW, at the start of the practical, whether you are doing the two day version of the practical or the four day mini-project version. Because the practical requires several long runs, it is important to set up the correct overnight and over-lunch runs to not lose time. The main script gives the recommended layout for the two day version of the practical. The recommended layout of the four day version of the practical is given in section 4 and is somewhat different. It is not possible to do the two day practical and then extend to the four day practical without the second half being hectic.

1.1 Detection of gamma rays

Gammas are detected by their interaction with matter (see figure 1). At energies ∼X-ray energies the photo-electric effect dominates; an electron (most likely a K-shell electron unless the photon energy is too low) is ejected from an atom with energy $E_\gamma - W$, where W is the ionisation energy of the atomic shell. The atom recoils, conserving momentum. At higher energies Compton scattering is more important. In this process an electron is ejected but is accompanied by a photon. The process is well approximated as elastic scattering of a photon by a free electron. Finally, at energies greater than $2m_e c^2$ production of an electron-positron pair in the coulomb field of a nucleus is possible and becomes dominant at energies $\gtrsim 10$ MeV. It is the energies of the electrons which are measured directly, through their collisions with electrons in the material of the detector (section 1.1).

Figure 1 shows the absorption coefficients for germanium in units of cm^{-1}. If there are N atoms cm^{-3} and the cross section for an individual process is σ cm^2, then $\tau = N\sigma$ cm^{-1}. Gammas are attenuated with depth x by a factor $\exp\{-\sum \tau_i x\}$ and the number of examples of the process i occurring when n gammas are incident on an infinitesimal layer of thickness dx is:

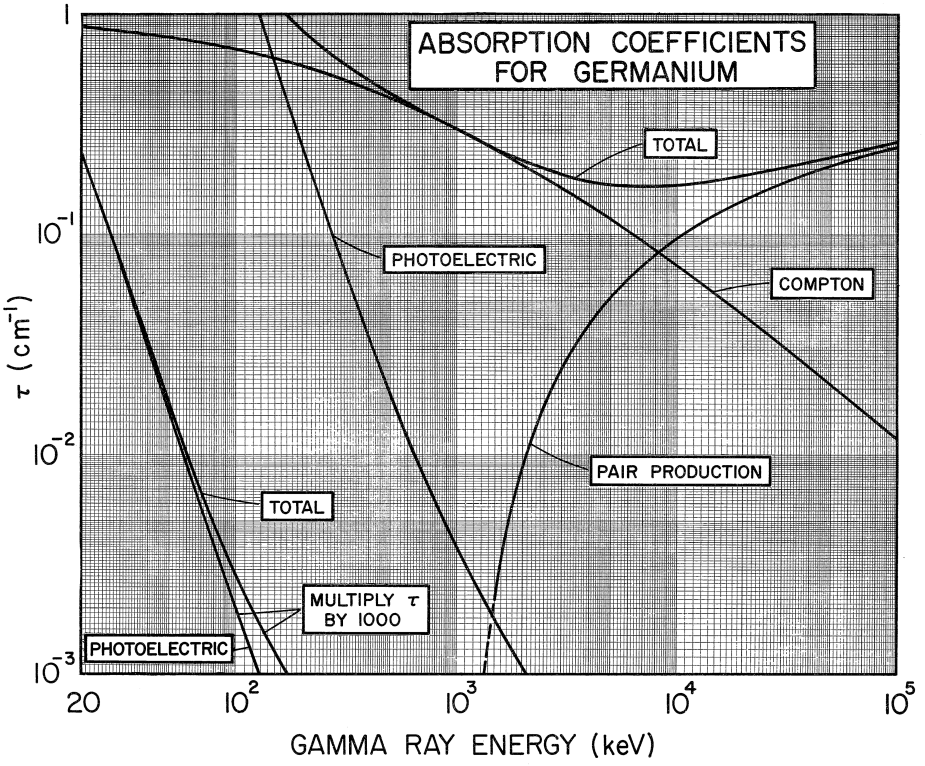


Figure 1: Absorption coefficients for germanium. Figure taken from [1].
Reproduced with permission from Elsevier.

$$\mathrm{d}n_i = n\tau_i \,\mathrm{d}x \tag{1}$$

This experiment utilises a single crystal of germanium (Z=32), which is a semi-conductor. At low temperatures, it is a good insulator, as electrons fill a band of states formed from the overlapping atoms. Another band of states begins 0.74 eV above this insulating band. Electrons promoted into this conduction band are collected on an output capacitor through application of $\sim 3\,\mathrm{kV}$ across the germanium crystal. The voltage on the capacitor is proportional to the number of electrons promoted and this number is very accurately proportional to the kinetic energy of an electron (or electron-positron pair) generated in the detector by an incident gamma.

In the photo-electric effect this energy is $E_\gamma - W$, but the photo-electric ejection is immediately followed by X-ray emission or ejection of atomic electrons and the X-rays almost invariably produce photo-electrons. Thus the voltage on the output capacitor is proportional to E_γ.

The Compton electrons have a continuous energy spectrum, from zero to a maximum energy given by

$$E_{\max} = \frac{E_\gamma}{1 + \frac{m_e c^2}{2E_\gamma}} \tag{2}$$

(the back-scattered gamma has energy $E_\gamma - E_{\max}$). This is an elementary calculation in relativistic mechanics. If the scattered gamma escapes the detector without further interaction, the voltage on the output capacitor is proportional to the energy of the electron. A *Compton edge* appears at $E_{\max}$. If the gamma scattered in a first Compton interaction does NOT escape without further interaction, we have

either a chain of Compton scatters followed by escape of a degraded photon, or eventually a photo-electron is produced. In the latter case the voltage on the output capacitor will be proportional to E_γ and will register in the full energy (or photo-electric) peak.

In the case of pair production the primary energy deposited in the detector is $E_\gamma - 2m_ec^2$. The stopped positron annihilates, if both 511 keV photons escape the output voltage is proportional to $E_\gamma - 2m_ec^2$, if one photon is eventually absorbed by the photo-electric effect the voltage is proportional to $E_\gamma - m_ec^2$ and if fortuitously both gammas are absorbed the voltage is proportional to the full energy, E_γ.

2 Experiments

2.1 Apparatus

The core of the apparatus is a high resolution single crystal germanium detector, cooled to the temperature of liquid nitrogen, with a built-in high resolution pre-amplifier which amplifies the voltage developed across the output capacitor. It is followed by a good main amplifier, which amplifies and shapes the pulse from the pre-amp. The electronics rack also contains a detector bias supply (3 kV). The apparatus should have been switched on before you arrive; if this has not been done ask a demonstrator or technician to do it for you.

Do not switch on yourself. Do not change the bias voltage; too high a voltage can ruin the expensive germanium detector.

The output from the main amplifier is fed to a Personal Computer Analyser (PCA). This contains a card with an Analogue to Digital Converter and a Multi Channel Analyser. The signal from the main amplifier is sorted according to its magnitude (pulse height) and the contents of the corresponding channel incremented by 1 for each pulse arriving. Thus channel number n (the x-axis on the display) is related to the energy dumped in the germanium crystal by $E = an + b$, where the slope a depends on the amplification and b is called the zero offset (and can be adjusted with a potentiometer but don't try this without consulting a demonstrator).

Always remove and put away sources that are not in use. Even a few centimetres of lead does not absorb high energy gammas efficiently.

2.2 Energy Calibration

Energy calibration consists of determining the constants a and b. First use a ^{22}Na source. The parent is ^{22}Na, which decays to the first excited state of the daughter ^{22}Ne. The decay scheme is shown in figure 2. There is a nuclear gamma of energy 1.2746 MeV and the source also emits 511 keV photons from positron annihilation.

Adjust the gain of the main amplifier so that the photopeak from the 1.27 MeV gamma occurs at about channel 1270 on the PCA display (the gain is then about right for the other spectra you may take). Amplifiers are limited in their output voltage, look at the output signal from the main amplifier on an oscilloscope. Both the voltage pulses should look approximately Gaussian, check that the pulse corresponding to the 1.27 MeV gamma does not have a flat top (clipping) corresponding to amplifier saturation. You could also check that the relation between amplification and channel number is linear. You can print out the spectrum of counts as a function of energy (also known as the pulse height distribution). Now, without changing the settings, accumulate a spectrum with several sources present one source at a time.

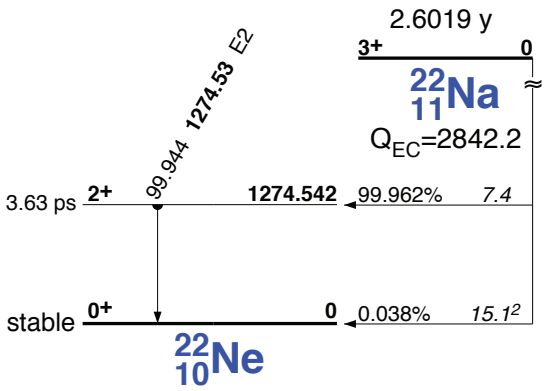


Figure 2: Decay scheme of ^{22}Na
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For calibration these must be sources for which you know the gamma energies. Table 1 lists some suitable sources and their energies.

Source (Parent)	Energies in keV
^{60}Co	1173.2, 1332.5
^{137}Cs	661.6
^{22}Na	511.0, 1274.6
^{152}Eu	121.78, 244.7, 344.28, 778.90, 964.08 1085.87, 1112.08, 1408.0

Table 1: Suitable calibration sources

Use the energy calibration mode of the PCA to turn channel number into energy, the PCA will remember. When calibrating the detector, check that the 1.27 MeV gamma has not shifted, because high count rates can cause gain shifts. If there is gain shift with multiple sources, move them further away from the detector to reduce the count rate. Calibrate with as many lines as the software will accept ($\geq$ 2!) and use others to check the calibration.

Having calibrated the system, do not alter any settings during the following experiments.

It is a good idea to check the calibration every few hours. It is also a good idea to examine spectra displayed on a logarithmic scale

Take an energy spectrum for a ^{60}Co source. The source emits two ^{60}Ni gammas in cascade, the decay scheme is shown in figure 3. Check that the energies given by the calibration are correct. Identify salient features in the energy spectrum as best you can, if necessary return to it after studying ^{137}Cs in the next section.

▶ Use the Region Of Interest mode of the PCA to determine the total number of counts in each of the two photopeaks and compare the ratio with the ratio of photo-electric absorption coefficients. They won't be the same. Why?

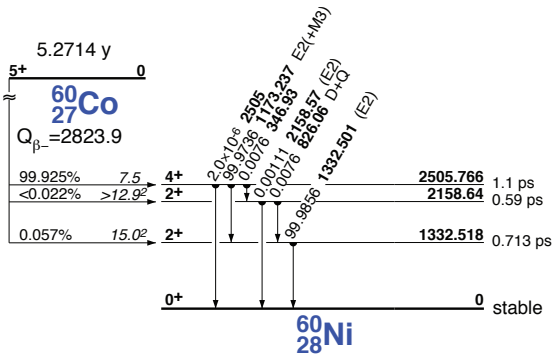

Figure 3: Decay scheme of ^{60}Co
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2.3 Compton Scattering

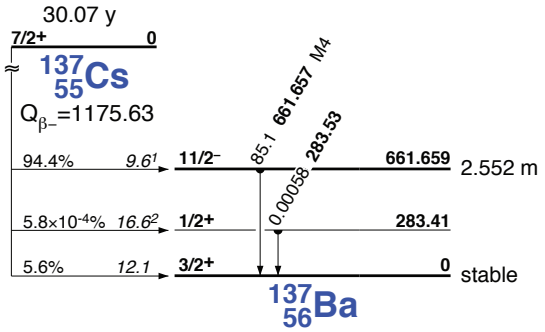

Figure 4: Decay scheme of ^{137}Cs
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The decay scheme of ^{137}Cs is shown in figure 4. ^{137}Cs decays preferentially to the first excited state of ^{137}Ba at 661.6 keV and the energy spectrum consists of a single sharp peak from events in which the full photon energy is absorbed and a continuous distribution from events in which a photon escapes the detector after one or more Compton scatters. The probability of Compton scattering is greatest for the configuration in which the electron has its maximum energy. The full energy peak is broadened by statistical fluctuations in the number of electrons collected and by noise in the electronics; the Compton edge is spread over a few channels for the same reasons. An example of the energy spectrum is shown in figure 5.

> The energy spectrum you take should be very similar to the one shown; there may be minor differences because of differing geometry. Find the channel number for the photopeak and then the channel number corresponding to the Compton edge, think carefully about just where this is located and remember that the spectrum contains events where the photon escaped after two or more Compton scatters.

▶ From these channel numbers calculate the energy of the ^{137}Cs gamma without using the calibration (or, if this seems ridiculous because you already know it, verify that the Compton edge appears in the correct channel).

Remember that zero energy is most unlikely to correspond to channel zero, you determined the zero offset in the course of the calibration.

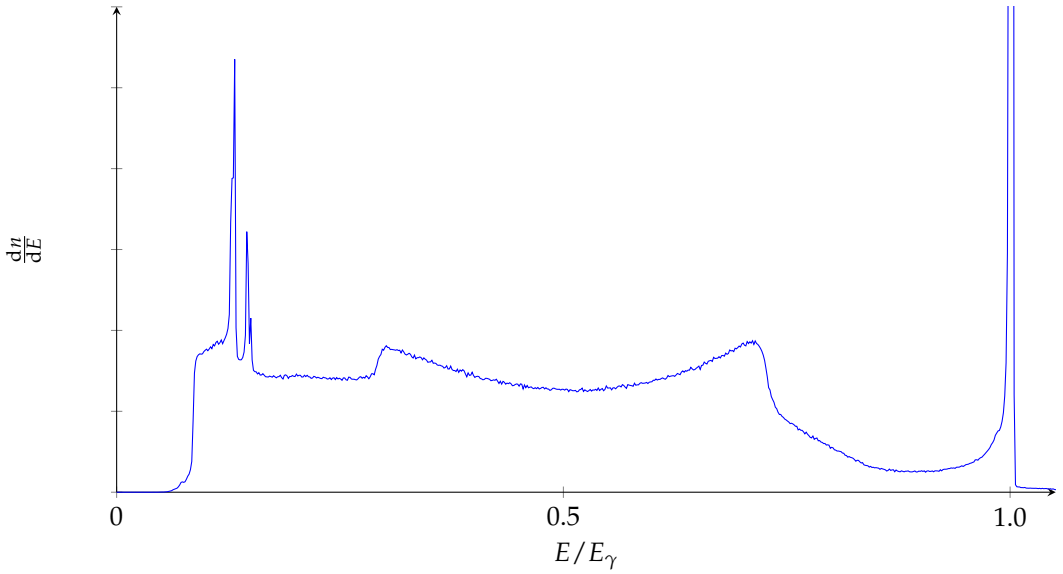

Figure 5: Distribution of energy dissipation in the detector. (n is number of events, E the energy dissipation and E_γ the photon energy.)

Photons which pass through the detector without interaction or which miss it all together have a high probability of being Compton scattered in material around the detector. Some of these will be scattered into the detector and absorbed. Those which were only scattered once will produce a spectrum which is a mirror image of that produced by single Compton electrons. These photons have energies exceeding the minimum photon energy and a so-called reverse Compton edge should be clearly visible.

▶ Figure out what the relation between the Compton edge and the reverse Compton edge should be and check it against your data.

2.4 Natural Radioactivity

This section requires you to make a long data run and a long background run. Try to do one of these starting at lunchtime on Monday and the other overnight.

All things are naturally radioactive at a low level. The main radioactive decays come from electron capture in ^{40}K and the radioactive decay series of ^{235}U, ^{238}U and ^{232}Th which each consist of chains of about 14 alpha and beta decays before they reach a stable nucleus. In each radioactive series, the first element has a very long half-life which is why there are still some of these nuclei sitting around in nature. Details of the decay sequences of ^{238}U and ^{232}Th are given in the lab copy of this script.

▶ Within a decay chain, the type of the element changes only with the emission of an alpha or beta particle (not gamma). Use this fact to show that the atomic weight A can only change by units of four and that therefore there are four distinct chains of radioactive decay. i.e. a nucleus which starts in one of the decay chains has to stay within that chain all the way down the sequence. Radioactivity from the daughters of only three of these chains are actually seen in natural radioactivity. What happened to the fourth chain?

At some points in the decay sequences, the decay occurs to a nucleus in an excited state. This produces a γ ray. Since we have a very nice γ detector, we can try to look for these γ rays and try to identify if there is any particularly high concentrations of decays.

2.4.1 Brazil Nuts

Brazil nuts are one of the most radioactive foods available, see [2] and references therein for some background. The challenge with this measurement is that there is a general low level of background natural radioactivity in the lab, so the question we must ask is whether there is a statistically significant excess in the sample we try.

> Take long exposures of the brazil nuts and of the empty detector (in both cases, with the lid of the lead shield shut). Identify as many γ peaks as you can from the ^{232}Th and ^{238}U decay chain schemes in the lab copy of the manuscript. Also cross check whether the ratio of the peak heights from each chain is consistent between the background and brazil nut exposures. There are sources of both thorium (gas mantles for camping lights) and uranium available for comparison.

▶ Does the change in the level of Compton scattered background look consistent with any increase in radioactivity?

Uranium is slightly toxic, somewhat like lead. So wash your hands thoroughly after handling and before consuming any food or drink.

We are collecting a list of the level of brazil nut radioactivity, add your result to the list (even if you saw nothing above the background). In all these low background measurements, it is important that we keep the contamination of the natural radioactive elements in the lab low. Please keep all the samples in their packets. You are welcome (indeed encouraged) to obtain your own brazil nuts or salt from the shops, but please place in containers before use.

Optional

2.4.2 Low-Sodium Salt

This measurement is kept as a reserve in case the brazil nuts didn't work out. The demonstrator might steer you to this measurement. First explain briefly in your logbook why the brazil nuts didn't work. It might be there was an overnight power cut, or the computer froze, or there simply wasn't enough time to take both signal and background spectra, or perhaps the amplifier gain drifted. Let's compare the radioactivity of normal salt with low-sodium salt. Salt is normally NaCl, but low-sodium salt contains some potassium instead and the isotope ^{40}K is one of the sources of natural radioactivity. Measure

(a) empty detector

(b) normal salt

(c) potassium salt

▶ Can you see ^{40}K? Is it statistically significant? How has the level and shape of the Compton scattering background changed?

2.5 Statistical Analysis

To perform an analysis of the brazil nut or potassium salt data which convincingly shows that the amount of radioactive substance has increased, you need to show that any increase in the peaks is not simply a statistical fluctuation. The statistical error in the number of events which arrives follows

a Poisson probability distribution. Provided the number of events is bigger than about 100, this can be approximated by a Normal (Gaussian) distribution and the error on the number of events N is $\sqrt{N}$.

Try computing the significance of any excess you find in one of the most significant peaks in the spectrum. The calculation is complicated by several effects, e.g. (a) the sample and background samples may have been taken with different life-times, (b) the continuous background below the peaks might be different.

▶ What causes the background, and why might it change?) See if you can increase the statistical significance of your measurement by combining the data from several peaks from the same decay sequence.

Optional

3 Detector Efficiency

The higher the energy of a gamma, the less likely it is that all the energy will be absorbed. The detection efficiency falls as function of energy due to the changing interaction probabilities in figure 1. The absolute efficiency with which a gamma is recorded in the full energy peak is obviously a function of the distance between source and detector and is also a function of the geometrical configuration of the detector. The relative efficiency is also a function of the size and shape of the detector. An example of the variation of relative efficiency with photo-peak is shown in figure 6 — but it may not apply to your detector! You should be able to construct the relative efficiency of the detector you are using in the range $\sim 0.4\,\text{MeV}$ to $\sim 1.3\,\text{MeV}$ from some of the peaks in one of the radioactive decay chains (use either the Brazil nut data or use the lab source of either thorium or uranium). The relative efficiency should be a reasonably smooth curve, demonstrating that the peaks in your spectrum appear with heights which are consistent with the radioactive decay chain.

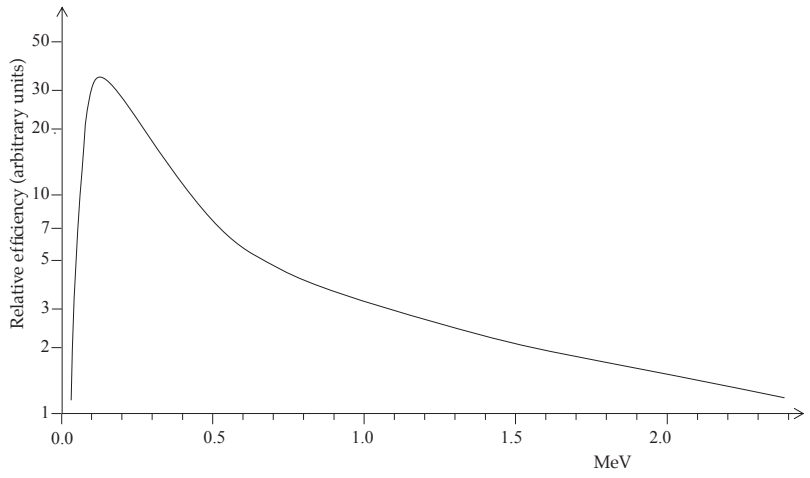

Figure 6: An example of germanium detector relative efficiency. The decrease of efficiency at low energy is an effect of absorption in the wall of the source container.

4 Project

The two-day version of the practical covers several important concepts about photon detection — that due to the competing processes of photoproduction, Compton scattering and pair production, the detec-

tor doesn't always see the whole photon and so the measured energy spectrum needs decoding somewhat to tell what gamma rays are present. The two-day practical goes through measurements with "standard" lab sources ^{60}Co, ^{22}Na and ^{137}Cs, and then an extensive part of the practical is to try to detect residual natural radioactivity in brazil nuts by doing a careful statistical comparison with a background sample collected with the same detector.

For the four day version of the practical, there are three additional investigations (a) to study a type of induced radioactivity, that of Indium; (b) to investigate using a simulation, the effect of the varying cross sections of Compton Scattering and photoproduction with photon energy on the efficiency of detection and (c) an improved study of the brazil nut sample: one improvement is to use the efficiency information, and the other is to get a more optimal sample of data to improve the statistics on the brazil nut analysis.

As this is a project, there is considerably more latitude to your creativeness in deciding the exact direction the project should go. These instructions are deliberately somewhat more vague and open ended than a normal script. You need to do some investigative reading as a part of this practical. Please discuss ideas with a demonstrator.

4.1 Overview of the four day project

Start on the first Monday morning with the same investigation of the lab sources and calibration as in the two day practical and aim, as in that experiment, to start a background run for the brazil nuts over the first lunchtime and extending into the afternoon. During the afternoon, while that is running, start the analysis of the simulated data as described below to determine the efficiency. At the end of Monday afternoon, recalibrate the detector with the standard lab sources and then do the overnight brazil nut run as in the two-day experiment. On the second day, analyse the brazil nut spectrum as described in the two day experiment, but also recalibrate with the standard lab sources again to see if there has been any drift since yesterday. You will need to use your judgement of what measurements comprise a calibration — the most likely change would be in either the pedestal or gain of the amplifier.

During the second week, you can arrange your schedule according to your own plan. You should aim to do the three components (a), (b) and (c) as described at the start of this introduction, however if you get particularly interested in one part of this and want to extend it, it may be possible to skip one of the other sections — discuss with a demonstrator. Use the information from the first analysis of the brazil nuts to devise a measurement schedule for the second week. By doing more calibrations, you will probably be able to include the data from the first week into the overall analysis plan. Then plan the other two activities to fit in with this.

4.2 Induced radioactivity

Indium is an example of an element with a metastable state: similar to the way atoms can have electrons in excited states, the nucleus can elevate a proton or neutron to an excited state, which may subsequently decay by radioactive gamma emission. A metastable state is formed where the decay rate is unusually long. Look up the level structure of Indium-116.

The normal naturally occurring isotope is ^{115}In. ^{116}In may be made from ^{115}In by bombarding it with neutrons. The ground state decays with a half life of 8s, but one of the excited states has a half life of 52 minutes. In this part of the experiment, we are going to try to make some ^{116}In and observe it decay.

A suitable source of neutrons can be obtained by bombarding beryllium with alpha particles from the decay of ^{241}Am. In practice, the americium and beryllium are mixed together and the resulting neutron

source is referred to as an 'AmBe source'. A demonstrator or technician will expose a piece of indium to our AmBe source and then you may make measurements of the gamma rays emitted to determine whether there was any induced radioactivity during the neutron exposure. It is possible to modify the energy spectrum of the neutrons in the source by passing them through a moderator such as plastic or water. To avoid problems with possible activation of water (and the subsequent problem of disposing of it safely), we will use solid plastic. Discuss with a demonstrator any plans you have to investigate the effect of a moderator. Planning is needed to make sure there is time for the measurements.

4.3 Detector efficiency from simulation

One of the difficulties with doing quantitative analysis with a detector such as this is that the cross sections for Compton scattering and photoproduction vary rapidly as a function of photon energy. There is a modern way to obtain estimates of the efficiency (defined as the number of detected photons divided by the number of incident photons) as a function of energy for any particular geometrical configuration, and that is to use simulation with the 'Monte-Carlo' technique.

In the Monte-Carlo technique, a large set of 'events' is produced, each event representing a complete history of the way in which one individual photon could interact in the detector. Each time there is a choice in the possible things the photon can do (e.g. move forward without interacting, or interacting in one of the ways discussed (photo-production, Compton scattering, pair production)) a random number, generated by the computer, is used to decide which of these happens for this simulated event. Any daughter particles produced are also kept and tracked by the same technique. This continues until all particles have lost their kinetic energy. The output is a 'tree like structure' which tracks the photon and all the daughters. At each node in the tree, the position of the interaction, a particle code (electron, photon or positron) and interaction code (photoelectric, Compton, pair production, bremsstrahlung, stop or leave) are stored. Provided the simulation takes account of the probabilities of each choice correctly, the Monte-Carlo program can be used to make a large number of simulated events and distributions can be made to obtain the detector efficiencies. Originally, physicists wrote their own simulation programs, but more recently, standard modules for simulating particle processes have been collected together under the name 'Geant4' and the 'Geant4' simulation is available for use from CERN. This is the same program used to simulate photons in the LHC (e.g. those from Higgs decays).

We have run Geant4 by injecting a 'particle gun' of photons starting at the origin, and moving in the positive `z` direction onto a semi-infinite block of detector materials. The photons are generated with random energies distributed uniformly between 0 and 3 MeV. We have made two runs, one for a silicon detector, the other for a germanium detector. You can use these two files to pick the one corresponding to your detector and use the other file to study any systematic effect of whether the Z of the detector isn't actually the Z which was simulated. You will use the output files from these simulation runs. A `c` program which reads these files is included on the lab machines. Inside the program, there is a loop over all the events. Inside that, there is another loop over all the particles in the event. This second loop does a 'depth-first' loop through the tree of particles, i.e. it follows the first particle through all the interactions it has until it stops or leaves the semi-infinite detector material, and then goes back to the furthest branch point from the original photon along that track and does the next particle and so on. There is a clearly marked `if` statement which allows the loop to be aborted at any point and progress on to the next particle from higher up in the tree, i.e. to bypass a whole section of branches. The place to jump forward to from any point is stored as one of the variables in the file, it was computed when the file was generated. This `if` statement is how you can use this rather general file to simulate your particular geometry of detector. You want to define your detector geometry shape using a series of `if` statements, test this at every branch-point, and as soon as the particle leaves your volume, cut off the rest of that branch. Then you add up all the energy of the particles which is visible in the detector (i.e. the kinetic energy of all the charged particles). As an approximation, to make it simple, do not worry

about the fact that the electrons move as they lose energy and could move outside your detector volume; if the electron was produced inside the volume, count all it's energy as being detected.

This particular technique of lopping off complete branches as soon as a particle leaves the volume has the effect of simulating the situation where the detector is surrounded by vacuum. How could you simulate the situation where the detector is completely surrounded by dead material of the same Z as the detector?

Use the simulation and the example program to make a simulated distribution of the energy spectrum from ^{137}Cs both in the case of a detector surrounded by vacuum and surrounded by dead material (you will need to select initial photon energies in a range close to the known ^{137}Cs gamma energy).

Then use the simulation to generate the efficiency curve as a function of photon energy (i.e. count the number of photons in a given energy range and count the number which deposit all (or most of) their energy within the detector). Use this efficiency curve to analyse the data you have obtained in the other sections of this practical (in particular, return to the question of the relative heights of the two ^{60}Co peaks you obtained on the first Monday morning. You can also quantify the relative heights of any significant peaks from the brazil nuts and from the induced activity in the Indium.

Bibliography

[1] J. B. Marion and F. C. Young, Nuclear Reaction Analysis; Graphs and Tables, *Nuclear Instruments and Methods*, 65, 358 (1968). doi: 10.1016/0029-554X(68)90122-5

[2] `https://www.orau.org/ptp/collection/consumer%20products/brazilnuts.htm` , ORAU (2009).

