Laboratory Exercise 3 – NUCLEONIC MEASUREMENTS

Introduction

Experimental techniques in nuclear and elementary particle physics can be extremely complex, requiring expensive apparatus and sophisticated treatment of data. However many of the principles can be illustrated by measurements that use radioactive sources, fairly familiar apparatus, and only simple arithmetic to derive results. This exercise uses a sample of the radioactive isotope cobalt-60 (^{60}Co) and a Geiger counter to demonstrate the absorption of γ-rays; it also illustrates the treatment of errors due to the variability of repeated measurements. Finally, the fact that radioactivity is an inescapable feature of our environment is illustrated by a short study of a natural radiation source that is commercially available.

The operation of a Geiger counter is described in many textbooks, though you do not need to know how it works in order to use it. There is a short description of how a Geiger counter works at the end of this lab script. You will use a standard commercial Geiger tube, the Mullard MX168, which has a thin (and delicate!) end-window made of mica that allows particles of low penetrating power to enter. Ionising particles such as α-, β- and γ-rays, and cosmic rays, will, if they cause sufficient ionisation, give rise to electrical impulses that can be recorded and counted by suitable circuits. The necessary electronics — a power supply of up to 500 volts, and a counter (called a **scaler**) are incorporated in a commercial instrument (either **Griffin** or **Philip-Harris**).

A note on radioactivity

Helium nuclei or electrons (α- or β-particles, respectively) are emitted when an unstable nucleus disintegrates, forming a **daughter** nucleus of a different element. Often the daughter nucleus is left with excess energy. The excess energy is lost via the emission of photons, just as an excited atom loses energy and gives off light. An important difference between the two cases is that the photons (γ-rays) from *nuclear* de-excitation are typically a million times more energetic than those from *atoms*. The isotope ^{60}Co is unstable, undergoing β-decay to yield the daughter nucleus nickle-60 (^{60}Ni) with a half-life of 5 1/4 years,. This nucleus has excess energy[†] of 2.5 MeV which it then liberates by emitting γ-rays of energies 1.17 and 1.33 MeV in quick succession.

The source you will use is a tiny quantity of ^{60}Co securely sealed inside a small aluminium rod, which in turn is placed in a small hole in the base of a lead pot. The β-particles from ^{60}Co decay have low energy and are absorbed in the aluminium — only the γ-rays emerge from the top of the pot, and when this is covered by a lead brick even they are absorbed and there is no radiation hazard.

> **All** radioactive sources must be treated with respect and handled carefully. The ^{60}Co source must **not** be removed from its lead pot, nor should you gaze down at it. The lead brick should only be removed when you are ready to begin your measurements, and replaced when you have finished.

The strength of a radioactive sample is measured by its **activity**, that is the number of disintegrations per second. This is measured in units called **becquerels** (1 Bq = 1 disintegration per second), although an older unit, the **curie** (1 Ci = 3.7×10^{10} disintegrations per second) is still in common use. Note the huge difference — 1 Bq is an incredibly weak source, while one

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[†] **Footnote:** Energies in nuclear physics are conveniently measured in electron volts (eV) or the multiples kilo-eV (keV, 1000 eV) or mega-eV (MeV, 10^6 eV). 1 eV is the energy gained by an electron accelerated through a potential difference of one volt, and is equal to 1.6×10^{-19} joules.

curie is an extremely potent one. The sources used in this exercise had activities of 100 μCi (100×10^{-6} Ci) when they were produced as much as 15 and 25 years ago; their present activities, three to five half-lives later, have therefore declined to between $(1/2)^3$ and $(1/2)^5$ of their initial values, that is to between 12 and 3 μCi. So you will notice quite a wide variation in count rate, depending on which source is in your lead pot. As mentioned above, each disintegration is accompanied by the emission of two γ-rays. These are emitted in random directions so only a small number will pass out of the lead pot and into the Geiger counter, the rest passing into the lead walls where their energy is absorbed. The number of γ-rays recorded by a Geiger counter placed several centimetres above the pot will be of order ten per second. [Note the use of the phrase 'of order …' or 'of the order of …'. It means 'to the nearest power of ten', so in this case it is telling you to expect a count rate *greater* than *one* per second but *less* than *one hundred* per second. In physics the phrase is always used in this technical sense.]

Measuring the count rate: the Poisson distribution

If random events such as radioactive decays are counted, the number *N* counted in a time *t* is not constant even if each interval is exactly *t* seconds long. We shall explore how *N* varies, and we shall see that once this variability is understood we can get, from only a *single* measurement, estimates of *both* the average value of *N and* its uncertainty.

• Before asking the demonstrator for your Cobalt-60 source take a background reading over 100s. Move the Geiger tube well away (at least a metre) from any sources in the laboratory and observe the number of **background** counts due to cosmic rays, natural radioactivity and electronic 'noise'. Switch on the power supply and turn the **HT** (i.e. high voltage) control fully clockwise to 500 volts.

> For the **Griffin** instrument the function switch should be set to **COUNT 10³** and each measurement timed with a stop watch for 100 seconds. Lift the **RESET** switch on the instrument and release it to start. At the end of the time interval, press the switch down to **HOLD** the reading, and *keep it there* while you record it.

> For the **Philip-Harris** instrument the time interval should be set to 100 seconds (10 seconds is too short, 1000 seconds is far too long!) and the slide switch set to **SINGLE READING**. Press **RESET** to start.

• Now read the source safety sheet and then ask a demonstrator for your Cobalt-60 source. Make a note of the source ID. Place the Geiger tube just above the mouth of the lead pot — see figure 1. We want to make repeated measurements of the number of counts in a fixed time, say one second — the procedure for doing this is slightly different for instruments from the two manufacturers:

Figure 1 Set-up

Griffin: Set the function switch to **RATE 10³ s⁻¹**.

Philip-Harris: Set **RANGE** to **1 sec**. and slide switch to **CONTINUOUS**.
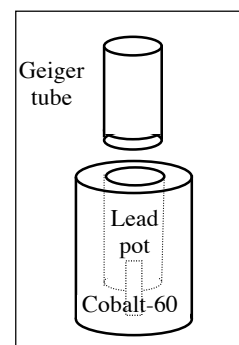
• In each case the instrument will automatically record and display the number of counts in a one second interval, updating the display every 2 1/2 seconds. This gives you sufficient time to write down the number before it is updated. Record a large number of counts, say **50**.

• Plot a **histogram** showing your results, grouping them into **bins** of equal width so that the largest bin contains perhaps ten counts, as shown in figure 2. We want to find $\langle N \rangle$, the **mean** of N for a sample of 50 measurements:

Figure 2 Histogram of number of counts per second

$$\langle N \rangle = \frac{\sum N}{50}$$

and also the quantity σ given by:

$$\sigma^2 = \frac{\sum (N - \langle N \rangle)^2}{49}$$

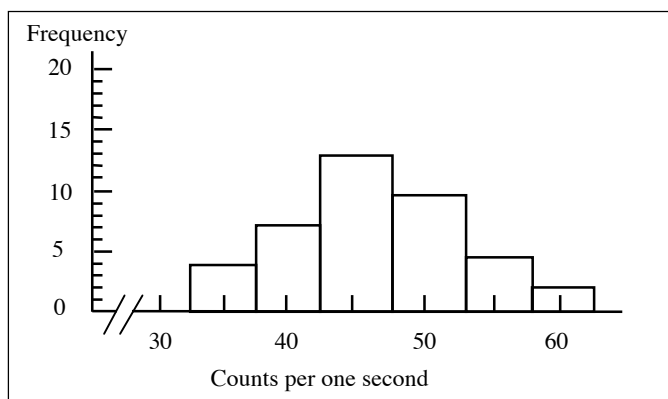These calculations are tedious! Many electronic calculators are pre-programmed to perform them, and you should either use such a calculator, or even better use the computers in the teaching laboratory which will also prepare your histogram. (PhysPlot will work them out).

As you see, there is a lot of scatter in your results. It is a fact of life that no single measurement can ever be completely relied upon; the best we can do, if asked to measure radioactivity, is to quote $\langle N \rangle$, the **mean value**, and σ, the **standard deviation** which measures the uncertainty in

$$\sigma^2 = \langle N \rangle$$

$\langle N \rangle$. But does this mean we have to take lots of measurements in every case? Fortunately not — a simple result from statistical theory comes to our aid. This states that the distribution of counts shown by your histogram is a very special one called the **Poisson distribution**, which has the extremely useful property that the square of the standard deviation (called the **variance**) is equal to the mean value:

• Check this by comparing your own values of $\langle N \rangle$ and σ^2. Since you've only taken 50 readings the agreement will not be exact but it should be reasonably good, probably within 20% (if not you have probably made an arithmetic blunder). If we make only one measurement, say N, then **N itself is the best estimate of the true mean value**, and the **square root of N is the best estimate of the true uncertainty**, or experimental error. There is more on means, standard deviations and distributions in the lectures, and in the recommended books.

Absorption of γ-rays in steel

It is found that the absorption of γ-rays in material is roughly exponential, that is the number N emerging from a thickness t is:

$$N = N_0 e^{-\mu t}$$

where N_0 is the number entering the material. The quantity μ, called the **absorption coefficient**, depends on the nature of the material and on the energy of the γ-rays. A knowledge of μ is essential in nuclear technology and medicine. We shall measure μ for steel, using the ^{60}Co γ-rays, which are close enough in energy to allow their average value, 1.25 MeV, to be taken as the energy at which μ is measured.

• Again with the Geiger tube above the lead pot, record the number of counts in equal time intervals, first with no steel interposed and then with successively more and more steel plates covering the mouth of the pot. Add the sheets four at a time until you reach 36 sheets, and count rates more than a factor of ten below where you started.

The background count you measured earlier must be **subtracted** from each of your measurements to obtain the **true signal** due to the ^{60}Co γ-rays alone.
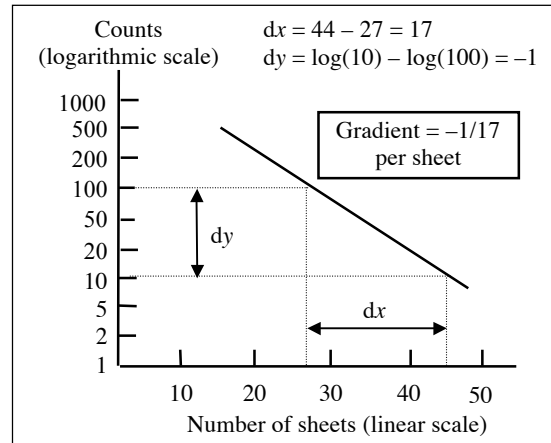

Figure 3 Finding slope of a log graph

By taking natural logarithms (i.e. log base e) of the expression above we obtain:

and a graph of ln N versus t should contain a set of points that lie in a straight line with a gradient $-\mu$. In numerical work it is more convenient to work with decimal number systems, so

$$\ln N = \ln N_0 - \mu t$$

converting to log base 10 gives:

$$\log N = \log N_0 - 0.4343 \mu t$$

where we have replaced log e by its value, 0.4343. A graph of log N versus t will have a gradient of $-0.4343\,\mu$. To avoid the tedium of calculating a logarithm for every point plotted, we use printed graph paper which has one axis graduated with a logarithmic scale (see figure 3). The heavy lines at equal intervals correspond to the numbers 1, 10, 100, 1000, etc. whose logs are 0, 1, 2, 3, etc., and the intervening numbers are shown as lighter rulings more closely spaced as the number increases. You will soon find it very easy to use this **log–linear** (or **semi-log**) graph paper. Figure 3 shows how to calculate the gradient.

• Using log–linear graph paper, **plot** log N versus number of sheets of steel, **draw** a straight line, and find its **gradient**.

• Then **repeat**, this time using the **computer** to do the plotting, in order to obtain a printed graph and a more reliable value for the gradient.

Note: you may find that the point with *no* sheets is awkwardly high and seems to pull the graph up more steeply than the other points require. This is because some energetic electrons from the β-decay of ^{60}Co penetrate a small amount of steel. Disregard this point if necessary.

• Measure the thickness of several sheets using a **micrometer screw gauge**. Compute the average thickness, and use this to convert your gradient (units: per sheet) to a value for the absorption coefficient μ (units: per metre) at a γ-ray energy of 1.25 MeV.

Natural radioactivity

The laboratory technicians will give you a cotton 'mantle' for an incandescent gas lamp, such as those used by campers. The fabric is impregnated with a salt of the element cerium, which has the property of glowing brilliantly when heated. Cerium itself is not radioactive, but is so similar chemically to the radioactive element thorium that the two tend to be associated in nature. The same manufacturing process that concentrates cerium also selects thorium.

• Use the Geiger counter to observe the count rate from the gas mantle, comparing it with that from the ^{60}Co source. This is easiest if you measure both the gas mantle and the source at equal

distances from the Geiger counter. (If not, measure the distances from the Geiger tube to the ^{60}Co and to the mantle.)

• Make a rough estimate of the activity of the gas mantle, using knowledge of the activity of the ^{60}Co. (If the distances were not equal, take that into account using the inverse square law.) The laboratory technicians can tell you the original activity and age of each ^{60}Co source, and so you can work out your source's present activity. Note that for low-level sources it is important to take background into account.

This gas mantle, which was bought in a local High Street shop, is one of the most radioactive items in common use, though certainly not so active that its sale or possession is forbidden by relevant safety regulations. (The same is true of Brazil nuts, which are rich in uranium!)

Geiger counters

Geiger counters (or Geiger-Muller counters) are one of the oldest forms of radiation detectors that have been developed. They were invented in 1928, and modern Geiger counters are in widespread use today. This section gives a very brief overview of how a Geiger counter works. The aim of a Geiger counter is to detect a single particle of radiation. A single particle, such as an electron is difficult to detect with non-specialist modern electronics, the Geiger counter operates in a mode that results in a magnification, or amplification, of the signal to a level that is measurable. The device uses a high voltage signal to establish a high electric field between an anode wire and cathode (the walls of the Geiger tube). A gas fills the volume between the anode and cathode. Typically an inert gas is used to fill a Geiger tube (like Neon), with a small amount of a halogen quenching gas such as chlorine. A signal event occurs when radiation travelling through the gas ionizes one of the molecules. The ion-electron pair are accelerated in opposite directions in the electric field. As the field around the anode is large, the electron signal, which travels toward the anode, causes further ionization of the gas. This mechanism results in what is called an avalanche. Once an avalanche has been produced in a Geiger tube, it is possible that subsequent avalanches will occur until the device has been saturated. When the Geiger tube has been fully saturated it is not possible for any more charge to be released from the gas, and the tube will be insensitive to additional particles of radiation until it has recovered. This recovery period is called dead-time and this is typically of the order of 50-100μs. The amplification factor achieved using this process is typically of the order of 10^9 to 10^{10} ion pairs. This corresponds to a signal pulse of the order of a few volts, which is straight forward to measure. Figure 4 illustrates three avalanches starting from an individual ionised electron in a Geiger tube.
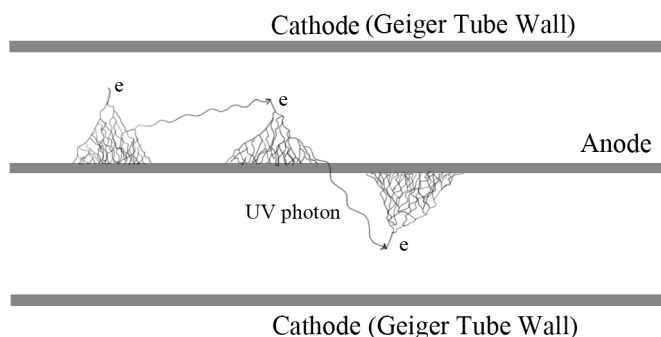

Figure 4: A Schematic of a Geiger tube with three avalanches initiated from a single ionised electron.