Lab 12 - Radioactivity, Beta, and Gamma rays

“Classic atomic and radioactive symbol”

OBJECTIVES

- Learn about radioactivity.
- Understand the random nature of radioactivity.
- Investigate the $1/r^2$ dependence of particle decay.
- Investigate the interaction of radiation with matter.
- Measure the range of $\beta$ rays in matter.
- Measure the attenuation of $\gamma$ particles in matter.
- Determine the relative efficiency of detecting $\beta$ and $\gamma$ rays in a Geiger-Müller detector.

OVERVIEW

In 1896 Antoine Henri Becquerel discovered that uranium salts emitted a penetrating radiation that was able to blacken photographic plates. Soon other elements were found that were similarly...
radioactive. As is often the case in science, when a new field is discovered a terminology evolves before things are properly understood. The names given to phenomena persist even if, in the light of later knowledge, they turn out to be inappropriate, as is the case in this field. The early investigators found that radioactive nuclei emit three different kinds of radiation that they, lacking an understanding of their nature, named alpha (α), beta (β), and gamma (γ) rays. We will discuss these three kinds of radiation in sequence although not in that order.

\[ E = mc^2 \]  

(12.1)

This famous law, discovered by Albert Einstein in 1905, tells us that it is possible to convert mass into energy and vice versa. The law is universally valid but it is in nuclear physics that its effects first become noticeable. When we burn 2 g of hydrogen with 16 g of oxygen the resulting amount of water will have a mass that is less than 18 g by a small amount \( \Delta m \). This mass difference \( \Delta m \) multiplied by \( c^2 \), the square of the velocity of light does equal the amount of heat energy released in the process. However, \( \Delta m \) is so small that even the best chemical balances cannot detect it.

In nuclear processes the energies involved are typically a million times larger than chemical energies and routinely, we include the energy, divided by \( c^2 \), in the mass balance. Energy is measured in Joule [J]. One J is the energy that is needed to move a charge of one Coulomb [C] against a potential difference of one Volt [V]. In atomic and nuclear physics it is customary to measure energies in electron volts [eV]. One eV (“e-vee”) is the energy that is needed to move a particle with one elementary charge \( e \) against a potential difference of one Volt [V]. The binding energies of the (outer) electrons in an atom are of the order of eV, whereas the binding energies of the nucleons in a nucleus are of the order of MeV. (1 “em-e-vee” = 1 million electron volts).

**Gamma Rays**

Atomic electrons can go from states of higher to those of lower energy by emitting photons, which is simply electromagnetic radiation (just as visible light, radar, microwave, etc.). This produces the familiar line spectra that you observed last week in the spectroscopy experiment. Similarly the excited state of an atomic nucleus can decay to a state of lower energy by emitting a photon, customarily referred to as a \( \gamma \) rays or \( \gamma \) particles or simply a \( \gamma \). One can think of this process as a change of the quantum state of one of the nucleons (neutrons and protons) that make up the nucleus. The chemical nature of an element is determined by the electric charge of its nucleus, the atomic number \( Z \). Photons are neutral which means that \( \gamma \)-ray emission does not change the chemical nature of an element. The nucleons in a nucleus are bound much more tightly than the electrons in an atom. As a result up to a million times more energy is released in nuclei when they go from one quantum state to another than in atoms. That makes the photons emitted in the process that much more energetic. But, they are photons all the same.

**Beta rays**

Another mechanism by which a nucleus can lose energy is the emission of an electron; this process is called beta decay and the emitted electrons are called beta rays. Since a β ray carries with it one unit of negative charge, the remaining nucleus, called the daughter (nucleus), must have one more unit of positive charge than the parent nucleus. The atomic number of the daughter is thus one higher than that of the parent; the chemical nature of the atom has changed.
The beta decay presented its discoverers with a puzzling problem: While the parent and the daughter nucleus are in well-defined energy states, the energy of the electron emitted in beta decay varies between zero and a maximum value. This maximum value \( E_{\text{max}} \), often called the end point energy, is exactly equal to the energy difference between the parent and the daughter nucleus. A typical beta energy spectrum is shown in Figure 12.1. If the electron has energy other than \( E_{\text{max}} \), where is the rest of the energy? On the face of it, this seems to defy one of the most fundamental laws of physics, the conservation of energy. Wolfgang Pauli (1900-1958) came up with the correct solution in 1931: He concluded that, together with the electron, another particle had to be emitted that carried away the missing energy. He gave a detailed description of the properties of this other particle, named the neutrino by Enrico Fermi:

- It had to be neutral because parent and daughter differed by just one charge unit, accounted for by the simultaneous emission of the electron.
- Its mass had to be very small, perhaps zero, because the maximum electron energy was, within experimental errors, equal to the energy difference between parent and daughter.
- The conservation of angular momentum required it to carry the same intrinsic angular momentum (spin) as the electron.
- It could have almost no interaction with other matter or it would have shown up in one of the many different detectors employed to observe nuclear particles.

Despite this detailed description it took experimentalists until 1957 to find the neutrino. This was not for lack of trying: The neutrino is incredibly elusive, a neutrino could travel through a layer of lead one light year thick without colliding with any of the electrons or nuclei in it. Neutrinos are constantly passing through Earth with no interaction.

**Alpha Particles**

Last we mention \( \alpha \) particles, although you will not study them in this experiment. An \( \alpha \) particle is a helium nucleus. Nuclei do not emit individual neutrons and/or protons because the emission of a bound system i.e. a He nucleus is energetically favored. Alpha particles, because of their double electron charge and slow speeds, are easily stopped by matter. A 5 MeV \( \alpha \) particle is easily stopped by a few sheets of notebook paper! Alpha particles produced by radioactive sources will not penetrate human skin. However, it would be very dangerous to ingest \( \alpha \) particle emitting radioactive sources.
The Detector

To detect both $\beta$ and $\gamma$ rays, you will use a Geiger-Müller (GM) tube in this lab. The apparatus that includes a Geiger-Müller tube is often called a Geiger counter. The tube is simply a gas filled metal cylindrical tube through which runs, concentrically, a fine wire. This wire is insulated from the tube and maintained at a high positive voltage with respect to it, as shown in Figure 12.2. The length of the active area is 3.30 cm, and the diameter is 9.14 mm. When a charged particle, such as a $\beta$ ray, enters the tube through the thin window at one end, it ionizes some gas atoms. The electrons, thus freed, are accelerated toward the positive central electrode wire by the electric field around it. In the process the electrons themselves gain enough energy to ionize more gas atoms and an avalanche results. This causes a burst of current, a pulse, that can be detected by a suitable circuit. The pulse can be used to produce an audible signal in a speaker and can also be counted in an electronic scaler. A Geiger-Müller counter is a very efficient detector for $\beta$ rays.

Gamma rays, on the other hand, are more difficult to detect because they have no electrical charge. They must first produce electrons by other processes (that will be discussed in Investigation 3) before they can be counted. The GM counter gas has a low density, and the average path length of a $\gamma$ ray in the detector is quite large. Indeed, most of the $\gamma$ rays that are detected are those that knock an electron out of the wall of the tube and into the gas. As a result a Geiger counter is not a very efficient detector of $\gamma$ rays: most of them will pass right through the tube without being registered. This difference in counting efficiency will become very apparent to you. We will investigate the interaction of $\gamma$ rays in matter in Investigation 4.

During the Cold War of the 1950–1980 eras, millions of Geiger counters were produced for civil defense purposes in the United States. They had a characteristic yellow color. Almost all such counters had a meter to denote the radioactive intensity, and most had a connection for a speaker. We will try to have one available in the lab for you to try with your radioactive source. Such Geiger counters are still used for health physics monitoring.

**INVESTIGATION 1: RADIOACTIVITY**

Radioactive decay is governed by the laws of quantum mechanics. The time it takes an individual nucleus to decay is uncertain, only the probability that it will decay in a given time is determined by nature. This leads to an exponential decay law

$$N = N_0 e^{-t/\tau},$$  \hspace{1cm} (12.2)

where $N_0$ is the initial number of parent nuclei, $\tau$ is the lifetime, and $N$ is the number of parent nuclei that is still left after the time $t$. This means that after one lifetime ($t = \tau$), $N_0/e$ remaining nuclei will be left of an initial population of $N_0$ nuclei ($e = 2.71828$ is the basis of the natural logarithms). The lifetime $\tau$ is related to the decay constant $\lambda$ by $\tau = 1/\lambda$. The half-life $t_{1/2}$ is the time it takes for half of the nuclei to decay. It is related to the lifetime and decay constant by
\[ t_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2 \quad (\ln 2 = 0.693) \] (12.3)

All three terms \( \tau, \lambda \), and \( t_{1/2} \) are used. The decay constant is related to the probability per unit time that any given nucleus will decay. The activity \( R \), which is the number of decays per unit time, is given by

\[ \text{Activity} = \frac{\text{decay/unit time}}{} = \lambda N \] (12.4)

where \( N \) is the number of nuclei at the time \( t \) (see in Equation (12.2)).

Nuclear lifetimes range from the incredibly short (10-20 s) to billions of years. The lifetimes of \( \gamma \)-emitters is usually very short although it may not seem that way: Following an \( \alpha \) or \( \beta \) decay with a long lifetime, the daughter nucleus is often left in an excited state from which it immediately decays to the ground state by \( \gamma \) emission. If one observes only the \( \gamma \) ray, it will look as if the \( \gamma \) decay itself had a long lifetime.

**Apparatus**

- PASCO Geiger-Müller counter SN-7927A
- Two stands and associated pieces to hold radioactive source and counter
- \(^{137}\text{Cs}\) radioactive source (in plastic disk)
- 3-m measuring tape

Your radioactive source is a little plastic red disk that contains a small amount of radioactive cesium, \(^{137}\text{Cs}\). Its strength is about 10 \( \mu \text{Ci} \) (microcuries). The decay scheme of \(^{137}\text{Cs}\) is shown in Figure 3. This isotope has a half life of 30.174 years. Most of the time (94%) it decays to \(^{137}\text{Ba}\) by emitting a beta particle with an end point energy of 0.514 MeV. The \(^{137}\text{Ba}\) nucleus with a lifetime of 2.55 minutes, is left in an excited state, which decays to the ground state by emitting a \( \gamma \)-ray of 0.662 MeV energy. Your source thus emits \( \beta \) and \( \gamma \)-rays in approximately equal numbers. Because of energy taken by the neutrinos and also energy losses of the \( \beta \) rays through the plastic cover and air, the electrons emitted by your \(^{137}\text{Cs}\) source cover a continuous spectrum from 0 to 0.514 MeV (plus a small admixture of electrons with energies between 0 and 1.176 MeV). (Do not be concerned if the energies here and in the figures are slightly different. They are not precisely known.)

**Question 1-1:** A few percent of the beta decays lead directly to the \(^{137}\text{Ba}\) ground state (6%) and are thus not accompanied by a \( \gamma \)-ray. What is the end point energy of these \( \beta \) rays? Explain how you determined this value.

1. Place the the GM counter into the stand as shown in Figure 12.4. The counter will be horizontal. Plug the counter into digital channel 1 of the PASCO interface. Take the cap off the counter (if it is on) and be careful not to touch the entrance membrane. You probably will hear an (annoying) beep coming from the GM counter. This is due to the
counter actually detecting radioactive particles entering the counter. We have tried to
disconnect this sound, but the manufacturer said it was not possible. These beeps are
due to radioactivity in the walls of the laboratory and cosmic rays, high-energy particles
coming in from outer space. It will become more annoying when you count at a high
count.

Figure 12.3: Decay scheme of $^{137}$Cs

Figure 12.4: Photo of the experimental setup

both a meter and digit counter. Start counting.
3. Hold the source near (≈ 5 cm) the GM tube entrance while you are counting. Flip the source to determine which side of the source is stronger. Place the source in the lens holder on the other stand with the stronger source side facing the GM tube. Move the lens holder so that the source is about 5 cm from the GM tube.

**WARNING: THE GM TUBE HAS A DELICATE MEMBRANE COVERING ITS WINDOW. DO NOT TOUCH, PUNCTURE, OR OTHERWISE DAMAGE THIS MEMBRANE.**

4. Open experimental file `L12.A1.Radioactivity.StatisticalData.ds` on DataStudio. You will count for twenty periods of 10 s each the number of decays \( N \) detected by the GM tube. That will be for a total of 200 s. You should detect a few thousand counts during each 10 s period. Write down your data in Table 12.1 while collecting data and stop data taking after 200 s.

5. Open the Excel file named `L12.A1.Radioactivity.StatisticalData.xls`. You can enter your data easily into Excel by highlighting the data you have taken in Data Studio, copy it, and then go to cell A2 in the Excel file and paste the data. Your data should be placed in the appropriate columns. The number of counts for the first 10 s period should be located in cell B4 and the last 10 s period data should be placed in cell B23.

6. Print out one copy of your Data Studio data for your group.

7. Before coming to lab you should have refreshed your knowledge in Appendix C on statistical uncertainties. We have calculated the average number of counts \( \langle N \rangle \) and various other values in the Excel file. The average number of counts \( \langle N \rangle \) is given by

\[
\langle N \rangle = \frac{\sum_i N_i}{n}
\]  

(12.5)

8. Find the square root of \( \langle N \rangle \) and check how many of your runs (i.e. measurements) gave a result within, respectively, the intervals:

\[
\langle N \rangle \pm \sqrt{\langle N \rangle}, \quad \langle N \rangle \pm 2\sqrt{\langle N \rangle}, \quad \text{and} \quad \langle N \rangle \pm 3\sqrt{\langle N \rangle}.
\]  

(12.6)

The results should be, approximately, 67%, 95%, and 99.5%. This has been done in the Excel file.

9. Write down below the number and percentage of times your results fall within

\[
\begin{align*}
\pm \sqrt{\langle N \rangle} & : \quad \text{Number:} \quad \ldots \quad \text{Percentage:} \quad \ldots \\
\pm 2\sqrt{\langle N \rangle} & : \quad \text{Number:} \quad \ldots \quad \text{Percentage:} \quad \ldots \\
\pm 3\sqrt{\langle N \rangle} & : \quad \text{Number:} \quad \ldots \quad \text{Percentage:} \quad \ldots
\end{align*}
\]

**Question 1-2:** Discuss whether your results are consistent with the expectations given in step 7. How concerned are you that they don’t agree?
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Number of Counts $N$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>2</td>
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<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>$\langle N \rangle$</td>
<td></td>
</tr>
</tbody>
</table>

Table 12.1:

10. **Print** out your data in Excel and include it in your group report.

**Question 1-3:** Why are we not able to measure the half life of the $^{137}$Cs source in this lab?

**INVESTIGATION 2: $1/R^2$ DEPENDENCE**

In the previous investigation we looked at the statistical interpretation of radioactive decay. When the decay particles are emitted they have equal probability of decaying in any direction. If
we have a detector of constant area, we will detect more particles the closer we are to the source. As we move further away, we will count fewer, because we are subtending a smaller solid angle of the source. We believe there should, therefore, be a $1/r^2$ dependence of the count rate as we move further away from the source with a detector of constant area.

To verify the $1/r^2$ dependence of the radiation intensity, we vary the distance between the source and detector by moving the source (held by the lens holder on the stand) along the table. Keep the GM counter fixed, because its cable is short. You will not need any additional material for this investigation.

1. The radioactive source should still be mounted on the lens holder. Vary the distance $r$ between source and counter starting at 5 cm and measure the counting rate at the distances given in Table 12.2. The distance should be measured from the front of the cesium source to the center of the GM tube, which is approximately the green line on the tube.

2. Open the experimental file L12.A2.Radioactivity.DistanceDependence.ds in Data Studio, which is set to count for an interval of 60 s. This will probably produce a number of counts more than 30,000 at the 5 cm separation. Measure for all the distances given in Table 12.2.


4. Remove the $^{137}$Cs far away from the GM tube and take a background measurement for 60 s.

<table>
<thead>
<tr>
<th>Distance between source and GM tube (cm)</th>
<th>Number of Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
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<tr>
<td>7</td>
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<td>10</td>
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<td>15</td>
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<tr>
<td>22</td>
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<tr>
<td>30</td>
<td></td>
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<tr>
<td>Background (60 s)</td>
<td></td>
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</tbody>
</table>

Table 12.2: Distance Data

**Question 2-1:** If we had more lab time, we would have you take the background measurement for 600 s instead of 60 s. Why would that be better?

5. Subtract the number of background counts for 60 s from each of your values measured in step 3. Do this in Excel. This is the number of actual $\beta$ rays and $\gamma$ rays detected at each
distance. Call this number $NR$ to denote the fact that the background has been subtracted. We plot $NR$ versus the distance on a graph in Excel.

6. **Print** out your data and graph and include it in your group report.

**Question 2-2:** Does the graph look like the $1/r^2$ dependence that you expect? If not, explain. What would you plot $NR$ versus if you wanted to see the data represented by a straight line? Explain.

7. In order to see whether the data indeed are dependent like $1/r^2$, plot the number of counts $NR$ versus $1/r^2$. We have done this for you in Excel. Add a linear trendline and under “Options” click on “Display equation on chart” and “Display R-squared value on chart”. You might also try “Set intercept = 0” to see if better results are obtained.

**Question 2-3:** Does the data agree with this function? If not, explain. Write down the best fit equation and the value of $R^2$ below.

**Question 2-4:** Between what two points is your measurement of the distance $r$ taken? Think carefully about the interaction of the $\beta$ rays and $\gamma$ rays inside the GM tube. Can you think of more accurate positions to measure between? If so, explain.

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**INVESTIGATION 3: ENERGY OF BETA RAYS**

The main objective of this investigation will be to study the interaction of radiation with matter. Electrons ($\beta$ rays), because they are charged, interact very strongly with matter. Along their path in matter they knock other electrons out of the atoms they encounter, ionizing them in the process. In this way they lose energy rapidly and come to rest after they have traveled a distance $R$ called the **range.** The exact theory of the energy loss of electrons in matter is very complicated and will not be discussed here. Former UVa President and physics professor Frank Hereford did definitive work in this subject (see Physical Review, vol. 78, p. 727 (1950)). Figure [12.6] shows the **range energy curve** or **range curve** for electrons in copper. Gamma rays, on the other hand, interact much less strongly with matter, because they have no charge.

It is customary (and convenient) to express $R$ not in units of length, e.g. cm, but in units of g/cm$^2$. This is because the range expressed in these units is independent of the absorber material, whether it is a solid, liquid or gas. To convert from a range given in g/cm$^2$ to a range given in
cm, we divide by the density of the material (g/cm³). Thus, in a layer of matter with a thickness of, say 1 g/cm², there is 1 g of matter behind every square centimeter of surface, regardless of the density of the material.

Range curves such as that shown in Figure 5 give the range of mono-energetic electrons. Remember that the electrons emanating from your $^{137}\text{Cs}$ source holder cover a continuous spectrum from 0 to 0.514 MeV (plus a small admixture of electrons with energies between 0 and 1.176 MeV). It will thus not be possible for you to verify a given range curve in this experiment.

In this investigation you will determine the energy of $\beta$ rays by allowing the particles produced by the $^{137}\text{Cs}$ source to pass through a series of thin brass foils. Brass consists mostly of copper, so we will be using the properties of copper when needed.

**Apparatus**

![Figure 12.5: Range measurement source and detector](image)

In addition to the material you have already used, you will need the following material:

- 14 thin brass (Cu) foils
- plastic holder for source, foils, and GM tube
1. The setup for this experiment is shown in Figure 12.5.

2. There is a collection of 14 thin brass (Cu) foils; each foil is 0.001" (1 mil) thick. Be careful not to touch the thin foils, because it is easy to poke holes through them. Insert all 14 Cu foils into the wide slot of the plastic holder. Place the $^{137}$Cs source into the holder with the recessed circle that holds the source. Slide the holder with the radioactive source below the thin foils with the source as close as possible.
3. Take the GM tube off the mount from the previous experiment and place it down into the cylindrical hole of the plastic holder. You want the GM tube to be quite close to the top of the Cu foils. This will allow a maximum count rate, because you are minimizing the distance between the source and detector.

4. Open the experimental file **L12.A3.Radioactivity.Range.ds** in Data Studio. Open the Excel file **L12.A3.Radioactivity.Range.xls**. With all 14 foils in place take your first measurement and enter your data in Table [12.3] and in the Excel file. Each measurement will be for 10 s. Measure the count rate as a function of Cu foil thickness by removing one or two foils at a time as given in Table [12.3] The detector and radioactive source must remain fixed as you remove foils.

5. Remove the $^{137}\text{Cs}$ source and set it far away. Open experimental file **L12.A3.Radioactivity.Range.Background** and take the background for 120 s. Enter your data into Table [12.3] and in the Excel file.

6. Subtract a background in Excel for 10 s from each of the measurements with the foils.

<table>
<thead>
<tr>
<th>Number of Foils</th>
<th>Number of Counts</th>
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<tbody>
<tr>
<td>14</td>
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<td>Background (120 s)</td>
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**Table 12.3: Range Data**

**Question 3-1:** Why do you think the number of 14 foils was chosen? Why not 6 foils or 25 foils? The total thickness of the 14 foils is 0.014 inches. Is this important? Explain.
7. The β rays are more easily stopped in material than γ rays, which are much more penetrating through matter. In the present experiment there is only a small probability that a γ ray will be absorbed or scattered enough to miss the detector. However, the 14 Cu foils should be enough to stop all the 0.51 MeV β rays. If we plot the number of counts versus the number of foils, we should see a change in slope of the data. Make a plot in Excel of the natural logarithm of the number of counts (minus the background) ln (NR) versus the number of foils.

**Prediction 3-1:** You will be plotting your experimental data on a semi-log plot in Excel, that is, ln (NR) versus the number of foils. Explain in detail what the shape of the data should look like both before and after all the β rays are stopped. Make a sketch of ln(NR) versus the number of foils. **Do this before coming to lab.**

8. You should be able to see a clear break in slope of the data when all the β rays have been absorbed. Write down the number of foils when you believe this has happened. Write down the thickness of the foils when this occurs.

Number of foils that stop β rays: ______________

Thickness: ____________ cm

**Question 3-2:** Does the plot of your data agree with your Prediction 3-1? Discuss the shape of your data.

9. The range is the material thickness required to stop all the particles of a given energy and is normally quoted in terms of g/cm² or mg/cm². Use the density of Cu (8.92 g/cm³) to calculate the foil thickness in units of mg/cm² and write it below.

Range: ______________ mg/cm²

10. Use Figure 12.65 to obtain the β-ray energy that corresponds to this range and write it down.

β-ray energy: ______________ MeV
Question 3-3: Does this energy agree with what you expect? If not, explain. Do you need to take into account the absorption by the air between source and GM tube?

11. Print out your Excel file and include the graph.

INVESTIGATION 4: ATTENUATION OF GAMMA RAYS

A γ ray, having no charge, interacts much less with matter than does a β ray. Indeed, it does not interact at all ... until it does. You might liken an electron traveling through matter to a man fighting his way through underbrush, constantly having to push branches out of the way. A γ ray is like a man running at night through a open field populated by a very few tall trees. The going is smooth ... until he runs against a tree trunk. If the trees are widely spaced, the average distance he travels between bumps, his mean free path $\lambda$, will be large; in a dense forest the mean free path will be small. In an open field, the mean free path will be long. We can think of the mean free path as being related to the mass that the gamma ray passes through. There are three principal mechanisms, by which a γ ray can interact with matter:

- **Photoelectric absorption**, in which it loses all its energy to one of the inner, i.e. more tightly bound, atomic electrons of an atom, thus ionizing the latter.
- **Compton scattering**, in which the γ-ray is scattered by one of the loosely bound (or free) electrons, losing only part of its energy, and
- **Pair production**, in which the γ-ray converts into an electron-positron pair in the field of the nucleus.

Pair production requires the γ ray to have an energy that is at least 1.022 MeV, the rest-mass of the electron-positron pair multiplied by $c^2$. It is not important in our case where the maximum γ-ray energy is 0.662 MeV. When a beam of γ rays with an initial intensity $I_0$ passes through an absorber of thickness $x$, its intensity will be reduced to a value $I(x)$ given by

$$I(x) = I_0 e^{-\mu x} = I_0 e^{-x/\lambda}, \quad (12.7)$$

where $\mu$ is the linear attenuation coefficient and $\lambda$ the mean free path. You will measure $\mu$ and $\lambda$ for brass in this experiment. Intensity is related to the number of particles per unit area per unit time. We will measure the number of counts $N$ for a given time period for a given fixed geometry; in this case the number of counts $N$ is directly proportional to the intensity $I$, so Equation (12.7) becomes

$$N = N_0 e^{-\mu x} = N_0 e^{-x/\lambda}, \quad (12.8)$$

The number of counts $N$ for a fixed time period clearly depends on the thickness $x$ of the absorber brass. We expect to see an exponential decrease of the number of counts with thickness $x$. Let’s take the natural logarithm of Equation (12.8).
\[
\ln(N) = \ln(N_0 e^{-\mu x}) = \ln(N_0) + \ln(e^{-\mu x}) = \ln(N_0) - \mu x
\]  
(12.9)

**Apparatus**

In addition to the material you have already used, you will need the following material:

- Seven pieces of brass plates, different thicknesses.

1. We will again use the plastic holder. Remove everything in the plastic holder. There are seven pieces of brass of three difference thicknesses. Insert all of the brass plates in and around the wide space in the plastic holder. Then insert the \(^{137}\text{Cs}\) source in its holder as close as possible below the brass. Then insert the GM tube as in the last investigation in the top as close as possible to the brass (but with a little space so the brass can be slid out). You may be able to move the brass pieces around a little to make the distance between source and detector as small as possible.

**Prediction 4-1:** You will measure the number of counts versus the total brass thickness. What shape curve do you expect to see if you plot \(\ln(NR)\) versus thickness \(x\)? (Remember that \(NR\) is the number of counts with the background subtracted.) Explain. **Do this before coming to lab.** Hint: see Equation (12.9).

2. Open the experimental file **L12.A4.Radioactivity.Attenuation.ds** in Data Studio. You will now measure the number of counts as a function of total brass thickness \(x\) for five measurements. We would do more measurements if we had time. **Use a time interval of 60 s.** Enter your data in Table 12.4 and into the Excel file **L12.A4.Radioactivity.Attenuation.xls**.

<table>
<thead>
<tr>
<th>Number of 1/8” pieces</th>
<th>Number of 1/16” pieces</th>
<th>Number of 1/32” pieces</th>
<th>Total thickness (inches)</th>
<th>Number of Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0.71875</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.59375</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.34375</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.15625</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.03125</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Background (120 s)</td>
<td></td>
</tr>
</tbody>
</table>

Table 12.4: Attenuation Coefficient Data

3. Use the background measurement you made in the last investigation for 120 s. We subtract the background for 60 s from your data in Excel and put the results \(NR\) for each thickness
in the next column in Excel. In the next column in Excel we take the natural logarithm of the number of counts less background. We make a plot in Excel of the $\ln (NR)$ versus the brass thickness $x$ (in cm).

**Question 4-1:** The thinnest piece of brass used was 1/32 in. Why was this chosen? Are beta rays reaching the GM tube?

**Question 4-2:** Does the plot of your data agree with your Prediction [4][1]? If not, explain.

4. Fit the data shown on your Excel plot with an appropriate function. Show the trendline of your fit, the equation, and the $R^2$ function on the plot. Write the values of your equation and the value of $R^2$ below:

   Equation: ______________
   $R^2$ value: ______________

**Question 4-3:** Look at Equation (12.9) and discuss how to find the linear attenuation coefficient $\mu$ and the mean free path $\lambda$ from the information found in step 4. Write down the values of $\mu$ and $\lambda$. Pay attention to units.

   Linear attenuation coefficient: ______________
   Mean free path: ______________

**Question 4-4:** Look at $\ln(N_0)$ of Equation (12.9). Can you experimentally measure $N_0$? Why or why not? How can you determine the value of $N_0$? Explain and show how you do it. Write the value down below.

   $N_0$: ______________
**Question 4-5:** The density of air is $1.3 \times 10^{-3}$ g/cm$^3$, and the density of copper is 8.92 g/cm$^3$. If the mean free path of gamma rays in a material depends on the mass a gamma ray passes through (see the trees in the forest argument earlier), estimate what you would expect for the mean free path in air of the gamma rays used in this measurement. Show your calculations below. Do we have to be concerned about the attenuation of gamma rays in air in this experiment? Explain.

5. **Print** out your data and graph from Excel and include it in your group report.

**Before Leaving make sure you have:**

1. Put the GM tube back in the holder

2. Given the $^{137}$Cs source back to the TA

3. Checked with you TA that above tasks have been completed