Radioactivity

Experiment Five

Physics 192
Michigan State University

Before Lab

- Carefully read the entire lab guide and attempt the theory questions
- **Arrive to lab on time for a presentation on radiation safety!**

Experiment Overview

This is a two-week lab exploring aspects of radioactivity. Using a special type of detector, you will directly observe the effects of ionizing radiation and use the information to understand how materials can absorb high-energy particles.

- Learn about the different types of nuclear radiation
- Test Poisson statistics as a model of radioactive decay
- Investigate the radiation energy spectrum from ^{137}Cs and ^{60}Co
- Characterize the radiation absorption properties of different materials

1 The Atomic Nucleus

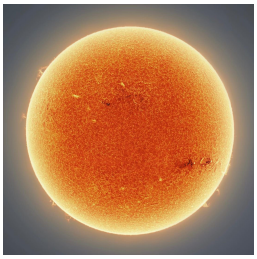


Figure 1: Nuclear reactions in stars produce a diverse array of stable and radioactive isotopes (Source: Andrew McCarthy).

It can be hard to comprehend the incredibly small size of the nucleus. A typical nuclear radius is $\sim 10^{-15}$ m, or about 100,000 times smaller than the scale of electron orbitals. Magnifying an atom to the size of Spartan Stadium would reveal a nucleus the size of a sesame seed. Despite the minuscule scale, about 99.9% of the mass of an atom is concentrated in the nucleus. The nuclear length scale 10^{-15} m $= 1$ fm is called the femtometer, but is often called a *fermi* in honor of Italian-American physicist Enrico Fermi, who created the first nuclear reactor in 1942.

The periodic table of elements is ordered by **atomic number**, which is defined as the number of protons, Z, within the nucleus. The number of protons determines the number of electrons, and therefore the chemical properties of an element. Each element has multiple variants determined by the number of neutrons, N, contained in the nucleus. The different varieties of an element are called **isotopes**, categorized by **mass number**

$$A = Z + N.$$

The notation ^{A}X is commonly used in the context of nuclear physics. For example, ^{12}C (spoken as "carbon-12") is the most abundant form of carbon, consisting of 6 protons and 6 neutrons. Natural processes also produce heavier isotopes of carbon, ^{13}C and ^{14}C. The additional neutrons do not affect chemical reactions, so heavy isotopes of carbon are readily incorporated into structures, including those in your own body. What does change with the neutron number is the *stability* of a nucleus. While protons bound in a nucleus experience an immense repulsive electrostatic force, electrically-neutral neutrons are not subject to the same repulsion. The primary difference between isotopes is the internal balance of forces responsible for maintaining nuclear structure.

1.1 Nuclear Structure

Confined within the volume of a nucleus is an unfamiliar fundamental force of nature aptly named the **strong force**. Protons and neutrons are composite particles composed of elementary particles called *quarks*. Acting only on unimaginably small lengths scales of < 1 fm, the strong force far exceeds the strength of the other fundamental forces shown in Table 1. The present understanding of nuclear structure presumes that protons and neutrons themselves are bound together by a residual effect of the strong force.

Force	Strength	Range (m)
Strong	1	$< 10^{-15}$
Electromagnetic	$\frac{1}{137}$	∞
Weak	10^{-6}	$< 10^{-18}$
Gravitational	10^{-39}	∞

Table 1: The four fundamental interactions with relative strengths and effective ranges of action.

Imagine trying to assemble a nucleus by squeezing protons together. Even at large separations, the electrostatic force

$$F_E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2} \tag{1}$$

acts to repel the protons. Bringing them together takes a tremendous amount of work to overcome this repulsion as the value of r approaches the nuclear length scale.

Once the protons reach a separation of around 2 fm, the peculiar behavior of the strong force emerges. At this distance, the residual effects of the strong force extend between the protons, producing an attractive mechanism called the **nuclear force**. Figure 2 compares the nuclear and electrostatic forces. Along the curve marked (a), the nuclear force is *very* strong and attractive. As the separation continues to decrease, the nuclear force quickly becomes repulsive. This behavior constrains the size of the nucleus as the net force is attractive only over a narrow range of separations.

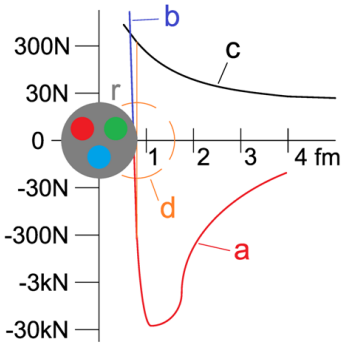
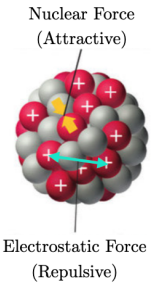


Figure 2: Comparison between the electrostatic (black) and nuclear (red) forces (source).

Adding a neutron to our hypothetical nucleus effectively increases the nuclear force without adding another repulsive electrostatic component. This increase in attraction is necessary to bind protons in a stable state, which is why all stable nuclei have at least one neutron (with the exception of hydrogen, which has a nucleus consisting of a single proton).

The protons and neutrons in a nucleus occupy quantized shells analogously to electrons. In the spectroscopy lab, you observed how electrons can transition from high to low-energy states by emitting a photon. Nuclei operate in the same way, except the photons involved in the nuclear transition process are of much higher energies.

2 Radioactive Decay



The balance between the electromagnetic and nuclear forces is highly sensitive to the number of protons and neutrons in a nucleus. If the attractive and repulsive forces are well balanced, the energetic configuration of the nucleus is minimized, and the nucleus is said to be *stable*. The attractive force in a nucleus is insufficient to overcome the electrostatic repulsion between protons if the nucleus contains more protons than neutrons. In this situation, the nucleus is *unstable*. Instability also occurs in neutron-rich nuclei. Figure 3 shows a plot of known isotopes with atomic number on the vertical axis and neutron number on the horizontal axis.

Each colored box represents an isotope, and the black boxes correspond to stable nuclei. The 1:1 proton-to-neutron ratio line illustrates the tendency for nuclei to have more neutrons than protons. **Radioactive decay** is the process by which an unstable nucleus transforms by releasing energy to reach a more-stable state. All of the colored boxes in Figure 3 represent isotopes which undergo radioactive decay, and the color indicates the **mean lifetime** before the isotope decays. The vast majority of isotopes are radioactive; only 251 out of approximately 2400 known isotopes are stable.

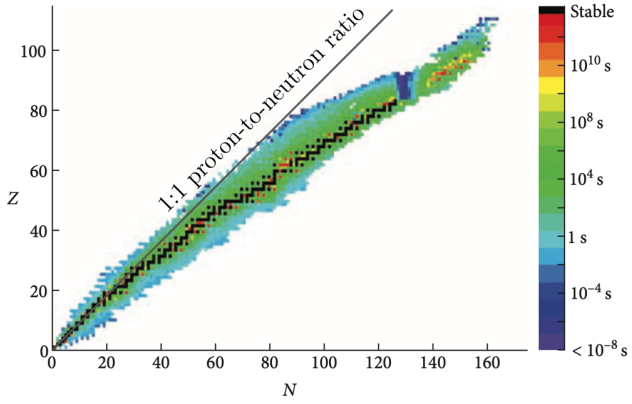


Figure 3: A table of known isotopes organized by proton number (Z) and neutron number (N) with measured lifetimes indicated by color.

The process of radioactive decay is inherently probabilistic. There is no way of knowing whether a particular nucleus in a radioactive sample will decay in any given second. What is known is that the probability of observing a decay in a given time interval, dt, is proportional to the total number of nuclei. The **decay constant** is the probability of decaying per unit time, denoted by λ, and is a unique characteristic of each isotope. This means that a sample of N nuclei will decay at a rate of

$$\frac{dN}{dt} = -\lambda N$$

where the negative sign indicates that the number of nuclei decreases as the decay process occurs. The solution to this differential equation is the exponential decay law,

$$N(t) = N_0 e^{-\lambda t}, \tag{2}$$

where N_0 is the number of nuclei at $t = 0$. The decay constant is directly related to the mean lifetime, τ, by

$$\tau = \frac{1}{\lambda}. \tag{3}$$

It is this property that permits the mean lifetime measurements shown in Figure 3. Lifetimes vary over an incredible range. There are radioactive isotopes with lifetimes greater than the age of the universe. Experimentalists do not have this much time, so they measure the decay constant for a particular isotope and make use of Equation 3 to determine the mean lifetime.

2.1 Types of Radiation

An unstable nucleus exists in a high-energy state and has a tendency to undergo one or more transitions to reach a state with a lower total energy. The transition process involves the emission (radiation) of excess energy in some form. Some nuclei decay directly to a stable state, while others follow more complicated processes involving intermediate metastable states. Each transition involves one of three primary types of nuclear radiation:

Alpha decay (α): an alpha particle is a ^{4}He nucleus (two protons and two neutrons bound together). Emission of an alpha particle reduces the charge of the nucleus by $2e$ and the mass number by four.

Beta decay (β): a beta particle can be an electron (β^-) or a positron (β^+). Emission of a β^- involves the conversion of a neutron to a proton. Emission of a β^+ involves the conversion of a proton to a neutron. Beta decay leaves the mass number unchanged, but the nuclear charge is shifted by $\pm e$.

Gamma decay (γ): a gamma particle, or gamma ray, is a high-energy photon. Gamma emission is qualitatively different from alpha and beta decay in that the mass and charge numbers of the nucleus do not change. Gamma rays are produced when a nucleus relaxes from an excited nuclear state in the same way that electrons emit photons when moving from high to low energy orbitals (as was observed in spectroscopy).

2.2 Absorption of Radiation

The three types of nuclear radiation interact with matter differently. Understanding how different types of radiation are absorbed is crucial to developing shielding mechanisms to protect people and equipment from harmful effects of exposure to high-energy particles.

- Alpha particles have a relatively high mass, so they are not significantly deflected by electrons in a medium. With a charge of $2e$, alpha particles ionize atoms through collisions are quickly stopped over a short distance. Shielding from alpha particles can usually be accomplished by a piece of paper or a few centimeters of air.
- Because beta particles have a lower mass and charge, they are able to penetrate deeper into media before stopping. Beta particles experience more deflection, bouncing between electrons along torturous trajectories before reaching a stop. Instead of a single sheet of paper, a book of a few hundred pages is sufficient to shield from most beta particles.
- Gamma radiation is significantly more difficult to absorb. Because they are uncharged, gamma rays readily pass through media with few interactions. It would take an entire bookshelf to significantly reduce the intensity of a beam of gamma rays.

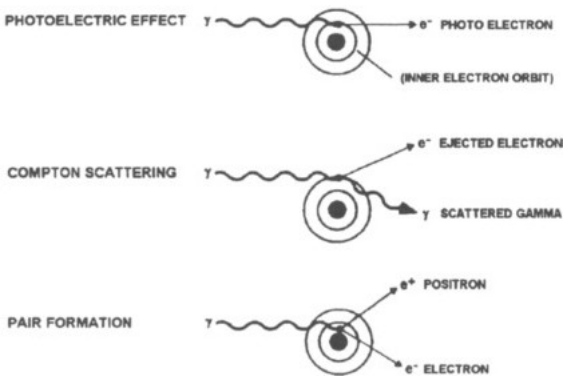


Figure 4: Primary gamma-matter interactions.

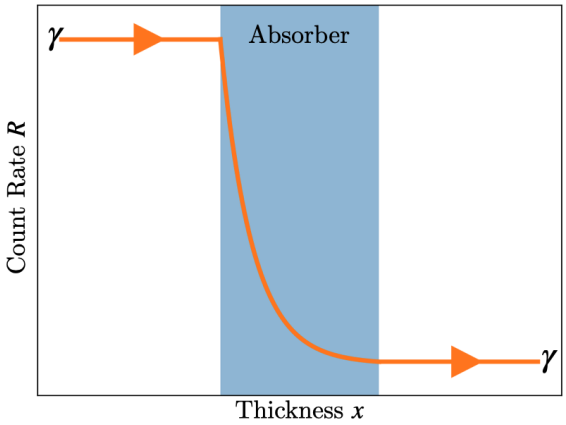


Figure 5: Exponential absorption.

In this lab, you will closely analyze the absorption of gamma rays by two different materials. The absorption characteristics are strongly dependent upon the photon energy and the density of the absorbing material. Figure 4 shows the primary interaction processes responsible for attenuating gamma rays.

Photoelectric effect: results in a complete removal of a photon. It occurs when an inner-orbital electron absorbs all the photon energy and is ejected from the atom. The liberated electron is subsequently stopped by the material in a short distance as described for beta particles. This is the primary mechanism for photons with $E < 0.5$ MeV.

Compton scattering: results in a photon with a reduced energy. It occurs when a photon collides with an outer-orbital electron, providing the electron with kinetic energy and reducing the energy of the photon. This interaction does not completely remove a photon from a beam. It is the primary mechanism for photons with $E \sim 0.5 - 1$ MeV.

Pair formation: results in the production of an electron positron pair and the complete removal of a photon. Pair formation only occurs in close proximity to a nucleus, in which case the nucleus serves as a recoil to conserve energy and momentum. The process only occurs for photons with very high energies of $E > 1$ MeV.

All of the mechanisms described above contribute to the absorption characteristics of a material. Each type of interaction results in different penetration depths through a material, which means the net attenuation of a beam is dependent upon the interaction type. By studying a narrow range of photon energies, we can construct a simple model of absorption that has a purely exponential dependance on absorber thickness:

$$R(z) = R_0 e^{-(\mu/\rho)z} \tag{4}$$

where

- $R(z)$ is the counting *rate* (counts/second) as a function of effective absorber thickness.
- R_0 is the counting rate with no absorber ($z = 0$)
- ρ is the mass density of the absorber (units of g/cm^3)
- (μ/ρ) is the **mass attenuation coefficient**, which characterizes how much radiation is absorbed by the material (units of cm^2/g)
- z is the *mass thickness* measured in g/cm^2

It is important to recognize that z is not the linear distance traveled through the absorber. The absorption process is best described in terms of **mass thickness** which characterizes the amount of material encountered by the photon. For a linear thickness x, a material with density ρ has a mass thickness of $z = \rho x$.

2.3 The Statistics of Radioactivity

Radioactive decay belongs to a class of statistical problems called **Poisson processes**, which are characterized by events that occur randomly over time with a certain average rate, and the occurrence of one event do not affect the occurrence of subsequent events. Examples of such processes are everywhere; for instance, the arrival of computer network traffic occurs randomly with a well-defined mean rate.

Each nucleus in a radioactive sample has the same probability of decaying in a given second, and the decay of one nucleus does not influence another. In order to determine the decay rate of a sample, you can use a radiation detector and measure the number of events over some time interval. Even with an idealized detector with 100% efficiency, the number of decays measured over two different intervals will likely be different as a consequence of the random nature of radioactivity. In order to quantify the random behavior and determine a best estimate at a count rate, we can make use of the properties of Poisson statistics.

Imagine making N measurements of the number of counts, C, occurring over a fixed time interval with your detector. The best estimate of the number of counts over the interval is the mean,

$$\bar{C} = \frac{1}{N}\sum_{i=1}^{N} C_i. \tag{5}$$

The problem now is to determine the uncertainty in the mean number of counts. In all preceding experiments, measurements obeyed the statistics of the normal distribution. This property was exploited to determine well-defined confidence intervals for measurements. It was shown that a given measurement has a 68% chance of being within one standard deviation (σ) of the true mean value. This allowed us to use the standard error as the uncertainty in the mean with a 68% confidence interval. Poisson processes have the special property $\sigma_i = \sqrt{C_i}$. This can be extended to any series of counts, arriving at

$$\sigma = \sqrt{\bar{C}}, \tag{6}$$

which implies that the entire distribution is characterized by the mean.

Figure 6 shows a comparison between a normal distribution and a Poisson distribution for a mean of 10 with $\sigma = 3$. The two curves are not the same, but they are similar enough that we can safely apply the same confidence intervals to Poisson processes for sufficiently large sample sizes. Evidently, a single measurement of the count rate can be stated with uncertainty as

$$C_i \pm \sqrt{C_i} \tag{7}$$

with 68% confidence. The analysis can be extended to determine the uncertainty in the mean. As always, the uncertainty in the mean is the standard error, which can be combined with Equation 6 to obtain

$$\delta\bar{C} = \frac{\sigma}{\sqrt{N}} = \sqrt{\frac{\bar{C}}{N}}. \tag{8}$$

The fractional uncertainty in the mean takes a remarkably simple form, dependent only on the total number of counts registered by the detector. The first step is to use the definition of fractional uncertainty and Equation 8,

$$\frac{\delta\bar{C}}{\bar{C}} = \sqrt{\frac{\bar{C}}{N}}\left(\frac{1}{\bar{C}}\right) = \sqrt{\frac{1}{N\bar{C}}}.$$

The quantity $N\bar{C}$ can be deduced by examining the equation for the mean. Referring to Equation 5, we find

$$N\bar{C} = \sum_{i=1}^{N} C_i = C_{tot}.$$

The number C_{tot} is the total number of counts registered by the detector, and so we arrive at a fractional uncertainty in the mean of

$$\frac{\delta\bar{C}}{\bar{C}} = \frac{1}{\sqrt{C_{tot}}}. \tag{9}$$

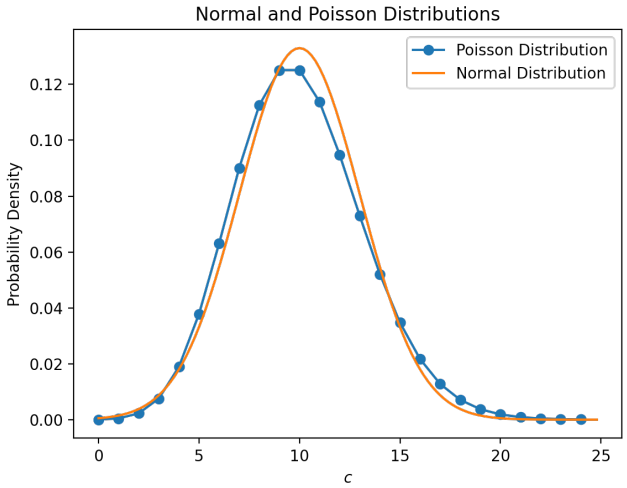


Figure 6: Comparison between the normal and Poisson distributions.

Once the mean number of counts over an interval is determined, the mean count rate can be calculated using the time interval used for measurements. If each trial was conducted over an interval T, then the **mean count rate** is determined by

$$\bar{R} = \frac{\bar{C} \pm \delta\bar{C}}{T}. \tag{10}$$

2.4 Background Radiation

Nuclear radiation is classified as **ionizing radiation** because it has the ability to ionize atoms or molecules upon interaction. In addition to radioactive processes, cosmic sources like the sun and stars also produce large amounts of ionizing radiation called cosmic rays. The earth is constantly bombarded by high-energy particles that can cause significant damage to living tissues and technology. Fortunately, Earth's atmosphere and magnetic field provide substantial protection from the harmful effects of cosmic rays, but they do not completely eliminate their presence.

Your detector is sensitive to all forms of ionizing radiation, so the effects of background sources will be indistinguishable from those caused by your radioactive sample. In order to reduce the noise caused by background radiation, you will run your detector for a period of time, T_{bgd}, to estimate the background activity. From this, you can calculate the mean background rate as

$$\bar{R}_{bgd} = \frac{\bar{C}_{bgd}}{T_{bgd}}, \tag{11}$$

and the total rate from your source can be obtained by subtracting the background: $\bar{R}_{sce} = \bar{R}_{tot} - \bar{R}_{bgd}$.

2.5 Experiment Isotopes

You will study two different isotopes in your experiments. **Cesium-137** is an unstable isotope primarily produced as a byproduct in nuclear reactors. It is a silvery-white alkali metal with the atomic number 55. With a half-life of about 30 years, meaning that it takes about 30 years for half of the initial amount of ^{137}Cs to decay.

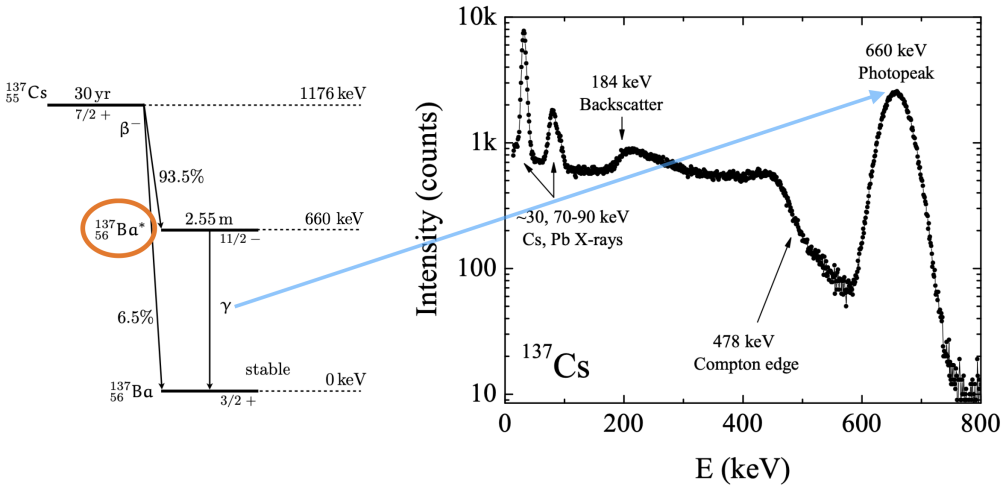


Figure 7: The decay scheme (left) and energy spectrum (right) for ^{137}Cs .

The left side of Figure 7 shows the decay process for the isotope in an energy-level diagram. Note that 1 MeV = 1000 keV. The ^{137}Cs nucleus always decays by emitting a β^- particle (electron) while a neutron is converted into a proton, increasing the atomic number by one. In 93.5% of decays, the decay forms a ^{137}Ba* nucleus where the $*$ indicates an excited nuclear state (circled in orange). The excited state has a half-life of only 2.55 minutes, so it is considered *metastable*. De-excitation results in the emission of a gamma ray with $E = 660$ keV. Evidence of this photon is apparent in the energy spectrum shown on the right side of Figure 7, where the blue arrow shows the peak in events at 660 keV.

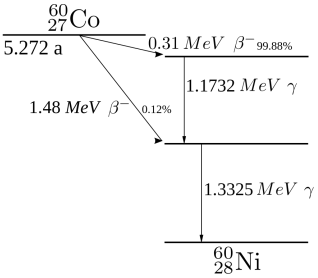


Figure 8: ^{60}Co decay.

You will also study **cobalt-60**. ^{60}Co is a radioactive isotope of cobalt, a hard, gray metal with the atomic number 27. ^{60}Co is another artificially produced isotope formed in nuclear reactors. It has a shorter half-life of about 5.27 years. Figure 8 shows the dominating decay scheme of ^{60}Co . In another example of beta decay, the transition forms an excited state, ^{60}Ni*. De-excitation occurs in $\sim 10^{-12}$ sec through the emission of two photons with energies $E_1 = 1.17$ MeV and $E_2 = 1.33$ MeV.

3 Theory Questions

1. (1 pt) Use Equation 1 to calculate the electrostatic force between two protons in a nucleus separated by a distance of $r = 1$ fm.

2. (1 pt) The proton has a mass $m_p = 1.673 \times 10^{-27}$ kg. Determine the acceleration experienced by a proton from the repulsive force calculated in the previous problem. How many times larger is this number than the gravitational acceleration?

3. This problem is designed to prepare you for the analysis of exponential relationships. The number of particles, N, in a radioactive sample with a decay constant λ can be calculated as a function of time by

$$N(t) = N_0 e^{-\lambda t} \tag{12}$$

where N_0 is the initial number of nuclei.

   a. (1 pt) If t has units of time, what must be the units of λ?

   b. (2 pt) Qualitatively sketch three exponential curves with decay constants 2λ, λ, and $\lambda/2$ and label each curve. Which decay constant produces the fastest decaying curve?

c. (2 pt) Make use of the natural logarithm and a substitution that would linearize Equation 12. In particular, what could you define as y such that a plot of y vs. t would be linear?

d. (2 pt) Assume you have various measurements of N with known uncertainties δN. Use uncertainty propagation to calculate δy in terms of δN.

4. (1 pt) When a ^{60}Co atom undergoes beta decay, the transformation of a neutron to a proton forms an isotope of nickel (Z=28). A β^- particle (electron) is emitted in the process. Does this violate the conservation of charge?

4 Experimental Apparatus

Your experiment involves an extremely sensitive light detector called a **photomultiplier tube** (PMT). The device houses a NaI(TI) crystal that interacts ionizing radiation. Gamma rays are absorbed, producing electrons that travel in erratic paths, emitting photons through collisions with the crystal lattice. The number of photons generated increases with the energy of the absorbed gamma ray. The PMT, which is sensitive to individual photons, outputs a voltage that is proportional to the energy of the absorbed radiation. The voltage is sent to a digital spectrometer, which converts the performs a conversion to generate a digital signal.

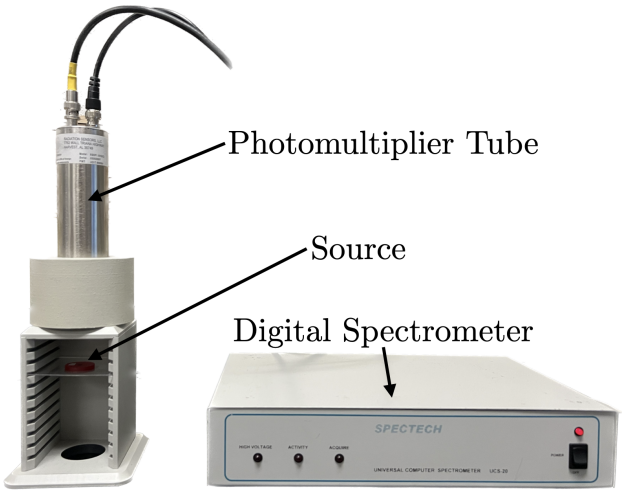


Figure 9

Figure 9 shows the equipment used in the experiment. The sample is housed on a plastic shelf inside of a partially shielded box. The distance from the sample to the PMT can be varied by placing the source on different levels. You have lead (Pb) and aluminum (Al) absorbers that can be placed directly on top of the source. Additional information:

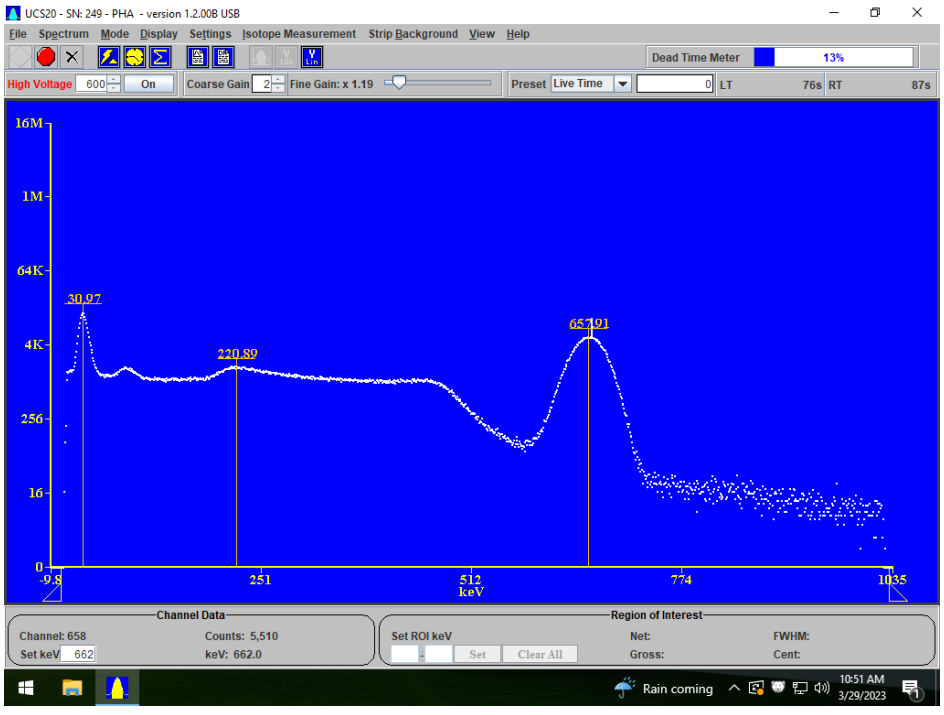
- The two radioactive sources must be signed out and returned before anyone leaves the room. Your TA will assist you with the procedure.
- **Under no circumstances should you lose track of a radioactive source.**
- **Do not lift the PMT outside of the housing. It is extremely sensitive.**
- The spectrometer used is a Spectrum Techniques Spectrum Techniques UCS-20. Click this link for the full technical documentation.
- While the sources are radioactive, you are not at any health risk under normal handling. Holding the ^{137}Cs sample for 12 hours would provide a whole-body dose of about 1 mrem. A typical chest x ray gives an absorbed dose between 40 and 200 mrem.

4.1 Calibration

The first step is to calibrate the spectrometer. The device is controlled using the computer at your bench. Turn on the spectrometer with the switch on the front face.

- Login to the lab account using password: **Physics191**.
- Create a temporary folder in the U drive for storing your data. Give the folder a unique name.
- Click the icon for the virtual machine on the desktop to use the 32-bit operating system. Once again, you will be asked to login. Use the same password.
- Click the icon to run the UCS20 software.
- Once the program has opened, click the USB icon in the bottom toolbar of the virtual machine and ensure the spectrometer is connected.
- Click *Spectrum* → *Connect to Device*
- Obtain the ^{137}Cs source from your TA. Place the source on the topmost shelf with the transparent window pointed upward. Make sure the ^{60}Co source is far from the detector.
- Click *Settings* → *Energy Calibration* → *Autocalibration*. Then, allow the software to determine the proper operating voltage. You will get a notice when calibration is finished.

A screenshot of a calibrated ^{137}Cs spectrum is shown below (compare to RHS of Figure 7. The peak energies can be toggled in the *View* menu. On the top-left side of the toolbar, red and green buttons can be used to start and stop the detector. The X button clears the display. Hover the mouse over each button to see what it controls.



5 Background Measurement

To measure the background, you need to remove your ^{137}Cs source from the detector and move it far away from the detector. Click *Run* → *MCS - Internal* to set the detect the total number of counts per unit time.

1. With the dwell time set to 0.4 s, record the background radiation for the full 1024×0.4 seconds. The progress will display on the screen. Click the y-axis scale buttons to switch between linear and logarithmic view. Use the mouse wheel to scroll on the linear scale.

2. **Save the output file to your folder in the U drive in CSV format**. Double check that you saved the correct format. Once you clear the display, your data will be erased from the program.

3. (2 pt) Organize the data in a spreadsheet. Make a histogram of the number of counts measured over each interval.

4. (2 pt) Calculate the mean number of counts $\bar{C}_{bgd} \pm \delta\bar{C}_{bgd}$. Compare the standard deviation with that predicted by Poisson statistics ($\sigma = \sqrt{\bar{C}}$).

5. (1 pt) Calculate $\bar{R}_{bgd} \pm \delta\bar{R}_{bgd}$.

6. (1 pt) Explain exactly what the histogram and calculated numbers represent.

6 Count Rates

For the next two measurements, you will continue to use MCS-Internal mode. Press the X button to clear the display. Your objective for this section is to perform statistical analyses of ^{137}Cs and ^{60}Co count rates.

1. (3 pt) Place the ^{60}Co source on the top shelf. With the dwell time set to 0.4 s, record the activity for the full 1024×0.4 seconds. **Save the output file to your folder in the U drive in CSV format**. Organize the data in a spreadsheet. Make a histogram of the number of counts measured over each interval.

2. (2 pt) Calculate the mean number of counts $\bar{C} \pm \delta\bar{C}$. Compare the standard deviation with that predicted by Poisson statistics ($\sigma = \sqrt{\bar{C}}$).

3. (2 pt) Calculate $\bar{R}_{Co} \pm \delta\bar{R}_{Co}$. Make sure you subtract the background rate determined in the previous section.

4. (7 pt) Repeat the process using the ^{137}Cs source. Include a properly-labeled histogram, $\bar{C} \pm \delta\bar{C}$, and $\bar{R}_{Cs} \pm \delta\bar{R}_{Cs}$.

5. (2 pt) Include a summary table with your results for each isotope, and interpret your findings. Quantify the precision of each set of measurements by calculating the fractional uncertainties.

7 Mass Attenuation Coefficients

Your final experiment is to study the effectiveness of different absorbers. To do this, you will operate the spectrometer in Pulse Height Analysis (PHA) mode. This is accessed through the *Mode* menu bar. All remaining measurements will be made using the ^{137}Cs source.

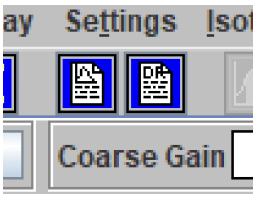
Reference values

Absorber	ρ (g/cm^3)	μ/ρ (cm^2/g)
Aluminum	2.70	7.802×10^{-2}
Lead	11.34	1.050×10^{-1}

1. (1 pt) Put the source on the 4^{th} shelf to ensure that you will have space to stack absorbers. Clear the screen with the X button and then press the green GO button to view the radiation energy spectrum. Allow the program to run for 10-15 sec. Then, from right to left, click and drag over the entire 660 keV photopeak to set a region of interest (ROI). This defines the energy range over which counts will be measured. Screenshot the spectrum and include a picture in your report with a description.

2. (1 pt) Measure four different thicknesses of aluminum. Organize your measurements into a table and add a column for the mass thickness, $z = \rho x$.

3. (2 pt) Now you will obtain the count rates for each thickness. Clear the screen on the spectrometer, then press the green GO button to begin a measurement. Run the detector for at least 1 minute per trial. Use the buttons shown below to view the count statistics. Record the Live Time, Gross Count, and Net Count for each thickness. Calculate $R \pm \delta R$ for each absorber thickness.



4. (3 pt) According to Equation 4, the event rates R have an exponential dependance on mass thickness z. Determine a way to linearize your data and obtain the mass attenuation coefficient using curve.fit. Label your plot axes, include a good title, and include horizontal and vertical error bars.

5. (7 pt) Repeat the procedure to obtain the mass attenuation coefficient for Lead. **Always wear rubber gloves while handling the lead absorbers.**

6. (4 pt) Include a summary table with the mass attenuation coefficients and uncertainties for both Al and Pb. Include the fractional uncertainties and percent errors. Interpret the meaning of your results. Which material is a more effective absorber? Why do you think the most sensitive particle detectors are placed deep underground?