Modern Physics Lab

Introduction to Nuclear Radiation **9/04**

Purpose of the Experiment

- become familiar with detectors for radioactive decay products
- apply statistical analysis techniques to data
- understand the interaction of nuclear radiation with matter

Introduction

Nuclear reactions in which a nucleus decays into a "daughter" nucleus and releases various low mass (or no mass) energetic particles is an important process for investigation in experimental nuclear physics. We typically look at the energetic particles which escape. The most common types to study are:

alpha particles - Helium nuclei (two neutron and two protons)
beta particles - electrons
gamma rays - high energy (short wavelength) electromagnetic radiation
neutrons - neutral, fundamental building block (along with protons) of a nucleus

In this lab we will study the interactions of beta and gamma radiation with matter.

PART 1: Measuring Nuclear Radiation

Beta and gamma radiation are often detected using a Geiger-Muller tube. The tube typically consists of a thin walled cylindrical metal tube with a tungsten wire running down the center of the cylinder and electrically insulated from the walls of the tube. The tube walls are grounded and the central wire is connected to a positive high voltage source as shown in Figure 1.

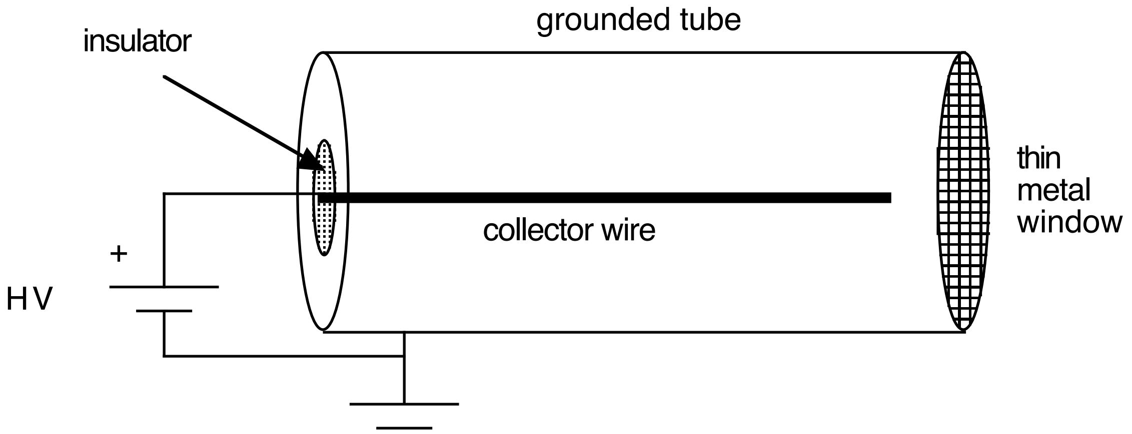

Figure 1. Geiger-Muller tube

Nuclear radiation enters the tube through then end of the cylinder opposite where the electrical contacts are made. The tube contains a noble gas such as argon. The entry end of the tube is covered with a thin metal window to contain the gas. This needs to be very thin to avoid absorbing a large fraction of the radiation (as we will see in a later part of this experiment). **Do NOT touch this window since it is easily broken.**

Alpha particles are so readily absorbed in the thin metal window that very few, if any, will be detected in a Geiger-Muller tube. When charged particles, such as beta particles, enter the tube they can ionize the noble gas atoms by knocking off an outer electron or two. These liberated electrons are then accelerated toward the positively charged central wire. If the voltage between the collector wire and the walls is sufficiently high, the electrons gain enough energy between collisions with gas atoms to cause additional ionizations of noble gas atoms. This chain-reaction, or avalanche effect, results in a large number of electrons reaching the collector wire for each beta particle that enters the tube. The result is a current pulse measurable by an external circuit.

The operation of the Geiger-Muller tube is complicated by the presence of the heavy noble gas ions which move much more slowly than the electrons. A cloud of ions in the vicinity of the central wire results in a “space charge” which effectively reduces the voltage.

If the applied voltage is not too high, each avalanche process would be expected to eventually self-terminate or “quench”. The excited gas atoms, however, can create additional electrons by emitting light which strikes the tube and causes photoelectric emission of electrons. To prevent these additional electrons from complicatiing the measurement, the tube contains a “quenching gas” which absorbs the light before it can produce significant photo-emission.

The external circuit is also designed to assist in quenching the discharge. The detection of a current pulse causes a reduction in the voltage applied to the tube. After each pulse, the voltage across the tube must be re-established. This requires about 200 microseconds and results in a “dead time” during which another ionizing particle which enters the tube will NOT be detected.

If the applied voltage on the tube is too large, then the avalanche will not be properly quenched and a continuous discharge can occur. This will damage the tube.

Gamma radiation can also be detected with a Geiger-Muller tube. The radiation causes photoelectric emission of electrons from the walls of the tube. These electrons can then be detected. This process is not particularly efficient and so only a few percent of the gamma rays which enter the tube result in a signal.

From the preceding discussion we expect the rate at which particles are detected to depend not only on the rate at which particles are incident on the tube, but also on the voltage that we apply to the tube. If we plot the detection rate against the applied voltage, we typically find a curve like that shown in Figure 2.

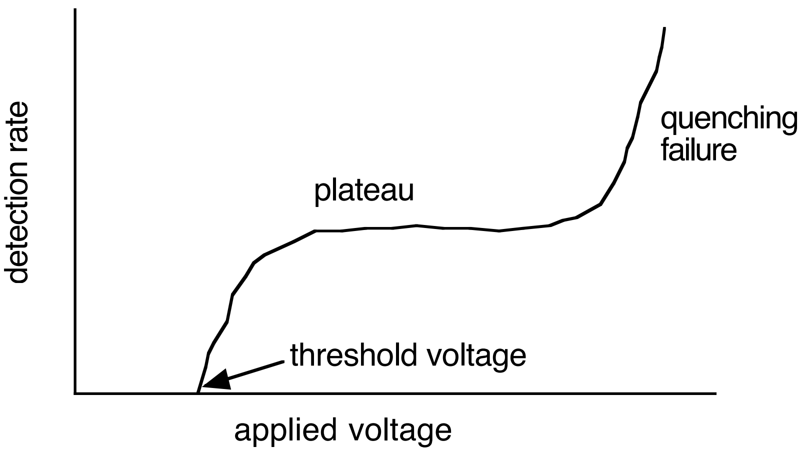

Figure 2. Variation in detection rate with applied voltage to tube

The graph clearly shows that we must apply a minimum voltage (threshold voltage) to the tube in order to detect any particles. There is then a range of voltages where the detection rate is relatively stable. At too high a voltage, quenching no longer occurs and a continuous discharge can set in. In order to use the tube, we need to determine what voltage to operate at. Since the plateau region produces a relatively stable detection rate, we will operate in that range of applied voltages.

Another complication of radiation detection is the existence of natural sources of radiation such as cosmic rays, rocks or concrete. This "background" radiation represents random events from many sources and is typically rather small - but measurable.

Experiment 1: Determination of the Operating Voltage of the Geiger-Muller tube

We will use a beta source to make a plot similar to Figure 2 and determine the optimum operating voltage for the particular Geiger-Muller tube which you are using. This value will vary for different tubes and different electronics, so you will want to make sure you use the same equipment if you continue this experiment on a second week. (You might even want to write down the serial number of the scaler since they all look alike!)

We do not want to recreate all of Figure 2, since running the tube at high voltages in the quenching failure region will damage it. You will need to plot your data as you collect it in order to find the plateau and stop the experiment before you reach the quenching failure.

Equipment needed:
    Geiger-Muller tube and scaler
    beta source

Procedure:

1. Place a Sr-90 beta source under the window of the Geiger-Muller tube.

2. Determine the threshold voltage: Set the count interval knob on the scaler to manual counting (MAN). Start at the lowest voltage settings (course and fine) on the scaler and gradually increase the voltage until the scaler begins to record events (usually between 200 and 400V). This is the threshold voltage. Use the COUNT, STOP and RESET buttons to collect data.

3. Now change the count interval knob on the scaler to count for one minute (+/- $1\text{x}10^{-6}$ sec). Measure the count rate for one minute at the threshold voltage and plot this point on a graph of count rate (counts/min) vs. applied voltage.

4. Increase the voltage by 20 V and measure the count rate for one minute. Plot this point. Repeat this procedure until you just reach the onset of quench failure. **Do not let the count rate rise more than 10% about the plateau level.** (If you are unsure, ask the instructor before you destroy the tube).

5. The normal operating voltage is about 50 volts above the lower end of the plateau. Determine this value and use it as your operating voltage in all subsequent experiments. For most of our detectors, this value will be in the 450 - 550 V range.

Experiment 2: Background Radiation

1. Remove the beta source from the vicinity of the Geiger-Muller tube.

2. Make 60 separate one-minute background counts. Your values will probably mainly be in the 10-20 counts/minute range.

Since the probability of any particular atoms giving a background count is very small, we can use this data to investigate the probability distribution of random events. Ideally we would take even more than 60 measurements, but this should be enough to approximate the data with a Poisson distribution.

Recommended analysis:

1. Construct a frequency distribution of the background count measurements. (How many measurements yielded one count, how many yielded two . . .). Plot a histogram of the data. Compute the mean value and standard deviation for your data.

2. Use a Poisson distribution to develop a theoretical curve to compare with your data. You might compare the mean value to the square of the standard deviation. These should be about equal if the data is really represented by a Poisson distribution. You will need to scale your theoretical curve to get it to fit your data. Appendix 4 of "A Practical Guide to Data Analysis for Physical Science Students" by L. Lyons (Cambridge University Press, NY, 1991) has a description of the Poisson distribution.

PART TWO: The Absorption of Beta and Gamma Radiation

As <u>beta particles</u> move through a solid, they interact with the atoms in the solid and lose energy. The energy loss as the particle travels a distance x is inversely related to the kinetic energy (E) of the particle.

$$\frac{dE}{dx} = -k\frac{1}{E}$$

The proportionality constant, k, depends on the material through which the particle is travelling. Intergrating this with the assumption that the particle had a kinetic energy E_o as it entered the material gives us

$$E^2 = E_0^2 - 2kx$$

This is the energy of the beta particle after travelling a distance x into a material.

We are often interested in the maximum penetration distance which occurs when E=0. This is clearly given by

$$x_{\max} = \frac{E_0^2}{2k}$$

Radioactive sources do not emit beta particles with just one energy. Particles escape from the source with energies varying from zero up to some maximum energy, E_{max}, which is characteristic of that isotope. (Why?)

This analysis works well for beta particles with E_o values up to about 0.1 MeV. Above this value we need to use a relativistic analysis which yields a result that the rate of energy loss approaches a constant value. In other words, the maximum penetration depth would increase linearly with energy for these higher energy particles.

The relationship between the beta particle energy and the maximum penetration depth is given in Figure 2. The constant, k, in the relationships depends primarily on the atomic density of the material. The graph presents the penetration depth in terms of (mg/cm^2). The density and thickness of material needed to equal 100 mg/cm^2 is provided in Table 1 for several common materials.

material	density (g/cm^3)	thickness (inches) for 100 mg/cm^2
polyethylene	0.96	0.0411
Al	2.70	0.0146
Cu	8.92	0.0044
Fe	7.86	0.0050
Pb	11.34	0.0035

Table 1. Beta absorption properties of common materials

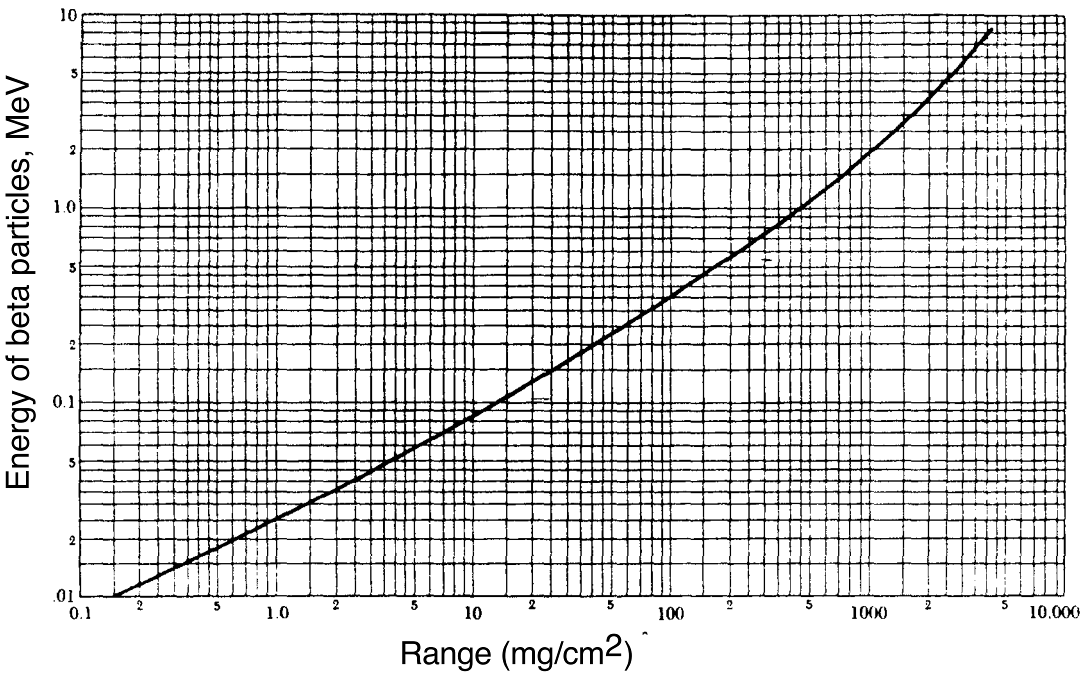

Figure 2. Kinetic Energy vs. maximum penetration depth for beta particles

Gamma radiation from the source that we will be using tends to come off with a single characteristic energy or discrete set of energies. When this radiation encounters matter, it tends to interact very strongly at one point rather than gradually losing energy over an extended range.

We will think of gamma radiation as particles (photons) for this lab. Each photon has a specific energy associated with it, and the energy of the photon is directly related to the light properties (such as wavelength) of the radiation.

The way in which a photon interacts with atoms in material varies depending on how energetic the incident photon is. At lower energies (below 1 MeV) the primary interaction is photoelectric scattering in which a photon is totally absorbed and an electron is knocked out of an atom. This is the energy range that we will be working in.

At higher energies a different type of interaction, known as pair production, dominates. In this interaction, the photon is absorbed and a pair of electron-like particles (one of matter, the other of anti-matter) are created. The matter particle is an electron which has a negative charge. The anti-matter particle is just like an electron except that the charge is positive. We call this particle a "positron". The electron-positron pair production needs a minimum energy of 1.02 MeV.

At intermediate energies (near 1MeV) a third mechanism, Compton scattering, can dominate the interaction between gamma radiation and matter. In this process, the photon is scattered from an electron, losing some of its energy and changing direction. Some of the sideways or backward scattered photons will not reach the G-M tube detector, thus reducing the count rate.

In this experiment, we will use a gamma source which has a characteristic energy around 1 MeV so that photoelectric scattering is the dominant absorption mechanism. With photoelectric scattering each gamma particle will interact only once, losing all of its energy in that single interaction. There is a certain small probability that this interaction will occur with each electron that the gamma particle passes.

The total flux of gamma rays, I, is thus decreased as a function of distance into the material, x, according to

$$dI / dx = - \mu I$$

where μ is the linear absorption coefficient. Integration of the above equation yields an expression for the flux inside the absorbing material

The flux of gamma particles decreases as they penetrate a distance, x, into an absorbing material as

$$I = I_o e^{-\mu x}$$

where I_o is the initial flux of gamma particles.

The linear absorption coefficient is proportional to the density of the absorber material so that a mass absorption coefficient μ_m is often defined according to

$$\mu_m = \mu / \rho$$

where ρ is the mass density of the absorbing material. Lead, a common absorber, has a density of 11.34 g/cm^3. The mass absorption coefficent depends on the energy of the incident gamma rays as shown in Figure 3.

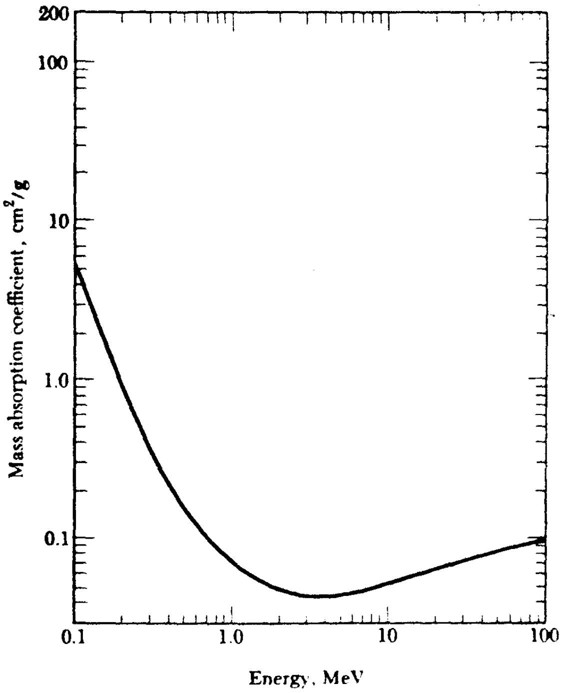

Figure 3. Mass absorption coefficient as a function of gamma ray energy.

Experiment 3: Absorption of Beta Particles

1. Place a Sr-90 beta source in the third slot of the plastic tray below the Geiger-Muller tube. Determine the count rate (counts/min). (You should see <u>at least</u> 1000 counts/minute!) Record this value. You might average several readings or measure for longer than a minute to get a good value. You decide what is appropriate.

2. Use the plastic absorber materials. (They behave much like the metals described earlier). Place the thinnest absorber on a slot between the source and the tube. Record the absorber thickness from the chart in the absorber set (in both inches and mg/cm^2) and the counting rate. Repeat this process for thicker absorbers. You can combine absorbers if needed. You will need at least 10 different thicknesses to get good results.

Recommended analysis:

Remember that you took background counts earlier in the lab and you should really subtract those values from your data here.

We want to compare our results to the theory discussed earlier, so we will need some graphs of the data to compare to theory. We could try to find the maximum penetration depth of beta particles into the plastic and the maximum energy at which Sr-90 emits beta particles.

To do this you might start by plotting the count rate (corrected) vs. absorber thickness (since this is pretty easy to do). You could try to read off from this graph the thickness at which the Count rate reaches zero - but that is not very easy to do. A more accurate method is to take the derivative of the data (change in count rate per change in thickness). This can be done using some plotting programs or spreadsheets. Otherwise you can go back to your plot of count rate vs. thickness and choose evenly spaced points to calculate the derivative by hand. If you plot the derivative vs. thickness, you should find a straight line relationship where the intercept of the x axis is x_{max}.

You can find the maximum energy of Sr-90 beta particles as well. First we need to find the energies that correspond to the maximum depth (in mg/cm^2) for each absorber using Figure 2. Next you can plot the counts vs. these energy values. Again the relationship should be linear with the maximum energy for Sr-90 being given by the intercept with the energy axis. (For comparison, the reported value is 0.546 MeV).

Experiment 4: Absorption of Gamma rays

1. Place a 0.3 inch thick Al absorber on the absorber tray in the second slot. The purpose of this is to remove the beta radiation, but still allow gamma rays through.

2. Place the Co-60 gamma/beta source on a tray in the third slot. Measure the number of counts with only the Al absorber in place above the source. Again you can decide how to make this measurement to get an accurate result. The detector is less efficient for gamma rays so your count rate will be much lower, probably in the 50-100 counts/minute range.

3. Measure the number of counts for a total of 10 thicknesses or combinations of thicknesses of
   the lead absorbers with a maximum thickness of 0.375 inches.
   Leave the Al absorber in place during the entire experiment.

Recommended analysis:

Remember to correct for background radiation.

We can determine the linear absorption coefficient μ from the slope of a line fitted to a plot of the corrected count rate vs. lead thickness on semi-log graph paper. [Be careful if you are using graphing programs to do this. Some of them will not calculate slope correctly on semilog graphs. For some programs you need to take the natural logarithm (ln) of each count rate and plot it against lead thickness on a linear scale in order to have the computer calculate the correct slope.] You can also calculate the mass absorption coefficient using the theory discussed earlier and the density of lead which is 11.34 g/cm^3.

Use the measured μ_m with the graph in Figure 3 to determine the characteristic gamma energy from this source and compare this energy (using a percent error calculation) with the established values of gamma energies for the Co-60 source which are 1.173 and 1.333 MeV.