PHYS 2LC: Lab 8  
Radioactivity  
(Includes Pre-Lab Assignment)

Objectives

These lab activities will focus on the concepts of radioactivity and the random nature of radioactive decay. Read all the steps in each part before you start. Work in your assigned groups and maintain a collaborative and communicative team.

The primary objectives for this lab are to give you familiarity working with a Geiger counter and to identify the three primary ways to work with radiation safely: minimize the time exposed to the source, maximize your distance from the source, and shield yourself from the source appropriately.

For the following activities, you will use a physics simulation program. Visit: https://uglabs.physics.ucr.edu/ for lab downloads and links.

Introduction

Radioactive decay and many other processes on nuclear scale are completely “random” in character. In particular, the occurrence of the spontaneous decay of radioactive nucleus is random in time. By “random” we mean that the probability of a single decay is completely independent of the time of the decay and of the behavior of the other nuclei that may be present.

Most radioactive processes can only happen once for a given radioactive nucleus, because it changes the nucleus into another state in the process (possibly a different radioactive state or even a different element). This means that for a given sample of radioactive material, the original radioactive substance is constantly being depleted. And since random decay is well modeled by exponential functions, we might write:
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\[ N(t) = N_0 e^{-\lambda t} \]

where \( N(t) \) is the number of nuclei of the original substance at time \( t \), \( N_0 \) is the number of nuclei at time \( t = 0 \) s, and the decay constant, \( \lambda \), is material-dependent and is positive because the amount of the substance is decreasing.

This relation also implies that the rate of decay must also look like an exponential:

\[ r(t) = r_0 e^{-\lambda t} \]

where \( r_0 \) is the rate of decay at time \( t = 0 \). The units of \( r \) are decays-per-second. While it is usually not feasible to measure the number of radioactive nuclei (\( N \)) at any given time, it is possible to measure decays and hence the decay rate. We can then use the rate to determine the decay constant and the half-life, \( t_{1/2} \).

Not all radiation or radioactive material is the same. As far as negative effects on humans, we are mainly concerned with ionizing radiation (radiation with enough energy to ionize particles). This includes ultraviolet rays (the source of sunburns), x-rays, gamma rays and cosmic rays.

Microwaves, for example, do not have enough energy to ionize particles. Instead the energy from excited molecules is transformed into heat.

The main types of radiation that occur during the decay of an atomic nucleus are alpha, beta, and gamma rays (heavy nuclei can also decay by spontaneous fission). Alpha particles are composed of two protons and two neutrons. Alpha particles pose minimal external threat as they cannot penetrate even a sheet of paper; the range of the most energetic alpha particle in air is about 10 cm. They can, however, cause serious internal damage if ingested. A beta particle is either an electron or a positron. Beta particles are lighter and faster and can penetrate farther. The energy of beta particles can vary, but most will have a range in air of about 1 foot. Gamma rays are transmitted by excited nuclei in their transition to lower-lying nuclear states, and often accompany alpha and beta decay. They have a long penetration depth and require careful shielding.

The average person is exposed to about 0.35 rem (350 millirems) per year from cosmic rays, medical and dental x-rays, televisions and computers, nuclear plants, weapon test fallout, etc. Over half of this is background radiation, from cosmic
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rays and from natural sources on earth. The majority of the rest of the radiation we are exposed to is from medical and dental x-rays. A typical chest x-ray exposes a person to 5 to 30 millirems. Fallout from old bomb tests and waste from the nuclear industry account for about 2% of the annual exposure. Coal power plants also produce significant amounts of radioactive waste.

General Safety: Radiation is not to be feared but to be respected. Many people work with and handle radioactive materials. These people abide by a set of safety rules and regulations for protection against the hazards of radiation. Either through ignorance or carelessness on the part of the experimenter, it is possible for radioactive material to gain entrance into the body via the hands to the eyes, nose, or mouth and then continue its dangerous activity from within the body.

1. Experimental Setup and Background Calibration

1.1: This simulation provides a Geiger counter, two radioactive sources, radiation shielding and power source for the detector. You will first calibrate this system and observe the background radiation due mainly to cosmic rays and natural sources on earth.
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1.2: You will use Strontium-90 as a calibration sample. Drag and drop it into the sample box below the tube.

1.3: You will now find the threshold voltage, the minimum voltage that will produce any counts with the detector tube. Set the Voltage Source to ~280 volts and press START under Both. Increase voltage until the detector begins to register counts. Once you see the counter active, begin to slowly reduce the voltage until you do not register any counts in a 30s period. That will be the threshold voltage, record it in your notebook.

1.4: Begin an Excel spreadsheet with columns for Voltage and Counts per Minute (CPM). CLEAR your existing data. The image below is a plot of sensor voltage and CPM; there are three distinct regions.

- The first slope is the linear increase in the sensitivity of the sensor. Before this line peaks, the sensor is not measuring all potential counts.
- The final data set on the line is due to over voltage in the sensor and counts no longer reflect a measure of radiation.
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- The plateau shows you where the count rate is approximately independent of the voltage. You will select a voltage value within this range and use it as your operating voltage for the remaining parts of the lab.

1.5: Starting with your threshold voltage, measure how many counts are registered in a minute. Record voltage and CPM in your spreadsheet. Repeat this measurement in 25v increments. Periodically plot the data to observe the construction of a data set similar to the image above.

Hint: A fair approximation is that you can measure for 30s and multiply by 2 to get CPM 😊.

1.6: Now use this operating voltage to measure the background radiation. Ensure that the sample chamber is empty and CLEAR all measurements. Set the voltage to your selected operating voltage and take a three-minute reading. Calculate and record your background radiation below in counts per minute. Repeat this procedure 3 more times. Calculate and record the mean counting rate and standard deviation (in counts/minute) in your notebook. This is the mean background counting rate from the environment. We will use this value as a correction in the upcoming sections of the experiment to make your measurements of radiation emitted from the source more precise.

Background Radiation _________ counts/min

2. Effect of Exposure Time on Radiation Counts

2.1: Prepare your Ba-137 source and place it under the Geiger counter. Ba-137 has a very short half-life, so work quickly, or too much Barium may decay before you can take measurements.
   a. To do this begin by moving the Cs-137 minigenerator over to the empty blue planchette.
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b. Pull down on the plunger of the syringe to chemically separate Ba-137 from the Cs-137. We call this process “milking” Ba-137 from the Cs-137 source.
c. Quickly move the now filled blue planchette over to the Geiger counter (in lab you would need to be careful as you do this not to spill any of the radioactive Ba-137).
d. Click “Start” for both the timer and the counter.
e. Record the counts at the 0-, 1-, 2-, and 3-minute marks in your lab notebook.
f. At the 3-minute mark, hit stop.

2.2: Draw a graph showing the collection time on the horizontal axis and the total radiation counts on the vertical axis. You should have four data points: 3 minutes through 0 minutes. Note that the total radiation counts after three minutes is the sum of all collected counts up to that point. The sensor is detecting the cumulative number of counts per second. For each data point, subtract the background counting rate (counts/min.) found in 1.3 multiplied by the number of seconds elapsed for that point.

2.3: Approximately how many radiation counts would expect the sensor to collect if left in the same configuration for 60 minutes? 120 minutes? Would that many counts be considered dangerous if you absorbed them instead of the counter? Explain.

2.4: You are using a Cs-137 radiation source with an “activity” level of 5 µCi that emits primarily beta particles with energy 0.5120 MeV. Use the equation below to calculate the total beta-radiation exposure you would experience in 3 hours of lab work with this radioactive source.

\[ H = 5.55 \times 10^{-3} \frac{AE}{r^2} \]

Here, \( H \) is the equivalent dose rate in mrem/hr, \( A \) is the activity of the sample in Ci, \( E \) is the energy of the emitted radiation in eV, and \( r \) is the average distance from the source during the exposure in meters. For comparison, you would be exposed to approximately 3.5 millirems if you were to fly from the east coast to the west coast of the United States.
3. Effect of Shielding on Radiation Counts

3.1: You first need a measurement for the radiation counting rate with no shielding above the source. Use the mean counting rate (with the background counting rate subtracted) from the data collected in 2.1 as this data point so you don’t need to repeat the measurement.

3.2: The simulation will have some aluminum disks to use as shielding. Using one disk (.02 cm thick), click record and stop data collection after 3 minutes. Record the mean counting rate and standard deviation both after subtracting the background counting rate. Repeat the measurement again with two, three, and then four aluminum disks.

3.3: Calculate the total thickness of the aluminum disks and make a table of shield thickness vs. counting rate. Draw a graph that shows the shield thickness on the horizontal axis and the counts per minute on the vertical axis. You should have five data points corresponding to 0 disks through 4 disks.

3.4: Draw a smooth line through your data points and estimate the shielding thickness needed to reduce the counts by a factor of two. This is called the “half value thickness”. Discuss any uncertainties in your measurements.

3.5: In step 2.4, you estimated the total beta-radiation exposure you will experience in 3 hours of lab work with the Cs-137 source working from the assumption that the emitted radiation was primarily in the form of beta particles. After these shielding experiments, how valid do you think that assumption was? Explain.

4. Effect of Distance on Radiation Counts

You have seen inverse square laws in both mechanics and E&M. In mechanics, you saw the gravitational force was related to the separation between two astronomical objects like:
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\[ F_G = G \frac{Mm}{r^2} \]

In E&M, you saw the electrical force was related to the separation between two charges like:

\[ F_E = k_e \frac{q_1 q_2}{r^2} \]

In this section, you will determine if the inverse square law holds true for nuclear radiation. *i.e.* Is the radiation counting rate inversely proportional to the square of the distance from the source?

4.1: In Simulation #2 a point source of β radiation. A person standing 130 ft away experiences 2.217 mR/hr dose of radiation. Start a new tab in your Excel spreadsheet and record these values.

4.2: Move the person in ~30 ft increments toward the source and record data at each iteration.

4.3: Make a scatterplot of Distance v. Dose.

4.4: Next, fit the data set with a curve of best fit. Add a trendline (more options), with a power function. Display the equation on the chart and write the equation down in your lab report.

How well does the inverse square model fit the data?

4.5: *Thought Experiment:* Like in the models used in gravitation and electricity and magnetism above, we know that there must be some constant of proportionality between counting rate, \( r \), and the separation distance from the source, \( d \), *i.e.* \( r(t) = C \frac{1}{d^2} \). Given your responses to 4.4, formulate a hypothesis to describe what this constant of proportionality, call it \( C \), must depend on.

4.8 Write a short summary of today’s activities. Please include the following:
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- What experimental parameters help protect those who work regularly with radioactive materials and why?
- Radioactive decay is an inherently random process. How precise were your radiation counting measurements? What could you do to increase the precision of your measurements?
- The radioactive samples you used are not brand new. How did the relative age of the sample affect your measurements?
The rate of decay for a radioactive sample changes over time – an atom can only decay once. The half-life of a radioactive nucleus is a measure of the amount of time it takes for half of the nuclei in a given sample to undergo radioactive decay. This is convenient because it is the same regardless of how many undecayed nuclei are in a sample. For example, if you start with 800 undecayed Cs-137 nuclei, after one half-life has elapsed, there will be 400 undecayed nuclei, then after another half-life has elapsed, there will be 200 undecayed nuclei, and so on.

1. The radioactive source you will be working with in this lab is Cs-137. Look up the half-life of this material and report the value in units of seconds.

2. The relationship between decay constant (λ) and half-life is:

   \[ t_{1/2} = \frac{\ln 2}{\lambda} \]

   For Cs-137, what is the value of \( \lambda \) in \( \text{s}^{-1} \)?

3. If you start at \( t = 0 \) with a decay rate of \( r = 1000 \) Cs-137 decays per second, how many decays per second would you expect to find after 30 s? After 300 s? After 1000 s?