# Lab 12. Radioactivity

## Goals

- To gain a better understanding of naturally-occurring and man-made radiation sources.
- To use a Geiger-Müller tube to detect both beta and gamma radiation.
- To measure the amount of background radiation from natural sources.
- To test whether the radiation intensity from a physically small radiation source decreases as one over the distance squared. (The light intensity from a single incandescent light bulb decreases according to this same inverse-squared law as one moves away from it.)
- To compare our ability to shield beta and gamma radiation.
- To understand the meaning of the term “half-life” by simulating the decay process and calculating the half-life in arbitrary time units.

## Introduction

The nucleus of an atom consists of protons and neutrons. Since the protons are positively charged and confined to a very small space, they exert strong repulsive electrical forces on each other. Another force of nature, called the strong nuclear force, binds all the components of the nucleus together. Neutrons also help keep the nucleus together by increasing the distance between protons. As with electrons in atoms, however, the nucleus wants to be in its lowest energy state. If it is in an excited state, having too many protons or neutrons, it will spontaneously rearrange itself, giving off particles and/or energy in the process. This process is called radioactive decay or, simply, radioactivity. The three most common types of radiation resulting from this decay process are alpha, beta, and gamma radiation. These names are just the first three letters of the Greek alphabet—not very imaginative.

Alpha particles are just nuclei of helium-4 atoms. Because they are relatively large particles and electrically charged, they interact easily with matter. Most alpha particles are blocked by human skin, but they can be dangerous if the radioactive material is ingested into the body. Beta particles are simply electrons. Gamma particles, commonly called gamma rays, are high-energy photons, the same particles as visible light but of a much higher energy. They penetrate matter most easily.

# Safety

## Radiation sources

The radiation sources used in this lab are "exempt" sources, meaning that anybody can purchase them and use them without a special license. Although the radiation from exempt sources is not particularly hazardous, the basic principles of minimizing radiation dose should be followed:

- Do not eat, drink, or apply cosmetics while handling the sources.
- Do not hold sources longer than necessary; do not put sources in pockets.
- Hold the disks by their edges. Avoid touching the unlabeled flat sides of the disks.
- Place sources away from living organisms with the printed label facing up when not in use.
- Wash hands after handling sources (after the laboratory).

In keeping with campus radiation safety policies, we require you to view a short presentation on radiation safety prior to working with any radioactive sources.

## Geiger-Müller tube

A Geiger-Müller tube (also called a Geiger tube or a Geiger counter) is used to measure beta and gamma radioactivity. The tube is filled with a low-pressure gas and contains two electrodes with a potential difference of typically 500–1000 V between them. An incoming particle ionizes some of the gas, freeing electrons from the gas atoms, and initiates a gaseous discharge, or "spark." The potential difference across the electrodes drops precipitously during the discharge and is detected by external circuitry as a "count."

**Caution: The "end window" on the bottom end of the Geiger-Müller tube, where the particles actually enter the tube, is thin and fragile. Do not touch it or poke anything at it! If the window is broken, the tube becomes inoperable.**

# Background radiation

Nuclei are disintegrating around us all the time. This includes nuclei in our own bodies. To make quantitative measurements of radioactivity from a source, the ever-present, randomly occurring background radiation must be independently determined and then subtracted from the radiation measured with the source present. The difference gives the intensity of the radiation from the source alone. With the radioactive sources removed far from the Geiger-Müller tube, count the background radiation in the laboratory room for at least 100 seconds and display it in a table using Captstone. Record the mean value of the counts/second and the standard deviation. Increase the precision of the data in the table to display more digits. (Ask your TA how to do this if you don't remember!) Also display the data in the form of a histogram. This shows the number of times one gets zero counts in a one-second time interval, the number of times one gets one count in a one-second time interval, and so on. Note the random variation about the average value. Comment on the range of counts/second displayed on the histogram or shown on the table of data.

On the last page of this lab is a radiation dose worksheet published by the US Nuclear Regulatory Commission. You can use it to estimate your annual radiation exposure in millirems. You can download a copy for yourself at:

http://www.nrc.gov/reading-rm/basic-ref/teachers/average-dose-worksheet.pdf

More information, including an interactive radiation dose calculator, can be found at:

http://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html

## Beta radiation—Effect of distance and shielding

Place the thallium-204 (thallium with mass number 204, or $^{204}$Tl) source directly under the Geiger-Müller tube. This source only emits beta particles with energies of 0.7634 MeV (1eV $= 1.602 \times 10^{-19}$J). Set the initial distance from the top of the active source to the end window of the Geiger tube to 2 cm. Record the mean and standard deviation of the count rate (counts/s) for this geometry. Keep the histogram of the data stored in the computer. Now increase the distance from the source to the end of the Geiger tube to 2.5 cm and repeat the data collection. Repeat for larger distances; 3, 4, 6, and 10 cm. As the count rate changes how are the shapes of the histograms altered?

If all the emitted beta particles come from a single point, then we should expect the number of detected particles to drop as the detector is moved away from the source. The magnitude of the electric field due to a point charge drops in a similar fashion as you move away, falling as $1/r^2$, where $r$ is the distance to the charge. Similarly the intensity (brightness) of a light bulb decreases as $1/r^2$ as you move farther away. Use your data to test the hypothesis that the count rate decreases in proportion to one over the square of the distance from the source to the detector. Explain your method, justify why it is a valid method, and discuss your findings. Suggestion: expressing the distances in centimeters gives easier numbers to graph.

Another way to reduce the intensity of radiation from radioactive sources is shielding. Cobalt-60 emits beta and gamma radiation while thallium-204 is strictly a beta emitter. Different types of radiation are affected by different types of shielding, so that one material may be useful as a shield for certain types of radiation, while not as useful for other types. In a few specialized applications, the wrong kind of shielding can be worse than no shielding at all.

Carefully place a lead sheet on top of the thallium-204 source with the end of the Geiger tube mounted about 4 cm above the lead. Record the mean and standard deviation of the count rate. Compare this count rate with your measured background count rate. How good is the lead sheet in shielding the detector from the beta radiation?

Place a thin white plastic square on top of the source and repeat the measurement? How well do beta particles penetrate through the plastic?

# Beta radiation with gamma radiation—Effect of shielding

Place the Co-60 ($^{60}Co$) source about 2 cm from the end of the Geiger-Müller tube. Each radioactive decay of the cobalt nucleus yields one 0.3179 MeV beta particle, one 1.1732 MeV gamma ray, and a 1.3325 MeV gamma ray. Count the source for 100 seconds and record the mean and standard deviation of the count rate.

Now place the thin white plastic square on top of the source and repeat the measurement and record the results. Remove the plastic sheet and place one lead sheet on top of the source and repeat the measurement process. Add another lead sheet and repeat. What thickness of lead will block half of the gamma radiation produced by this source? Justify your method and explain your results.

Now it is easy to understand how shielding radiation workers from alpha and beta particles is relatively simple, but that shielding from gamma rays is much more difficult.

# Half-life simulation

Since the radioactive decay of a nucleus occurs spontaneously and the probability of any one kind of nucleus decaying is the same for all of them, the decay rate (number per unit time) is directly proportional to the total number of radioactive nuclei present at any given time. In other words, if you have ten million radioactive nuclei, the decay rate is twice as great as when you have five million nuclei. In this experiment we are going to simulate the decay process using white beans to represent undecayed nuclei and colored beans to represent decayed nuclei. We will assume that approximately 10% of the nuclei radioactively decay during a time interval of one bn. (We will measure time in arbitrary bn units, where bn is an abbreviation for bean.) The simulation is constructed so that if we start out with 100% of our sample, we will have $0.9 \times 100\% = 90\%$ of our sample left undecayed after a time of 1 bn. After a time of two bns has elapsed we will have $0.9 \times 90\% = 81\%$. Note that $81\% = 0.9^2 \times 100\%$. Following this pattern it is easy to see that after a time of $n$ bns has passed, the remaining undecayed sample will be $(0.9)^n \times 100\%$. The term “half-life” refers to the elapsed time at which half of the original sample of undecayed nuclei is present.

Note that the decay rate, $R$, the number of nuclei decaying in a time interval of one bn, follows the same pattern as the total number of undecayed nuclei. In other words we expect that the decay rate after $n$ one-bn time intervals will be $(0.9)^n \times R_0$, where $R_0$ is the initial decay rate. Similarly when the decay rate drops to half of its original value, a time interval of one “half-life” has elapsed. At your laboratory station you will find a container with 200–240 g of beans in it. Ten percent of the beans are colored indicating that they are “decayed” nuclei. An electronic balance is also present at each station.

## Data acquisition

1. Find the initial decay rate, $R_0$, by pouring all of the beans into a flat pan and counting the number of colored beans. Count carefully!
2. Pour all of the beans back in the original container and make sure that the colored beans are

mixed as randomly as possible. (A pencil or pen can serve as a suitable stirring rod.) The decay rate, $R_1$, after a one-bn time interval is found by transferring 10% of the beans to a second container. Then count the colored beans in the remaining 90%. A shallow pan is provided to make the counting process easier.

3. Pour all of the beans back in the original container and make sure that the colored beans are mixed as randomly as possible. The decay rate, $R_2$, after a two-bn time interval is found by dumping out 19% of the beans into a second container and counting the colored beans in the remaining 81% ($0.9^2 \times 100\%$). Failure to follow this procedure can bias your data significantly, because random variations in your first choice of beans affect all your other measurements. In radioactive materials, the decayed atoms are not replaced—but the number of radioactive nuclei is enormous; over human time scales, the effect of this bias is quite small.

4. Repeat the procedure of Step 3 to find $R_3, R_4, \ldots R_{15}$. You should have sixteen data points in all, counting $R_0$.

## Data analysis

1. Use Excel to plot a graph of the decay rate as a function of time in bn units. Plot the rate, $R_0$, at the time $t = 0$

2. Assuming that the uncertainty of the decay rate value is simply the square root of the value, add vertical error bars to the graph in Step 1 using Excel. (While the square root assumption is good for most radioactivity counting experiments, not all of the necessary criteria are met in our simulation; it is only a reasonable approximation. Ask your TA for help if you are unfamiliar with adding "custom" error bars in Excel.)

3. To determine whether or not the graph made in the previous two steps is actually an exponential function of the form $y = ae^{bx}$, you must use the technique found near the end of the "Uncertainty/Graphical Analysis Supplement" at the back of your lab manual. If the function is an exponential of the form given, plotting the natural logarithm of $y$, $\ln y$, on the vertical axis and $x$ on the horizontal axis as usual will result in a straight line. For this experiment, $y$ is the radioactive decay rate, $R$, and $x$ is the time in bn units. Such a graph is called a "semi-log" graph. If the graph is reasonably linear, then we can be quite certain that the decay rate and time are related by an exponential mathematical function of the simple form given with a slope $= b$ ($b < 0$ in our case) and a vertical axis intercept $= \ln a$. Calculate the natural logarithms of your sixteen rate values and plot them on another graph as a function of time in bn units using Excel. The syntax in Excel for calculating natural logarithms is ln(number).

4. Add a "trend line" by right clicking on one of the data point symbols on the graph. A linear trend line is the default. Under the "Options" tab, check the box for "Display equation on graph." The trend line is a so-called "least squares fit" calculated by minimizing the square of the vertical differences between points on the line and the actual data points corresponding to the same value of $x$.

5. To give a better idea of whether a straight line fit is justifiable, appropriate vertical error bars

need to be added to the semi-log graph. It is tempting but incorrect to use the $\ln(R^{1/2})$ as the uncertainty estimate. The reason is that $\ln(R+R^{1/2}) \neq \ln(R)+\ln(R^{1/2})$. Consequently, to calculate the "positive" part of the error bar one must use $[\ln(R+R^{1/2})-\ln(R)]$. The "negative" part of the error bar is calculated similarly using $[\ln(R)-\ln(R-R^{1/2})]$. Use Excel to do these calculations. Then add the vertical error bars to the graph.

### Half-life calculation

After the time of one half-life has elapsed, the decay rate, $R = R_0/2$, by definition, where $R_0$ is the initial decay rate. As you have hopefully demonstrated with your graphs, the decay rate can be written in the following mathematical form (see your textbook):

$$R = R_0 \exp(-\lambda t) \tag{12.1}$$

where $t$ is the elapsed time and $\lambda$ (the "decay constant") is a positive constant. The half-life is often denoted symbolically as $T_{1/2}$. When $t = T_{1/2}$, $R = R_0/2$. Therefore Equation 12.1 may be rewritten as:

$$\frac{R_0}{2} = R_0 \exp(-\lambda T_{1/2}) \qquad \text{or simply} \qquad \frac{1}{2} = \exp(-\lambda T_{1/2}) \tag{12.2}$$

Remember that the decay constant $\lambda$ is determined by the negative of the slope of the straight-line fit to the semi-log graph. Refer to the lab manual appendix referenced earlier for the details. Now all that remains is to solve for the half-life, $T_{1/2}$. The simplest way to remove the exponential in Equation 12.2 is to take the natural logarithm of both sides of the equation. This maintains the equality. So:

$$\ln(0.5) = -\lambda T_{1/2} \tag{12.3}$$

Equation 12.3 can easily be solved for $T_{1/2}$. Remember that your calculated half-life value is in time units of "bns."

## Summary

Comment on your findings about the behavior of beta and gamma particles with regards to shielding and the source-detector distance.

How "good" is your value of half-life? In other words how precise is it? The Regression function of Excel can provide an error estimate rather simply. Follow the instructions given on the last two pages of the "Computer Tools Supplement" near the end of your lab manual. The Regression function can give you the uncertainty (called the "standard error" in Excel) of the slope of your semi-log graph. This is the uncertainty in $\lambda$. Then the maximum and minimum values of the half-life can be calculated using the "maximum-minimum method" of propagating the uncertainty. (See the "Uncertainty/Graphical Analysis Supplement" toward the end of the lab manual for the details if you have forgotten.) Now summarize these results and clearly state the conclusions that you can draw.

Before you leave the lab please:
Straighten up your lab station.
Report any problems or suggest improvements to your TA.