

Geiger Counter Measurement of the Half-Life of ^{137}Ba

Purpose:

This laboratory will use a short-lived ^{137}Ba isotope and a Geiger counter to accomplish the following objectives:

- Measurement of the activity of the ^{137}Ba source as a function of time.
- Determination of the half-life of the ^{137}Ba from the activity versus time data.

Equipment:

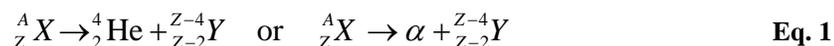
- Radiation Monitor (Geiger Counter)
- ^{137}Ba Source and Eluting Solution
- Disposable Planchet
- Logger-Pro, ULI, etc.

Theory:

Atoms are composed of a nucleus containing neutrons and protons surrounded by a cloud of electrons. A given chemical element contains a fixed number of protons in the nucleus but possibly differing numbers of neutrons. The forms of a given element having different numbers of neutrons are called *isotopes* of this element. The complete description of all aspects of a given isotope is given by the symbols ${}^A_Z X_N$ where X stands for the chemical symbol of the element, Z is the number of protons which is called the atomic number, N is the number of neutrons, and A is called the mass number where $A = Z + N$. As an example the symbol ${}^{226}_{88}\text{Ra}_{138}$ stands for the isotope of radium with 88 protons and 138 neutrons, and thus 226 neutrons plus protons. Other isotopes of radium must also have 88 protons but can have a different number of neutrons. Usually the number of neutrons is not displayed explicitly and the symbol is given as ${}^{226}_{88}\text{Ra}$. It is inferred from this symbol that the number of neutrons is $226 - 88 = 138$.

Some nuclei are unstable and decay spontaneously into other nuclei. There are three different types of processes that occur naturally and produce natural radioactivity. In addition, there are a large number of radioactive isotopes that are produced by nuclear reactions for isotopes that no longer appear naturally. Many such isotopes are available commercially for many practical uses. Presumably all the man-made radioactive isotopes were naturally occurring at one time, but they decayed away because their half-lives were much shorter than the age of the earth. For all types of radioactivity the process is identified by the type of particle produced in the decay.

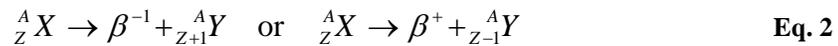
Alpha decay is a process by which an unstable nucleus ejects a particle called an alpha particle. In fact an alpha particle is really just a twice ionized ${}^4_2\text{He}$ atom. Thus an alpha particle is just the nucleus of an ${}^4_2\text{He}$ atom consisting of the two protons and two neutrons left when the two electrons have been removed from a neutral atom. The process in which a radioactive nucleus ${}^A_Z X$ decays by alpha decay is described by



where the symbol α stands for the alpha particle or ^4_2He nucleus produced. As an example of alpha decay consider the case when the radioactive nucleus is $^{226}_{88}\text{Ra}$.

According to Eq. 1, the decay produces an alpha particle and a daughter nucleus of $^{222}_{86}\text{Rn}$.

Beta decay is a process taking place inside the nucleus which essentially amounts to either a neutron being turned into a proton or a proton being turned into a neutron. When this process happens either an electron or anti-electron (called a positron) is produced. When the particle produced is an ordinary electron, it is called a β^- and when the particle produced is a positron, it is called a β^+ . The process in which a radioactive nucleus $^A_Z X$ decays by one of the beta decay events is described by one of the equations shown below:



Actually, Eqs. 2 are not complete. In each case there is in fact another particle created called a neutrino or an antineutrino. These particles interact very weakly with matter and are extremely difficult to detect. They could not be detected by the detection process that will be used in today's laboratory. As an example of Eqs. 2 the radioactive nuclide $^{40}_{19}\text{K}$ decays both by β^+ and β^- . In the case of β^- decay the daughter nucleus is $^{40}_{20}\text{Ca}$ and in the case of β^+ decay the daughter nucleus is $^{40}_{18}\text{Ar}$. Many nuclides that undergo beta decay only do so by one of the processes.

Gamma decay is a process in which a nucleus that has an excess of energy lowers its energy state by the emission of a high energy photon called a gamma ray. The process is very much analogous to the process whereby excited atoms lose energy when they emit visible light photons. The decay is described by



where the * indicates the excess energy, and γ is the symbol for a gamma ray or photon. Note that when gamma emission occurs there is no change in the nucleus as far as the number of protons or neutrons. Only the energy of the nucleus is altered.

A basic concept of radioactive decay is that the probability of decay for each type of radioactive nuclide is constant. In other words, there are a predictable number of decays per second even though it is not possible to predict which nuclei among the sample will decay. A quantity called the decay constant λ characterizes this concept. It is the probability of decay per unit time for one radioactive nucleus. The fundamental concept is that because λ is constant, it is possible to predict the rate of decay for a radioactive sample. The value of the constant λ is, of course, different for each radioactive nuclide.

Consider a sample of N radioactive nuclei with a decay constant of λ . The rate of decay of the nuclei $\frac{dN}{dt}$ is related to λ and N by the equation

$$\frac{dN}{dt} = -\lambda N \quad \text{Eq. 4}$$

The symbol $\frac{dN}{dt}$ stands for the rate of change of N with time t . The minus sign in the equation means that $\frac{dN}{dt}$ must be negative because the number of radioactive nuclei is decreasing. The number of radioactive nuclei at $t = 0$ is designated as N_o . The question of interest is how many radioactive nuclei N are left at some later time t . The answer to that question is found by rearranging Eq. 4 and integrating it, subject to the condition that $N = N_o$ at $t = 0$. The result of that procedure is:

$$N = N_o e^{-\lambda t} \quad \text{Eq. 5}$$

Eq. 5 states that the number of nuclei N at some later time t decreases exponentially from the original number N_o that are present. A second question of interest is the value of $\frac{dN}{dt}$ of the radioactive sample. That can be found by substituting the expression for N from Eq. 5 back into Eq. 4. The result is

$$\frac{dN}{dt} = -\lambda N_o e^{-\lambda t} \quad \text{Eq. 6}$$

Furthermore, the expression for $\frac{dN}{dt}$ in Eq. 4 can then be substituted into Eq. 6 leading to

$$\lambda N = \lambda N_o e^{-\lambda t} \quad \text{Eq. 7}$$

The quantity λN is called the activity of the radioactive sample. Since λ is the probability of decay for one nucleus, the quantity λN is the number of decays per unit time for N nuclei. Typically λ is expressed as the probability of decay per second and so in that case, λN is the number of decays per second from a sample of N nuclei. The symbol A is used for activity ($A = \lambda N$) and thus Eq. 7 becomes

$$A = A_o e^{-\lambda t} \quad \text{Eq. 8}$$

Eqs. 5 and 8 state that both N , the number of nuclei, and A , the activity, decay exponentially according to the same exponential factor. For measurements made on real radioactive nuclei the activity A is usually measured. Another useful form of Eq. 8 can be derived by inverting the equation and taking the natural logarithm of both sides of the equation leading to

$$\ln(A_o/A) = \lambda t \quad \text{Eq. 9}$$

An important concept associated with radioactive decay processes is the concept of half-life. The time for the sample to go from the initial number of nuclei N_o to one-half that value $N_o/2$ is defined as the half-life $t_{1/2}$. If Eq. 5 is solved for the time t when $N = N_o/2$ the result is

$$t_{1/2} = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda} \quad \text{Eq. 10}$$

This same result could also be obtained by considering the time for the activity to go from A_0 to $A_0/2$.

In order to study these radioactive processes, it is necessary to be able to detect the presence of these particles that are the product of the decay. Although there are many forms in which devices can be constructed to accomplish the detection, they all have one feature in common. Every practical device that detects radiation does so by allowing the particles to interact with matter, and then uses that interaction as the basis for detection. The particular device that will be used in this laboratory is called a Geiger counter. It consists of a tube in which the incident particle interacts and a scaling circuit to count the pulses. A diagram of a Geiger tube is shown in Fig. 1.

The Geiger tube is a small metal cylinder with a thin self-supporting wire along the axis of the cylinder. The wire is insulated from the cylinder. The cylindrical wall of the tube serves as the negative electrode (cathode), and the wire along the axis is the positive electrode (anode). At the entrance end of the tube there is a thin “window” formed by a very thin piece of fragile mica. Inside the counter is a special gas mixture that is ionized by any radiation that penetrates the “window”.

In operation a voltage is applied across the electrodes. The applied voltage creates a large electric field in the tube and the field is especially large in the region near the central wire. When radiation passes through the window and ionizes the gas, the large electric field causes an acceleration of the free electrons. These accelerated electrons cause additional ionizations creating what is referred to as an “avalanche” effect. The total number of ion-electron pairs created by a single incident particle is of the order of one million.

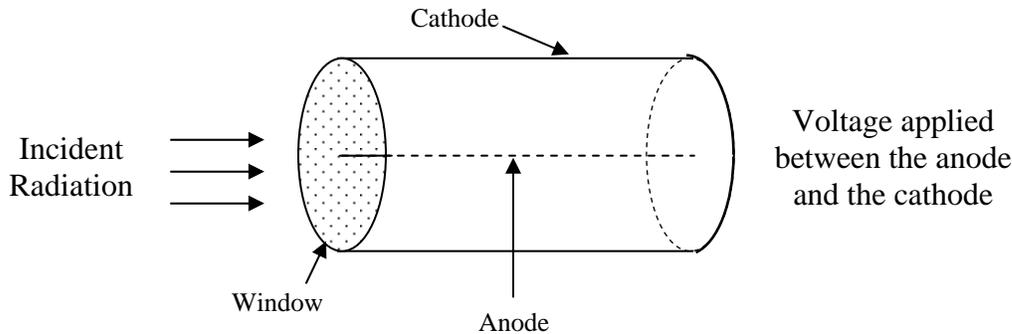


Figure 1 Diagram of the essential elements of a Geiger tube.

The electrons are more mobile and drift toward the positive central wire. When they arrive at the wire their negative charge causes the voltage of the wire to be lowered, and this sudden drop in voltage creates a pulse which is counted by the electronic circuitry. Each pulse counted signifies the passage of a particle through the counter. The ions recombine with electrons, leaving the gas neutral again and ready for the passage of another particle. The whole process takes a time of the order of 300 microseconds, and during that time if another particle goes through the counter, it may not be counted. Thus one disadvantage of Geiger counters is the “dead time” during which counts may be missed. This is a negligible effect unless the count rate is very high.

In conducting half-life experiments it is desirable to use an isotope whose half life is short enough that multiple half-lives can be measured during a laboratory period. The problem with this is that within a relatively short period of time, the usefulness of the sample is gone. This problem is solved by the *Spectech* Cs/Ba-137m Isotope Generator:

A small quantity ($<10\mu\text{Ci.}$) of radioactive Cs-137 is bound on a special ion exchange medium. The Cs-137 parent isotope beta decays with a 30.17y half-life to produce Ba-137m which in turn decays with a 2.55min half-life, generating a 661.6keV gamma ray emission. This gamma ray may be readily detected using a GM or scintillation radiation detector.

An eluting solution is used to selectively extract the Ba-137 isotope from the exchange medium leaving the parent Cs-137 isotope in place to generate more Ba-137. Equilibrium is re-established in less than 1 hour.

Approximately 30 minutes after elution, the residual activity of the Ba-137 solution has decayed to less than 1/1000 of its original activity making it safe for normal disposal.

Experiment:

Part A: Halflife of Ba 137

1. Connect the AC adapter to the LabPro by inserting the round plug on the 6-volt power supply into the side of the interface. Shortly after plugging the power supply into the outlet, the interface will run through a self-test. You will hear a series of beeps and blinking lights (red, yellow, then green) indicating a successful startup.
2. Attach the LabPro to the computer using the USB cable that is Velcro-ed to the side of the computer box (do not unplug the USB cable from the computer!). The LabPro computer connection is located on the right side of the interface. Slide the door on the computer connection to the right and plug the square end of the USB cable into the LabPro USB connection.
3. Connect a Radiation Monitor to a digital port (DIG/SONIC1) on the LabPro. The digital ports, which accept British Telecom-style plugs with a left-hand connector, are located on the same side as the computer connections. You will probably need to use the digital adapter (phono to British Telecom) to connect the radiation monitor. Make sure you do not have the radiation monitor with a note on it's back saying that it does not work with Logger Pro.
4. Open the **Experiments** folder on the desktop and open the file **radiation.xmbl** (or **.cml**). This will start the program *Logger Pro3.3* and bring up the appropriate data file. If you do not have an auto-ID sensor (which is the likely case), a dialog box will pop up asking you to confirm the sensors being used. If you have the suggested sensor attached to the LabPro in the suggested port, click "OK". If the "OK" button is not active, ask your instructor for help.
5. We now need to determine the amount of background radiation. With no radioactive source near the window of the radiation monitor, click the **Collect** button and collect data for 300 seconds (5 minutes). The file should be set up to automatically collect

data in 5-second intervals. When you have reached the end of the collection time, use the **Analyze > Examine** function to determine the average number of radiation counts per interval.

6. Go to **Experiment > Data Collection > Collection** and change the length of the experiment to 600 seconds (10 minutes).
7. The ^{137}Ba isotope must be prepared at the time of its use because it has such a short half-life. You must be completely ready to take data before getting your sample. You should set the radiation monitor on its end so that the Geiger window points upward (toward the ceiling). You will be placing the planchet directly on the screen protecting Geiger window, being **VERY CAREFUL** not to spill the isotope. Any radioactive substance spilling into the window will ruin the Geiger counter.
8. Obtain the isotope sample from your instructor. Gently place the planchet on the radiation monitor. Immediately click **Collect**. Now sit back and let the computer take data.
9. When you are done, carefully remove the planchet from the radiation monitor. Pour the remaining liquid down the sink and thoroughly rinse and dry the planchet.
10. Repeat the entire procedure, if required by your instructor.

Analysis:

Part A: Half life of Ba 137

1. Copy the *time* and *radiation* data into Graphical Analysis so that you can manipulate the data. Double-click on each column heading to re-name the column. The unit of *time* is *seconds*, and *radiation* has no units.
2. To subtract the average background radiation counts per time interval from each *radiation* data point, go to **Data > New Calculated Column**. In the dialog box that pops up, title the new column *counts*, and in the **Equation** area choose **Variables > radiation**, then subtract your number of background counts.
3. Plot a graph of *counts vs. time*. You will work with this set of data to determine the half-life of ^{137}Ba .
4. Remember that the half-life is defined as the time it takes for *half* of the original sample to decay. The number of nuclei, N , is directly related to the activity, A , which is essentially what you have graphed. You can make a direct estimate of the half life, and its uncertainty, by finding the time, $t_{1/2}$, at which $A(t) = 1/2 A_0$.
5. Determine, from your data, how to find λ , the decay probability. Determine also, the uncertainty in λ .
6. Once you have the decay probability, you can calculate the half-life from Eq. 10.

7. Calculate the percent difference between the half-life determined in Step 4, and that determined in Step 6.
8. Do your values for $t_{1/2}$ agree within uncertainties?

Results:

Write at least one paragraph describing the following:

- what you expected to learn about the lab (i.e. what was the reason for conducting the experiment?)
- your results, and what you learned from them
- Think of at least one other experiment might you perform to verify these results
- Think of at least one new question or problem that could be answered with the physics you have learned in this laboratory, or be extrapolated from the ideas in this laboratory.

This experiment was adapted from:

David H. Loyd. *Physics Laboratory Manual*, 2nd Edition. Orlando, FL: Harcourt, Inc, 1992.
Experiment 45.

Clean-Up:

Before you can leave the classroom, you must clean up your equipment, and have your instructor sign below. How you divide clean-up duties between lab members is up to you.

Clean-up involves:

- Completely dismantling the experimental setup
- Removing tape from anything you put tape on
- Drying-off any wet equipment
- Putting away equipment in proper boxes (if applicable)
- Returning equipment to proper cabinets, or to the cart at the front of the room
- Throwing away pieces of string, paper, and other detritus (i.e. your water bottles)
- Shutting down the computer
- Anything else that needs to be done to return the room to its pristine, pre lab form.

I certify that the equipment used by _____ has been cleaned up.

(student's name)

_____, _____.

(instructor's name)

(date)