What is Radiation?

This section will give you some of the basic information from a quick guide of the history of radiation to some basic information to ease your mind about working with radioactive sources. More information is contained in the introduction parts of the laboratory experiments in this manual.

Historical Background

Radiation was discovered in the late 1800s. Wilhelm Röntgen observed undeveloped photographic plates became exposed while he worked with high voltage arcs in gas tubes, similar to a fluorescent light. Unable to identify the energy, he called them "X" rays. The following year, 1896, Henri Becquerel observed that while working with uranium salts and photographic plates, the uranium seemed to emit a penetrating radiation similar to Röntgen's X-rays. Madam Curie called this phenomenon "radioactivity". Further investigations by her and others showed that this property of emitting radiation is specific to a given element or isotope of an element. It was also found that atoms producing these radiations are unstable and emit radiation at characteristic rates to form new atoms.

Atoms are the smallest unit of matter that retains the properties of an element (such as hydrogen, carbon, or lead). The central core of the atom, called the nucleus, is made up of protons (positive charge) and neutrons (no charge). The third part of the atom is the electron (negative charge), which orbits the nucleus. In general, each atom has an equal amount of protons and electrons so that the atom is electrically neutral. The atom is made of mostly empty space. The atom's size is on the order of an angstrom (1 Å), which is equivalent to 1×10^{-10} m while the nucleus has a diameter of a few fermis, or femtometers, which is equivalent to 1×10^{-15} m. This means that the nucleus only occupies approximately 1/10,000 of the atom's size. Yet, the nucleus controls the atom's behavior with respect to radiation. (The electrons control the chemical behavior of the atom.)

Radioactivity

Radioactivity is a property of certain atoms to spontaneously emit particles or electromagnetic wave energy. The nuclei of some atoms are unstable, and eventually adjust to a more stable form by emission of radiation. These unstable atoms are called radioactive atoms or isotopes. Radiation is energy emitted from radioactive atoms, either as electromagnetic (EM) waves or as particles. When radioactive (or unstable) atoms adjust, it is called radioactive decay or disintegration. A material containing a large number of radioactive atoms is called either a radioactive material or a radioactive source. Radioactivity, or the activity of a radioactive source, is measured in units equivalent to the number of disintegrations per second (dps) or disintegrations per minute (dpm). One unit of measure commonly used to denote the activity of a radioactive source is the Curie (Ci) where one Curie equals thirty seven billion disintegrations per second.

$$1 \text{ Ci} = 3.7\text{x}10^{10} \text{ dps} = 2.2\text{x}10^{12} \text{ dpm}$$

The SI unit for activity is called the Becquerel (Bq) and one Becquerel is equal to one disintegration per second.

$$1 \text{ Bq} = 1 \text{ dps} = 60 \text{ dpm}$$

Origins of Radiation

Radioactive materials that we find as naturally occurring were created by:

1. Formation of the universe, producing some very long lived radioactive elements, such as uranium and thorium.
2. The decay of some of these long-lived materials into other radioactive materials like radium and radon.
3. Fission products and their progeny (decay products), such as xenon, krypton, and iodine.

Man-made radioactive materials are most commonly made as fission products or from the decays of previously radioactive materials. Another method to manufacture radioactive materials is activation of non-radioactive materials when they are bombarded with neutrons, protons, other high-energy particles, or high-energy electromagnetic waves.

Exposure to Radiation

Everyone on the face of the Earth receives background radiation from natural and man-made sources. The major natural sources include radon gas, cosmic radiation, terrestrial sources, and internal sources. The major man-made sources are medical/dental sources, consumer products, and other (nuclear bomb and disaster sources).

Radon gas is produced from the decay of uranium in the soil. The gas migrates up through the soil, attaches to dust particles, and is breathed into our lungs. The average yearly dose in the United States is about 200 mrem/yr. Cosmic rays are received from outer space and our sun. The amount of radiation depends on where you live; lower elevations receive less (~25 mrem/yr) while higher elevations receive more (~50 mrem/yr). The average yearly dose in the United States is about 28 mrem/yr. Terrestrial sources are sources that have been present from the formation of the Earth, like radium, uranium, and thorium. These sources are in the ground, rock, and building materials all around us. The average yearly dose from these sources in the United States is about 28 mrem/yr. The last naturally occurring background radiation source is due to the various chemicals in our own bodies. Potassium (^{40}K) is the major contributor and the average yearly dose in the United States is about 40 mrem/yr.

Background radiation can also be received from man-made sources. The most common is the radiation from medical and dental x-rays. There is also radiation used to treat cancer patients. The average yearly dose in the United States is about 54 mrem/yr. There are small amounts of radiation in consumer products, such as smoke detectors, some luminous dial watches, and ceramic dishes (with an orange glaze). The average yearly dose in the United States is about 10 mrem/yr. The other man-made sources are fallout from nuclear bomb testing and usage, and from accidents such as Chernobyl. That average yearly dose in the United States is about 3 mrem/yr.


SPECTECH
ST360 COUNTER
COUNTS
TIME
RATE
HIGH VOLTAGE
ALARM POINT
COUNT
STOP
RESET
DISPLAY SELECT
DOWN
UP
Spectrum Techniques

Equipment

Lab #1: Plotting a GM Plateau

Objective:

In this experiment, you will determine the plateau and optimal operating voltage of a Geiger-Müller counter.

Pre-lab Questions:

1. What will your graph look like (what does the plateau look like)?
2. Read the introduction section on GM tube operation. How does electric potential effect a GM tube's operation?

Introduction:

All Geiger-Müller (GM) counters do not operate in the exact same way because of differences in their construction. Consequently, each GM counter has a different high voltage that must be applied to obtain optimal performance from the instrument.

If a radioactive sample is positioned beneath a tube and the voltage of the GM tube is ramped up (slowly increased by small intervals) from zero, the tube does not start counting right away. The tube must reach the starting voltage where the electron "avalanche" can begin to produce a signal. As the voltage is increased beyond that point, the counting rate increases quickly before it stabilizes. Where the stabilization begins is a region commonly referred to as the knee, or threshold value. Past the knee, increases in the voltage only produce small increases in the count rate. This region is the plateau we are seeking. Determining the optimal operating voltage starts with identifying the plateau first. The end of the plateau is found when increasing the voltage produces a second large rise in count rate. This last region is called the discharge region.

To help preserve the life of the tube, the operating voltage should be selected near the middle but towards the lower half of the plateau (closer to the knee). If the GM tube operates too closely to the discharge region, and there is a change in the

Name: ______________________________ Lab Session: ____________________
Date: ______________________ Partner: ________________________

Data Table for Geiger Plateau Lab

Tube # ____________________

Voltage	Counts

Voltage	Counts

Don't forget to hand in this data sheet with a graph of the data.

Lab #8: Inverse Square Law

Objective:

The student will verify the inverse square relationship between the distance and intensity of radiation.

Pre-lab Questions:

1. Write a general mathematical expression for an inverse square law.
2. What are other examples of inverse square laws?

Introduction:

As a source is moved away from the detector, the intensity, or amount of detected radiation, decreases. You may have observed this effect in a previous experiment, **Shelf Ratios Lab**. If not, you have observed a similar effect in your life. The farther you move away from a friend, the harder it is to hear them. Or the farther you move away from a light source, the harder it is to see. Basically, nature provides many examples (including light, sound, and radiation) that follow an inverse square law.

What an inverse square law says is that as you double the distance between source and detector, intensity goes down by a factor of four. If you triple the distance, intensity would decrease by a factor of nine. If you quadruple the distance, the intensity would decrease by a factor of 16, and so on and so on. As a result, if you move to a distance d away from the window of the GM counter, then the intensity of radiation decreases by a factor $1/d^2$.

Equipment:

- Set-up for **ST-360** Counter with GM Tube and stand (Counter box, power supply – transformer, GM Tube, shelf stand, USB cable, and a source holder for the stand) – shown in Figure 1.

Name: ____________________ Lab Session: ____________________
Date: ________________ Partner: ____________________

Data Sheet for Inverse Square Law Lab

Tube #: ______________ Run Duration: ____________
Dead Time: ______________ (Time)

Counts	Corr. Counts	Distance	1/d^2

Counts	Corr. Counts	Distance	1/d^2

Don’t forget to hand in a graph of the data with this table.

Lab #10: Absorption of Beta Particles

Objective:

The student will investigate the attenuation of radiation via the absorption of beta particles.

Pre-lab Questions:

1. How does activity of a source vary with distance?
2. How do you predict activity will vary with increasing absorber thickness, when an absorber is placed between the source and window of the GM tube?

Introduction:

Beta particles are electrons that are emitted from an atom when a neutron decays by the weak force. The neutron (n) becomes a proton (p), an electron (e^-), and an anti-neutrino ($\bar{\nu}$)[1]. When an electron originates in the nucleus, it is called a beta particle.

$$n \rightarrow p + e^- + \bar{\nu} \tag{1}$$

Unlike alpha particles that are emitted from the nucleus with the same energy (~5 MeV), beta particles are emitted with a range of energies between 0 MeV and the maximum energy for a given radioactive isotope. The velocity of a beta particle is dependent on its energy, and velocities range from zero to about 2.9 x 10^8 m/s, nearly the speed of light. So the beta particles do not all have the same kinetic energy and thus they do not all have the same range. When the range varies over different values, this is called range straggling. It represents the different energy losses all of the beta particles have given their different initial values. Figure 1 shows a typical absorption curve for beta particles, which illustrates the range straggling.

[1] The purpose of the anti-neutrino's creation is to carry off extra energy and momentum for the conservation of those quantities.

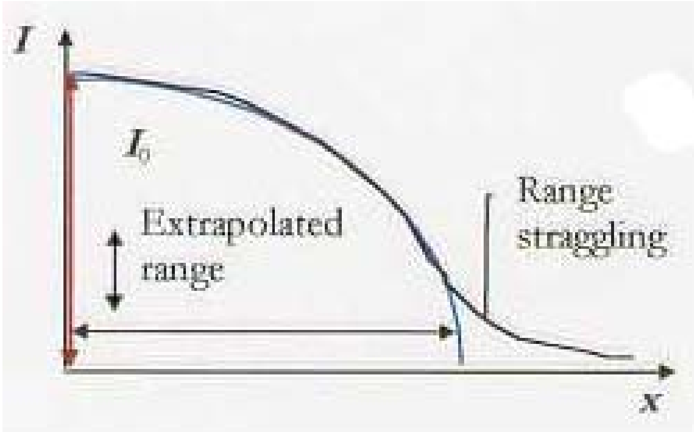

Figure 1: Typical absorption curve for beta particles. Plot is of intensity (activity) vs. absorber thickness (x)

Equipment:

- Set-up for **ST-360** Counter with GM Tube and stand (Counter box, power supply – transformer, GM Tube, shelf stand, USB cable, and a source holder for the stand) – shown in Figure 2.

Figure 2: Setup for ST360 with sources and absorber kit.

Name: ______________________ Lab Session: ______________________

Date: ______________ Partner: ______________________

Data Sheet for Beta Absorption Lab

Tube #: ______________ Run Duration: ______________

Dead Time: ______________ (Time)

Counts	Corr. Counts	Thickness	ln (Counts)

Don’t forget to hand in a graph of the data with this table.

Lab #11: Beta Decay Energy

Objective:

The student will determine the maximum energy of decay of a beta particle.

Pre-lab Questions:

1. What is the decay mechanism for beta decay? Why are there three decay products?
2. What are the units of thickness for an absorber?
3. Why shouldn't a beta source be placed below the third shelf? Or above the second shelf?

Introduction:

When beta particles are emitted from a nucleus, they are emitted over a wide range of energies. Recall that this is different from alpha particles, which are emitted monoenergetically. The maximum energy of the emitted beta particles is a characteristic signature for different radioisotopes.

In this experiment, you will find the range of beta particles by measuring their attenuation[1] with absorbers and extrapolating the absorption curve. The range R will then be substituted into the formula

$$E_{\beta} = 1.84R + 0.212 \tag{1}$$

where R is in g/cm^2. (Note that the units for R are not the same as the absorber thicknesses. You must convert at the end.) See Figure 1 for an example of an energy curve for beta particles.

[1] Attenuation is a term used for the exponential decrease of a quantity.

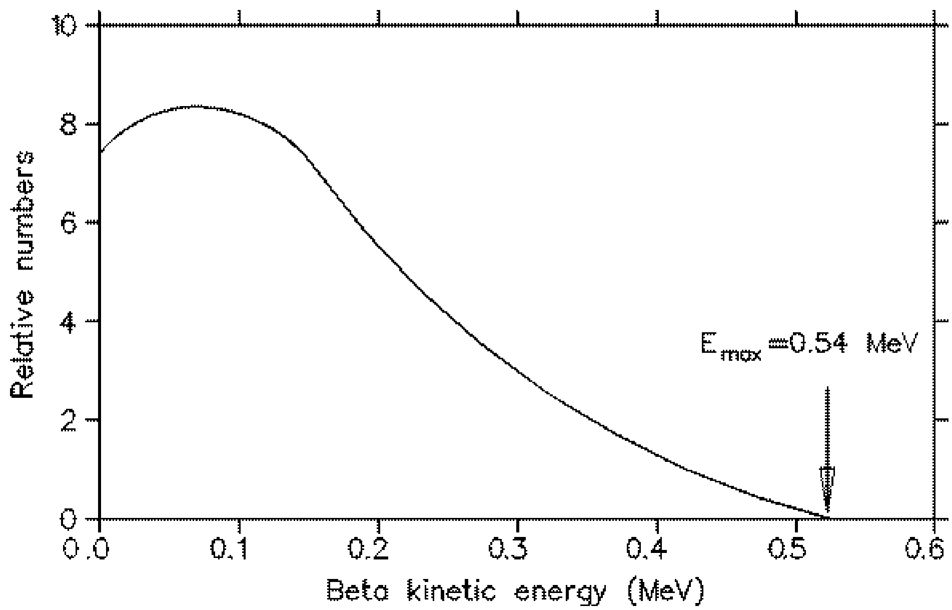

Figure 1: Typical plot of beta particle energy curve.

The spectrum is not linear and "tails" off at high energy, which means that there are very few beta particles (This effect is seen with the phenomenon of range straggling, which was observed in the absorption curve in the previous experiment.) The reason is that most of the beta particles cannot penetrate the absorber and most of the counts are background counts. Thus, one must assume linearity and extrapolate the line to the x-axis. There are two options to finding this x-intercept. The first is to find an equation for the best-fit line of the data in slope-intercept form, $y = mx + b$. Then set $y = 0$ and solve for the x value, since the x-intercept is the point on the line where the y – coordinate is zero. The second method is to take a copy of the plot and use a rule to continue the linear part of the data through the x-axis and finding that point.

Equipment:

- Set-up for **ST-360** Counter with GM Tube and stand (Counter box, power supply – transformer, GM Tube, shelf stand, USB cable, and a source holder for the stand) – shown in Figure 2.
- Radioactive Source (beta sources – Sr-90 or Tl-204 are recommended) – green source shown in Figure 2.

Lab #13: Half-Life of Ba-137m

Objective:

The student will measure the half-life of metastable Barium-137.

Pre-lab Questions:

1. Explain how you will obtain Ba-137m from the isotope generator.
2. Draw the decay diagram for the process you describe in #1.
3. If a Sr-90 source has a count rate of 7020 cpm today, when will it have a count rate of 1404 cpm? The half-life of Sr-90 is 28.6 yrs. When will Po-210 reach 1404 cpm from 7020 cpm (half-life for Po-210 is 138 days)?
4. If a Tl-204 source has 1.34 x 10^{21} atoms today. When will it have 1.675 x 10^{18} atoms? The half-life for Tl-204 is 3.78 years.

Introduction:

The decay of radioactive atoms occurs at a constant rate. There is no way to slow it down by maybe refrigeration or to accelerate the process with heat. The rate of decay is also a constant, fixed rate regardless of the amount of radioactive atoms present. That is because there are only two choices for each atom, decay or don't decay. Thus, the amount of radioactive atoms we have on hand at any time is undergoing a consistent, continuous change.

The change in the number of radioactive atoms is a very orderly process. If we know the number of atoms present and their decay constant (probability of decay per unit time), then we can calculate how many atoms will remain at any future time. This can be written as the equation

$$N(t) = N - \lambda N \Delta t \quad , \qquad (1)$$

where N(t) is the number of atoms that will be present at time t, N is the number of atoms present currently, λ is the decay constant, and Δt is the elapsed time. If the number of radioactive atoms remaining is plotted against time, curves like those in Figure 1 can be obtained. The decay constant can be obtained from the slope of these curves (discussed more below).

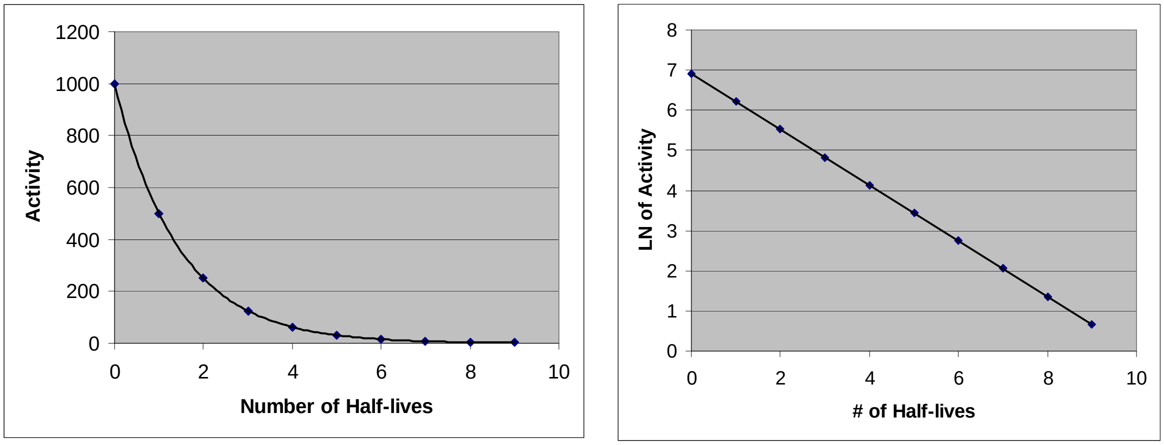

Figure 1: Exponential and Linear decay curves shown respectively

A more common way of expressing the decay of radioactive atoms is the **half-life**. The half-life of a radioactive isotope is the time required for the disintegration of one-half of the atoms in the original sample. In the graphs in Figure 1, 1000 atoms were present at t = 0. At the end of one half-life, 500 atoms were present. At the end of two half-lives, 250 atoms were present, one-quarter of the original sample. This continues on and on, and example of what happens in the first nine half-lives is shown in Table 1.

# of Half-lives	Activity	Percent	Fraction
0	1000	100%	1
1	500	50%	1/2
2	250	25%	1/4
3	125	12.5%	1/8
4	62.5	6.25%	1/16
5	31.25	3.125%	1/32
6	15.625	1.563%	1/64
7	7.8125	0.781%	1/128
8	3.90625	0.391%	1/256
9	1.953125	0.195%	1/512

Table 1: Table of Example of Radioactive Decay

Since the observed activity of a sample as detected by a Geiger counter is proportional to the number of radioactive atoms, it is not necessary to know exactly how many atoms are present to determine either the half-life or the decay constant. Any quantity of sample providing a suitable activity may be used. The derivations presented below use the number of radioactive atoms but could very easily be substituted with activity, since activity $= \frac{\# of\ counts}{time} = \frac{\# of\ atoms}{time}$. (Each count of a GM tube represents one atom decaying and releasing one particle or ray of radiation.)

Looking back at Equation (1) in a slightly rearranged form

$$N(t) - N = -\lambda N \Delta t \, . \quad (2)$$

But *N(t)-N* is just the change in the number of radioactive isotopes of the original type present, so we can define

$$\Delta N = N(t) - N = -\lambda N \Delta t \, . \quad (3)$$

Dividing both sides of the equation gives

$$\frac{\Delta N}{\Delta t} = -\lambda N \, , \quad (4)$$

but in calculus[1] we write changes, especially small, or infinitesimal, changes as

$$\frac{dN}{dt} = -\lambda N \, . \quad (5)$$

This is a separable differential equation that becomes

$$\frac{dN}{N} = -\lambda dt \, , \quad (6)$$

which can be solved by integrating both sides. When we do this we impose limits for the integrals[2], and pull λ out of the integral because it is a constant. The limits for *dN'/N'* are from N_o to *N*, which is from the initial number of particles (N_o) to the new amount of particles (*N*). The limits for *dt* are from the beginning, where *t=0*, to the end

$$\int_{N_o}^{N} \frac{dN'}{N'} = -\lambda \int_0^t dt' \, . \quad (7)$$

The solution to this equation is

$$\ln(N) - \ln(N_o) = -\lambda t \, . \quad (8)$$

Solving for ln(N), gives

$$\ln(N) = \ln(N_o) - \lambda t \, . \quad (9)$$

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1 If you have not had Calculus yet, do not worry about the details of the derivation. Concentrate on the second part where natural logarithms are used. You should have this knowledge to perform the lab.

2 We have to change *dN/N* to *dN'/N'* because one of the limits is *N,* and we are not allowed to have a limit that is the same as the differential (*dN* part). For the same reason, we change *dt* to *dt'*. This is a basic substitution.

Thus, if we plot the natural log of the number of atoms (or activity) versus time, we will get a straight line with slope = $-\lambda$ and y-intercept = $\ln(N_o)$. This would allow us to find the decay constant. Why?

We will need the decay constant in the next step, which is to find the half-life of the radioactive isotope we are studying. Starting from Equation (8) and applying a simple logarithmic identity, we get

$$\ln\left(\frac{N}{N_o}\right) = -\lambda t \, . \tag{10}$$

If we are considering the half-life, then N is one-half of N_o (reduced ratio) and t is $t_{1/2}$. This changes our equation to be

$$\ln\left(\frac{1}{2}\right) = -\lambda t_{1/2} \, . \tag{11}$$

Applying the reverse of our previous logarithmic identity, we get

$$\ln(1) - \ln(2) = -\lambda t_{1/2} \, . \tag{12}$$

The ln(1) = 0, so now we have

$$-\ln(2) = -\lambda t_{1/2} \, . \tag{13}$$

Finally, we can solve for the half-time

$$t_{1/2} = \frac{\ln(2)}{\lambda} \, . \tag{14}$$

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Name: ______________________ Lab Session: ______________________
Date: ______________________ Partner: ______________________

Data Sheet for Half-Life Lab

Tube #: ______________ Run Duration: ______________
Dead Time: ______________ (Time)

Counts	Corr. Counts	ln(Counts)	Time
			30
			60
			90
			120
			150
			180
			210
			240
			270
			300
			330
			360
			390
			420
			450

(Background Count)

Data Sheet for Half-Life Lab (Cont'd)

Counts	Corr. Counts	ln(Counts)	Time
			480
			510
			540
			570
			600
			630
			660
			690
			720

Data	λ	$t_{1/2}$	**Error**	**# of σ's**
First Half				
Second Half				
Whole				

Don't forget to hand in a graph of the data with this table.