Spectrum Techniques

Lab Manual
Student Version

Revised, September 2014

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Student Usage of Lab Manual

This manual is written to help students learn as much as possible about radiation and some of the concepts key to nuclear and particle physics. This manual in particular is written to guide you through a laboratory experiment set-up. The lab manual has the following layout:

- Detailed background material on radiation, the Geiger-Müller counter and its operation, and radiation interaction with matter.
- Thirteen laboratory experiments with instructions, data sheets, and analysis instruction.

A piece of standalone equipment from Spectrum Techniques may not be entirely equipped for the laboratory environment. Additional resources and recommendations are made in the teacher's notes of the experimental write-ups for schools that wish to run the specific experiments. Also, schools operate on different class schedules, varying from 42-minute periods to 3-hour lab sessions. Thus, the labs are written with flexibility to combine them in different manners (our suggestions are listed below).

The lab manual is not intended to be a "recipe" book but a guide on how to obtain the data and analyze it to answer certain questions. What this means is that explicit directions as to every single button to push are not given, but the student will have guidance where this can be inferred.

NOTE: All directions in this laboratory manual assume the use of a PC computer with Microsoft Excel® used for the experiments. Any manual operation has the appropriate directions given in the product manual. All operations listed in the directions below may be carried out on the screen of the Spectrum Techniques equipment. Also, all instructions use the **ST-360** model Geiger-Müller counter, but the other models, **ST-160** and **ST-260**, have similar functions available.

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.

Adding up the naturally occurring and man-made sources, we receive on average about **360 mrem/yr** of radioactivity exposure. What significance does this number have since millirems have not been discussed yet? Without overloading you with too much information, the government states the safety level for radiation exposure **5,000 mrem/yr**. (This is the Department of Energy's Annual Limit.) This is three times below the level of exposure for biological damage to occur. So just living another year (celebrating your birthday), you receive about 7% of the government regulated radiation exposure. If you have any more questions, please ask your teacher.

The Geiger-Müller Counter

Geiger-Müller (GM) counters were invented by H. Geiger and E.W. Müller in 1928, and are used to detect radioactive particles (α and β) and rays (γ and x). A GM tube usually consists of an airtight metal cylinder closed at both ends and filled with a gas that is easily ionized (usually neon, argon, and halogen). One end consists of a "window" which is a thin material, mica, allowing the entrance of alpha particles. (These particles can be shielded easily.) A wire, which runs lengthwise down the center of the tube, is positively charged with a relatively high voltage and acts as an anode. The tube acts as the cathode. The anode and cathode are connected to an electric circuit that maintains the high voltage between them.

When radiation enters the GM tube, it will ionize some of the atoms of the gas[*]. Due to the large electric field created between the anode and cathode, the resulting positive ions and negative electrons accelerate toward the cathode and anode, respectively. Electrons move or drift through the gas at a speed of about 10^4 m/s, which is about 10^4 times faster than the positive ions move. The electrons are collected a few microseconds after they are created, while the positive ions would take a few milliseconds to travel to the cathode. As the electrons travel toward the anode they ionize other atoms, which produces a cascade of electrons called gas multiplication or a (Townsend) avalanche. The multiplication factor is typically 10^6 to 10^8. The resulting discharge current causes the voltage between the anode and cathode to drop. The counter (electric circuit) detects this voltage drop and recognizes it as a signal of a particle's presence. There are additional discharges triggered by UV photons liberated in the ionization process that start avalanches away from the original ionization site. These discharges are called Geiger-Müller discharges. These do not effect the performance as they are short-lived.

Now, once you start an avalanche of electrons how do you stop or quench it? The positive ions may still have enough energy to start a new cascade. One (early) method was external quenching, which was done electronically by quickly ramping down the voltage in the GM tube after a particle was detected. This means any more

electrons or positive ions created will not be accelerated towards the anode or cathode, respectively. The electrons and ions would recombine and no more signals would be produced.

The modern method is called internal quenching. A small concentration of a polyatomic gas (organic or halogen) is added to the gas in the GM tube. The quenching gas is selected to have a lower ionization potential (~10 eV) than the fill gas (26.4 eV). When the positive ions collide with the quenching gas's molecules, they are slowed or absorbed by giving its energy to the quenching molecule. They break down the gas molecules in the process (dissociation) instead of ionizing the molecule. Any quenching molecule that may be accelerated to the cathode dissociates upon impact producing no signal. If organic molecules are used, GM tubes must be replaced as they permanently break down over time (after about one billion counts). However, the GM tubes included in Spectrum Techniques® set-ups use a halogen molecule, which naturally recombines after breaking apart.

For any more specific details, we will refer the reader to literature such as G.F. Knoll's *Radiation Detection and Measurement* (John Wiley & Sons) or to Appendix E of this lab manual.

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[*] A γ-ray interacts with the wall of the GM tube (by Compton scattering or photoelectric effect) to produce an electron that passes to the interior of the tube. This electron ionizes the gas in the GM tube.

Good Graphing Techniques

Very often, the data you take in the physics lab will require graphing. The following are a few general instructions that you will find useful in creating good, readable, and usable graphs. Further information on data analysis are given within the laboratory write-ups and in the appendices.

1. Each graph **MUST** have a TITLE.

2. Make the graph fairly large – use a full sheet of graph paper for each graph. By using this method, your accuracy will be better, but **never more accurate that the data originally taken**.

3. Draw the coordinate axes using a **STRAIGHT EDGE**. Each coordinate is to be labeled including **units** of the measurement.

4. The NUMERICAL VALUE on each coordinate MUST INCREASE in the direction away from the origin.

   Choose a value scale for each coordinate that is easy to work with. The range of the values should be appropriate for the range of your data.

   It is NOT necessary to **write** the numerical value at each division on the coordinate. It is sufficient to number only a few of the divisions. **DO NOT CLUTTER THE GRAPH.**

5. Circle each data point that you plot to indicate the uncertainty in the data measurement.

6. CONNECT THE DATA POINTS WITH A <u>BEST-FIT</u> **SMOOTH CURVE** unless an

    abrupt change in the slope is JUSTIFIABLY indicated by the data.

    DO NOT PLAY CONNECT-THE-DOTS with your data! All data has some

    uncertainty. Do NOT over-emphasize that uncertainty by connecting each point.

7. Determine the slope of your curve:

    (a) Draw a slope triangle – use a <u>dashed line</u>.

    (b) Your slope triangle should **NOT** intersect any data points, just the best-fit curve.

    (c) Show your slope calculations right on the graph, e.g.,

    $$slope = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1} = answer$$

    BE CERTAIN TO INCLUDE THE UNITS IN YOUR SLOPE CALCULATIONS.

8. You may use pencil to draw the graph if you wish.

9. Remember: **NEATNESS COUNTS.**

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

performance of the tube. Then you could possibly operate the tube in a "continuous discharge" mode, which can damage the tube.

Geiger Plataeu
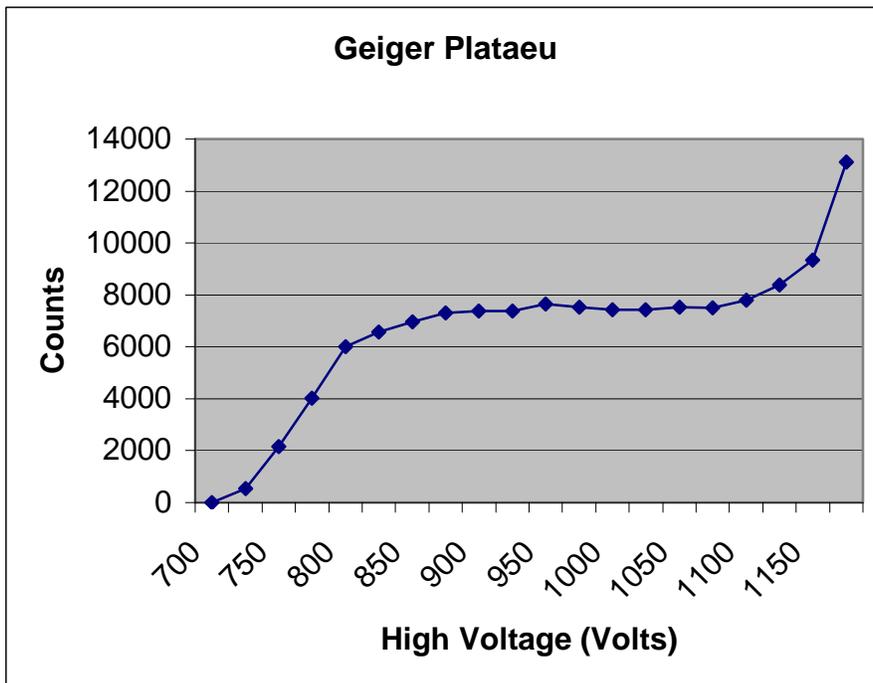
Figure 1: A plateau graph for a Geiger-Müller counter.

By the end of this experiment, you will make a graph similar to the one in Figure 1, which shows a typical plateau shape.

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) as shown in Figure 2.
- Radioactive Source (e.g., Cs-137, Sr-90, or Co-60) – One of the orange, blue, or green sources shown above in Figure 2.

Figure 2: ST360 setup with sources and absorber kit.

Procedure:

1. Plug in the transformer/power supply into any normal electricity outlet and into the back of the **ST-360** box. Next, remove the red or black end cap from the GM tube VERY CAREFULLY. (**Do NOT touch the thin window!**) Place the GM tube into the top of the shelf stand with the window down and BNC connector up. Next, attach the BNC cable to the GM tube and the GM input on the **ST-360**. Finally, attach the USB cable to the **ST-360** and a USB port on your PC (if you are using one).

2. Turn the power switch on the back of the **ST-360** to the ON position, and double click the **STX** software icon to start the program. You should then see the blue control panel appear on your screen.

3. Go to the **Setup** menu and select the **HV Setting** option. In the High Voltage (HV) window, start with 700 Volts. In the **Step Voltage** window, enter 20. Under

Enable Step Voltage, select **On** (the default selection is off). Finally, select **Okay**.

4. Go under the **Preset** option and select **Time**. Enter 30 for the number of seconds and choose **OK**. Then also under the **Preset** option choose **Number of Runs**. In the window, enter 26 for the number of runs to make.

5. You should see a screen with a large window for the number of **Counts** and **Data** for all the runs on the left half of the screen. On the right half, you should see a window for the **Preset Time, Elapsed Time, Runs Remaining, and High Voltage**. If not, go to the view option and select **Scaler Counts**. See Figure 1, below.
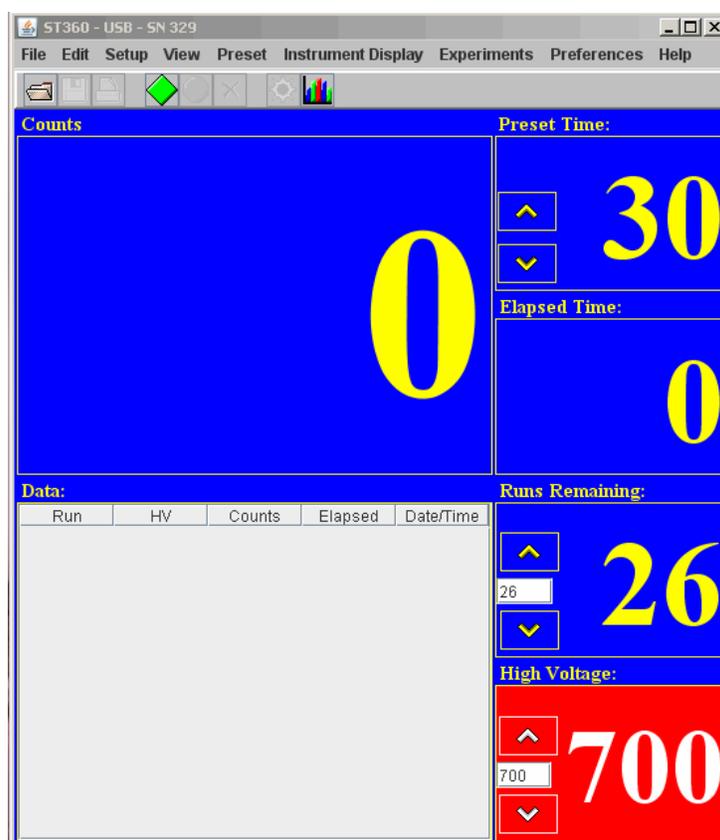
Figure 1, STX setup for GM experiment

6. Make sure no other previous data by choosing the **Erase All Data** button (with the red "**X**" or press F3). Then select the green diamond to start taking data.

7. When all the runs are taken, choose the **File** menu and **Save As**. Then you may save the data file anywhere on the hard drive or onto a floppy disk. The output file is a text file that is tab delimited, which means that it will load into most

spreadsheet programs. See the Data Analysis section for instructions in doing the data analysis in Microsoft Excel®. Another option is that you may record the data into your own data sheet and graph the data on the included graph paper.

8. You can repeat the data collection again with different values for step voltage and duration of time for counting. However, the GM tubes you are using are not allowed to have more than 1200 V applied to them. Consider this when choosing new values.

Data Analysis

1. Open Microsoft Excel®. From the File Menu, choose **Open**. Find the directory where you saved your data file. (The default location is on the C drive in the SpecTech directory.) You will have to change the file types to **All Files** (*.*) to find your data file that ends with .*tsv*. Then select your file to open it.

2. The **Text Import Wizard** will appear to step you through opening this file. You may use any of the options available, but you need only to press *Next*, *Next*, and *Finish* to open the file with all the data.

3. To see all the words and eliminate the ### symbols, you should expand the width of the A and E columns. Place the cursor up to where the letters for the columns are located. When the cursor is on the line between two columns, it turns into a line with arrows pointing both ways. Directly over the lines between the A and B columns and E and F columns, double-click and the columns should automatically open to the maximum width needed.

4. To make a graph of this data, you may plot it with Excel® or on a sheet of graph paper. If you choose Excel, the graphing steps are provided.

5. Go the **Insert Menu** and choose *Chart* for the Chart Wizard, or select it from the top toolbar (it looks like a bar graph with different color bars).

6. Under **Chart Types**, select *XY (Scatter)* and choose *Next*. (This default selection for a scatter plot is what we want to use.)

7. For the **Data range**, you want the settings to be on "=[your file name]!$B$13:$C$32", putting the name you chose for the data file in where [your file name] is located (do not insert the square brackets or quotation marks). Also,

you want to change the **Series In** option from **Rows** to **Columns**. To check to see if everything has worked, you should have a preview graph with only one set of points on it. Or you can go to the Series Tab and for X Values should be "=[your file name]!$B$13:$B$32" and for Y Values should be "=[your file name]!$C$13:$C$32". If this is correct, then choose **Next** again.

8. Next, you are given windows to insert a graph title and labels for the x and y-axes. Recall that we are plotting **Counts** on the y-axis and **Voltage** on the x-axis. When you have completed that, choose the **Legend** tab and unmark the **Show Legend Option** (remove the check mark by clicking on the box). A legend is not needed here unless you plotting more than one set of runs together.

9. Next, you are asked to choose whether to keep the graph as a separate worksheet or to shrink it and insert it onto your current worksheet. This choice is up to your instructor or you depending on how you want to choose your data presentation for any lab report.

10. If you insert the chart onto the spreadsheet, adjust its size to print properly. Or adjust the settings in the **Print Preview Option** (to the right of print on the top toolbar).

Conclusions:

Now that you have plotted the GM tube's plateau, what remains is to determine an operating voltage. You should choose a value near the middle of the plateau or slightly left of what you determine to be the center. Again, this will be somewhat difficult due to the fact that you may not be able to see where the discharge region begins.

Post-Lab Questions:

1. The best operating voltage for the tube = _____ Volts.

2. Will this value be the same for all the different tubes in the lab?

3. Will this value be the same for this tube ten years from now?

4. One way to check to see if your operating voltage is on the plateau is to find the slope of the plateau with your voltage included. Determine where your plateau begins and ends, and confirm it is a typical plateau. The equation for slope is

$$slope(\%) = \frac{100(R_2 - R_1)/R_1}{V_2 - V_1} \times 100,$$

where R_1 and R_2 are the activities for the beginning and end points, respectively. V_1 and V_2 and the voltages for the beginning and end points, respectively. (This equation measures the % change of the activities and divides it by 100 V.)

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 #2: Statistics of Counting

Objective:

In this experiment, the student will investigate the statistics related to measurements with a Geiger counter. Specifically, the Poisson and Gaussian distributions will be compared.

Pre-lab Questions:

1. List the formulas for finding the means and standard deviations for the Poisson and Gaussian distribution.
2. A student in a previous class of the author's once made the comment, "Why do we have to learn about errors? You should just buy good and accurate equipment." How would you answer this student?

Introduction:

Statistics is an important feature especially when exploring nuclear and particle physics. In those fields, we are dealing with very large numbers of atoms simultaneously. We cannot possibly deal with each one individually, so we turn to statistics for help. Its techniques help us obtain predictions on behavior based on what most of the particles do and how many follow this pattern. These two categories fit a general description of mean (or average) and standard deviation.

A measurement counts the number of successes resulting from a given number of trials. Each trial is assumed to be a binary process in that there are two possible outcomes: trial is a success or trial is not a success. For our work, the probability of a decay or non-decay is a constant in every moment of time. Every atom in the source has the same probability of decay, which is very small (you can measure it in the Half-life experiment).

The Poisson and Gaussian statistical distributions are the ones that will be used in this experiment and in future ones. A detailed introduction to those distributions can be found in Appendix C of this manual.

Equipment

Figure 1: Setup for ST360 with sources and absorber kit

- 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.
- Radioactive Source (Cs-137 is recommended – the blue source in Figure 1)

Procedure:

1. Setup the equipment as you did in the Experiment #1, and open the computer interface. You should then see the blue control panel appear on your screen.
2. Go to the **Preset** menu to preset the **Time** to 5 and **Runs** to 150.
3. Take a background radiation measurement. (This run lasts twelve and half minutes to match the later measurements.)
4. When you are done, save your data onto disk (preferred for 150 data points).

5. Repeat with a Cesium-137 source, but reset the **Time** to 1 and the **Number of Runs** to 750 (again will be twelve and a half minutes.)

Data Analysis

1. Open Microsoft Excel®. Import or enter all of your collected data.

2. First, enter all of the titles for numbers you will calculate. In cell G10, enter **Mean**. In cell G13, enter **Minimum**. In cell G16, enter **Maximum**. In cell G19, enter **Standard Deviation**. In cell G22, enter **Square Root of Mean**. In cell H10, enter N. In cell I10, enter **Frequency**. In cell J10, enter **Poisson Dist.** Finally, in cell K10, enter **Gaussian Dist.**

3. In cell G11, enter =AVERAGE(C12:C161) – this calculates the average, or mean.

4. In cell G14, enter =MIN(C12:C161) – this finds the smallest value of the data.

5. In cell G17, enter =MAX(C12:C161) – this finds the largest value of the data.

6. In cell G20, enter =STDEV(C12:C161) – this finds the standard deviation of the data.

7. In cell G22, enter =SQRT(G11) – this takes a square root of the value of the designated cell, here G11.

8. Starting in cell H11, list the minimum number of counts recorded (same as Minimum), which could be zero. Increase the count by one all the way down until you reach the maximum number of counts.

9. In column I, highlight the empty cells that correspond to N values from column H. Then from the **Insert** menu, choose **function**. A window will appear, you will want to choose the **FREQUENCY** option that can be found under Statistical (functions listed in alphabetical order). Once you choose Frequency, another window will appear. In the window for **Data Array**, enter C12:C161 (cells for the data). In the window for **Bin Array**, enter the cells for the N values in column H. (You can highlight them by choosing the box at the end of the window.) **STOP HERE!!** If you hit OK here, the function will not work. You must simultaneously choose, the **Control key, the Shift key, and OK button** (on the screen). Then the frequency for all of your N values will be computed. If you did not do it correctly, only the first frequency value will be displayed.

10. In cell J11, enter the formula =$G$11^H11/FACT(H11)*EXP(-$G$11)*150 for the **Poisson Distribution**. (You must multiply the standard formula by 150, because the standard formula is normalized to 1[1].)

11. In cell K11, enter the formula =(1/($G$20*SQRT(2*PI())))*EXP(-((H11-$G$11)^2)/(2*$G$20^2))*150 for the **Gaussian Distribution**. Note that in Excel® the number π is represented by PI(). Again, you must multiply by 150 to let the function know how many entries there are. (_NOTE_: The formula this is derived from can be found in Appendix C.)

12. Next, make a graph of all three distributions: **Raw Frequency**, **Poisson Distribution**, and **Gaussian Distribution**. Start with the Chart Wizard either by choosing Chart 8 from the Insert Menu or pressing its icon on the top toolbar. (See Lab #1 if you need more detailed instructions.)

13. For your graph, select the N values in the H column and the Frequency values in the I column. Now add two more series, one for the **Poisson Distribution** and one for the **Gaussian Distribution**.

14. Print the graph to hand in to your instructor.

15. Repeat this whole data analysis procedure for your counts with Cs-137.

Conclusions:

What you have plotted is the frequency plot for your data. In addition, you have plotted on top of them the predictions of a **Poisson** and **Gaussian Distribution**. (Note: for the Cs-137 data, the Poisson distribution will read #NUM, because the number is too high for Excel® to deal with, even in scientific notation.) How well do the statistical distributions predict the data? How close are the standard deviations? Is one better than the other? Do the conditions of when to use the **Gaussian** or **Poisson Distributions** apply correctly for our data?

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[1] Normalization is a common higher math procedure. One common technique is to make the highest value 1 and scale all the data below it.

Post-Lab Questions:

1. Which distribution matches the data with the background counts? How well does the **Gaussian** distribution describe the Cs-137 data?

2. Why can't you get a value for the **Poisson** distribution with the data from the Cesium-137 source?

3. How close are the standard deviation values when calculated with the **Poisson** and **Gaussian Distributions**? Is one right (or more correct)? Is one easier to calculate?

Name:	Lab Session:
Date:	Partner:

Data Sheet for Statistics Lab

Tube #: _____
Source: _____
Run Duration: _____
(Time)

Tube #: _____
Source: _____
Run Duration: _____
(Time)

Run #	Counts

Run #	Counts

Data Set	Mean	Gaussian σ	Poisson σ
Background			
Cs-137			

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

Lab #3: Background

Objective:

The student will investigate background radiation, learn how to measure it, and compensate for it.

Pre-lab Questions:

1. Name the four natural sources and three man-made sources of background radiation.
2. Approximately how much background radiation is received by an average American citizen every year? Is this very high (dangerous)?

Introduction:

In an introductory section of this manual called, *What is Radiation*, there is a section that deals with the radiation that is around us everyday of our lives. Normally we don't even think about it. However, every living organism contains a radioactive isotope of carbon, Carbon-14. Whenever you watch TV or look at any object, you must receive the light waves, which are electromagnetic radiation. Cell phones also transmit via are electromagnetic radiation. It is all around us and we can't escape from it. But we are lucky; because the power and dosage in everyday life is so small there are no immediate biological effects.

The GM tube is just like a human; it is being bombarded by radiation constantly. That extra radiation shows up in our GM tube as a count, but it is impossible to determine the origin of the count as from the radioactive source being investigated or background. This causes an erroneous sample count. The error can be very high, especially when the counts are low. Therefore, the background count must be determined and the sample's counts must be corrected for it. It is not a difficult process and is rather straightforward. You find the number of counts with a source present and without a source present. You subtract the counts obtained without the source from those obtained with a source, and that should give you the true number of counts from the source itself.

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.

Figure 1: Setup for ST360 with sources and absorber kit.

- Radioactive Source (e.g., Cs-137, Sr-90, or Co-60 – one of the blue, green, or orange sources shown in Figure 1, respectively)

Procedure:

1. Setup the Geiger Counter as you have in the past two experiments. Set the Voltage of the GM Tube to its optimal operating voltage (found in the Plateau Lab). This voltage should be around 900 Volts.

2. Under the **Preset** Menu, choose **Runs**. Set the number of runs at 3 and the time for 5 minutes (or 300 seconds).

3. After the third run has finished, record your data by saving the data to the hard drive, a floppy disk, or using a data table.

4. Insert a radioactive source into one of the (upper) shelves. Complete at least another 3 runs of 5 minutes each with the radioactive source.

5. Record your data on some scrap paper or a data table, because you will combine it with the rest of the data later.

Data Analysis:

1. Open Microsoft Excel® and import your data.

2. Beginning in cell A4, fill in the appropriate data for the three runs you performed with the radioactive source inserted. You do not have to fill in the Time/Date information, but the **run number**, **high voltage**, **counts**, and **elapsed time** should all be filled with data.

3. Go to cell A19, insert the title **Average Counts**. In cell A20, put the title **Average Background**. In cell A21, put the title **Average True Counts**.

4. In cell B19, enter an equation to calculate the average of the counts with the source present. In cell B20, enter an equation to calculate the average number of background counts. In cell B21, enter the equation =B19-B20 to calculate the number of counts from the source accounting for background radiation.

Conclusions:

As you should see from your data, the background radiation is not high compared to a radioactive source. You should now know how to deal with background radiation to obtain a more accurate reading of counts from a radioactive source.

Post-Lab Questions:

1. Is there anyway to eliminate background radiation?

2. What is your prediction for the number of background radiation counts that your body would receive a day? (Hint: convert from cps or cpm into cpd, counts per day.) How many counts per year?

3. Are all the background measurements exactly the same number of counts? Is there a systematic cause for this?

Name:		Lab Session:	
Date:		Partner:	

Data Sheet for Background Lab

Tube #: _____

Run Duration: _____
(Time)

Tube #: _____

Run Duration: _____
(Time)

Run #	Counts

Run #	Counts

Background Count	

Run #	Corrected Counts

Run #	Corrected Counts

Don't forget to hand in this data sheet with any lab report.

Lab #4: Resolving Time

Objective:

The student will determine the resolving time of a GM counter.

Pre-lab Questions:

1. When radiation travels through the window of the GM tube, what happens so that the tube sends a signal that it has detected a particle?
2. Can the GM counter distinguish between one or more particles when they are present in the tube at the same time?

Introduction:

When a particle decays and produces radiation, those particles or rays can produce an ion pair through ionization in the Geiger tube[1]. The electrons travel to the anode more quickly than the positive ions travel to the cathode. During the time it takes the positive ions to reach the cathode, the tube is insensitive to any radiation. During this time, if a second ionizing ray strikes the tube it will not be detected because the tube cannot tell there is another electron avalanche present. The Geiger counter only sees one "big" electron avalanche, until it has been reset after detection. Basically, the counter cannot produce pulses for more than one particle, because the counter is "occupied" with the particle that arrives earliest. This phenomenon is sometimes called coincidence.

As a result of coincidence, the observed counts are always lower than the true counts. An approximate correction for coincidence is made by adding approximately 0.01% per 100 cpm (counts per minute) to the observed count rate, if it is assumed that the resolving time[2] is about 5 μs. True resolving times span a range from a few microseconds for small tubes to 1000 microseconds for very large detectors. The loss

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[1] Make sure you read the appendix on the operation of a Geiger-Müller counter. Some aspects on how the Geiger counter works are assumed knowledge for the student.

[2] Resolving Time is more commonly referred to as Dead Time by scientists, because in essence the detector is "dead" and cannot detect any other radiation in this time window.

of counts is important, especially when there are high count rates involved and the losses accumulate into large numbers.

In this experiment, you will perform a more accurate analysis of dead time via a method that uses paired sources. The count rates, or activities, of two sources are measured individually (r_1 and r_2) and then together (r_3). The paired samples form a disc cut into two lengthwise. A small quantity of radioactive material is placed on each half making each a "half-source" of approximately equal strength. A blank disk is used to duplicate the set-up geometry while using only one half-source. (NOTE: You must keep the experimental set-up the same or there is a chance that results may change. This is a common experimental requirement for all sciences.)

Theory:

If we anticipate a counting rate, R, from a radioactive source, then the presence of coincidence will mean that the rate we actually measure, r, will be less than the expected value ($r < R$). If this GM tube has a dead time of T, then the equation for the true count rate is

$$R = r + rRT. \tag{1}$$

This allows us to find an equation to correct our counting rate for dead time

$$R = \frac{r}{1 - rT}. \tag{2}$$

You will have r from your data, and you will be asked to find R. What about T? We look at our two-source method of data taking, where we measure the activity from two half-sources, r_1 and r_2. Then, we measure their combined activity, r_3, so we can use this set-up to our advantage. We expect that the

$$r_1 + r_2 = r_3 + b \tag{3}$$

where b is the background counting rate. If each of these counting rates are corrected for dead time, then Equation (3) becomes

$$\frac{r_1}{1 - r_1 T} + \frac{r_2}{1 - r_2 T} = \frac{r_3}{1 - r_3 T} + b \tag{4}$$

We do not correct b, because any correction would only be a fraction of a count. Since the background count rate is negligible, Equation (4) can be changed into the form of a quadratic equation

$$r_1 r_2 r_3 T^2 - 2r_1 r_2 T + r_1 + r_2 - r_3 = 0. \tag{5}$$

T is on the order of microseconds, so T^2 will also be negligible. This allows a very simple algebraic equation to be solved for T:

$$T = \frac{r_1 + r_2 - r_3}{2r_1 r_2}. \tag{6}$$

Now, we can solve for R in Equation (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.

Figure 1: Setup for ST360 with sources and absorber kit.

- Radioactive Half-Source Kit (3 Half Discs – One Blank and Two of Tl-204) – shown in Figure 2

Figure 2:Radioactive Half-Source Kit used for Resolving Time determination

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to zero and set the **Time** to 60 (You want to measure counts per minute (cpm), so 60 seconds allows you to convert the number of counts to cpm).

3. First do a run without a radioactive source. This will determine your background level. Use two blank disks in the sample tray if they are available.

4. Next, place one of the half-sources on the sample tray with the blank disc. (The orientation does not matter here but it must be the same throughout the experiment.) Insert this into one of the upper shelves to take data. Record the number of counts as r_1.

5. Replace the blank disc with the second half-source and start a second run. Click on the **green diamond** to take data. Record this number of counts as r_3.

6. Replace the first half-source with the blank disc and start a third run. Record this number of counts as r_2.

7. Save your data either onto disk or into a data table.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.

2. In cell G9, enter the word **Corrected**. In cell G10, enter the word **Counts**.

3. In cells G13-G15, enter the formula to correct for the background. On the data sheet attached to this lab, the **Corrected Counts** column is for the final corrected counts, which means that the correct for resolving time is also done.

4. In cell E2, enter "**Resolving Time =**".

5. In cell F2, enter the equation =(G13+G15-G14)/(2*G13*G15).

6. In cell H9, enter the word **New** and in cell H10 enter **Counts**.

7. In cells H13-H15, enter the formula =G13/(1-(G13*$F$2)) to correct for resolving time.

8. In cell I9, enter the words **% Counts** and in cell I10 enter **Added**.

9. In cells I13-I15, enter an Excel formula to find the percent of change, which is

$$\% = \left(\frac{|corrected - measured|}{measured} \right) \times 100$$, where the corrected counts are from Column H

and the measured counts are from column H. This value for the percent of the measurement that was missing due to resolving time will be large, from 20-60% due to the very active source Tl-204 and the high count rates we are using.

10. Save your worksheet or print it out per your teacher's instructions.

Post-Lab Questions:

1. What is your GM tube's resolving (or dead) time? Does it fall within the accepted 1 μs to 100 μs range?

2. Is the percent of correction the same for all your values? Should it be? Why or why not?

Name: _____   Lab Session: _____

Date: _____   Partner: _____

Data Sheet for Resolving Time Lab

Tube #: _____   Run Duration:

Source: _____   (Time)   _____

	Counts	Corr. Counts	% Missing
r1:			
r2:			
r3:			

T: _____

Tube #: _____   Run Duration:

Source: _____   (Time)   _____

	Counts	Corr. Counts	% Missing
r1:			
r2:			
r3:			

T: _____

Lab #5: Geiger Tube Efficiency

Objective:

      The student will determine the efficiency of a Geiger-Muller counter for various types of radiation.

Pre-lab Questions:

1. How can you determine the activity of a radioactive source? Find the activity of the three sources you will use in this experiment.
2. Do you expect efficiency to be good or bad for each of your sources? (Consider real-world effects)

Introduction:

      From earlier experiments, you should have learned that a GM tube does not count all the particles that are emitted from a source, i.e., dead time. In addition, some of the particles do not strike the tube at all, because they are emitted uniformly in all directions from the source. In this experiment, you will calculate the efficiency of a GM tube counting system for different isotopes by comparing the measured count rate to the disintegration rate (activity) of the source.

      To find the disintegration rate, change from microCuries (μCi) to disintegrations per minute (dpm). The disintegrations per minute unit is equivalent to the counts per minute from the GM tube, because each disintegration represents a particle emitted. The conversion factor is:

$$1\,Ci = 2.22 \times 10^{12}\,dpm \qquad or \qquad 1\,\mu Ci = 2.22 \times 10^{6}\,dpm \, . \tag{1}$$

Multiply this by the activity of the source and you have the expected counts per minute of the source. We will use this procedure to find the efficiency of the GM tube, by using a fairly simple formula. You want to find the percent of the counts you observe versus the counts you expect, so you can express this as

$$\%\ Efficiency = \frac{r(100)}{CK} \, . \tag{2}$$

In this formula, r is the measured activity in cpm, C is the expected activity of the source in μCi, and K is the conversion factor from Equation 1.

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.

Figure 1 – Setup for ST360 with sources and absorber kit

- Radioactive Source (one each of an alpha, beta, and gamma sources – we recommend Po-210, Sr-90, Co-60 respectively.) – shown in Figure 2.

Figure 2 – Kit with one each of an alpha emitter, beta emitter, and gamma emitter

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 60 to measure activity in cpm.

3. First do a run without a radioactive source to determine your background level.

4. Next, place one of the radioactive sources in the top shelf and begin taking data

5. Repeat this for each of your other two sources. Remember that the first run is a background number.

6. (OPTIONAL) From the **Preset** menu, change the **Preset Time** to 300, and take data for all three sources again.

7. Save your data to disk or to a data table before exiting the **ST-360** program.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.

2. In cell E2 enter constant, **K =** and in cell F2 enter **2.20E6** (or 0.00000220). In cell E3 enter (conversion from μCi to dpm). (To create the μ, you need to change to the Symbol font and then simply type the letter m. Don't forget to switch back to your original font when you are done.)

3. In cell E5 enter **Dead Time =** and in cell F6 enter the dead time for your GM tube found in Lab #4: Resolving Time.

4. In cell G10, enter **Activity (μCi).** Then cells G13-G17, enter the activities of the sources used. (Remember to not enter one for the background counts row.)

5. In cell H9 enter **Res. Corr.** and in cell H10 enter **Counts**. In cell C13, enter the formula to correct for resolving time. Copy this formula to cells C14 and C15. Then, in cell H16, enter the formula again and copy to cells H17 and H18. This should change the five minute counts to counts per minute, and corrects them for resolving time.

6. In cell I9 enter **Bkgd Corr.** and in cell I10 enter **Counts**. In cell I13, enter the formula =H13-$C$12. Copy this formula to the other cells. (You may have to adjust the formula if you took a five minute background count, but don't forget to convert it to cpm by dividing by 5.)

7. In cell J10, enter **% efficiency**. In cell J13, enter the formula for efficiency and copy it to all the relevant cells.

8. Copy your results to your data table or print out a hard copy if you need to hand one in attached to a lab report

Conclusions:

Are your results reasonable? How do you know? You should have numbers above zero but below 10 if you performed the experiment correctly. Answer the post-lab questions to help you form a conclusion from your results.

Post-Lab Questions:

1. Is the efficiency you calculated for each isotope valid only for that isotope? Explain your answer.

2. If a different shelf is used, will the efficiency change? Explain your answer.

3. The radius of the GM tube's window is 3.5 cm. The source is 3 cm from the GM tube. Compare the surface area of a sphere 3 cm from the source to the area of the GM tube's window. (Hint: find the ratio) How is this related to this experiment? Can this tell you if your results are reasonable?

4. (Correlates if five minute and one minute runs were taken.) Are the efficiencies different? How different? Why?

Data Sheet for GM Tube Efficiency Lab

Tube #: _____   Run Duration: _____

Dead Time: _____   (Time)

Source	Counts	Corr. Counts	Expect. Counts	Efficiency

Tube #: _____   Run Duration: _____

Dead Time: _____   (Time)

| Source	Counts	Corr. Counts	Expect. Counts	Efficiency

Lab #6: Shelf Ratios

Objective:

The student will investigate the relationship between the distance and intensity of radiation. The student will also measure the shelf ratios of the sample holder.

Pre-lab Questions:

1. Does radiation gain intensity or lose intensity as a source gets farther from a detector?
2. How is radiation emitted from a radioactive source? (Hint: Think of the sun)

Introduction:

Although radiation is emitted from a source in all directions, only a small part actually enters the tube to be counted. This fraction is a function of the distance, h, from the point source of radiation to the GM tube. See Figure 1 for a picture of a "sphere" which represents the radiation emitted radially from the radioactive source. It can also be observed the small fraction of the "sphere" that will enter the window of Geiger counter, which is represented by the triangle of sides d and height h. If the source is moved further away from the tube, the amount of radiation entering the tube should decrease. This is due to the fact that the triangle's height will increase, and the triangle will represent less and less of the "sphere" of radiation.
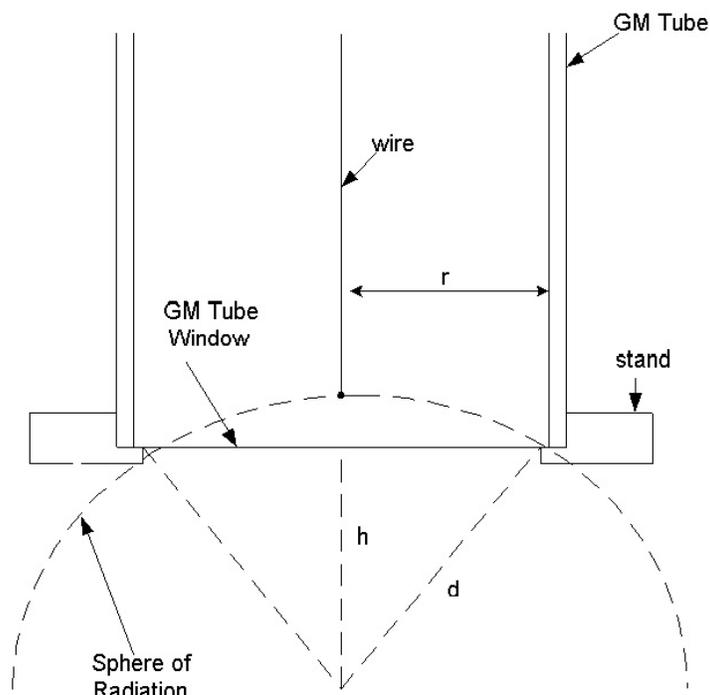
*Figure 1: Influence of the source-to-window
distance on the observed count rate.*

As a beta source is moved away from the detector, activity will decrease more rapidly than predicted by the inverse square law because beta particles are also attenuated or absorbed by air. The problem presented by this extra absorption is placing the source close enough to get a good fraction of the radiation in the window of the GM tube, but also not placing the source too far away where absorption becomes a important factor to consider.

It is sometimes convenient to take advantage of this change in activity with distance by moving less active samples toward the counter and samples which are too active away from the tube in order to obtain suitable counting rates. This is the reason that tube stands are made with multiple shelves.

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.

Figure 1 – Setup for ST360 with sources and absorber kit

- Radioactive Source (beta sources – we recommend Tl-204 or Sr-90) – green source in Figure 1.

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 30.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the top shelf and begin taking data. In this position, the source is 2 cm from the GM tube's actual detector components.

5. Move the source down one shelf each time and take another run. You should see the data accumulating in the Data window. After all ten shelves have been used, save the data onto disk or record in a data table. Remember that the first run is a background number.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.
2. In Cell E2 enter **Dead Time =** and in cell F2 enter the dead time for your GM tube (found in Lab #4).
3. In cell G9 enter **Res. Corr.** and in cell G10 enter **Counts**. In cell G13, enter the formula to correct for resolving, or dead, time and copy this to the rest of the cells corresponding to counts in column C.
4. In cell H9 enter **Bkgd Corr.** and in cell H10 enter **Counts**. In cell H13, enter the formula to correct for the background, and copy this to the rest of the cells corresponding to counts in column G.
5. In cell I9 enter **Shelf** and in cell I10 enter **Ratio**. In cell I13, enter the formula to compute the shelf ratio, and copy this to the rest of the cells corresponding to counts in column H. The shelf ratio is calculated by dividing the number of counts on any shelf by the number of counts from the second shelf. This should give you a shelf ratio of 1.00 for the second shelf, which is our reference point.

Conclusions:

You should see a decrease in your values as you move away from the source. If you do not, this may be caused by statistical fluctuations in your counts. Why?

Post-Lab Questions:

1. Does the shelf ratio depend on the identity of the sample used?
2. If the experiment is repeated with a gamma or alpha source, what differences would you expect?
3. Why is the second shelf the reference shelf?

Name:	Lab Session:
Date:	Partner:

Data Sheet for Shelf Ratios Lab

Tube #: _____

Dead Time: _____

Run Duration: _____
(Time)

Shelf #	Counts	Corr. Counts	Shelf Ratio
1			
2			1.00
3			
4			
5			
6			
7			
8			
9			
10			

Lab #7: Backscattering

Objective:

The student will investigate the relationship between absorber material (atomic number) and backscattering in Part One. In Part Two, the student will investigate the relationship between absorber thickness and backscattering

Pre-lab Questions:

1. Calculate what percentage of the entire "sphere" surrounding the source does the GM window occupy.

2. Backscattering does have dependencies on atomic number and on thickness. Does either one dominant the amount of backscattering versus the other? What kind of dependence do you predict for each (direct, inverse, inverse square for example – be descriptive)?

Introduction:

Radiation is emitted from a source in all directions. The radiation emitted within the angle subtended by the window of the GM tube is the only radiation counted. Most radiation is emitted away from the tube but it strikes matter. When it does so, the direction of its path may be deflected. This deflection is known as scattering. Most particles undergo multiple scattering passing through matter. Beta particles especially may be scattered through large angles. Radiation scattered through approximately 180^0 is said to be backscattered. For Geiger counters, backscatter is the fraction of radiation emitted away from the GM tube that strikes the material supporting the sample. It is deflected toward the tube window and is counted.

A beta particle entering matter undergoes a series of collisions with mostly nuclei and sometimes orbital electrons. A collision between particles does not occur in the same manner we picture them in the macroscopic world. There are very little contact collisions, but instead the term, collision, refers to any interaction, coulombic or otherwise. (A coulombic interaction is an electrical attraction or repulsion that changes the path of the particle's motion.) A collision may be elastic or inelastic, but in either

case the result is not only a change in direction but usually a decrease in the energy of the beta particle as well (inelastic).

In the first part of the experiment, we will investigate the effect of the size of the nucleus on backscattering since this would seem most likely effect the number of backscattered beta particles. This can be determined by using absorbers as backing materials. Even though the metal pieces you will use are called absorbers, in this experiment, they will also be used to deflect radiation upward into the GM tube. To eliminate any other effects, the absorbers will be the same thickness but different atomic number (and thus different sized nuclei). In the second part of the experiment, you will use absorbers of the same material (atomic number) and different thickness. This is a common experimental technique, fixing one variable and varying another to investigate each one individually

Normally when we think of thickness, we think of linear thickness that can be measured in a linear unit such as inches or centimeters. However, in nuclear and particle physics, thickness refers to **areal** thickness. This is the thickness of the absorbers in mg/cm^2. The absorptive power of a material is dependent on its density and thickness, so the product of these two quantities is given as the total absorber thickness, or **areal** thickness. We determine **areal** thickness with the equation:

Density (mg/cm^3) X thickness (cm) = Absorber thickness (mg/cm^2).   (1)

You will determine the dependence that absorber thickness has on backscattering.

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)

Figure 1 – Setup for ST360 with sources and absorber kit

- Radioactive Source (**THIN**[*] beta emitter)
- Part I: Backscatter Absorber Kit – Plastic (poly-carbonate), Aluminum, Copper, Tin, Lead, and "an unknown" Discs
- Part II: (Regular) Absorber Kit – the Aluminum and Lead pieces will be used. (Shown in Figure 1.)

Procedure:

Part I – Atomic Number Dependence

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 60.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the second shelf from the top and take data.

---

[*]   A thin source is required to reduce self-absorption by the source. This enables beta particles sent downward that are scattered back up toward the GM tube may pass through the source again.

5. Place an absorber piece, or disk, in the source holder and place the source directly on top of it.

6. Repeat this for all of the various absorbers (different materials) including the unknown.

7. Record the data to a file on disk or into a data table.

Part II – Thickness Dependence

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 60.

3. First do a run without a radioactive source to determine your background level. (Do not repeat if this is part is being performed in the same lab period as Part I.)

4. Next, place the radioactive source in the second shelf from the top and begin taking data.

5. Place the source directly on top of one of the absorbers. Take data by clicking on the **green diamond**.

6. Place the source on a different absorber and insert into the second shelf. Click on the **green diamond** to begin taking data.

7. Repeat for at least three other absorber thicknesses.

8. Record the data to a file on disk or into a data table.

Data Analysis:

Part I – Atomic Number Dependence

1. Open Microsoft Excel® and import your data into it.

2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.

3. In cell G9 enter **Dead Corr.** and in cell G10 enter **Counts**. In cell G13, enter a formula to correct for dead time. Copy this down for the cells that have counts in column C.

4. In cell H9 enter **Corrected** and in cell H10 enter **Counts**. In cell H13, enter a formula to correct for background counts. Copy this down for the cells that have

counts in column G. Is background significant? Can you back up your answer numerically?

5. In cell I9 enter **Atomic** and in cell I10 enter **Number**. In cell I13 and below, enter the atomic numbers for the absorbers you used to get obtain the corresponding counts. (Plastic is poly-carbonate[**] – Z = 6, Aluminum – Z = 13, Copper – Z = 29, Tin – Z = 50, and Lead – Z = 82)

6. To double-check the general result of our data that we will graph below, we will calculate the percentage of counts that were due to backscattering and compare that to the Z values. To calculate the percent of counts from backscattering, use the following formula $\% \, back = \left(\dfrac{r - r_o}{r_o} \right) \times 100$, where r is the corrected count rate (cpm) and r_o is the count rate without any absorber present. To do this in Excel, in cell J9 enter **Percent** and cell J10 **Backscatt.** In cell J13, enter the formula =((H13-$H$13)/$H$13)*100. This should give 0 for cell J13 but not for the rest.

7. Next, make a graph of Corrected Counts vs. Atomic Number. Start with the Chart Wizard either by choosing **Chart** from the Insert Menu or pressing its icon on the top toolbar.

9. Select the Atomic Number values in the I column and Corrected Counts values in the H column.

10. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

11. Choose whether you want to view your graph as a separate worksheet as your data, or you wish to see a smaller version of the graph with the data.

12. Adjust the size of the graph for your preference (or the instructor's). You may also wish to adjust the scales on one or more of the axes. Again, this is a preference issue.

13. Right click on one of the data points and from the menu that appears, choose **Add Trendline**. Make sure that the **Linear** option is chosen (should be darkened). Then click on the Options tab and check the boxes for **Display equation on chart** and

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[*]

  [*] Plastic is effectively carbon because that is the dominating element in this material.

Display R-squared value on chart. This will make the equation of the best fit line appear as well as a number that represents the percent of linearity of the data.

Part II – Thickness Dependence

1. Open Microsoft Excel® and import

2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.

8. In cell G9 enter **Dead Corr.** and in cell G10 enter **Counts**. In cell G13, enter a formula to correct for dead time. Copy this down for the cells that have counts in column C.

9. In cell H9 enter **Corrected** and in cell H10 enter **Counts**. In cell H13, enter a formula to correct for background counts. Copy this down for the cells that have counts in column G.

3. In cell I9 enter **Thickness** and in cell I10 enter **(in)**. In cell I13 and below, enter the thickness of the absorbers (0.32, 0.063, or 0.125 inches) for the aluminum and lead[***].

4. Calculate the percentage of counts that were due to backscattering. In cell J9 enter **Percent** and cell J10 **Backscatt.** In cell J13, enter the same formula as for Part I for percent of backscattering. This should give 0 for cell J13 but not for the rest.

5. Next, make a graph of Corrected Counts vs. Thickness. Start with the Chart Wizard either by choosing Chart from the Insert Menu or pressing its icon on the top toolbar.

6. Select the Thickness values in the I column and Corrected Counts values in the H column.

7. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

8. Choose whether you want to view your graph as a separate worksheet as your data, or you wish to see a smaller version of the graph with the data.

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[*]   [**] Lead has an absorber that is 0.064 inches thick instead of the listed 0.063 inches. Make sure you enter it correctly.

9. Adjust the size of the graph for your preference (or the instructor's). You may also wish to adjust the scales on one or more of the axes. Again, this is a preference issue.

10. Right click on one of the data points and from the menu that appears choose **Add Trendline**. Make sure that the **Linear** option is chosen (should be darkened). Then click on the Options tab and check the boxes for **Display equation on chart** and **Display R-squared value on chart**. This will make the equation of the best-fit line appear as well as a number that represents the percent of linearity of the data.

Conclusions:

What is your conclusion about the dependence of backscattering on atomic number? How about on thickness?

Post-Lab Questions:

1. Justify your answers to the questions about the dependences of backscattering.
2. Do your % backscattering calculations confirm your results?
3. What element (or material) is the unknown absorber?
4. What would be the predicted count rate for a uranium disk of the same size as those used in Part I? How about if it was ¼ in. thick (qualitative answer, higher or lower)? Show your work and explain any reasoning.

Data Sheet for Backscattering Lab

Tube #: _____   Run Duration: _____

Dead Time: _____   (Time)

Part I

Element (Z)	Counts	Corr. Counts	% Backscat.

Name: _____   Lab Session: _____

Date: _____   Partner: _____

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

Data Sheet for Backscattering Lab

Tube #: _____   Run Duration: _____

Dead Time: _____   (Time)

Part II

Thickness	Counts	Corr. Counts	% Backscat.

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

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.

Figure 1 – Setup for ST360 with sources and absorber kit

- Radioactive Source (beta sources – we recommend Tl-204 or Sr-90) – one of the green sources shown in Figure 1.

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 30.

3. First do a run without a radioactive source to determine your background level.

4. Next, place the radioactive source in the top shelf and begin taking data. In this position, the source is 2 cm from the GM tube's actual detector components.

5. Move the source down one shelf each time and take another run. You should see the data accumulating in the Data window. After all ten shelves have been used, save the data onto disk or record in a data table. Remember that the first run is a background number.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.
2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.
3. Go cell G9 and insert the word **True**. Go to cell G10 and insert the word **Counts**. In cell H10, insert **Distance (cm)**. In cell I10, insert **Distance (m)**. In cell J10, insert **1/d^2**[1].
4. In cells G13 down to G14, insert a formula to correct for dead time and background. (may need additional column).
5. In cell H13, insert the distances in centimeters. They should begin with 2 and increase by one until 11 is reached.
6. In cell I13, insert the formula to convert the distance from centimeters to meters. Copy this formula in each cell from I14 down to I22.
7. In cell J13, insert the formula =1/(I13*I13) or =1/(I13^2). Either form gets you the inverse square of the distance. Copy this formula in the cells down from J14 to J22.
8. Next, make a graph of Counts vs. $1/d^2$. Start with the Chart Wizard either by choosing Chart from the Insert Menu or pressing its icon on the top toolbar.
9. Choose the True Counts values in the H column and the $1/d^2$ values in the J column.
10. Fill in the Chart Title, Value (X) Axis, and Value (Y) Axis windows with appropriate names and units (if applicable) for those items. Recall that Counts are a unitless quantity.
11. Position your cursor directly over one of the data points on your graph. Then click the right button on the mouse and watch a small menu appear. Choose the **Add Trendline** option. You may click **OK** here or if you want more information choose the **Options** Tab. There you may click in the boxes for **Display Equation on Chart** (for the equation of the line in slope-intercept form to appear on the graph) or on **Display R-squared Value on Chart** (this gives a decimal representation of the percentage completely linear the data is).

Conclusions:

Use your graph to determine if the data does indeed obey inverse square law.

---

[1] The carrot, ^, is the computer programming way of indicating exponent or power.

Post-Lab Questions:

1. Does your data follow Excel®'s best fit line? If not, why?

2. Does this verify the inverse square law? Explain?

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 #9: Range of Alpha Particles

Objective:

The student will determine the range of an alpha particle in air, and consequently the alpha particle's energy.

Pre-lab Questions:

1. What is an alpha particle? How and why are they emitted?
2. What everyday material can block alpha particles?
3. Do you predict the range to be long or short? Why?

Introduction:

We know that particles that enter matter lose their energy[1] via collisions with atoms in the matter. So, a natural question would be, how far will the particle travel in the matter before it loses all of its energy? This quantity is called the **range** of a particle, and depends on the type of material, particle type, and its energy. Normally, we assume that the energy loss is continuous (particle loses some energy for each amount of distance it travels); the range will be a certain distance for the same particles with identical initial energies passing through the same type of material. In this experiment, you will look at alpha particles passing through air.

The alpha particle (α) is a helium ion (+2), which is composed of two protons (p) and two neutrons (n). Ramsay and Soddy observed that helium is constantly being produced from radium and that radioactive minerals invariably contain helium. Rutherford and Royds later showed that alpha particles form neutral helium atoms when they lose their kinetic energy. In the process, each alpha particle gains two electrons from the surrounding material.

Alpha particles emitted from a particular species of nucleus are mono-energetic; alphas from the same species have the same energy. The energy of most alphas falls

---

[1] When dealing with particles, we ignore potential energies from bonding mainly because the size is so small. The term energy refers solely to the kinetic energy of the particle.

in the range between 3 and 8 MeV. By comparison, chemical reactions have energies of 5 to 30 eV per molecule.

The velocity of an alpha particle upon emission from the nucleus depends upon the radioelement of its origin. The alpha particle has great ionizing power, but very little penetrating power. (If it enters the GM tube, then it will ionize the gas and be detected unless it is the dead time.) Its energy is approximated by its range in air in the equation:

$$E \cong R + 1.5 \qquad\qquad\qquad\qquad (1)$$

where R is the range in air of the alpha particle in centimeters and E is the energy of the alpha particle in MeV.

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.

Figure 1 – Setup for ST360 with sources and absorber kit

- Radioactive Source (alpha emitter – Po-210 is best for this experiment – the red source shown in Figure 1)

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to it optimal operating voltage, which should be approximately 900 Volts.
2. From the **Preset** menu, set **Runs** to three and set **Preset Time** to 60. (You will take three data sets from each shelf due to the low count rate on some shelves.)
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the top shelf from the top and begin taking data.
5. Move the source down one shelf and take data again.
6. Repeat this until you repeatedly get counts approximately equal to your background. (This means you will take data until the source reaches the sixth or seventh shelf approximately.)
7. Save your data either to disk or into a data table.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.
2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.
3. In cell G9 enter **Corrected** and in cell G10 enter **Counts**. In cells G15, enter a formula for dead time and background correction (average background runs first - Cells C12-C14), and copy that formula down to cell G32.
4. Now, average the three runs you preformed on each of the shelves. In cell H9 enter **Average** and in cell H10 enter **Counts**.
5. Next, add the distances to the chart. In cell J10, enter **Distance (cm)**. Starting in cell J13, enter 2. Then in cell J14, enter the formula =J13+1 and copy this down for all the distances you took data.

6. Use that number as R in Equation (1) to find the energy of your alpha particles. Compare this value of E to the expected value, 5.34 MeV, by finding the percent error. Record these values either in the spreadsheet or on your data sheet.

$$\% \ error = \left(\frac{|measured - theoretical|}{theoretical} \right) \times 100 \qquad (2)$$

OPTIONAL:

7. A graph is very tricky here because of lack of measurements below 2 cm. In addition, you would like measurements in increments less than 1 cm. Look at your data. Where is there a sudden fall-off in the counts per minute (going from thousands to tens)? Where does the data dip below the x-axis? Use extrapolation to guess where these two situations occur (i.e., 2.7 cm because it fell in-between 2 cm and 3 cm but seems closer to 3 cm). Average these two numbers and that gives the mean range of your alpha particles.

8. Make a graph of Corrected Counts per Minute vs. Distance. Start with the **Chart Wizard** either by choosing **Chart** from the **Insert Menu** or pressing its icon on the top toolbar.

9. Use the **Average Counts** in column I and **Distance** in column J columns of data.

10. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

11. Choose whether you want to view your graph as a separate worksheet as your data, or you wish to see a smaller version of the graph with the data. Click Finish when you have chosen one or the other.

Conclusions:

What you should see in a graph of your data (if you made one) is that as the data approaches the range, it does not drop immediately to the background level directly at the range value. Instead, the curve slopes down over a certain interval of distances. This is because our original assumption of energy loss being continuous is not quite accurate. Not every identical particle will have identical energy loss. That is because every particle suffers a different number of collisions when passing through matter and

thus have slightly different energy losses. This means that energy loss is statistical in nature.

If you measure an ensemble (or group) of identical particles passing through the same sample, then you will a statistical distribution of ranges centered about some mean value, the mean range. This phenomenon is known as **range straggling**. This means some alpha particles are stopped with less air than others, because of the difference in the number of collisions it has with air molecules.
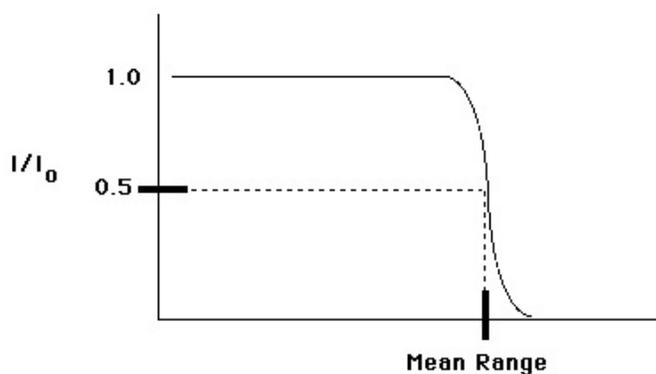

Figure 2: Alpha particle range straggling is shown. The intensity of alpha particles drops off over a small range and not immediately at one value.

An example of a plot of alpha range straggling is shown in Figure 2. You can see that at that point the counts first drop off sharply to the left of the mean range, which is one point you can identify on the graph from your data. Then there is a sudden drop off to zero to the right of the mean range where the counts above background are zero. This is the other point you should found. Then, the point in the point in the middle of these other two will be your mean range.

Post-Lab Questions:

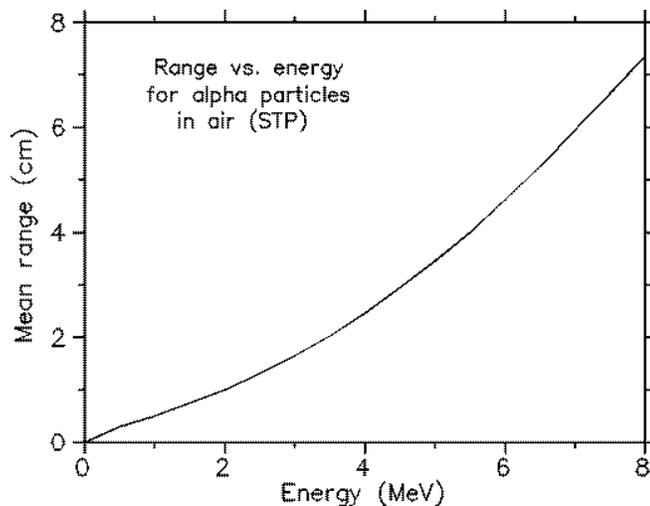1. Compare your results of range and energy to those values that can be found in a handbook (see Figure 3). Results?

Figure 3: Plot of Alpha particle range versus energy in MeV.

2. How far away should a person stand to not receive any alpha particles that are emitted from a nucleus at 8 MeV?

3. How reliable is your data? In other words, is the percent error high? (Explain why you think it is high) If it is high, is that OK? Why?

Name:		Lab Session:
Date:		Partner:

Data Sheet for Alpha Range Lab

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

Shelf	Counts	Corr. Counts	d (cm)

Fall off starts about: _____ Cm

Fall off ends about: _____ Cm

Center of Fall off: _____ Cm

E = R + 1.5

E = _____ MeV

Lit. Value: E= _____ MeV

% Error = _____

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 ($\bar{v}$)[1]. When an electron originates in the nucleus, it is called a beta particle.

$$n \rightarrow p + e^- + \bar{v}$$ (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 2.9×10^8 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.
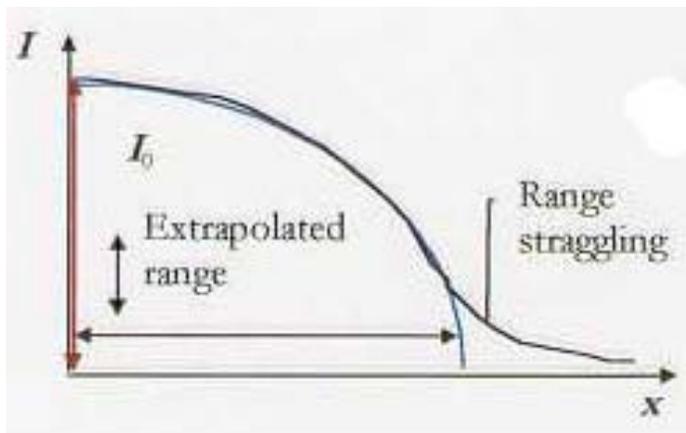
Figure 1: Typical absorption curve for beta particles. Plot is of intensity (activity) vs. absorber thickness (x)

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.

- Radioactive Source (beta emitter – any green source shown in Figure 2)

Procedure:

1. Setup the Geiger counter as you have in previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 60.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the second shelf from the top and begin taking data.
5. Place an absorber piece in the top shelf and take another run of data.
6. Repeat this a minimum of 5 more times with absorbers of increasing thickness.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.
2. In cell F6, enter **Dead Time =** and in cell G6 enter the dead time determined for your GM tube.
3. In cell G9, enter **Thickness** and in cell G10 enter **mg/cm²**. Then starting in cell G13, enter the thickness for the absorbers used. For cell G13, it should be zero (no absorber used). In column F, under Notes, it may be convenient to enter the letters associated with the absorbers you used.
4. In cell H9 enter **Dead Corr.** and in cell H10 enter **Counts**. Then starting in cell H13, enter a formula to correct for the dead time of the GM counter. Copy this formula down the column for all the data you collected.
5. In cell I9 enter **Corrected** and in cell I10 enter **Counts**. Then starting in cell I13, enter a formula to correct for the background of the GM counter. Copy this formula down for all the data you have.
6. In cell J9 enter **Natural Log** and in cell J10, enter **of Counts**. Then in cell J13, enter the formula =LN(I13) and copy this formula down for all the data you have.
7. Next, make a graph of **Corrected Counts vs. Thickness**. Start with the **Chart Wizard** either by choosing **Chart** from the **Insert Menu** or pressing its icon on the top toolbar.

8. Select the **Thickness** values in the G column and the **Corrected Counts** values in the I column.

9. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

10. Add a trendline to the graph. The x-intercept represents the extrapolated range.

Conclusions:

You should be able to characterize the relationship between beta particle activity and absorber thickness.

Post-Lab Questions:

1. Is your data linear? If not, what type of behavior does it exhibit?
2. What is the slope for your data? How did you obtain it?
3. What is the range of the beta particles, so that all of them stop?
4. Bremmsstrahlung (German for braking radiation) is the name given to x-rays produced by beta particles reacting with matter. Was any Bremmsstrahlung produced during the experiment? Can it minimized?

Data Sheet for Beta Absorption Lab

Tube #: _____

Dead Time: _____

Run Duration: _____

(Time)

Counts	Corr. Counts	Thickness	In (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

$$E_\beta = 1.84R + 0.212$$

(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.

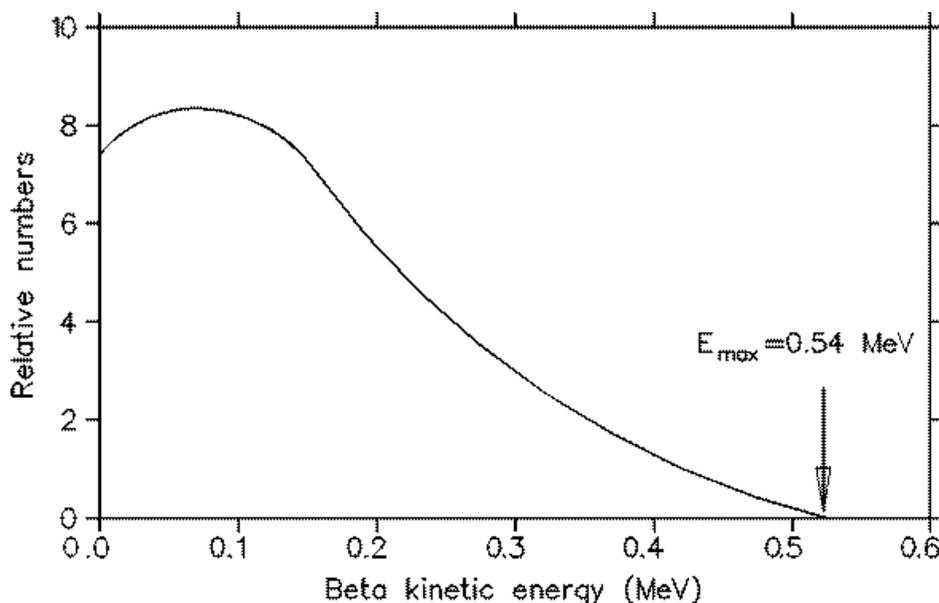[1] Attenuation is a term used for the exponential decrease of a quantity.

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.

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

Procedure:

1. Set up the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to three and set **Preset Time** to 60.

3. First do a run without any absorber and with a radioactive source. Place the source in the second shelf and click the **green diamond** to begin taking data. No background reading is taken because ^{204}Tl and ^{90}Sr are relatively strong beta sources (high count rates) and the background will be negligible (20-40 cpm).

4. Next, place the first absorber in the top shelf, directly above the source, and begin taking data.

5. Change your absorber each time for as many absorbers as the instructor gives to you. You should see the data accumulating in the **Data** window. After all the absorbers have been used, save the data onto disk or record in a data table.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.

2. In cell E2 enter **Dead Time =** and then in cell F2 enter the value for your GM tube's resolving time.

3. In cell G9 enter **Corrected** and in cell G10 enter **Counts**. Next, in cell G13, enter a formula to correct for your data for resolving time. Copy this formula down for all the cells that should contain data.

4. In cell H9 enter **Thickness** and in cell H10 enter **(mg/cm²).** Then, in column H beginning with cell 12, enter the thickness values you used taking data.

5. In cell I9 enter **Log of** and in cell I10 enter **Activity**. Next, in cell I13, enter the formula =LOG(G13) to calculate the logarithm (base 10) of your data. Copy this formula down for all the cells that should contain data. Taking the logarithm of the data substitutes for plotting your data on semi-log paper.

6. Next, make a graph of Log of Activity vs. Thickness. Start with the Chart Wizard either by choosing Chart from the Insert Menu or pressing its icon on the top toolbar.

7. Select the thickness values in the H column and the Log of Activity values in the I column.

8. Fill in the Chart Title, Value (X) Axis, and Value (Y) Axis windows with appropriate names and units (if applicable) for those items.

9. Add a trendline to your graph.

10. In cell A34, copy the equation shown for the best-fit line in your graph. Then, set y = 0 and solve for x. This breaks down to dividing the negative of the y-intercept by the value for the slope (should be negative). Take the value for x and divide it by 1000, because your answer was in mg/cm². But to use the equation given earlier for maximum energy, you need x in units of g/cm². This is your value of the range R of a beta particle emitted from your source.

11. Then plug your value for R into $E = 1.84R + 0.212$ and get a value for E. Place this value in cell B36. In cell A36, enter E =.

12. In cell A38 enter True Value for E =. Then in cell B38, enter the literature value for your source. (Sr-90 has E = 0.546 MeV and Tl-204 has E = 0.7634 MeV.)

13. In cell A40 enter Percent Error =. In cell B40, enter the formula =((ABS(B36-B38))/B38)*100. This formula represents the formula

$$\% \ error = \frac{|true - measured|}{true} \times 100 .$$ (2)

Conclusions:

You should have found the value for the maximum energy of a beta particle from your source and the percent error of this result when compared to the literature value. However, this percent error is not a good way to determine experimental error. As discussed in a previous lab, the best way to determine error is to use the standard deviation. So, calculate σ for your value of E – you will have to use propagation of errors. (OPTIONAL)

Post-Lab Questions:

1. Does your data follow Excel's® best fit line? If not, why?
2. Why does the data fluctuate so much at high absorber values, especially those above 1400 mg/cm^2? How can this be handled in the data analysis stage?
3. Is your result for E accurate? Is it still a good result even if it is not exactly the same as the literature value?

Name:		Lab Session:	
Date:		Partner:	

Data Sheet for Beta Energy Lab

Tube #:   Run Duration:

Dead Time: _____   _____

                                                                 (Time)

Counts	Corr. Counts	Thickness	In (Counts)

Equation for line: y=

For y=0,   x= _____ mg/cm^2

Conversion   x= _____ g/cm^2   (This is the range)

Use E =
1.84*R+0.212

                              E= _____ MeV

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

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Lab #12: Absorption of Gamma Rays

Objective:

The student will investigate the attenuation of radiation via the absorption of gamma rays.

Pre-lab Questions:

1. How do gamma rays interact with matter (hint: there are three)?
2. Where are gamma rays on the electromagnetic spectrum? What are the characteristics (high, low, short, or long) of their wavelength, frequency, and energy?
3. How do you calculate mass thickness (g/cm^2) from other quantities of a material?

Introduction:

Gamma radiation unlike alpha and beta radiation, consists of electromagnetic waves. Gamma rays are emitted as photons, or little "packages" of energy called quanta, which travel at the speed of light ($c = 3.0 \times 10^8$ m/s[1]). What differentiates gamma rays, x-rays, visible light, and radio waves is their position in the electromagnetic spectrum (see Figure 1). What actually happens is that some of these "zones" actually overlap, especially between x-rays and gamma rays. While this is not shown in explicitly in Figure 1, you can see that the x-rays and gamma rays do reside next to one another on the spectrum.

---

[1] A unit conversion shows that 3.0×10^8 m/s = 30 cm/ns. That means in one nanosecond light travels 30 cm or in one second light travels 30 billion centimeters.
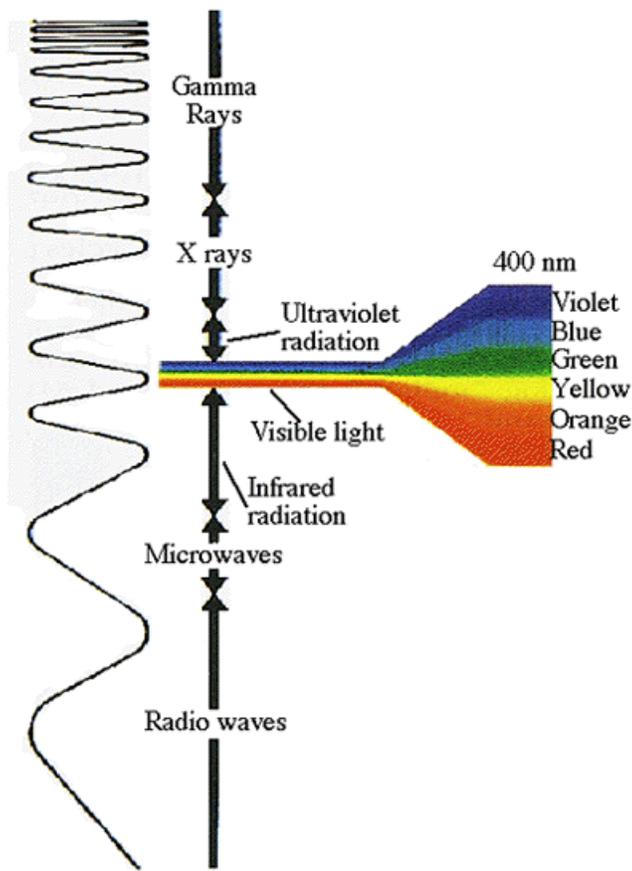
Figure 1: The electromagnetic spectrum

One significant difference between x-rays and gamma rays is their origin. X-rays are produced in the electron shells, while gamma rays are produced in the nucleus. X-rays are created when electrons undergo a deceleration or jump to lower energy levels. Gamma rays are created by energy transitions in the nucleus. In this experiment, we are mostly concerned with gamma rays, because any x-rays present will be shielded by air and matter acting as absorbers.

When a beam of gamma rays impinges on a sheet of absorbing material, some of the radiation will be absorbed or scattered[2]. As the thickness of the absorber is increased, the fraction of the radiation passing through will decrease. When exactly half the radiation passes through the absorber (and the other half is absorbed or scattered), the thickness of the absorber is called the **half thickness**, $X_{1/2}$.

---

[2]   Gamma rays interact with matter in three ways: (1) photoelectric effect (ionization), (2) Compton effect, and (3) pair production (e^+e^-). Your instructor can explain more.

This thickness, $X_{1/2}$, is not normally how we perceive thickness. We normally consider it to be a distance possibly in cm. Here, thickness is short for **mass thickness**. Why? Because the thickness of different materials represents different amounts of matter (atoms). But a mass thickness is used to represent how much matter is being passed through (regardless of whether it is air, aluminum, or lead). To calculate mass thickness you simply multiply the density of the material (g/cm^3) times its length, or normal thickness, (cm) to get the mass thickness (g/cm^2). The absorbers you will use for this experiment have their thickness listed as mass thickness because that quantity can be used to compare the plastic to lead absorbers.

Since the intensity of radiation is reduced by 50% by passing through one $X_{1/2}$, it will be reduced by another 50%, or only to 25% of the original intensity, in passing through a second $X_{1/2}$ of absorber. A linear relationship is obtained if the data are plotted using semi log paper or if the logarithm of the activity is plotted as a function of the absorber thickness.

The attenuation (or absorption and scattering) of gamma rays is exponential in nature, which is shown by the equation:

$$I = I_o e^{-\mu X} \tag{1}$$

where I is the intensity of the beam after passing through X amount of absorbing material, I_o is the original intensity, μ is the mass attenuation coefficient, and X is the mass thickness. Since the intensity of the gamma rays is cut in half after passing through $X_{1/2}$, we can rewrite Equation 1 as

$$\frac{1}{2} I_o = I_o e^{-\mu X_{1/2}} . \tag{2}$$

The I_o terms cancel giving

$$\frac{1}{2} = e^{-\mu X_{1/2}} , \tag{3}$$

which can again be rewritten by taking the natural logarithm of both sides

$$\ln\left(\frac{1}{2}\right) = -\mu X_{1/2} . \tag{4}$$

Using the rules of exponents, we know that $\ln(1/2) = -\ln(2)$, so that gives

$$\ln(2) = \mu X_{1/2} . \tag{5}$$

One final rearrangement gives us a value of the mass attenuation coefficient

$$\mu = \frac{\ln(2)}{X_{1/2}} = \frac{0.693}{X_{1/2}}.$$

(6)

During your data analysis, you will find a value for $X_{1/2}$, and thus one for μ.

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.

- Radioactive Source (gamma ray emitter – any of the sources pictured in Figure 3).

Figure 3: Kit of eight different gamma sources.

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.

2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 60.

3. First do a run without a radioactive source to determine your background level.

4. Next, place the radioactive source in the second shelf from the top and begin taking data.

5. Place an absorber piece in the top shelf and take another run of data.

6. Repeat this a minimum of 5 more times with absorbers of increasing thickness.

Data Analysis:

1. Open Microsoft Excel$^{®}$ and import your data into it.

2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.

3. In cell G9, enter **Thickness** and in cell G10 enter **mg/cm^2**. Then starting in cell G13, enter the thickness for the absorbers used. For cell G13, it should be zero (no absorber used). In column F, under Notes, it may be convenient to enter the letters associated with the absorbers you used.

4. In cell H9 enter **Dead Corr.** and in cell H10 enter **Counts**. Then starting in cell H13, enter a formula to correct for the dead time of the GM counter. Copy this formula down the column for all the data you collected.

5. In cell I9 enter **Corrected** and in cell I10 enter **Counts**. Then starting in cell I13, enter a formula to correct for the background of the GM counter. Copy this formula down for all the data you have.

6. Next, make a graph of Corrected Counts per Minute vs. Thickness. Start with the **Chart Wizard** either by choosing **Chart** from the **Insert** Menu or pressing its icon on the top toolbar.

7. Select the **Thickness** values in the G column and the **Corrected Counts** values in the I column.

8. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

9. Choose whether you want to view your graph as a separate worksheet as your data, or you wish to see a smaller version of the graph with the data.

10. Right click on the y-axis of the graph and choose the **Format Axis** option. Then choose the **Scale Tab**, and check the **Logarithmic Scale** option towards the bottom.

11. Add a trendline to your data to obtain the equation of the best fit line through your data.

Conclusions:

From your best-fit line equation, find the values for $X_{1/2}$ and μ. Make sure your answers are in the appropriate units (involving grams and centimeters).

Post-Lab Questions:

1. Is your data linear? If not, why?
2. Looking at your data and equating intensity and counts per minute, does your result for $X_{1/2}$ a correct approximation? (Does your result match the data?)
3. Can we be completely shielded from gamma rays? If not, then why bother?

4. Comparing your range for alpha particles, the absorption of beta particles, and now the results for gamma rays, why are they different?

Name:		Lab Session:	
Date:		Partner:	

Data Sheet for Gamma Absorption Lab

Tube #: _____

Run Duration: _____

Dead Time: _____

(Time)

Counts	Corr. Counts	Thickness	ln (Counts)

Equation for line:

y= _____

μ= _____ mg/cm^2

OR

μ= _____ g/cm^2

Calculate $x\_1/2 = \ln(2)/\mu$

$x\_1/2 =$ _____ g/cm^2

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

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 1.34×10^{21} atoms today. When will it have 1.675×10^{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

$$N(t) = N - \lambda N \Delta t \tag{1}$$

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).
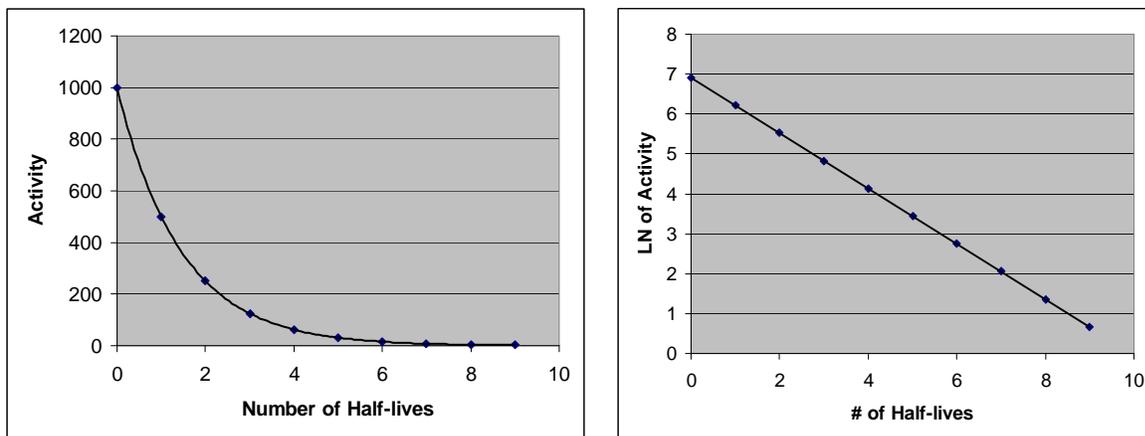
Figure 1: Exponential and Linear decay curves shown respectively

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 $activity = \dfrac{\# \, of \, counts}{time} = \dfrac{\# \, of \, atoms}{time}$. (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

$$N(t) - N = -\lambda N \Delta t \tag{2}$$

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

$$\Delta N = N(t) - N = -\lambda N \Delta t \tag{3}$$

Dividing both sides of the equation gives

$$\frac{\Delta N}{\Delta t} = -\lambda N \tag{4}$$

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

$$\frac{dN}{dt} = -\lambda N \tag{5}$$

This is a separable differential equation that becomes

$$\frac{dN}{N} = -\lambda dt \tag{6}$$

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

$$\int_{N_o}^{N} \frac{dN\,'}{N\,'} = -\lambda \int_{0}^{t} dt' \tag{7}$$

The solution to this equation is

$$\ln(N) - \ln(N_o) = -\lambda t \tag{8}$$

Solving for ln(N), gives

$$\ln(N) = \ln(N_o) - \lambda t \tag{9}$$

---

[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

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

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.

- Radioactive Source (Cs/Ba-137m Isotope Generator – shown in Figure 3)

Figure 3: Isotope Generator to make Ba-137m from Cs-137

Procedure:

1. Setup the Geiger counter as you have in the previous experiments. Set the **Voltage** of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the **Preset** menu, set **Runs** to zero and set **Preset Time** to 30.
3. First do a run without a radioactive source to determine your background level.
4. Next, from the **Preset** menu, set the Runs to 31. (This will take 30 more runs so the total number of runs is 31.)
5. From the isotope generator, obtain 10-12 drops of Ba-137m. Place the radioactive source in the second shelf from the top and begin taking data.
6. Record the data to a file on disk or into a data table.
7. You may wish to do a second trial if time allows.

Data Analysis:

1. Open Microsoft Excel® and import your data into it.
2. In cell E2, enter **Dead Time =** and in cell F2 enter the dead time determined for your GM tube.
3. In cell G9 enter **Dead Corr.** and in cell G10 enter **Counts**. In cell G13, enter a formula to correct for resolving time and copy it down for the cells that have counts in column C.
4. In cell H9 enter **Corrected** and in cell H10 enter **Counts**. In cell H13, enter a formula to correct for background radiation and copy this down for the cells that have counts in column G.
5. In cell I9 enter **Natural Log** and in cell I10 enter **of Activity**. In cell I13 and below, enter a formula for the natural log (ln) of the corrected counts, and copy this down for the cells that have counts in column H.
6. In cell J10 enter **Time (s).** In cell J13, enter 30. In cell J14, enter the formula =J13+30, and copy this down for the cells that have entries in column I.
7. Next, make a graph of Natural Log (Ln) of Activity vs. Time. Start with the **Chart Wizard** either by choosing **Chart** from the Insert Menu or pressing its icon on the top toolbar.
8. Select **Time** values in the J column and the Ln of **Activity** values in the I column.

9. Fill in the **Chart Title, Value (X) Axis**, and **Value (Y) Axis** windows with appropriate names and units (if applicable) for those items.

10. Adjust the size of the graph for your preference (or the instructor's). You may also wish to adjust the scales on one or more of the axes. Again, this is a preference issue.

11. Right click on one of the data points and from the menu that appears, choose **Add Trendline**. Make sure that the **Linear** option is chosen (should be darkened). Then click on the **Options** tab and check the boxes for **Display equation on chart** and **Display R-squared value on chart**. This will make the equation of the best-fit line appear as well as a number that represents the percent of linearity of the data.

12. Make another graph, except this time use the Corrected Counts vs. Time. From this graph, you will be able to see the true exponential nature of the decay and also be able to estimate approximate half-lives.

13. Now, you will perform a linear regression over three different sets of numbers. A linear regression finds the slope and y-intercept for the best-fit line through the data chosen.

14. In the Tools menu, choose **Data Analysis** (ask your teacher if this option does not appear). Then a small window will appear. Scroll down and choose the **Regression** option. Now, a larger will appear. You will have to choose **X-Values, Y-Values**, and an **Output Range**.

15. For the first linear regression, choose the first 15 data points under **Natural Log of Activity** (column I) for the Y-Values by clicking on the box at the end of the input window, outlining these numbers in column I, and then pressing the Enter key. (You can either count 15 data points, or a small yellow box will appear and you enclose numbers in the column until it reads 15R x 1C which means 15 rows in one column.) Now, for the **X-Values**, choose the first 15 Time values in column J. Make sure the **Output Range** is chosen. Then, either enter $M$1 in the input window or click on the box and choose the M1 square. Click on **OK** and the results will appear on the spreadsheet.

16. For the second linear regression, choose the data points 16-30 and choose the output range to be M19. (We are squeezing them together because if you print in landscape, these two will be on the same page.)

17. For the third linear regression, choose all 30 data points and choose the output range to be M37. Does the slope for this linear regression match the slope from the first graph?

18. To perform your final calculations, you will need the slopes from these linear regressions and the error for the slope. The slope is the **Coefficient** of the X-Variable (Why?) and is found in cells N18, N36, and N54. The error is the **Standard Error** of the X-Variable and is found in cells O18, O36, and O54.

Conclusions:

Fill in the following table:

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

The variable λ is the **decay coefficient**. If you assumed you plotted Equation (9), then the slope from the linear regression is the negative of λ

$$\lambda = -(slope).$$ (15)

From Equation (14), you can calculate the half-life:

$$t_{1/2} = \frac{\ln(2)}{\lambda} \approx \frac{0.693}{\lambda}.$$ (16)

If you perform the proper error propagation, then you will end up with a final equation of

$$\frac{\sigma_{t_{1/2}}}{t_{1/2}} = \frac{\sigma_\lambda}{\lambda}.$$ (17)

Rearranging this equation to calculate $\sigma_{t_{1/2}}$ gives

$$\sigma_{t_{1/2}} = \frac{\sigma_\lambda \cdot t_{1/2}}{\lambda}.$$ (18)

Now, to find the number of σ's that your result is away from the true value of $t_{1/2}$ = 153 s, we use the following equation

$$\# \; of \; \sigma's = \frac{|measured - true|}{\sigma_{t_{1/2}}}. \tag{19}$$

What you measure is the distance from your result to the true value and then see how many **standard deviations** that is. The rule of thumb is that the result should be no more than 2 σ's away from the true value to be statistically good.

Post-Lab Questions:

1. Write your result with the error, i.e. 153 s ± 1 s. Is this result (statistically) good? (Recall that any value judgments must be justified.)
2. Which of the three results is better? Why?
3. How can the situation in #2 be resolved so that a linear regression over all the data gives a more valid result? (How can you combine the halves of the data?)

Name:		Lab Session:	
Date:		Partner:	

Data Sheet for Half-Life Lab

Tube #: _____   Run Duration: _____

Dead Time: _____   (Time)

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

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.

Appendix A – SI Units

        The standard units of measure used in physics are the MKS (Meter, Kilogram, Second) version of the International System (SI) of Units. They are commonly referred to as the metric units. The latest version of the standards can be found in the following three resources:

- "Preferred Metric Units for General Use by the Federal Government," (Federal Standard 376B), January 27, 1993, General Services Administration.
- "Guide for the Use of International System of Units (SI)," (NIST Special Publication 811) (obtainable at the NIST website - http://www.nist.gov)
- "The International System of Units (SI)," (NIST Special Publication 330) (obtainable at the NIST website – http://www.nist.gov)

        Below, you will find the proper SI units – base and derived – that we will use. Also, there is a table showing the latest prefixes for SI Units.

Physical Quantity	Name of Unit	Symbol
Base Units		
Length	meter	m
Mass	kilogram	kg
Time	second	t
Electric current	ampere	A
Derived Units		
Force	newton	N
Energy	joule	J
electric potential	volt	V
electric resistance	ohm	Ω
electric capacitance	farad	F
activity (radioactive source)	becquerel	Bq

Table 1: Proper SI units that may be used in the lab manual.

Mulitplication Factor	Prefix Name	Prefix Symbol
$1\,000\,000\,000\,000\,000\,000\,000\,000 = 10^{24}$	yotta	Y
$1\,000\,000\,000\,000\,000\,000\,000 = 10^{21}$	zetta	Z
$1\,000\,000\,000\,000\,000\,000 = 10^{18}$	exa	E
$1\,000\,000\,000\,000\,000 = 10^{15}$	peta	P
$1\,000\,000\,000\,000 = 10^{12}$	tera	T
$1\,000\,000\,000 = 10^{9}$	giga	G
$1\,000\,000 = 10^{6}$	mega	M
$1\,000 = 10^{3}$	kilo	k
$100 = 10^{2}$	hecto	h
$10 = 10^{1}$	deca	da
$0.1 = 10^{-1}$	deci	d
$0.01 = 10^{-2}$	centi	c
$0.001 = 10^{-3}$	milli	m
$0.000\,001 = 10^{-6}$	micro	μ
$0.000\,000\,001 = 10^{-9}$	nano	n
$0.000\,000\,000\,001 = 10^{-12}$	pico	p
$0.000\,000\,000\,000\,001 = 10^{-15}$	femto	f
$0.000\,000\,000\,000\,000\,001 = 10^{-18}$	atto	a
$0.000\,000\,000\,000\,000\,000\,001 = 10^{-21}$	zepto	z
$0.000\,000\,000\,000\,000\,000\,000\,001 = 10^{-24}$	yocto	y

Appendix B – Common Radioactive Sources

    Below is a list of commonly used radioactive sources. All of these sources are available from Spectrum Techniques, Inc. The standard radioisotopes sold by Spectrum Techniques, Inc. are exempt from NRC licensing and require no special handling, storage or disposal.

Isotope	Activity	Half-Life	Emissions	Energies
Ba-133S	1 µCi	10.7 years	Gamma	81.0, 276.3, 302.7, 355.9, 383.7
Cd-109S	1 µCi	453 days	Gamma	88.0
Co-57S	1 µCi	270 days	Gamma	122.1, 136.4
Co-60S	1 µCi	5.27 years	Gamma, Beta	1173.2, 1332.5, ß317.9
Cs-137S	1 µCi	30.1 years	Gamma, Beta	32, 661.6 ß511.6, ß1173.2
Cs-137S5	5 µCi	30.1 years	Gamma, Beta	32, 661.6 ß511.6, ß1173.2
Cs/ZnS	1 µCi	Mixed	"Unknown"	32, 661.6, 1115.5
Eu-152	1 µCi	13.5 years	Gamma	Multiple
Mn-54S	1 µCi	312 days	Gamma	834.8
Na-22S	1 µCi	2.6 years	Gamma	511.0, 1274.5
Po-210S	0.1 µCi	138 days	Alpha	5304.5
Sr-90S	0.1 µCi	28.5 years	Beta	546.0
Tl-204S	1 µCi	3.78 years	Beta	763.4
Zn-65S	1 µCi	244 days	Gamma	1115.5

Isotope Generator

The Cs-137/Ba-137m Isotope Generator provides a convenient means of producing a short half-life isotope for demonstrating radioactive decay experiments. This improved design is based on the original Union Carbide patent and can produce up to 1000 samples of the Ba-137 isotope with a half-life of 2.6 minutes using a simple eluting solution of 0.9% NaCl. The kit is supplied complete with the Cs-137/Ba-137m generator, 250 ml of eluting solution, a syringe for the elution, planchets and a storage case.

Appendix C – Statistics

Statistics play a very important part of physics, especially nuclear physics, because we are dealing with atoms that number on the order of Avogadro's number. It is impossible to deal with every single atom individually, so we rely on statistics to give us a prediction of behavior.

Statistics uses two main quantities in predicting behavior, the **mean** and the **standard deviation**. The mean is the average, what most of the particles are doing. The standard deviation tells us how many particles are also doing almost the same thing as the mean. The previous experience that students usually have with mean and standard deviation is from mathematics class (unless a statistics class has been taken). From this experience, they know that mean can formulated by

$$\overline{x} = \sum_{i=0}^{N} \frac{x_i}{N}, \tag{1}$$

where $\overline{x}$ is the mean of a set of measurements x_i (i = 1, 2, 3, …, N), and N is the number of measurements taken.

Most students can recall how to calculate the standard deviation

$$\sigma = \sqrt{\frac{\sum_{i=0}^{N} \left(\overline{x} - x_i\right)^2}{N-1}}. \tag{2}$$

What this equation does is measure the variance without regard to direction above or below the mean (that is why you square and then square root – it is equivalent to absolute value which just measures distance). These equations hold for most everything the students have dealt with up to this point in school. The reason is that most measurements follow a **Gaussian distribution** (symmetric about a mean).

Counting in nuclear physics is not symmetric about a mean. There is usually some count rate that is pretty small because probability of decay is pretty small. Then you also get high count rates. (Look back at the data from the statistics experiments you performed this year.) When the data collects to a small number with a bit of a tail, this is no longer a Gaussian distribution. The standard three statistical distributions will

be discussed below to assist the student learning more in detail about the statistics of counting in nuclear physics. There are many more statistical distributions used for various reasons but they will not be discussed here. (An example is the Landau distribution used in describing the energy loss of a charged particle in matter, which is different because it has an infinitely long tail to it.)

The first distribution is the **Binomial** distribution. This distribution is used when you have two possible outcomes, the probability of getting one of those outcomes (and thus the other) is a constant number independent of the number of trials, and the selection of either outcome does not affect that outcome again in later trials. A good example of this is flipping a coin.

To look at an example, we have an experiment where there are only two outcomes A and B. In a binomial distribution, we deal with p, the probability that you will get one of the outcomes (A), and q, the probability that the other outcome occurs (B). Sometimes, instead of q, statistics books use $1-p$, which is how q is calculated. Then, the binomial distribution gives the probability, $P(n)$, that n out of N objects are A is given by

$$P(n) = \frac{N!}{(N-n)!n!}p^n q^{N-n} = \frac{N!}{(N-n)!n!}p^n (1-p)^{N-n} .$$

(3)

Now for this distribution the mean, m, is given by

$$m = pN$$

(4)

and the standard deviation is calculated with any of the following

$$\sigma = \sqrt{mq} = \sqrt{Npq} = \sqrt{Np(1-p)} .$$

(5)

In order to study radioactive decays, we need a more useful distribution. We need one for a very large number of counts and one that can handle a very small probability of success (large N and small p). It just happens that the **Poisson** distribution is the special case of the binomial distribution given those two conditions. The Poisson distribution gives the probability, $P(n)$, that n out of N objects are A as

$$P(n) = \frac{m^n}{n!}e^{-m} ,$$

(6)

where m is the mean of the distribution ($m = Np$). The nicest feature of the Poisson distribution is the ease to calculate standard deviation. The formula is

$$\sigma = \sqrt{m} \;.$$ (7)

But for individual measurements, we take the standard deviation to be the square root of the number of counts, here N,

$$\sigma = \sqrt{N} \;.$$ (8)

So if you have a count rate of 10,000 cpm, then the standard deviation is ±100 cpm.

You may have noticed that for large values of m, the Poisson distribution becomes hard to use. So we use a special case of the Poisson distribution for $m > 20$ (the accepted rule of thumb), or a different special case of the Binomial distribution that has large counts, low probability, and a large mean. This new distribution is called the <mark>Normal or Gaussian</mark> distribution. This is the distribution that most students are familiar with, its common name is the **bell curve**. Another added feature of this distribution is that it can handle continuous variables (like most of those in our experiments), unlike the Poisson and Binomial distributions, which can only handle discrete variables[*]. The Gaussian distribution is given by

$$P(n) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-m)^2}{2\sigma^2} \right].$$ (9)

This equation gives us the mean and standard deviation equations that we are accustomed to in Equations (1) and (2).

More details about statistical distributions must be researched in other books. There is a huge amount of resources out there, statistical books and methods in experimental physics books abound. There are some of the latter books listed below if you wish to do more research. These should be available at most university libraries, or through interlibrary loan services.

1. P.R. Bevington, D.K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, (McGraw-Hill, 1992).
2. G. Knoll, *Radiation Detection and Measurement*, (John Wiley & Sons, 1989)[**].
3. N. Tsoulfanidis, *Measurement and Detection of Radiation*, (McGraw-Hill, 1995).

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[*] The number of counts is a discrete, there is no such thing as a fraction of a count (there is nothing between 1 and 2). Length is a continuous variable, between 1 and 2 is 1.5. Between 1 and 1.5 is 1.25 and so on.

[*] [*] There is a newer edition this one. This edition is the one the author owns.

4. W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, (Springer-Verlag, 1994)

Linear Regression

When Excel® or a graphing calculator performs a linear regression, it makes two calculations to determine the slope and y-intercept of the best-fit line for the data. How does it do it? Linear regressions are carried out using the method of least squares. This method finds the line that minimizing the distance all the data points are away from the best-fit line. This may sound complicated but it is really not if you know a little algebra and one concept from calculus. Recall, that in math to find distance we use absolute value, which is equivalent to the square root of the square[*]. (The squaring and subsequent square rooting of a quantity is a common mathematical trick to substitute taking an absolute value.) Let us start with an experiment, where you measure variables x and y over N trials. The expected result is

$$y = mx + b$$

but remember that we take N measurements. So we get

$$y_1 = mx_1 + b$$
$$y_2 = mx_2 + b$$
$$....$$
$$y_N = mx_N + b.$$

These equations are not in general consistent; if we take different pairs of equations, and solve them for m and b, we obtain different values for m and b. The reason for the various values of m and b, of course, is that there are experimental errors in the y_i. Since the two sides of the equation, $y_i = mx_i + b$, are not exactly equal, but differ by an amount let's call d. To calculate d, we use

$$d_i = mx_i + b - y_i,$$

where d_i is the deviation corresponding to the ith equation and the pair of observations (x_i, y_i). Since the values for d_i are the results of the experimental errors, we can assume

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[*] The terms for absolute value and square root of a square are equivalent. That is $|x| = \sqrt{x^2}$.

that they are distributed according to the **Gaussian** (or **normal**) distribution. This allows us to use the method of maximum likelihood to find the most probable values of m and b.

This method finds the most probable values of m and b by minimizing the sum of the squares of the deviations. That is, we minimize the quantity, d^2, which has the form

$$d_i^{\;2} = \sum_i \left(mx_i + b - y_i\right)^2 .$$

The principle of least squares is finding the values of m and b that minimize d^2. To minimize the two variables, we take the partial derivative (due to the fact that m and b are in the equation) of the function with respect to each of the variables (m and b) in turn and set each derivative equal to zero. Rearranging the equations, we get [1]

$$\sum y_i = m\sum x_i + bN \text{ and } \sum x_i y_i = m\sum x_i^{\;2} + b\sum x_i ,$$

where N is the number of points that are being used in the fitting process. Further rearrangement, gives the following results for m and b:

$$m = \frac{N\sum x_i y_y - \left(\sum x_i\right)\left(\sum y_i\right)}{N\sum x_i^{\;2} - \left(\sum x_i\right)^2} \text{ and } b = \frac{\left(\sum y_i\right)\left(\sum x_i^{\;2}\right) - \left(\sum x_i y_i\right)\left(\sum x_i\right)}{N\sum x_i^{\;2} - \left(\sum x_i\right)^2} .$$

These values for m and b, are the slope and y-intercept, respectively, for the best-fit line for the data. This is the calculation that a computer or calculator makes to output the equation of the best-fit line.

Propagation of Errors

Often in laboratory experiments, the results will not be measured directly. Rather, the results will be calculated from several measured physical quantities. Each of these measured quantities consists of a mean (average) value and an error. What is the resulting error in the final result of such an experiment? It is difficult to say how the error of the measured quantities will translate (or propagate) to the error of the final result.

The difficulty arises because we do not which sign, plus or minus, really exists for the error. Recall that when reporting error, we show both signs, ±, to indicate that we

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[1] The summations, Σ, are still over the index *i* but it has been dropped for convenience.

do not truly know where the true values lie. As an example, assume that we measure two quantities, A ± ΔA and B±ΔB. (ΔA and ΔB represent the error on A and B, respectively.) Then, we combine A and B into Z by Z = A + B. The extreme values of the error are easy to predict, they are given by

$$(A + \Delta A) + (B + \Delta B) = (A + B) + (\Delta A + \Delta B)$$ or $$(A - \Delta A) + (B - \Delta B) = (A + B) - (\Delta A + \Delta B).$$

The problem is that most likely there is a mixture, some error from A cancels some of the error or vice-versa. Then the situation becomes more complicated. However, this problem has arisen before, the distance between two points on the Cartesian plane. There we treat the distances independently (actually, perpendicular), but combine them by the Pythagorean theorem. Simple enough solution, but what if the result, Z, depends on both A and B (Z is a function of A and B). Then the problem uses the same method but involves partial derivatives. (Note: The author considers this too complex of a concept to explain here and refers any interested readers to their instruction or multivariable calculus textbooks.) Due to the complexity of the work with partial derivatives, the results of the error for various operations are given in the table below.

Operation	Relation between ΔZ, ΔA, and ΔB
Z = A + B	$(\Delta Z)^2 = (\Delta A)^2 + (\Delta B)^2$
Z = A − B	$(\Delta Z)^2 = (\Delta A)^2 + (\Delta B)^2$
Z = AB	$\left(\dfrac{\Delta Z}{Z}\right)^2 = \left(\dfrac{\Delta A}{A}\right)^2 + \left(\dfrac{\Delta B}{B}\right)^2$
Z = A/B	$\left(\dfrac{\Delta Z}{Z}\right)^2 = \left(\dfrac{\Delta A}{A}\right)^2 + \left(\dfrac{\Delta B}{B}\right)^2$
Z = nA *	$\dfrac{\Delta Z}{Z} = n\dfrac{\Delta A}{A}$
Z = ln (A)	$\Delta Z = \dfrac{\Delta A}{A}$
Z = e^A	$\dfrac{\Delta Z}{Z} = \Delta A$

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* n is a constant (any real number)

Any further discussion of data analysis and error analysis techniques should be referred to Taylor, John R. *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements.* University Science Books, 1982.

Appendix D - Radiation Passing Through Matter

Our three forms of radiation must interact with matter while passing through it or we would never be able to detect them. However, how they interact with matter is completely different. Therefore, I will break this appendix up into three sections to study alpha particles, beta particles, and gamma rays individually.

Alpha Particles

Alpha particles are helium nuclei, two protons and two neutrons, so it is considered a heavy particle (compared to other particles in the universe). As an alpha particle passes through matter, it passes close to many atoms. The positive charge from the alpha particle attracts an electron from the valence shell of an atom it passes. Sometimes the attraction is strong enough to free the electron from the atom, this process is known as ionization. During this process, the alpha particle ends up giving up some energy to the freed electron. This is the only true interaction that the alpha has besides depositing its energy in some atoms through inelastic collisions. Either way, the alpha particle loses some energy each time it interacts, which is denoted by physicists as *dE/dx*. To calculate *dE/dx*, one uses the Bethe-Bloch formula which is

$$ -\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \tag{1} $$

where $2\pi N_a r_e^2 m_e c^2 = 0.1535 \; MeV \; cm^2 / g$ and

r_e: classical electron radius = 2.817 x 10^{-13} cm

m_e: electron mass = 9.11 x 10^{-31} kg

N_a: Avogrado's number = 6.022 x 10^{23} / mol

I: mean ionization energy

Z: atomic number of absorbing material

A: atomic mass of absorbing material

ρ: density of absorbing material

z: charge of incident particle in units of *e*

β = v/c of the incident particle

$$ \gamma = \frac{1}{\sqrt{1 - \beta^2}} $$

δ: density correction

C: shell correction

W_{max}: maximum energy transfer in a single collision $\approx 2m_e (c\beta\gamma)^2$.

Note that the equation for *dE/dx* is negative to indicate that it is an energy loss. There are two correction terms, one for density effects and one for shell effects. While there are many other possible corrections that could be made, they are negligible ($\approx$ 1%).

The ***density effect*** arises due to the fact that atoms in the matter are polarized by the electric field of the alpha particle passing through it. Thus, the electrons on the far side of the atom will be shielded from interactions with the particle. However, the denser the material, the closer the atoms are together and more shielding that occurs. Since this term takes away possible interactions, is subtracted from the original formula.

The ***shell effect*** gives a small correction to the Bethe-Bloch formula, but still must be taken into account. This effect only occurs when the velocity of the incident particle is equal to or less than the orbital speed of the electrons. This situation invalidates the assumption that the electrons are stationary with respect to the incident particle.

While an alpha particle will lose energy in a collision, it is not much to make it stray from its path. Therefore, an alpha particle passing through matter traverses it in a relatively straight path while giving up energy in mainly ionization interactions.

Beta Particles

Beta particles are electrons that are emitted by the nucleus. They also undergo the ionization energy loss as predicted by the Bethe-Bloch formula (Equation 1). However, electrons are much less massive than alpha particles, $m_\alpha = 7342 m_\beta$, so there is additional interaction due to the fact that the beta particle is greatly scattered through matter. A beta particle passing close to a nucleus can have an electromagnetic interaction that will slow the beta down and cause it to change directions; in essence it will be braking. This "braking radiation" is described by its German name, ***bremmstrahlung***. Whenever the beta particle undergoes bremmstrahlung, it loses energy but when an electron changes energy, it must absorb or emit electrons. Thus, bremmstrahlung is the production of x-ray photons due to the interactions of electrons (beta particles) with nuclei in matter.

Again, an alpha particle will pass almost straight through matter. The opposite is true for a beta particle. It undergoes multiple scatterings that cause it path to be very much of a "zigzag" pattern with no way to predict its path.

Gamma Rays

Gamma rays are photons that have an energy, frequency, and wavelength sufficient enough to be classified as a gamma ray in the electromagnetic spectrum. Photons interact three different ways in matter: (1) Photoelectric effect, (2) Compton scattering, and (3) Pair production.

The ***photoelectric effect*** is when a photon is absorbed by an electron with the subsequent ejection of the electron from the atom. The maximum energy of the ejected electron is given by

$$KE_{max} = E_\gamma - \Phi \tag{2}$$

where E_γ is the energy of the incident photon and Φ is the work function (energy necessary to free the electron).

Compton scattering is the scattering of photons on electrons. Originally, this was only for free electrons but if the photon energy is sufficient to overcome the binding energy, then we can consider the electron as free. In this collision, the photon is incident on the electron with an energy $h\nu$, where h is Planck's constant and n is the frequency of the photon. The photon undergoes an inelastic collision with the electron, so the photon gives some of its energy to the electron. The photon leaves with a new energy $h\nu'$ and the electron leaves with a certain amount of kinetic energy that is $\Delta E = h\nu - h\nu'$. We can calculate $h\nu'$ by determining the scattering angle of the photon, θ. Then we can use the equation:

$$h\nu' = \frac{h\nu}{1 + \gamma(1 - \cos\theta)} \tag{3}$$

The process of *pair production* refers to the transformation of a photon into an electron-positron pair. In order to conserve momentum, this process can only occur when the photon is close to the nucleus. Theoretically, the photon needs only the energy that equates to the mass of an electron-positron pair. This energy is 1.022 MeV. However, this process very, very rarely occurs below 1.5 MeV of photon energy,

because nature does not like creating the electron and positron and then having them just sit there. Therefore, pair production only occurs when there is not only the mass (energy) available, but also some extra energy for kinetic energy for the electron and positron.

The **photoelectric** effect dominates for photon energies from 4 eV up to 0.5 MeV. Then **Compton scattering** dominates up to 2 MeV. Finally, **pair production** dominates above 10 MeV, but only if a nucleus is present to absorb the momentum. (Between 2 MeV and 10 MeV there is no true dominating absorption mechanism for photons.)

For further reading on this topic, please refer to the Suggested References section.

Appendix E – Suggested References

There is a large amount of information in books, journal articles, and on the Internet relating to the topics in this lab manual (Radiation, particle interaction with matter, and particle detection). Since many high school teachers do not have access to journals, I have only listed books and website references.

Two of the best books on the topics of particle detectors that cover Geiger counters are

- Knoll, G. *Radiation Detection and Measurement*, John Wiley & Sons, 1989.
- Tsoulfanidis, N. *Measurement and Detection of Radiation*, McGraw-Hill, 1995.

As for websites, there is a very large number of websites that would consume page after page of this manual. Instead, this is a small sample of websites, which represent the ones that the author deemed most helpful while writing this manual. They are not listed in any particular order of importance, just alphabetically. Also, these sites were verified in July of 2002, and any further accuracy of the information cannot be guaranteed. In addition, if further resources are desired, do a search on a website such as Google (http://www.google.com).

- **American Nuclear Society** – http://www.ans.org
  This is the professional organization for nuclear engineers, nuclear scientists, and other nuclear related professionals. They sponsor very good programs for teachers in different areas of the country. There is large public information section covering many different levels of education.

- **EPA – Radiation Protection Program** – http://www.epa.gov/radiation

  This is the EPA's webpage for how to protect the environment from radiation's harm and explains how they clean it up after it happens. The EPA also tries to educate people that not all radiation is harmful.

- **Health Physics Society** – http://www.hps.org

  This is the professional organization for health physicists. It has more public information available, as well as an "Ask the Expert" area. Some of its regional chapters are excellent resources as well.

- **Nuclear Engineering 104A: Radiation Detection and Nuclear Instrumentation Laboratory (Fall 2001)** – http://www.nuc.berkeley.edu/dept/Courses/NE_104A

  This link leads you to a list of files that comprise the course information. There is no main page that accesses all of the files. This course contains many materials on the basics of radiation and its detection.

- **RadEFX Radiation Health Effects Information Resource** - http://radefx.bcm.tmc.edu/chernobyl

  This is a very neat webpage where experts answer questions from basic radiation facts to questions mainly focusing on the worldwide effects of Chernobyl.

- **Radiological Information from the Collider-Acceleration Group at Brookhaven National Laboratory** – http://www.agsrhichome.bnl.gov/AGS/Accel/SND/radiological_information.htm

  This site covers radiation safety information from the most basic form to the very advanced concepts that are involved at the AGS and RHIC particle colliders at BNL. The link on elements is very good.

- **Texas Department of Health – Bureau of Radiation Control** – http://www.tdh.state.tx.us/ech/rad/pages/brc.htm

  This is the website of the State's controlling entity in Texas. (It is suggested that you find your state's radiation department for information relevant to your state.) There may or may not be education information available, it depends on the state.

- **The Radiation and Health Physics Page** –
  http://www.umich.edu/~radinfo/nojava.html

  This is perhaps one of the best, or at least most referenced, webpage dealing with radiation on the Internet. It is a comprehensive website that does supply educational resources.

- **US Nuclear Regulatory Commission** – http://www.nrc.gov

  Find out what the controlling entity in the US for radiation does. There are also public information materials available.

- **University of Waterloo Radiation Safety Training** –
  http://www.rstp.uwaterloo.ca

  Good online training manual with a lot of basic information using animated gifs. Many of the particle interactions with matter are animated.

- **Uranium Information Centre (Melbourne, Australia)** –
  http://www.uic.com.au/ral.htm

  This is an awesome introduction to radiation all around us in everyday life. There are many good cartoon figures that explain the concepts being discussed.

- **Worcester Polytechnic Institute's Radiation Safety Training and Reference Manual** – http://www.wpi.edu/Admin/Safety/RSO/Training/trm.html

  This radiation safety manual is online and covers the basics for many different professions that interact with radiation.

Appendix F – NRC Regulations

10 CFR 30.18, 30.71 Schedule B, and 32.19

§30.18 Exempt quantities.
(a) Except as provided in paragraphs (c) and (d) of this section, any person is exempt from the requirements for a license set forth in section 81 of the Act and from the regulations in parts 30 through 34, 36 and 39 of this chapter to the extent that such person receives, possesses, uses, transfers, owns, or acquires byproduct material in individual quantities each of which does not exceed the applicable quantity set forth in §30.71, Schedule B.
(b) Any person who possesses byproduct material received or acquired prior to September 25, 1971 under the general license then provided in §31.4 of this chapter is exempt from the requirements for a license set forth in section 81 of the Act and from the regulations in parts 30 through 34 of this chapter to the extent that such person possesses, uses, transfers, or owns such byproduct material.
(c) This section does not authorize for purposes of commercial distribution the production, packaging, repackaging, or transfer of byproduct material or the incorporation of byproduct material into products intended for commercial distribution.
(d) No person may, for purposes of commercial distribution, transfer byproduct material in the individual quantities set forth in §30.71 Schedule B, knowing or having reason to believe that such quantities of byproduct material will be transferred to persons exempt under this section or equivalent regulations of an Agreement State, except in accordance with a license issued under §32.18 of this chapter, which license states that the byproduct material may be transferred by the licensee to persons exempt under this section or the equivalent regulations of an Agreement State.
[35 FR 6427, Apr. 22, 1970, as amended at 36 FR 16898, Aug. 26, 1971; 43 FR 6921, Feb. 17, 1978; 52 FR 8241, Mar. 17, 1987; 58 FR 7736, Feb. 9, 1993]
§30.71 Schedule B.

Byproduct material	Microcuries
Antimony 122 (Sb 122)	100
Antimony 124 (Sb 124)	10
Antimony 125 (Sb 125)	10
Arsenic 73 (As 73)	100
Arsenic 74 (As 74)	10
Arsenic 76 (As 76)	10
Arsenic 77 (as 77)	100
Barium 131 (Ba 131)	10
Barium 133 (Ba 133)	10
Barium 140 (Ba 140)	10
Bismuth 210 (Bi 210)	1
Bromine 82 (Br 82)	10
Cadmium 109 (Cd 109)	10
Cadmium 115m (Cd 115m)	10
Cadmium 115 (Cd 115)	100
Calcium 45 (Ca 45)	10
Calcium 47 (Ca 47)	10
Carbon 14 © 14)	100
Cerium 141 (Ce 141)	100
Cerium 143 (Ce 143)	100
Cerium 144 (Ce 144)	1
Cesium 131 (Cs 131)	1,000
Cesium 134m (Cs 134m)	100
Cesium 134 (Cs 134)	1
Cesium 135 (Cs 135)	10
Cesium 136 (Cs 136)	10
Cesium 137 (Cs 137)	10
Chlorine 36 (Cl 36)	10
Chlorine 38 (Cl 38)	10
Chromium 51 (Cr 51)	1,000
Cobalt 58m (Co 58m)	10
Cobalt 58 (Co 58)	10
Cobalt 60 (Co 60)	1
Cobalt 64 (Cu 64)	100
Dysprosium 165 (Dy 165)	10
Dysprosium 166 (Dy 166)	100
Erbium 169 (Er 169)	100
Erbium 171 (Er 171)	100
Europium 152 9.2 h (Eu 152 9.2 h)	100
Europium 152 13 yr (Eu 152 13 yr)	1
Europium 154 (Eu 154)	1
Europium 155 (Eu 155)	10

Fluorine 18 (F 18)	1,000
Gadolinium 153 (Gd 153)	10
Gadolinium 159 (Gd 159)	100
Gallium 72 (Ga 72)	10
Germanium 71 (Ga 71)	100
Gold 198 (Au 198)	100
Gold 199 (Au 199)	100
Hafnium 181 (Hf 181)	10
Holmium 166 (Ho 166)	100
Hydrogen 3 (H3)	1,000
Indium 113m (In 113m)	100
Indium 114m (In 114m)	10
Indium 115m (In 115m)	100
Indium 115 (In 115)	10
Iodine 125 (I 125)	1
Iodine 126 (I 126)	1
Iodine 129 (I 129)	0,1
Iodine 131 (I 131)	1
Iodine 132 (I 132)	10
Iodine 133 (I 133)	1
Iodine 134 (I 134)	10
Iodine 135 (I 135)	10
Iridium 192 (Ir 192)	10
Iridium 194 (Ir 194)	100
Iron 55 (Fe 55)	100
Iron 59 (Fe 59)	10
Krypton 85 (Kr 85)	100
Krypton 87 (Kr 87)	10
Lanthanum 140 (La 140)	10
Lutetium 177 (Lu 177)	100
Manganese 52 (Mn 52)	10
Manganese 54 (Mn 54)	10
Manganese 56 (Mn 56)	10
Mercury 197m (Hg 197m)	100
Mercury 197 (Hg 197)	100
Mercury 203 (Hg 203)	10
Molbdenum 99 (Mo 99)	100
Neodymium 147 (Nd 147)	100
Neodymium 149 (Nd 149)	100
Nickel 59 (Ni 59)	100
Nickel 63 (Ni 63)	10
Nickel 65 (Ni 65)	100
Niobium 93m (Nb 93m)	10
Niobium 95 (Nb 95)`	10
Niobium 97 (Nb 97)	10

Osmium 185 (Os 185)	10	Sulphur 35 (S 35)	100
Osmium 191m (Os 191)	100	Tantalum 182 (Ta 182)	10
Osmium 191 (Os 191)	100	Technetium 96 (Tc 96)	10
Osmium 193 (Os 193)	100	Technetium 97m (Tc 97m)	100
Palladium 103 (Pd 103)	100	Technetium 97 (Tc 97)	100
Palladium 109 (Pd 109)	100	Technetium 99m (Tc 99m)	100
Phosphorus 32 (P 32)	10	Technetium 99 (Tc 99)	10
Platinum 191 (Pt 191)	100	Tellurium 125 m (Te 125 m)	10
Platinum 193m (Pt 193m)	100	Tellurium 127m (Te 127m)	10
Platinum 193 (Pt 193)	100	Tellurium 127 (Te 127)	100
Platinum 197m (Pt 197m)	100	Tellurium 129m (Te 129m)	10
Platinum 197 (Pt 197)	100	Tellurium 129 (Te 129)	100
Polonium 210 (Po 210)	0.1	Tellurium 131m (Te 131m)	10
Potassium 42 (K 42)	10	Tellurium 132 (Te 132)	10
Praseodymium 142 (Pr 142)	100	Terbium 160 (Tb 160)	10
Praseodymium 143 (Pr 143)	100	Thallium 200 (Tl 200)	100
Promethium 147 (Pm 147)	10	Thallium 201 (Tl 201)	100
Promethium 149 (Pm 149)	10	Thallium 202 (Tl 202)	100
Rhenium 186 (Re 186)	100	Thallium 204 (Tl 204)	10
Rhenium 188 (Re 188)	100	Thulium 170 (Tm 170)	10
Rhodium 103m (Rh 103m)	100	Thulium 171 (Tm 171)	10
Rhodium 105 (Rh 105)	100	Tin 113 (Sn 113)	10
Rubidium 86 (R86)	10	Tin 125 (Sn 125)	10
Rubidium 87 (Rb87)	10	Tungsten 181 (W 181)	10
Ruthenium 97 (Ru 97)	100	Tungsten 185 (W 185)	10
Ruthenium 103 (Ru 103)	10	Tungsten 187 (W 187)	100
Ruthenium 105 (Ru 105)	10	Vanadium 48 (V 48)	10
Ruthenium 106 (Ru 106)	1	Xenon 131m (Xe 131m)	1,000
Samarium 151 (Sm 151)	10	Xenon 133 (Xe 133)	100
Samarium 153 (Sm 153)	100	Xenon 135 (Xe 135)	100
Scandium 46 (Sc 46)	10	Ytterbium 175 (Yb 175)	100
Scandium 47 (Sc 47)	100	Yttrium 90 (Y 90)	10
Scandium 48 (Sc 48)	10	Yttrium 91 (Y91)	10
Selenium 75 (Se 75)	10	Yttrium 92 (Y92)	100
Silicon 31 (Si 31)	100	Yttrium 93 (Y93)	100
Silver 105 (Ag 105)	10	Zinc 65 (Zn 65)	10
Silver 110m (Ag 110m)	1	Zinc 69m (Zn 69m)	100
Silver 111 (Ag 111)	100	Zinc 69 (Zn 69)	1,000
Soldium 24 (Na 24)	10	Zirconium 93 (Zr 93)	10
Strontium 85 (Sr 85)	10	Zirconium 95 (Zr 95)	10
Strontium 89 (Sr 89)	1	Zirconium 97 (Zr 97)	10
Strontium 90 (Sr 90)	0.1	Any byproduct material not listed above other than alpha emitting byproduct materials	0.1
Strontium 91 (Sr 91)	10		
Strontium 92 (Sr 92)	10		

§32.19 Same: Conditions of licenses.

Each license issued under §32.18 is subject to the following conditions:

(a) No more than 10 exempt quantities set forth in §30.71, Schedule B of this chapter shall be sold or transferred in any single transaction. For purposes of this requirement, an individual exempt quantity may be composed of fractional parts of one or more of the exempt quantities in §30.71, Schedule B of this chapter, provided that the sum of such fractions shall not exceed unity.

(b) Each quantity of byproduct material set forth in §30.71, Schedule B of this chapter shall be separately and individually packaged. No more than 10 such packaged exempt quantities shall be contained in any outer package for transfer to persons exempt pursuant to §30.18 of this chapter. The outer package shall be such that the dose rate at the external surface of the package does not exceed 0.5 millirems per hour.

(c) The immediate container of each quantity or separately packaged fractional quantity of byproduct material shall bear a durable, legible label which (1) identifies the radioisotope and the quantity of radioactivity, and (2) bears the words "Radioactive Material."

(d) In addition to the labeling information required by paragraph (c) of this section, the label affixed to the immediate container, or an accompanying brochure, shall also (1) state that the contents are exempt from NRC or Agreement State licensing requirements; (2) bear the words "Radioactive Material -- Not for Human Use -- Introduction Into Foods, Beverages, Cosmetics, Drugs, or Medicinals, or Into Products Manufactured for Commercial Distribution is Prohibited -- Exempt Quantities Should Not be Combined"; and (3) set forth appropriate additional radiation safety precautions and instructions relating to the handling, use, storage, and disposal of the radioactive material.

[35 FR 6428, Apr. 22, 1970]

Contact us: If we may be of help to you, feel free to contact us. Visit our web site for up-to-date information and products.

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