Nuclear Physics Lab Manual

Based on Spectrum Techniques Student Lab Manual

Student A	Student B
Plateau	Plateau
Inverse square law	Statistics of counting
Alpha particles range	Beta decay energy and absorption coefficient

Plotting GM Plateau

Objective:

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

Pre-lab Questions:

1. What graph do you expect to get?
2. How does electric potential affects a GM tube's operation?

Introduction:

Different Geiger-Müller (GM) counters do not operate exactly the same way. Consequently, each GM counter needs a different voltage to be applied for optimal performance.

When a radioactive sample is positioned beneath a tube and the voltage of the GM tube is ramped up (slowly increased by small steps) from zero, the tube does not start firing right away. The tube must reach a starting voltage for electron avalanche to begin generate current pulses. As the voltage is increased beyond this point, the counting rate increases quickly before it stabilizes. The stabilization begins at voltage commonly referred as the knee. Furter voltage increase above the knee is expected to lead to only moderate increase of the count rate, see Fig. 1 (this is not exactly the case for the GM tubes you are going to use). You should find a voltage that satisfies the following:

1. Be above the knee, so the counting rate is large enough
2. Counting rate does not depend strongly on the voltage (ideally it would be a plateau).
3. Be below the breakdown voltage--fast increase of the current past the plateau. 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 a GM tube operates too close to the discharge region, it can damage the tube.

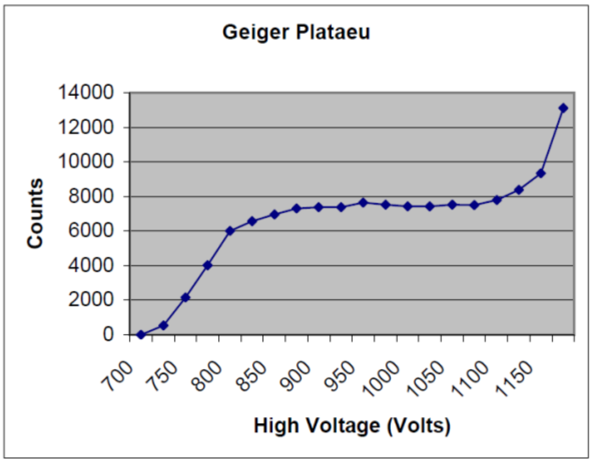

Figure 1: A plateau graph for a Geiger-Müller counter.

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

- The set-up of the experiment consists of **ST-360** Counter with GM Tube, Counter, a stand as shown in Figure 2.
- Radioactive sources (e.g., Cs-137, Sr-90, or Co-60).

Figure 2: ST360 setup with sources and absorber kit

Approximate system dimensions:

Distance between the shelves	*~10 mm*
Distance between the top shelf and the GM window	*~12.3 mm*
GM window diameter	*31.6±0.1 mm*
Sample stage thickness	*~1 mm*

Procedure:

1. 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, as presented in Figure 3.
2. Insert a radioactive source from the equipment list into the first (closest) shelf.

3. Set High Voltage (HV) to 1200V. and measure how long it takes to get ~600 counts in the counter (so random error is around 4% of value). To start a measurement, press the green “diamond” button. “Preset Time” is the time allotted for the measurement. “Elapsed time” displays the time that has passed since the start of the measurement.

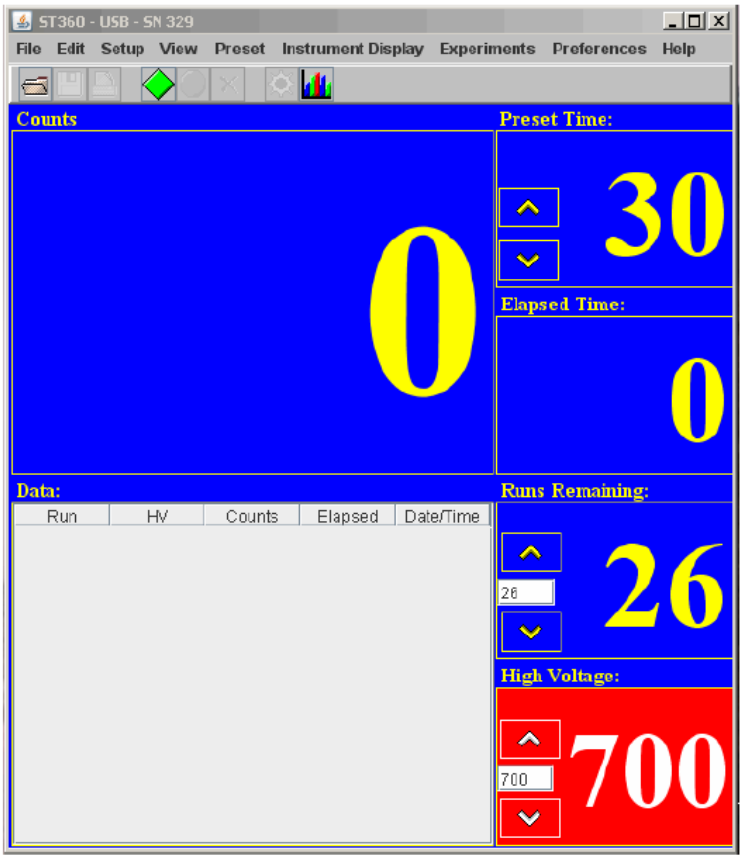

Figure 3: STX program interface.

4. Go to the **Experiments** menu and select the **Plateau** option. Set the voltages range between 500 and 1200[V]. Choose an appropriate step voltage (to not “miss” the start of the plateau) and a preset time (the time you found above). Set the number of runs to 1.
5. Write down the parameters you chose and the source into you lab notebook.
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. 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**.
8. During the measurement check the obtained data by going to the **View** menu and choosing a plot of counts versus voltage. Did you obtain a desirable plateau?
9. When all the runs are taken, choose the **File** menu and **Save As**. Then you may save the data file. The output file is a text file that is tab delimited, which means that it will load into most spreadsheet programs.

10. Plot the rate (cps) as function of voltage.

Discussion:

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 since you may not be able to see where the discharge region begins.

Post-Lab Questions:

1. <u>Determine the operating voltage for the tube for the next experiments.</u>
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?

Statistics of counting and Background Radiation Measurement

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

Pre-lab Questions:

1. List the formulas for finding the means and standard deviations for the Poisson and Gaussian distribution.
2. Name the four natural sources and three man-made sources of background radiation.
3. Approximately how much background radiation is received by an average American citizen every year? Is this very high (dangerous)?

Introduction:

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 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 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 the source present. You subtract the counts obtained without the source from those obtained with the source, and that should give you the number of counts from the source itself.

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 for the

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.
Radioactive decay measurements can be thought of as counting the number of “successes” resulting from a given number of “trials”. Each trial is assumed to be a binary process in which there are two possible outcomes: a “success” or a “failure”. For our work, the probability of a decay or non-decay is constant in every moment of time. Every radioactive atom in the source has the same probability of decay, which is very small.
The Poisson and Gaussian statistical distributions are the ones that will be considered in this experiment and in future ones.

Poisson versus Gaussian process

We present tree main issue that that you need to take into account.

1. **Notations:** mean value, denoted by overbar
$$\bar{x} = \frac{1}{m}\sum_{i=1}^{m} x_i.$$
where m is a finite number of trials; $\bar{x} \xrightarrow{m\to\infty} \langle x\rangle$ for infinite number of trials, where $\langle x\rangle$ is the expectation value.
2. Let us consider independent evens during a fixed time interval τ. The probability of n events during τ is described by the Poison process:
$$\mathbb{P}(n) = \frac{\lambda^n}{n!}e^{-\lambda}$$
We can determine from this the average $\langle n\rangle = \lambda$. For independent events $\langle n\rangle$. The standard deviation (STD) is $\sigma = \sqrt{\langle (n-\langle n\rangle)^2\rangle} = \sqrt{\lambda}$.
Check it at home.
3. Consider third central moment of the distribution $\kappa_3 = \langle (n-\langle n\rangle)^3\rangle$. It is related to skewness of the distribution: $s_3 = \frac{\kappa_3}{\sigma^{3/2}}$. For the Poison distribution $\kappa_3 = \langle n\rangle = \lambda$, and for Gaussian one $\kappa_3 = 0$.
We therefore shall look at:
$$K_3 = \frac{1}{m-1}\sum_{i=1}^{m}(n_i - \bar{n})^3$$

Since the Gaussian distribution is symmetric about average, its skewness is zero. We therefore use the skewness (or rather κ_3) to distinguish between the distributions. If K_3 is significantly different from zero and close to the mean value $\bar{n}$, it indicates that the distribution is rather Poissonian and not Gaussian.
In general, you need all the moments to distinguish between distributions.

Procedure:
We want you to distinguish between these two distributions by looking at K_3. For this you will need to do a large number m of the measurement, this number is estimated below.

1. Setup the Geiger counter. Set the **Voltage** of the GM tube to its operating voltage according to the previous experiment.
2. Measure Background rate
    - Set measurement time to 100 s.
    - Calculate the background rate, save it for the future.
3. Take a relatively weak source. Like Cesium/Co-60, and put it label up on the farthest shelf.
4. Set the measurement time to $1s$, and take, say 10 measurements. Calculate $\bar{n}$. You want it to be relatively small, less then ≤ 5 . You can play with the source-to-counter distance to get the counts in this range.
5. Take the set of at least $m = 150\bar{n}$ measurements. The reason for such a large m is that we want uncertainty of K_3 to be reasonably small. Should we have chosen a larger $\bar{n}$, we would need to do more measurements, and the measurement time would be too long .
6. Calculate the $\bar{n}$ and $STD(n)$. The expected standard deviation of the *mean* $\bar{n}$ can be estimated as $STD(\bar{n}) = STD(n)/\sqrt{m-1}$. This is an important result from statistical theory, and you should know it e.g., from the Data Analysis Booklet.
7. Calculate K_3. Compare it with $\bar{n}$. Remember that for Poisson statistics we expect $\bar{n} \to \lambda$ and $K_3 \to \lambda$ for $m \to \infty$.
8. We need to check if the value of K_3 that we got is statistically significant. For this it is worth to compare $K_3$with expectation for the Gaussian statistics for which $\kappa_3 = 0$. But a legitimate question to ask: what is the expected uncertainty of the K_3. We don't have the luxury to repeat sets of m measurements many times.
   Let us consider $\xi_i = (n_i - \bar{n})^3$ as new random (stochastic) variable. Calculate the variance $Var(\xi)$. Statistics predicts that if K_3 is measured m times, then $Var(K_3)$ can be estimated as $Var(\xi)/(m-1)$. Use this to estimate $STD(K_3) = \sqrt{Var(K_3)}$. Compare the $K_3 \pm STD(K_3)$, and $\bar{n} \pm STD(\bar{n})$.

   Below is a justification of the procedure:
   $K_3 = \frac{1}{m}\sum\xi_i$ is an average of a large number m of independent variables. It is a random variable by itself, so the Central Limit theorem is applicable to it. Therefore $Var(K_3) = \frac{1}{m-1}Var(\xi)$.
   Although it is not very important, we just note that factor $m-1$ instead of m in the formulas for variance obtained from a sequence of measurements is due to the fact that out of m random measurements only $m-1$ are independent. The last one is fixed by use $\bar{\xi}_i$ instead of κ_3 for variance calculations.

Post-Lab Questions:

1. Can we conclude that the distribution of n is rather Poissonian than Gaussian?

2. If the same measurement would be performed with a strong radioactive source leading to a large number of counts per a measurement, would it be possible to distinguish between the Gaussian and Poisson distribution with the same number of measurements?

Inverse Square Law

Objective:

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

Introduction:

As a source is moved away from the detector, the intensity—the amount of detected radiation, decreases. The farther you move away from a friend, the harder is to hear him. Or the farther you move away from a light source, the harder is to see. Basically, nature provides many examples (including light, sound, and radiation) that follow an inverse square law.
What the 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 $1/d^2$.

GM counter is a few millimeters above the top of the shelf box, and radiation is not immediately detected after entering the counter. Therefore, some factor a should be added to the distance x between the source and top of the box for the radiation intensity to fit $1/d^2$ law: $d = x + a$. This factor a will be useful in your experiments with α –particles that have a short range, so distance a is not negligible.
You are going to use a beta-radiation source to find the effective distance a. Although one might argue that a for electrons and α –particles can be different, it is probably not very different, and we don't have other way to determine it.

Procedure:

1. Measure the distances between shelves and estimate the error of these measurements.
2. Set up the Geiger counter. Set the **Voltage** of the GM tube to the operation voltage you have already determined.
3. Place the radioactive source to the medium shelf and begin taking data. Use a beta source – Tl-204 or Sr-90. Use the stronger one.
4. From the **Preset** menu, set **Runs** to zero. Set an appropriate **Preset Time** to get a relative random error <3% (assuming Poisson distribution). You may stop measurements that are "too long", and repeat the "too short" ones.
5. Take measurements on each shelf. You should see the data accumulating in the Data window.
6. Make several measurements with the source above the top shelf using aluminum spacers or just coins.

7. Calculate the rate $R = counts/time$.
8. Save the data. Subtract the background radiation rate R_b from your measurements.
9. Fit your data in Python: Plot $1/\sqrt{R - R_b}$ as a function of x, and use linear regression to find distance a. Try to fit the data in the whole region of x, and only at $x < 2$cm. Pay attention to the difference.

Post-Lab Questions:

1. Does this verify the inverse square law? Explain?
2. What is the source of distance correction factor?
3. What is the physical reason for the deviation of the data points at $x < 2$cm from the linear fit?

Range of Alpha Particles

Objective:

Determine the range of an alpha particle in air, and from it the alpha particle's energy.

Pre-lab Questions:

1. What is an alpha particle? How and why are they emitted?
2. What everyday materials 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 via collisions with atoms of the matter. So, a natural question would be: how far will a particle travel in the matter before it loses most of its energy? This quantity is called the ***range*** of the particle and it depends on material type, particle type, and its energy. In this experiment, you will look at alpha particles passing through air.
The alpha particle (α) is a helium ion He^{+2}, which is composed of two protons and two neutrons. 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 nuclei are mono-energetic: alphas from the same species have the same energy. The energy of most alphas falls 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 on the radioactive source. 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. Its energy can be approximated by its range in air according to the following empirical graph:

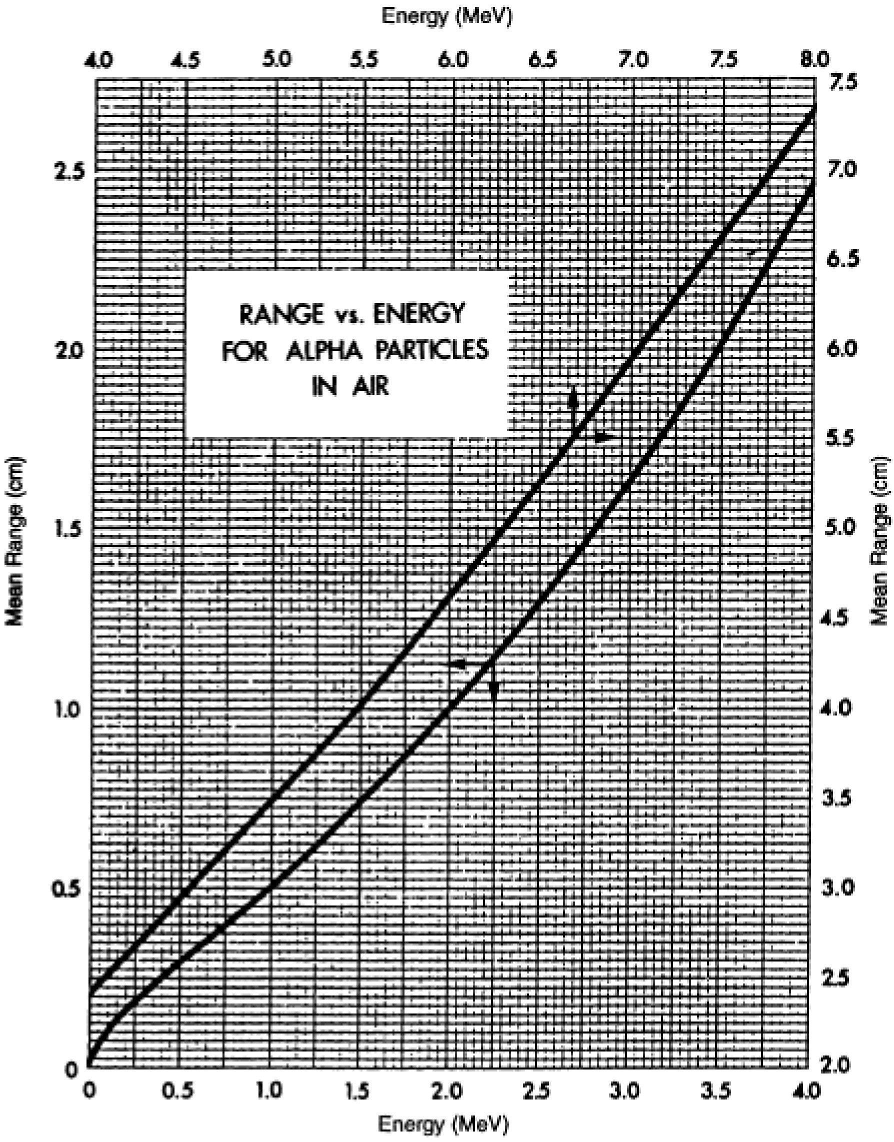

Figure 4: Range-energy plot for alpha particles in air at 15oC and 760mm Hg pressure.
(Knoll, G.F., Radiation Detection and Measurement, 3rd ed., page 35.)

Procedure:

1. Set the **Voltage** of the GM tube to the operating voltage.
2. Place the radioactive source in the 1rd shelf and measure. Use ^{210}Po as an alpha-particle source. *Important: place the source with label down, otherwise it would absorb the alpha-particles.* Acquire about 1000 counts in order to have an error of $\sim 3\%$.
3. Move the source down one shelf and take data again. If the rate is too small, say less than $1cps$, put a spacer over the second shelf to get a reasonable count rate. *Plot your data during the measurements to see at which distance from the detector you need to get more data points.*
4. Now measure above the top shelf. Use copper/aluminum plates to get data points in a range of [0,1] cm from the GM counter.

Data Analysis:

1. Subtract the background and correct the distance according to the previous experiment. In order to account for the geometry, divide the count rate by the solid angle in which the counter sees the source. In practice it means multiplying the rate by $d^2 = (x + a)^2$. Use a determined with beta-radiation.
2. Look at your data. You are not going to get the dependence similar to the textbook one in Fig. 5. Still, you can determine the alpha-particle energy by making a linear fit to the data and look at the extrapolation to zero rate. Evaluate alpha particles energy according to the mean range.
Compare your results of range and energy to those values that can be found in a handbook?

Notes:

1. You got a graph different from the textbook one.
2. You underestimated the alpha-particle energy.

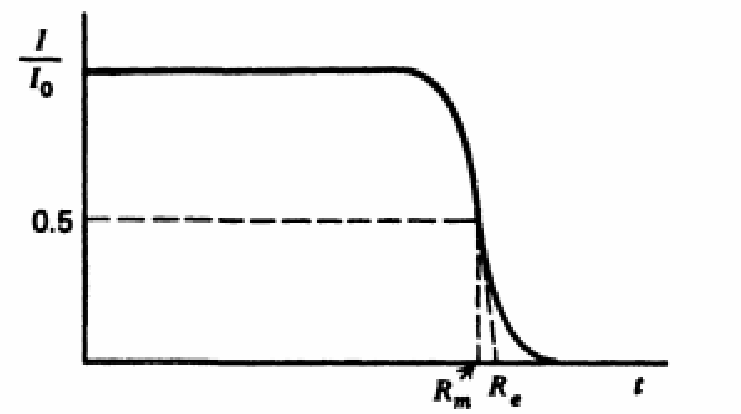

Figure 5: An alpha particle transmission experiment. I is the detected number of alpha particles through an absorber thickness t, whereas I_0 is the number detected without the absorber. The mean range R_m and extrapolated range R_e are indicated. **(Knoll, G.F., Radiation Detection and Measurement, 3rd ed., page 34.)**

Absorption of Beta Particles and Beta Decay Energy

Objective:

You should investigate attenuation of radiation via absorption of beta particles. You will compare the spectra of two beta particle sources.

Pre-lab Questions:

1. What is the mechanism of beta decay.
2. How does radiation flux from a source vary with distance?

3. How do you predict radiation flux 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 a nucleus when a neutron decays by the weak force. The neutron (n) becomes a proton (p), an electron (e^-), and an anti-neutrino ($\overline{\nu}$). When an electron originates in the nucleus, it is called a beta particle.

$$n \rightarrow p + e^{-} + \overline{\nu} \qquad (1)$$

Unlike alpha particles that are emitted from the nuclei with a well-defined energy, beta particles are emitted with a range of energies between 0 MeV and the maximum energy for a given radioactive isotope. The energy is distributed among the beta particle and antineutrino. The maximum energy of the emitted beta particles is a characteristic signature for different radioisotopes. An example of the energy curve for beta particles is shown in Fig. 6:

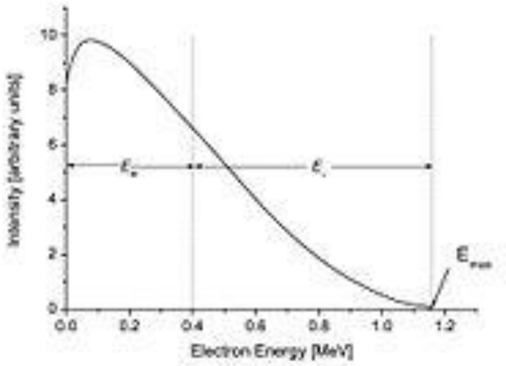

Figure 6: Typical plot of beta particle energy curve. This spectrum can be obtained using energy resolving detector such as scintillator and not the GM tube.

Fig. 7 shows a typical absorption curve for beta particles. The range is set by the particles with the maximal energy, and is determined from the knee of the plot in semilogarithmic scale when the count rate drops to the background one. One can translate the range into the maximal energy using the data [here.](#)

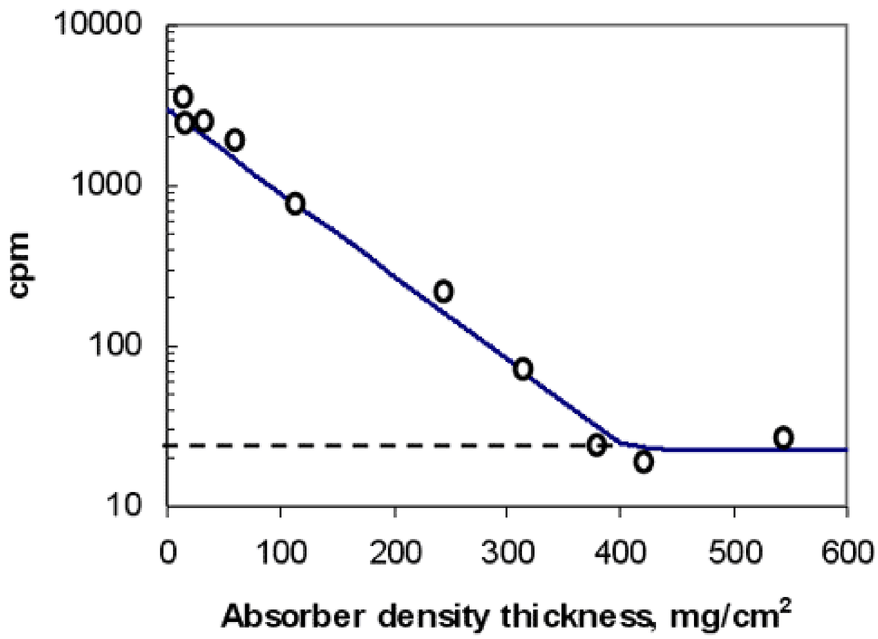

Figure 7: Curve of 210Bi 1.17MeV beta partivles with Al absorbers. ***Range determination according to the end point in absorption plot.*** *[2]*

Second parameter that you will find is beta-particles mass attenuation coefficient μ in Al. The radiation attenuation caused by passage through absorbing material can be approximated by Beer Lambert law:

$$(1)\ I = I_0 e^{-\mu t}$$

Where I_0 is the measured intensity without absorber, μ is the mass attenuation coefficient, and t is material density-thickness.

Procedure:

1. Set the **Voltage** of the GM tube to its operating voltage.
2. From the **Preset** menu, set **Runs** and **Preset Time** in order to get relative random error <3%.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the **third** shelf from the top and begin taking data. Perform the procedure with Tl.
5. Place an Al absorber piece in the top shelf and take another run of data.
6. Repeat this a minimum of 7 more times with absorbers of increasing thickness. You can use the two upper shelfs to combine two absorbers to get the sum of their thicknesses. You should measure increasing thicknesses until the counts drop to the background level (radiation is completely absorbed).

Perform the procedure with Tl-204 and Sr-90 beta sources and compare between the measurements

Data Analysis:

1. Subtract the background and present the data versus density*thickness (**mg/cm²**.)
2. Extract the Range R from your data and define β particles maximal energy. Find a reasonable way to determine the error. Compare to literature values using Statistical Significance Tests.

3. Present the data in semi log plot and extract μ, the attenuation coefficient. Compare it to literature values, suggested source: Baltakmens, T., *A simple method for determining the maximum energy of beta emitters by absorption measurements*, Nucl. Instr. Meth. Phys. Res. 82, **1970**, pp. 264-268.
4. Suggest a physical reason for the data and literature values discrepancies based on the β particles section in "Radiation detection and measurement book"[1], pages 43-47.

Conclusions:

You should have found the value for the maximum energy of a beta particle from your source and the error of this result when compared to the literature value. You should be able to characterize the relationship between beta particle activity and absorber thickness.

Post-Lab Questions:

1. Compare between the spectra for Sr-90 and for Tl-204. What are the differences between the spectra and why?
2. Discuss the quality of the fitted curves and its implication on your calculations.
3. What is the slope for your data for attenuation coefficient? How did you obtain it? Compare to literature values.
4. What is the range of the beta particles, so that all of them stop? Is your result for E accurate? Is it still a good result even if it is not the same as the literature value?
5. What are the interactions of β particles with material at the given energies?[1]

References

[1] G.F. Knoll, *Radiation detection and measurement*. (Wiley, 1977).
[2] https://courses.ecampus.oregonstate.edu/ne581/three/index3.htm