Physics 145: DATA ANALYSIS I

What's the point? You will study radioactive decay as a context for exploring the concepts, tools, and techniques of data analysis, including probability distributions, statistical measures and linear curve fitting. You **MUST** take care to save your data from this lab since it will be used extensively in the next lab.

Equipment: Geiger counter and sample holder, weak sealed radioactive Cesium 137 sources, stack of aluminum and lead absorber plates.

Additional Required Reading: Read the entire Data Analysis Reference guide, except for the last section on error propagation.

Introduction: As there are a growing number of useful applications for radioactive sources, it is becoming increasingly important to understand radiation phenomena and basic radiation measurements. Such an understanding should dispel some of the unfounded fear felt by many uninformed people. **Radioactivity** is the name given to an atomic or nuclear process in which the nucleus spontaneously (without cause or stimulation) changes by throwing out one or more of its constituent parts. The nucleus often transforms into a different element of the periodic table in this process and is thus said to **decay**. Most **radioactive sources** have nuclei that emit one or more of the following high-energy particles: **beta** rays (electrons), **alpha** rays (^{4}He nuclei consisting of two protons and two neutrons), **neutrons**, or **gamma** rays (photons, which are high-energy electromagnetic radiation quanta). In contrast to microwave or visible light radiation, radioactive sources produce **ionizing radiation**, meaning that the emitted particles have enough energy to remove an electron from an atom in a collision. Hence the possibility of creating chemical changes that kill cells or permit genetic mutations. Because the radioactive source that we use in this lab are sealed so that no radioactive material can leak out, and because they are weak sources to begin with, the radiation levels that you will be exposed to are very low --comparable to the natural background radiation received from a few days of skiing or hiking in the mountains. Of course, your exposure will increase if you hold the radioactive sources for long periods of time, carry them in your pocket, or worst of all -- eat them. Common sense and good hygiene are essential to safety in any laboratory. You will use a standard **Geiger counter**, an inert gas-filled tube that briefly conducts electricity when an emitted particle passes through and ionizes the gas, to detect decay events. Your Cesium 137 source emits betas and gammas. While Geiger counters are most commonly used for alpha and beta ray detection, we will also use them for gamma detection.

Exponential radioactive decay over time: The spontaneous decay of any specific atomic nucleus is not predictable but is a chance process described by statistical mathematics -- there is a fixed but small probability that a given nucleus will decay in any given time interval. Since individual nuclei are not readily observable, we cannot measure the actual number of nuclei ΔN

that decay. However, we can measure the number of particles (alpha, beta, or gamma) emitted by the decay events using a Geiger counter, a device that detects and registers individual radiation products as they pass through it. We then record the decay *rate* R in units of events per minute. If you place a Geiger counter some distance from a radioactive source, a fixed fraction of the particles emitted from the sample will pass through the counter and be measured. Since there are an enormous number of atoms (> 10^{18}) in any macroscopic sample, many nuclei will decay each second. Consider a sample containing N nuclei. The basic concept of radioactive decay is expressed by the equation

$$\frac{\Delta N}{\Delta t} = \lambda N \qquad (1)$$

where ΔN is the number of nuclei decaying within a time interval Δt and the decay coefficient λ is the probability of an individual nuclei decaying within the interval. Because rate of decay $R = \Delta N / \Delta t$ is proportional to N itself, the time dependence of N follows the well-known expression for exponential decay:

$$N = N_0 e^{-\lambda t} \qquad (2)$$

where N_0 is the initial number of nuclei at the time arbitrarily defined as $t = 0$. The decay rate also falls off exponentially with time as shown in Figure 1. After a sufficient time, which we call the half-life ($T_{1/2}$) of the radioactive isotope, the number N of undecayed nuclei that remain will be equal to one-half of the initial number N_0. The decay coefficient λ and the half life $T_{1/2}$ are related simply as:

$$T_{1/2} = \frac{\ln(2)}{\lambda} \qquad (3).$$

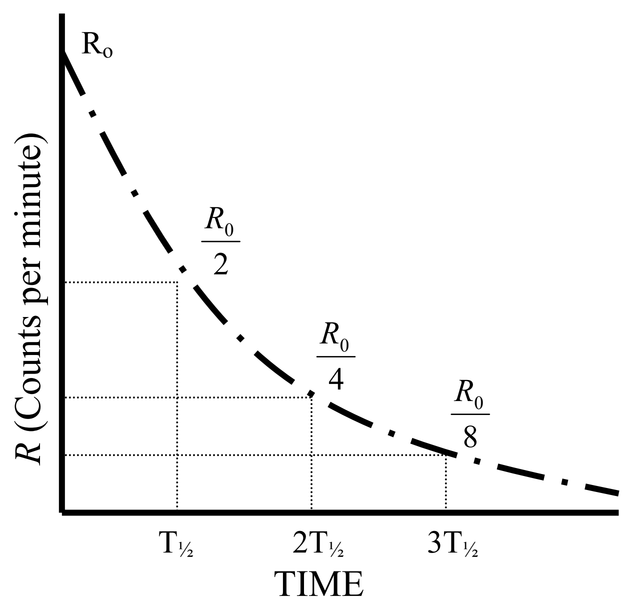

Fig.1 Counting rate vs. time

If we start with a decay rate of R_0, the rate after after a period of 20 half lives will be reduced to $R_0/2^{20} \sim R_0 \times 10^{-6}$. Because ^{137}Cs has a long 35-year half life, the count-rates that you observe will not vary appreciably during the course of the laboratory period.

Radiation absorption: Because alphas and betas are electrically charged, they interact strongly with the electrons and protons in ordinary materials that they impinge upon, and thereby become scattered or absorbed. Alpha particles are readily absorbed by the air. Beta particles will penetrate a few inches of air, but are easily stopped by a paper-thin sheet of metal. While the details of this absorption are quite complex, it can be shown that most alpha and beta particles are absorbed or scattered after traveling a rather short distance. Gamma rays, on the other hand, interact only weakly with matter, and are therefore, much more penetrating. This actually makes them easier to detect for the present experiment. Gammas typically interact with atoms via one of three quantum-mechanical processes. (1) Low-energy gamma rays interact with an atom by the photo-electric effect in which the energy of the gamma photon is transferred entirely to an electron in the atom. (2) Medium-energy gamma rays interact via Compton scattering in which the gamma get redirected and weakened through an inelastic collision with the atom. Scattering is technically distinct from absorption, though we won't differentiate the two here. (3) Very high-energy gamma rays interact with a nucleus through a process called "pair production" in which part of the energy of the gamma ray is used up to create an electron-positron pair in accordance with Einstein's mass-energy equation $E=mc^2$.

The absorption of gamma radiation in a material is also a random statistical process whereby individual gamma-ray photons interact with individual atoms of the material and are scattered or absorbed. These gamma rays are thus lost from the transmitted beam of gamma rays that would have otherwise entered the counter. If N gamma rays would have passed from the source into the counter without the absorbing material present, the number ΔN lost from the beam by its passing through a thickness Δx of the material is given by

$$\frac{\Delta N}{\Delta x} = \mu N \qquad (4)$$

where μ is the probability of scattering of each gamma ray as it passes through a thickness of one centimeter. The parameter μ, which has units of inverse distance (e.g. 1/mm), is often called the *absorption coefficient*. The analogy with Eq. 1 above is obvious and the decay in the number of gammas in the transmitted beam as a function of distance in the material also decays exponentially (see Fig 2).

$$N = N_0 e^{-\mu x} \qquad (5)$$

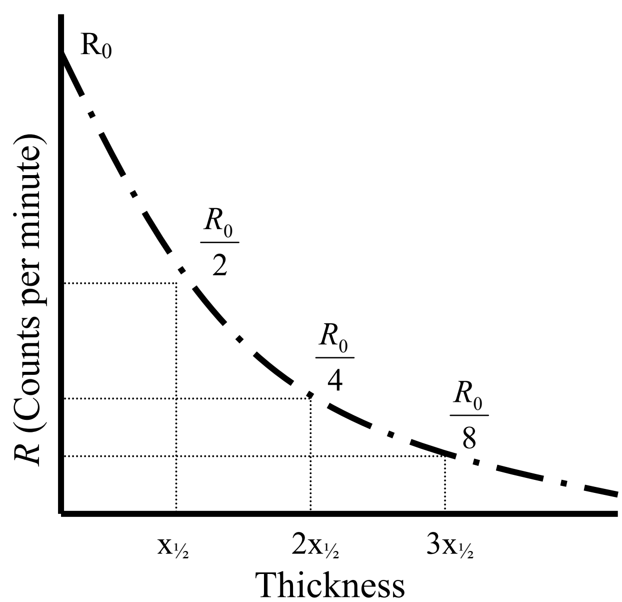

Fig. 2 Rate of gamma-ray photons entering the detector after passing through a sheet of thickness x.

The inverse of the absorption coefficient, $1/\mu$, provides a good measure of how deeply the radiation penetrates the absorbing material. The half-length ($x_{½}$) is a related quantity that shows us how far the radiation penetrates the material before absorption reduces the radiation intensity to half its original value. The absorption coefficient and the half-length are related according to

$$x_{1/2} = \frac{\ln(2)}{\mu} \qquad (6).$$

PROCEDURE

A: Get familiar with your equipment.

1) To become familiar with the counting apparatus shown in Figure 3, first place your ^{137}Cs source with the top facing up under the counting chamber (Fig. 3 without the absorbers), turn the counter on and slowly increase the high voltage up to 900 volts. **Do not let the voltage exceed 900 volts** -- the expensive Geiger tube can be easily destroyed by excessive voltage. Practice counting for an interval of one minute.
2) You will see a small background count rate at all times due to cosmic rays and radioactive materials that occur naturally in the walls of the building. To measure this background, remove the cesium source and all other sources of radiation from the vicinity of the counter (at least two meters away) and observe the counts accumulated during a period of several minutes. Divide the number of counts N_B by the time interval T_B in minutes to get the background count rate R_B, and record it in your lab notebook.
3) Using your apparatus as shown in Fig 3, measure the 15-second count rates using several different thickness of aluminum. Try a very thin sheet, a medium-thickness sheet, a thick slab and a combination of several thick slabs. You will observe that the rate initially falls off quickly with increasing thickness, but falls off more slowly as additional plates are added. Explain that weakly penetrating beta rays contribute to the detected signal at small absorber thicknesses, while only gamma rays penetrate at larger thicknesses.

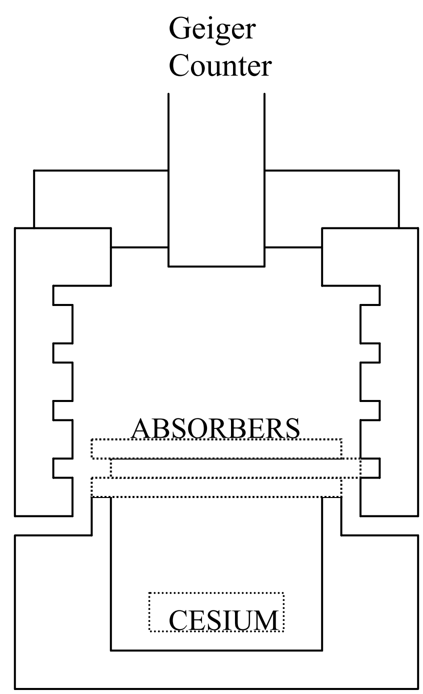

Fig. 3. Sample chamber

B: Measure the absorption half-length of Cs 137 gamma-ray through lead.

1) Carefully vary the lead absorber thickness from zero up to about 3 cm using the smallest available thickness increment (i.e. the relatively thin sheet of lead). For each thickness, count the number of gamma rays detected within a one-minute interval, and record ALL of your raw data (e.g. thickness in mm, number of counts, and counting interval in minutes) in your lab notebook. The total number of data points should be about 20.
2) Open an Excel spreadsheet called dataanalys.xls. Enter your data into this spreadsheet as three columns named "thickness(t)", "interval(T)", and "counts(N)". Add another column containing the "background(R_B)" count rate, which is the same for each data point. Next, add a column that computes the total count rate $R = N/T$ in counts/second, and another column that computes the natural log of the background-subtracted count rate, $\ln(R - R_B)$. Enter the "thickness" of the first data point as zero.
3) Use Excel to generate an XY scatter plot of R as a function of thickness (in mm) for your lab notebook. Do not use guide lines. Make sure that all axes are properly labeled including the correct units.
4) Make a similar plot for the value of $\ln(R - R_B)$ as a function of thickness. You should observe that the $\ln(R - R_B)$ graph has a well-defined linear slope. Use Excel's **linear-regression** feature to measure this slope (in 1/mm units) -- simply right click any data point in the plot, select "add trendline", and select the option that displays the fitted equation. Add the plot to your lab notebook.
5) Mathematically demonstrate (in your notebook) that the slope of your $\ln(R - R_B)$ curve should be equal to μ. Then use the slope value that you calculated above to estimate the absorption half-length for gamma-rays in lead.

C: Experimentally sample and analyze a statistical distribution.

1) Employ the number of aluminum absorbers needed to reduce the detected ^{137}Cs count rate to about 6000 counts/min (i.e. 1000 counts in 10 seconds). Now make 30 separate counting measurements using a 10-second time interval, and record the number of counts for each measurement. Do not compute a rate -- simply record the number of counts that you actually measured! You will need to work together as a team with a stop watch in order to keep the time-interval errors low.
2) Record the data (just the number of counts) in a new Excel spreadsheet called "poisson.xls" and perform a basis statistical analysis using the *Data* $\rightarrow$ *Data Analysis* $\rightarrow$ *Descriptive Statistics* menu option. Copy the resulting analysis into your lab notebook.
3) Ideally, you should obtain a Poisson distribution, which means that your variance should be approximately equal to your mean. Check this. If other sources of error have contributed to your variance (e.g. time interval measurement errors), the variance may be significantly larger than the mean, in which case your data is better described by a Gaussian distribution. State whether your data are better represented by a Poisson or a Gaussian distribution, and explain your reasoning.