The Stochastic Nature of Radioactivity

Objectives

- to become familiar with the Geiger tube and its use
- to examine the nature and use of Gaussian and Poisson distributions
- to determine the functional relationship between the counts the detector receives and the distance from an extended radioactive source

Introduction

In classical physics, experiments are performed and the results are somewhat predictable and reproducible. However, for non-classical processes, the result of a single observation may be unpredictable because of the stochastic, or apparently random, nature of the physical process. For these processes, events are observed many times; the results are expressed using statistics; and predictions are made using probabilities. Two such processes are (1) radioactive decay of atoms and (2) the spontaneous emission of a photon from an atom. The number of particles or photons emitted from a collection of such atoms is described by either a Gaussian or Poisson distribution.

The Poisson distribution applies when relatively few events are counted within each observation and many observations are made. When a histogram is made of the data, with the bin frequency (number of counts) on the vertical axis and the bin numbers, *r*, on the horizontal axis and a sufficient number of observations have been made, the distribution of data will resemble a bell-shaped curve. The probability of obtaining *r* events if the mean observed value is λ is

$$P(r) = \frac{e^{-\lambda}\lambda^{r}}{r!} \tag{1}$$

The Gaussian distribution applies when a large number of events are recorded within a single observation and many observations are made. The Gaussian probability function is given by

$$P(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(r-\mu)^2/2\sigma^2} \tag{2}$$

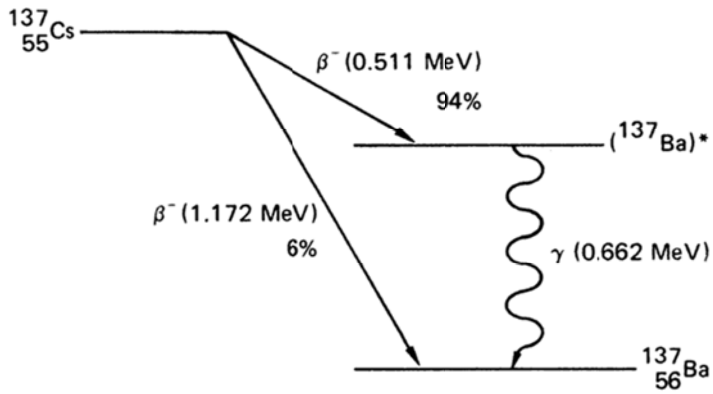
where σ is the standard deviation and μ is the mean value of the data.

In this experiment, the β decay of cesium will be examined. The decay may be expressed and represented schematically as follows:

$$^{137}_{55}\text{Cs} \rightarrow {}^{137}_{56}\text{Ba} + \beta^{-} + \bar{\nu}$$

Beta decay causes a transmutation of one element into another as a neutron in the unstable parent decays into a proton and an electron, which is the emitted β^{-} particle. In the diagram above, we see that the atom may also decay into a metastable barium atom, which subsequently emits a gamma ray. It is this later process that occurs most often (94.6% of the time). The beta particle energies are 1.172 MeV and 0.511 MeV; and the gamma ray energy is 0.662 MeV. Figure 1 is an illustration of the decay process.

Figure 1. The beta decay of Cs-137 is illustrated. Most of the cesium decay to the excited state of barium, which subsequently undergoes a gamma decay to its stable state. This figure was originally used in Physics Laboratory Experiments (5e) by Jerry D. Wilson.



Experimental Procedure

A radioactive cesium source will be provided. The beta particles will be counted using an RM-60 (www.aw-el.com) Geiger tube interfaced to a computer. For the measurements, the source is placed in alignment with the holes in the detector housing in front of the detector. To limit the number of particles entering the detector, a lead shield can be placed between the source and the detector or the distance between the detector and source can be varied. The computer program called Aw-Radw is used to record the data.

Part A. Counts versus Distance

Spend some time gaining familiarity with the computer program. After you choose to start measurements, you'll note that the observation intervals are fixed at 10 seconds. The program will display the time, the ionization activity in μR/hr, and the number of counts per interval. The output text file containing the data will only have the time and the ionization activity. You'll need to determine how to convert the activity into the number of counts per interval (find the calibration factor). Observe what happens when one side of the sample is near the detector and when the other side is near the detector. Why is there a difference in these measurements?

Set up the detector and the sample to measure the number of counts as a function of distance for 0 to 28 mm in 2 mm increments from the detector entrance. Record 12 observations at each location; and discard the first and last measurement for a total of 10 observations at each location. Take an average of the ten observations. Create a table of the position (in mm) and average counts.

Part B. Poisson Distribution

Adjust the experimental setup to give an average of approximately 12 counts per observation interval. Start the data collection and record two sets of more than 400 observations under these conditions. This can be 800 observation intervals that can be divided into two sets later. For your analysis, this data will be compared with the Poisson distribution.

Part C. Gaussian Distribution

Adjust the experimental set up to provide more than 250 counts per observation. Start the data collection and record eight sets of 400 observations each. This is normally done overnight so that many more than 3200 observation intervals will be collected and divided into 8 sets of 400 intervals. For your analysis, this data will be compared with the Gaussian distribution.

Part D. Background

Place the Cs source far from the detector. With the detector in the same position as when earlier measurements were made, start the data collection and record one set of 400 observations. This will provide information on activity received by the detector from the environment, including cosmic rays.

Part E. Data Analysis

Before beginning the following steps, take time to consider the effect the background measurement from part D has on your data in Parts A and B. Should it be included in the data analysis? Explain your reasoning.

You'll be introduced to the program Origin by MicroCal for analysis of your data.

1. Produce histograms for the two sets of 400 observations from Part B. The plots will be the number of observations with a particular count value versus the count value. Make sure the histogram bin centers have integer values. Then, using one of the sets of data, produce histograms for the first 50, 100, and 200 observations. Discuss the quality of these plots with regard to the number of observations plotted and in comparison to the two 400 observation graphs.
2. Using your data from the two sets of 400 observations, generate the predicted Poisson distributions. The Poisson distribution provides a probability. How does this probability relate to your experimental observations? To generate the expected values for your data, multiply the probability function given by equation (1) by the bin width and the total number of observations (400). Make graphs that show your histograms and calculated Poisson distributions for your report.
3. Make a graph using one of the two data sets from part B of counts versus observation number. What does this graph reveal about the stochastic nature of radioactivity? Explain.
4. Calculate χ^2 for both sets of your part B data and the expected Poisson values. In this calculation, neighboring bins with very small numbers of observations may be grouped. State the null hypothesis for this experiment. Based on a 95 % confidence level, should the null hypothesis be accepted or rejected? Discuss this in detail.
5. Choose <u>one</u> of the 8 sets of data from Part C. Make a histogram using a bin size between 5 and 20, depending on your data. Generate the Gaussian distribution for your data and include it on the graph with your histogram. To get the expected Gaussian values, multiply the probability by the bin width and the total number of observations (400). Compare your experimental observations with the Gaussian distribution by calculating χ^2. The count number is a continuous variable in the equation for the Gaussian distribution. The actual count number is not continuous, but the approximation works well.
6. Repeat the χ^2 calculations for the other 7 sets of data. What do these 8 - χ^2 values indicate about the quality of the data? State the null hypothesis for this experiment. Based on a 95 % confidence level, should the null hypothesis be accepted or rejected? Discuss this in detail.

Additional Questions

1. Be sure that all of the questions asked throughout the above procedure are answered somewhere in your report.

2. Describe how the Geiger-Mueller detector works to detect the beta particles in this experiment.

Additional Credit

One way to earn additional credit is to do a curve fit of the data from Part A using a theoretical functional dependence that you determine from the geometry of the experimental set up. A detailed derivation and explanation of the function used is expected.