EXPERIMENT: RANDOMNESS AND RADIOACTIVE DECAY

PURPOSE:
1. Determine the half-life of a short-lived radioactive nucleus.
2. Use dice to simulate radioactive decay.
3. Consider a model of radioactive decay

EQUIPMENT: Timer Geiger Counter Tube Radioactivity Demonstrator Dice Minigenerator

CAUTION: THERE IS TO BE NO EATING OR DRINKING IN THE LABORATORY DURING THE ENTIRE LAB PERIOD.

PART A.  Half-life of a short lived radioactive nucleus.
Radioactive nuclei are nuclei of a particular isotope of a specific element that exist in an unstable energy state. Occasionally, they will spontaneously make a transition to a lower energy state that might or might not be stable. Often the new state is also a different element. For example, $^{14}_6C \rightarrow ^{14}_7N + ^0_1e + ^\beta_0$ represents the $\beta$-decay of the isotope Carbon-14 resulting in Nitrogen-14. In contrast, $^{137m}_56Ba \rightarrow ^{137}_56Ba + ^\gamma_0$ represents the $\gamma$-decay of the excited (isomer) of Barium-137 to a stable form of Barium-137. One of the characteristics of radioactive decay is that, no matter how many of them there are at a particular time, there is a definite time interval after which only 1/2 of them will remain. This half-life is characteristic of the initial and final states of the particular isotope. Today you will determine the half-life of $^{137m}_56Ba$. It has a value that can be conveniently determined in one lab period. This isotope is itself a decay product of the much longer-lived parent isotope $^{137}_55Cs$. Your instructor will chemically separate the parent and daughter isotopes for you.

PROCEDURE:
CAUTION: The radioactive sources used in this experiment are very low level and perfectly safe as long as none of the radioactive material is taken internally. Since the $^{137m}_56Ba$ source is in liquid form, care should be taken not to spill the solution. Any spill must be wiped up immediately and your hands rinsed thoroughly in running water. There can be no eating or drinking during the course of this experiment. Read the entire procedure before starting.

Record in a neat and orderly fashion all observations, calculations, and answers to all questions.

1. You will need to make a table of times and count rates. Before doing so, read the rest of the procedure.
2. Use the $^{60}_29Co$ radioactive sample and follow the instructions on the last page to set the operating voltage of the Ratemeter. Return the $^{60}_29Co$ radioactive sample to the instructor when you finish setting the operating voltage.
3. Record the background count rate by visually averaging the needle position for a while (use the 500 cpm scale).
4. Get your $^{137m}_56Ba$ sample from the instructor. Since $^{137m}_56Ba$ decays very rapidly, you will have to act quickly once your source has been prepared. Your instructor will show you beforehand how to place your source close to the Geiger tube quickly. It should not take you more than one minute from the time you get your source until you are taking the first count rate reading. The initial count rate probably will be between 1000 and 2000 counts per minute. It is best if you and your partner make a dry run beforehand, rehearsing your procedure from beginning to end.
5. With your source in place near the Geiger tube start the timer and record the initial count rate.
6. Continue recording count rate readings every 30 seconds for a total of 9 minutes.
7. Shut down. Set the range switch to HV, and turn the high voltage down to its minimum value. Turn off the Ratemeter.

Analysis:
1. Use the Graphic Analysis program to make a graph of your data in the form of count rate (y) vs. time (x). You should subtract off the background count rate in order to get the counts due to your $^{137m}_56Ba$ sample. Have your instructor check your graph.
2. Examine your graph. What do you think is the functional relationship between count rate and time? Why do you think this? Check your ideas by curve fitting your data to different mathematical functions. Print a copy of your graph(s) and attach it (them) to your report. Your graph should include the curve fitting function you chose.

3. Choose a point on your graph near the beginning. Record the count rate and the time. Now divide the count rate by 2 and find and record the time for the point on the curve that corresponds to this value. What was the time interval required for the count rate to decrease to 1/2 the first value? Repeat this procedure for two more different beginning points and record the values and calculations.

4. How do the three time intervals compare, i.e., are they very different or about the same or what? Check your results with your instructor to be sure that they are reasonable. If they are nearly the same, calculate an average value for the half-life of your sample.

PART B, A simulation of radioactive decay using dice:

Questions:
B1. When you throw a die, what is the probability of two dots being on the top surface?
B2. If you were to through 120 dice all at once, how many might you expect to have two dots on their top surfaces?

Procedure:
1. Carry out an experiment with a batch of about 100 dice. Count and record the number of dice. Choose a number from 1 to 6 to represent a "decay". Toss the set repeatedly, each time recording the number that decay and removing them. The ones you remove represent nuclei that decayed (i.e., once a nucleus has decayed it is not the same nucleus so it is no longer a member of the original sample or radioactive nuclei).
2. Use the program Graphical Analysis to plot two graphs: the number in the sample before each throw (y) vs. the number of throws (x), and the number of decays for that throw vs. the number of throws. Print these graphs.
3. On the same graphs, plot with a pen or pencil what would have happened if exactly 1/6 of the dice decayed at each toss. Did you run into any problems making this last plot? If so, what did you decide was meant by a fractional number of dice? Did you get a straight line graph?
4. Compare your graphs from Part B with the graph from Part A. In what ways are they similar and in what ways are they different? Can you fit the dice data with the same mathematical function you used in Part A?

PART C, A Model for Radioactive Decay:

The accepted model of radioactive decay is based on probability and statistics. An initial assumption is that the sample of radioactive material contains a large number of the same species (isotope) nuclei in identical excited energy states. Furthermore, while in this excited energy state each nucleus has a definite, specific probability of undergoing a transition (decay) in any specified interval of time. That is, for each nucleus in a sample, the occurrence of a transition is determined purely by chance and the probability of decaying during a 10 seconds interval is greater than the probability of decaying during a 2 seconds interval.

A mathematical analysis based on these assumptions leads to the ideas that the number of nuclei \( \Delta N \) that will decay in the time interval \( \Delta t \) is proportional to \( \Delta t \) and also to the number \( N \) present at the beginning of the time interval, i.e.,

\[
\Delta N = -\lambda N \Delta t,
\]

where \( \lambda \) is the proportionality constant and the minus sign indicates the number of nuclei is decreasing (\( \Delta N = N_2 - N_1 \)). The mathematical relationship between \( N \) and \( t \) that corresponds to the above "difference" equation is

\[
N = N_0 e^{-\lambda t},
\]

and furthermore the rate of decay \( R \) (decays per second) is related to time by

\[
R = R_0 e^{-\lambda t},
\]

where \( R_0 \) is the initial rate of decay.

Question
C1. Is your data of PART A and PART B consistent with these last two equations? Explain your answers.

A set of dice is a useful analogy to the set of excited nuclei waiting to spontaneously decay. If we toss a set of N dice onto the table there is a good chance that N/6 of them will have a selected number (from 1 to 6) of dots on their upper face. We say that the probability is \( 1/6^{th} (=16.7\%) \) that the selected number will be on top for each die in the set each time they are tossed. Removal of the dice showing the selected number is analogous to a nucleus decaying since it is now a different nuclide and no longer belongs to the original set. In other words, a nuclear system which decays is now in a different state and can no longer be counted among those systems which still have a probability of decaying. So our model of the decision making process is that during each time interval the nucleus throws a die to determine whether it should decay. However,
the die it is tossing may have a number of sides very much larger than 6. How do we know this? If we have a mole of radioactive atoms and observe that 20,000 of them decay each second, then the probability of decaying must be $\frac{20,000}{(6.022 \times 10^{23})} = 3.32 \times 10^{-20}$/second. This means that its "die" must have $3.01 \times 10^{19}$ sides (= 1/probability).

**Question (C2):** What does the number of counts on the Geiger counter correspond to--the number remaining in the sample, or the number that decay?

**Question (C3):** To complete the analogy between the dice and the radioactive nuclei, approximately what time interval corresponds to one throw of the dice?

**PART D, A Computer simulation of our statistical model:**

A computer program (DECAY) has been written to simulate mathematically the throwing of a set of dice, and the removal of those decaying before the next throw. Decide on a number of dice in your sample and on the number of sides each is to have. To find and run DECAY, open the HardDisk folder and then the LabVIEW Student Edition folder. Double click on DECAY. Comment on a comparison of these results with those of Parts A and B. Try both large (1000) and small (20) initial numbers of dice. Compare the results.

**Ratemeter Operating Voltage**

1. Before turning it on, make sure the high voltage knob is turned all the way down (counterclockwise) and that the Geiger tube is plugged into the back. Set the range knob to HV so that the meter will indicate the voltage.
2. Turn it on and turn the speaker volume all the way up.
3. Place the radioactive sample ($^{60}$Co for example) near the Geiger tube and listen for counts as you turn up the high voltage. When the voltage gets to the threshold value (around 700 to 800 volts) you will hear the counts.
4. Increase the voltage about 50 volts beyond the threshold.
5. Set the range switch to an appropriate range for counts per minute, and adjust the speaker volume.