

Radioactivity

Purpose: Students will be introduced to nuclear statistics and half-life.

Introduction to Radiation:

Nuclear Magnetic Resonance, or NMR, is an important tool for chemists. It works by using a strong magnet to align the spinning nuclei in the atoms of a sample, then using radio waves to make the nuclei in the atoms of the sample resonate and broadcast their own radio waves when the radio frequency is just right. “Tuning the radio” then becomes a very sensitive way to do a chemical analysis. The positions of specific chemicals can be located by varying the magnetic field in time and space. Complex computer programs then convert this information to colorful images that allow doctors to “see inside” the human body. However, when NMR scanners were first introduced into hospitals in the 1980’s, the name very quickly changed from “NMR” to “MRI” (Magnetic Resonance Imaging). Why? Because ignorance is frightening. Patients were scared by the “N” word. They shouldn’t have been, because every atom in every human body contains a nucleus.

MRI doesn’t have anything to do with radioactivity. However, modern medicine and medical research use ionizing radiation and radioactivity extensively. Radiation is used to detect tumors and broken bones, to check the functioning of the thyroid gland and other organs, to treat cancer, to monitor brain function, and as “tracers” to label chemicals for medical laboratory tests or so that biological metabolic pathways in plants and animals can be studied. Radioactivity is also used in environmental studies, archaeology, geology, and many other sciences. Isotope analysis is used to identify bird and fish migration routes, origins of industrial waste, the ages of archaeological sites, the dates of volcanic eruptions, the places where diamonds were mined, and the age of the Earth. In industry, radiation is used for testing and measuring, cross-linking polymers, preserving food, and sterilizing food packaging, syringes, and other medical devices.

The types of ionizing radiation used in medicine include x-rays, alpha, beta, gamma, protons, and neutron radiation. A brief summary of these types is given in Table 1 on the next page.

What does radiation do to me? (People always ask that!)

Radioactivity won’t turn you into a superhero. *Radioactivity is a natural part of the environment.* We are constantly exposed to radiation from the sky (cosmic rays), the ground (radioactive elements in rock and soil), and our own bodies (internal radiation from naturally occurring radioisotopes such as ^{40}K and ^{14}C). The largest part of our radiation exposure comes from radon, which is made by the decay of heavy elements in the ground and which can become concentrated in our basements. Airline crews, frequent fliers, and people living at high altitudes receive much more radiation from cosmic rays than those who live near sea level. Some buildings and building materials such as granite can be noticeably radioactive. Some plants, including tobacco, concentrate radioisotopes from the soil they are grown in. Many of the smoking-related lung cancers are caused by these radioactive particles. Isotopes such as ^{40}K and ^{14}C are produced by cosmic rays striking the upper atmosphere. We cannot avoid them.

When an energetic photon or radiation particle passes through the human body, it usually passes right through without doing anything. Particles that stop in the body deposit their considerable

energy. This can break apart molecules, kill cells, and damage DNA. The body is very good at repairing cell damage, so most of the time nothing much happens. Very rarely, a damaged cell is damaged in just the right way to become cancerous. If the DNA in a gamete is slightly damaged and/or repaired incorrectly, a genetic mutation has occurred. If a cell's DNA is damaged badly enough, the cell just dies. Radiation sickness occurs when this happens to too many cells at once. Cells are particularly vulnerable to radiation damage while undergoing cell division, which is why pregnant women should avoid radiation as much as possible. This is also why radiation is used to cure cancer, because cancerous tumors contain more dividing cells than healthy tissue. Since dividing cells are also found in hair roots, bone marrow, and the digestive system, the symptoms of radiation sickness include hair loss, anemia, and vomiting/diarrhea. There are no "safe" levels of radiation. All one can do is limit one's exposure when possible, unless (as in medical treatment, for example) the benefits outweigh the risks. Doctors should take these risks into consideration before requesting x-rays, PET scans, CAT scans, etc. and order these tests only when there are no alternative ways to make the diagnosis.

Table 1: Summary of Ionizing Radiation Types Used in Medicine

Type of ionizing radiation	Origin	Approx. energy*	Ability to pass through tissue	Ability to damage tissue	Medical Uses
Alpha ^4He nucleus	Radioactive isotope, for example ^{210}Po .	$10^6 - 10^7$ eV	Poor, stopped by one sheet of paper	Very high, especially when inhaled or ingested.	Few medical uses due to short particle range. ^{241}Am is used in smoke detectors.
Beta Electron or Positron	Radioactive isotope, for example ^{90}Sr , ^{131}I .	$10^5 - 10^6$ eV	Medium, stopped by a book	Medium	PET scans, radioactive tracers for diagnostics, some treatments.
Gamma Photon (light)	Radioactive isotope, for example ^{60}Co or ^{137}Cs .	$10^3 - 10^7$ eV	Very high, long range	Medium	Cancer treatment, sterilization of medical devices.
X-ray Photon (light)	Particle accelerator (X-ray tube)	$10^2 - 10^5$ eV	High	Medium	Detection of broken bones, etc. inside the body.
Ultraviolet Photon (light)	Sunlight, electric arcs, quartz lamps	$10 - 10^3$ eV	Poor	Medium, causes sunburn and skin cancer	Sterilization of medical devices, treatment of jaundice.
Proton	Particle accelerator	$10^6 - 10^8$ eV	Medium to high	Maximum damage is done at the end of the track, so good targeting of tumors	Hadron therapy for cancer (available in only a few locations).
Neutron	Radioactive isotopes, nuclear reactors, particle accelerators	$10^5 - 10^7$ eV	Medium to high	High	Radioisotope generation, sterilization, hadron therapy.

*These numbers are very approximate. The photon ranges overlap because the names "ultraviolet", "x-ray" and "gamma ray" only roughly denote their energy ranges.

About Isotopes:

An atom's **number of protons** determines its chemical **element**. This is the atomic number.

An atom's **number of neutrons** determines its **isotope**. Each chemical element has many different isotopes.

Example:

^{12}C or Carbon - 12: 6 protons, 6 neutrons, not radioactive.

^{13}C or Carbon - 13: 6 protons, 7 neutrons, not radioactive.

^{14}C or Carbon - 14: 6 protons, 8 neutrons, radioactive.

Natural carbon is a mixture of all three isotopes.

The **isotope number** is the sum of the number of protons and the number of neutrons.

Causes and Types of Radioactive Decay:

Radioactivity occurs because some nuclei are unstable.

Alpha Decay: The nuclear strong force is a very short-range force, and large nuclei are pushing its limits. Occasionally an alpha particle (^4He nucleus) pops off. The new element has two fewer protons than the original element.

Beta decay: This is caused by processes involving the nuclear “weak force.” There are three common kinds of beta decay:

- **β^- Decay:** A neutron splits into a proton, an electron, and an antineutrino. The electron flies away as the “beta particle.” The antineutrino flies away also. The new element has one more proton than the original element and therefore moved one space higher in the Periodic Table. The ^{90}Sr sample used to generate the data for Experiment 1b is a β^- emitter.
- **β^+ Decay:** A proton is converted to a neutron, emitting a positron and a neutrino. The new element is one space lower in the Periodic Table. The positron is an example of antimatter. It is a positively charged electron, and will annihilate as soon as it meets a regular electron. Potassium-40 is a β^+ emitter. Who knew that antimatter comes from bananas?
- **Electron Capture (E.C.):** A proton captures one of the atom's inner electrons, forming a neutron and an antineutrino. The new element is one space lower in the Periodic Table.

Gamma Decay: When a nucleus has undergone one of the other types of decay, it is often left in an excited energy state. Gammas are emitted when a nucleus returns to its ground state.

Nuclear Fission: This occurs in large nuclei, often as a result of being struck by a neutron. The nucleus splits nearly in half and often emits smaller particles as well. Spontaneous fission occurs naturally, but fission can also be induced in the laboratory.

Half-Life:

Radioactivity is a statistical process. There is no way to know when a particular nucleus will decay. However, we can say, with confidence, how many nuclei in a large sample will decay in a given time. The time needed for half of the nuclei in a sample to decay is the “half-life.” Measured half-lives vary from 10^{-22} seconds to over 10^{10} years (10^{17} seconds) – an enormous range! Note that two half-lives do NOT make a “whole life”. After half of the atoms decay, we reset the clock. After two half-lives, $\frac{1}{4}$ of the original sample remains, not half.

The equation that describes radioactive decay is

$$\frac{N}{N_0} = e^{-\lambda t} \quad \text{Equation 1}$$

where N_0 is the initial number of atoms, N is the final number of atoms, t is the elapsed time, and λ is the decay constant. The half-life $t_{1/2}$ is related to λ by the equation

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \quad \text{Equation 2}$$

Half-life is an intrinsic and constant property of the nucleus. The half-life of a radioactive isotope is unaffected by chemical processes. It can be measured whether the isotope is pure or part of a chemical compound. This makes half-life a very useful physical property.

Experiment 1: Statistical Nature of Radioactivity with Coins

Nuclear decay is a random process. If you count the number of decays that occur in 10 seconds and repeat this measurement over and over, you will get different answers. This has nothing to do with your ability to measure. Nature just works that way. Therefore, any measurement of the decay rate (the number of decays per second) will be a range of numbers, not a single value. For example, a properly stated answer would be "the decay rate is 247 ± 11 decays/second."

We will simulate radioactive decays by flipping coins. The mathematics is the same, and you can see what is going on. We will NOT use the computers in this part of the lab. Doing this lab the "old-fashioned" way allows you to better appreciate what the computer is doing.

What to do:

- Flip 25 coins, count the heads, and record the number in the Data Table.
- Do this 200 times, then plot the data on a histogram. You may divide the work by sharing data with your classmates.
- Make a histogram of your data BY HAND, using the procedure described in Lab 1: Measurement.

What to look for: As you add data to your histogram, you will see how the peak grows as more data is collected. Find the average and standard deviation of your data by using the peak and FWHM (full width at half maximum) of your graph. You may wish to refer to the handout for Lab 1 and the Measurement and Error Handout.

Experiment 1b: Counting Statistics For a Radioactive Source

On your computer, you will find a data file that contains repeated measurements of a sample of radioactive Strontium-90. ^{90}Sr is a product of fission in nuclear power plants. It is a β^- emitter with a half-life of 28.9 years. Each data point represents the number of radioactive decays occurring in a second. The data file contains several hundred repeated measurements.

What to do:

Import the data into Graphical Analysis and create a graph of counts vs. time. (“Time” is the elapsed time as the computer repeatedly recorded the data from the Geiger counter.) Note that there is a natural variation in the number of counts. The width of the “stripe” in this graph is an indication of the measurement uncertainty.

Click **Insert** → **Additional Graphs** → **Histogram** to create a histogram of this data. The width of the histogram should roughly numerically match the width of the stripe on your first graph.

Use the curve fit button in Graphical Analysis to fit a Gaussian curve to your histogram. Print this graph and answer the Analysis Questions at the end of the lab.

Experiment 2a: Half-Life of Coins

What do radioactive decay, flipping coins, and the temperature of a cooling cup of coffee have in common? They’re all examples of exponential decay. In this lab, we’ll simulate radioactive decay with a large pile of coins. Each coin is an “atom,” which “decays” when it comes up tails. After you see how this mathematics works, you’ll analyze another data file from an actual radioactive source.

What to do:

- You have a box of pennies. Count and record the number of pennies in the box. This is N_0 .
- The pennies that show “tails” have decayed. Remove the tails, count the heads, and record the number of heads. This is N_1 , or the coins remaining after the first “toss.”
- Flip the heads. Remove the tails, count the heads, and record the number of heads.
- Keep flipping and removing coins until all of the pennies have “decayed.”
- Graph the data (by hand, on the Data Sheet). Sketch a smooth curve through the data points.
- Answer the Analysis Questions at the end of the lab.

Experiment 2b: Half-Life of a Radioactive Isotope

The data file for this experiment is on your computer. This data is for the isotope $^{137}\text{Ba}^*$, which has a half-life of a few minutes. The “*” indicates that the barium nucleus is in a nuclear excited state. The nucleus emits a gamma ray as it drops down to its ground state energy.

To obtain the sample, we started with a sample of Cesium-137, with a half-life of 30 years. The ^{137}Cs beta-decayed into an excited state of Barium-137. The $^{137}\text{Ba}^*$ was washed out of the ^{137}Cs sample with a few drops of dilute hydrochloric acid. This sample was quickly placed under a Geiger counter. A computer tallied and recorded the number of clicks in several successive 30-second intervals. As time progressed, the count rate gradually diminished. If you wish, you can view a sample being prepared at http://education.jlab.org/frost/halflife_part1.html.

What to do:

- Import the data into Graphical Analysis and create a graph of counts vs. time. Remove “connect the dots”.
- Use the curve fit button to fit an exponential decay curve to your data.
- Go to the Data Sheet, where you’ll find the instructions for completing your analysis.

P31220 Lab

Name: _____

Lab Section: _____ T.A.'s _____

Today's Lab Partners: _____

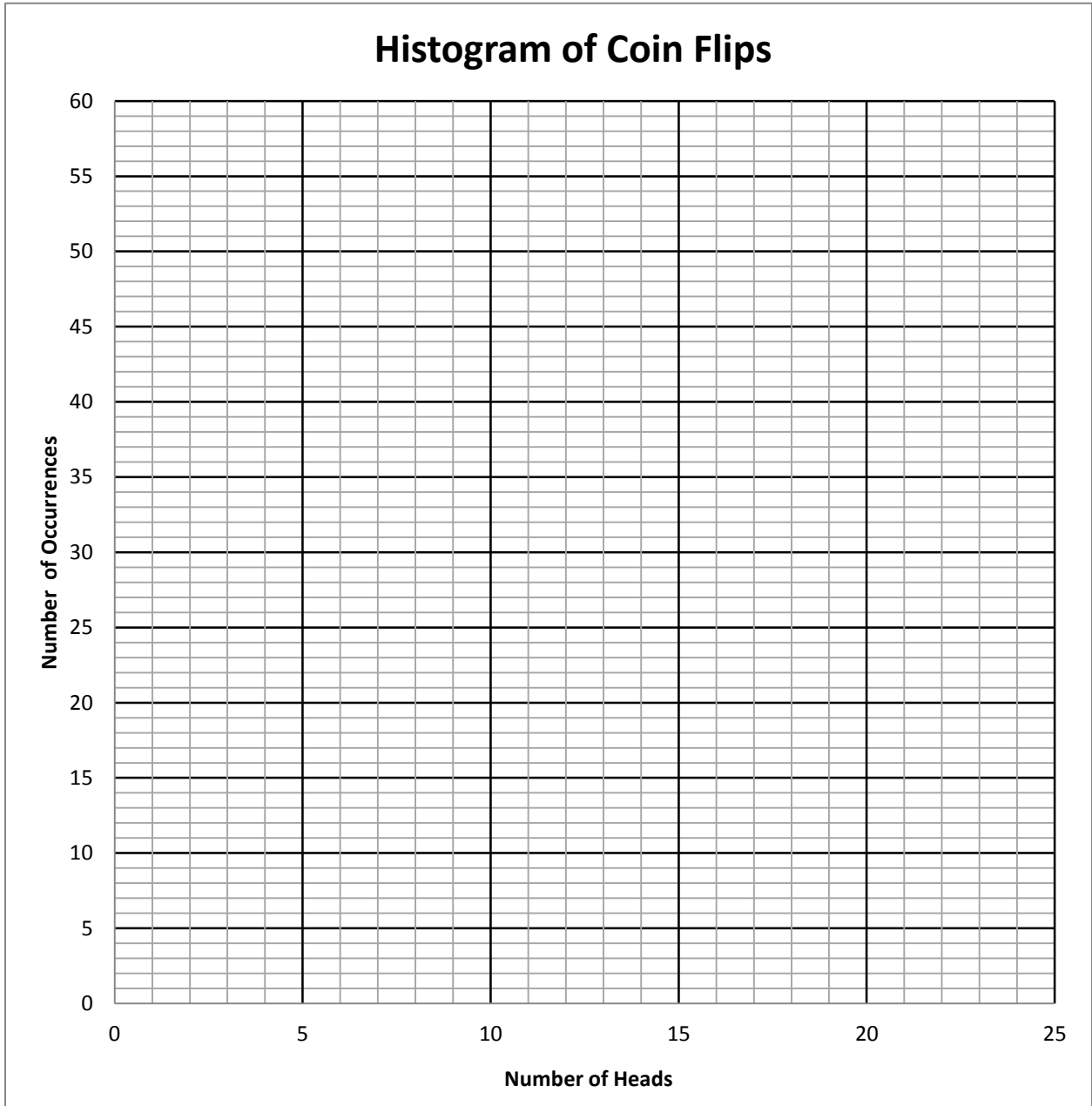
Radioactivity

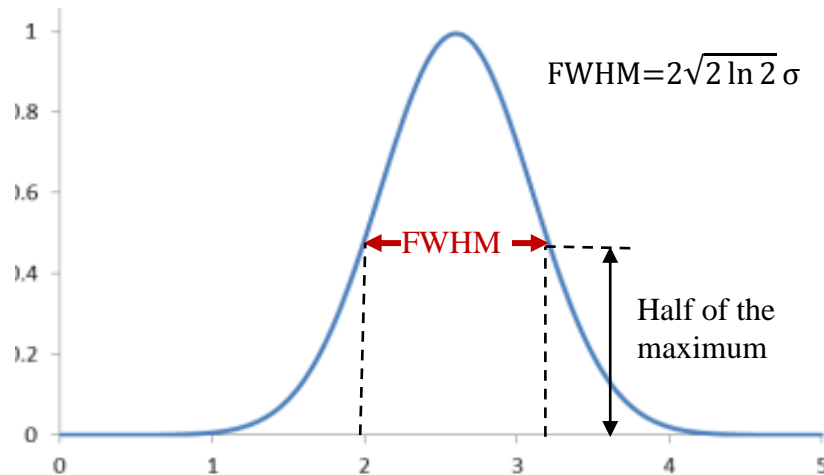
Data Sheets and Analysis Questions

Experiment 1a: Counting Statistics with Coins

Record your data here. Yes, you need to fill in all the boxes with numbers! It won't take as long as you think it will.

Plot your histogram here. You can graph the data as fast as you can read it IF you stack the x's like you did in Lab 1.





Examine your histogram. Sketch a bell-shaped curve, ignoring any spikes or dips in your data. (These would go away if you had a lot more data.) The peak of the curve is the average number of heads. The FWHM (full width at half maximum) of the curve is 2.35σ . Report these values below:

Peak: _____ FWHM: _____ Standard Deviation: _____

Analysis Questions:

1. Is your data consistent with a truly random event? How can you tell?

2. Does the histogram confirm that the expected probability of getting heads is 50%? How can you tell?

3. What numbers of heads would you consider to be likely?

4. What numbers of heads would you consider to be unlikely?

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5. What are your criteria for “likely” and “unlikely”? Express your answer in terms of the size of the standard deviation.

Experiment 1b: Analysis of Data For a Radioactive Source

Examine your histogram. Use the Gaussian curve fit (not the data) to determine the following values:

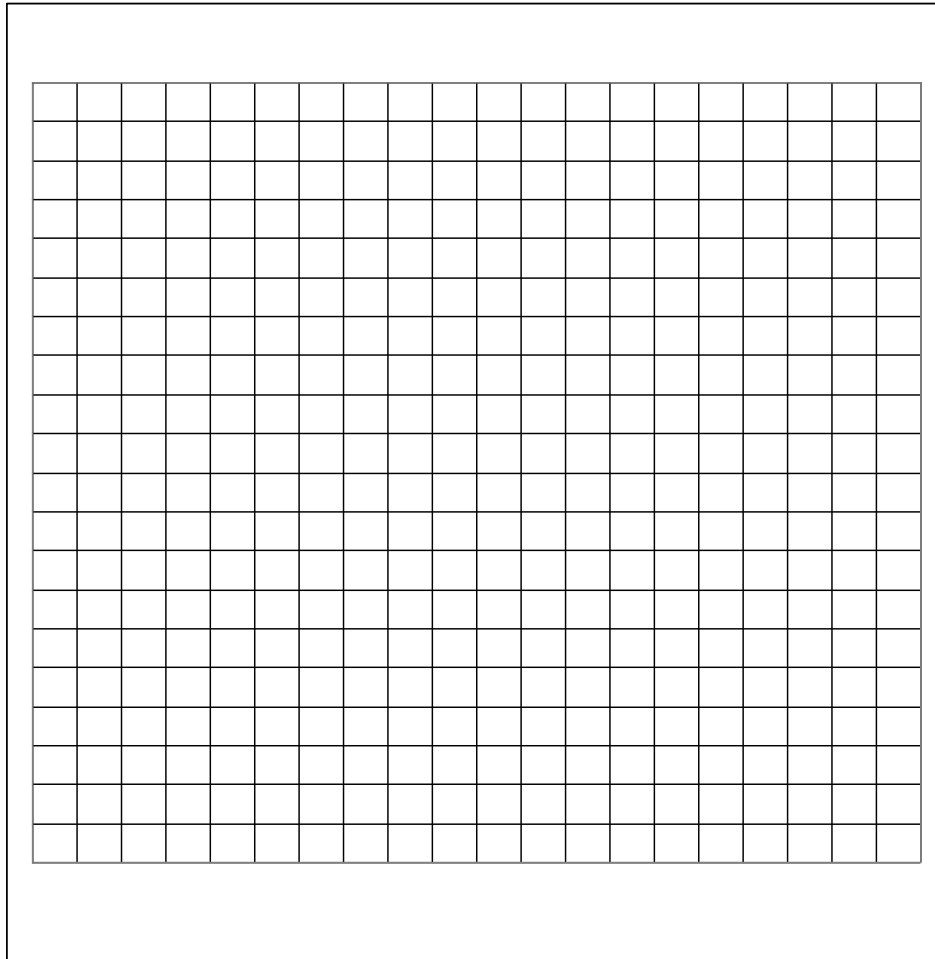
Peak: _____ FWHM: _____ Standard Deviation: _____

6. Compare your histograms for Experiments 1a and 1b. Is coin-flipping a good analog to the behavior of an actual radioactive source? How can you tell?

Experiment 2a: Half-Life of Coins

Time unit (Toss)	Number of coins remaining	Time unit (Toss)	Number of coins remaining
0		7	
1		8	
2		9	
3		10	
4		11	
5		12	
6		13	

Plot the data on the graph below. Put the Number of Coins Remaining on the vertical axis, and Time Units (Tosses) on the horizontal axis. Don't forget to label the axes, draw a smooth curve through your data, and put point protectors (circles) around your data points. In science, the data points should be OBVIOUS.



EXAMINE your graph. Answer the following questions by reading your graph.

- 7. If you started with 300 pennies, how many "tosses" would it take to decrease the number to approximately 150 pennies? Fractional "tosses" are OK.

Answer:

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8. If you started with 200 pennies, how many “tosses” would it take to decrease the number to approximately 100 pennies?

Answer:

9. If you started with 100 pennies, how many “tosses” would it take to decrease the number to approximately 50 pennies?

Answer:

10. SUMMARIZE: Does the number of tosses required to reduce the number of pennies by half depend on the number of pennies that you start with? How can you tell?

11. **Based on this experiment**, why do you think that we talk about “half-life” in radioactive decay, rather than the time needed for all of the atoms to decay?

12. How do you think that your graph would change if you tossed dice instead of coins? In the case of dice, the die will “decay” if it shows a “one”, but not if it shows any other number. **Sketch your guessed line on the graph above, using a dotted line.** THINK this out – don't make a wild guess. Why did you put your line where you did?

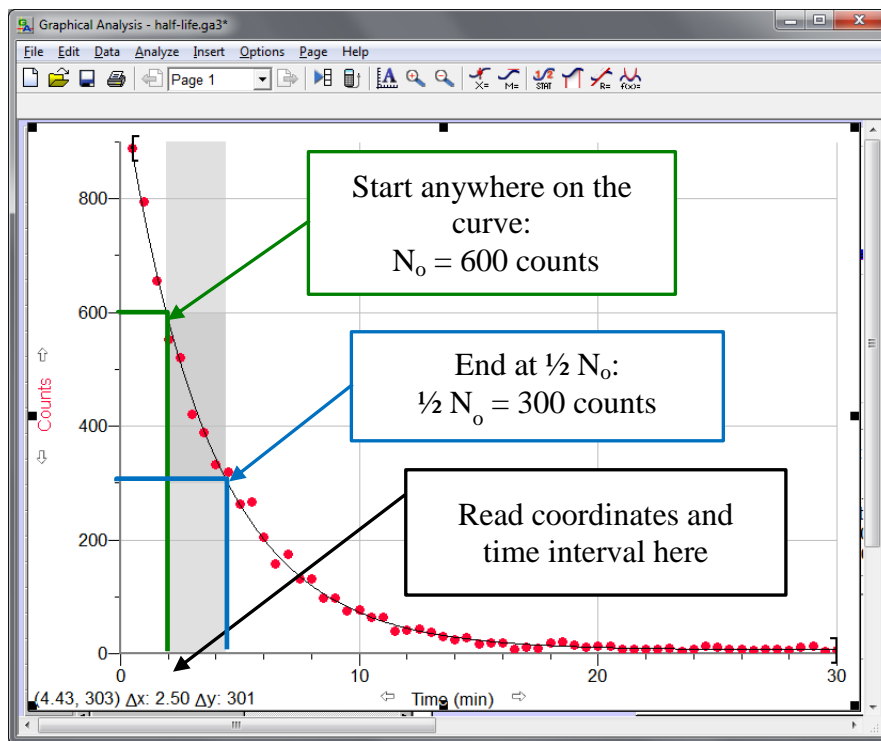
Experiment 2b: Half-Life of a Radioactive Isotope

You have a graph of the data, with the fitted exponential decay curve. You'll be analyzing this data in three different ways. Print this graph and turn it in with your lab.

13. Examine your graph. Why do most of the data points lie scattered on either side of the fitted line, rather than on it?

14. Use the information from the curve fit to determine the half-life of $^{137}\text{Ba}^*$. Show your work below.

Answer:



Next, determine the half-life by reading it directly from the graph using the method shown in the above figure. Use the curve fit for this analysis, NOT the data points. Your work will be much easier if you use the coordinates of the mouse cursor, located at the bottom left corner of your graph. Do this five times, using five different arbitrary starting points. Some of your intervals should overlap. If you always use the end of one interval as the start for the next, you'll run out of good data. Record your results on the next page.

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You may use the margin for calculating the standard deviation.

Start number of counts	End number of counts	Time difference (Half-Life)
Average Half-Life:		
Standard Deviation:		

And now, let's slice and dice this data one more way. Create a new Calculated Column in Graphical Analysis and use it to calculate the natural logarithm of your data. Plot $\ln(\text{counts})$ vs. time. When plotted this way, your data should approximate a straight line. Do a linear fit to your data after doing a "click and drag" to select your best data. The half-life can be calculated from the slope of this graph. Print this graph and turn it in with your lab.

15. What half-life did you measure? _____ Show your work below.

Finally, put it all together and attempt to find your best value for the half-life of $^{137}\text{Ba}^*$:

Analysis method:	Half-Life of $^{137}\text{Ba}^*$	% difference with accepted value
Graphical Analysis curve fit		
Direct reading of exponential curve		
Linear fit of log plot		

The "Percent Difference" compares your average to the accepted value of **2.55 minutes**. We expect your result to differ from the accepted value because of possible contamination of the sample with low concentrations of longer-lived isotopes.

$$\% \text{ Difference} = \frac{|(\text{Your value}) - (\text{Accepted value})|}{(\text{Accepted Value})} \times 100\%$$

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16. Please answer this question based on the amount of confidence that you have in the answer, NOT what is closest to the “accepted” value. What is your “best” measurement for the half-life, and why did you pick this value?

17. What are your overall thoughts and impressions of what you learned in this lab?

Graphs to print and turn in:

- Experiment 1b histogram
- Experiment 2b Half-life exponential curve
- Experiment 2b Half-life log plot

Clean-Up:

- **Please check the floor for dropped pennies and return them to the boxes.**
- Place all trash and recyclables in the proper containers.

Thank you!

Please enjoy:

<http://www.sciencecourseware.com/VirtualDating/>

These Virtual Labs are well worth doing. “Isochron” shows you how to use radioactivity to date rocks. “Virtual Dating Radiocarbon” shows you how to use radioactivity to date biological materials from archaeological sites. Have fun!

<http://ie.lbl.gov/education/isotopes.htm> <http://www.nndc.bnl.gov/chart/>

Interactive chart of the nuclides, and excellent in-depth information in “The ABC’s of Radioactivity”.

http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html

Online explanation of radioactive decay, with an applet that simulates radioactive decay for several different isotopes.