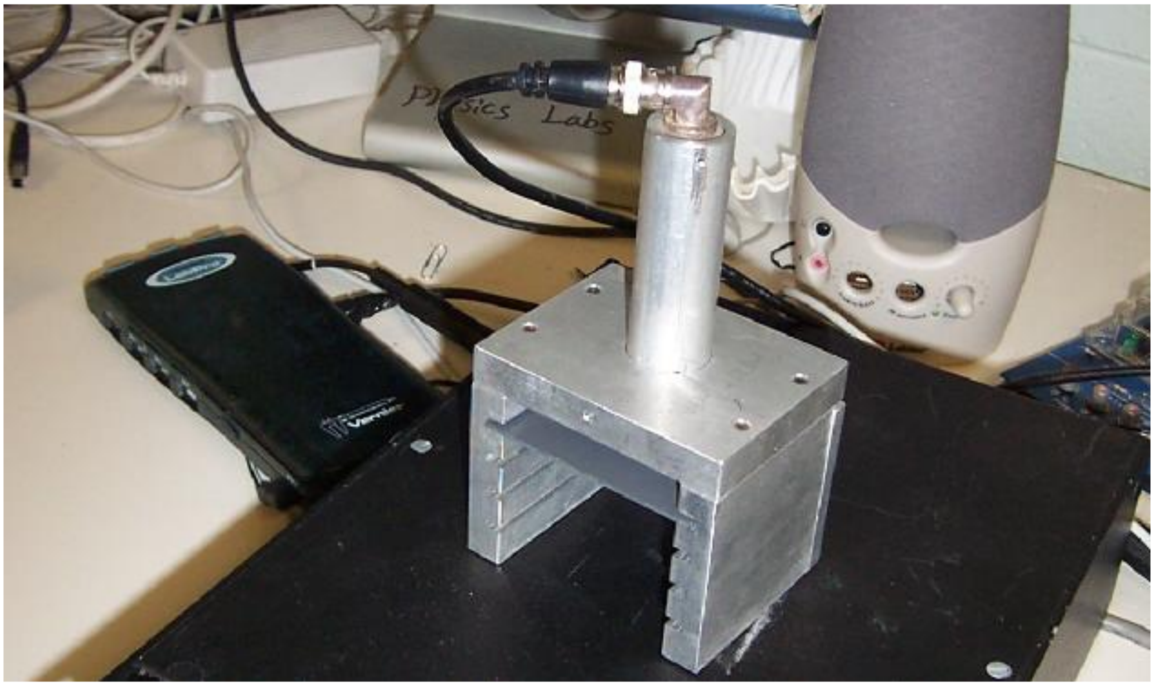
RADIOACTIVE DECAY



Purpose: To examine the exponential decay associated with a short-lived radioactive source and determine its half-life. To observe the Gaussian (bell-shaped) curve from the counting statistics of a long-lived radioactive source.

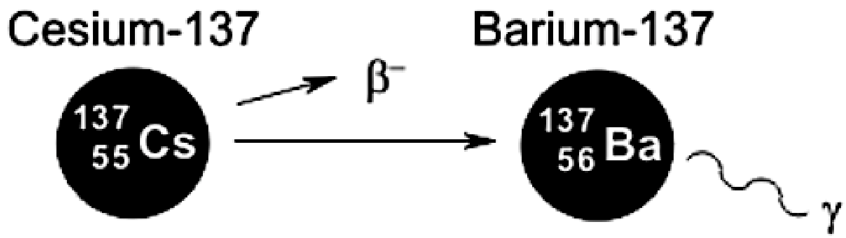
Apparatus: Radioactive sources (long and short-lived), Geiger counter and tray holder, Timer/Counter (only used to power Geiger counter, not for counting or timing), computer.

Introduction

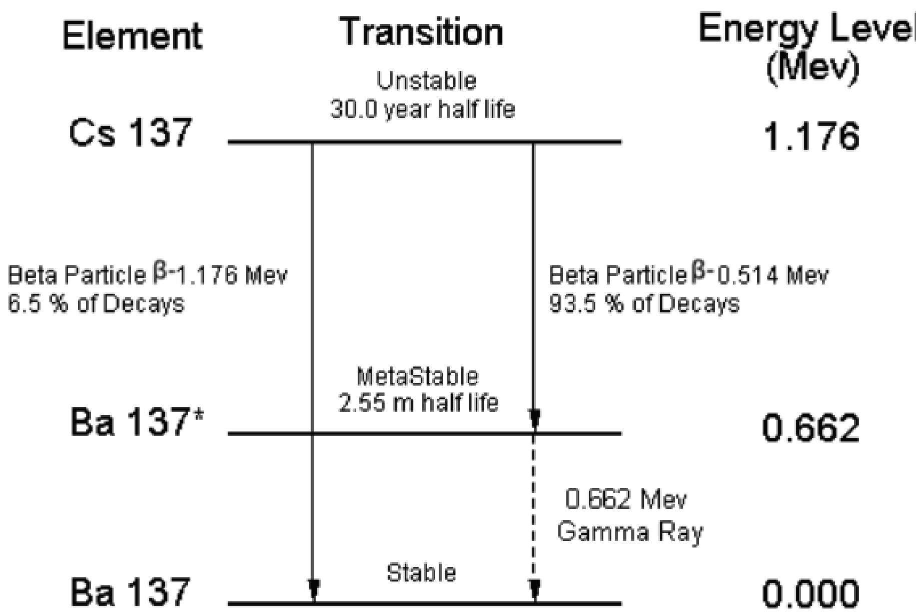
It is assumed that you have covered Radioactive Decay in lecture. If you have not, refer to Chapter 31, Sections 1-5 of Physics, 11th ed. (Cutnell & Johnson, Wiley, 2018).

If you are not currently taking the General Physics 204 lecture course, or don't have the above textbook, here is link to a free textbook with similar content (read sections 1-5): *<u>https://openstax.org/books/college-physics/pages/31-introduction-to-radioactivity-and-nuclear-physics</u>*

Radioactivity comes from the decay products of unstable elements; one such example is Cesium-137 (Cs, whose atomic weight is 137 and atomic number 55) is an unstable element which decays via a beta particle (β-) to an isotope (same number of protons, but different number onuetrons) of Barium-137 (Ba*, whose atomic weight is 137 and atomic number is 56). Ba* then decays via a gamma particle (γ) to Ba (still with atomic weight 137 and atomic number 56), which is the stable form of the element:



Note that there are two pathways to Cesium's decay – most of them (about 94%) involve the emission of a β- of lower energy (0.514 Mev) while relatively few of them (about 6%) involves the emission of a β- of higher energy (1.176 Mev). Ba* then decays through the emission of a γ of energy 0.662 Mev to Ba. The half-life (see Lifetime Measurement section further down) of Cs is ~30 years while the half-life of Ba* is about 2.55 min:



In this lab we will detect the particles emitted from these two unstable nuclei:

1) A long-lived (half-life on the order of years) Cs-137 nucleus

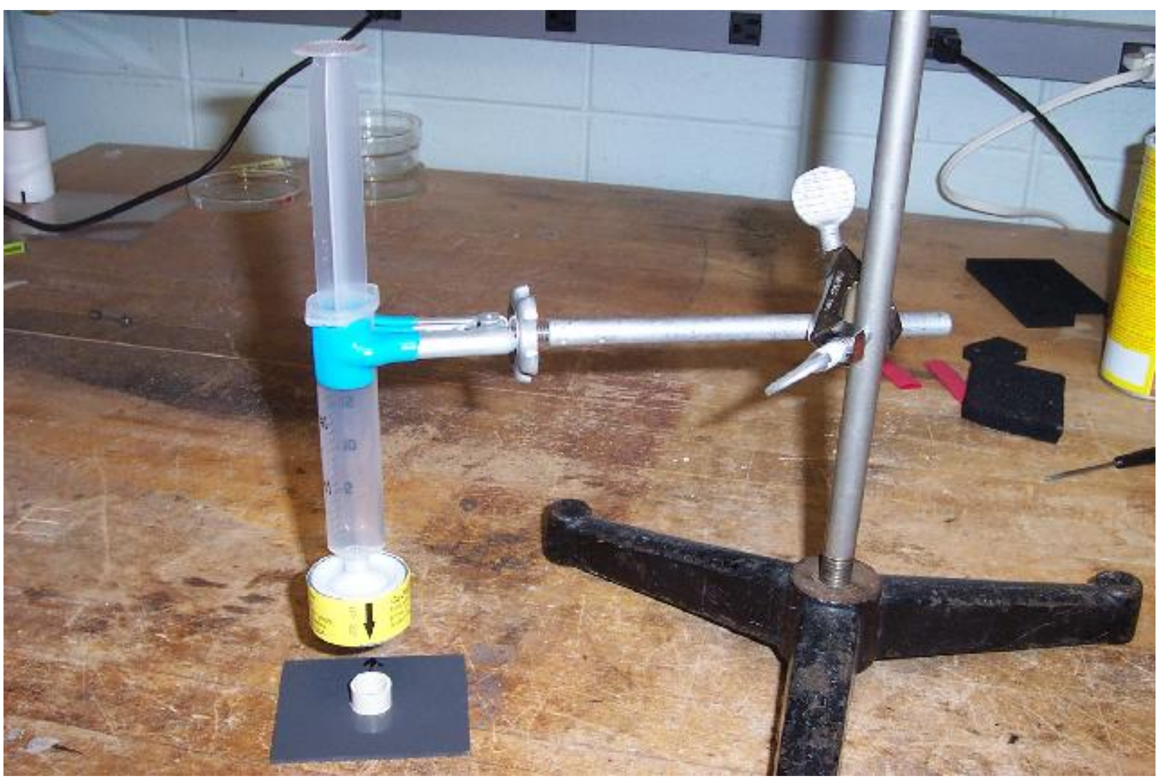
2) A short-lived (half-life on the order of minutes) Ba* nucleus, which your TA will produce in the lab.

The Geiger counter on your table will detect both the and the particles but will not differentiate between them; each count registered by it due to **ionizing radiation** (where electrons are removed from atoms) from a decay particle. Note that ionizing radiation is different from **non-ionizing radiation**, which consists of energy waves of Electromagnetism – such as radio waves, e.g. AM/FM radio, WiFi, Bluetooth, etc.

The first radioactive source comes in a sealed plastic disk, mounted on an aluminum rectangle (see picture below):

A long-lived radioactive source

The second radioactive source will actually be created in the lab by “milking” the decay products from a radioactive source using a mild HCl solution. The extracted liquid is then used as the radioactive sample (see extraction technique below, which may be slightly different on Busch as it is on Douglass):



Producing a short-lived radioactive source in the lab

You will first observe the statistical character (Gaussian Probability Distribution) of nuclear radiation, using a long-lived source of radioactive ^{137}Cs. Then you'll determine the decay constant and half-life (from Exponential Decay) of the short-lived ^{137}Cs daughter ^{137}Ba* (itself unstable): a parent – daughter – granddaughter situation (see textbook).

Gaussian Distribution A long-lived source (^{137}Cs, ^{60}Co) will decay negligibly during a few hours. Nevertheless, the counts observed during equal sampling intervals can fluctuate substantially due to the statistical (random) nature of decay processes.

Strictly, radioactive decay is described by a Poisson Probability Distribution, which is a *discrete* distribution. If the counts per interval are more than a few tens, the spread in individual measurements will be very closely Gaussian, which is a *continuous* distribution with standard deviation about equal to the square root of the mean. In other words, for large values of N (meaning measurements), the Gaussian (a distribution which is symmetric about the mean) serves as a good approximation for the Poisson (which is not strictly symmetric about the mean)

Thus, the size of the fluctuations will grow as the square root of the mean value (i.e., as the square root of the counting time per sample), but the percentage fluctuations will decrease as the inverse. Study Figures 1 and 2. Note the approximate equality among stdev, sqrt(mean) and width (C parameter) of the distribution histogram. The exact equality of sqrt and stdev is not to be expected, statistically, and the bin size chosen for the histogram can affect the fit.

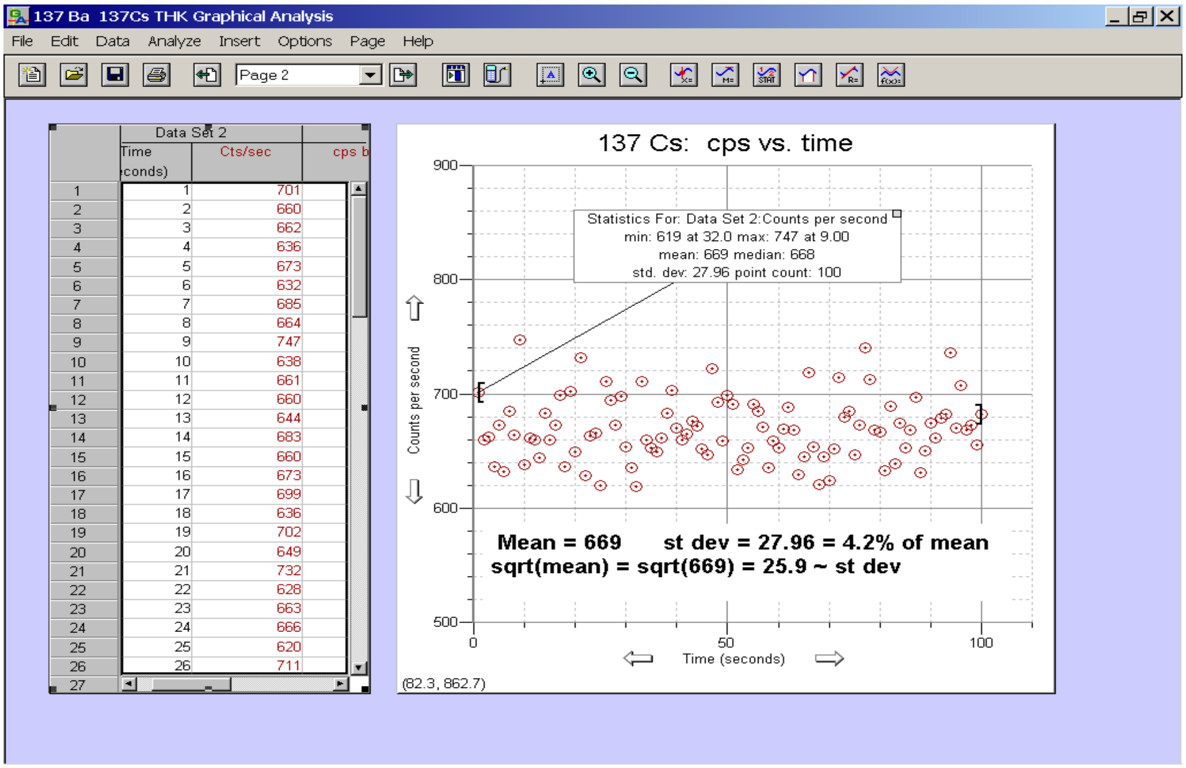


Figure 1 Statistical fluctuations in the random decay process

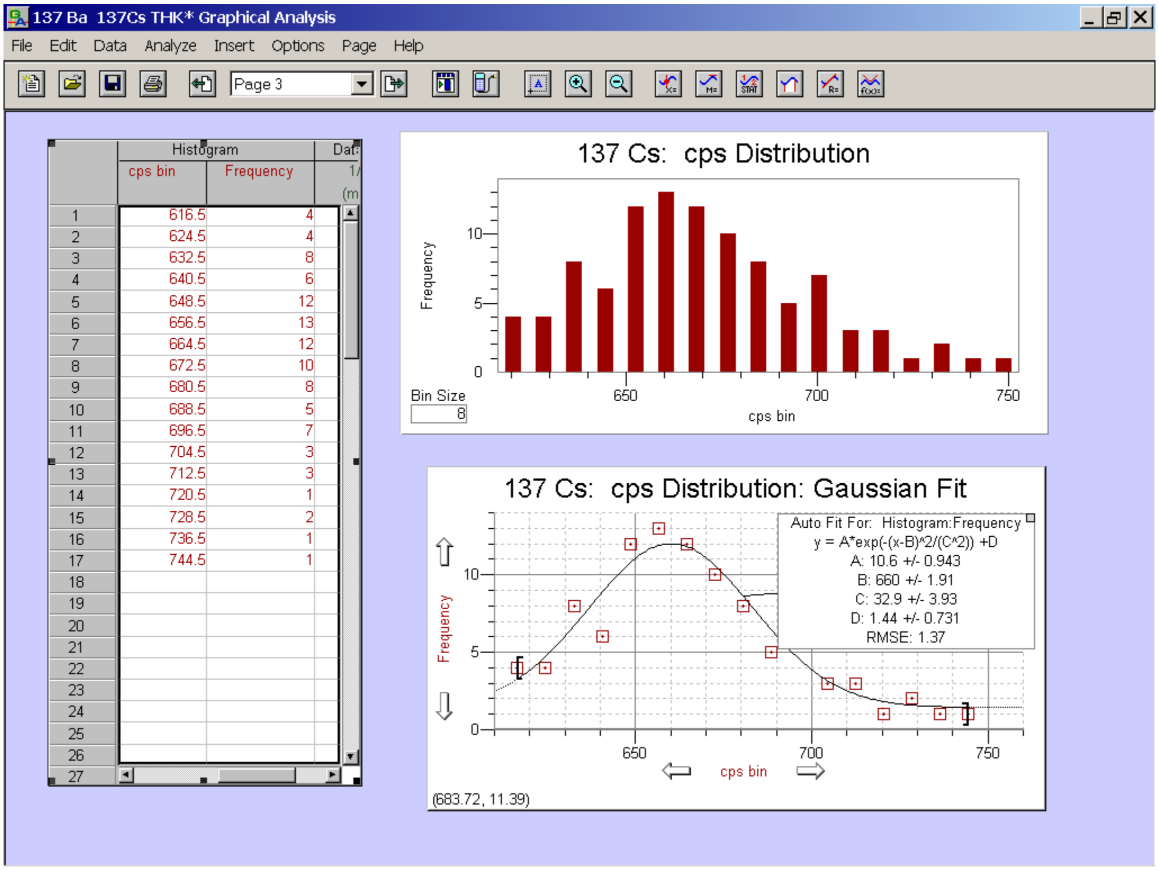


Figure 2 Distribution of counts for equal counting intervals

Lifetime Measurement The decay of ^{137}Ba* follows an exponential law, similar to what you may have seen in the Capacitance lab. In this case, however, you will be interested in number (or change in number) with respect to time, rather than Voltage with respect to time. In the following equation, we can see that the decay rate R drops off exponentially from the initial value R_0. Note that we do not actually measure the *number* of decays, but rather the *rate of change of number* of decays (since *rate of change of number* is merely the time derivative of *number*, both have similarly shaped exponential curves:

$$R = R_0 e^{(-\lambda t)} \qquad \left(\tau = \frac{1}{\lambda} = mean\ life\right)$$

A curve-fit to the rate vs. time curve will give the decay constant λ, and its inverse - the mean lifetime τ (tau). Half-life is sometimes used instead of τ:

$$T_{\frac{1}{2}} = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda}$$

Procedure

As usual, write your lab report in Google Docs and share it with lab partner(s), TA and LA.

Open Radioactivity.CMBL, which is a Logger Pro file in experiment folder of your lab Mac. After you confirm the attached Radiation sensor, ou should see two sub-windows: a Radiation-Latest display and a Table. The former will give you a real-time count rate (counts/interval) based on an interval you specify; the latter will display the results of many intervals over time. Go to Experiment-->Data Collection-->Collection. Here the two important parameters you will vary are Duration and Seconds/Sample. Radiation Counts will display the number of hits the Geiger Counter has registered in the last Seconds/Sample. Duration determines how many of these intervals for which the software should take data. For example, if Seconds/Sample is set to 10 seconds and Duration 100 seconds, there will be 10 pairs of data pairs (Time, Radiation) in the Table, each corresponding to the number of hits the Geiger counter has received in 10 time intervals. **For Part A your Radiation values should fluctuate around a mean value through the experiment; For part B your Radiation values will drop during the experiment.** After you press the Collect button, the software will collect data ("LabPro is collecting" is shown in upper left-hand corner). When the Duration is reached, the software stops gathering data ("Ready" is shown in left hand corner).

Part A - Gaussian Distribution (40 pts)

Seconds/Sample = 1 second, Duration = 300 seconds

0. The fairly large black box labeled "RU Timer" will provide the high voltage necessary for the Geiger tube (counter) to operate. You need to make sure that:

a. The Power toggle switch is set to **On**

b. The Function toggle switch is set to **Counter**

c. The Selector knob is set to **Continuous**

1. Place a long-lived source in the **top slot**. You can start collecting data anytime by pressing the Collect button. Do not disturb the setup during the experiment. However, you can see a real-time plot during the 5 minutes of data collection by going up to the menu bar in Logger Pro and selecting Insert-->Graph. Selecting Page-->Auto-arrange will group your windows more neatly.

2. Your data will automatically be tabulated and plotted. After the experiment is finished, your Table should have 300 sets of data pairs.

3. Go to Analyze-->Statistics. Note the Mean, Max, Min and Standard Deviation and record in your lab report. Calculate sqrt (mean), stdev/mean (%) and ratio stdev/sqrt(mean) and record as well. (15 pts)

4. Go to Insert-->Additional Graph-->Histogram. You will get a histogram ('frequency of value' vs. 'value'; in this case). Note that the most frequent values are those centered around the mean that you recorded from the previous step.

5. Reduce the gaps in your histogram by increasing the bin width - double click on the histogram and increase the bin width to say, 10 or 15 and hit OK. Adjust the bin width until you get a histogram that looks like the one in Figure 1.

6. Normal curve-fitting procedure is to go to Analyze-->Curve Fit-->choosing Gaussian in General Equation, selecting the region of the plot to analyze by clicking-and-dragging on it horizontally and click on Try Fit. However, this sometimes yields a straight line (or no fit), so you may have to help the fitting program as follows:

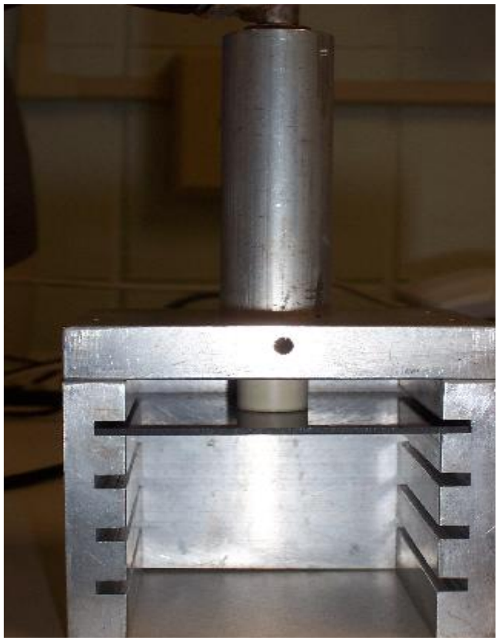
a) Increase bin size if hist-data is too widely scattered.

b) Manual fit, to provide reasonable starting parameters for the auto fit. Input estimated A (maximum height), B (center of peak) and C (width), D (vertical offset). Adjust these parameters for visual fit. Then switch to automatic and Try It.

If the D parameter remains, the auto fit can sometimes do really stupid things, such as finding a large positive A and a large negative D, with the difference being around your manual fit starting value for A or giving a horizontal line fit. If so, try getting rid of the D parameter, then

c) Define function - choose Gaussian, then remove D parameter (vertical offset), manual fit, switch to auto and Try Fit. Whether you were immediately able to get a curve-fit, or you had to do it manually, include your histogram screenshot/photo (**with fit**) in your lab report. (15 pts)

7. Resize the windows such that you can see the three (original, histogram, curve fit) graphs and print out; then take a screenshot or photo for inclusion into your lab report. (10 pts)



Geiger Counter tray with sample holder in top tray

Part B - Lifetime Measurement (40 pts)

Seconds/Sample = 40 seconds, Duration = 1800 seconds (30 minutes)

1. **Make sure you have set the parameters in Logger Pro as specified immediately above. Remove any nearby long-lived source - you only want the radiation from the short-lived source.**

2. When you have read all of Part B instructions and are ready to perform the experiment, get the sample from your TA, and insert it in the **top slot**. Insert the tray in the direction of the arrow marked, since sample tub is not exactly centered.

3. Start taking data by clicking the Collect button. Leave the apparatus undisturbed for 30 minutes. You can, however, generate a real-time plot by (in Logger Pro) going to the menu bar and selecting Insert-->Graph. Double-click on the graph, choose the Graph Options tab on the top, and make sure Point Symbols is *checked* and Connect Points is *unchecked* (to be able to see the points in your plot clearly)

4. After the experiment, try to **estimate** the half-life by visual inspection – from the graph, **eyeball the time at which the count rate has dropped to approximately half its starting value**. Write this estimated value in your lab report. (5 pts) NOTE THAT THE COUNT RATE NEVER DROPS TO ZERO, DUE TO BACKGROUND RADIATION (SOME LEAKAGE OF ^{137}Cs AND COSMIC RAYS, RADIATION IN WALLS, FLOOR, ETC)**.**

5. Do an **exponential** curve fit by going to Analyze-->Curve Fit-->select Natural Exponent in General Equation and click on Try Fit. Record the fit equation in the lab report, including the fit coefficients (A, B, C...) that Logger Pro has determined for the fit. (10 pts) Calculate the decay constant λ (compare fit coefficients with exponential decay equation) and $T_{1/2}$. Show all calculations and include the fitted graph in your lab report. (20 pts)

6. How close (percentage difference) was your visually-determined half-life to your calculated half-life? (5 pts)

7. Dump sample in sink; rinse tray and <u>wash hands</u> (you wouldn't want anything with a 30y half-life to stay on them).

Questions (20 pts)

1. How closely does your curve fit for the long-lived radiation source resemble a Gaussian Distribution? What could you do in your experiment to obtain a curve that looks more like it? (5 + 5 = 10pts)

2. Given a half life of 30 years, by how much does the counting rate change (in %) during the five minutes you are taking data? (10pts)