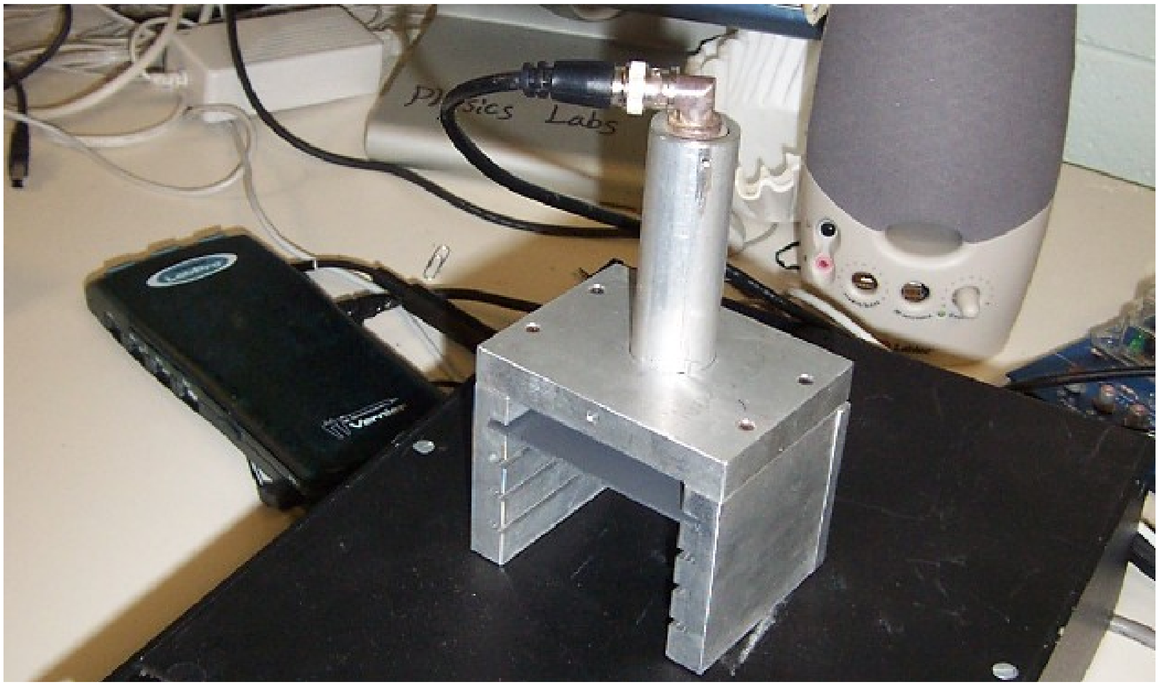
RADIOACTIVE DECAY



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 the Appendix at the end of this write-up.

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

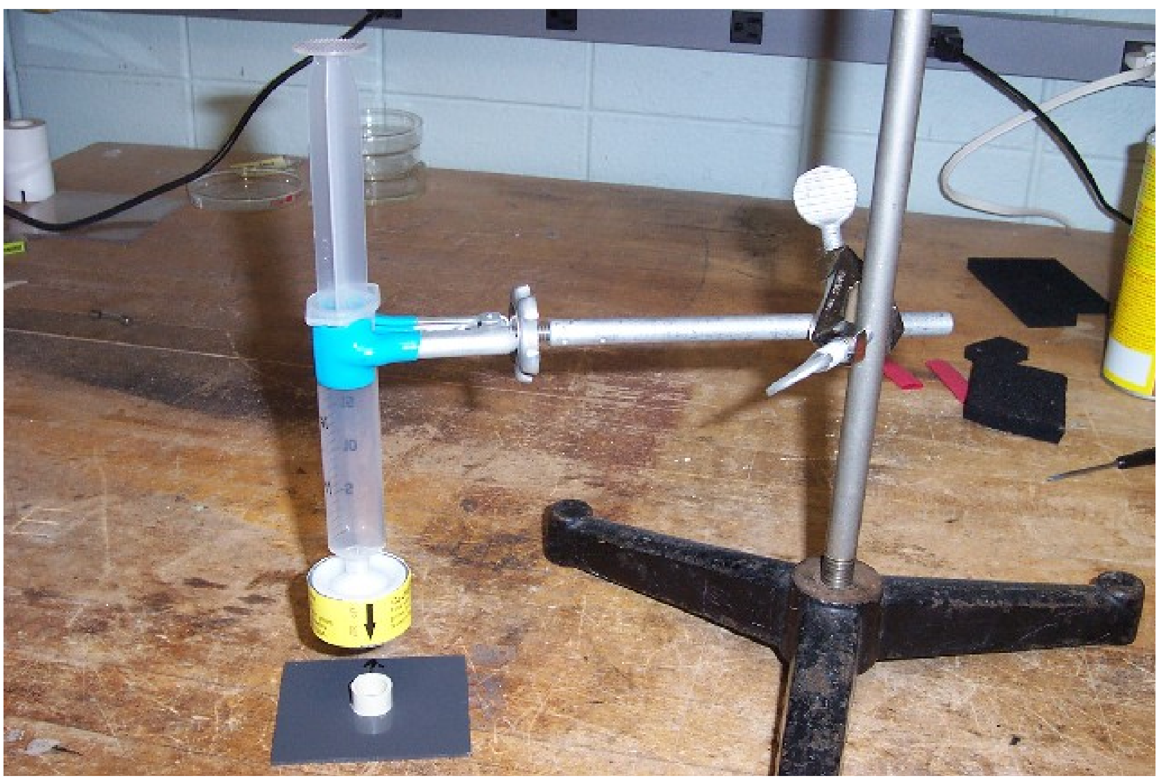
1) A long-lived (half-life on the order of years) ^{137}Cs nucleus, and

2) A short-lived (half-life on the order of minutes) $^{137}Ba^*$ nucleus, which we will produce in the lab.

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):



Producing a short-lived radioactive source in the lab

We will first observe the statistical character (Gaussian Distribution) of nuclear radiation, using a long-lived source of radioactive ^{137}Cs. Then we will determine the decay constant/half life (Exponential Decay) of the short-lived ^{137}Cs daughter ^{137}Ba* (itself unstable): a parent – daughter – granddaughter situation (see Appendix).

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.

If the counts per interval are more than a few tens, the spread in individual measurements will be very closely Gaussian, with standard deviation about equal to the square root of 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. Exact equality of sqrt and stdev is not to be expected, statistically, and the bin size chosen for the histogram can affect the fit.

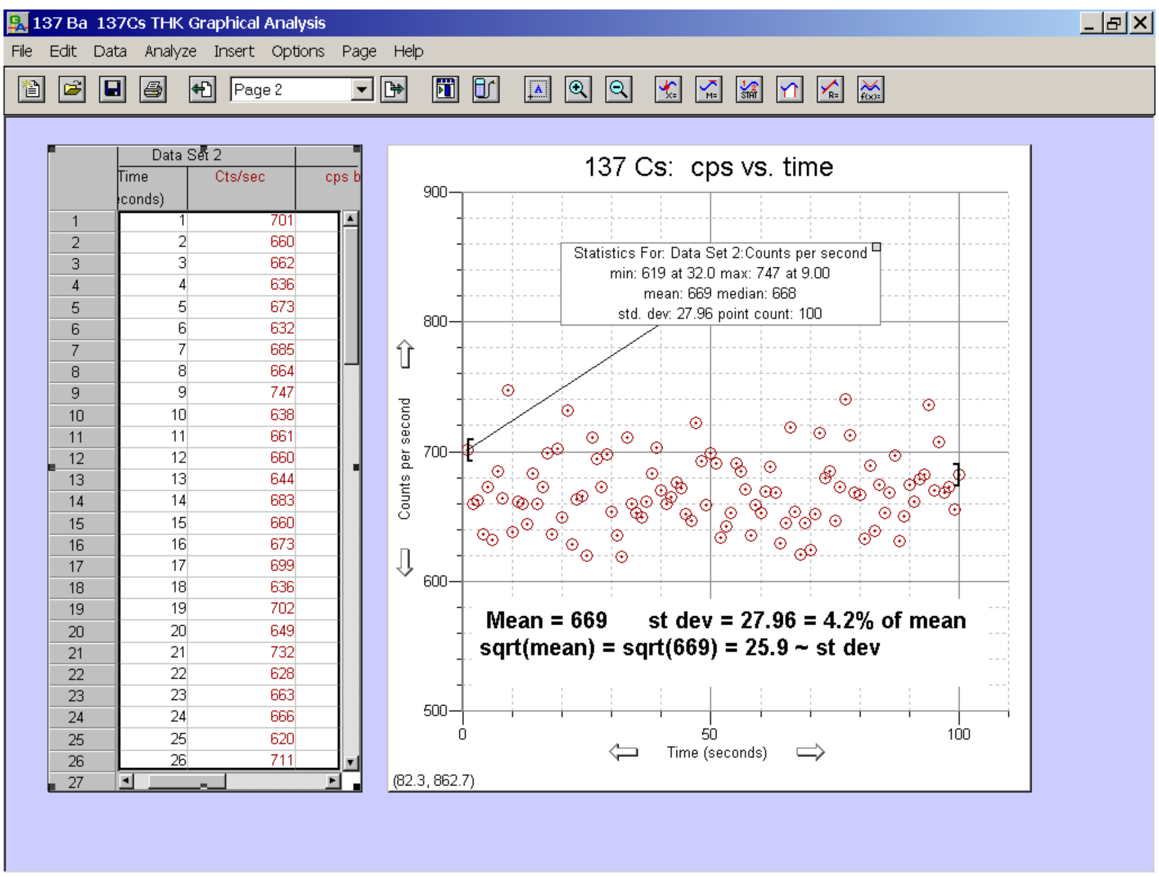


Figure 1 **Statistical fluctuations in the random decay process**

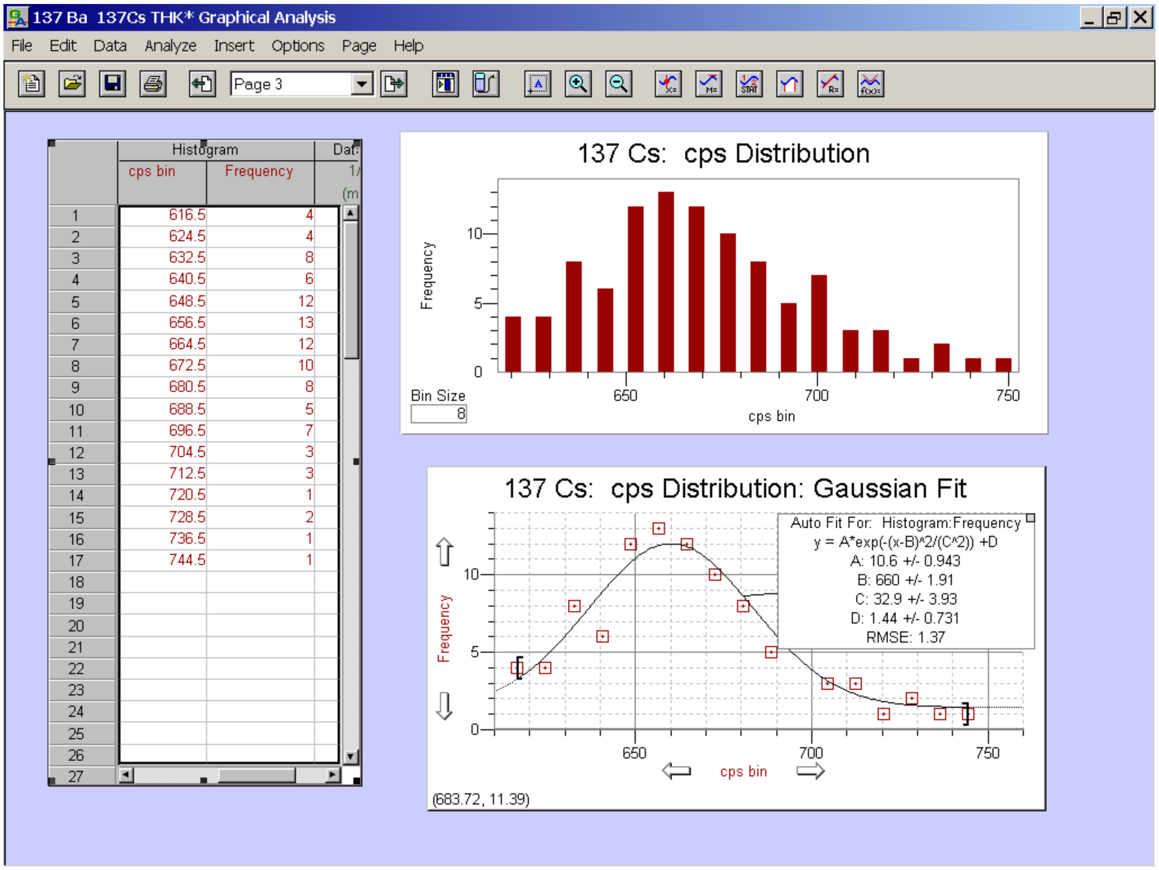


Figure 2 Distribution of counts for equal counting intervals

Lifetime measurement The decay of $^{137}Ba^*$ follows an exponential law, similar to what you saw 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:

$R = R_0 e^{-\lambda t}$ ($\tau = 1 / \lambda$ = mean life) $R = R_0 e^{-\lambda t}$

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: $T_{1/2} = \tau \ln(2) = 0.693\ \tau$.

Procedure

Open Radioactivity.XMBL, which is a Logger Pro file in the same folder as this write-up. You 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 Length and Seconds/Sample. Radiation Counts will display the number of hits the Geiger Counter has registered in the last Seconds/Sample. Length determines how many of these intervals for which the software should take data. For example, if Seconds/Sample is set to 10 seconds and Length 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 Length is reached, the software stops gathering data ("Ready" is shown in left hand corner).

<u>Part A - Gaussian Distribution</u>

Seconds/Sample = 1 second, Length = 300 seconds

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.

2. After the experiment is finished, your Table should have 300 sets of data pairs. Select the Table window, and Copy all the data using Edit-->Select All-->Copy. If you are familiar with Windows keyboard shortcuts, you can alternatively use those.

3. Open Part A.ga3, which is a Logger Pro template file in the same folder as this write-up. Click on the first cell of the Time column, then Paste the data from the previous step using Edit-->Paste. You should see something very similar to the Figure 1 graph.

4. Go to Analyze-->Statistics. Note the Mean, Max, Min and Standard Deviation and record in your hand-in sheet. Calculate sqrt (mean), stdev/mean (%) and ratio stdev/sqrt(mean) and record as well..

5. Go to Insert-->Additional Graph-->Histogram. A blank graph should pop up. Double-click on the Frequency axis label of this graph and check the Y box. After you click OK, you will get a histogram ('frequency of value' vs. 'value'). Note that the most frequent values are those centered around the mean that you recorded from the previous step.

6. 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.

7. Normal curve-fitting procedure is to go to Analyze-->Curve Fit-->select Gaussian in General Equation and click on Try Fit. However, this will most likely yield a straight line, so you may have to help the fitting program as follows:

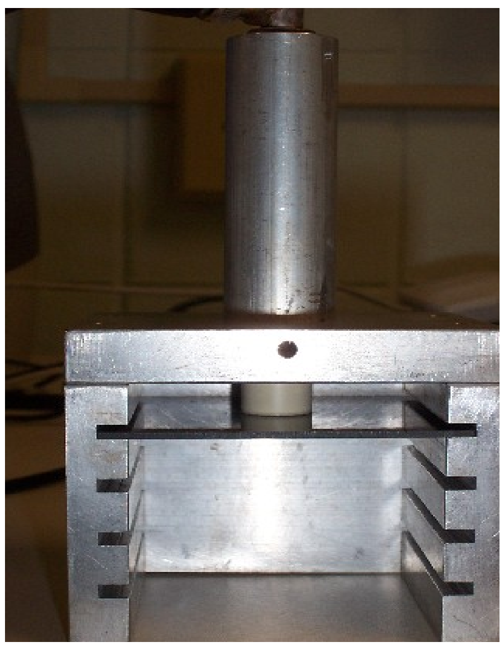
a) Increase bin size if hist-data is too widely scatteed.

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 It.

8. Resize the windows such that you can see the three (original, histogram, curve fit) graphs and print out .



Geiger Counter tray with sample holder in top tray

Part B - Lifetime Measurement

Seconds/Sample = 20 seconds, Length = 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 in **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 apparatus undisturbed for 30 minutes. You can however, switch to another application on the computer thanks to the wonder of multi-tasking.

4. After the experiment, copy and paste the data (as you did in Part A) to the Part B.ga3 template. Try to **estimate** the half-life by visual inspection, just as you did to find the time at which the voltage dropped to one-half in the Capacitance lab. Write this estimated value in your hand-in sheet. **NOTE THAT THE COUNT RATE NEVER DROPS TO ZERO, DUE TO BACKGROUND RADIATION (SOME LEAKAGE OF 137Cs 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 hand-in sheet. Calculate the decay constant λ (compare fit coefficients with exponential decay equation) and $T_{1/2.}$ Print the graph and attach to hand-in sheet.

6. Dump sample in sink; rinse tray and hands.

Appendix

Nuclear radioactivity is a random process, obeying a statistical law, on the average:

$dP/dt = - \lambda P$ Eq. 1 where P = number of remaining unstable parents.

For every parent P death, a daughter nucleus D is born:

$dD/dt = -dPdt = + \lambda P$ (where dP is negative, since the # of P's decreases).

The solution of this simple differential equation is

$P = P_0 e^{-\lambda t} = P_0 e^{-t/\tau}$ ($\tau = 1 / \lambda$ = mean life) Eq. 2 where

$dD/dt = \lambda P_0 e^{-\lambda t}$. Since each death/birth is accompanied by radiation (which is what we will observe; we won't count P's or D's directly) the radiation rate is

$R = \lambda P_0 e^{-\lambda t} = R_0 e^{-\lambda t}$ Eq. 3 Daughter decay rate

The slope of the rate vs. time curve will give the decay constant λ, whence its inverse, the mean lifetime τ (tau). Half life is sometimes used instead of τ: $T_{1/2} = \tau \ln(2) = 0.693\,\tau$.

The lifetime measurement involves a daughter which is also radioactive: a parent – daughter – granddaughter situation. The daughter is very short-lived, relative to the parent. In that case, daughters quickly build up until daughter production (by death of parents, at essentially constant rate) equals daughter death rate (by decay to granddaughter). This is called secular (i.e. time) equilibrium. The buildup involves the same time daughter time constant λ as daughter decay $[\exp(-\lambda_{daughter}\, t)]$ = growth is proportional to

$[1 - \exp(-\lambda_{daughter}\, t)]$ Eq. 4 Daughter regrowth after depletion

There is a practical aspect. After the instructor separates the $^{137}Ba^*$ daughter out of the ^{137}Cs parent source with a weak hydrochloric acid solution and dispenses a few samples for $^{137}Ba^*$ lifetime determination, he or she must wait for several $^{137}Ba^*$ half lives (10 – 15 minutes) before further sample dispensing, while the daughter again comes to secular equilibrium with its parent in the ^{137}Cs source.

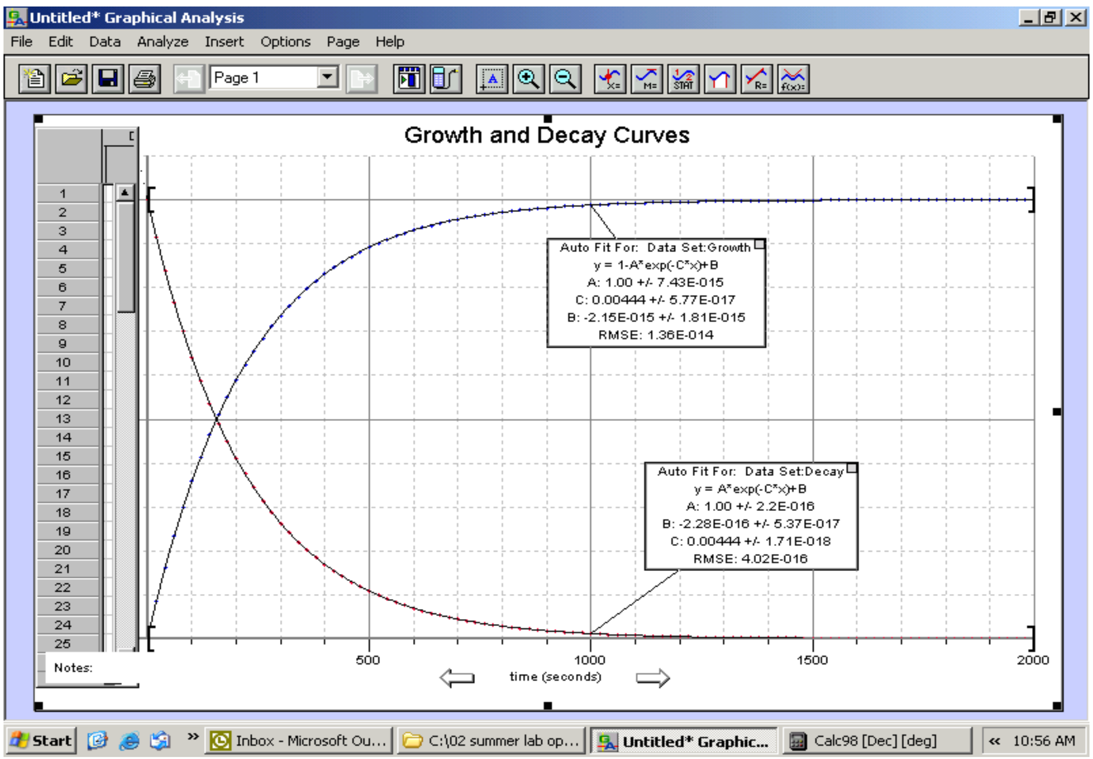
Natural radiation comes from naturally occurring unstable nuclei of lifetime comparable to that of the earth (e.g., 40 K, or from unstable nuclei recently produced in the atmosphere by “cosmic rays”(e.g. 14 C).

Standard radiation types are:
alpha (α): **^{4}He nucleus**, 2 protons and 2 neutrons, A = 4, Z = 2
beta(β, + or -): Identical to an atomic **electron** (if -), but non pre-existing, and
gamma (γ): EM radiation **photon**, usually of much greater energy than an atomic transition photon.

In addition the neutron (n) **a nuclear constituent** (A = 1, Z = 0) is sometimes a secondary product of natural alpha decay, but produced copiously in fission reactors (along with α, β and γ's) , where they keep the “chain” going, easily penetrating a fissile nucleus (because uncharged), such as ^{235}U or ^{239}Pu .

The reactor-produced ^{137}Cs has a half life of 30 years. It can decay (by beta$^-$ emission) either to the stable ground (lowest energy) state of daughter ^{137}Ba or (more often, also with lower energy β^- emission) to a short-lived (a few minutes) excited state (denoted $^{137}Ba^*$). This excited state decays to the ^{137}Ba ground state with emission of an (uncharged) gamma ray.

The detector will be the same for all – a gas-filled Geiger counter, where collisional passage of a charged particle releases ionization (free atomic electrons and positive gas ions) for collection by an electric field, producing an electrical current pulse. In the statistical countin of ^{137}Cs, the charged decay beta will be detected, so the counter efficiency will be essentially 100% (if the β is headed in the right direction). In the lifetime study, the primary decay photons (gammas) are uncharged; only if the gamma interacts with a gas atom to release an atomic electron, with subsequent charge-release cascade, is the γ detected. The detector efficiency will therefore be < 100%.



Decay of radioactive daughter after separation from long lived radioactive parent.
Regrowth of daughter in parental environment.