Radioactivity

APPARATUS

- Computer and interface
- Geiger-Muller detector
- Co and Sr sources
- Source and detector holder
- One in lab: neutron source with bars and silver foil

INTRODUCTION

In this experiment, you will use weak radioactive sources with a radiation counting tube interfaced with the computer to study radioactive decay as a function of time.

RADIATION SAFETY

California State Law requires that a permanent exposure record be filed for all persons who handle radioactive material. Therefore, everyone enrolled in the lab must be registered by the course instructor with the University Environmental Health and Safety Office. Your TA will pass out the radioactive sources for this experiment only after you print your name on the Physics Laboratory Class Roster. You are responsible for the safe return of the sources at the end of the laboratory period. Failure to comply with safety rules or failure to return the sources will result in expulsion from the course and a grade of F.

It is a University of California rule that pregnant women are not permitted to participate in the radioactivity experiment or to be in the lab room where these experiments are performed. If you think you may be pregnant, discuss it privately with your TA. He or she is authorized to excuse you completely from this experiment.

Radioactive materials are potentially dangerous to your health and should always be handled with great caution. It is a prudent practice to wash your hands thoroughly after this experiment is finished.

THEORY

Radioactivity was discovered by Henry Becquerel in 1896. Becquerel found that compounds of uranium would expose a photographic film, even in total darkness. Marie Curie took up the research topic, coined the term radioactivity, and determined that this effect was independent of the chemical compound in which the radioactive element was found and independent of any pressures or temperatures that could be produced. In other words, radioactivity was somehow an internal property of the element itself. Marie Curie later isolated the previously unknown elements polonium and radium, and won two Nobel prizes for her work, the first of which was shared with Becquerel

and her husband Pierre Curie. She and other researchers soon established that the energies per atom emitted by radioactive decay were millions of times larger than chemical energies, and that transmutation of the elements was involved.

Early researchers discovered that radiation from natural radioactive elements came in three types: (1) alpha (α) rays, which traveled in a curved path similar to positively charged particles in a magnetic field; (2) beta (β) rays, which traveled in a curved path similar to negatively charged particles in a magnetic field; and (3) gamma (γ) rays, which traveled in a straight line in a magnetic field and were therefore neutral. Today we know that alpha "rays" are helium nuclei, beta "rays" are high-energy electrons, and gamma "rays" are high-energy photons (particles of light). Certain isotopes of radioactive elements emit positive electrons called positrons or $\beta+$ particles.

As an example, α particles are emitted in the decay of natural uranium:

$$_{92}\text{U}^{238} \rightarrow {}_{90}\text{Th}^{234} + {}_{2}\text{He}^{4}. \tag{1}$$

(The $_{2}\text{He}^{4}$ nucleus is the α particle.) With the emission of β particles, a neutron changes into a proton (or vice versa) :

$$_{6}\text{C}^{14} \rightarrow {}_{7}\text{N}^{14} + \text{e}^{-} + ? \tag{2}$$

(The e- is the β particle. We will discuss the ? below.) Gamma rays are emitted when an excited state of a nucleus makes a transition to a lower level, in the same way that an atom emits a photon of ordinary light when it is deexcited. Excited states of nuclei are denoted by an asterisk ($*$):

$$_{28}\text{Ni}^{*60} \rightarrow {}_{28}\text{Ni}^{60} + 2\gamma. \tag{3}$$

The unique characteristics of α, β, and γ particles are responsible for differences in the ways that these particles lose energy when passing through matter. For example, shown below are the typical ranges of 8 million electron-volt (8 MeV) particles in aluminum:

$$\text{Range in meters: } \alpha = 0.00006 \beta = 0.02 \gamma = 0.2. \tag{4}$$

The description of β decay given above is actually somewhat incomplete and must be expanded in the context of the range of β particles in matter. While α and γ particles are found to have definite energies (dependent only on the emitter), β particles emitted by a single nuclide can have any energy between zero and some definite maximum value. Careful examination of this fact in the context of a definite decay scheme, such as Eq. 2, led scientists to conclude that β decay violates the three basic conservation laws of energy, momentum, and angular momentum. Enrico Fermi noted in 1934 that if an additional neutral particle were emitted in β decay, the three conservation laws would remain intact. Such neutral particles have actually been found and are called *neutrinos*. Thus, the correct description for the decay in Eq. 2 is

$$_{6}\text{C}^{14} \rightarrow {}_{7}\text{N}^{14} + \text{e}^{-} + \nu, \tag{5}$$

where ν is the neutrino emitted in β decay.

HALF LIFE

Radioactive substances are unstable. They transmute from one isotope to another by the process of radioactive decay until they reach a stable isotope. The number of nuclei Δn that decay in the subsequent time interval Δt is proportional to the number of non-decayed nuclei $n(t)$ present and to the time interval Δt. Thus, we can write

$$\Delta n = -n(t)\,\lambda\,\Delta t. \tag{6}$$

The minus sign accounts for the fact that $n(t)$ decreases with time, and λ is a proportionality factor called the *decay constant*. Eq. 6 leads to

$$\mathrm{d}n/\mathrm{d}t = -n(t)\,\lambda, \tag{7}$$

which can be integrated to

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where n_0 is the number of nuclei at $t = 0$.

We define the *half-life* $t_{1/2}$ as the time required for half of the parent nuclei to decay. Then

$$n/n_0 = 1/2 = e^{-\lambda t_{1/2}}. \tag{9}$$

Taking the natural logarithm of Eq. 9 leads to

$$\ln(1/2) = -\lambda t_{1/2}, \tag{10}$$

or

$$t_{1/2} = (\ln 2)/\lambda. \tag{11}$$

Since it is easy to obtain λ from the slope of the exponential, Eq. 11 can be used to determine half-lives.
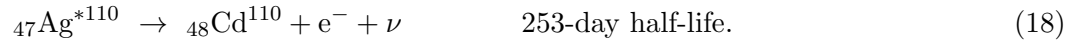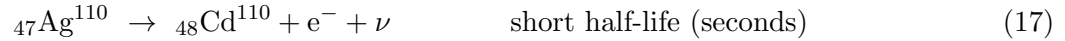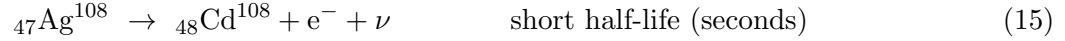
In this experiment, we will be measuring the half-lives of two silver isotopes. The radioactive silver is prepared in the lab by irradiating silver foil with neutrons. A strong neutron source is contained in a heavy shielded tank operated by the radiation safety officer. Inside the tank is a mixture of plutonium and beryllium. The radioactive plutonium emits α particles which react with beryllium according to the scheme

$$_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 \ \rightarrow \ {}_6\mathrm{C}^{12} + \mathrm{n}. \tag{12}$$

Natural silver consists of the two isotopes $_{47}\mathrm{Ag}^{107}$ and $_{47}\mathrm{Ag}^{109}$. The neutrons react with them according to these schemes:

$$_{47}\mathrm{Ag}^{107} + \mathrm{n} \ \rightarrow \ {}_{47}\mathrm{Ag}^{108} \tag{13}$$

$$_{47}\mathrm{Ag}^{109} + \mathrm{n} \ \rightarrow \ {}_{47}\mathrm{Ag}^{110}. \tag{14}$$

Some of the silver is produced in an excited state, and both isotopes decay via β and γ emission, but with very different half-lives. The decay schemes for the isotopes are as follows:

$$_{47}\text{Ag}^{108} \rightarrow {}_{48}\text{Cd}^{108} + \text{e}^- + \nu \qquad \text{short half-life (seconds)} \tag{15}$$

$$_{47}\text{Ag}^{*108} \rightarrow {}_{48}\text{Cd}^{108} + \text{e}^+ + \nu \qquad \text{greater than 5-year half-life} \tag{16}$$

$$_{47}\text{Ag}^{110} \rightarrow {}_{48}\text{Cd}^{110} + \text{e}^- + \nu \qquad \text{short half-life (seconds)} \tag{17}$$

$$_{47}\text{Ag}^{*110} \rightarrow {}_{48}\text{Cd}^{110} + \text{e}^- + \nu \qquad \text{253-day half-life.} \tag{18}$$

In each case where an isotope of cadmium (Cd) is produced by β decay, the nucleus is formed highly excited. The nuclei are stabilized by subsequent γ emission, where the half-life is very much shorter than a microsecond. Hence, the decay rates of the radioactive silver isotopes to the stable isotopes of cadmium are completely governed by β decay.

As you can see from the decay schemes above, there are actually two different ways each isotope of silver can undergo β decay. One method, corresponding to the long half-life, is relatively improbable. The other method, however, occurs quite often and implies a relatively short half-life (of the order of minutes). In this part of the experiment, you will determine the short half-lives of the radioactive silver isotopes.

The proportion of two short-lived cadmium isotopes present in your specimens after irradiation depends on the probability of process 13 compared with process 14, and also on the relative concentrations of the two silver isotopes in the sample. Rather than determining the concentration of each isotope separately and studying its decay, we will utilize a simple and useful technique for half-life determinations that depends only on an accurate measurement of the variation of count rate with time.

In half-life measurements (which we will perform below), Eq. 8 gives the number of parent radioactive material left after a time t:

$$n(t) = n_0 e^{-\lambda t}, \tag{8}$$

where λ is related to the half-life. A common goal is to determine the slope λ of the exponential. Exponential relationships such as these are common in scientific work, so we would like a rapid way of obtaining the slope and checking the fit. If we plot them on ordinary graph paper, then the slope would be the curve of the exponential. A curve-fitting program could fit an exponential to the experimental curve and determine the value of the slope, but it would still be difficult to see at a glance how good the fit is.
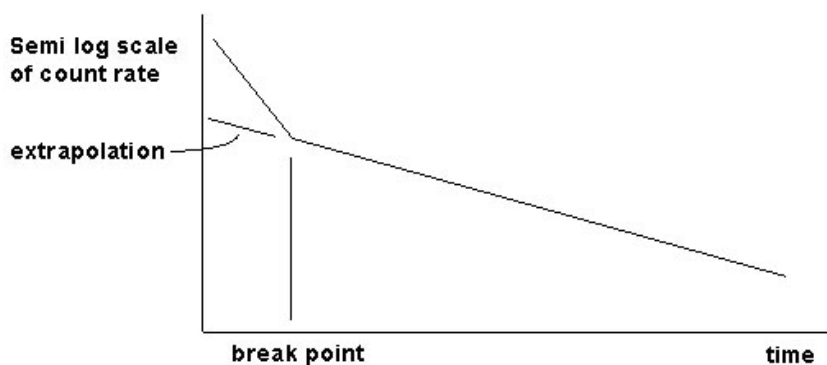
Instead, we will plot these relationships on a special kind of graph: a *semilog* graph. In a semilog graph, the exponential relationship becomes a straight line. The y-axis is the logarithm of the dependent variable, and the x-axis is the independent variable treated in the normal linear manner. Taking the natural logarithm of Eq. 8, we find

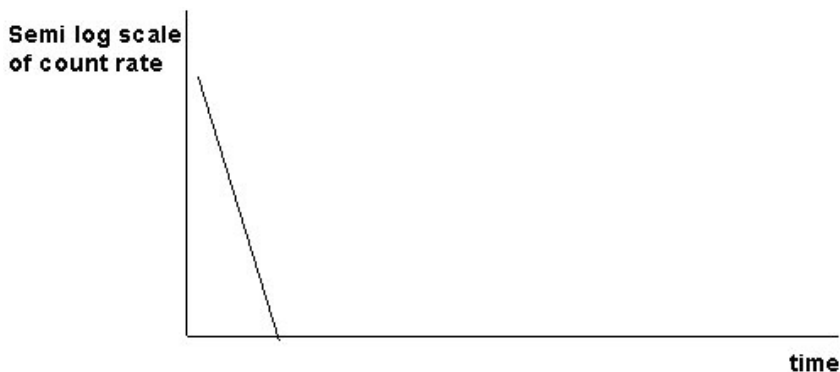$$\ln n(t) = \ln n_0 - \lambda t. \tag{19}$$

Note that the logarithm of the dependent variable ($n(t)$ in this case) now satisfies a linear relation, and can therefore be plotted as a straight line on a semilog graph. In addition, the slope of the semilog graph is equal to the coefficient $-\lambda$ of the exponential.

If the radioactive decay of only a single isotope were involved, then a semilog plot of the count data as a function of time would look as follows:

The slope of the exponential is the negative of the decay constant λ, and the half-life can be determined from Eq. 11. In our case, two isotopes are decaying at different rates, so the semilog plot looks more like Figure 2:

**Semi log scale
of count rate**

extrapolation

break point   **time**

At long times, the slope of the graph is controlled by the longer of the two half-lives. This is sufficient to determine the long half-life, since essentially all of the short-lived isotope has decayed. By extrapolating this longer time region back to $t = 0$, one can subtract out the effect of the long-lived isotope. This corresponds to determining the contribution of the long-lived isotope to the full rate at each time and subtracting it out. From a semilog plot of the remaining data, one can determine the short half-life from the slope of its exponential:

**Semi log scale
of count rate**

time

ANALYSIS WITH SEMILOG PLOTS

Some of the older Excel programs will perform semilog plots directly, but other recent versions do not have this feature. It is possible to do a semilog plot by hand on special semilog graph paper. However, once we have a list of the count data in an Excel column, we can simply take the logarithms of the data in the next column with the "Fill Down" operation and plot the logarithms of the counts as functions of time.

By convention, base 10 logarithms are written as just "log" (no subscript), and logarithms of base

$e = 2.718...$ are written as "ln". Our purpose in plotting the semilog graph of the count data is to determine the break point, as in Figure 2. Therefore, it does not matter whether we take the base 10 logarithms (log) or the base e logarithms (ln), since these quantities are related by a constant. Either the log or ln of the count data as functions of time will plot as a straight line (for a single isotope).

The basic definition of the logarithm function gives

$$x = b^{\log_b x}, \tag{20}$$

where $\log_b$ is base b logarithm. Using $x = e \ln x$, we find a conversion between base 10 logarithms (log) and natural logarithms (ln) :

$$\log x = (\log e)(\ln x). \tag{21}$$

Since the different base logarithms are related by a constant $(\log e)$, data that plot as a straight line in one base will also plot as a straight line in the other base.

STATISTICS IN RADIOACTIVITY MEASUREMENTS

The process of radioactive decay is completely random. Quantum mechanics can predict the probability of a decay per second, but the time at which any particular nucleus decays cannot be predicted, even in principle. Thus, with a sample of radioactive material, the number of nuclei that will probably decay in any time period (such as the 10-second intervals we will be using in the experiments below) is determined by the half-life, but there will be random variations in the number that decay in any particular 10-second interval. The same is true of the background radiation from cosmic rays and terrestrial radioactivity: the counts detected by a Geiger counter come at random, although they have a *mean* or average rate. For example, here is a list of the counts during 10-second intervals, taken in the Knudsen nuclear lab, where the neutron source and several other sources are stored:

$$9, 18, 7, 13, 8, 11, 8, 8, 9, 12, 5, 8, 5, 13, 9, 8, 9, 12, 9, 6, 8, 5, 8, 15, 10, 5, 11, 12, 9, 8.$$

The computer calculates quickly and automatically the mean number of counts as 9.3, but also gives another number called the *standard deviation* (denoted by σ). The standard deviation is a measure of the spread in the number of counts. For the numbers above, $\sigma = 3.1$. This means that 68% of the counts in any 10-second interval fall between $(9.3 - 3.1)$ counts and $(9.3 + 3.1)$ counts. Please refer to the additional credit section for more discussion.
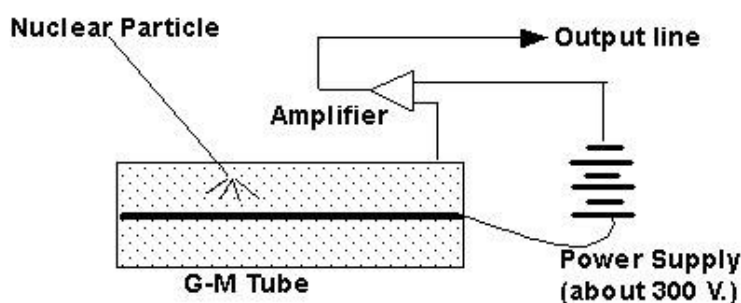
The standard deviation has an exact definition in the science of statistics. In fact, when any experimental measurement is taken, there will be a spread in the values of the measurements along a bell-shaped curve that can be described by a standard deviation. An example is if we had a large number of students measure the length of the same lab bench with a meter stick; we would find that these measurements also fit a bell-shaped curve with a mean and standard deviation.

THE GEIGER-MULLER TUBE

The experiments below use a Labnet Geiger-Muller (GM) detector which is plugged into one of the digital channels of the Pasco signal interface. When you look into the transparent cylinder of the

detector, the actual GM tube is the copper cylinder at the bottom end, which appears similar to a large bullet cartridge. The rest of the electronics inside the transparent tube consists of the power supply for the GM tube which operates at $300 - 400$ V DC, and the digital interface that amplifies the GM pulses and converts them to digital pulses accepted by the signal interface box.

The GM tube is a closed cylinder containing a gas mixture which includes a halogen compound. A thin wire filament is aligned along the tube axis and maintained at a large positive voltage with respect to the outer wall. When an ionizing particle (α, β, or γ) passes through the gas, ion-electron pairs are created. The electrons are quickly drawn to the center wire by the strong electric field, where they are collected as a "pulse" of current.

This current pulse is electronically amplified and then sent on to the signal interface. Another function of the gas is to quench the electrical breakdown quickly so that the system can count successive pulses separated in time by very small intervals. Halogens are found to be particularly effective for this purpose.

Because β rays are easily stopped by the outer metal cylindrical shell, it is necessary to construct the GM tube with a very thin (about 1.5 mg/cm2) mica window at one end. <u>Be careful with this end window, as it is easily damaged, rendering the tube useless and irreparable.</u>

PROCEDURE PART 1: THE NUCLEAR SENSOR

Pasco's generic name for the GM detector is "Nuclear Sensor". The device itself is labeled "GM - Detector". However, in the analog sensor menu of the Capstone, it is called a "Geiger Counter". These names all refer to the same instrument.

The device has a plastic cap over the detector end for protection. The actual GM tube is recessed in the plastic cylinder at the end of the detector. Remove the plastic cover for use, and replace it when you are finished. <u>The GM tube itself has a delicate, thin mica window at its end through which radiation passes. If this window is damaged, the tube is ruined, so be careful not to poke anything into the plastic cylinder or to push the tube toward anything that pokes out.</u>

1. Turn on the interface and the computer.

2. Call up Capstone.

3. The GM detector has a line-cord plug and a phone-cord interface to the digital plug which

goes into the signal interface. When the line cord of the GM detector is plugged in, a neon bulb inside lights up, indicating that the instrument has power. The other neon bulb flashes intermittently as each count is detected. This happens whether or not you are recording or monitoring and even if there are no radioactive materials nearby, because the tube detects stray cosmic rays and terrestrial radioactivity that are always present.

4. Choose the "Table & Graph" option in Capstone. Under "Hardware Setup", click on Channel 1 of the interface and select "Geiger Counter". At the bottom of the screen, change the sample time to 10 seconds. This will give you one measurement every 10 seconds of recording time. Click on the y-axis of the graph and select "Geiger Counts (counts/sample)". Click on "Select Measurement" in your table and choose "Geiger Counts (counts/sample)". If your watch has a continuously illuminated night dial, it may contain a small amount of radioactive material. Check the watch with the detector if you wish, and take it off and move it some distance away if you find that it is radioactive.

5. Move all radioactive materials at least one meter from the detector and take a background count by clicking "Record" and counting for 100 – 120 seconds. Then click "Stop". Your table should now have approximately 10 entries for the count every 10 seconds.

6. When you click the $\sum$ symbol on the table, the computer will calculate the mean count and standard deviation below (along with the minimum and maximum count). Record the mean background count and its standard deviation. Your count will be higher than "normal" if your lab station is close to the neutron source used in the half-life measurement below.

Background count (mean) = _____

Standard deviation = _____

PROCEDURE PART 2: HALF-LIFE MEASUREMENTS

(The instructions for Excel are abbreviated, as it is assumed that you are familiar with the operations.)

1. Check that you are counting for 10-second intervals. Prepare your computer to start taking count data on the next mouse click by setting the mouse arrow on the "Record" button.

2. When you are ready, the radiation safety officer will hand you a rod with the activated silver foil on the end. As quickly as possible, but still being careful, place the rod in the holder with the silver close to the GM counter, and click to start recording. Stop after approximately 10 minutes.

3. Copy the silver count data from your table into a column of a new Excel worksheet.

4. Subtract out the background count in the next column of the worksheet.

5. Use the "Fill Series" operation to fill the next column of the worksheet with the time of the center of the 10-second intervals (i.e., 5, 15, 25, etc.), up to 10 minutes.

6. Use the "Fill Down" operation to take the logs or lns of the count data (it doesn't matter which) in the next column.

7. Chart the logs of the data as functions of time. (Select and chart the last two columns.) This semilog chart should look something like Figure 2: a straight line of steeper slope breaking to a line of shallower slope, corresponding to the two half-lives involved. The data at large times is likely to look ragged due to fluctuations in the statistics. We now wish to extract the two half-lives.

8. Locate the break point in time where the slope changes at about 150 seconds.

   Break point = _____

9. Back in Excel, select and chart only count data after the break point. (Chart the actual data, not their logs.) Select the data points on the chart, and use the trendline operation to fit an exponential curve. Check the box for "Equation on Chart" to obtain the slope of the exponential. From this slope, extract the longer half-life using Eq. 11, and record this half-life below.

   Longer half-life = _____

10. To obtain the shorter half-life, start a new column in Excel, and subtract from the background-corrected data, the data for the longer half-life using the equation that you obtained in step 10. (Your entry before "Fill Down" will look something like "= C4 - 609*exp(-0.0035*B4)".)

11. Chart the resulting data, and extract the shorter half-life as before with the trendline operation.
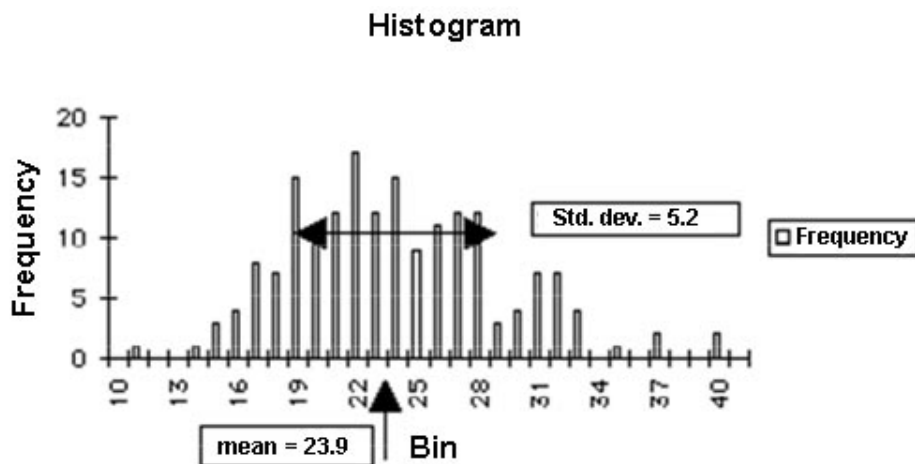
    Shorter half-life = _____

12. Rearrange your Excel tables and charts neatly on one or two sheets.

ADDITIONAL CREDIT: HISTOGRAM OF NUCLEAR STATISTICS (up to 3 mills)

Prepare an annotated histogram of radiation counting data in Capstone (2 mills) or Excel (3 mills). The additional credit is for figuring out how to do this without the help of your TA.

Obtain a sample of radioactive material in plachet form from the radiation officer, and place it near the GM counter front. Arrange the GM tube, plachet, and shielding pieces so that you are obtaining a fair number of counts in the 10-second intervals (say, 50 – 100). Count for 10 minutes or so.

Calculate the mean count and standard deviation. Use the "Help" sections of the programs if needed. For Excel, pull the "Tools" menu down to "Data Analysis", and choose "Histogram". Follow the instructions, using the "Help" function as necessary. Below is a sample histogram.

Histogram

Annotate your graph with the mean and standard deviation. For Excel, you need to use the "Draw" and "Text Box" functions to put in the mean and standard deviation in some nice way, perhaps even better than shown above. (Note that this histogram, which is based on 30 minutes of counting, will probably be "smoother" than one based on 10 minutes of counting.)

RETURN YOUR RADIOACTIVE PLACHET TO THE RADIATION OFFICER.

Time (s)	counts (delta n total)	counts - bg (n = n total - n bg)		ln (n)	n long	n short	ln (n short)
10	1588		1582	7.366445	414.304	1167.696	7.062788
20	1271		1265	7.142827	394.4924	870.5076	6.769076
30	1088		1082	6.986566	375.6283	706.3717	6.560142
40	878		872	6.770789	357.6661	514.3339	6.242873
50	703		697	6.546785	340.563	356.437	5.876158
60	642		636	6.455199	324.2776	311.7224	5.742113
70	511		505	6.224558	308.771	196.229	5.279282
80	494		488	6.190315	294.0059	193.9941	5.267827
90	353		347	5.849325	279.9469	67.05308	4.205485
100	344		338	5.823046	266.5602	71.43983	4.268856
110	309		303	5.713733	253.8136	49.18644	3.895618
120	292		286	5.655992	241.6765	44.32351	3.791515
130	272		266	5.583496	230.1198	35.88021	3.580186
140	230		224	5.411646	219.1157	4.884278	1.586022
150	224		218	5.384495	208.6379	9.362145	2.236674
160	186		180	5.192957	198.661	-18.66103	
170	204		198	5.288267	189.1613	8.838717	
180	212		206	5.327876	180.1158	25.8842	
190	144		138	4.927254	171.5029	-33.50287	
200	158		152	5.023881	163.3018	-11.3018	
210	152		146	4.983607	155.4929	-9.492889	
220	127		121	4.795791	148.0574	-27.05739	
230	148		142	4.955827	140.9775	1.022543	
240	150		144	4.969813	134.2361	9.763925	
250	146		140	4.941642	127.8171	12.18294	
260	155		149	5.003946	121.705	27.29501	
270	132		126	4.836282	115.8852	10.11481	
280	102		96	4.564348	110.3437	-14.3437	
290	115		109	4.691348	105.0672	3.932815	
300	92		86	4.454347	100.043	-14.04299	
310	124		118	4.770685	95.25905	22.74095	
320	128		122	4.804021	90.70387	31.29613	
330	110		104	4.644391	86.36651	17.63349	
340	76		70	4.248495	82.23656	-12.23656	
350	80		74	4.304065	78.3041	-4.304103	
360	84		78	4.356709	74.55969	3.440311	

370	92	86	4.454347	70.99433	15.00567
380	86	80	4.382027	67.59946	12.40054
390	70	64	4.158883	64.36693	-0.366931
400	64	58	4.060443	61.28898	-3.288977
410	54	48	3.871201	58.35821	-10.35821
420	71	65	4.174387	55.56758	9.432417
430	56	50	3.912023	52.9104	-2.910404
440	46	40	3.688879	50.38029	-10.38029
450	36	30	3.401197	47.97116	-17.97116
460	54	48	3.871201	45.67723	2.322767
470	60	54	3.988984	43.493	10.507
480	54	48	3.871201	41.41321	6.586786
490	48	42	3.73767	39.43288	2.567119
500	48	42	3.73767	37.54724	4.452755
510	40	34	3.526361	35.75178	-1.751778
520	46	40	3.688879	34.04217	5.957832
530	38	32	3.465736	32.41431	-0.41431
540	40	34	3.526361	30.86429	3.135705
550	36	30	3.401197	29.3884	0.611601
560	38	32	3.465736	27.98308	4.016921
570	24	18	2.890372	26.64496	-8.64496
580	28	22	3.091042	25.37083	-3.370828
590	36	30	3.401197	24.15762	5.842377
600	30	24	3.178054	23.00243	0.997567

Counts vs. Time

12