Name:________________________ **ID:**________ **Section:**____

NAT Sci 102 Breakout Activity

Radioactivity and Age Determinations

Due Date: April 21

How do we know that the Solar System is 4.5 billion years old?

During this lab session you are going to witness how radioactive decay works, and you will see firsthand what "half life" means. You will also explore the character of randomness in nature as radioactive decay is a random process. This means one that in any given one second time interval, you won't be able to predict whether an atom will decay or not, but you can predict the results of averaging what happens in many one second intervals.

Radioactivity (read before coming to the Lab session)

Recall that atoms are comprised of electrons, neutrons, and protons with the neutrons and protons being concentrated in their centers, called "atomic nuclei". The number of protons equals the number of electrons, and the electrons orbit the nucleus in a fashion similar to planets orbiting the Sun. The protons and electrons are electrically charged with protons having a positive charge and electrons having a negative charge. The equal numbers of each ensures that the atom itself has no net electrical charge. The number of protons (or equivalently, the number of electrons) determines the element of the atom -- for example, carbon atoms have 6 protons while iron atoms have 26 protons. There are about 100 elements, that is, atoms can be reasonably stable with anywhere from 1 to 100 protons in their nuclei.

The number of protons in an atomic nucleus is not the whole story. Atomic nuclei also contain neutrons which have nearly the same mass as protons but have no electrical charge. For light elements (those with relatively few protons), the number of protons and neutrons in the nucleus is roughly equal. For example, the most abundant form of carbon has 6 protons and 6 neutrons in its nucleus. As more and more protons are added to the nucleus, larger numbers of neutrons tend to be added also. The uranium nucleus has 92 protons and 146 neutrons. The sum of the number of protons and neutrons in a nucleus is equal to the atomic weight of the atom (and gives the actual mass of the atom if the atomic weight is multiplied by $1.6x10^{-24}$ grams = mass of a proton or neutron). The atomic weight is usually written as a superscript to the letter symbol denoting the element so you will see C^{12} and U^{238} for the common types of carbon and uranium.

The number of neutrons in a nucleus is not fixed so other variants of an element can exist, such as C^{13} indicating a carbon atom with 6 protons and 7 neutrons. Most elements have two or three variants called **isotopes**, with differing numbers of neutrons. Some isotopes are not stable and can spontaneously eject particles with the isotope being transformed into a different type of atom (either different element, or different isotope of the same element). This process is called radioactive decay, and the process of ejecting a particle is radioactivity. Isotopes with larger than average numbers of neutrons or very large atoms like uranium are the most likely to be radioactive. Radioactive decay can involve ejection of alpha (α) particles made of 2 protons and 2 neutrons or beta (β) particles which are just electrons. Radioactive decays may also involve the emission of very energetic photons called gamma (γ) rays (and other particles also).

Look at the following two reactions, which are examples of radioactive decays:

$C^{14} \rightarrow N^{14} + e-$ (e- = electron = β particle)

$U^{238} \rightarrow Th^{234} + He^{4}$ (He^{4} = α particle)

In the first case, a neutron in the C^{14} nucleus changes into a proton so the atom becomes nitrogen (which is the element with 7 protons in its nucleus); the atomic weight doesn't change because the numbers of protons and neutrons sum to the same total. In the second case, the number of protons changes by 2 so the element changes from uranium to thorium and the atomic weight also changes by a total of four. These decays can be measured by counting the α and β particles using a Geiger counter.

Half Lives and Measuring Ages (read before coming to the Lab session)

Radioactive isotopes decay in a random fashion. The likelihood that isotopes will decay in any particular time interval is expressed by the **half life** which is equal to the time for 50% of a sample of isotopes to decay. The half life of the C^{14} decay is 5,730 years while that of U^{238} to Th^{234} is 4.45×10^9 years. By measuring the amount of an isotope that has decayed, the age of a sample can be determined. For example, a sample of wood found in an ancient Indian camp site is found to have 12.5% of its original C^{14}. The age of this site is equal to three half-lives of the C^{14} because 12.5% = 1/8 = ½ x ½ x ½ . Three half lives equals 17,190 years so this site is an exciting find. Note that in this process it is essential to know what the starting amount of the radioactive substance is. This can be a tricky problem in using the radioactive dating technique. In the case of C^{14} this problem is solved by knowing that a living organism incorporates C into its substance by breathing in CO_2 from the atmosphere. As long as the organism is alive, the amount of C^{14} relative to C^{12} is kept replenished at the average value for the earth's atmosphere. When the organism dies, the replenishment stops. The amount of C^{12} stays fixed because C^{12} is stable while the C^{14} decays away thus making it possible measure the age by comparing the ratio of C^{12} to C^{14} in the dead organism to that in the atmosphere.

However, C^{14} is not useful for measuring astronomical time scales because its decay is too rapid. The decay U^{238} to Pb^{206} with a half life of 4.5×10^9 years and the decay of K^{40} to Ar^{40} with a half life of 1.3×10^9 years are good choices. The starting values for uranium and potassium measurements get addressed in different manners. The K^{40} to Ar^{40} measurement can take advantage of argon being a gas that can be driven out of a sample that is heated. The Ar^{40} present in a sample is then indicative of the number of K^{40} decays occurring since the sample was last heated. Since uranium decays only to Pb^{206} and not to the more commonly occurring Pb^{204}, uranium dating works by measuring the relative amounts of the two lead isotopes, Pb^{204} and Pb^{206}.

Measuring the Half Life of Pa^{234} (to be done in the Lab Session)

Your instructor has a Geiger counter that will be projected in the lecture hall so you can see the rate of particles emitted by decaying atoms in a sample of material. The decaying atom, Pa^{234} (Pa = protactinium), has a half life measured in minutes. Your job will be to determine the value of the half life. To be able to measure radioactivity from a rapidly decaying atom like protactinium requires a fresh source of Pa^{234} for each experiment. We have such a renewable source. It works by virtue of Pa^{234} dissolving in a different liquid than the Th^{234} which decays into Pa^{234}. When the bottle of liquids is shaken up and then allowed to settle, the liquid on the top has the Pa^{234} in it while the bottom has the remaining Th^{234}. The Geiger counter is arranged to detect the particles emitted from the top, eg., by the Pa^{234}. **Fill out the following table with the times and counts observed in Lab (the Geiger counter we will use is calibrated in thousands of counts per minute). We will repeat the experiment, so the entry columns provide for two runs.**

Clock Time		Elapsed Time in sec		Counts per minute		Background counts per minute		Net Counts per minute		Log (net counts per minute)	
		0.00	0.00								

We will also be determine a quantity to put into the background column -- the same value will apply for all times. The other columns will be filled in later after you understand more about random processes**.**

Random Processes and Counting Statistics

Randomness plays a large role in what can observed and learned about nature. This stems from several causes including the fact that some things come in indivisible units -- photons and electrons are examples where you cannot have a third of a photon or 80% of an electron. Either you have one or you don't. Therefore, an experiment that expects 3.4 protons to be detected will have to contend with never getting this exact number! Another way in which randomness enters is in the fundamental laws of physics. The branch of physics called quantum physics shows that all knowledge of locations and velocities of objects can only be described by probabilities. This behavior becomes very noticeable when studying small objects like atoms but mostly indistinguishable from behavior you would predict using Newton's Laws on scales like the sizes of people. You are going to perform an experiment where you count items and then you will look at the distribution of values that you have counted. Some forms of randomness can be quantified because although we can only get an integer number of electrons, for example, we may have an experiment where on average we would get 3.4 electrons. This means that some of the time we might get 0, sometimes we would get 1, and most of the time we get 3 or 4. If we repeat the experiment many times, we can prepare a plot showing how many repetitions of the experiment saw 3 electrons, how many saw 5 and so on. Figure 1 shows such a plot where the horizontal axis shows the number of radioactive decays and the vertical axis shows the number of repetitions of a radioactive experiment which saw a given number of decays. For example, 100 decays were observed in 50 repetitions of the experiment. In an experiment of this type, the spread of values that you will observe depends on the $\sqrt{average}$ where average is the average number of counts you get – in Figure 1 the spread (sometimes called the error or uncertainty) = $\sqrt{100}$ =10. You are going to repeat a counting experiment 20 times to see randomness in counting for yourself. In each repetition you will toss a coin 10 times and see how many heads you get.

You need to perform 20 counting experiments. Each experiment consists of tossing a coin 10 times. For each experiment, record the number of times out of 10 that you got "Heads" in the table.

Experiment	No. of Heads	Experiment	No. of Heads
1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	

After you have filled in your table, prepare a bar graph where the horizontal axis is labeled from 0 to 10 indicating the possible values for the number of heads in an experiment and with the vertical axis labeled from 0 to 20 indicating the number of experiments that had any of the values for the number of heads. Count how many experiments had 0 heads, 1 head, 2 heads and so on and plot the values on the graph. Figure 1 shows a similar plot for an experiment counting radioactive decays.

Question 1: Given that any one coin toss has equal probability of being heads or tails, how many heads do you think will most likely occur in an experiment consisting of 10 tosses?

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Question 2: On your graph, which bar is highest? ________________

Is this the number of heads you expected _____________________________

Question 3: Not all of your experiments gave the same number of heads. If you repeat a counting experiment many times, you will learn what is the most likely outcome or average result for the experiment.. The uncertainty in any one experiment is related to the spread of values observed in repeats of the same experiment. Look at your graph and determine the range of values for the number of heads in an experiment. Figure 1 shows how you should determine this range. Look for the number of heads that occurred most often – the most frequently occurring number of heads is the "maximum". Compute the value of the maximum divided by 2. The range of most likely values begins at the lowest number of heads that occurred at least half of the maximum number of times up to the highest number of heads that occurred at least half of the maximum number of times. What is your range? ______________________

Compare your range to $2 \times \sqrt{5}$:__________________

The uncertainty in an experiment is approximately half the range computed in this manner.

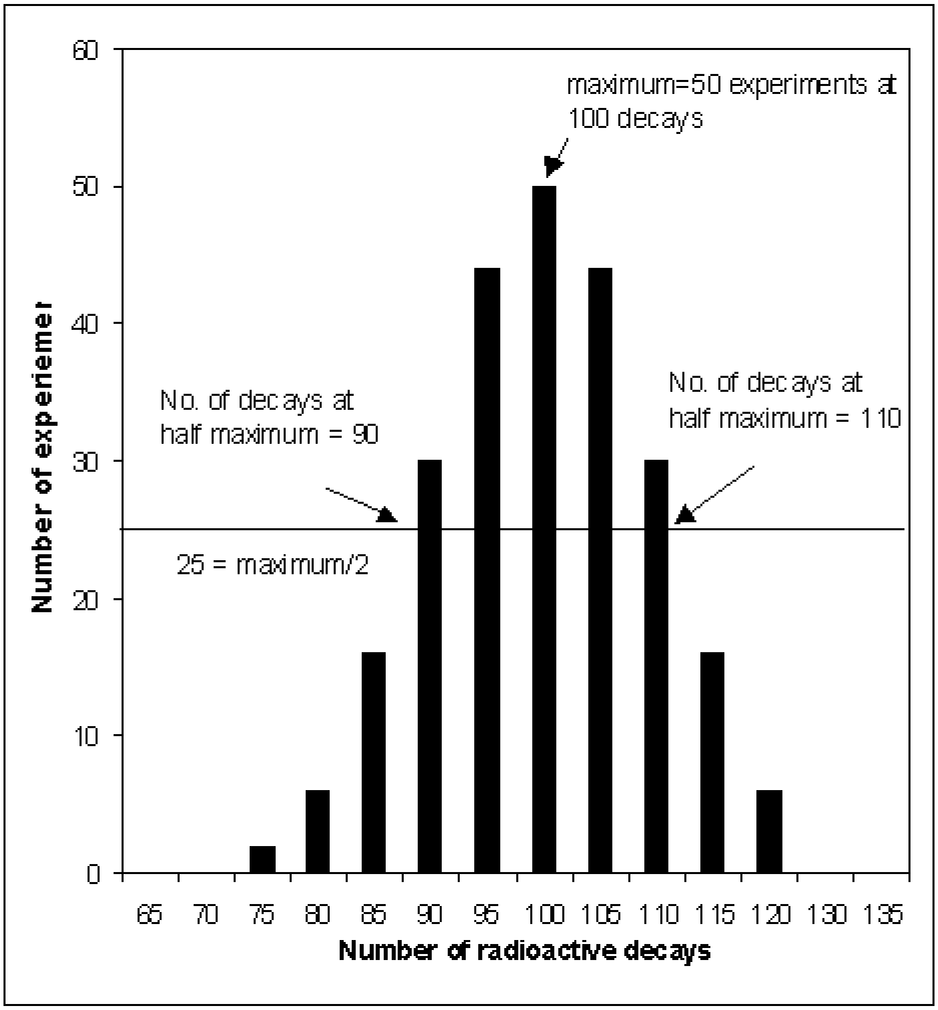

Figure 1: How to measure the range of values. The range in this figure is 90 to 110.

What you have just illustrated is the principle that in an experiment where you count items, there is an uncertainty proportional to the square root of the counts. These means that if you expect to count 100 α -particles, your counts will most probably lie in the range from 100 - $\sqrt{100}$ to 100+ $\sqrt{100}$, 90 to 110. It is still possible for an experiment to result in counts outside this range but with lower probability.

Completion of Measuring the Half Life of Pa^{234}

Return to the table of counts and times observed in Geiger counter experiment. Fill in the column labeled elapsed time by subtracting the start time from subsequent entries and, where necessary, multiplying by 60 to convert to seconds. Determine the background counts from the Geiger counter reading long after the radioactivity has decayed. Complete the table by computing the net counts by subtracting the background counts from each of the counts that was observed during the decay of the protactinium. Then fill in the logarithm of the net counts in the last column. Do these steps for both runs.

Prepare a graph where the horizontal axis represents elapsed time and the vertical axis represents net counts. Plot the results of both of the runs. The number of decays will change with time as the quantity of protactinium changes.

Estimate the half life of protactinium: _____________

Make a second graph with the logarithm of the counts for the vertical axis, time for the horizontal axis. Is it easier to estimate the half life on the logarithmic plot? (The logarithm of 2 is 0.3, so the half life is when the logarithm of the counts has decreased by 0.3).

Estimate the half life measured from the logarithmic plot: ______________

Do you see any deviations from a smooth decay with time? _____________

Do the two runs agree perfectly, or are there differences? _____________

Give an explanation for these deviations and differences, if there are any: