Lab 6: Radioactive Decay

Introduction:

Ernest Rutherford began his studies of radioactive decay at the Cavendish Laboratory at Cambridge under J. J. Thomson (1856-1940). In 1898, he took a position McGill University in Montreal and was joined by a chemist named Frederick Soddy (1877-1956). Around the turn of the century, Rutherford and Soddy's proved that radioactive decay involved the transmutation of one element into another, for which Rutherford won the 1908 Nobel prize in chemistry. He was one of seven of Thomson's students who eventually won Nobel Prizes (Thomson himself got the 1906 Physics Nobel for the discovery of the electron).

In today's lab you will measure the decay rate of two radioactive silver isotopes. U. S. quarters, dimes, and half-dollars made in 1964 and before are an alloy of 90% silver and 10% copper. The silver is approximately 53% ^{107}Ag and 47% ^{109}Ag. Both of these isotopes are stable. However, when the silver is irradiated in the neutron howitzer, the Ag nuclei undergo neutron capture, which converts them into unstable isotopes:

$$^{107}Ag_{47} + {}^{1}n_0 \rightarrow {}^{108}Ag_{47} \qquad {}^{109}Ag_{47} + {}^{1}n_0 \rightarrow {}^{110}Ag_{47} \tag{1,2}$$

Both of these isotopes β–decay; that is, they decay via the release of an electron (and a neutrino – more on this later):

$$^{108}Ag_{47} \rightarrow {}^{108}Cd_{48} + e^- + \bar{\nu}_e \qquad {}^{110}Ag_{47} \rightarrow {}^{110}Cd_{48} + e^- + \bar{\nu}_e \tag{3,4}$$

The silver actually transmutes into cadmium. Alchemists tried for centuries to accomplish this feat, but were unsuccessful. Of course the alchemists sought to transform something base (lead) into something valuable (gold), and this is just the opposite (silver to cadmium). Fortunately, only a tiny amount of the silver actually undergoes transmutation (a few million atoms, less than 10^{-15} g). The $^{108}Ag_{47}$ and $^{110}Ag_{47}$ half-lives are about 145 s and 24.6 s, respectively.

Safety Notes:

In today's experiment we will use a "neutron howitzer" which is a kind of neutron source. It contains a strong source of neutron radiation that is normally kept in a low, shielded position. When lifted (remotely, of course), the exposure levels near the howitzer port become quite high, but careful precautions will keep exposures well below NRC limits.

Use the howitzer only under the supervision of the lab instructor. While the howitzer is in use, keep away from the port. Do not touch the port or samples under any circumstances while the source is in the high position. Lower the source into its shielded position as soon as it is no longer needed.

Apparatus:

1. The neutrons are created in a three-step process using $^{242}Pu_{94}$ (Plutonium) & $^{9}Be_4$ (Beryllium):

$$^{242}Pu_{94} \rightarrow {}^{238}U_{92} + {}^{4}\alpha_2 \tag{5}$$

$$^{9}Be_4 + {}^{4}\alpha_2 \rightarrow {}^{13}C_6^* \tag{6}$$

$$^{13}C_6^* \rightarrow {}^{12}C_6 + {}^{1}n_0 \tag{7}$$

   The carbon created in Eq. (6) is in an excited state (denoted by the asterisk). Normal $^{13}C_6$ is stable, but because the α-particle carries some kinetic energy into the nucleus, the resultant carbon atom is not. It decays to $^{12}C_6$ through the loss of a neutron.

2. After irradiating the quarters you will measure their decay rate using a Geiger-Müller counter. A Geiger-Müller counter is similar to the proportional counter you were to use in the Moseley's Law. As in the proportional tube, incident particles (in this case β^- rays a.k.a. electrons) collide with gas atoms in the tube and liberate electrons. These energetic electrons then liberate more electrons as they cascade toward wire at the center of the tube. The arrival of electrons at the wire produces a voltage pulse. The difference between a proportional tube and a Geiger tube is mainly the operating voltage.

With a proportional tube the voltage is low enough that the number of electrons liberated is directly proportional to the energy of the incident particle. The operating voltage of a Geiger tube is much higher. This makes the number of electrons that participate in the cascade event much larger (and hence the detector is more sensitive), but the cascade occurs in such a way that the number of liberated electrons is no longer proportional to the incident particle's energy. Thus, Geiger-Müller tubes are sensitive radiation counters but have no energy resolution.

3. The signal from the Geiger-Müller tube will be fed into the same multichannel analyzer as in the Moseley's Law experiment. However, the analyzer will operate in a different mode. Instead of sorting the pulses into different bins depending on their *voltage*, the multichannel analyzer will sort the pulses into different bins depending on their *arrival time*. The analyzer will regularly step from bin to bin at a predetermined rate. In this way the number of pulses in each bin is a measure of the average pulse rate at each particular time.

Experiment:

1. First you will irradiate the quarters for about 10 min. During this time you should discuss with your instructor the theory behind neutron capture.

2. Monitor the number of background counts for several minutes to determine the background rate.

3. After the quarter has been irradiated and the neutron howitzer has been stored in the safe position, remove the quarter and (quickly) place it in the holder near the Geiger-Müller tube.

4. Monitor the decay rate for 5 min. or more. When you are finished, print out your graph and save your data to a text file.

Analysis:

1. Since the expression for the rate of radioactive decay is

$$R(t)=R_0 exp(-t/\tau) \quad (8)$$

a plot of the natural log of the number of counts vs time would give an (approximately) straight line if there were only one half-life. The challenge is that the silver isotopes have different lifetimes. Fortunately, one of the isotopes decays much faster than the other. After the first (short-lived) isotope has decayed away, the remaining counts are all due to the second (long-lived) isotope, so its natural lifetime can be found from the remaining data. Make a plot of ln(R) vs t. Include uncertainties and be sure to subtract the background. You should get a steeply falling curve with a long, relatively straight tail. Decide from your plot when most of the ^{110}Ag has decayed, leaving (mostly) ^{108}Ag. Make a second plot which includes only the data after the time you choose. Fit it with a straight line, and find the lifetime τ_{108} of the ^{108}Ag.

2. Now that the ^{108}Ag lifetime is known, you can calculate its expected decay rate as a function of time (Eq. 8). To get the ^{110}Ag decay rate, subtract the ^{108}Ag rate from the total. Remember that the error on the ^{110}Ag rate is still the square root of the total number of counts, before subtraction. That is, the error on the ^{110}Ag rate is the same as the error on the total rate. Make a plot of the subtracted data (the ^{110}Ag decay rate) and use it to calculate the ^{110}Ag lifetime τ_{110}.

3. Estimate errors in the half-life from the graphs. By what percentage do you think the graph could (reasonably) be changed and still fit the data? Is it fair to use this as a percentage error on the half-life?

4. Your completed lab should have three plots: one for the total rate, one for the ^{108}Ag decay, and one for the ^{110}Ag decay. You should calculate the half-lives and their error from the lifetimes (and their error). Discuss how well the data and expected values agree.

This lab will require a Full Written Report: Due two weeks from the day of this experiment
Be prepared to answer questions like the following:

- How does the Geiger-Müller tube work?
- What is the difference between the lifetime and the half-life?
- How does the cross-section affect the relative activity of the Ag isotopes?

Notes on background subtraction:

The proportional tube will not only record data from the Ag β^- decays, but also from background sources: cosmic rays, natural environmental radioactivity, and possibly even a few counts from the neutron howitzer (although the shielding is quite good). This must be subtracted from the data taken with the decaying silver. Record the count rate for 300 s with no source, and find the average number of counts expected in ten seconds. As in the Rutherford lab, the uncertainty is governed by Poisson statistics:

$$\delta N = \sqrt{N} \tag{9}$$

The uncertainty on the silver count rate has two components: the uncertainty of the silver counts, and the uncertainty of the background. Using TPOUR you get

$$\begin{aligned} \delta N_{\text{total}} &= \sqrt{\left(\delta N_{\text{Ag}}\right)^2 + \left(\delta N_{\text{back}}\right)^2} \\ &= \sqrt{N_{\text{Ag}} + N_{\text{back}}} \\ &= \sqrt{N_{\text{total}}} \end{aligned} \tag{10}$$