Theory

Originally, nuclei were believed to be made up of protons and electrons. However, experiments in which beryllium was bombarded with alpha particles (helium nuclei) resulted in a very penetrating radiation. Subsequent investigation showed this radiation to be a flux of electrically neutral particles of about the same mass as a proton. These particles, called neutrons, were being ejected from the beryllium nucleus by the alpha bombardment.

Neutrons have a mass approximately the same as that of a proton, are unstable in the free state with a half-life of about 13 minutes, are electrically neutral, and have a spin of 1/2, a fact which contributed to the hypothesis that neutrons are building blocks of nuclei. (According to the proton-electron theory, nitrogen 14 should consist of 14 protons and 7 electrons, a total of 21 particles. Nitrogen 14 should, therefore, have a 1/2 integral spin. However, the measured spin is integral which would agree with a postulated structure of 7 protons and 7 neutrons).

Neutrons, because of their electrical neutrality, are difficult to detect with normal radiation detectors which depend on ionization processes. Neutrons must, therefore, be detected through indirect methods. One such method depends on a process known as resonance capture. When certain elements are bombarded by neutrons, they become radioactive because the neutrons are captured by the nuclei of stable isotopes of the element which then becomes unstable and subsequently decays to a stable isotope of another element by, for example, electron emission (beta decay). The beta particles can be detected by a Geiger counter. The magnitude of the induced beta activity is a function of the neutron flux and the bombardment time and thus it can be used as a quantitative measure of neutron flux. The neutron capture cross section (or the probability that an incoming neutron will be captured) varies as a function of neutron kinetic energy and frequently will have one or more broad peaks at discrete energies. These peaks are called resonance peaks and, as can be seen from figure 1, the capture cross section increases significantly at those energies. The process of causing a normally stable element to become artificially radioactive by neutron bombardment is called neutron activation. In this experiment, we will activate two isotopes of silver, Ag\textsuperscript{107} and Ag\textsuperscript{109}, by neutron bombardment and measure their half lives.

The apparatus you will use consists of a General Radio counter, a high voltage power supply, a large block of paraffin, a Geiger tube, a silver foil and a neutron source. A schematic of the apparatus is shown in figure 2 on the top of page 3. The neutron source is a mixture of americium 241 and beryllium 9 sealed in a stainless steel capsule. The neutrons are produced by these reactions:

\[
\text{Be}^9 + \text{He}^4 \rightarrow \text{C}^{12} + \text{n}
\]
Neutron Capture Cross Section for Ag$^{107}$ and Ag$^{109}$.

Figure 1
The alpha particles are provided by decay of the americium, a radioactive transuranic element, and they eject the neutrons from the beryllium nucleus. The energy distribution of the ejected neutrons ranges from a few kilovolts to a maximum of 11 MeV (million electron volts); the mean being about 5 MeV. Referring to figure 1, one can see that the resonance peaks occur at less than 100 eV. Therefore, it will be necessary to slow the neutrons down to activate the silver efficiently. This is the function of the paraffin block. Since the mass of a neutron is essentially the same as that of a proton, a proton-rich material such as water or paraffin will serve as a good moderator. As the fast or energetic neutron flux enters the paraffin, the neutrons will lose energy in elastic collisions with the room-temperature protons and consequently become thermalized to room temperature (i.e., their average kinetic energy will become of the order of KT). It takes about fifty collisions for a several MeV neutron to be slowed to thermal velocities. Although 300 K (room temperature) is only 0.025 eV, because of the Maxwellian velocity distribution of thermalized particles, there will be many neutrons with the proper energy for resonance capture.

The paraffin block has a hole in its center and five more holes spread throughout the remainder of the block. Silver foils are positioned around the inside of each of these five holes. The Geiger tubes are inserted into the foil lined holes. The net effect is to have Geiger tubes which are surrounded by silver foils embedded in the paraffin. To activate the silver, the neutron source is placed in the center hole for approximately ten minutes. The neutrons emitted by the source travel through the paraffin and are slowed to thermal energies. As the silver foil is bombarded by the thermalized neutrons, the Ag$^{107}$ nuclei are transmuted into Ag$^{108}$ and the Ag$^{109}$ nuclei are transmuted into Ag$^{110}$. [Note: As can be seen from figure 1, the largest cross section for resonance capture is for Ag$^{109}$ so that the dominant isotope produced is Ag$^{110}$. This isotope decays with a short half-life (24.6 seconds). For these reasons, after neutron activation ceases and the decay-counting begins, most of the activity in the sample is due to Ag$^{110}$. However, the half life of Ag$^{108}$ is much longer (2.37 minutes) and thus after a few half-lives of Ag$^{110}$ most of the activity in the sample is due to Ag$^{108}$. In other words, in the early stages of the measurement Ag$^{110}$ domi-
nates and in the later stages Ag\textsuperscript{108} dominates. It is this fact that enables us to measure the half-lives of the two isotopes.\]

After the silver has been sufficiently activated, the neutron source is removed and the radioactive decay of the Ag\textsuperscript{108} and Ag\textsuperscript{110} nuclei can be observed. Radioactive decay proceeds in time according to the equation

\[ N(t) = N_0 e^{-\lambda t} \]  \hspace{1cm} (1)

where \( N_0 \) is the number of atoms at \( t = 0 \), \( N(t) \) is the number of atoms at time \( t \), and \( \lambda \) is the probability of decay per unit time (see Weidner & Sells, p. 330). The half-life \( t_{1/2} \) is the time for \( N(t) \) to decrease to one half its original value. In other words, \( t_{1/2} \) is the time it takes the ratio \( N(t)/N_0 \) to equal 1/2. Dividing both sides of equation (1) by \( N_0 \), setting the resulting ratio \( N(t)/N_0 \) equal to 1/2 and then taking the natural log of both sides shows that

\[ t_{1/2} = \frac{0.693}{\lambda} \]  \hspace{1cm} (2)

From equation (2) we see that to compute \( t_{1/2} \) we only need to know \( \lambda \). If we take the derivative of both sides of equation (1) with respect to time and then take the natural log of both sides of the resulting equation, we get

\[ \ln\left(-\frac{dN}{dt}\right) = -\lambda t + \ln (N_0 \lambda) \]  \hspace{1cm} (3)

Letting \( \ln(-dN/dt) = y \), \( t = x \), \( -\lambda = a \) and \( \ln(N_0 \lambda) = b \), we see that equation (3) is an equation of the form \( y = ax + b \). A plot of \( \ln(-dN/dt) \) vs \( t \) will be a straight line with a slope equal to \( -\lambda \). Therefore, an experimental value for \( \lambda \) can easily be obtained by measuring \( -dN/dt \) (the number of decays per unit time) as a function of time, plotting \( \ln(-dN/dt) \) vs \( t \) and computing the slope of the resulting graph.

Equations (1) and (3) apply to a sample containing only one active material. For a mixture of two active materials, equation (1) becomes

\[ N(t) = N_1(t) + N_2(t) = N_{01}e^{-\lambda_1 t} + N_{02}e^{-\lambda_2 t} \]  \hspace{1cm} (4)

where the subscripts 1 and 2 indicate \( N \) and \( \lambda \) for the two active materials. Equation (4) cannot be plotted as a straight line if the half-lives of the two materials are close to one another. However, as was noted earlier the half-lives of the two silver isotopes are much different, so that the decay process occurs in two stages with Ag\textsuperscript{110} dominating the first stage and Ag\textsuperscript{108} dominating the second. The graph of \( \ln(-dN/dt) \) vs \( t \) will separate approximately into two linear parts, and equation (3) can be applied to each part separately.
Experimental Purpose

The primary experimental purpose of this lab is to measure the half lives of two isotopes of silver, Ag\(^{107}\) and Ag\(^{109}\), formed by the activation of silver foil by slow neutrons.

A secondary purpose is to demonstrate several processes and techniques of interest in nuclear physics: thermalization of fast neutrons, resonance neutron capture, neutron counting, beta decay, and data analysis of radioactive decay.

Procedure

1. Preliminary Preparations. Before beginning the actual measurements, complete these preparations.

   a. Check to see that the electronic equipment is wired as shown in figure 2. Set the high voltage power supply to 900 volts positive polarity and turn it on. Turn on the counter and set the GATE TIME knob to the TIME INTERVAL position, the DISPLAY control to the HOLD position, the COUNT (START-STOP) button to the in position and all other buttons to the out position. [Note: The DISPLAY control should click into the HOLD position. If you do not click it into place, the counts will be displayed for approximately 10 milliseconds before resetting to zero. Unless you are very fast, this will be too quick for you to read the number of counts and you will have to repeat the counting interval which can be painful if you just counted for ten minutes.] Adjust the trigger level until background counts begin to register on the counter. Normal background rates are ~ 6-10 counts per 10 second interval. If the background radiation can be detected, then the detection system is operating correctly and you are ready to take data. If it does not, then there is a problem with your setup and you should notify your TA.

   b. Turn on the stopwatch and reset it to zero. Hold in on the RESET button on the counter. Simultaneously, start the stopwatch and release the RESET button. At exactly ten minutes as indicated on the stopwatch, set the COUNT (START-STOP) button to the out position. Be careful not to accidentally hit the RESET button when operating the COUNT (START-STOP) button. That would reset the display to zero and you would need to start over again.

   c. Adjust the General Radio counter so that it counts for 10 seconds and displays for 2 sec-
1. Turn the GATE TIME knob to the 10S position and the DISPLAY knob to a little over the 1 second display position. Set the FREQUENCY button to the in position. On the left hand side of the display you should see the word COUNT periodically appear and disappear. COUNT is displayed when the counter is actively counting and it is off when the counter has stopped counting and is displaying the total number of events with the previous counting interval.

2. Using the stopwatch, measure the time interval between the beginning of one counting interval to the beginning of the next counting interval. If the measured time is 12 seconds then go on to the next instruction. If not, adjust the DISPLAY knob for a different display time and repeat the time measurement. Continue until the counting interval plus display time is exactly 12 seconds. Once this is done, do NOT touch the DISPLAY knob again.

d. Prepare data tables for three activations. The data taking for each activation will last ten minutes. The data will consist of (count interval number, total number of counts measured in that interval) pairs. There are fifty counting intervals in ten minutes. Each person should do this as each person will be taking his/her own data.

Once these preliminaries are done, your instructor will activate the silver and discuss the details of the lab with you.

2. **Data Acquisition.** Make sure the counter GATE TIME knob is still set to 10S and the FREQUENCY button is still in the in position. The data taking consists of recording the number of counts in each 10 second interval for a total of 50 consecutive intervals. The counter will automatically count for ten seconds, display for 2 seconds, reset the display and start counting again. All you need to do is record the number of counts as they are displayed.

When the actual counting is about to start, your instructor will transfer the neutron source back to its container and remove the container from the room. As he is doing so, hold in the RESET button on the counter. When your instructor says "begin", release the RESET button and begin filling in your data tables. The counting should continue for 10 minutes following activation.

Repeat this step for two more activations.

3. **Data Analysis.**

a. Two things must be noted about the equations for radioactive decay given in the introduc-
tion: (1) they apply to decay on a continuous time scale, not to decay with two second time intervals taken out of it after every ten seconds and (2) they apply only to the decay of the nuclei under consideration and do not include provisions for any background radiation that may be present. Therefore, before the data can be plotted, two operations must be performed on each datum:

1. The gross count, the number of counts in a 10-second interval, must be adjusted to reflect the number of counts you would have had had the counting interval been 12 seconds. This is easily done by assuming the counting rate to be constant throughout the entire 12 second interval. This is called normalizing the data.

2. The background counting rate must be subtracted from the normalized counting rate. In this case, the background counting rate is the number of background counts in a twelve second time period.

Perform these operations on each datum for all three activations.

b. Equation (3) relates the decay rate, $dN/dt$, to time, $t$. Normally, we would think of $dN/dt$ as the number of decays per second and $t$ as the time in seconds. In this experiment, however, we took data in twelve second time blocks rather than every second. Therefore, $dN/dt$ in our case becomes the number of decays in twelve seconds and $t$ becomes a twelve second time interval. Keeping this in mind, plot $dN/dt$ vs $t$ for activation #1 on three cycle semilog paper.

After plotting the data, you will note that the graph is not a straight line as predicted by equation (3). As was pointed out earlier, this is because equation (3) applies only to the decay of a single type of nuclei whereas in this experiment there are two decaying isotopes. The graph can be roughly divided into two parts. The second part is linear and begins after approximately twenty twelve second time intervals have gone by. This is the region where the decay of the Ag$^{108}$ isotope dominates. Almost all of the shorter half life Ag$^{110}$ has already decayed and the number of counts that the remainder contributes to the gross count is negligible. The first part is not linear because both isotopes are present in large quantities and both are contributing significant number of counts to the gross count. Before the half lives can be computed, the data for the two isotopes must be separated.

1. On your plot of $dN/dt$, draw a straight line through the second portion of the graph. Extend the line all the way to the y-axis of the graph. [Note: Due to the random nature of the decay process, there will be a great deal of scatter in the data and it may be hard to judge exactly where the straight line should lie. A good approximation would be draw the line in such a way that there are an equal number of points above the line as below the line. A more exact method would be to use a mathematical fitting routine, such as a least squares fit, to calculate the equation of the best straight line through the
data and then plot the line of that equation through the data. You may use either method for this lab. The extension of this line under the first part of the graph represents the number of counts in the gross count in that region which are attributable to the decay of Ag$^{108}$ nuclei.

2. For each counting interval in the nonlinear part of the graph, use the extension to estimate the amount of the normalized gross count which is attributable to the Ag$^{108}$ isotope;

3. For each counting interval in the nonlinear part of the graph, subtract the amount attributable to the Ag$^{108}$ isotope from the normalized gross count to get the counting rate attributable to the Ag$^{110}$;

4. Plot the data $dN/dt$ (Ag$^{110}$) vs $t$ computed in steps 1-3 above on semilog paper. This graph should be linear. Draw a straight line through the data.

Repeat this step for the other two activations.

c. For each activation, compute the half life of the Ag$^{108}$ isotope from the slope of the line draw through the second portion of the graph of the original data and compute the half life of the Ag$^{110}$ isotope from the slope of the line draw through the $dN/dt$ (Ag$^{110}$) vs $t$ graph. In both computations, don't forget to take into account that: (1) you are taking the slope of a line drawn on semilog paper and (2) that the time as plotted on the graphs was measured in twelve second time blocks rather than in seconds.

Before leaving, turn off the counter and the high voltage power supply.

Lab Report

Follow the usual lab notebook format. Your lab report should include the answers to all of the questions asked in the introduction or procedure, all raw and derived data, and an estimate of the magnitude and sources of error in any data recorded. When answering any question or when giving any comparison or explanation, always refer to specific data to support your statements. For this lab, also include the following:

1. a table summarizing the final results, $dN/dt$ vs $t$, for each activation.

2. samples of all calculations done;

3. graphs of $\ln(-dN/dt)$ vs $t$ for the three activations;

4. graphs of $\ln(-dN/dt \text{ (Ag}^{110}\text{)})$ vs $t$ for the three activations;

5. computations of the half-lives for the two silver isotopes for each activation;
6. computation of the average $t_{1/2}$ for the three activations for each isotope;

7. a comparison of your average experimental values of $t_{1/2}$ for each isotope with their respective accepted values; and

8. a discussion of the sources of error with an estimate of their magnitude and effect on the final results.