

Understanding the Universe: Physics Through the Ages

Laboratory 4

Irène Curie, Frederic Joliot and Artificial Radioactivity

A. Introduction

After **Henri Becquerel's** discovery of radioactivity in 1895, many leading European physicists experimented with radioactive materials. **Marie Curie** coined the term "radioactivity," invented apparatus to measure very small amounts of radioactivity and discovered several previously unknown elements (polonium, radium). Curie and her husband, Pierre, also defined the half-life, or time required for half of a radioactive substance to decay (see below). **Ernst Rutherford** and others realized that various radioactive substances emit three different kinds of radiation (α , β and γ rays), differing in their penetrating power and electric charge, and that in radiating, substances are transmuted into other elements or isotopes which themselves may also radiate and decay until a stable isotope is reached. All of these processes of radioactive transmutation and decay seemed related to the structure and behavior of atomic nuclei.

After the discovery of the neutron in 1932, experimenters possessed a much more powerful tool to explore the nucleus, since the neutron was electrically neutral (**why would a neutral particle make a more powerful probe?**). Using neutrons, **Curie's daughter, Irène** and her husband, **Frederic Joliot** discovered in 1934 artificial radioactivity. That is, they created new radioactive isotopes not found in nature, and then measured their decay back to stable isotopes.

Some months ago we discovered that certain light elements emit positrons [particles with the mass of electrons but positive charge] under the action of α -particles. Our latest experiments have shown a very striking fact: when an aluminium foil is irradiated on a polonium preparation, the emission of positrons does not cease immediately, when the active preparation [i.e., the stream of α -particles] is removed. The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element. We observed the same phenomenon with boron and magnesium. The half life period of the activity is 14 min. for boron, 2 min. 30 sec. for magnesium, 3 min. 15 sec. for aluminium.... These radio-elements may be regarded as a known nucleus formed in a particular state of excitation; but it is much more probable that they are unknown isotopes which are always unstable [Joliot and Curie, "Artificial production of a new kind of radio-element," *Nature*, 10 Feb 1934, quoted in Emilio Segré, *From x-rays to quarks: Modern physicists and their discoveries* (Berkeley 1980) 198].

For this discovery, Curie and Joliot won the Nobel Prize in chemistry in 1935 (like mother, like daughter ... Irène's mother, Marie, had won the Nobel Prize in physics in 1903 for the co-discovery of radioactivity). In this lab, you will repeat Curie's and Joliot's work--although for a different element, silver.

B. Some preliminary points in nuclear physics

Recall that the atomic mass number (A) refers to the total number of protons (Z) and neutrons (N) in the nucleus of a given atom, and that we write:

$${}^A_{\text{element}}Z$$

where "element" denotes the chemical abbreviation for the element. For example, ${}^4\text{He}_2$ refers to the common helium isotope with an atomic weight of 4 and 2 protons. Z also

indicates the number of + charges on the nucleus. Note that in all radioactive transmutations, the total number of protons and nucleons must balance across the reaction.

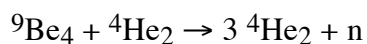
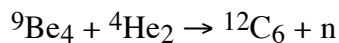
The purpose of this experiment is to measure the half-lives of two radioactive isotopes of silver. You will thereby demonstrate several processes and techniques that are crucial in nuclear physics:

- i) thermalization of fast neutrons, i.e., how they are slowed down by collisions with a medium;
- ii) resonance neutron capture, i.e., only neutrons with the right incoming energy are captured by the silver (Ag) atoms to form isotopes;
- iii) beta decay;
- iv) data analysis of radioactive decay.

As noted in class, James Chadwick in 1932 identified neutrons with the very penetrating radiation that appeared after beryllium was bombarded with α particles. Neutrons have a mass approximately equal to that of protons, are electrically neutral (hence their name), and if not in the atomic nucleus, are unstable. An isolated neutron spontaneously decays into a proton, an electron and another particle called an anti-neutrino, in about 13 minutes. Because they are electrically neutral, they are not easy to detect--indirect methods are required. One such method depends on a process known as resonance capture. When bombarded by neutrons, certain elements become radioactive (like Ag in this experiment). A stable isotope of an element captures a neutron, thereby becoming unstable and decaying into a stable isotope of another element. The particles released during the decay can be detected by a Geiger counter.

The probability that an incoming neutron will be captured varies with the neutron's kinetic energy and will have maxima at the so-called resonance peaks. In other words, certain incoming energies for the neutrons happen to be the right ones for the stable isotope to capture them. At these resonant energies, the stable isotope will absorb the neutron and become unstable.

In this experiment, you will activate two isotopes of silver (Ag, from *argentum*, the Latin word for silver or money) by neutron bombardment: $^{107}\text{Ag}_{47}$ and $^{109}\text{Ag}_{47}$. In its natural state, silver occurs in a ratio of 51.35% to 48.65% of isotopes 107 to 109. Our neutron source is a mixture of americium 241 and beryllium 9 sealed in a stainless steel capsule. The neutrons that eventually will hit the Ag atoms are produced by the following two reactions, with the α particles (naked nuclei of He atoms) coming from the decay of the americium.



The energy distribution of the ejected neutrons ranges from a few keV [thousand electron-volts] to a maximum of 11 MeV [million electron-volts].¹ The mean energy of the ejected neutrons is about 5 MeV. However, for both silver isotopes, the resonant peaks occur at energies of less than 100 eV. We thus have to slow down these neutrons significantly so that they will have the right energy to activate the silver.

¹The energy unit electron-volt is frequently used in nuclear and particle physics: $1\text{eV} = 1.6 \times 10^{-19}$ Joules.

This is where the **moderator** comes in. In this experiment, we will use paraffin (such as surfers rub on surfboards). As fast neutrons enter the moderator, they will lose energy as they collide with the moderator's protons (mostly in carbon atoms) and quickly become thermalized to about room temperature. That is, their average kinetic energy will become about kT , where k is Boltzmann's constant. Although a T of 300°K (room temperature) is only 0.025 eV , statistically there will be a substantial number of neutrons with the energy in the right range of about 100 eV to then activate the silver. See Fig. 1.

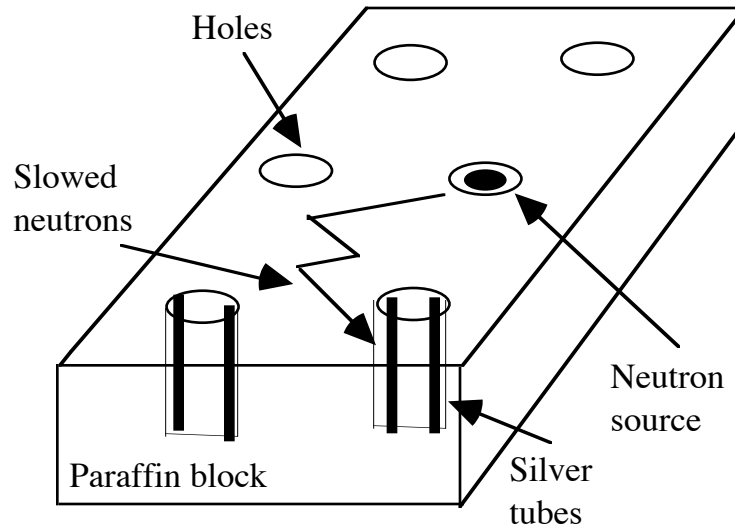
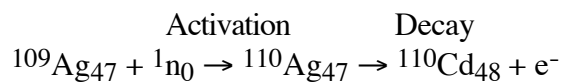


Fig. 1: Thermal neutron activation of silver

When the silver is bombarded by the thermalized neutrons, the ^{107}Ag nuclei are transmuted into ^{108}Ag , and the ^{109}Ag into ^{110}Ag . The dominant isotope produced is ^{110}Ag (basically because the nucleus of ^{109}Ag is larger than the nucleus of ^{107}Ag and so the neutrons find it more easily). ^{110}Ag decays with a short half-life of 24.6 secs. For this reason, after neutron activation is stopped and you start to count the decaying isotopes, at first most activity will be due to ^{110}Ag . Since the half-life of ^{108}Ag is much longer (2.37 mins), after a few half-lives of ^{110}Ag (i.e., after a few multiples of 24.6 secs), most of the activity will be due to ^{108}Ag decay. Some of the possible transmutations undergone by these Ag isotopes include:



Do you see why the Ag isotopes, after negative beta decay, transmute into cadmium, and after positron (e^+) decay, transmute into palladium? Note that these isotopes of Cd and Pd are themselves stable (i.e., no further radioactive decay occurs).

In this experiment, there are two distinct stages of decay, first the decay of ^{110}Ag and then the decay of ^{108}Ag . This is why it is possible to measure the half-lives of both isotopes in the same experiment.

C. The mathematics of radioactive decay

Radioactive decay (the number of atoms that decay as a function of time) follows what we call an **exponential decay law**. We all know what a power decay law is. Let's say we have a certain number of grains of sand N_0 inside a glass tube. We can make a tiny hole in the bottom of the tube so that the grains of sand will start falling out of the tube. If I tell you that the grains of sand are disappearing according to the relation:

$$N(t) = N_0 2^{-t/\text{sec}}, \quad [1]$$

what do I mean? First note that $2^{-t/\text{sec}} = (\frac{1}{2})^{t/\text{sec}}$. At each value of t in secs, this relation tells me how many of the initial N_0 grains of sand remain in the glass tube. For example, at $t=0$ secs, $N(0) = N_0$; at $t=1$ sec, $N(1) = N_0/2$; at $t=4$ secs, $N(2) = N_0/4$, and so on. An exponential decay law is exactly the same thing, but instead of having the number 2 elevated to a (negative) power of time, we have the irrational number $e = 2.71828\dots$. So, for the radioactive decay of an atom, we would write:

$$N(t) = N_0 e^{-pt}, \quad [2]$$

where p is a constant with dimensions of inverse time (1/sec), related to the probability of decay per unit time. So, just as with the example of the glass tube, at $t=1$ sec, you would have $N_0/e^{p\text{sec}} = N_0/2.718^{p\text{sec}}$ of the original atoms still remaining in the sample. If we know what the constant p is, we can get the exact number of atoms remaining. For example, if $p = 0.5/\text{sec}$, then after 2 secs we would have $N_0/e = N_0/2.718$ atoms remaining.

Finally we need to define **half-life** more carefully. The half-life of an isotope, abbreviated as $t_{1/2}$, is the time it takes for $N(t)$ to decrease to half its original value. In other words, $t_{1/2}$ is the time it takes for the ratio of $N(t)/N_0$ to equal 1/2. From Eq. [2] above, we can write:

$$N(t_{1/2})/N_0 = 1/2 = e^{-pt_{1/2}}. \quad [3]$$

But this equation is somewhat awkward. What we want to find is the value of $t_{1/2}$ as a function of the constant p , which will be different for each isotope. How can we "solve" Eq. [3] for $t_{1/2}$? By using a wonderful mathematical device called a **logarithm**! Just as division is the inverse operation of multiplication, logarithm is the inverse operation of power laws. In particular, if the power law involves the number e , the logarithm comes with the special name of natural logarithm, represented by $\ln(x)$, where x is a number.

So the same way that I "invert" a division to multiply (e.g., $4 \times 1/2 = 2$), to "invert" an exponential power law I take the natural logarithm:

$$\ln(e^x) = x. \quad [4]$$

For example, $\ln(e^1) = 1$; $\ln(e^2) = 2$; $\ln(e^{-5.41}) = -5.41$, etc. We can now take the logarithm of Eq. [3] to get:

$$\ln(1/2) = \ln(e^{-pt_{1/2}}) = -pt_{1/2}. \quad [5]$$

But we still have a problem. What does $\ln(1/2)$ mean? Well, the logarithm is just a function like any other function. A function is a device that converts one number into another number according to fixed rules. For example, the function x^2 converts any number to its square. Just as with a number x I get a new number by elevating e to its power e^x , $e^1=2.718$, $e^2=7.389$, or $e^{10} = 22,026.47$, so too do I get a new number by taking its logarithm, $\ln(x)$. The only difference is that it is hard for us to compute the logarithm of numbers. We must resort to tables or pocket calculators. With the latter, you can find the \ln of any number. For example, $\ln(1/2) = -0.693$. Using this result in [5] we obtain, for the half-life of an isotope:

$$-0.693 = -pt_{1/2}, \text{ which may be rewritten as } t_{1/2} = 0.693/p \quad [6]$$

So, if we know the constant p for a given isotope, we can immediately get its half-life. **It is this constant p that you will measure in this experiment.**

As we can see from Eq. [6], in order to obtain the half-life of each of the two silver isotopes, we must measure the decay probability constant p . The larger the decay probability, the smaller the half-life is. This is not hard to understand: if atoms have a larger probability of decaying, after some time there will be a smaller number of atoms than if the probability of decay is small. We can determine p by counting the number of decays per interval of time (we will use time intervals of 12 secs) and making a plot of this number as a function of time. It turns out that if we take the natural logarithm of the number of decays per unit time, and then plot the resulting numbers as a function of time, we get a straight-line plot, as in Fig. 2 below.

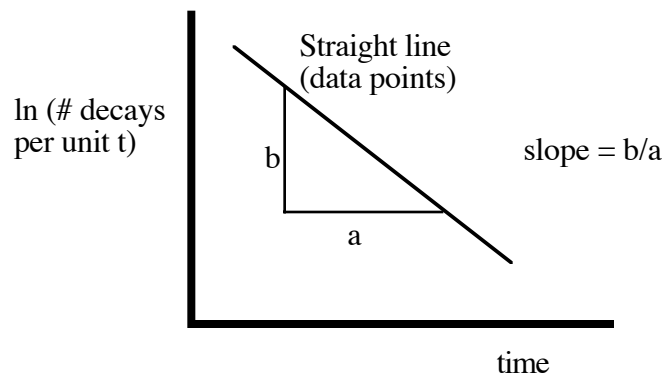


Fig. 2: Radioactive decay, plotted on regular graph paper

The slope of the straight line (a negative value) gives the negative value of the decay probability constant, p (a positive value). Because there are two isotopes of silver being produced by the neutron activation, there will be two (approximately) straight lines with different slopes. Each slope will give the p of each isotope. All you have to do then is to produce a curve like the one above, read off its slope by dividing the height of the base of a triangle as indicated in Fig. 2, and then compute the half-lives by Eq. [6].

D. Procedures

CAUTION: This lab employs radioactive sources that can be dangerous if you are overexposed to them. You must wear a safety badge during this entire lab session. Record your name, social security number and birthdate on the badge. At the end of the session, turn the badge in to your TA. All badges will then be sent to a biosafety company which will determine your exposure level.

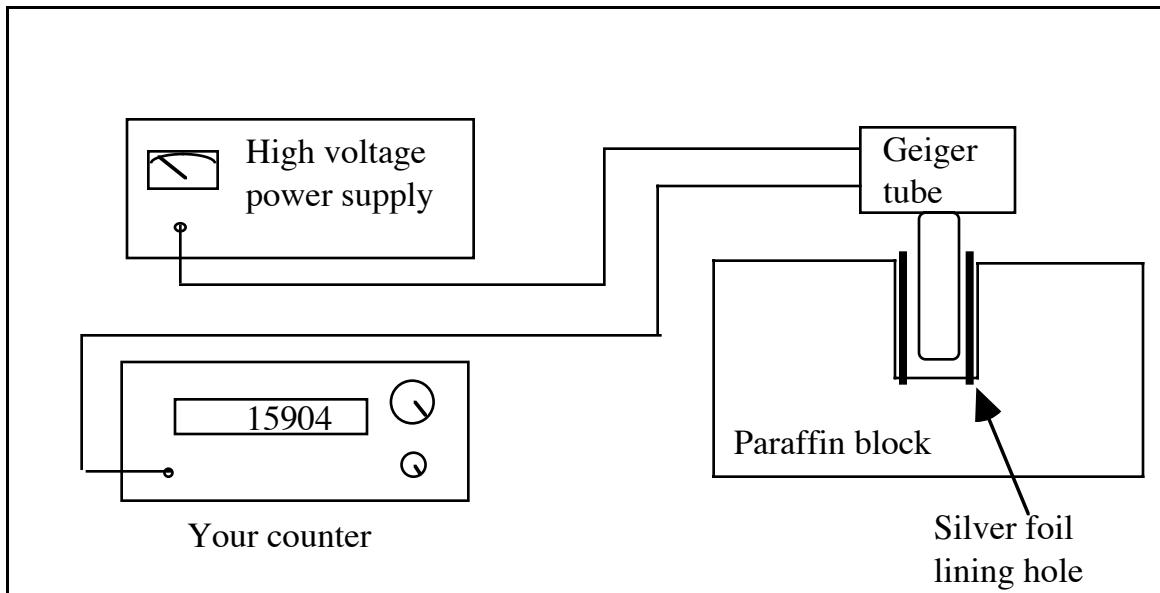


Fig. 3: Counting decay rates of radioactive Ag isotopes

1) First you must measure the background radiation, which is due to natural radioactivity. You will want to subtract the background count from the decay counts of the Ag isotopes. To do this, turn the GATE TIME knob to the "time interval" position. Do a 2-minute count of the background radiation by pushing the COUNT button and counting for 2 minutes (you might prepare your data table [see 2 below] while you're waiting).

2) Prepare your data table, into which you will enter the results of your decay measurements. The table should contain seven columns (see Fig. 4):

- i) Time elapsed. Each interval will take 12 secs. You will count for 10 mins, over a total of fifty 12-sec intervals. You will thus have 50 lines in your table.
- ii) Gross count, or the total number of counts in 10 secs. The counter counts for 10 secs, and then displays the result for 2 secs, before starting the next interval.
- iii) Normalized count - background count. Since you don't want gaps in your counting, you must extend the count from the 10 secs of actual counting to cover the 12 secs of the total interval. If, for example, you counted 100 decays in 10 secs, the normalized value for 12 secs would be 120. Hence, $\text{normalized count} = \text{gross count} \times 1.2$. Then you must subtract the background count (over 12 secs) from the normalized count.

- iv) $\ln(\text{normalized count} - \text{background})$. You must take the natural logarithm of the number in col. iii, using a calculator.

Fig. 4: Sample data table

Time elapsed	Gross counts (10 secs)	Normalized counts (12 sec - backgd*)	$\ln(\text{norm. counts})$	$\ln(108\text{Ag counts})$	108Ag counts	$\ln(110\text{Ag counts})$
12	2232	2660	7.886	6.7	812	7.52
24	1609	1913	7.557	6.6	735	7.07
36	1278	1516	7.324	6.5	665	6.75
48	1051	1244	7.126	6.4	602	6.46
60	781	920	6.824	6.3	545	5.93
.						
.						
.						
600	38	28	3.336			

*Assumes a background of 17 counts/12 secs.

3) Calibrate the counter. You will use the counter to record how many decays occur in 10 secs. After it counts the 10 secs, you must read the result. To do that, set the counter to display the result for 2 secs. Hence, each counting interval will be 12 secs; you will count for a total of 10 mins.

Calibration:

- i) Turn the GATE TIME knob to the 10-sec position and the DISPLAY knob to a little over the 1-sec display position.
- ii) With the stop watch provided, measure the time interval from the beginning of one count (light shows on the left side) to the beginning of the next count. If the measured time is 12 secs, you're set. 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 secs. Once this is set, do NOT touch the DISPLAY knob again. Before starting the measurement, press the FREQUENCY button.

NOTE: Our counters, for unknown reasons, sometime place decimals in the number of counts displayed. Disregard all decimals! Counts are always integers.

4) Your TA will activate the silver by placing the neutron source in the paraffin moderator for about 10 mins (see Fig. 1). Free neutrons are harmful to your health--**PLEASE FOLLOW ALL SAFETY PRECAUTIONS DURING THIS PERIOD!**

5) Measure the decay rates. When the actual counting is about to commence, your TA will transfer the neutron source back to its container. As this is being done, hold in the RESET button on your counter. When your TA says "begin," release the button and begin recording the counts (at 12-sec intervals) into your data table. The counting should be continued for 10 mins after activation. REPEAT steps 4-5 to collect a second set of measurements.

6) Data analysis and presentation (we strongly urge you to begin preparing your written lab report while still in the lab, so that you can consult with your TA). After you have completed all columns in your data table, plot the results of $\ln(\text{normalized counts})$ versus time on graph paper. The line for shorter times is dominated by the decay of ^{110}Ag , the line for longer times by the decay of ^{108}Ag . The slopes of these two lines will give you the decay probability constant, p , for each isotope. You can then use Eq. [6] to compute the half-lives for each isotope.

7) Note however that when computing the slope for the ^{110}Ag , there will be counts due to the ^{108}Ag which will interfere with your measurements. To take this into account and get a better measurement of the half-life of ^{110}Ag , you should extend the line through the later set of data points (where ^{108}Ag dominates) back to the y-axis of the graph. Then add the following data to columns v – vii in your data table described above in Fig. 4:

- v) \ln of counts due solely to ^{108}Ag decay, read off your graph for the given time intervals from the line through the ^{108}Ag counts extended back to the y-axis.
- vi) Counts due solely to ^{108}Ag decay, i.e., $\exp(\ln[^{108}\text{Ag counts}])$. Use the \exp function on your calculator, remembering that \exp is the inverse function of \ln .
- vii) \ln of counts due solely to ^{110}Ag decay = $\ln(\text{normalized counts} - ^{108}\text{Ag counts})$, i.e., $\ln(\text{col. iii} - \text{col. vi})$.

Then plot the numbers you get for the $\ln(^{110}\text{Ag})$ counts in a separate graph, and use this graph to determine the decay probability constant and hence a more accurate half-life for ^{110}Ag .

Finally, discuss any possible sources of error in your work, and how they might have affected your results.

Accepted half-lives
^{110}Ag: 24.6 secs
^{108}Ag: 2.37 mins

Extra credit: Compute the time it would take for the decay rate to reach the background level! Does your answer make sense (look at your data)?