Physics 116C
Geiger Counter, Statistics, and Radioactive Decay

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The goals of this two-week lab are

1. to investigate the Geiger counter and basic data acquisition techniques with LabVIEW,
2. to investigate counting statistics (Poisson and Gaussian distributions as limits of the binomial distribution),
3. to collect data and perform a least-squares fit to measure the mean life of unstable $^{116}\text{In}$ nuclei and estimate the error in the mean life,
4. to evaluate the goodness of fit using the $\chi^2$ distribution, and
5. to make a complete report on your experiment.

Begin by reading the information from the Physics 122 Lab manual on Geiger counter basics and $^{116}\text{In}$ radioactive decay. It is provided at the end of this writeup. We have modified the 122 Lab procedure to use a National Instruments E-Series PCI data acquisition (DAQ) card and a LabVIEW program to do the counting and timing more accurately and faster than could have been done by hand. The program can also display the major results rapidly. Also, we will investigate the Geiger counter pulses in more detail.

Precautions with Geiger tube:

- Leave the cable from the Geiger counter controller to the Geiger tube in place at all times. The connector on the controller can carry a voltage of order 1000 V. If you leave the cable from the tube connected, nothing else can get connected to it by mistake (including fingers!).

- Leave the Geiger tube in its holder. It has a thin front window which could be broken.

Overview

The block diagram of the circuit is shown in Fig. 1. The idea is to use a continuously running counter which can be read at regular intervals by the computer to take the data (number of counts per interval). The computer program can make histograms to be read out manually and compared with statistical theory and saved to a file for further analysis. The timing accuracy is at least of the order of a few ms, which is sufficient for this application. (Greater timing accuracy could be achieved with external gating pulses.)
This experiment exemplifies a nuclear or particle physics experiment at possibly the simplest level. Particles (e.g., $\beta^-$, otherwise known as energetic electrons) enter on the left, proceed through detectors and produce electronic pulses. These go through pulse shapers, data acquisition circuits and a computer, producing data files and histograms, which come out at the right. These result in publications, or at least in lab reports.

Figure 1: Circuit block diagram.

The salient features of the Geiger counter controller are shown in Fig. 2. It has a pair of terminals on the back marked “Oscilloscope” (bottom one is ground). The output is a fast-rising pulse with height of approx. 2.5 V and a decay time constant $\approx 200 \, \mu s$ superimposed on a DC pedestal $\approx 5 \, V$.

Figure 2: Geiger counter control box.

To get a logic pulse for the computer interface, we need to build a circuit to trigger on pulses exceeding a certain amplitude above the pedestal. That is the circuit in Fig. 3.

The data acquisition VI was adapted from an example called Count Edges (DAQ-STC).vi included in the daq-stc.llb library file which came with the Student Edition of LabVIEW. The original program counted leading edges of pulses from the DAQ counter. It was modified to make a fixed number of count samples, store them in an array and make a histogram of the results. The VI control panel is shown in Fig. 4 and the VI block diagram in Fig. 5.
Procedure for First Week

1. Record your observations and make preliminary curves in a loose leaf notebook (preferably quadrille-ruled engineering paper). Save files you have developed (data or VIs) in your disk space on “MyUCDavis” (you can upload and download files using a web browser) or on a USB flash drive.

The lab will be continued the following week to make a useful physical measurement with stated uncertainties ($^{116}\text{In}$ excited state mean life). A full lab report will be required at the end covering both weeks.

2. Check and turn on Geiger counter

Remember the warning above not to disturb the connection to the Geiger counter itself, but verify that it is connected to the control box HV. Turn on the Geiger counter control box, set the HV knob fully CCW (low voltage) and turn on the Geiger counter HV. We turn on this equipment at this point to let its temperature stabilize.

3. Trigger circuit

Wire the trigger circuit shown in Fig. 3. Use the lower left corner of the prototype board array. Be reasonably neat and use 5 V and ground busses appropriately. The input should be from the BNC connector on the left and the output to the BNC connector on the right. Connect the output to the DAQ interface panel BNC connector marked PFI0/TRIG1.

4. LabVIEW VI

Load the DAQ program (called geiger_all_v2.vi). In the lab, become familiar with the diagram, particularly that within and to the right of the For loop. (The block diagram shown in this report is an earlier version without file output but the basic structure is the same). The DAQ counter I/O is from the example; understanding details of the DAQ sub-vi’s will be deferred until later.

Note how the loop delay timer waits until a fixed multiple of a system clock (in ms) before reading the continuously running counter and exiting the loop. The Geiger count sample for the current interval is found by subtracting the counter reading from the previous iteration.

This is put in an array (Count Array). But first the zeroth and first element are deleted: the zeroth element winds up being the initial value of the counter (0) and the first element the
value from the incomplete period of the first loop iteration (the loop is only synchronized after the first loop ends).

Also observe how the histogram works. You specify the minimum and maximum limits of the histogram and the number of bins. For example, if you wanted to have bins corresponding to 990 to 1010 with 20 bins, you would enter these numbers. The histogram x-axis would then show 0 to 20. The lower bin edge of the lowest bin would correspond to 990, the upper edge of highest bin would correspond to 1010 and each bin width would correspond to 1 count. The “inclusion” parameter has been set to “lower” so a number on the lower bin boundary is assigned to that bin. There is a quirk, though, in that the histogram maximum value is assigned to the highest bin. This would normally be the lower boundary of the next higher bin so if there were one, this value should go there, but in this case, it is counted in the highest bin. For example, if you had entered the 21 data values, 990 through 1010, each bin would contain one count except for the highest bin, which would contain two entries, one for “1009” (corresponding to the lower bin edge) and another one for “1010” (corresponding to the histogram maximum). This will not be important if you set up your histograms so the minimum and maximum bins are not populated. In any case, you should be aware of this.
behavior of the histogram VI.

The histogram display shows the bin contents with bin number along the bottom. *(This could be improved by using an xy plot for the histogram display and using the x-axis information from the histogram VI to enter the proper x axis values.)*

The samples outside the histogram range are also tallied to the lower left of the display, above the output arrays. Running tallies during program execution are at the upper right. The histogram is not produced until the end of the run.

The time stamp array represents the time in s since Friday, January 1, 2004 Universal Time. This is here mainly for the radioactive decay measurement.

5. Test the count accuracy and repeatability

Use the signal generator to produce a 1 kHz square wave of 2 V amplitude (4 v peak-to-peak) and connect it to the input of your trigger circuit on the breadboard.

Now set your VI to count 10 samples of 1000 ms. As they come in, watch the count increment (it should be close to 1000 but with variations). You can review them when you are done and set the histogram accordingly for a longer run. The bin settings I gave in the section above would be appropriate. With a longer run (50 samples, say) you can accumulate statistics on the counting accuracy.

Record the histogram, measured frequency and signal generator frequency.

When you are finished, disconnect the signal generator from your trigger circuit input and connect the cable from the Geiger counter Control Box output instead. The cable connects to the scope output screw terminals on the back of the control box (bottom terminal is ground).
6. Set Geiger counter operating voltage

The $^{137}$Cs source should be in the second slot from the top of the Geiger tube holder. (Caution: don’t touch the source. Leave it in its tray at all times. The TA or lab assistant will provide the sources and deal with moving them from place to place.) Be sure the Geiger counter control box is set to count. We will leave it in this mode at all times. Also, don’t push the reset button. It can generate spurious pulses in the output to the discriminator. This source emits energetic $\beta^-$ particles which enter the Geiger tube through the thin window and ionize the gas to cause output pulses.

(a) Finding the threshold

Use the LabVIEW VI (not the counter control box itself—leave it counting continuously; it will have a somewhat lower counting threshold).

Be careful not to exceed 1000 V. If you hear a ticking sound from the counter (HV breakdown), reduce the voltage immediately and call the TA.

Set the VI to count a large number of samples (10000, say) with a short count interval (100 ms). Start the VI and watch the count increment window as you slowly increase the Geiger counter HV from its minimum setting. If the VI terminates, start it again. Find the minimum HV setting for which you get reliable counting. Record this threshold voltage.

(b) Making a plateau curve

Start at the next 50 V HV multiple above the threshold (e.g., if the threshold was 730 V, start at 750). Set the VI to acquire 1 sample with a 10000 ms count interval and start the program. After 20 s or so, you will get a count measurement (0th element of the count array). Record this and the voltage. Now increase the voltage in 50 V increments up to 1000 V (or 300 V above threshold, whichever is less—don’t exceed 1000 V) and repeat the count measurements. You should get samples, $n_i$, of order 1000 counts each on the plateau.

Make a (hand-drawn) graph of your result with error bars. We assume Poisson statistics here, so we can estimate $\sigma_i = \sqrt{n_i}$. The threshold voltage in our discriminator is too high to observe the linear or proportional region of the counter, but there should be a gently rising linear plateau in the Geiger region above the threshold and to the left of any sharp rise at large voltages. Set the voltage near the center of this plateau and record this operating voltage (it will probably be $\approx 100$ V above your first measured point above the counting threshold).

Fig. 6 shows a typical plateau curve and the chosen operating point.
7. Observe Geiger pulses and dead time

Sketch the pulses at four points: trigger circuit input, comparator “-” input, comparator output and trigger circuit output. Note: check the output pulse at a high sweep speed to be sure there are no spurious extra pulses at the end (glitches) which could be counted by the 20 MHz counter. (The low pass filter at the output is provided to suppress such glitches.)

Now set the oscilloscope time base to 50 µs/division. The source should now be in the top slot, nearest the tube. You should see additional output pulses on the same trace as the triggering pulses. These appear at random, following a uniform distribution except near the beginning of the trace. Estimate how long this gap lasts where no additional pulses are seen. This is the overall dead time of the circuit. Record this information.

Actually, the counter is recovering from delivering its previous pulse toward the end of this period. If you hook the scope probe to the comparator “-” input, you should see small pulses occasionally near the end of the deadtime region below the 0.5 V threshold (scope trigger level needs to be set low enough to capture them). These pulses increase in size until they reach the maximum. This is the Geiger counter “recovery” region. See if you can observe this.

8. VI file output

An output text file of the samples is written so other histogram binning could be done if desired using LabVIEW or other analysis software. We also need this capability for the radioactive decay experiment. Examine how this works and check that the data agree with what you expect. The text entry field on the VI front panel provides a place where you can type identification information for the run before you start the VI. This information is output as the first line in the output file.
9. Observe Poisson statistics with mean near 0

This should be done with the source in the bottom slot (away from the tube) and with a relatively short count interval (100 ms, say). The mean number of counts should be of order 2 or 3; be sure it is low enough that you get a reasonable number of zero count samples. The histogram should be set to have bin widths of one count and start at 0.

Do a run of 10 samples and check that the histogram of the samples \( n_i \) is correct—i.e., make the histogram by hand and see that it agrees with the computer. Include the check histogram in your lab notes (this is to verify that the software is working as expected). As this is done (or redo if necessary), check that the count increments on the Geiger counter scale roughly agree with what you see with the program. Don’t reset the Geiger counter readout—this causes spurious pulses to be injected into the discriminator. Just read the counter on the fly and subtract, as the program is doing. At this low rate, you should be able to check that the two tallies agree closely. If not, discuss with the instructor. Note: lesson learned from experience!

Do a 100 sample run under these conditions and record the histogram contents in your data. Be sure to record the conditions of the run, particularly the histogram setup. Be sure your upper limit is such that there are no overflows. Be sure the histogram looks reasonable before proceeding.

10. Observe Poisson statistics with mean \( > 100 \) and compare with normal distribution

The source should now be in the slot second from the top. A counting interval of 5000 ms will probably be appropriate for this section. Make a histogram with 5 counts per bin which includes the entire distribution on \( n_i \) (within at least \( 2\sigma \)) and has boundaries that are easy to understand. For example, if the expected number of counts were 400, you could make a histogram with lower limit 350, upper limit 450 and 20 bins.

Do a run of 100 samples, save the output data file for further analysis and record the histogram in your lab notes. Be sure to record the histogram limits. Make sure the histogram looks reasonable.

11. Suggested analysis and writeup for this part

The idea is to plot the histograms and compare with Poisson (low rate) or Gaussian (high rate) statistics. For the high rate data, we want to compare with the Gaussian limit by calculating the number of counts expected in each bin using differences of the Gaussian cumulative distribution function, given the measured mean value.

The writeup should be brief but complete. It should briefly describe your procedure and the equipment used, including Geiger counter operation.
Outline of Procedure for Second Week

1. Prepare equipment and program
   For this week’s lab, the first hour will be spent completing unfinished work from last week, becoming familiar with the complete program for data acquisition (or testing your own) and preparing for a two hour run to measure the $^{116}$In half-life.

2. Geiger counter background rate measurement
   The background counting rate must be subtracted from the observed counting rate to get the decay rate. Be sure the source is well away from the counter (have the instructor put it away). Then count for approximately 10 min (or more if time permits) using 30 s count intervals and record your data to a file.

3. Radioactive decay half-life measurement
   After one hour, the instructor should appear with a freshly irradiated In sample to be placed in the holder in the slot nearest the Geiger tube (the activity will be considerably lower than that of the Cs source). as soon as possible, start the program to record counts in 30 s intervals for a total of 2 hours (240 samples). Observe the numbers to be sure that things are proceeding properly. The time series display should show an exponentially falling rate with statistical scatter in the points.

   Once you are sure it is running properly, this could be a time to work on other things.

   If possible, make another background counting rate measurement at the end of the run.

4. Analysis of decay constant
   We want to estimate the decay constant $\lambda$, its error and test the goodness of fit of the resulting decay curve. One way would be to use weighted least-squares. But the LabVIEW version does not appear to allow the use of errors. The general Marquardt method does allow this and has some additional advantages, not the least of which is that the entire work can be done with LabVIEW Student Edition (including making plots). It is also more general; you could use it to fit a sum of two exponentials, for example. The vi is known as Nonlinear Lev-Mar Fit for Levenberg-Marquardt (another name for the Marquardt method). By now you should have done some Nonlinear Lev-Mar examples in Essick.

   First you will need to find the background decay rate with errors using all of your background data. This is subtracted from the counting rate measured for each interval to give the radioactive decay rate for that interval (also find the resulting error for this quantity). This array of measurements and errors should be input into the Lev-Mar fit routine (nonlinear function: you fit the exponential directly). You can then plot the measured values (perhaps you can also figure out how to plot error bars) and the fitted function. You can also obtain the reduced $\chi^2$ for the fit find the probability of exceeding this value. Find $\lambda$ and its error from the fit. Compare your result with the accepted value and discuss your results.

5. Complete writeup
   Combine the material from the first week with this week’s material. The additional introductory material would be a brief discussion of the radioactive decay sequence (see the appendix
or Melissinos and Napolitano, Sec. 8.6.1) and a brief description of your procedure plus the Levinberg-Marquardt fits and resulting decay constant or half-life value with error. Comment on the goodness of fit and agreement with the accepted value or lack of it.

**Brief Note on Writeup**

I advise you to read Ch. 13 of *Practical Physics* by Squires on writing a paper. He suggests breaking the report into four sections: Introduction, Experimental Method, Results, Discussion. Of course, there are also the Title and the Abstract plus the list of references at the end. He gives guidelines on what to include and how to make things clear. The entire chapter covers 7 pages. While you are there, Ch. 10-12 are also worth investigating.
Geiger Counter, Counter Statistics and Half Life Determination

References

Adrian Melissinos, *Experiments in Modern Physics*, Ch. 4-5; Ch. 5-1 & 5-3; Ch. 10-1, 10-2 & 10-5, QC33 M52

Philip R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences*, QA278 R48


1. Geiger Counter

A Geiger counter is a charged capacitor with the region between the electrodes filled with a gas. As ionizing radiations pass through this gas, the molecules of the gas are ionized, so that the gas contains free electrons and positive ions. The electric field in the capacitor separates the ions from the free electrons and prevents them from recombining.

If air is used as the counter gas, then the energy needed to form an ion-electron pair is about 34 eV, so a 1 MeV gamma ray will produce about $3 \times 10^4$ such pairs, and with a typical capacitance of $10^{-11}$ farads, one will observe a voltage of about ½ millivolt, which is too small to be detected in our apparatus. The counter, when operating in this mode, is called an *ionization chamber*; you will not be able to observe counter operation in this mode.

As the voltage on the counter is increased, the electrons that are released through ionization of the counter gas by the original ionizing radiation are accelerated. When the voltage is large enough, these accelerated electrons can themselves ionize the counter gas, giving rise to more ion-electron pairs. Thus the current in the capacitor that forms the counter is amplified through the production of these secondary electrons. The result is a *Thomson avalanche*. The current through the counter is found to be proportional to the applied voltage. This device is called a *proportional counter*.

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If the voltage is increased still further, photons generated in the ionization process can participate in ionizing the counter gas, and these photons can travel throughout the counter. So, when this point is reached, the entire counter is participating in delivering current and the counter becomes saturated. The current through the counter becomes independent of the voltage, and the device is called a Geiger-Müller counter.

The output signal consists of the collected electrons from the avalanche processes. The collection time is of the order of $10^{-6}$ sec, during which time the positive ions do not move very far. This process therefore produces a cloud of positive ions around the anode which reduces the electric field generated by the capacitor plates and eventually terminates the avalanche process.

![Graph](image)

**Fig. 1.** Pulse height vs. voltage for gas-filled counters.

In order to help terminate the avalanches, a quenching gas is added to the counter gas during manufacture. The quenching gas is usually consists of organic molecules such as ethanol, while the counter gas might be argon or nitrogen. Dissociation of the organic molecules can prevent ionization by accelerated ions, which would otherwise cause the release.
of new electrons and resumption of the avalanche process. When the quenching gas is all
dissociated, the Geiger tube fails and must be replaced.

There is a considerable voltage region where the counter current is independent of voltage. This *plateau* region is where one should operate a Geiger counter. If one raises the voltage too high, successive Geiger pulses are generated by a single ionizing event, and an audible ticking noise can be heard. At such a point, the quenching gas is being rapidly destroyed, and unless the voltage is reduced, the counter will fail. IF TICKING IS HEARD, REDUCE THE VOLTAGE AND CALL YOUR INSTRUCTOR OR TA.

For the counters being used in the laboratory, ONE MUST NOT RAISE THE VOLTAGE ABOVE 1000 VOLTS.

The current in the counter is converted to a voltage by passing it through a resistor. The voltage signal is then passed through a discriminator, which selects for counting those pulses larger than a specific value and rejects the others. Thus in the proportional region, the number of counts recorded by the instrument is proportional to the counter voltage, while in the Geiger region, it is independent of the voltage.
Half Life of $^{116}$In

For each nucleus of a radioactive isotope there is a constant probability per unit time that it will undergo radioactive disintegration or transformation. For a sample of $N$ atoms of a given isotope the number disintegrating in time $dt$ is given by

$$dN = -\lambda N dt$$  \hspace{1cm} (14)

where $N$ is the total number of nuclei (or atoms) of the isotope present and $\lambda$ is the constant of proportionality called the decay constant. The solution to this equation is

$$N(t) = N_0 e^{-\lambda t}$$  \hspace{1cm} (15)

where $N_0$ is the number present at $t = 0$. Evidently, the decay constant is related to the half-life, $T_{1/2}$:

$$T_{1/2} = \frac{\ln 2}{\lambda}$$  \hspace{1cm} (16)

The decay rate, $R$ is easily calculated from (14), because when decay occurs, a nucleus is lost and $N$ reduces by 1.

$$R(t) = -\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t}$$  \hspace{1cm} (17)

In this section of the experiment, you will observe a sample of radioactive nuclei having a half life of about 1 hour by counting for a large number of time intervals of duration $\Delta t$. That means that your data will consist of numbers of counts, $n(t)$.

$$n(t) = \int_{t-\Delta t/2}^{t+\Delta t/2} R(t') dt'$$  \hspace{1cm} (18)

If the time intervals are short enough,

$$n(t) \approx R(t) \Delta t$$  \hspace{1cm} (19)
Evidently, \( n(t) \) is also exponential:

\[
n(t) = n(0)e^{-\lambda t}
\] (20)

One way in which a radioactive isotope may be produced is by the capture of a neutron by a stable nucleus. The reaction used in our lab is

\[
_{49}^{115}\text{In} + n \rightarrow _{49}^{116}\text{In} + \gamma
\] (21)

\( _{49}^{116}\text{In} \) then undergoes beta decay to \( _{50}^{116}\text{Sn} \) with a half-life of about one hour.

\[
_{49}^{116}\text{In} \rightarrow _{50}^{116}\text{Sn} + e^- + \bar{\nu}
\] (22)

The half-life is the time required for half of the radioactive atoms present to disintegrate and is related to the decay constant.