

RUT - Rutherford Scattering
Physics 111B: Advanced Experimentation Laboratory
University of California, Berkeley

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1 Rutherford Scattering Description (RUT)

Revised 2025-09-30

1. **Note that there is NO eating or drinking in the 111-Lab anywhere, except in rooms 282 & 286 LeConte on the bench with the BLUE stripe around it.** Thank you – the Staff.

An experiment that shook the world of physics was carried out by Rutherford in 1910. He found that when scattering α particles from gold foils, far more of them were scattered at large angles than were expected to by theory. He explained the finding by assuming that all of the mass and positive charge of an atom are concentrated in a small volume at the center, in a compact nucleus. He derived an equation in which the differential cross section for scattering by an atomic nucleus is proportional to the inverse fourth power of the sine of the scattering angle.

In this experiment the scattering formula is confirmed for the case of α particles scattered by gold nuclei in a thin gold foil. The charge on the gold nucleus will also be determined.

This experiment needs long counting times owing to the fact that only a small fraction of incident particles is scattered to large angles. The counting rate in the forward direction is on the order of 10^5 particles/hour, while in the backward direction it is of the order of 10^{-1} particles/hour. This low count rate makes the experiment challenging since background and electronic noise can dominate the counts. You set up the equipment and count, only returning to read out data and start another set. You will want to carefully schedule your measurement runs to optimize your results. This requires patience, but the experimenter is rewarded with an unambiguous insight into the nature of the atom. It is also a good introduction to the electronics used in physics experiments (detectors, amplifiers, shapers, delay lines, pulse height analyzers, computer interfacing). Analyzing the data with a computer is necessary.

1. Pre-requisites: None
2. Days Allotted for the Experiment: 6

This lab will be graded 20% on theory, 30% on technique, and 50% on analysis. For more information, see the [Advanced Lab Syllabus](#).

Comments: E-mail [Dr Winthrop Williams](#)

2 Rutherford Experiment Pictures

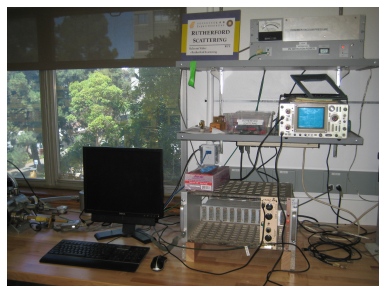


Figure 1: Rutherford Scattering Apparatus

[Click here to see larger picture](#)



Figure 2: Vacuum Valve

[Click here to see larger picture](#)



Figure 3: Rutherford Scattering Chamber

[Click here to see larger picture](#)

3 Before the 1st Day of Lab and SOP for this experiment

Complete the RUT Pre Lab found in the [Signature Sheet](#) for this lab. Print the signature sheet, discuss the experiment and pre-lab questions and answers with any faculty member or GSI, and receive their signature. In the course of the lab there will be examination points where you must STOP and get a GSI or professor to verify your understanding and/or verify proper experimental setup. You cannot skip these checkpoints, and must receive signatures demonstrating that you've consulted the staff. Some experiments may have mid lab questions that must be completed by specific days of the experiment. The completed [Signature Sheet](#) MUST be submitted as the first page of your lab report. Quick links to the checkpoint questions are found here: [1](#) [2](#) [3](#) [4](#) [5](#)

1. *Note: In order to view the private Youtube videos hosted by the university, you must be signed into your berkeley.edu Google account.*
View the [Rutherford Scattering Video](#).
2. View the [Radiation Safety Video](#). After watching the video in the 111-Lab, get a pink Radiation Safety form from a 111-Lab staff person. Fill it out & sign the form for getting a **Radiation Ring**.

3. Now complete the [Radiation Safety Training](#). After completion of training turn in all forms to Winthrop Williams.
4. View the [Introduction to Error Analysis video](#) and [Error Analysis Notes](#).
5. Read the Standard Operating Procedures ([SOP](#)) for this lab before starting.
6. Last day of the experiment please fill out the [Experiment Evaluation](#)

Suggested Reading:

1. A. C. Melissinos, “[Chapter 2: Rutherford Scattering.](#)” *Experiments in Modern Physics*. 1966
2. R. D. Evans, *[The Atomic Nucleus](#)*. McGraw Hill (1972).
3. “[Rutherford Experiment](#)”, Physics 111-Lab Reprints in Physics Library.
4. J.R. Comfort et al., “[Energy Loss and Straggling of \$\alpha\$ particles in Metal Foils](#)”; Physical Review **150**, 249 (1966).
5. “[High-Energy Particle Data Volume II](#)”; UC Radiation Lab: UCRL 2426, two pages.
6. F.S. Goulding and D. Landis, “[Linear Amplifier Gating & Timing System](#)”, Instrumentation Techniques in Nuclear Pulse Analysis, No. 1184, pp. 121-133.
7. E. Rutherford, “[The Scattering of \$\alpha\$ and \$\beta\$ Particles by Matter and the Structures of the Atom](#)” *Philosophical Magazine* 21, 699 (1911), and “[Collision of \$\alpha\$ Particles by Light Atoms](#)” *Philosophical Magazine* 37, 597 (1919). This reference appeals to students who are attracted to the historical aspects of the experiment. It contains references to other papers of historical importance.

More [References](#)

You should keep a laboratory notebook. The notebook should contain a detailed record of everything that was done and how/why it was done, as well as all of the data and analysis, also with plenty of how/why entries. This will aid you when you write your report.

4 Objectives

- Learn what real experimental physics is about.
- Learn the synergy between experimental and theoretical work.
- Learn to use pieces of equipment that are commonly used in research.
- Learn how measurements are performed, analyzed, and interpreted.
- Learn how to present your work and results.
- Learn problem solving strategies.
- Learn how to manage and organize your time.

5 Introduction

The Rutherford Scattering Experiment, in which α particles are scattered by a gold foil, is one of the most famous experiments ever performed in physics, because it demonstrated the validity of the *nuclear* model for the atom and permitted a direct measurement of the nuclear charge. When α particles in a beam strike a gold foil and collide with individual gold nuclei, they are elastically scattered (no loss of energy). The

collisions and the angles into which the the α particles are scattered are described by a model in which both the gold nuclei and the α particles act like charged spherical particles. The force of repulsion between them is described by the Coulomb's Law. The fraction of particles that are scattered into a particular solid angle at a given direction relative to the incoming beam is called the differential cross section and is given by

$$\frac{d\sigma}{d\Omega} = \left(\frac{1}{4\pi\epsilon_0} \frac{Z_1 Z_2 e^2}{4E} \right)^2 \sin^{-4} \left(\frac{\theta}{2} \right)$$

where particle 1 is the helium nucleus (α particle), particle 2 is the gold nucleus, and E is the kinetic energy of the α particle¹. Of course there are electrons around each gold nucleus, but they are so light that the energetic α particles push them aside with a relatively small loss of energy.

In the experiment you will measure the relative numbers of α particles scattered as a function of scattering angle. You will observe the $\sin^{-4} \left(\frac{\theta}{2} \right)$ dependence and from your data calculate the nuclear charge of gold.

6 Equipment used in this experiment

1. [Analog Discovery Studio](#) or ADS (Used for digital scope and pulse height analyzer measurements.)
2. [Radiation Safety Video](#)
3. Gloves
4. [PHA-5124 Program](#)
5. Tran-L-Amp Linear Amplifier
6. [PN Detector](#) (Do Not Touch this, it is very expensive)
7. PN Detector Power supply and divider box
8. [Vacuum ion gauge and pressure meter, Varian 801](#)
9. [Vacuum Chamber with Gold Foil Mount](#)
10. Radioactive source ^{241}Am (130 μCi)
11. Vacuum Pump and valve (to open and close vacuum for chamber)
12. Gold Foil and holder to be used in vacuum

¹Note that the formula in Melissinos and Napolitano, whence this discussion is taken, seems to be missing a factor of $1/4\pi\epsilon_0$ that is needed when using SI units

7 Theory

It is your responsibility to reproduce the necessary derivations for this experiment. Information on Rutherford scattering is usually first presented in Physics 7C. Detailed derivations are given in Physics 137A or Physics 105 courses and their associated texts. The recommended text for this course ([Melissinos](#) or Taylor's Mechanics) is an excellent source for rutherford scattering. The bottom line is that you will need to find a relationship between what you measure - number of counts in a given time interval as a function of scattering angle - to the charge on the nucleus. The Rutherford formula after some algebra gives

$$Z = K\sqrt{N} * \sin^2\left(\frac{\theta}{2}\right)$$

where K is a constant depending on the thickness of the foil, the strength of the source, the angular beam-width $\Delta\theta$ and the counting time, and N is the number of counts.

There are some models that are helpful in thinking about this experiment. The derivation of the formula for Rutherford scattering assumes a single, heavily charged point target and an α particle. But this experiment uses a gold foil, not a single gold nucleus. What difference does this make to your experiment? It may help to think of the possible effects by breaking down the problem into two views. First, imagine the gold foil as an array of immobile gold atoms in space. Now remove the electrons from your picture. The remaining array of fixed bare nuclei is the first order experiment of Rutherford scattering. In this view you can see what it means to have a single scattering event or multiple scattering interactions.

To think of other effects in scattering, imagine the same gold foil array but remove the nuclei from your picture. What remains is a combination of fixed localized electrons (bound electrons) and an electron cloud (conduction electrons) in space. This picture greatly complicates the interpretation of the experimental data. The α particles lose some energy in passing through this array of nuclei and the cloud of electrons. Because the electron- α particle interaction is actually quite complicated and difficult to treat, we create approximations for the interaction.

In our discussion we assumed that the α particles have definite energies that you can look up in a table. They do when emitted, but when we use them they do not, because the source is enclosed in a metallic capsule and the particles lose energy in passing through the capsule wall. Melissinos has a discussion on the loss of energy by α particles passing through matter. It is also true that they lose energy as they pass through the foil, as mentioned above. In principle, you must account for this when you analyze your data. The energy loss changes as the scattering angle changes. However, there is simply not enough time to discuss the detailed determination of energy loss. Instead, take the energy of the α particles in this experiment to be on average 3.77 MeV, and use this in your calculation of the nuclear charge of gold. You may wonder how Rutherford coped with this and other problems, since he had no sophisticated equipment. He had very much stronger radioactive sources, the sources were not shielded (the shields are a major source of energy loss), and he had people rather than a solid-state detector and electronics to count scintillation photons, the flashes of light emitted when α particles strike a fluorescent screen used as a detector.

There are other reactions taking place that we ignore: Cherenkov radiation, bremsstrahlung and inelastic nuclear interactions. If you have the time and interest, you can pursue the subject of energy losses in either of the two references given immediately below.

- J.R. Comfort, et al., “[Energy Loss and Straggling of \$\alpha\$ particles in Metal Foils](#)”, Phys. Rev. **150**, 249 (1966). Includes data for gold foils.
- J.H. Atkinson, Jr. and B.H. Wills, “[High Energy Data, Volume II](#)”, UCRL Report No. 2426 (1957). Page 35 of this report is a useful Range-Energy plot for α particles of 4 to 10 MeV Kinetic energy. Gold is not included, but lead is.

8 Experimental Overview

The overall plan of the experiment is as follows. α particles from a radioactive source called an alpha gun are made into a beam by two collimating apertures and directed toward a thin gold foil. Particles scattered by gold nuclei are counted by a detector placed at various angles to the beam direction. A histogram of particle counts vs. energy is made at each angle chosen. Even though nuclear scattering is elastic, some energy is always lost because of interactions with atomic electrons as mentioned above, and these losses are not exactly the same for every α particle. Consequently the histogram is a broad distribution rather than a delta function. The area under the curve is proportional to the number of counts. With these numbers the angular dependence of the scattering law mentioned above can be demonstrated, and the nuclear charge be calculated.

The source of α particles is the isotope 241 of Americium at $130\mu\text{Ci}$. Its half-life is 458 years. The energies of emitted α particles are 5.49 MeV (86%), 5.44 MeV (13%), and 5.39 MeV (1.3%). This also has a 59.6 KeV X-Ray which is used in the Compton experiment (neglecting other very infrequent α energies, all in the range of 5.55 to 4.8 MeV). The Americium is deposited as a thin layer on an aluminum foil located in the gun as shown below in Figure 4. This deposit randomly flakes off so always wear your gloves.

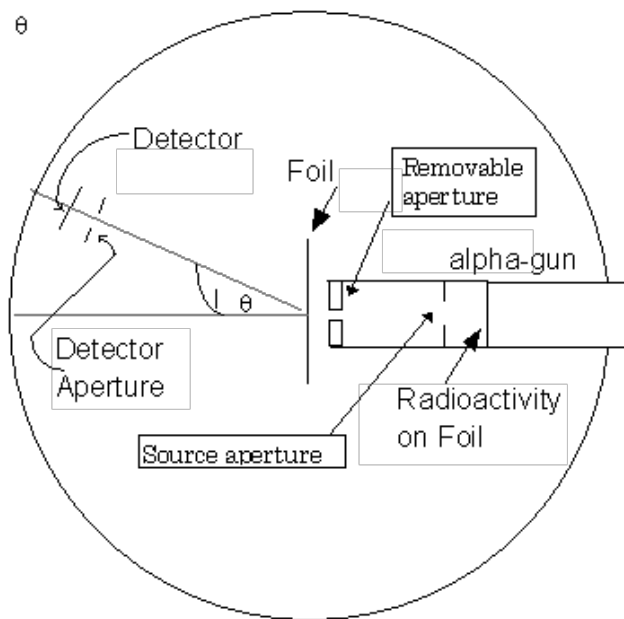


Figure 1

Figure 4: Diagram of Vacuum Chamber

The α particle gun and 2 pieces of gold foil, each is 1 inch square, are held in fixed positions when data are taken, (you need to know the weight of each foil it should be in the log book) but the detector can be moved at a constant radial distance from the foil. The particle beam is collimated by two apertures adjustable from the alpha gun. If necessary, changing the aperture separation is the easiest way to modify the collimation, since it can be changed without losing vacuum. It is also possible to remove the gun from the chamber and the removable aperture can be changed in size or removed entirely, **but do not touch the interior aperture**. This aperture size is already measured and can be found in Figure 7.

If we use a well collimated beam from the alpha-gun in order to have a well defined angular resolution, the total flux of α particles will be weak so that the counting rate at any appreciable scattering angle is extremely low. You will need a few all-night and week-end runs to collect data. Hence, plan accordingly.

The experiment is done in a **vacuum chamber and valve** because the range of α particles in air at

atmospheric pressure is only a few cm.

9 Procedure: Getting Started on Rutherford Scattering

- You must have a radiation ring and wear it when working near the apparatus, since there is an Americium-241 source which emits α particles and gamma rays. For safety, check the apparatus with a Geiger counter before you begin (counter usually kept at X-Ray or Gamma Ray experiments).
 - Procedure for making of Gold Foil and mounting on brass holder: [Making of Gold Foil](#)
1. Familiarize yourself with the apparatus. Refer to Figures 4, 5, 7. Start by removing the front cover from the chamber. Be aware of the angle cover piece, because **the detector is light sensitive. Keep it covered when using the experiment.** Put the screws somewhere where they won't be lost. Open the chamber and look at its construction. The detector is an extremely fragile device. There is a microscopically minute platinum wire between the attachment post and the evaporated gold surface of the detector. Break anything and you'll be out of commission for a week, minimum!

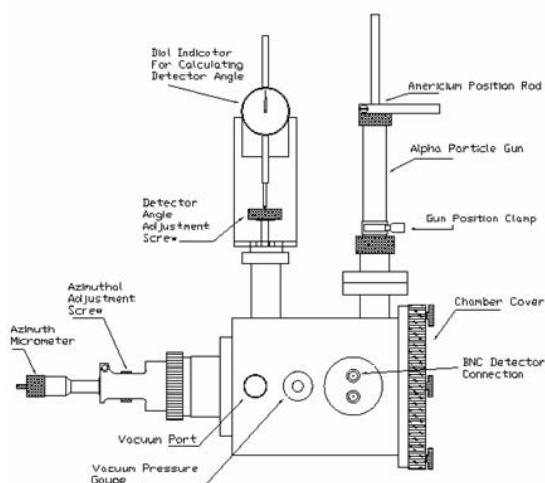


Figure 5: Diagram of Apparatus, Top View

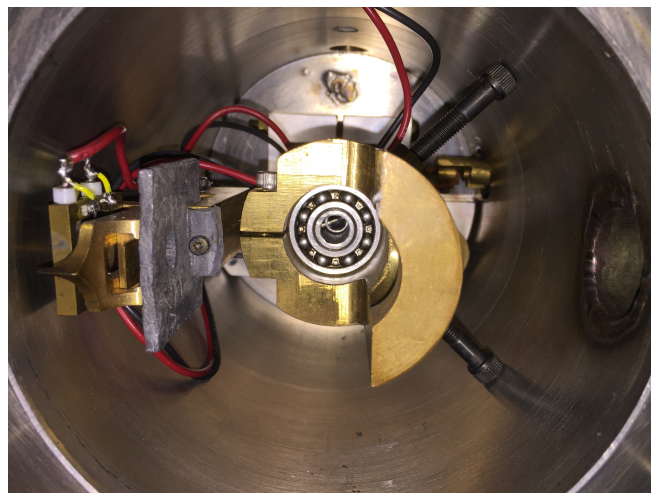


Figure 6: Chamber Interior, Front View

2. Gently change the position of the detector using the “**detector angle adjusting screw**” shown in Figure 5. Leave it at about zero degrees (protractor on front face of chamber). Be aware that this is not necessarily the exact angle of the beam to the target and you will have to calibrate the offset on this scale. **Remember Do NOT change angle more than +30 to -30 degrees. NOTE: Keep window covered when in use.** Remove the foil holder from the chamber by grasping it firmly, pulling and wiggling it from side to side.

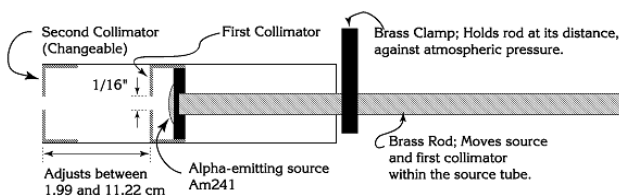


Figure 7: Alpha Gun

Figure 7 shows the source in the gun assembly with the two collimators. You should be careful to never remove the collimators as they help to keep the radioactive source contained. Never loosen the

rectangular brass clamp as it keeps the brass rod from sliding under atmospheric pressure and pushing out the collimators. To adjust the position of the alpha gun, loosen the both the hose clamp and the knurled “O-ring” clamp (nut) on the source tube. Move the tube to the center of the chamber, and then retighten the clamp (finger tight). Also move the hose clamp on the source tube so that it is flush against the O-ring clamp, and tighten the hose clamp. It is important to retighten this clamp in the proper position after moving the gun. Otherwise atmospheric pressure on the outside will push the gun into the detector arm when the chamber is evacuated. Do not change the angle with the gun in this position or it can collide with the detector holder. Collect data with no foil and the collimated beam going directly into the detector in order to find the beam flux, energy intensity profile and proper electronic settings.

3. Pump down the chamber with the following procedure. Making sure that the cover is clean replace the chamber cover and tighten the thumb screws **by hand only**. Check to see if the cover is evenly seated on the vacuum chamber. Open the venting valve between the chamber and the pump on top of the bench near the chamber. Start the pump under the bench see switch for power **Pump On/Off Switch** you then should here a hissing sound when the pump is running. The switch is located near the motor. Slowly close the valve the sound should go away. To open the chamber, reverse the process—slowly open the valve 1st and listen for the hissing sound, then turn off the pump. These precautions prevent shock waves from damaging the delicate gold foils, and minimize the amount of oil vapor from the pump entering the chamber. We are now going to use the scope to follow the signal through the electronics to set everything at proper levels. Do this carefully and ask questions if something does not seem right, but don’t expect an Instructor to do your thinking for you and tell you what to do.

Checkpoint PN Detector:[†] Explain how the PN detector sends a signal to the computer. Also, without touching the PN detector, determine the solid angle of the detector. As stated below, the diameter is roughly 0.75 inches.

10 Electronics

See diagram [here](#)

1. Turn the electronics on. There are four switches to check: the master power switch in the lower right side of the Nim Bin, the then the Tran-L-Amp should be inside the Nim Bin rack.
2. DETECTOR and PRE-AMP: The detector is a Silicon PN-junction with about 250 microns of gold on it. It has a bias of 50 volts at 4 microamps with a diameter of 0.75 inches. The detector receives its power through a voltage divider to get 50 volts from the 100 volt power supply in the rack. Take the output from the pre-amp (BNC coaxial cable) and feed it into the scope. Adjust the A TRIGGER LEVEL on the scope and see if you can obtain the positive pulse as shown in Figure 8. You may have to increase the intensity of the trace, and put a hood on the oscilloscope to shut out room light. This pulse is the amplified signal from the detector. The positive voltage pulses represent the detected α particles, and the height of the pulses is proportional to the energy of the particles. Reconnect the output of the pre-amp to the AMP IN of the linear amplifier (PG1).
3. Tran-L-Amp: This unit amplifies and shapes the unipolar pulse (unipolar means it goes up and comes down without crossing zero) from the pre-amp. The polarity knob must be set properly for the input pulses, should it be set to POSITIVE or NEGATIVE? To start with, also set the DIFF to 1.0 μ s, INT to 0.05 μ s, Coarse Gain to 100, and Vennier Gain to about 5.9 for now (you should optimize the settings of this amplifier before starting taking serious data). Use the BNC cable to look at point PG2—the output of the Linear – by connecting to channel 1 of the ADS oscilloscope. Use the WaveForms scope to view the signal. You should see a positive signal like Figure 8.

Checkpoint Signals:[†] Call a GSI or Professor over and show them all the signals you have found. Explain the signals.

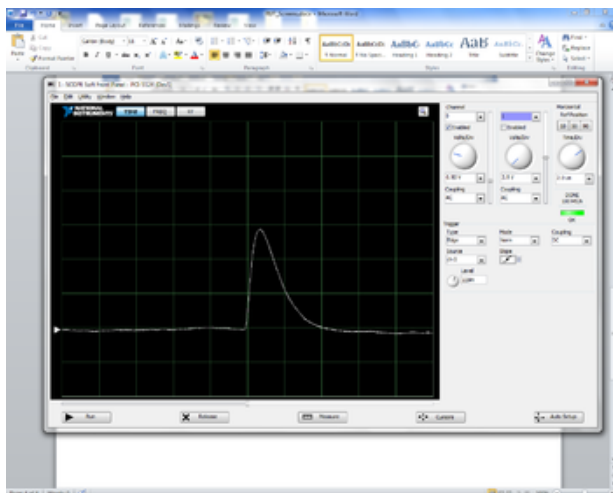


Figure 8: The pulse should look something like this (you will be using WaveForms).

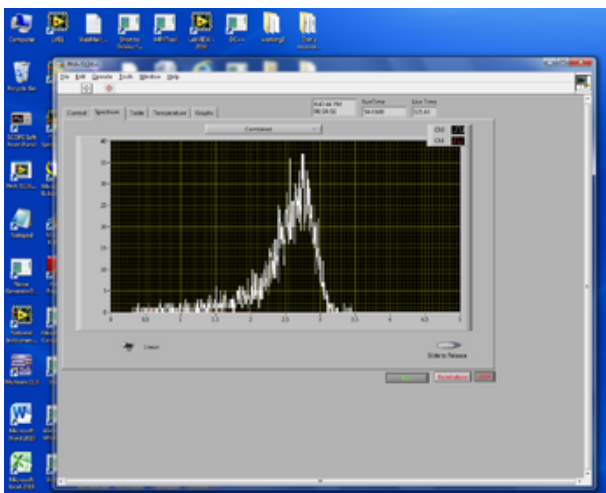


Figure 9: Example spectrum with gold foil (you will be using the Fancy Histogram software).

11 PHA Setup and Operation

There are two portions to the software - WaveForms, which you should be familiar with from 111A, and a live histogram viewer so you can watch the spectra build up from the scope.

In WaveForms (see Figure 10), open the oscilloscope and view Channel 1. You will set the trigger to the desired level - below this, pulses will be discarded as noise (you should choose this value based on the pulses you observe on the Tektronix scope). In the time drop down, select the appropriate sampling rate (you should again choose this value based on the pulses you observe on the Tektronix scope).

Next, open the 'Logging' tab, and set the 'Execute' setting to 'Each triggered acquisition'. Set the 'Maximum' to some relatively high value - say 10000. On the Desktop, there is a shortcut to the script you should paste into the WaveForms script box. Modify the file name to something which informs you about the type of data you're saving. When you are ready to begin recording data, hit 'Run' in the top left.

After you have begun the measurement, you can watch the spectra build up in real time by using the 'Live Histogram' shortcut from the desktop (see Figure 11). Select the file you are saving data to. Then set the number of bins, the min value, and the max value. The histogram and the number of data points you have acquired will update as the pulses are recorded (there may be some lag, especially as you get to many thousands of counts). Once you have recorded sufficient data, close the histogram viewer and use the .csv file of data for your own further analysis.

12 Handling Gold Foils

[How to make and mount the gold foils]

Since the scattering target is a gold foil, you need to know something about them. The foils are of very nonuniform thickness (think hole-y Swiss cheese) so you use double layers of gold leaf foil, each layer of which is about 10 milligrams by weight because of the holes and very fragile. Each pair of foils is fastened to a numbered holder by plastic tape. A weighed sample of each foil sheet is kept with the experiment. The weights should be recorded in the log book for each holder used. With them you can determine the surface density of each foil. In some cases this surface density is tabulated directly in the log book.

Handle the foils by the edges of the brass holder. Place foils carefully in the slotted repository when they are not in the chamber. The retaining fingers of the foil holder in the chamber are purposely loose so as not

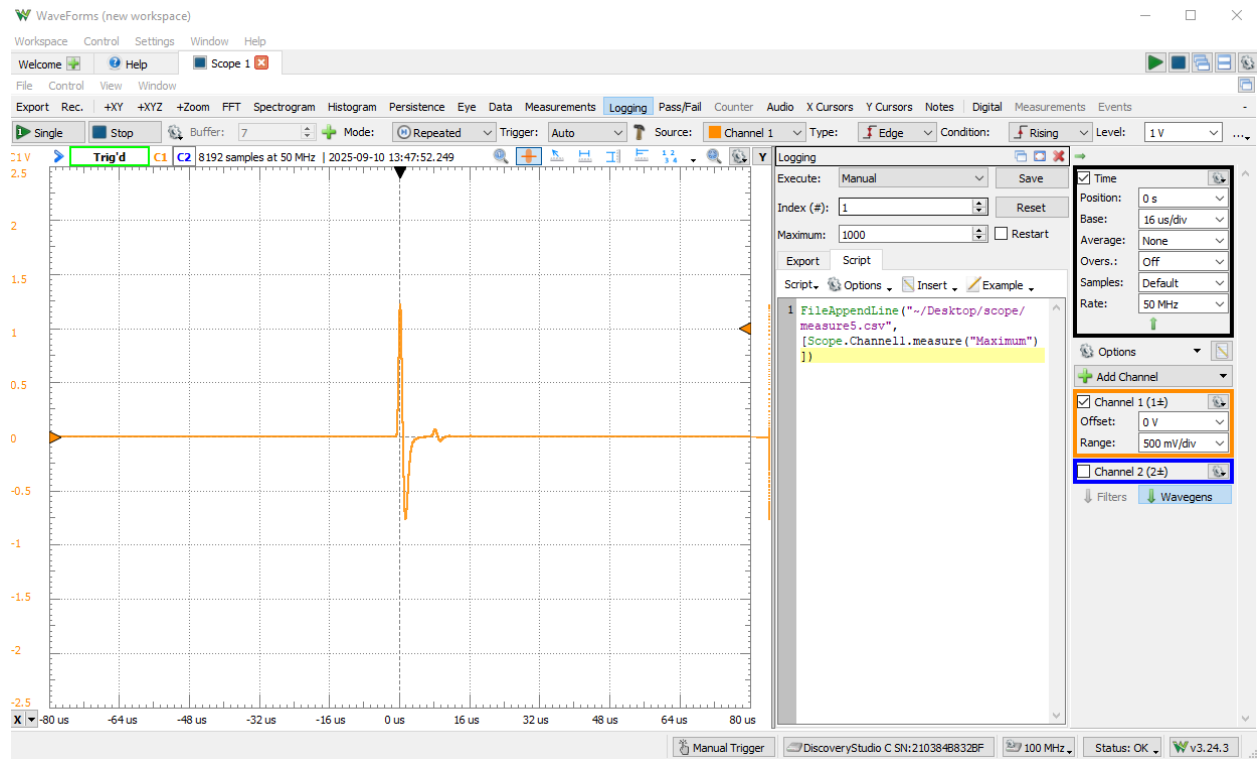


Figure 10: Image of WaveForms set up for logging. Instead of 'Manual', set the 'Execute' setting to 'Each triggered acquisition'. Adjust the filename in the script appropriately.

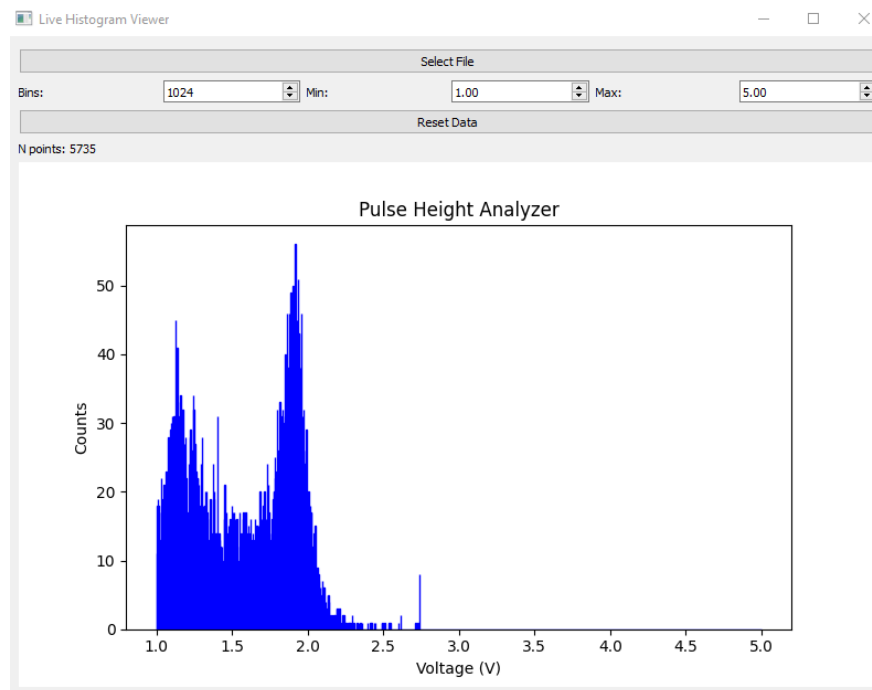


Figure 11: Live view of the pulse height spectra.

to abrade the tape. Keep them that way. You are now ready to go!

13 Data Collection (see Appendix on Error Analysis)

Error Analysis Notes

Careful planning is essential if you want to complete this experiment. You can't possibly take all the data you need for a research-type project. As you take data, you will see where you have to make compromises. Talk them over with an instructor at every stage.

First you need to decide what you are going to measure. To do this, write down the equations you are going to use, identify those quantities you can measure (such as angle of scattering), those that are given (like the charge of the electron), and those that you want to determine. Then decide how you are going to make the measurements and what parameters you are going to vary to make the measurement an optimum for accuracy and time.

For example, you need to measure scattering angles. Therefore you need to establish the zero-degree position of the detector (it is not necessarily when the protractor reads zero). How are you going to do this? Can you do it without the gold foil in place?

Checkpoint Measurements:[↑] **Talk with a GSI to determine if you're on the right track with your proposed measurements. Don't ask first – figure it out for yourself, then explain to the GSI what you are going to do and why.**

You will need to determine solid angles of the detector. You may want to change the solid angle for some measurements, by changing the aperture size.

The signals get weaker as the angles get larger. Think ahead, about how much time each data-taking run will require.

You may find it helpful to make a few trial runs, and analyze the data from them, before taking final measurements. If you are not doing the right thing, you want to find out about it immediately.

Checkpoint Trial Run Analysis:[↑] **Show a GSI your analysis of your trial runs to check if you're doing the right thing.**

Finally, analyze your data, remembering that your goal is to observe the angular dependence of the Rutherford scattering formula, and to calculate the atomic number of gold.

One way to test the angular dependence of the differential scattering cross section is to fit a straight line to the data (review the formula and come up with a physical quantity based on the scattering angle that you should use for the x variable such that you end up with a linear function) and to determine the slope of this line by a least-squares fit. Follow the example given in Lyons, *Data Analysis for Physical Science Students*, Chapter 2, especially Section 2.9, p. 63ff, in which is a worked example.

14 Questions

1. Estimate whether screening of the nucleus by electrons is relevant for your data? How would you adapt your data analysis to take this effect into account?
2. At what scattering angles in your experiment will deviations from the Rutherford scattering law occur because of non-zero size of the nucleus?
3. To what extent (be quantitative) do you expect α particles to experience multiple scattering in the foil?
4. Last day of the experiment please fill out the **Experiment Evaluation**

Checkpoint Spectrum:[↑] Show a Professor or GSI your spectrum taken over the weekend. Discuss if you think it is behaving as expected. Also discuss the questions above and how you will tackle them in your write up.

15 References

1. At the lab station there is an Americium-241 Data Sheet. Please take the time to read this and how to mount the gold foils.
2. [Rutherford Detector](#)
3. [Rutherford Chamber and Alpha Gun Assembly](#)
4. E.Segre, Nuclei and Particles 2nd.Ed., "[Scattering from a Fixed Center of Force](#)"

There are many texts which incorporate a discussion of Rutherford Scattering at the junior level, such as Kennard, et al., Modern Physics, and Taylor, Classical Mechanics, available in the Physics-Chemistry Library.

Other reprints and reference materials can be found on the [Physics 111 Library Site](#)