

### Equipment Needed from ORTEC

- 142B Preamplifier
- 4001A/4002D Bin and Power Supply
- 428 Detector Bias Supply
- 480 Pulser
- 575A Amplifier
- ULTRA™ Ion-Implanted-Silicon, Charged-Particle Detector, Model BU-021-450-100
- Easy-MCA 2k System including a USB cable, a suitable PC and MAESTRO-32 software (other ORTEC MCAs may be substituted)
- Coaxial Cables and Adapters:
  - One C-18-2 Microdot 100-Ω Miniature Cable with two Microdot male plugs, 0.61-m (2-ft) length; to connect the ULTRA detector in the Rutherford Scattering Chamber to the vacuum feedthrough.
  - One C-13 BNC to Microdot Vacuum Feedthrough with female BNC and male Microdot (may already be part of the Rutherford Scattering Chamber).
  - One C-30 Microdot to Microdot Connector with female Microdot on both ends to adapt the C-13 to the C-18-2 (may already be part of the Rutherford Scattering Chamber).
  - One C-24-1/2 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 15-cm (1/2-ft) length. Connects the vacuum feedthrough to the INPUT of the 142B Preamplifier.
  - Two C-24-12 RG-62A/U 93-Ω coaxial cables with BNC plugs on both ends, 3.7-m (12-ft) length.
  - One C-24-4 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 1.2-m (4-ft) length.
  - One C-36-12 RG-59B/U 75-Ω cable, with SHV female plugs on both ends, 3.7-m (12-ft) length.

### Equipment Required from Other Manufacturers

- Oscilloscope (bandwidth  $\geq 100$  MHz).
- Small, flat-blade screwdriver for screwdriver-adjustable controls, or an equivalent potentiometer adjustment tool.
- 1 mCi  $^{241}\text{Am}$  source with no absorbing window for the alpha emissions.
- Target Kit M-15: Metal foils of the nominal, listed thicknesses: Au (1.6 mg/cm<sup>2</sup>), Al (0.65 mg/cm<sup>2</sup>), Ni (0.87 mg/cm<sup>2</sup>), Cu (0.89 mg/cm<sup>2</sup>), and Ag (1.1 mg/cm<sup>2</sup>).
- Rutherford Scattering Chamber (May require custom fabrication. See figures 15.2 and 15.3.)
- Vacuum Fore Pump with suitable venting/pump-down valve and hose for connection to the scattering chamber.

### Purpose

In this experiment the scattering of alpha particles by a gold foil will be measured, and the results will be interpreted as experimental cross sections, which will be compared with theoretical equations. Optionally, the dependence of the scattering cross section on the atomic numbers of different metal foils can also be explored.

### Introduction

No experiment in the history of nuclear physics has had a more profound impact than the Rutherford elastic scattering experiment. It was Rutherford's early calculations based on the elastic scattering measurements of Geiger and Marsden that gave us our first correct model of the atom. Prior to Rutherford's work, it was assumed that atoms were solid spherical volumes of protons and that electrons intermingled in a more or less random fashion. This model was proposed by Thomson and seemed to be better than most other atomic models at that time.

Geiger and Marsden made some early experimental measurements of alpha-particle scattering from very thin, hammered-metal foils. They found that the number of alphas that scatter as a function of angle is peaked very strongly in the forward direction. However, these workers also found an appreciable number of scattering events occurring at angles  $>90^\circ$ . Rutherford's surprise at this observation is captured by his comment in one of his last lectures: "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back and hit you."

Rutherford tried to analyze this angular dependence in terms of the atomic model that had been proposed by Thomson. But, he observed that the Thomson model could not explain the relatively large back-angle cross section that had been found experimentally. Measurements by Geiger and Marsden revealed that 1 out of 8000 alpha particles incident on the platinum foil experienced a deflection  $>90^\circ$ . This was in conflict with calculations based on the Thomson model which predicted that only 1 alpha in  $10^{14}$  would suffer such a deflection.

With intense effort, coupled with his unusual physical insight, Rutherford developed the nuclear model of the atom. His calculations, based on Coulomb scattering from the proposed hard central core of positive charge, produced the required  $10^{10}$  increase in cross section found by Geiger and Marsden. Of course, the cross section was very difficult to determine experimentally with the equipment available to these workers (an evacuated chamber with a movable microscope focused on a scintillating zinc sulfide screen). The experimenters had to observe and count the individual scintillation flashes caused by each alpha particle impinging on the zinc sulfide screen. It was only through very careful and tedious measurements that the angular distribution was experimentally determined.

The term, "cross section," mentioned above is a measure of the probability for the scattering reaction at a given angle. From a dimensional standpoint, cross section is expressed by units of area. This seems reasonable since the relative probability of an alpha particle striking a gold nucleus is proportional to the effective area of the nucleus. The concept is similar to throwing a tennis ball at a basketball hanging from a string. The probability of hitting the basketball is proportional to the projected area of the basketball ( $\pi$  times the square of the basketball radius) as viewed from a distance by the person throwing the tennis ball. Cross sections are usually expressed in a unit called "barn," where one barn is  $1 \times 10^{-24}$  cm<sup>2</sup>. This is a very small effective

area. But, it is not unreasonable, when one considers the small size of the nucleus in comparison to the much larger size of the atom. The term, “barn,” originated during the WWII Manhattan project. Experimenters discovered cross sections for slow neutron interactions with atomic nuclei that seemed so large they were colloquially described to be “as big as a barn.”

For a Rutherford scattering experiment it is most convenient to express the results in terms of cross section per solid angle. The solid angle referred to is the solid angle that the detector makes with respect to the target, and is measured in steradians, (sr). The solid angle,  $\Delta\omega$ , in steradians is simply  $A/R^2$ , where  $A$  is the sensitive area of the detector and  $R$  is the distance of separation between the detector and the target. The measurement of cross section is expressed in barns/steradian or more conveniently millibarns/steradian, i.e., mb/sr. The cross section defined here is referred to as the differential cross section, and it represents the probability per unit solid angle that an alpha will be scattered at a given angle  $\theta$ . The theoretical expression for the Rutherford elastic scattering cross section can be simplified to the following formula:

$$\frac{d\sigma}{d\Omega} = 1.296 \left( \frac{Z_1 Z_2}{E} \right)^2 \left[ \csc^4 \left( \frac{\theta}{2} \right) - 2 \left( \frac{M}{A} \right)^2 \right] \text{ mb/sr} \quad (1)$$

Where  $Z_1$  and  $Z_2$  are the atomic numbers of the projectile and target, respectively,  $E$  is the energy of the projectile in MeV,  $M$  is the mass number of the projectile, and  $A$  is the mass number of the target nucleus. For our experiment,  $^{197}\text{Au}$  ( $^4\text{He}$ ,  $^4\text{He}$ )  $^{197}\text{Au}$ ,  $Z_1 = 2$ ,  $Z_2 = 79$ ,  $E = 5.48$  MeV,  $M = 4$ , and  $A = 197$ . In alpha scattering from gold, it is quite difficult to measure the cross section for scattering angles  $>90^\circ$ . The reason for this difficulty is that it takes a prohibitively long period of time to make a measurement at the back angles. To limit the duration of this experiment, only the forward angles will be investigated.

Even for the lightest foil (Al) used in experiment 15.2, the term  $2(M/A)^2$  is always quite small compared to  $\csc^4(\theta/2)$  and hence can be ignored without much error. To a good approximation, the differential cross section is then given by

$$\frac{d\sigma}{d\Omega} = 1.296 \left( \frac{Z_1 Z_2}{E} \right)^2 \csc^4 \left( \frac{\theta}{2} \right) \text{ mb/sr} \quad (2)$$

Note that the expression in Eq. (2) varies 4 orders of magnitude from  $\theta = 8^\circ$  in the forward direction to  $\theta = 90^\circ$ .

The purpose of this experiment is to show that the experimental cross section can be favorably compared with the theoretical expression in Eq. (2).

### POST-EXPERIMENT EXERCISE

The differential cross section in equation (2) tends toward infinity as the scattering angle,  $\theta$ , approaches zero. Although this may initially seem counter-intuitive, there is a rational physical explanation for that asymptotic behavior. Explain the physical meaning of the infinite differential cross section at  $\theta = 0^\circ$ .

### EXPERIMENT 15.1

#### Angular Dependence of the Rutherford Cross Section

**SAFETY ADVISORY:** The  $^{241}\text{Am}$  radioactive source used in this experiment has no protective window over the source. Such a windowless configuration is necessary to emit alpha particles with their full energy. Do not touch the active surface of this radioisotope source. Follow all the safety precautions as outlined in the page on “Safe Handling of Radioactive Sources” at the front of AN34 Experiments in Nuclear Science.

#### Procedure

- Set up the electronics as shown in Fig 15.1 and the mechanical arrangement in Fig. 15.2 and Fig. 15.3.
  - For the cable connections between the ULTRA™ charged-particle detector and the 142B preamplifier, see the description in the list of equipment.

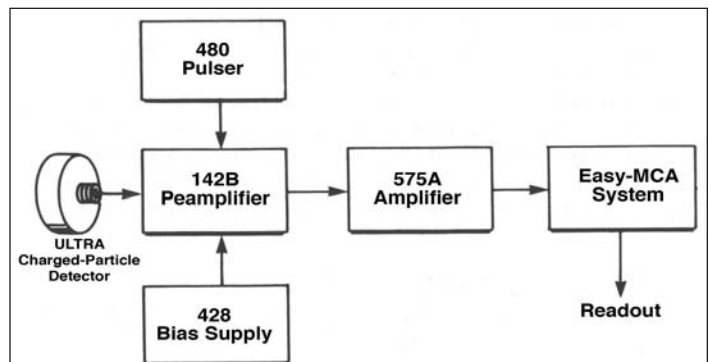


Fig. 15.1. Electronics for the Rutherford Scattering Experiment.

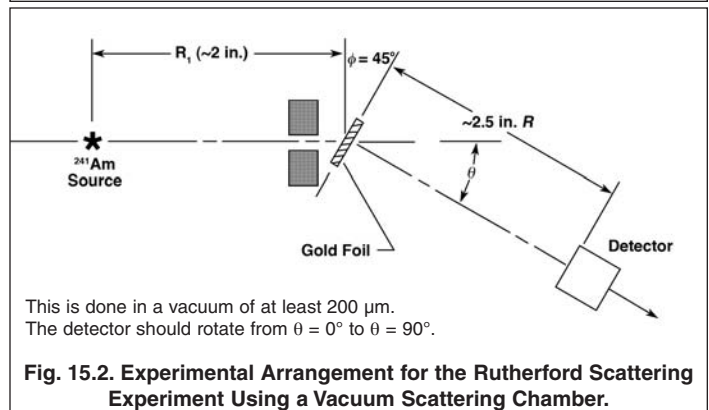


Fig. 15.2. Experimental Arrangement for the Rutherford Scattering Experiment Using a Vacuum Scattering Chamber.

**Fig. 15.3. An Example of a Rutherford Scattering Vacuum Chamber.\***



\*The Rutherford Scattering Chamber incorporates a mount for the  $^{241}\text{Am}$  source with source collimator, a centered holder for a thin gold foil, and a silicon, solid-state detector mounted on an arm suspended from the lid. The arm permits detector rotation through the desired scattering angles. The silicon detector mounted in a fixed position is optional, and can be used for coincidence experiments. The collimator aperture limits the solid angle for alpha-particle emission so that the surviving alpha particles (with the foil removed) fall within the sensitive area of the detector when it is located at a  $0^\circ$  scattering angle. The central foil holder permits rotation of the foil with respect to the incident direction of the alpha particles. The chamber requires a fore pump capable of achieving a vacuum below  $200\ \mu\text{m}$ . A vent/pump valve is recommended to make pumping and release of the vacuum convenient without turning off the fore pump. A baffle may be needed in the chamber to prevent rupturing the thin metal foils during rapid pump-down and venting.

- b. Turn off the power to the Bin and Power Supply. Verify that the 480 Pulser, 428 Bias Supply and the 575A amplifier are all adjacent to each other in the Bin.
  - c. Check that the shaping time constant switches accessible through the side panel of the 575A are all set to  $1.5\ \mu\text{s}$ .
  - d. Connect the power cable from the 142B Preamplifier to the Preamplifier Power connector on the rear panel of the 575A Amplifier. Set the input polarity switch on the 575A Amplifier to POSITIVE.
  - e. Connect the E OUTPUT (Energy output) of the 142B Preamplifier to the INPUT of the 575A Amplifier using a C-24-12 RG-62A/U 93- $\Omega$  coaxial cable.
  - f. On the 428 Bias Supply, set the POS/OFF/NEG switch to OFF, and turn both ten-turn dials completely counterclockwise (zero Volts). Connect the B OUTPUT of the 428 to the BIAS input of the 142B Preamplifier using the C-36-12 RG-59B/U 75- $\Omega$  cable with SHV plugs.
  - g. On the 480 Pulser, set the OUTPUT polarity to NEGATIVE. Select OFF with the ON/OFF switch. Set all ATTENUATOR toggle switches to their maximum value. Using a C-24-12 RG-62A/U 93- $\Omega$  coaxial cable, connect the ATTENUATED OUTPUT of the 480 to the TEST input of the 142B Preamplifier.
  - h. Connect the UNIPOLAR OUTPUT of the 575A Amplifier to the analog INPUT of the Easy-MCA using a C-24-4 RG-62A/U 93- $\Omega$  coaxial cable.
  - i. Turn on the Bin power.
  - j. Turn on power to the computer supporting the Easy-MCA and activate the MAESTRO-32 MCA Emulator software.
  - k. Via the Acquire menu and the ADC tab in the MAESTRO software that operates the Easy-MCA, select the Gate Off option, and adjust the Upper Level discriminator to its maximum value. Adjust the Lower Level discriminator as low as possible without causing excessive counting rate on the noise. Under the Preset tab, clear all data fields, and do the same for the MDA Preset option (if supported). Clearing those fields will default to manual control for starting and stopping spectrum acquisition. Select the analog-to-digital conversion range to be either 2048 or 4096 channels for a 0 to +10-V input. Familiarize yourself with the software controls for setting up, acquiring and erasing spectra.
  - l. On the 428 Bias Supply, turn the POS/OFF/NEG switch to POS and adjust the B dial to the voltage specified by the manufacturer for the ULTRA™ detector.
2. To prepare for calibrating the system, remove the gold foil, and move the detector to  $\theta = 0^\circ$ . Pump a vacuum in the chamber to below  $200\ \mu\text{m}$ . Adjust the gain of the 575A Amplifier so that the peak from the 5.48-MeV alphas from  $^{241}\text{Am}$  accumulates in the top eighth of the analyzer.
 

**NOTE:** All further measurements involving detection of the alpha particles requires a vacuum better than  $200\ \mu\text{m}$ .
  3. Disconnect the 575A UNIPOLAR OUTPUT from the Easy-MCA, and connect it instead to the 1-M $\Omega$  input of the oscilloscope. Set the horizontal scale of the oscilloscope to 1 ms/cm and the vertical scale to 100 mV/cm. With a small, flat-blade screwdriver, adjust the PZ ADJ on the 575A Amplifier to make the pulses on the UNIPOLAR OUTPUT return to baseline as quickly as possible without undershooting the baseline between pulses. For further guidance on the Pole-Zero Cancellation adjustment, consult the instruction manual for the amplifier, or the introduction to the amplifier product family on the ORTEC web site at [www.ortec-online.com](http://www.ortec-online.com).
  4. Reconnect the 575A UNIPOLAR OUTPUT to the Easy-MCA INPUT.
  5. Calibrate the MCA with the  $^{241}\text{Am}$  alphas and the 480 Pulser in the same manner as outlined for Experiments 4 and 5. Plot the analyzer calibration on linear graph paper, or construct a spreadsheet graph on your own PC. Make sure you turn the pulser off after this calibration.
  6. Vent the vacuum. Insert the gold foil in the target position at an angle of  $45^\circ$  to the collimated alpha beam. Keep the detector at  $\theta = 0^\circ$ . Restore the vacuum. Acquire the spectrum on the Easy-MCA. From the peak position, measure the energy,  $E_f$ , for the alpha particles that pass through the gold foil. Calculate the energy loss,  $\Delta E$ , of the alphas in going through the foil (see Experiment 5); i.e.,
 
$$\Delta E = E_0 - E_f \quad (3)$$
 where  $E_0$  is 5.48 MeV for the source and  $E_f$  is the measured energy after the alphas pass through the gold foil.

#### EXERCISES

a. From  $\Delta E$  and Table 5.1 in Experiment 5, calculate the effective thickness of the gold foil in  $\text{mg}/\text{cm}^2$ . Keep in mind that the orientation of the foil at  $45^\circ$  increases the alpha-particle path length through the foil by a factor of  $\csc(45^\circ)$ . Consequently, the measured thickness will be larger than the specified mechanical thickness of the foil. Additional data on measured range-energy relationships for alpha particles in various materials is available on the Internet at the link in reference 10.

b. The average energy of alphas experiencing scattering in the foil is

$$E_{av} = \frac{E_0 + E_f}{2} \quad (4)$$

Determine  $E_{av}$  for the measurements made in step 6. Use  $E_{av}$  as the value for  $E$  in Eq (2), and calculate the values of  $d\sigma/d\Omega$  (Theory) from Eq (2) for the angles specified in Table 15.1. Fill in the entire "Theory" column in the table.

c. Plot  $d\sigma/d\Omega$  (Theory) versus  $\theta$  on 5-cycle semilog paper, or create an equivalent spreadsheet graph on your PC. Because of the extreme range of values, the differential cross section requires a logarithmic scale, while the angle should be plotted against a linear scale.

**Table 15.1. Comparison of the Theoretical and the Measured Differential Cross Sections.**

$\theta$ (degrees)	$d\sigma/d\Omega$ (Theory)	$d\sigma/d\Omega$ (Experimental)
10		
15		
20		
25		
30		
40		
50		
60		
70		
80		
90		

d. Calculate  $n_0$ , the number of gold target nuclei per  $\text{cm}^2$  from the following formula:

$$n_0 = \frac{(g/\text{cm}^2 \text{ of the foil}) \times 6.023 \times 10^{23}}{A} \quad (5)$$

The value of  $n_0$  will be used at a later time.

e. Calculate  $\Delta\Omega$  from the formula

$$\Delta\Omega = [\text{the sensitive area of the detector in cm}^2] / R^2 \quad (6)$$

Where  $R$  is the distance (in cm) from the detector to the gold foil. The sensitive area for the Model BU-021-450-100 ULTRA™ detector is nominally  $450 \text{ mm}^2$ .

**WARNING:** When measuring the diameter of the detector, do not touch the sensitive surface of the detector. Fingers often carry small dirt particles that can easily scratch the thin, ion-implanted window, rendering the detector permanently inoperative. Leaving a finger print on the window can increase the window thickness, thus increasing the energy loss experienced by the impinging alpha particles.

7. Remove the gold foil and check the alignment of the apparatus by measuring the counting rates for the values in Table 15.2. The counting rate is measured as follows:

a. Acquire a spectrum on the Easy-MCA and set a Region of Interest (ROI) across the entire alpha-particle peak at 5.48 MeV. Read the integrated counts,  $N$ , for the peak from the ROI. Read the elapsed Live Time,  $T_L$ , displayed by the Easy MCA software. The counting rate is calculated as

$$I = \frac{N}{T_L} \quad (7)$$

b. The alpha particles emitted by the radioactive source are distributed randomly in time. Consequently, the number of alpha particles,  $N$ , counted in the live time,  $T_L$ , is subject to a statistical variation. The expected uncertainty in  $N$  is characterized by the standard deviation

$$\sigma_N = \sqrt{N} \quad (8)$$

Consequently the expected standard deviation in the counting rate,  $I$ , is

$$\sigma_I = \frac{\sigma_N}{T_L} = \frac{\sqrt{N}}{T_L} \quad (9)$$

The expected percent standard deviation in  $N$  is equal to the expected percent standard deviation in  $I$ , viz.,

$$\sigma\%_N = \frac{\sigma_N \times 100\%}{N} = \frac{100\%}{\sqrt{N}} = \frac{\sigma_I \times 100\%}{I} = \sigma\%_I \quad (10)$$

c. For the data in Table 15.2, count for a long enough time to achieve a 1% standard deviation in  $I$ . This will require at least 10,000 counts in the ROI set across the peak.

8. Plot the data in Table 15.2. If the instrument is properly aligned, the data in the table should be symmetric about  $0^\circ$ , with the maximum counts at  $0^\circ$ . If not centered on  $0^\circ$ , a correction for the offset should be applied to the angles in the remainder of the experiment.

9. The number of alphas per unit time,  $I_0$ , that impinge on the foil can be calculated by one of the three following methods, depending on the specific geometry of the apparatus.

a. If the source collimator limits the divergence of the alpha particles so that no particles are missing the sensitive area



**Table 15.2. Testing Apparatus Alignment at  $\theta = 0^\circ$**

Angle $\theta$ (degrees)	Counts/s	Angle $\theta$ (degrees)	Counts/s
0		0	
1		-1	
2		-2	
3		-3	
4		-4	
5		-5	
6		-6	
7		-7	

of the detector when the foil is absent, **and** no particles are missing the foil when it is present, then  $I_0$  is the counting rate measured when the detector is centered on the calibrated  $0^\circ$ , as determined from Table 15.2.

- b. If the source collimator does not satisfy **both** conditions in method "a", **but** the exposed area of the foil defines the alpha particles that are able to scatter from the foil, then  $I_0$  can be calculated from

$$I_0 = (\text{activity of the source}) (\text{area of the foil}) / 4\pi(R_1)^2 \quad (11)$$

Where the area of the foil is the area projected perpendicular to the beam of alpha particles from the source (see Fig. 15.2). The activity of the source can be determined by the methods outlined in Experiment 4.

- c. If none of the conditions in "a" and "b" are met, but the source collimator restricts the alpha particles to illuminating only a portion of the foil area,  $I_0$  must be calculated from equation (11) by replacing the area of the foil with the area of the restricting aperture of the collimator, while substituting the distance from the source to the restricting aperture for  $R_1$ .

Check with your laboratory manager to determine which of methods a, b, or c is appropriate for your scattering chamber.

10. You are now ready to measure the cross section. Replace the gold foil (at the angle  $\phi = 45^\circ$ ). Set the detector at  $10^\circ$ , and count for a period of time long enough to get good statistics in the peak. Calculate the counting rate,  $I$ , at  $10^\circ$ . Repeat for all of the angles listed in Table 15.1. Keep a record of both the number of counts in the peak,  $N$ , and the related live time  $T_L$ , in case you need to calculate the statistical uncertainty. It should be obvious from the theoretical cross section that the counting time will have to be increased as  $\theta$  increases. For the smaller angles, you may be able to get close to a 1% standard deviation. For the larger angles, it will be difficult to find enough time to achieve better than a 15% standard deviation. Plan your counting strategy to match the available time.

### EXERCISE

11. Calculate the experimental cross section for each of the points in step 10 by using the following formula:

$$\frac{d\sigma}{d\Omega} = \left[ \frac{I}{I_0 n_0 \Delta\Omega} \right] \quad \text{cm}^2/\text{sr} \quad (12)$$

Since 1 barn =  $10^{-24}$   $\text{cm}^2$ , the values calculated from Eq. (12) can be converted to millibarns per steradian and entered as  $d\sigma/d\Omega$  (experimental) in Table 15.1.

Plot the experimental cross section on the same graph as the theoretical cross section. Discuss the degree of agreement/disagreement between the theoretical and experimental cross sections in light of the uncertainties from counting statistics (equations 8, 9 and 10) and any other potential sources of measurement error. What quantitative effect does the angle,  $\phi = 45^\circ$ , have on the results?

## EXPERIMENT 15.2

### The $Z_2^2$ Dependence of the Rutherford Cross Section

In this experiment alpha particles will be scattered from different foils to show the  $Z_2^2$  dependence in Eq. (2). The foils used (see Target Kit M-15) are aluminum ( $Z_2 = 13$ ), nickel ( $Z_2 = 28$ ), copper ( $Z_2 = 29$ ), silver ( $Z_2 = 47$ ), and gold ( $Z_2 = 79$ ). The student will then plot this  $Z_2$  dependence and show that it does agree with the theory.

#### Procedure

1. Ensure that steps 1 through 5 in Experiment 15.1 have been completed. Repeat step 6 of Experiment 15.1 for each of the foils. For each foil calculate  $n_0$  as in Experiment 15.1, Exercise d, Eq. (5).
2. For each foil set  $\theta = 45^\circ$ , and accumulate a pulse height spectrum for a period of time long enough to get at least 1000 counts in the scattered peak. Determine  $I$  (the number of scattered alphas per second) for each sample, per the methods used in Experiment 15.1.

### EXERCISE

Plot  $I$  as a function of  $n_0 Z_2^2$  for each sample. The curve should be a straight line. The slope of the line can be determined by equating the two expressions for cross section Eqs. (2) and (12) and solving for the product  $n_0 Z_2^2$ .

Therefore

$$1.296 \left( \frac{Z_1 Z_2^2}{E} \right) \csc^4 \left( \frac{\theta}{2} \right) \times 10^{-27} = \frac{I}{I_0 n_0 \Delta\Omega} \quad \text{cm}^2/\text{sr} \quad (13)$$

And hence

$$I = \left[ \frac{1.296 \times 10^{-27} I_0 \Delta\Omega Z_1^2 \csc^4\left(\frac{\theta}{2}\right)}{E^2} \right] n_0 Z_2^2 \quad (14)$$

Since every term inside the [ ] brackets is a constant for all foils†:

$$I = K n_0 Z_2^2 \quad (15)$$

Where the constant, K, is equal to the contents of the [ ] bracket in Eq. (14). Therefore, our experimental intensity should plot as a straight line in this exercise. The slope of the curve is K.

Explain any deviations of the data from a straight line by reference to the uncertainty from counting statistics or any other sources of error in the experiment.

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#### References

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8. G. Marion and P. C. Young, *Tables of Nuclear Reaction Graphs*, John Wiley and Sons, New York (1968).
9. Application notes, technical papers, and introductions to each product family at [www.ortec-online.com](http://www.ortec-online.com).
10. Measured data on dE/dx and range-energy relationships for alpha particles in various materials is available from the US National Institute of Standards and Technology(NIST) Physics Laboratory at:  
<http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html>

†This presumes that all the foils have been chosen with appropriate thickness so that  $E = E_{av}$  from Eq. (4) is approximately the same for all foils.

Specifications subject to change  
031609