# Rutherford Scattering of Alphas from Thin Gold Foil

**EQUIPMENT NEEDED FROM EG&G ORTEC**

| | |
|---|---|
| 142B Preamplifier | Oscilloscope |
| Bin and Power Supply | 1 mCi $^{241}$Am source |
| 428 Detector Bias Supply | Source Kit SK-1A |
| 480 Pulser | Target Kit M15 |
| 575A Amplifier | 307 Rutherford Scattering Chamber |
| Surface Barrier Detector R-024-450-100 | ORC-15 Cable Set |

ACE-2K MCA System including suitable IBM PC (other EG&G ORTEC MCAs may be used)

## Purpose

In this experiment the effect of gold foil for scattering alpha particles will be measured, and the results will be interpreted as experimental cross sections which will be compared with theoretical related expressions.

## 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°. Rutherford's surprise at this is this statement from 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 platinum foil experienced a deflection >90°. 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 proposed the nuclear model of the atom. His calculations, based on Coulomb scattering from the proposed hard central core of 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). 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 striking a gold nucleus is proportional to the effective area of the nucleus. Cross sections are usually expressed in units called "barns," where one barn is 1 x $10^{-24}$ cm$^2$. This is a very small effective area but is not unreasonable when one considers the size of the nucleus in comparison to the size of the atom.

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 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. 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:

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

where $Z_1$ and $Z_2$ are the atomic numbers of the projectile and target, 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, $^{197}Au(^{4}He,^{4}He)^{197}Au$, $Z_1 = 2$, $Z_2 = 79$, $E_\alpha = 5.8$ MeV, M = 4, and A = 197. In alpha scattering from gold it is quite difficult to measure the cross section for scattering angles >90°. The reason for this difficulty is that it takes a prohibitively long period of time to make a measurement at the back angles. Therefore 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

$$\frac{d\sigma}{d\Omega} = 1.296\left(\frac{\text{mb}}{\text{sr}}\right)\left(\frac{Z_1 Z_2}{E_\alpha}\right)^2 \csc^4\left(\frac{\theta}{2}\right). \qquad (2)$$

The expression in Eq. (2) varies 4 orders of magnitude from $\theta = 0°$ in the forward direction to $\theta = 90°$. The purpose of this experiment is to show that the experimental cross section can be favorably compared with the theoretical expression in Eq. (2).

**EXPERIMENT 15.1**

# The Rutherford Cross Section

## Procedure

**1.** Set up the electronics as shown in Fig. 15.1 and the mechanical arrangement in Fig. 15.2.

**2.** Set $\theta = 0°$ and remove the gold foil to calibrate the system. Adjust the gain of the 575A Amplifier so that the 5.8-MeV alphas from $^{241}Am$ are stored in the top quarter of the analyzer.

**3.** Calibrate the MCA with the $^{241}Am$ alphas and the 480 Pulser in the same manner as outlined for Experiments 4 and 5. Plot the analyzer calibration on linear graph paper.

**4.** Insert the gold foil at the target position at an angle of 45° to the collimated alpha beam. Measure the energy, $E_f$, that passes through the gold foil. Calculate the energy loss, ($\Delta E$), of the alphas in going through the foil (Experiment 5):

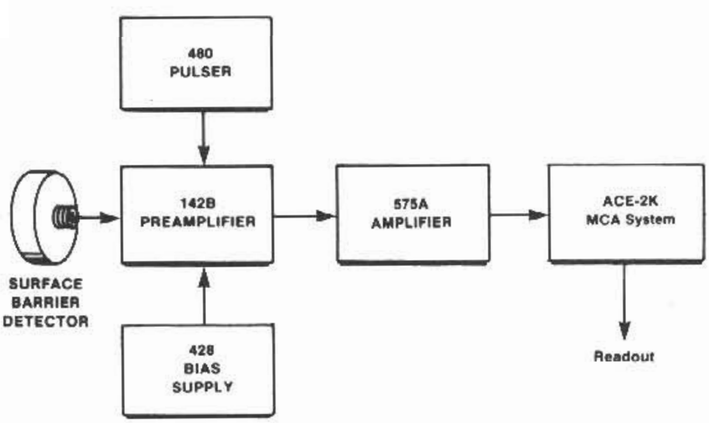
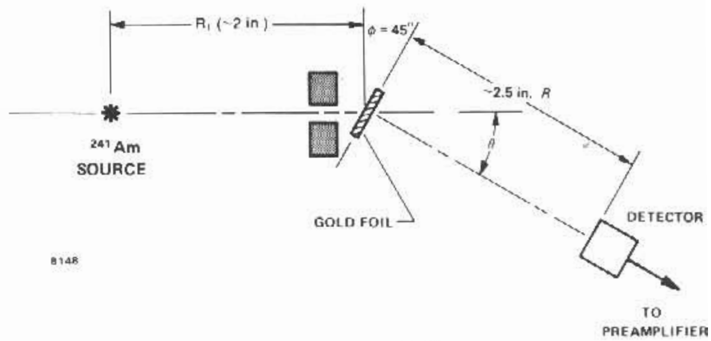



**Fig. 15.1. Electronics for Rutherford Scattering Experiment.**




This is done in a vacuum of at least 200 μm.
The detector should rotate from $\theta = 0°$ to $\theta = 90°$.

**Fig. 15.2. Experimental Arrangement for Rutherford Scattering Experiment Using an EG&G ORTEC 307 Chamber.**

$\Delta E = E_0 - E_f$, where $E_0$ is 5.8 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, calculate the thickness of the gold foil in mg/cm$^2$.

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

$$E_{av} = \frac{E_0 + E_f}{2}, \qquad (3)$$

Determine $E_{av}$ for the measurements made in step **4**. Use $E_{av}$ as $E_\alpha$ in Eq. (3) and solve the equation for the values of $d\sigma/d\Omega$ (Theory) in Table 15.1 and fill in this column in the table.

**c.** Plot $d\sigma/d\Omega$ (Theory) versus $\theta$ on 5-cycle semilog paper.

**Table 15.1**

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

Calculate $n_0$, the number of gold target nuclei per $cm^2$ from the following formula:

$$n_0 = \frac{(g/cm^2 \text{ of the target}) \; 6.023 \times 10^{23}}{197} \tag{4}$$

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

**d.** Calculate $\Delta\Omega$ from the formula

$$\Delta\Omega = \frac{\text{area of detector } (cm^2)}{R^2} \tag{5}$$

where R is the distance (in cm) from the detector to the gold foil.

**5.** Remove the gold foil and check the alignment of the apparatus by measuring the counting rates for the values in Table 15.2.

**6.** Plot the data in Table 15.2. If the instrument is properly aligned, the peak should be centered about zero degrees.

**Table 15.2**

| Angle (deg) | Counts/m | Angle (deg) | Counts/m |
|---|---|---|---|
| 0 | | 0 | |
| 1 | | −1 | |
| 2 | | −2 | |
| 3 | | −3 | |
| 4 | | −4 | |
| 5 | | −5 | |
| 6 | | −6 | |
| 7 | | −7 | |

**7.** The number of alphas per unit time, ($I_0$), that impinge on the foil can be calculated from the following expression:

$$I_0 = \frac{(\text{activity of the source}) \; (\text{area of the foil}^*)}{4\pi R_1^2} \tag{6}$$

(See Fig. 15.2) The activity of the source can be determined by the methods outlined in Experiment 4.

**8.** You are now ready to measure the cross section. Replace the gold foil. Set the detector at 10° and count for a period of time long enough to get good statistics in the peak. Calculate the counting rate, (I), at 10°. Repeat for all of the values listed in Table 15.1. It should be obvious from the theoretical cross section that the counting time will have to be increased as $\theta$ increases. You should try to get at least 15% statistics for all points.

*Area of the foil projected perpendicular to the source which is not shadowed by the collimator.

## EXERCISE

**e.** Calculate the experimental cross section for each of the points in step **8** by using the following formula:

$$\frac{d\sigma}{d\Omega} = \left(\frac{I}{I_0 \Delta\Omega n_0}\right) \left(\frac{cm^2}{sr}\right). \tag{7}$$

Since 1 barn = $10^{-24}$ $cm^2$, the values calculated from Eq. (7) can be converted to millibarns per steradian and entered as $d\sigma/d\Omega$ (Experimental) in Table 15.1.

**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 (which are included in the foil kit for this experiment) 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.** Repeat procedures **1** through **4** in Experiment 15.1 for each of the foils. For each foil calculate $n_0$ as in Experiment 15.1, Exercise **c**.

**2.** For each foil set $\theta = 45°$ 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.

## 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 (7) and solving for the product $n_0 Z_2^2$.

Therefore

$$1.296 \left(\frac{Z_1 Z_2}{E_\alpha}\right)^2 \csc^4\left(\frac{\theta}{2}\right) \times 10^{-27} \frac{cm^2}{sr} = \frac{I}{I_0 \Delta\Omega n_0} \; cm^2/sr, \tag{8}$$

and hence

$$I = \left[\frac{1.296 \, Z_1^2 \csc^4\left(\frac{\theta}{2}\right) I_0 \Delta\Omega \times 10^{-27}}{E_\alpha^2}\right] n_0 Z_2^2. \tag{9}$$

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

$$I = K n_0 Z_2^2.$$

Therefore our experimental intensity should plot as a straight line in this exercise. The slope of the curve K is the value that is calculated from Eq. (9).