

Rutherford Scattering

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This is an experiment which studies scattering alpha particles on atomic nuclei. You will shoot alpha particles, emitted by ^{241}Am , at thin metal foils and measure the scattering cross section of the target atoms as a function of the scattering angle, the alpha particle energy, and the nuclear charge. You will then measure the intensity of alpha particles scattered by thin metal foils as a function of the scattering angle for several elements of very different atomic number.

PREPARATORY QUESTIONS

Please visit the Rutherford Scattering chapter on the 8.13x website at mitx.mit.edu to review the background material for this experiment. Answer all questions found in the chapter. Work out the solutions in your laboratory notebook; submit your answers on the web site.

SUGGESTED PROGRESS CHECK FOR END OF 2nd SESSION

Plot the rate of alpha particle observations for 10° and 30° vs. $1/\sin^4(\theta/2)$. Comment on the agreement.

I. INTRODUCTION

Little was known about the structure of atoms when Geiger and Marsden began their experiments scattering alpha particles on thin metal foils in 1909 at the Cavendish Laboratory. A decade earlier at the Cavendish, J. J. Thomson had discovered the electron and determined the ratio of its charge to its mass by measuring the deflections of electron beams (cathode rays) by electric and magnetic fields. In 1909, Millikan measured the charge of the electron in the oil drop experiment. Thus by 1909 both the charge and mass of the electron were known with considerable accuracy. Furthermore, Thomson's interpretation of X-ray scattering from carbon and other light elements had established that the number of electrons per atom of a given element was equal not to its atomic weight, but to its atomic number, determined by its position in the periodic table. Since the mass of an electron is much less than the mass of the lightest atom, hydrogen, it was clear that most of the mass in any atom is associated with the positive charge. The central problem was to figure out how the positive and negative parts of an atom are held together, in such a way as to produce optical emission spectra with the regularities expressed by the Balmer formula (discovered by Johann Balmer in 1885) for hydrogen and the combination rules and series limits for the complex spectra of multielectron atoms.

Thinking within the limitations of Newtonian mechanics and Maxwell's electromagnetic theory, Thomson imagined the atom as a sphere of positive charge

within which the electrons occupy certain positions of equilibrium, like raisins in a pudding. Set in motion, the electrons should vibrate harmonically, radiating electromagnetic energy with characteristic sharp frequencies that would be in the optical range if the radii of the atomic spheres were of the order of 10^{-8} cm. However, the "raisin pudding" model yielded no explanation of the numerical regularities of optical spectra, *e.g.* the Balmer formula for the hydrogen spectrum and the Ritz combination principle [3] for spectra in general.

At this point, Ernest Rutherford got the idea that the structure of atoms could be probed by observing the scattering of alpha particles. Alpha particles, as Rutherford himself had recently demonstrated, are the positively charged emanations of radioactive substances. They are also bare helium nuclei. According to the raisin pudding model, an alpha particle traversing a thin gold film should experience many small angle deflections as it passes close to or through the positive spheres of the gold atoms. Rutherford showed [4] that the fraction of particles scattered in this way through an angle θ or greater should decrease exponentially according to the equation

$$F_\theta \approx \exp(-\theta^2/\theta_m^2), \quad (1)$$

where θ_m is the mean multiple scattering angle. For a typical foil of gold leaf, $\theta_m \approx 1^\circ$. Thus at $\theta = 30^\circ$, one finds F_θ on the order of $\exp(-30)$ or 10^{-13} .

Rutherford's formula turned out to be correct for very small angles of scattering. Evidently there was substantial truth in the idea of multiple scattering. But in experiments initiated at Rutherford's direction, Geiger and Marsden (1909) found that 1 in 8000 alpha particles passing through a thin film of platinum was scattered through more than 90° ! It was as though bullets fired at a bale of cotton could occasionally ricochet backward. Such an observation might lead one to suspect rocks in the cotton.

At this point Rutherford (1911) advanced the hypothesis that the positive charge and most of the mass of an atom is concentrated in a "nucleus" with dimensions of the order of 10^{-12} cm (10,000 times smaller than the atom as a whole) with the electrons in some sort of configuration around it. Applying the principles of classical mechanics, he calculated the trajectories of alpha particles passing near such nuclei, and derived an expression for the differential scattering cross section which accounted accurately for the scattering data, thereby vali-

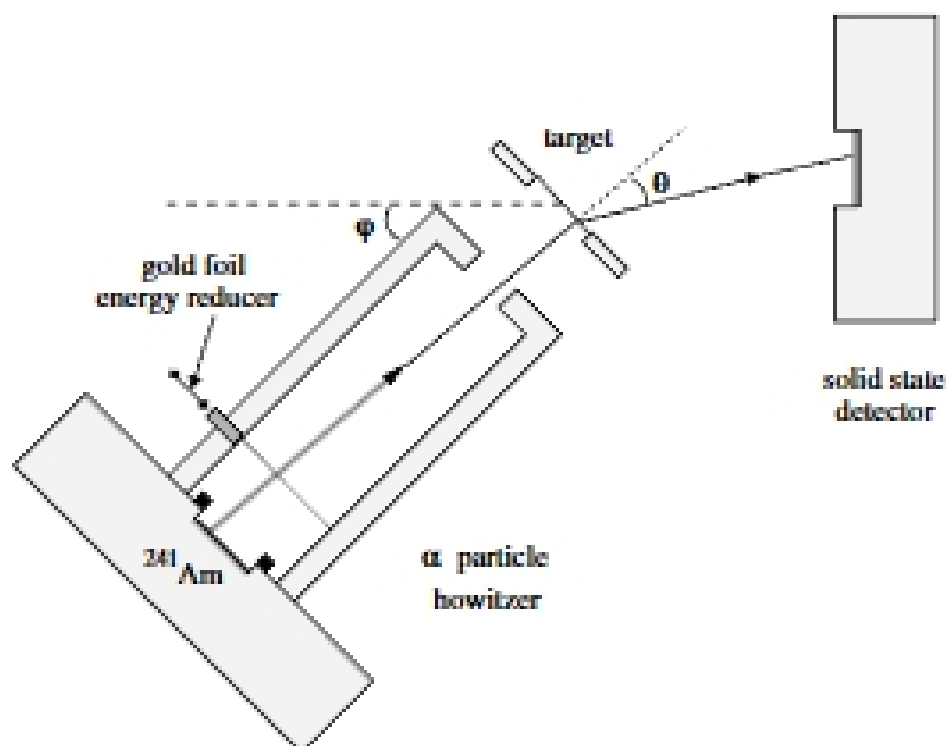


FIG. 1. Schematic of the howitzer, target, and detector in the vacuum chamber.

dating the hypothesis of the nuclear atom.

The Rutherford scattering differential cross section *per target atom* for any target atom is

$$\frac{d\sigma}{d\Omega} = \left(\frac{ZZ'e^2}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)} \quad (2)$$

where θ is the scattering angle, Ze is the charge of the target nuclei, $Z'e$ is the charge of the alpha particles and E is their kinetic energy. (For a derivation, see Reference [5].) Further excruciatingly tedious experiments by Geiger and Marsden confirmed the validity of the formula within the statistical errors of their measurements. Geiger hadn't invented the Geiger counter yet, and electronic detection methods were still 20 years in the future. They used a low power microscope to observe and count by eye the scintillations produced by the alpha particles when they impinged on a screen lightly coated with zinc sulfide dust.

References [5, 6] present the Rutherford theory and discuss the interpretation of data from a scattering experiment that is quite similar to that in the Junior Lab, with the exception of the specific detector and circuit arrangement. We will confine our discussion to the features of the experimental setup and procedures that are peculiar to our setup.

II. APPARATUS

Figure 1 is a schematic drawing of the apparatus in the vacuum chamber. The source, ^{241}Am , emits alpha particles of various discrete energies, the most frequent of which are 5.486 MeV (86%), 5.443 MeV (12.7%), and 5.391 MeV (1.4%). All these decays lead to excited states of ^{237}Np . The half-life of ^{241}Am is 458 years. The source, deposited on a thin metal disk with the highest activity

of ^{241}Am per unit area commercially available (about 1.5 millicuries per square inch) and sealed with an evaporated gold coating 1.5 microns thick, is covered by a metal washer with a 0.64 cm diameter hole and enclosed in a "howitzer" with a 0.64 cm diameter aperture in its snout. Due to the gold coating, the alpha particles' initial energies are reduced to a value closer to 4.8 MeV. Under near-vacuum, a collimated beam of alpha particles emerges from the snout (the range of 5.5 MeV alpha particles in air at atmospheric pressure is only about 4 cm).

If the setup is under vacuum, then decide whether you want to take the time to break and then reestablish the vacuum, or whether the sample currently mounted is adequate for your purposes. If you do wish to break vacuum, then turn the bias voltage on the detector slowly down to zero, close the vacuum valve between the pump and the chamber, and slowly open the vacuum release valve, leaving the pump running. Place the black hood on a table where it can serve as a cushion for the plastic cover. Lift the cover off the steel cylinder and place it flat on the hood, being careful not to damage the underside of the plastic cover. Find out how you can adjust the relative positions of the howitzer and detector with respect to the target, and how you can turn, raise and lower the target with the control rod that protrudes from the bottom of the chamber. Note how you can simultaneously rotate the howitzer and the target about a vertical axis through the target with the lever attached to the outer cylinder under the chamber. This feature enables you to maintain a fixed relative orientation of incident beam and target while you vary the scattering angles of the detected alpha particles.

Two warnings: **Do not remove the black cover while the detector is still on.** The lights in the lab are far stronger than what the detector is designed to absorb. Exposure to the background light in the lab may damage the detector. **Do not release the vacuum too quickly.** A rapid change in pressure can cause the delicate foil targets to rupture.

III. MEASUREMENTS

III.1. Calibrate the Measurement Chain

Move the howitzer support arm so that the howitzer points directly at the detector through the empty target hole. Pump the system down with the bias voltage off. Using an oscilloscope, you can watch the pulses from the unbiased detector appear and gradually grow in amplitude as the amount of air between the source and detector diminishes. The pressure should reach 200 microns in 10 to 15 minutes. If it doesn't, you probably have a leak around the O-ring seal under the plastic cover or around the gasket under the stainless steel cylinder. If necessary, a good way to apply the necessary pressure to initially seal the O-ring and gasket is by weighting the plastic cover with 6 – 8 lead bricks available next to the exper-

iment. Also, there is vacuum grease available, but don't overuse it! A pea-sized amount is more than enough for the surface of the O-ring, and should last for years.

Cover the vacuum chamber with a thick black cloth to eliminate room lights and protect the sensitive detector. Connect a voltmeter to the small aluminum switch box marked "68 volt limiter" that is situated between the bias voltage supply and the preamp for the detector. When the pressure is below 200 microns, you may switch on the bias voltage. The voltmeter should read around 45 volts. Adjust the amplifier gain so that the alpha-particle (bipolar) pulses have an amplitude of about +7 volts. The bipolar amplifier output is better for handling high count rate detection such as the case with no foil.

Observe the pulse size distribution with the MCA and readjust the gains so that the peak of the alpha-particle pulse-size distribution lies at a convenient position within the full range of the multi-channel analyzer. You can assume that the amplitude of a detector pulse is proportional to the energy lost by the particle in the silicon detector. Thus a linear plot of the channel number versus energy, scaled to match the energy of the alpha-particles coming straight from the source, should be an accurate plot for the interpretation of the pulse sizes you will be measuring.

III.2. Adjust the Position of the Target

Accurate vertical positioning of the target holder is essential to assure that the particle beam passes cleanly through one or another of the holes in the aluminum sheet that supports the foils, without touching the edge of the hole. Either you or your partner can manipulate the target holder from under the table while the other judges its position.

To aid you, there are 3 separate machined aluminum cylinders which can be placed on the vertical positioning shaft. These cylinders have been measured and machined to precisely place the desired target at the same height as the howitzer.

With the target holder in the open hole position, measure the counting rate as a function of the howitzer position angle from about -10° to about $+10^\circ$ relative to the nominal center position. **Plot the data as you proceed on a log scale. Log graph paper is available if desired.** Determine the exact pointer readings of the center position and at the positions of zero counting rate intercepts on either side of the center to determine the beam center and its total width.

III.3. Measure the Effects of Target Foils on the Pulse-Height Spectrum of Alpha-Particles

Using the preset accumulation time feature of the MCA accumulate a size spectrum of the pulses produced

by unscattered alpha particles with the howitzer position angle set at the center position. To characterize the width of the distribution, place the start and stop cursors on either edge of the distribution at the positions where the counting rate is half the maximum value, and note the channel numbers. Measure the channel number of the peak counting rate. Compare the results with no foil, the two gold foils, and the titanium foil, and figure out the most probable energy lost by the alpha particles in traversing each of the films. Describe and explain the changes in the shape of the size spectrum when a target foil is in the beam.

Determine the thicknesses of the target by reference to the range-energy data available on the web at [7]. Be sure to use the "projected range" data and not the CSDA range data. To interpolate this table plot the tabulated range versus energy. Call c_1 and c_2 the median channels of the pulse before and after passage through a target. You can assume with some confidence that the median channel number is proportional to the particle energy. From your range energy plot, read the range of the incident alpha particles E_0 and the range of particles with energy $(c_2/c_1)E_0$. The difference in range is the thickness of the target in $\text{mg} \cdot \text{cm}^{-2}$. Does your data fit better using $E_0 = 5.48 \text{ MeV}$ or using a reduced value accounting for the $1.5 \mu\text{m}$ gold coating on the source?

III.4. Plan and Execute Your Scattering Measurements

Your data from this experiment should consist of *at least* the results of the following operations:

1. Determine the essential characteristics of the experimental setup.
 - (a) Measure the counting rate as a function of howitzer position angle with the open hole.
 - (b) Measure the loss in energy of the alpha particles in traversing each of the three targets and determine the thicknesses of the targets from the data.
2. Measure the angular dependence of the scattering cross section of gold. Measure the counting rate with a gold target for the full energy alpha particle beam as a function of howitzer position angle out to the largest angles that counting statistics and time limitations allow.
3. Determine the total cross section σ . Measure the intensity of the beam that emerges from the howitzer. Note that the howitzer is designed so that the entire emergent beam irradiates the target foils; *i.e.*, the beam is sufficiently narrow to pass through the foils without intercepting the target holder.
4. Measure the Z -dependence of the Rutherford cross-section. Compare your results from the gold targets