Atomic Target Practice

Solving the Structure of the Atom

Introduction

Rutherford scattering is one of the most famous experiments of all time. More than 25 years after conducting the experiment, Ernest Rutherford described the results this way:

"It was about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

The experiment itself was actually the culmination of a series of experiments, carried out over a five-year period, dealing with the scattering of high-energy alpha particles by various substances. What is "Rutherford scattering" and why was it so important?

Concepts

- Atomic structure
- Atomic mass
- Nucleus
- Nuclear charge

Background

Ernest Rutherford received the Nobel Prize in Chemistry in 1908 for his investigations into the disintegration of the elements as a result of radioactive decay. Among the products of the radioactive decay of elements are alpha particles—small, positively charged, high-energy particles. In trying to learn more about the nature of alpha particles, Rutherford and his co-workers, Hans Geiger and Ernest Marsden, began studying what happened when a narrow beam of alpha particles was directed at a thin piece of metal foil. Alpha particles are a type of nuclear radiation, traveling at about 1/10 the speed of light. As expected for such high-energy particles, most of the particles penetrated the thin metal foil and were detected on the other side. What was unexpected was that a few—a very few, to be sure—of the alpha particles were actually reflected back toward the source, having been "scattered" or bent due to their encounters with the metal atoms in the foil target. The number of alpha particles that were reflected back depended on the atomic mass of the metal. Gold atoms, having the highest atomic mass of the metals studied, gave the largest amount of so-called "back scattering."

Rutherford's scattering experiments have been described as a "black box" experiment. The properties of the alpha particles, their mass, charge, speed, etc., were at least partially understood. The atoms making up the target, however, presented Rutherford with a kind of black box—the structure of the atom was not known at the time. In order to explain the results of the scattering experiments, Rutherford had to unlock the black box, that is, he had to solve the structure of the atom. In 1911 Rutherford proposed the following model for the structure of the atom:

- Most of the mass of the atom is concentrated in a very small, dense central area, later called the nucleus, which is about 1/100,000 the diameter of the atom.
- The rest of the atom is apparently "empty space." *(Most of the alpha particles traveled straight through the metal foil, as if nothing were in their path.)*
- The central, dense core of the atom is positively charged, with the nuclear charge equal to about one-half the atomic mass. *(As alpha particles randomly struck the gold target, a few approached the nucleus of an atom head on. The positively charged alpha particles were strongly repelled by the nuclear charge and "recoiled" or bounced back to the source.)*

It is not practical to recreate Rutherford's original scattering experiments in the high school laboratory. Some idea of the challenge that faced Rutherford and his co-workers can be gained from the following "black box" activity using marbles and an unseen, unknown target.

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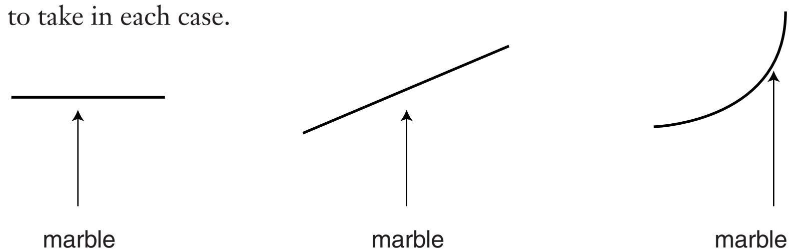
Experiment Overview

The purpose of this activity is to discover by indirect means the size and shape of an unknown object, which is hidden underneath the middle of a large board. The board is raised about 2 cm, leaving just enough space to roll or shoot a marble at the object. By observing and tracing the path the marble takes after striking the unknown target from a variety of angles, it should be possible to estimate the general size and shape of the unknown target.

Pre-Lab Questions

1. This activity is a simulation of Rutherford's scattering experiments. Read the entire procedure and compare the components used in this simulation (the marbles, the board, the unseen object, and the traced path of the marbles) to Rutherford's original experiments. What role is played by each component?
2. It is important to trace the apparent path of each marble roll, even when the marble rolls straight through without striking the unknown target. What general information about the target can be inferred based on where the marble rolls in one end and out the other?
3. The key skills in this activity, as in Rutherford's experiments, are the ability to make careful observations and to draw reasonable hypotheses. Assume that the marble strikes the following sides of a possible target. Sketch the path the marble might be expected to take in each case.



Materials

"Black box," consisting of a square, 17″ × 17″ cardboard cover and a hidden, unknown object underneath

Marbles, 2	Pencil
Paper, white, 8½ × 11 in, 2 sheets	Tape

Safety Precautions

Although the materials in this activity are considered nonhazardous, please observe all normal laboratory safety guidelines.

Procedure

1. Tape two pieces of standard size white paper together to form an 11″-square sheet.
2. Center the paper on top of a black box and tape it down to keep it in place. If there is a code letter for the black box, write the code on the sheet of white paper. Do not look underneath the "black box"!
3. Roll the marble with a moderate amount of force under one side of the black box. Observe where the marble comes out and trace the approximate path of the marble on the white paper. For example, if the marble rolls straight through, draw a straight line from one end of the sheet to the other. *Note:* Do not press too hard on the paper and black box when drawing the lines.
4. Working from all four sides of the black box, continue to roll the marble under the board, making observations and tracing the rebound path for each marble roll. Roll the marble at least 20 times from each side of the box. Vary the angles at which the marble is rolled into the box.
5. After sketching the apparent path of the marble from all sides and angles, the general size and shape of the unknown target should emerge "in the negative" from the area where there are no lines (where the marble does not penetrate).
6. Form a working hypothesis concerning the structure of the unknown target. Based on this hypothesis, repeat as many "targeted" marble rolls as necessary to either confirm or revise the structure.
7. Check your final results with your teacher. Do not look inside the "black box" until the teacher verifies your results.
8. If time permits, switch black boxes with another group of students and conduct a second investigation.

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Post-Lab Questions

1. Draw the general size and shape of the target to approximate scale in the square below. What characteristics of the target were easiest to determine? What characteristics of the target's shape were difficult to determine? Explain.

Shape #

2. The speed of the marble rolls was an uncontrolled variable in this activity. How would the outcome of the scattering test have been different if the marble speed had been faster or slower?

3. Compare the overall size of the target with the size of the marble used to probe its structure. How would the outcome of the scattering test have been different if different size marbles had been used? Explain.

4. In what ways did this activity simulate Rutherford's efforts to determine the structure of the atom? In what ways was it different? Be specific—consider the size, speed, and charge of both the particles and the target.

Teacher's Notes

Atomic Target Practice

Master Materials List (for a class of 24 students working in groups of three)

"Black boxes," 8
- 17″ × 17″ cardboard platforms
- Cork stoppers, size 5, 32 (to raise the black box platforms)
- Blocks, different shapes, 8
  - square, circle, rectangle, triangle, etc.
- Pushpins, 32
- Glue stick, 1
- Marbles, 24
- Paper, white, 8½ × 11 in, 32 sheets
- Pencils
- Tape

Preparation

Use pushpins to attach a size 5 cork stopper to each of the four corners of the cardboard to raise the platform about 2 cm off the tabletop.

Apply glue to the underside of each platform and to each block or object to be used as a target. Attach one target to each piece of cardboard.

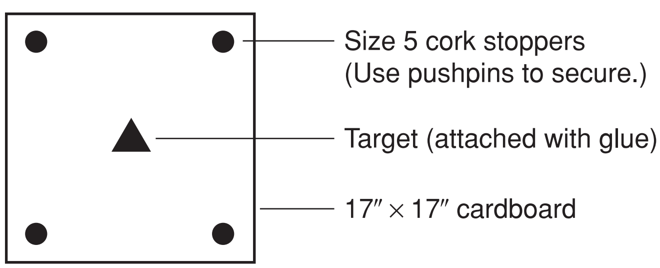


Figure 1. Bottom view of a "black box."

Safety Precautions

Although the materials in this activity are considered nonhazardous, please observe all normal laboratory safety guidelines. Ask students to be careful rolling the marbles and keeping them in a controlled area.

Disposal

None required. Save the cardboard, wood shapes, and marbles for future use.

Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

Unifying Concepts and Processes: Grades K–12
Evidence, models, and explanation
Content Standards: Grades 5–8
Content Standard B: Physical Science, properties and changes of properties in matter
Content Standard G: History and Nature of Science
Content Standards: Grades 9–12
Content Standard B: Physical Science, structure of atoms.
Content Standard G: History and Nature of Science

Lab Hints

- Examples of suitable-shape objects typically found in the lab include jar or bottle caps, Petri dishes, 23-well reaction plates, reaction strips, etc.
- This is a relatively quick and easy lab activity for students to perform. After some initial hesitancy ("You want me to do what?"), students usually find themselves enjoying the challenge of solving the black box structure. For this reason, it is probably best to let students work on at least two structures—consider the first one to be practice.
- Warn students to gently press on the paper or cardboard. This will extend the life of your cardboard.
- Students may be tempted to draw the lines through the center of the black box—this is not correct. Have them draw a line of the trajectory of the in-bound particle and a straight line of the out-bound particle—they will usually intersect at the edge of the block.
- Teachers can give students a valid grade without revealing the "right" answer.

  (1) Was the investigation thorough, based on students' description of what was done?

  (2) Does the original hypothesis (step 6) match the observations made by the lab team?

  (3) Was the hypothesis subjected to further testing?
- Step 6 is an important part of the procedure. Don't let students get away without testing their hypothesis in some way. This step also points out a shortcoming in many descriptions of the scientific method. Many sources seem to treat the hypothesis as a wild guess rather than an educated guess. The hypothesis is a tentative explanation based on preliminary observations or prior knowledge. The sequence should be observations, followed by hypothesis, and then re-testing.
- Students may have a little too much fun with this activity! Watch out for loose marbles rolling around on the floor in all directions. These may pose a safety hazard. Rulers, meter sticks or rubber tubing may be used as backstops to catch the rolling marbles. With students working in groups of three or four, however, there is really no reason that there should be stray marbles on the floor.

Tips

- Have students construct a timeline of discoveries in atomic and electron structure. One of the most useful lessons students may learn in constructing the timeline is the interconnectedness of the discoveries. The official website of the Nobel Foundation (www.nobel.se) serves as an "electronic museum" of information concerning both the scientists and their discoveries. The website includes fact-checked biographies, official award citations, and the presentation speeches of the prize-winning scientists. The presentation speeches are especially helpful in putting the discoveries in the context of the times and in showing how "one thing led to another."
- Rutherford's alpha-particle scattering apparatus is recognized as a precursor of particle accelerators. The basic features are the same—a source of particles, a means to accelerate them, a target, and a detector. *The Particle Adventure* is an award-winning Internet site that describes modern high energy particle physics in easy-to-understand fashion. Batavia, Illinois, home of Flinn Scientific, is also home to Fermilab, the site of the world's highest energy particle accelerator, the Tevatron, a proton–antiproton collider capable of producing collision energies of >1 TeV (teraelectron volt).

Answers to Pre-Lab Questions *(Student answers will vary.)*

1. This activity is a simulation of Rutherford's scattering experiments. Read the entire procedure and compare the components used in this simulation (the marbles, the board, the unseen object, and the traced path of the marbles) to Rutherford's original experiments. What role is played by each component?

   Marbles—alpha particles

   Board—gold foil target

   Unseen object—atomic nucleus

   Traced path of marbles—scattering angles of a-particles

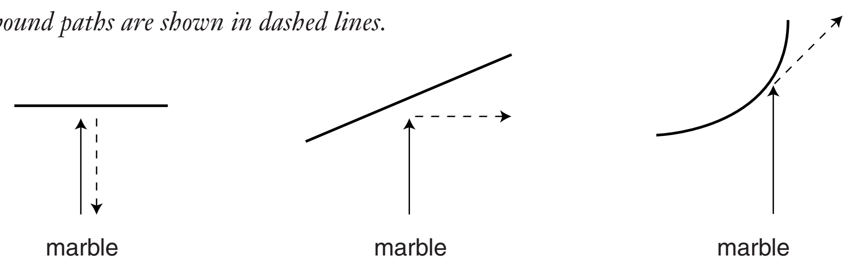
   Note to teachers: *This last parallel may be difficult for students to recognize. The traced path of each marble's roll is inferred based on where the marble enters and exits the box. The scattering angles of the a-particles were also inferred based on the location of spots on a detector. In Rutherford's scattering experiments, the detector was a zinc sulfide phosphorescent screen that flashed when struck by alpha particles. By placing the screen at an appropriate angle to the metal foil target, Rutherford and co-workers could detect the percent of alpha particles that were deflected by an angle of 90° or more. The number of flashes per minute was observed through a microscope.*

2. It is important to trace the apparent path of each marble roll, even when the marble rolls straight through without striking the unknown target. What general information about the target can be inferred based on where the marble rolls in one end and out the other?

   Knowing where the marble rolls in one end and out the other without striking the target is an important first step in determining the overall size of the target and its position in the box.

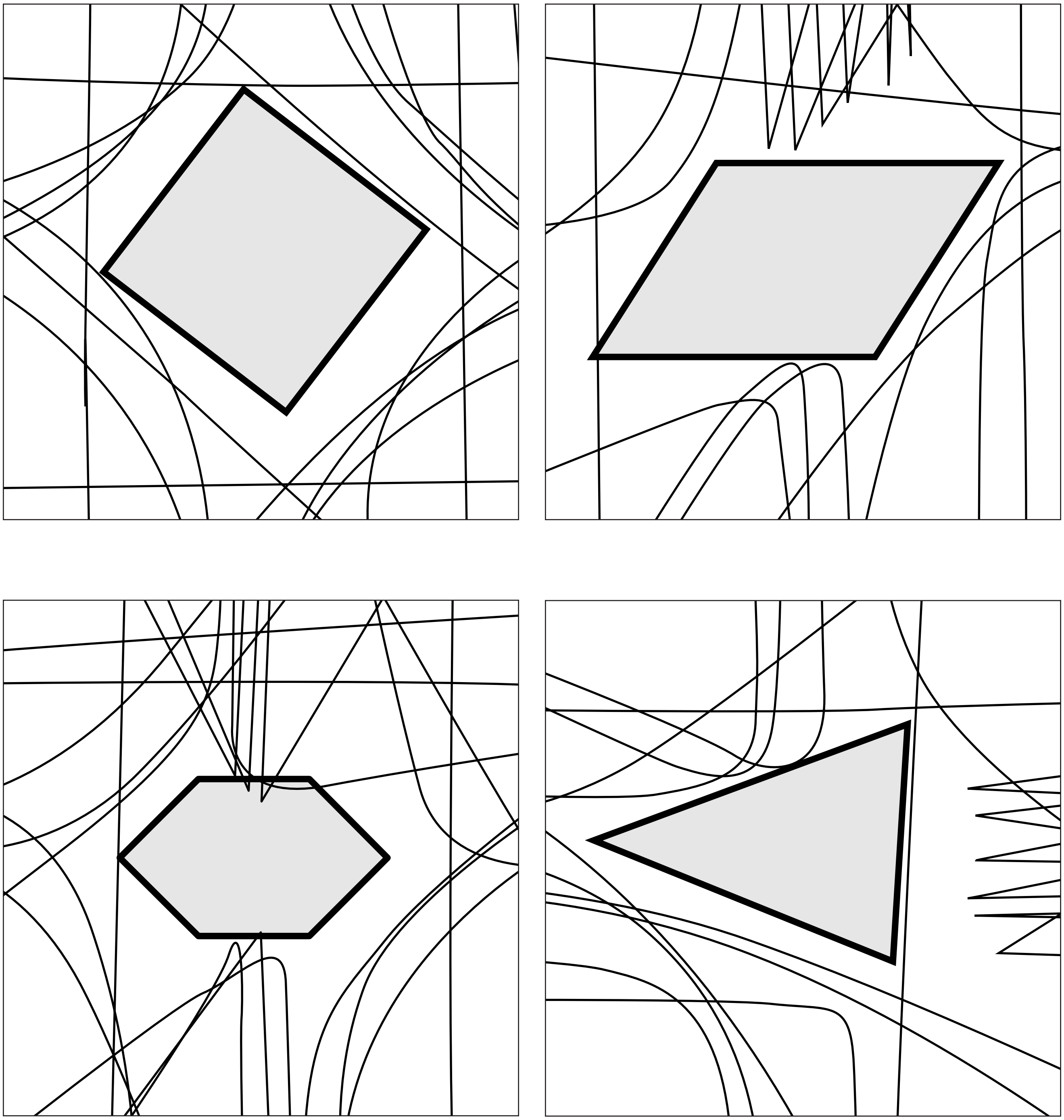
3. The key skills in this activity, as in Rutherford's experiments, are the ability to make careful observations and to draw reasonable hypotheses. Assume that the marble strikes the following sides of a possible target. Sketch the path the marble might be expected to take in each case.

   The hypothetical rebound paths are shown in dashed lines.



Sample Data *Student data will vary.*

The following traced paths were obtained using a variety of different shape wooden blocks available in the Atomic Target Practice Student Laboratory Kit, Flinn Scientific Catalog No. AP6496. The actual shapes are shaded and outlined in boldface. The targets appear much larger in the drawings than in the actual black boxes—only the center 9″ of the traced paths on the 17″ × 17″ boxes were scanned to produce these drawings. Notice the experimental error—remember that the students must infer the path based on where the marble enters and exits the black box.



Answers to Post-Lab Questions *(Student answers will vary.)*

1. Draw the general size and shape of the target to approximate scale in the square below. What characteristics of the target were easiest to determine? What characteristics of the target's shape were difficult to determine? Explain.

See the Sample Data section for representative drawings of student data.

It was easiest to determine the overall size and position of the target. It was also relatively easy to deduce straight edges on the target that were perpendicular to the marble roll. It was difficult to distinguish between curved edges and straight or slanted edges at an angle to the marble roll.

2. The speed of the marble rolls was an uncontrolled variable in this activity. How would the outcome of the scattering test have been different if the marble speed had been faster or slower?

The most obvious answer students will give is that the marble speed must be fast enough that the marble will penetrate the "black box" completely if the target is not in its path. Note to teachers: The speed of the marble will also affect the rebound path (angle of deflection) of the marble. If the marble speed is too slow, the rebound path or angle will change (decrease) as frictional forces further slow down the marble. Consider the simplest case of a marble striking a surface perpendicular to its path (see Pre-Lab Question #3). At a moderate rate of speed, the marble returns back to the origin. At a slower rate of speed, the marble's return may be deflected due to friction. If the marble is sent in fast enough, it may destroy the target. Ideally, the speed of the marble should result in an elastic collision (complete momentum transfer) with the target.

3. Compare the overall size of the target with the size of the marble used to probe its structure. How would the outcome of the scattering test have been different if different size marbles had been used? Explain.

The targets used in this study were approximately five times larger than the marbles. For example, the square target was 7.5 cm long, and the marble was 1.4 cm in diameter. In general, if any part of the marble hits the target, it will be deflected or scattered. Thus, the target will appear larger than it actually is by the diameter of the marble. This would only be a factor in the results if the target were small and the marble big. Using small pieces of metal shot (1-mm diameter) may actually give the most accurate results.

Note to teachers: *The scattering results will also depend on the mass of the "particle." Using a more massive steel ball rather than a glass marble resulted in less deflection. The greater mass means that the ball has greater rotational kinetic energy—the ball keeps spinning in its original, forward direction. Try it!*

4. In what ways did this activity simulate Rutherford's efforts to determine the structure of the atom? In what ways was it different? Be specific—consider the size, speed, and charge of both the particles and the target.

This activity simulates, albeit on a much larger scale, the relative sizes of the target (gold nuclei) and the scattering particle (alpha particles). An alpha particle corresponds to a helium nucleus (mass = 4 amu). The most abundant isotope of gold has a mass of 197 amu. This activity does not simulate at all either the relative speed of the alpha particles compared to the stationary target or their electrical charge characteristics. In Rutherford's experiments, the speed of the alpha particles was such that Rutherford anticipated there should be no scattering at all (even by small degrees). The large angle scattering observed by Rutherford was due to repulsion of the positively charged alpha particles by the atomic nuclei and the large mass difference between the gold nucleus and the alpha particles.

Reference

This activity is from *Flinn ChemTopic™ Labs*, Volume 3, Atomic and Electron Structure; Cesa, I., Ed; Flinn Scientific: Batavia, IL, 2003

Flinn Scientific—Teaching Chemistry™ eLearning Video Series

A video of the *Atomic Target Practice* activity, presented by Irene Cesa, is available in *Solving the Structure of the Atom*, part of the Flinn Scientific—Teaching Chemistry eLearning Video Series.

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Catalog No.	Description
AP6496	Atomic Target Practice

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