Rutherford Atomic Model: Hidden Obstacles
Teacher Version

This lab demonstrates the techniques that scientists used over a century ago to determine the basic structure of the atom. By rolling marbles past hidden obstacles and observing their trajectories, students will be able to make inferences on the shape and size of the obstacles.

California Science Content Standards:

- **1. Atomic and Molecular Structure: The periodic table displays the elements in increasing atomic number and shows how periodicity of the physical and chemical properties of the elements relates to atomic structure.**
- 1e. Students know the nucleus of the atom is much smaller than the atom yet contains most of its mass.
- **1h. Students know the experimental basis for Thomson's discovery of the electron, Rutherford's nuclear atom, Millikan's oil drop experiment, and Einstein's explanation of the photo-electric effect.

Note: This laboratory activity only models Rutherford's experimentation with the nuclear atom

Prerequisites:

- Students are expected to be able to aim a marble's trajectory by aligning a paper towel tube that acts as a ramp, so there is a bit of hand-eye coordination required.
- In the advanced version, students are expected to assess the approximate trajectory of a marble as it bounces off an unseen object under a cardboard square, so some spatial cognition skills are required.

Materials:

- A ~45x45cm cardboard platform – cardboard platform should be stabilized with other objects at each corner (ex: 1 inch slices of paper towel tubes)
- Two paper towel tubes; one to use as a ramp, the other to cut into 1-inch slices for stabilizing the cardboard platform.
- One marble (or more of the same size in case marble rolls away)
- One white standard 8.5in x 11in sheet of paper
- Writing utensil
- Scotch tape
- Ruler
- "Unknown Targets" – Examples for Part I: Several small, square Lego bricks (approx. 2cm x 2cm) equally spaced apart and taped under the board using masking tape. Examples for Part II: Advanced students should use objects that vary in shape, such as the lid of a peanuts jar (or something similar) or other objects that are triangular or diamond-shaped. Basic students should use an object rectangular in shape, such as a softbound or paperback book. Targets should be approximately 1 inch think.

Preparation and Lab Notes:

- The “wall of barriers” under a cardboard platform in Part 1 should be constructed ahead of time by the teacher (Part 1, steps 1-2).
- The “alternate shape” in Part 2 for either basic or advanced students should also be constructed ahead of time (Part 2, steps 1-3)

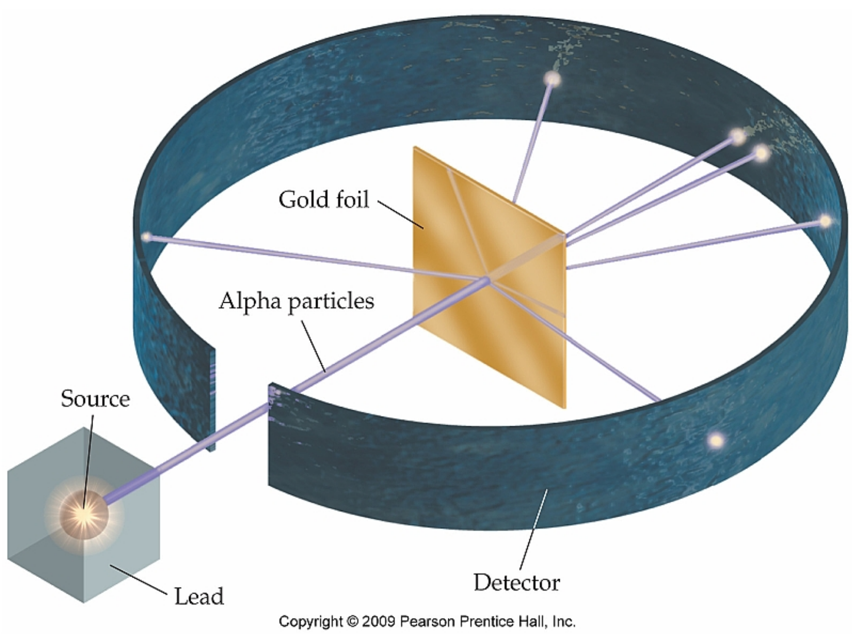
Key Concepts:

- Most of the mass of the atom is concentrated in a very small, dense central area, called the **nucleus**, which is about 1/100,000 the diameter of the atom.
- The rest of the atom is apparently “empty space”.
- The nucleus of the atom is positively charged, with the strength of this charge equal to the **atomic number**.
- Electrons occupy the bulk of the empty space in an atom and orbit the nucleus at a greater distance compared to the size of the nucleus.

Introductory Mini-lecture:

In 1911 Ernest Rutherford and his co-workers conducted an experiment in which they directed a narrow beam of alpha particles at a thin piece of metal foil. Alpha particles are small, positively charged, high-energy particles that travel at about 1/10 the speed of light. Expecting the particles to shoot straight through to the other side, they were surprised to find that a percentage of the alpha particles were actually reflected back toward the source or “scattered” at large angles due to their encounters with the metal atoms in the foil target. It became clear that only strong forces within the atom were deflecting the alpha particles. The structure of the atom was not known at the time, and these observations led Rutherford to believe that there is a small, positively charged nucleus at the center of every atom. This aspect of the atomic structure was not universally accepted as part of atomic theory before this experiment.

Rutherford’s Experimental Setup:



The purpose of this activity is to discover by indirect means the relative sizes (and shapes) of barriers that are hidden underneath the middle of a large board. This is the same general methodology that Rutherford used to determine the size of an atomic nucleus without directly observing it. By tracing the path the marble takes after striking the unseen shapes from various sides, it should be possible to estimate a) their relative amount of space occupied (i.e. their size) and b) the size and shape of a larger object of unknown size and shape.

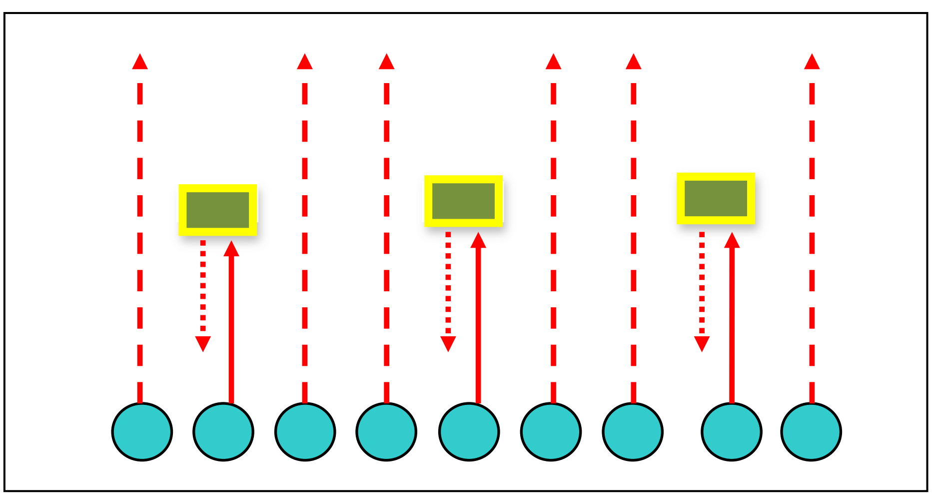
Pre-Lab Questions:

Q1. This activity is a simulation of Rutherford's scattering experiment. Read and describe the basic procedure to students, and compare the components used in this simulation to Rutherford's original experiment:

- *The first part of the lab requires you to shoot marbles through a row of equally spaced barriers, and observe the amount of marbles that cleanly pass through vs. the amount that bounce off the barriers. What aspect of Rutherford's experiment do the marbles represent?*
  The marble in the simulation represents the alpha particles that were shot towards the thin metal foil.

- *What aspect of Rutherford's experiment do the barriers represent?*
  The barriers represent the atomic nuclei that caused scattering of the alpha particles.

Q2. The key skills in this activity, as in Rutherford's experiment, are the ability to make careful observations that lead to reasonable conclusions and the ability to distinguish different paths of projectiles bouncing off an unknown object. In the box below, marbles (blue circles) are in one direction (up the page) toward a row of equally spaced barriers (in green/yellow). Sketch the paths the marbles will likely take and the rebound trajectories if contact is made with the targets.



Q3. Discuss what information can be inferred if the marble rolls straight through without striking the unknown target.

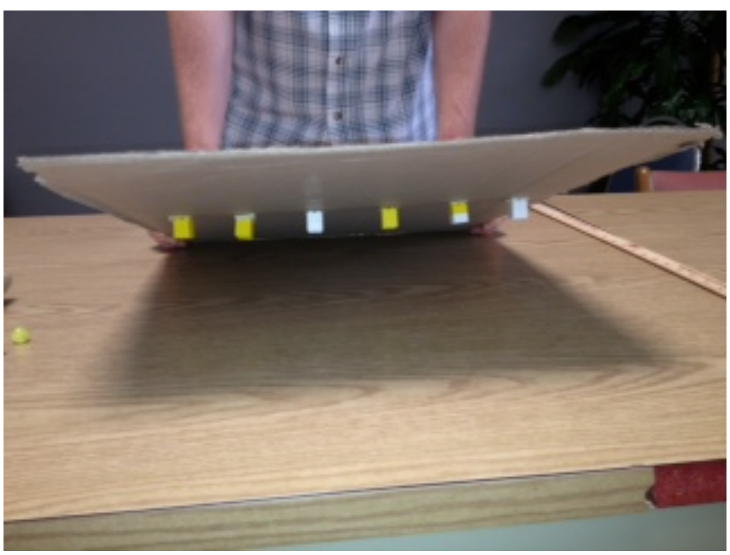
Observing a marble pass straight through is an important first step to determine the size of the object and its position on the board. If the marble rolls straight through without striking the unknown target, it becomes clear the object is not in that specific area. By identifying the range and size of lanes through which the marble passes, the size of the unknown object can then be estimated.

Part I: Wall of Barriers

Procedure:

Note: During this section, students should **NOT be able to see the row of barriers beneath the cardboard platform once it is set up.

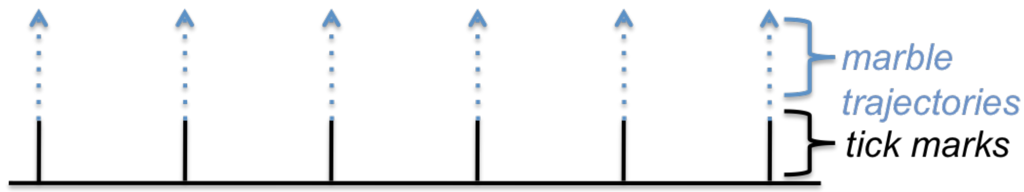
1. *Teacher Setup:*
   - Arrange five or six small, square Lego bricks or similar objects in an equally-spaced row on the cardboard platform, and tape them to the platform. If your platform is smaller than 45 cm, reduce the number of Legos in the row so that they are spaced out every 7-9 cm or so.
   - The picture below illustrates what the assembly should look like when flipped over.
   - Stabilize the corners of the platform by placing and taping 1-inch long "legs" at each corner, on the same side as the Legos. Circular disks cut out from paper towel tubes should work well.



2. Lay the platform on the table so the barriers are underneath the cardboard. From above, it should look like an elevated cardboard square, with no visible objects.

3. One student (the marble shooter) should stand along one side of the platform, so that he or she can shoot marbles perpendicular to the row of barriers. Another student should stand on the side across from him or her, ready to catch marbles.

4. Using a ruler, make a number of equally-spaced tick marks along the side of the board at which the marble shooter is standing, separated by 1 inch. Do not put tick marks on the very outer edges, where the "legs" exist. You will use these tick marks to line up your marble shots into the wall of barriers, so that they can easily be counted as "hits" or "misses", as diagrammed in the figure below.



5. You are now ready to shoot the marbles through these barriers. The marble shooting student should start by aligning the paper towel tube with a tick mark on one end of the cardboard edge, pointed totally perpendicularly to this edge. By creating a ramp with this tube, shoot the marble underneath the board.

6. If the marble is observed to hit a barrier as it rolls underneath the cardboard, mark that tick mark with an "H", and if it passes through without hitting anything, mark the tick mark with an "M" to signify a miss.
7. Line up the paper towel tube with the next tick mark along the edge and repeat steps 5 and 6. Continue along shooting the marbles from different points along the cardboard edge at all tick marks.
8. After the marbles have been rolled from all points along the edge, the total fraction of space occupied by the barriers underneath can then be approximated. The barriers in this experiment are analogous to the atomic nuclei in Rutherford's experiment.

Expected Total Space Fraction = # of marble hits ÷ total # of marble rolls

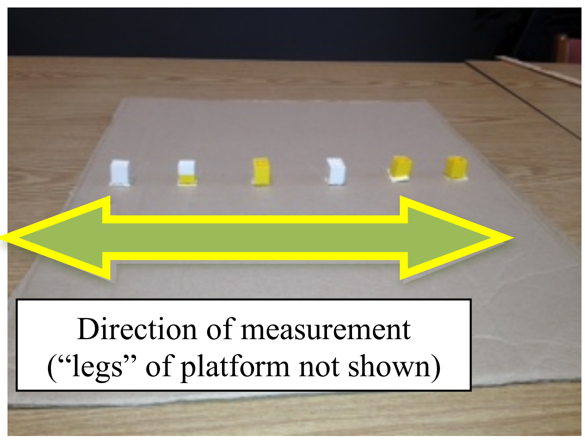
= ________________ ÷ __________________ =__________________

9. You can also observe the pattern of “hits” and “misses” across all tick marks to predict the number of Lego bricks concealed by the cardboard platform:

Predicted Total number of bricks used = ________________________

10. After the expected total space fraction is calculated and the number of barriers are predicted, students should turn over the cardboard platform to calculate the actual space fraction.
11. Begin by having students measure the length of the cardboard platform in the direction that the Lego bricks are arranged (see picture below). Subtract the length of the “legs” that you are using to stabilize the platform in the corners.

Total Space Available = _____________ *cm*



12. Next, measure the length of one Lego brick in the same direction.
13. Measure the width of the marble you are using and add that to the length of a Lego brick to get the “single obstacle size”.

Single Obstacle Size = _____________ *cm*

14. Multiply the ”single obstacle size” by the total number of Lego bricks used to get the “total obstacle size”.

Total Obstacle Size = single obstacle size × number of Legos used = _____________ *cm*

15. Calculate the actual space fraction of Lego bricks:

Actual Space Fraction = total obstacle size÷ total space available = _____________ *cm*

Questions:

Q4. Compare the expected space fraction and number of barriers that you predicted without seeing the barriers to their actual values. Were you close? What would account for any difference between the expected and actual values?

Student answers may vary. Typically, students will calculate a larger expected total space fraction, because marbles sometimes don't roll perfectly straight.

Q5. In Rutherford's experiment, he found that the nucleus of an atom was less than 1/1000th of the size of the rest of the atom, i.e. the space between barriers was more than 1000 times larger than the fraction of space that the barriers occupied. How does this compare to your experiment? Why do you think this experiment may be designed differently?

Our barriers are much closer together relative to their size. We design the experiment this way to avoid the need to shoot multiple thousands of marble trajectories to get meaningful data.

Q6. You were able to estimate the number of barriers under the cardboard. How were you able to do this? Do you think Rutherford was able to do this in his experiment?

In our experiment, the each individual marble could be recorded as a hit or miss depending on its starting point, showing discrete sections where "hits" were made, so we could count the different barriers. Rutherford was not able to track each trajectory individually, so while he was able to determine that the nucleus was very small compared to the rest of the atom, he could not accurately estimate the number of nuclei in his system

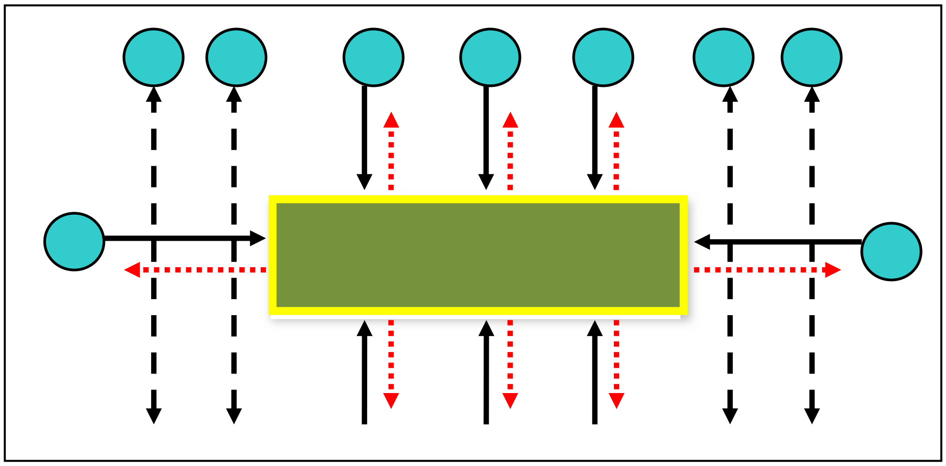
Part II: Alternate Shapes (Basic Version)

Procedure:

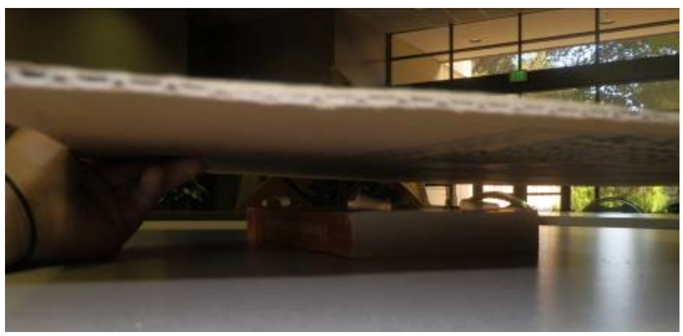
**Note: Students must not know size object is beneath the cardboard platform.

1. Teacher setup:
   - In this part, choose a rectangular object to place under the cardboard platform. A good example is a paperback book about 1 inch thick. Hard cover books do not work well because they present non-uniform ridges that will redirect the marbles.

Marbles will either bounce directly backwards off the shape or pass straight by the shape.



- Center the shape underneath the cardboard platform and adhere it to the cardboard with tape.



- Center a sheet of paper on the upper side of the cardboard platform, so that it completely covers the unseen object underneath, and tape this sheet down to the cardboard.

2. Again, students should stand on opposite sides of the cardboard platform while shooting and catching marbles.

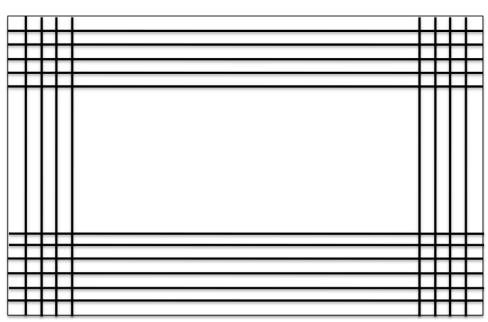
3. As in Part 1, use the paper towel tubes to shoot marbles underneath the cardboard platform. The marbles should still be shot perpendicularly to the edge of the cardboard. Shots should also be started at one end and moved across the cardboard edge in increments, as in Part 1.

4. If the marble rolls straight through to the other side, trace a line on the paper above its trajectory.

5. As shots are taken from points closer to the middle of the platform, the marble will eventually bounce off the object and back in the direction of the marble shooter. You don't need to trace the trajectories of these shots. When this is observed, shoot the marble several times more in the nearby region to identify the exact boundary of the rectangular object. Your paper should have several lines on it similar to the black lines in the picture below.

6. Once you have delineated one boundary of the rectangle, shoot marbles at points near the other end of the same side of the cardboard platform to find the opposite boundary, so the paper then resembles the picture below:

7. Rotate the board a quarter turn in either direction so your marble trajectories will then be perpendicular to the existing lines. Repeat the process in steps 6-8 until the other dimension of the rectangle is delineated. The paper should look similar to the image below:



8. Based on the outline you created on your sheet of paper, estimate the length and width of the rectangle under the cardboard.

Predictions:

Length (cm)	Width (cm)

9. Turn the cardboard over to measure the actual length and width of the object.

Actual Dimensions:

Length (cm)	Width (cm)

Questions:

QS7. How did your predicted object dimensions compare to the actual dimensions? What may have contributed to any discrepancy?

Student answers may vary. Measurements may be taken inaccurately because of marble rolls that aren't perfectly straight.

QS8. 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 speed of the marble must be fast enough to pass through to the other side of the board if the target is not in its way, or bounce back out from under the cardboard if it hits the object.

QS9. Compare the overall size of the unknown object 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 unknown objects used in this study were a lot larger than the marbles. This is important in distinguishing the size and shape of the object. If very large projectiles (like softballs) were rolled past the target, The object would appear larger, as the centers of mass of the softballs would have to be further away from the object to avoid bouncing off of it. This would cause an overestimation of the object size.

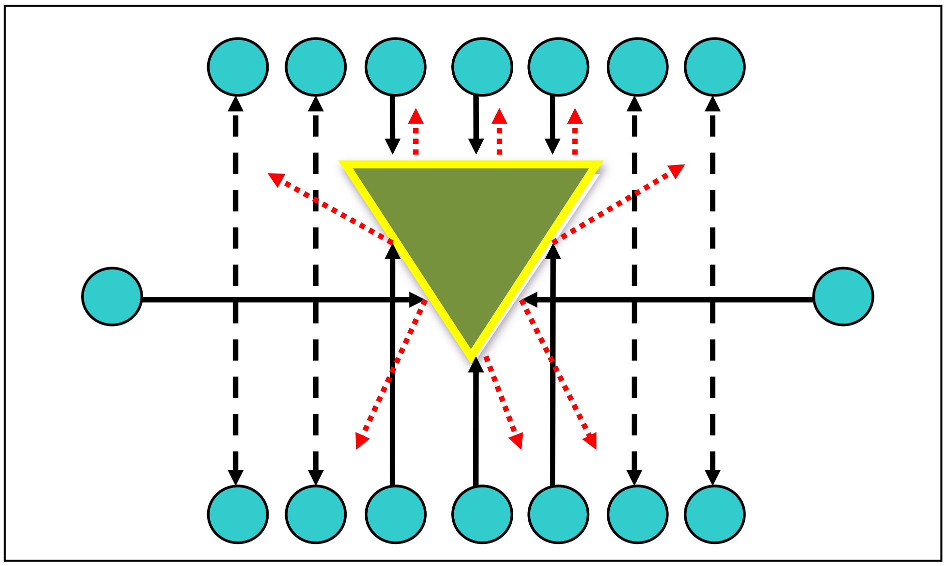
Part II: Alternate Shapes (Advanced Version)

Procedure:

**Note: Students must not know what object lies beneath the cardboard platform. In this part, students are encouraged to roll marbles at the unknown object from multiple directions.

1. Teacher setup:
    - This time, choose an alternate object to place under the cardboard platform. A good object for advanced students is a lid of a peanut jar or an object that is triangular or diamond-shaped.

Based on the angles at which the marble is deflected away from under the board, the shape of the 'unknown' object becomes clear. Example of Alternate Shape:



Center the shape underneath the cardboard platform and adhere it to the cardboard with tape.

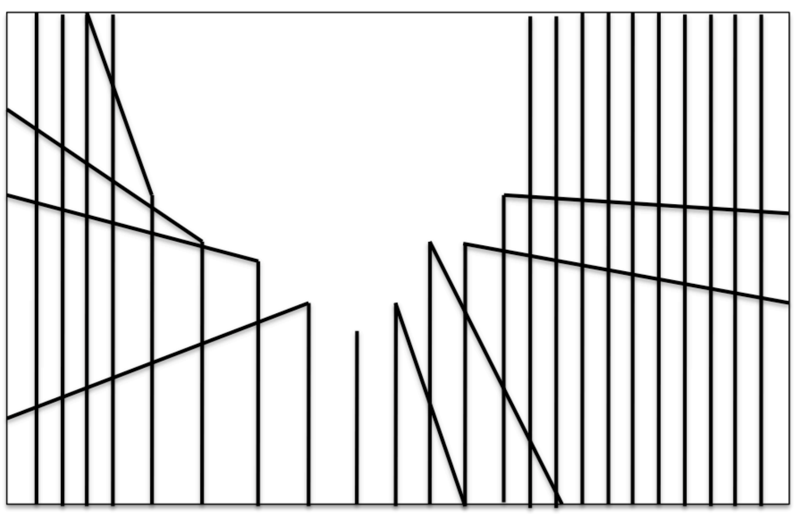
Center a sheet of paper on the upper side of the cardboard platform, so that it completely covers the unseen object underneath, and tape this sheet down to the cardboard.

2. Again, students should stand on opposite sides of the cardboard platform while shooting and catching marbles.

3. As in Part 1, use the paper towel tubes to shoot marbles underneath the cardboard platform. The marbles should still be shot perpendicularly to the edge of the cardboard. Shots should also be started at one end and moved across the cardboard edge in increments, as in Part 1. **Closely observe the trajectory that the marble takes as it emerges from the cardboard.**

4. Trace the trajectory that the marble takes on the sheet of paper attached to the cardboard. It is important to track the emerging trajectory of the marble as closely as possible. By connecting the emerging trajectory line with that of the incoming marble trajectory, you can find the point of impact with the unknown object.
   - In the cases when the marble bounces straight back to the shooter, it is impossible to find the exact point of impact. However, those rolls do show where the unknown object has a face perpendicular to the marble trajectory.

5. Repeat rolling marble from one side of the board and tracing its path until the boundaries of the shape facing that side are roughly determined. It may be helpful to delineate the boundaries of the object by starting to shoot marbles near the edges of the cardboard and working inward. The page should contain a number of straight lines, joining at the points where the marbles impacted the unknown shape. An example that may or may not look like your paper depending on the unknown object, is shown below:



6. Rotate the board a quarter turn and repeat steps 5-7 until the marble has been rolled from each side of the board with corresponding paths traced from all sides. The paper should include many lines crossing over one another.

7. After sketching (on the sheet taped on the upper side of the cardboard) the apparent paths of the marble from all sides, the general size and shape of the unknown target should emerge. Draw the general shape of the unknown object to approximate scale in the square below:

Predicted Object

8. Turn the cardboard over and examine the actual object.

Questions:

QSA7. How does the shape of the unknown object compare to the actual object? What may have caused any discrepancy.

Student answers may vary. Discrepancies are common in this procedure, because it is very difficult to accurately trace the emerging trajectory of a marble and combine it with its incoming path to find the point of impact.

QSA8. 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 speed of the marble must be fast enough to pass through to the other side of the board if the target is not in its way, and to bounce back from under the cardboard if it hits the object. The speed of the marble will also affect the angle of deflection (rebound path). If the marble is too slow, the rebound path or angle will change as friction forces slow it down further, or slight tilts of the table redirect it.

QSA9. Compare the overall size of the unknown object 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 unknown objects used in this study were a lot larger than the marbles. This is important in distinguishing the size and shape of the object. If very large projectiles (like softballs) were rolled past the target, The object would appear larger, as the centers of mass of the softballs would have to be further away from the object to avoid bouncing off of it. This would cause an overestimation of the object size. Also, the angles of deflection off the target would depend strongly on the size and shape of the balls, and not the shape of the book. This obscures the observations, and makes predicting the shape of the target very difficult.

QSA10. In Rutherford's experiment, he was able to determine the approximate size of an atom's nucleus. You were able to determine both an unseen object's shape and size. What key factor allowed you to make this prediction?

Observing the angle at which each individual marble was deflected allowed us to determine the shape of the object. In Rutherford's experiment, he was not able to trace individual trajectories – he could only count the number of trajectories that passed straight through the foil vs. the number that were reflected.