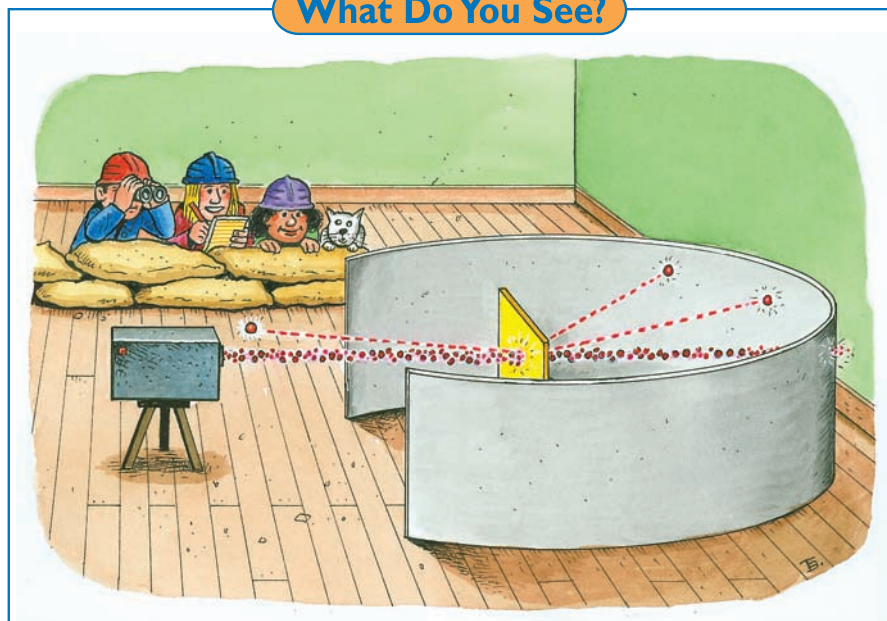


Section 3

The Size of a Nucleus: How Big Is Small?

What Do You See?



Learning Outcomes

In this section, you will

- **Calculate** the area of a penny using indirect measurement techniques.
- **Compare** statistical measurements to direct measurements.
- **Relate** the Rutherford scattering experiment to the penny simulation.
- **Describe** the relative scale of the nucleus to the atom.

What Do You Think?

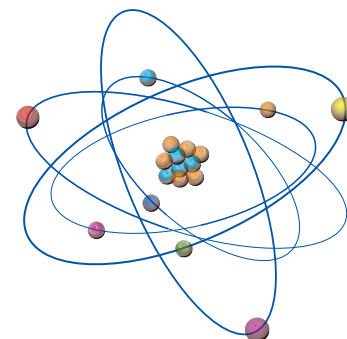
Everyone has heard of atoms, but no one has ever seen an atom. Look at the sketch below of an atom that you often see in advertisements and some science books.

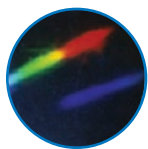
- How would you describe what is shown in the sketch of an atom?
- Are there any problems with this depiction of the atom? Explain your answer.

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

You will use an indirect method to calculate the area of a penny by counting the number of times a pencil hits or misses a target. You will also apply a direct method to calculate the area of the penny and compare the results of the





two methods. You will then extend your reasoning in the *Investigate* to determine the size of an unknown object.

1. Suppose you randomly throw darts at a circular area of a dartboard that is partially shaded. After many trials, you count 50 hits in the shaded area of the 100 darts you threw in the dartboard.

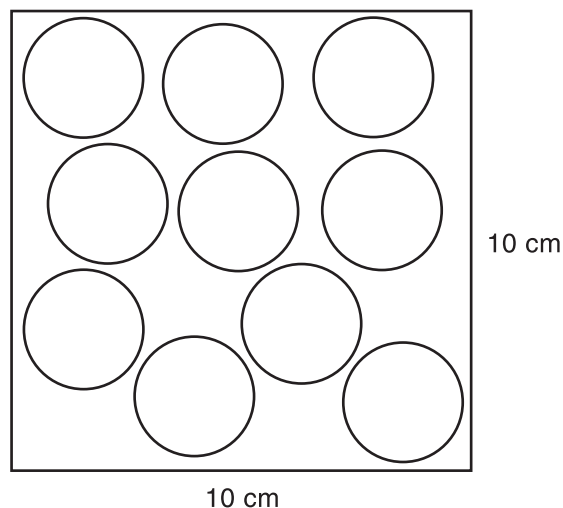
- a) Which of the dartboards below could you have been using? Explain your answer.
- b) Would your answer change if the number of shaded hits were 25? Explain your answer.



2. Work with a partner. Use a ruler and a pencil to outline a square that is 10 cm \times 10 cm on a card. Trace a penny as many times as you like within the square.



Draw the circles similar to the ones shown so that they do not touch each other. Make the circles as close to the actual size of the penny as you can. Note that the diagram is not drawn to scale.



3. Place the card on the desk and stand beside it. Drop a pencil onto the card so that the point hits within the square. Do not aim the pencil. It is actually better if you don't look. You want the drops to be as random as possible. Your partner may actually shift the card after each drop so that there is less chance of you dropping the pencil in the same place.





Have your partner watch as you do your drops. If the pencil falls outside the square, ignore that drop. Make 50 "countable" drops. Switch roles with your partner, and continue until 100 drops are recorded.

Count the number of drops where the pencil landed inside circles. Call these drops "hits."

- a) Record the number of hits.
- b) Should the total number of hits be related to the area of the pennies? Explain your answer.

4. To test the hypothesis that the percentage of hits is related to the percentage of area occupied by the pennies, use the proportion given below to find the area of all the pennies.




$$\frac{\text{hits}}{\text{drops}} = \frac{\text{area of all pennies}}{\text{total area}}$$






-  a) Show your calculations in your log.
5. Find the area of one penny by dividing the area of all the pennies by the number of penny outlines on your card.
-  a) Record your calculation in your log.
-  b) Compare your value with that of other lab groups. How close are the values?
-  c) Why do you think this method of determining the area of a penny is an indirect method?
6. You can also find the area of one penny directly by using this equation:

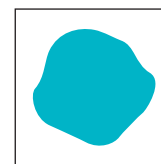
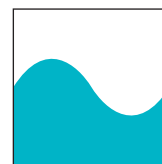
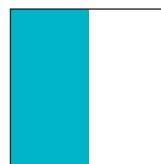
$$\text{Area} = \pi r^2$$



where $\pi = 3.14$ and

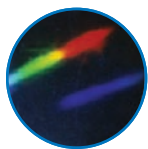
r = radius of the penny


-  a) Measure the diameter of a one-penny circle on your card with a ruler. Record your measurement. (The radius is one-half the diameter, the distance across.)
-  b) Calculate the area of a penny and record your calculation in your log.
-  c) To get a more accurate value of the diameter of a penny, you could line up 10 pennies before making the measurement with a ruler. Why would that give you a better result?
7. Compare the results you obtained using *indirect measurement* (dropping the pencil) and *direct measurement* (using a ruler).


-  a) How close are the results you got using the two different methods?
-  b) Compare your results with those of other lab groups. How do your results compare?
-  c) Which method is more accurate? Explain your answer.
-  d) Why is it important not to aim the pencil in the indirect measurement?
8. Average the results of the indirect measurements and direct measurements from the entire class.
-  a) How close are the results your class got using the indirect and direct methods?
9. Extend the experiment to an unknown object. Suppose a student conducts a similar experiment, but replaces the penny with a single unknown object. If that student got 50 hits out of 100 drops, then you would conclude that the unknown object's area was approximately 50%, or one half, of the total area of the 10 cm \times 10 cm square. You don't know from the data the shape or the location of the object. All of the following are possible because one half of the total area of each square is shaded.



-  a) What might the unknown object look like if it was reported to have 75 hits out of 100 drops? Draw the outer square and the size of the unknown object inside.
-  b) What might the unknown object look like if it was reported to have 25 hits out of 100 drops? Draw the square and the unknown object's size.



 c) What might the unknown object look like if it was reported to have one hit out of 100 drops? Draw the square and the unknown object's size.

 d) What might the unknown object look like if it was reported to have one hit out of 10,000 drops? Draw the square and the unknown object's size.

Physics Words

indirect measurement: a technique that uses proportions or probability to find a measurement when direct measurement is not possible.

direct measurement: a method that uses a measuring device to determine the size of an object.

atom: the smallest particle of an element that has all the element's properties; it consists of a nucleus surrounded by electrons.

nucleus: the positively charged mass of an atom surrounded by electrons.

alpha particles: a beam of positively charged particles.

Physics Talk

MEASURING THE SIZE OF THE NUCLEUS

Indirect Measurement

In this section, you used indirect measurement to find the area of a penny. **Indirect measurement** is a technique that uses proportions or probability to find a measurement when **direct measurement** is not possible, or measuring something by directly measuring something else. Finding the size of the penny without directly measuring it may seem like a good trick. However, you know that you can always verify the size by using direct measurement. You can measure a penny with a ruler. You may think that by using direct measurement you would obtain more accurate results. However, you found in the *Investigate* that both indirect and direct measurements gave very similar results.

Indirect measurement has been very useful in science. Quite often, indirect measurement is also necessary. The sizes and distances to the other planets in the Solar System, for example, have never been directly measured with a ruler or tape measure. The **atom** also cannot be measured with a ruler. Scientists must rely on an indirect method to obtain these measurements.

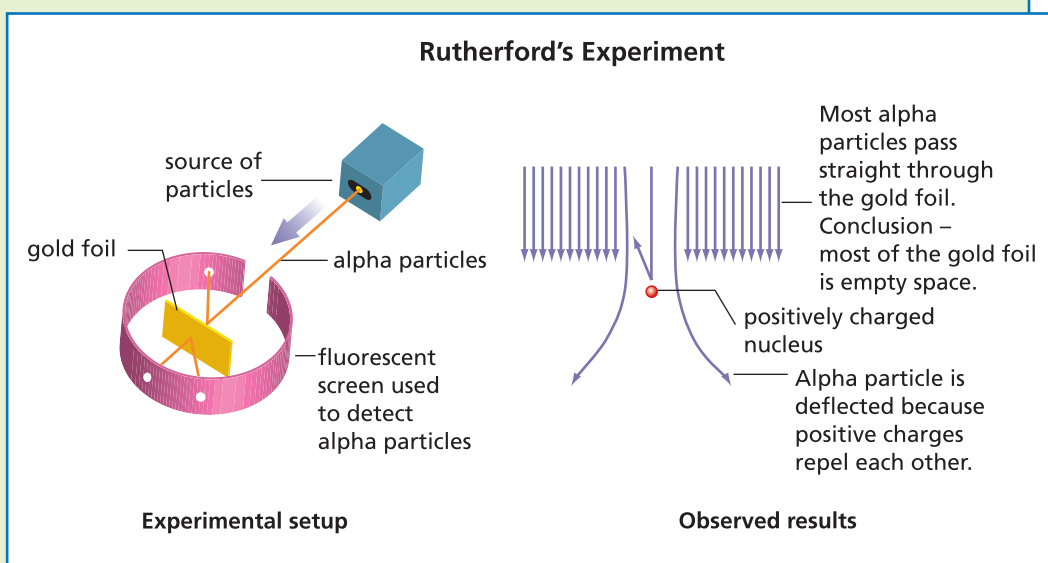
In this section, you probably concluded that if a single object was in a square and you only got 1 hit in 100 drops, the object would be small in comparison to the square's area. If you only got 1 hit in 1000 drops, the object would be very tiny indeed. And if you only got 1 hit in 10,000 drops, you probably recognize that you could not even draw such a small object in the square. This penny lab and these conclusions can be a model to help explain Rutherford's famous scattering experiment.

Rutherford's Experiment

A key scientific discovery, the discovery of an atom's **nucleus**, was made using a method similar to the one you used in this section. Ernest Rutherford and his colleagues, Hans Geiger and Ernst Marsden, made the discovery. In the lab, the team bombarded a piece of thin gold foil with a beam of positively charged particles called **alpha particles**. The alpha-particle beam was like your "dropping pencil." The foil was like your card. When they completed their experiment, they found that when they shot particles at an area of gold, they got one hit out of every 100,000 drops. Rutherford's conclusion was that there is a single object in each atom and that it must be extremely small. He called it the nucleus.

Of course, Rutherford's experiment was more complicated. As you learn the details, don't lose sight of the conclusion and its relation to the penny-lab simulation.

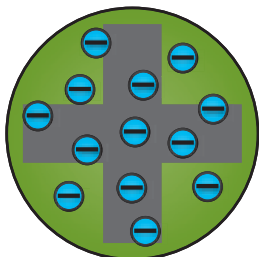
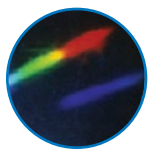
In Rutherford's experiment, most of the particles went straight through the gold foil. These were like the pencil drops that missed the circles. However, to the surprise of the team, Marsden saw that a very few of the alpha particles bounced back toward the source of the beam. This observation was similar to the pencil drops that hit the circles. When Marsden told Rutherford about the results, Rutherford was astonished. Rutherford said the actual result was as amazing "as if you fired an artillery shell at a piece of tissue paper and it bounced back and hit you!"



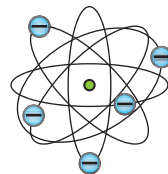
Developing a Model of an Atom

Rutherford thought deeply about these observations. He also thought about all of the ideas that scientists had about what was in the atoms. The fact that most of the alpha particles went essentially straight through the foil suggested that most of them missed the atom's positive charge and mass entirely. He concluded that the positively charged alpha particles bounced back when they hit an area of concentrated positive charge and mass. This model was an improvement to the earlier model of the atom developed by Thomson. Thomson's model had positive and negative charges distributed evenly. Thomson said it was like plum pudding (a British dish). If he were American, he may have said it was like raisin bread with the negative charges (the raisins) spread evenly throughout the dough (the positive charges).





In the Thomson model of the atom, the electrons are like raisins in the dough of positive charge.



In the Rutherford model of the atom, the electrons are moving around a very, very small, tightly-packed sphere which contains all the positive charge and most of the mass of the atom.

Rutherford's model had all the mass and positive charge in a tiny location that he called the nucleus. He used his results to calculate the size of the nucleus of these atoms. He could have compared the number of hits, particles that bounced back, with the total number of particles sent toward the foil. He could have used that information to determine the area of the foil where the atomic nuclei could be found. However, Rutherford's mathematics was a bit more complicated. In his situation, the hit was neither "yes" nor "no," but an angle of deflection that could range from 0° to 180° . In future courses, you may study the calculations in detail. Rutherford calculated the diameter of the atomic nucleus to be 10^{-15} m. The diameter of the atom is 10^{-10} m. The nucleus is only $\frac{1}{100,000}$ the size of the atom!

It would be great if it were possible to check Rutherford's indirect measurement. However, a direct measurement to measure the size of a nucleus is impossible because the nucleus is so small. In a direct measurement scientists use a measuring device to determine the size of an object. Because of the impossibility of using direct measurement, only the indirect measurement is available. This measurement is used as evidence of the existence of a nucleus and its size.

Rutherford's nucleus provides a view of matter as mostly empty space. In an atom, which is the smallest particle of an element, the electrons surround a tiny nucleus with nothing between the electrons and the nucleus. The nucleus has all the positive charge and almost all the mass of an atom. Why then do solids appear so solid? How can the empty space of your fist hurt so much when it hits the empty space of a table? Electrons whizzing around the nuclei of the atoms in your fist are repelled by the electrons whizzing around the nuclei of the atoms in the table. The closer you try to bring your fist to the table, the stronger the force of repulsion between the electrons. The force of repulsion can be greater than the force of attraction holding your fist together, and bones can break.

How can empty space exert such forces? Imagine a thin propeller blade. If the blade is still, it is surrounded by mostly empty space. When the blade rotates, it seems to fill that empty space and create a solid wall. The tiny electrons, in rapid motion, create a similar effect—as if the electrons are everywhere at once—and the empty space appears solid.

Your sense of touch is the repulsion of electrons. It follows Coulomb's law:

$$F = k \frac{q_1 q_2}{d^2}$$

Isn't it amazing that you are able to feel this force when it is as tiny as a kiss or as large as striking a table with your fist? The next time you kiss someone, remember that you are experiencing the repulsion of electrons!

Checking Up

1. Why would you rely on an indirect method to measure the size of an atom?
2. How was Rutherford able to determine the size of a nucleus?
3. How do electrons fill the empty space of matter?

Active Physics

+Math	+Depth	+Concepts	+Exploration
♦	♦		

Plus

Making a Model of an Atom

Rutherford's experiment is the only evidence that you have for the existence of the nucleus. In Rutherford's model of the atom, the nucleus takes up only $\frac{1}{100,000}$ of the atom's diameter. Drawing an atom with the nucleus to the proper scale requires ingenuity. The atom has a diameter of 10^{-10} m and the nucleus has

a diameter of 10^{-15} m. If the nucleus were the size of a table-tennis ball, how large would a field have to be to represent the atom?

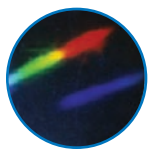
Use this model to create an illustration of a solid composed of a three-dimensional grid. Each atom would be represented by a field or stadium. Each nucleus would be represented by a table-tennis ball.

What Do You Think Now?

At the beginning of the section you were asked the following:

- How would you describe what is shown in the sketch of an atom?
- Are there any problems with this depiction of the atom? Explain your answer.

Now that you know Rutherford's model of an atom, you should be able to describe a nucleus and electrons in your sketch of an atom. Do the electrons have a fixed position in the atom, like the nucleus?



Physics

Essential Questions

What does it mean?

How can recording the number of “hits” and the number of “misses” tell you the size of targets? Why are such methods necessary for “seeing” the nucleus of an atom?

How do you know?

Compare and contrast your experiment determining the size of the penny with Rutherford’s experiment determining the size (and existence) of the nucleus. Provide two similarities and two differences in the experiments.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Atomic and nuclear	Models	* Experimental evidence is consistent with models and theories

* Physicists create models to provide a better understanding of the world.

You know from observation that iron is different from water and you might wonder why. Unfortunately, you cannot see the tiniest structure of matter. Knowledge of that structure could provide insights into why materials are different and why they exhibit different properties. Physicists use a model to explain observations. They then conduct new experiments to test the model and amend that model to better accommodate new observations. Rutherford conducted his scattering experiment and concluded that his model of an atom would have a dense, tiny nucleus containing all the positive charge of the atom, and the rest of the atom would be mostly empty space. Rutherford could not “look up” in a book to see if his model of an atom was “right.”

Why do you believe in Rutherford’s model of an atom?

Why should you care?

Knowing about the structure of matter allows scientists to create technologies that can alter the world. Understanding these technologies and their impact on society may depend on people understanding the structure of matter. How can you use your museum exhibit to help visitors understand Rutherford’s model of an atom and the evidence you have for that model? How can you communicate to the visitors that this knowledge is important to them?

Reflecting on the Section and the Challenge

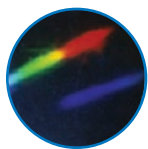
By shooting particles at thin foils and seeing how the particles scatter, you can investigate the structure of matter. Rutherford's scattering experiment revealed that a tiny nucleus contains all of the positive charge of the atom. This also implies that most of the atom is empty space. In your museum exhibit, you will certainly want to help visitors to get a sense of the structure of the atom with its tiny nucleus and orbiting electrons. Is there a way in which you can get visitors to your exhibit to explore the size of the nucleus? You may also want to help visitors understand how "mostly empty space" can make hard, solid objects.

Probability was important in this indirect method of measuring the size of a penny or the size of the nucleus. If you had aimed the pencil, the experiment would not have given good results. The use of probability and indirect measurements may be something you wish to include in your museum exhibit.

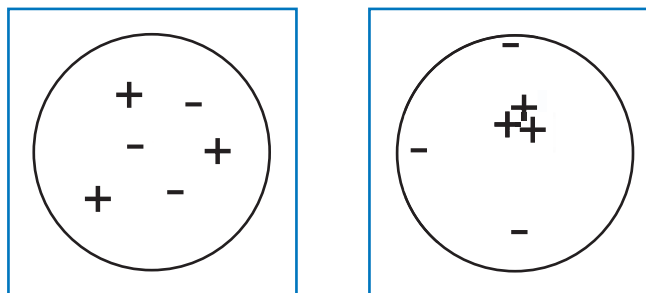
The museum exhibit must capture a visitor's attention within 30 s. How can you "grab" the visitor?

Physics to Go

- Determine the size of a quarter indirectly by repeating the pencil-dropping experiment, substituting quarters for the pennies.
 - Record your results.
 - How close are the results you got using the direct and indirect method of measurement?
 - Which method is more accurate? Explain your answer.
- Repeat the quarter experiment, but this time aim at the card to get as many hits as possible.
 - Record your results.
 - How does aiming change the results?
- Which is greater, 10^{-15} m or 10^{-10} m? How many times greater?
- Find the areas of circles with the following diameters:
 - 4 cm
 - 7 cm
 - 10 cm
- Why do you get better results when you drop the pencil 1000 times instead of 10 times?
- You drop a pencil 100 times and get 23 hits. There are seven coins on a card 10 cm \times 10 cm. How large in area is each coin?



7. If the nucleus could be enlarged with a projector so that it was 1 cm in diameter, how far away would the next nucleus be? (Each nucleus is 10^{-15} m and each atom is 10^{-10} m.)
8. In the Rutherford scattering experiment, the alpha particles were deflected at different angles. It was not simply a hit or miss as it was in your penny simulation. How would you expect the angle of deflection to be affected as the positive alpha particles come closer to a positive nucleus?
9. Consider a square target foil of area A that has 10 atoms. If 999 out of 1000 alphas pass through undeflected, how big are the target positives as a fraction of A ?
10. When Marsden told Rutherford about the results of the scattering experiment, Rutherford was astonished. Rutherford expected results predicted by Thomson's model of an atom. The Thomson "plum pudding" model (or raisin bread model) has a positive charge spread all through the atom like the raisins in raisin bread. Using this model, Rutherford expected the alpha particles would go straight through the foil but emerge with a smaller speed. Rutherford said the actual result was as amazing "as if you fired an artillery shell at a piece of tissue paper and it bounced back and hit you!" Explain what Rutherford meant with his artillery shell metaphor. When Rutherford adopts his new model of the atom, with all the positive charge residing in a tiny nucleus, how does the artillery shell metaphor now make sense to him?
11. Suppose two people are discussing how the electric charge is distributed in neutral atoms. Each draws a picture to help explain his or her idea.



- a) Which person do you believe, and why?
 - b) Are there problems with either of the models? Explain.
12. *Preparing for the Chapter Challenge*

How might you show the proper scale of the nucleus and the atom in your museum exhibit? In other words, if a model of the nucleus were the size of a grape, how large would the entire atom be (with its electrons)?