SECTION 3

The Size of a Nucleus: How Big Is Small?

Section Overview

Using a piece of paper, a penny, and a pencil, students perform an experiment similar to Rutherford's and calculate the area of a penny by counting the number of times a pencil hits or misses a target. The experiment, which is similar to Rutherford's experiment to determine the existence and size of the nucleus, helps students discover how indirect measurements are useful in determining the size and presence of an entity that cannot be seen or measured directly. Students relate their *Investigate* to Rutherford's determination of the size of the nucleus, and the development of the planetary model of an atom and learn how it differs from Thomson's plum-pudding model. In the *Physics Talk*, they read how Rutherford used alpha particles to bombard the gold foil and from the results calculated the presence and size of the nucleus. The structure of an atom is thus gradually revealed through experiment and discovery and students test their understanding by solving problems at the end of this section.

Background Information

The Rutherford scattering experiment is one of the hallmark achievements in physics. It not only yielded our understanding of the structure of the atom with a dense, positive nucleus at the center, but it provided a size for that nucleus. It created a gateway to our understanding of atomic structure that led to much of twentieth-century physics.

In this section, students learn how Ernest Rutherford discovered the size and placement of the positive charge in the atom. To do this, students will set up a simulation of Rutherford's experiment. Rutherford (with his colleagues Marsden and Geiger) fired positively charged particles (alpha particles) at a gold foil, which was thin enough to be about one atom thick to avoid the chances of multiple scatterings by a single alpha (the gold foil was thin like the gold leaf used to make lettering on glass). The alpha particles are emitted in some kinds of radioactive decay (Rutherford's source of alphas), and turn out to be helium-4 nuclei. They are very energetic (kinetic energies of several MeV) when striking the gold.

Alpha particles have a mass 7,344 times the mass of the electron and a charge opposite the electron's, but twice the magnitude. Therefore, with so much energy and mass, the effect of the electrons on the alphas is negligible. The alphas interact with essentially only the positive charges in the gold metal, and thus can probe how that positive charge is distributed. From the statistics of the deflection in the trajectories of the alpha particles, Rutherford inferred the size of the positive charge in the atom, and thereby discovered the nucleus.

Crucial Physics

- Indirect measurement techniques are necessary to measure the size of the nucleus. The Rutherford experiment of bombarding the nucleus with alpha particles is an example of such a technique.
- Models of the atom allow scientist to develop a picture of the atom. The Rutherford model showed that the atom consists of a nucleus that has a positive charge and almost all of the atom's mass. The nucleus is surrounded by negatively charged electrons that have a total charge equal in magnitude to the charge on the nucleus.
- The nucleus of the atom is of the order of 10^{-5} times the size of the atom, defined by the electron-orbit radius. This means the interior of the atom consists of mostly empty space.

Learning Outcomes	Location in the Section	Evidence of Understanding
Calculate the area of a penny using indirect measurement techniques.	***Investigate*** Steps 2–6	Students trace a penny many times within a 10 cm × 10 cm square and drop a pencil on the card to see where it lands. They record the number of times the pencil lands within a circle, calling it a hit, and using the hypothesis that the ratio of hits to misses is related to the percentage of area occupied by the pennies calculate the area a single penny.
Compare statistical measurements to direct measurements.	***Investigate*** Step 7 ***Physics Talk***	Students compare the difference in results of the area of a penny using direct and indirect measurements. They measure the diameter of a penny with a ruler, calculate its area and compare the value to the area obtained by the indirect (dropping the pencil) method.
Relate the Rutherford scattering experiment to the penny simulation.	***Physics Talk*** ***Checking Up***	Students relate their indirect method of measuring a penny in the *Investigate* to Rutherford's experiment where few alpha particles are deflected when they are bombarded on a piece of gold foil.
Describe the relative scale of the nucleus to the atom.	***Physics Talk*** ***Physics to Go*** Questions 7 and 12	Students read and describe how tiny the nucleus is compared to the size of an atom.

Section 3 Materials, Preparation, and Safety

Materials and Equipment

PLAN A and PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Ruler, metric (in./cm)	1 per group	
Paper, single sheet	1 per group	
Pennies*		600 per class
Pencil*	2 per group	

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the students to complete the *Investigate* portion of the section.

Teacher Preparation

- If desired, prepare copies of the 10 cm by 10 cm square with circles. A scale copy is provided as a Blackline Master in the *Teacher Resources* CD.
- Have a pencil available for each group to use to drop, with spares if the point breaks when dropped. Pencils will leave a small clear mark that is easy to interpret as to location.
- Search the Internet to find a Web site that has an animation of the Rutherford experiment to show the students.

Safety Requirements

- Safety goggles are of particular importance in this activity.
- "Markers" are not suggested for use since their tips will become deformed and may splatter ink.
- Caution the students to stand clear of the target area when the pencil is being dropped to avoid possible injury due to a bounce.

NOTES

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Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Counting the number of hits on the pencil drop	***Investigate*** Step 3 ***Physics to Go*** Steps 1 and 2	**Augmentation** • Students who struggle with attention or visual tasks may have a difficult time accurately counting the number of hits resulting from their pencil drops. When counting, ask students to use a colored pencil to mark each hit they count. If students use a light color the first time, they can check their count with a darker color a second time. • Some students may be distracted by other students counting aloud and then lose track of which dots they have already counted. Ask students to count quietly. • Pair students strategically to make sure there is at least one student in each group who will be focused and as accurate as possible.
Solving for the unknown in a proportion	***Investigate*** Step 4 ***Physics to Go*** Questions 1, 2, 6, and 9	**Augmentation** • Students who struggle with math calculation may need to review the strategy for finding the unknown value in a proportion. Remind students that they can cross multiply and then set the cross products equal to each other and solve for the unknown variable.
Comparing small decimal numbers	***Investigate*** Step 7 ***Physics to Go*** Question 3	**Augmentation** • Understanding decimal values is very important in this chapter because charge, electrical force, and atomic size are all very small values. However, comparing decimal values is a very difficult task for many students. When asked which number is larger, students often choose the decimal number with more digits or the decimal number that begins with the larger number, and they often misunderstand the role of zeros in decimals. • Show students how to line up the decimal numbers one below the other with the decimal points lined up. This helps students compare the decimals at each place value. Then they will be able to compare their results for the area of a penny. **Accommodation** • Provide graph paper for students to use to line up their decimal numbers for comparison.
Understanding the development of the atomic model	***Physics Talk***	**Augmentation** • Help students who struggle with reading comprehension understand and compare the atomic models by making a class chart to compare the different atomic models. The chart could include who made the model, when the model was made, the process by which the discovery was made, and how it changed from previous models. Many students will have trouble doing this activity on their own and will comprehend more if this is tackled as a group. Each small group could find the information for one discovery, and then the whole group could complete the comparison by discussing how the model changed. Students can also add to the chart as they progress through the chapter and more discoveries are discussed. • This comparison chart can be used to help students develop their museum exhibit. **Accommodation** • Provide students with a completed chart that includes the scientists and their addition to the atomic model. Students can use this list to help them develop their museum exhibit.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Comprehension	***Investigate***	Collaborate with the students' math teachers to determine what level of comprehension students have obtained for working with probability, ratio, and pi (π).
Vocabulary comprehension	***Investigate*** Step 4	Take this opportunity to review the definition of "hypothesis" with your class.
Comprehension	***Physics Talk***	Have students read a section of text. Then connect the reading back to the portion of the *Investigate* that addressed related concepts. Breaking the reading into smaller portions and providing direct connections with hands-on learning will solidify content for English learners as well as for kinesthetic learners.
Understanding concepts Writing skill	***Physics Talk*** Rutherford's Experiment	After students have read about Rutherford's discovery of the nucleus, hold a class discussion to go over his procedure. Clear up any questions students may have. Challenge students to explain why his investigation is known as his "scattering experiment." Then have students close their books and write a summary of the experiment in their *Active Physics* logs. Review the summaries, providing feedback to ELL students on their use of grammar, spelling, punctuation, vocabulary, full sentences, and accuracy.
Organizing information	***Physics Essential Questions*** How do you know?	Comparing and contrasting is an important skill in science, but one that many students find difficult. Sometimes, visual displays of information can help students understand concepts better than plain text can. Suggest that ELL students and visual learners use Venn diagrams to organize the similarities and differences between their experiment and Rutherford's experiment.
Reading comprehension	***Checking Up*** ***What Do You Think Now?***	Provide additional practice using technical terms in the lesson. One way to do this is to ask students to include certain terms in their responses for *Checking Up* and *What Do You Think Now?* Possible terms in this activity include "atom," "nucleus," "indirect measurement," "direct measurement," and "alpha particles."
Higher order thinking	***Physics to Go*** Question 5	After students have answered Question 5, have them think back to the preceding section, when they compared their determined value for the mass of a penny to the values arrived at by other groups. Remind them that they were increasingly confident in their own value when they learned that other groups had come up with similar values. Now ask, "How is the experimental reliability of several groups conducting one trial each similar to the reliability of one group conducting several trials?"
Understanding concepts	***Physics to Go*** Question 10	Students learned about analogies in the previous section and were challenged to come up with some of their own. Here, students have an opportunity to learn about metaphors. Review the definition of "metaphor" with students, discuss Rutherford's artillery shell metaphor, and then have students come up with a metaphor of their own.

SECTION 3

Teaching Suggestions and Sample Answers

What Do You See?

This illustration captures the curiosity of three investigators who seem to be recording the path of the projector's rays through a gold screen. You might want to ask students why one person has binoculars, the other is recording, while the third is just observing. As the students are initiated into discussion, ask them to note aspects of this visual because the artist is trying to convey a famous scientific experiment. At this stage, they do not have to know the experiment but they are expected to describe what they actually see in the illustration. Point out that the more intently they look at this visual, the more nuances they will be able to describe. Remind students that the *What Do You Think?* questions are a precursor to the continuing array of inquiry-based investigations. Insist that their active participation in what they see will lead them to think of what the artist is trying to convey through this illustration.

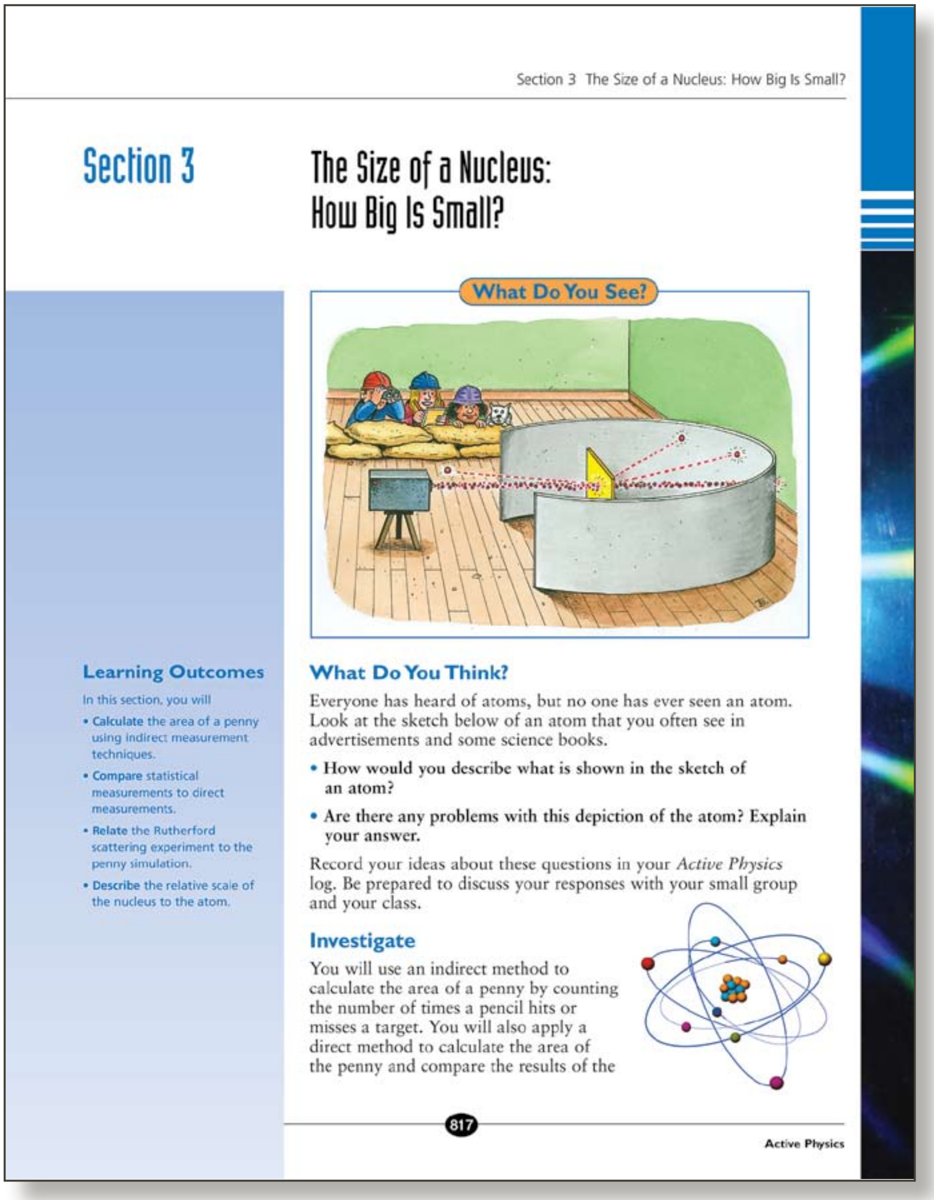
What Do You Think?

Students might be familiar with the structure of an atom and you could find them responding quickly to the first question but they may not be so immediate in their response to the second question. Encourage them to think of the size of the parts comprising an atom. Let students know that each question is meant to guide them through an inquiry-based technique that helps them focus on concepts they will be learning in the section. Emphasize that this stage is not for evaluating what they know, but rather it is to prepare them to actively seek answers by making connections to what they have previously learned. Require students to write their responses in their *Active Physics* logs and share their answers with their class members.

Students' Prior Conceptions

The discussion of the classic gold foil experiment conducted by Rutherford and the comparison of the penny-drop experiment to the scattering pattern of alpha particles encourages students to develop a mental image of an atom, particularly of the nucleus of an atom and the distribution of mass and charge within the atom.

1. **Students often hold the beliefs that there is only one correct model of the atom and physicists currently have the "right" model of the atom.** As this chapter proceeds and students meet scientists that continue to explore the nature of the atom and atomic structure, you may focus on the historical models of the atom from the Greeks to modern times. Encourage students to explore the modern atom at "The Particle Adventure" on the Web. This site also provides excellent insight into the nature of fundamental forces and particles.
2. **Students believe that hydrogen is a typical atom.** Emphasize hydrogen's special location in the Periodic Table and that it is the only atom containing a single positively charged proton bound through Coulomb forces to a single, negatively charged electron. Hydrogen does not have a neutron in the nucleus. The typical diagram that is used to depict an atom, such as the diagram below *What Do You Think?* in the student text, is occasionally confused with a hydrogen atom, though it has numerous electrons, protons, and neutrons.



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

What Do You Think?

A Physicist's Response

The sketch shows a central core called the nucleus, which has protons and neutrons, while the electrons seem to be spinning about the nucleus in different orbits. Although this is a very common depiction of the nucleus, there are numerous errors in the presentation. The relative size of the nucleus containing the protons and neutrons is much smaller (approximately $1/10{,}000$ the size of the atom) compared to the size of the electron orbits. In the diagram shown, the nucleus should be so small as to be virtually invisible to the student. In addition, it appears that the number of protons in the nucleus is not equal to the number of electrons in orbit, as is necessary for a neutral atom. Finally, as the students will see in the following section, the orbits of the electrons are far more complex than the simple circles shown, and indeed circular orbits such as these are impossible.

3. **Students believe that electrons physically are larger than protons.** As you discuss the meaning of Rutherford's experiment, students should recognize that the alpha particles passed through the orbit of electrons to reflect off the heavier, more massive nucleus composed of protons and neutrons. An electron is about $1/1800$ times the mass of a proton.

Investigate

1.a)

You could have been using B, C, or E.

1.b)

Yes, your answer would change because the number of hits would occupy one-fourth the space on the circular area of the dartboard. Therefore, the choice would be D.

2.

Students trace a penny many times within a square they hand sketch with a ruler, or use the to scale copy provided as a Blackline Master in the *Teacher Resources* CD.

8-3a **Blackline Master**

Teaching Tip

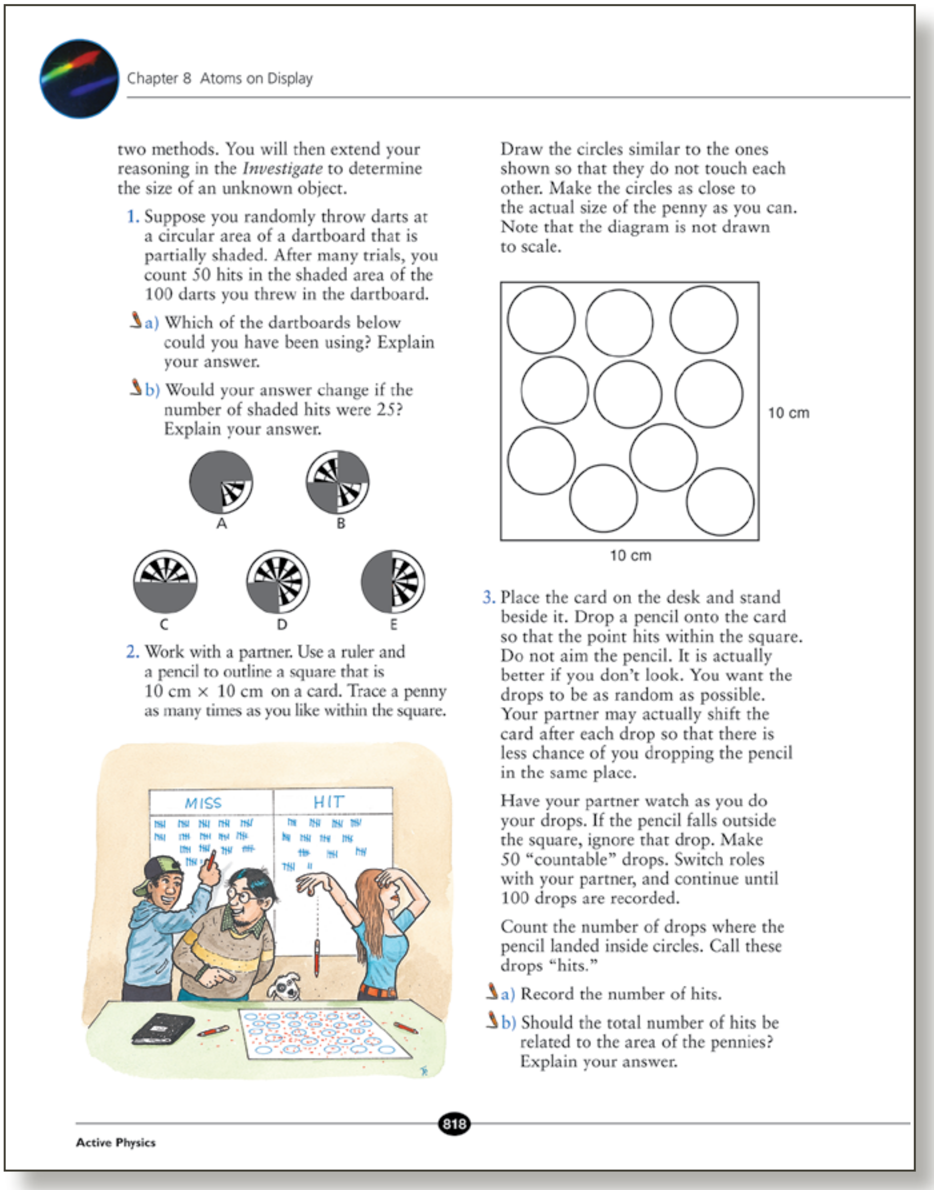
Have pencils available for each group to drop on the targets, rather than pens or markers. Both pens and markers will leave marks, but do not survive repeated drops well. Sharpened pencils leave a clear mark that is easy to distinguish. If it is necessary to save time, students could only do 50 drops, in which case a square of 7.1 cm on a side will have an area of 50 cm^2, keeping the ratio of hits to drops math friendly.

3.a)

Students record the number of hits in 50 drops.

3.b)

The total number of hits is related to the number of drops because the pencil can fall anywhere in the square and the area of the "pennies" is a fraction of the total area of the square.



Chapter 8 Atoms on Display

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 × 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.

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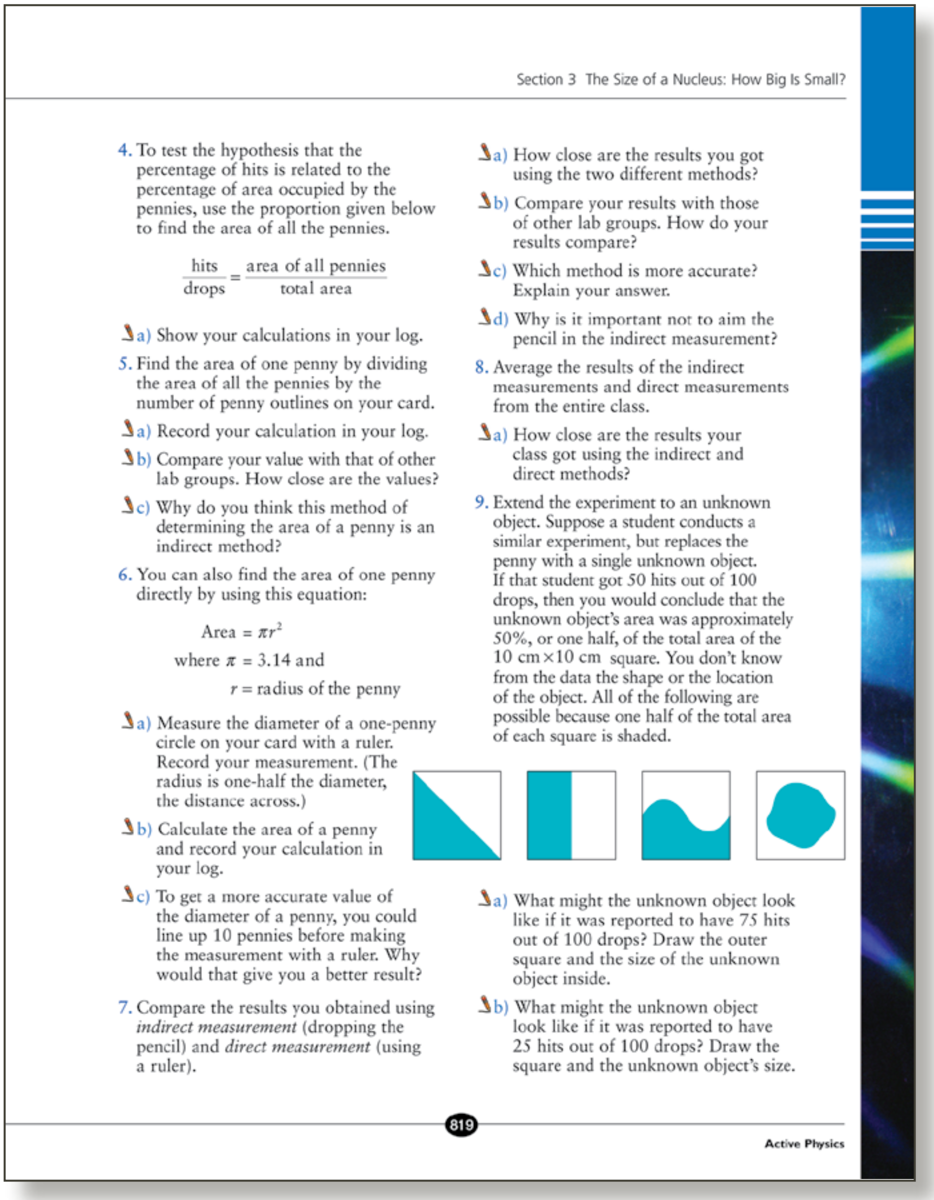
Active Physics



Section 3 The Size of a Nucleus: How Big Is Small?

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 $10\text{ cm} \times 10\text{ cm}$ 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.

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Active Physics

4.a)

Students' calculations will vary. Let's assume 28 hits out of 100 drops.

28 hits/100 drops = area of all pennies/100 cm^2

area of all pennies = 28 cm^2

5.a)

Assuming 10 penny-outlines on the card: Area of one penny = 28 cm^2/10 = 2.8 cm^2.

5.b)

Students' values will vary, but the average of the class should be quite close to the actual value for the penny.

5.c)

The method is indirect because the actual radius of a penny is not used to calculate area.

6.a)

Radius of a penny = 0.95 cm

6.b)

Area = πr^2 = $(3.14)(0.95\text{ cm})^2 = 2.84\text{ cm}^2$

6.c)

By lining up 10 pennies, you get to measure a larger distance and then divide by 10. The potential error in your number will now be only one-tenth as high as before.

7.a)

Students respond based on their data.

7.b)

Students compare their data with other lab groups and record how their results compare with other groups.

7.c)

Direct measurement with a ruler may seem more accurate, but if enough trials are done, then statistically, the method using the indirect measurement will be more accurate.

7.d)

Aiming the pencil in the indirect measurement adds statistical bias.

8.a)

For the entire class, the average of the groups for the statistical method of dropping the pencil should be quite close to the measured value.

9.a)

Many shapes are possible, but the object should cover 75% of the square.

9.b)

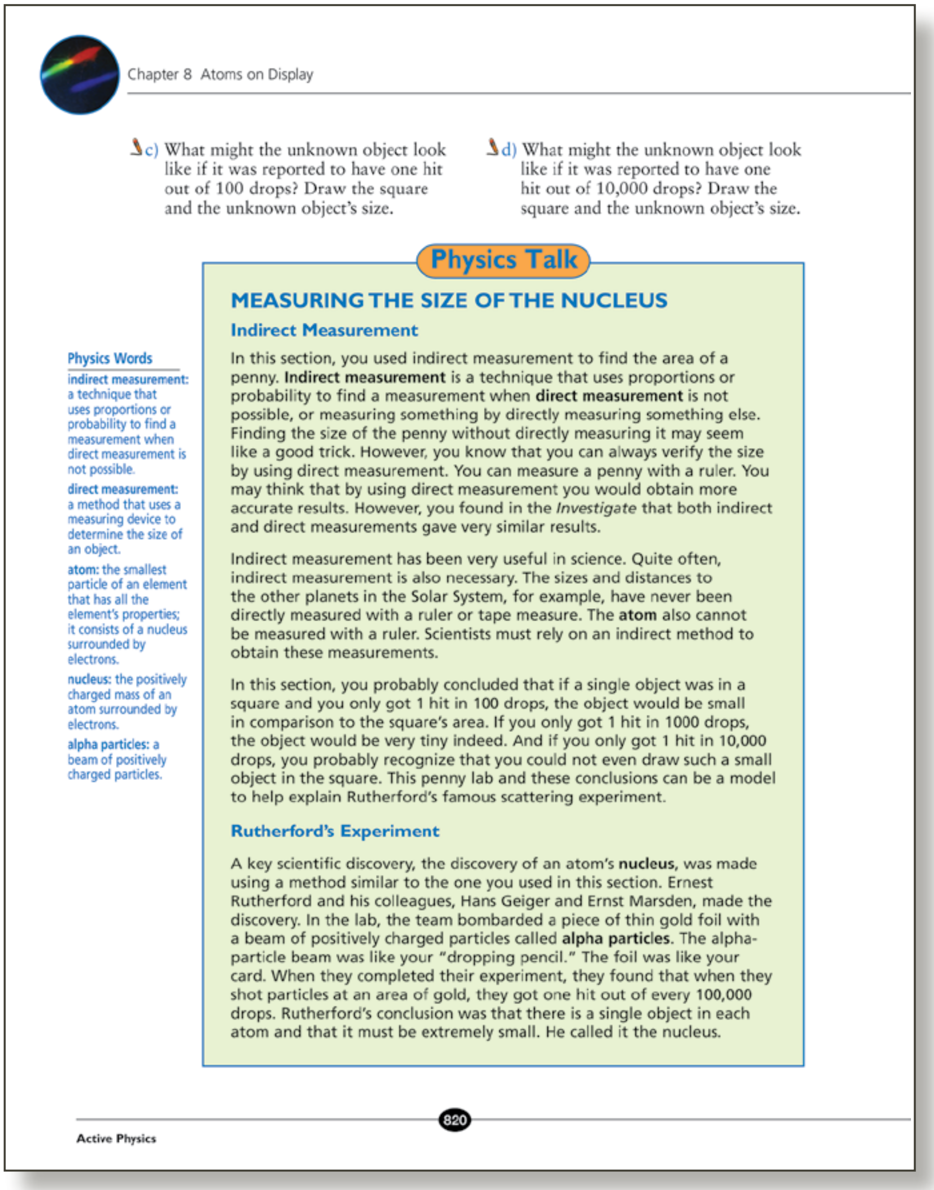
Many shapes are possible, but the object should cover 25% of the square. A square that is quartered into four equal pieces with one quarter shaded will be the most common answer.

9.c)

If there was one hit for every 100 drops, the shaded area would be very small (1/100th of the total area). Students should realize this would be a box 1 cm on a side when drawn within a 10 cm by 10 cm box.

9.d)

If there is one hit for every 10,000 drops, students should recognize that the shaded area marking the region is so small that it would be difficult to draw, even within a 10 cm by 10 cm box, a square being only one millimeter on a side.



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.

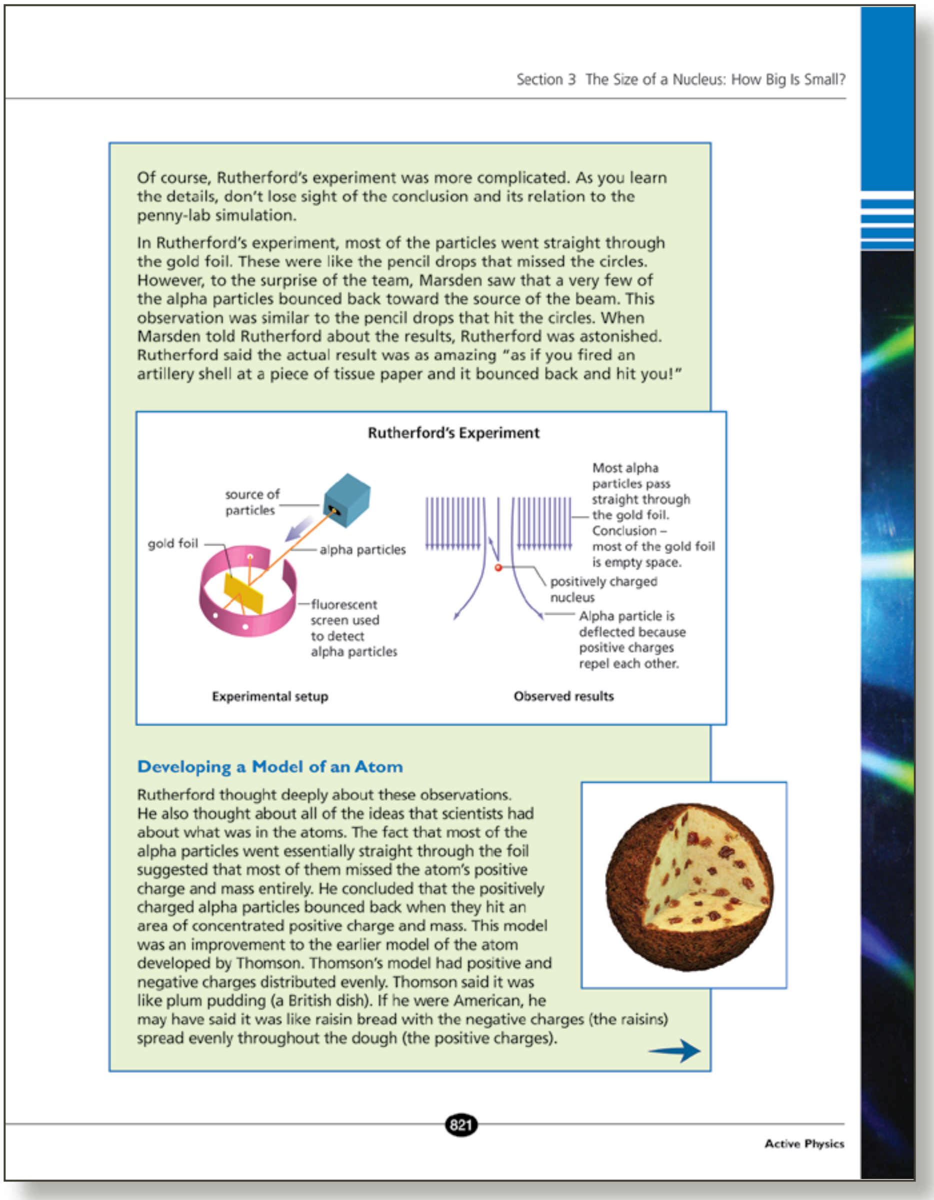
Physics Talk

This section leads students through an explanation of how scientists measure something when it is not possible to carry out a measurement directly. Direct and indirect measurement techniques are defined and differentiated to show how accurate results are obtained using both methods. Students read about Rutherford's experiment and learn how the planetary model of an atom was developed. They discover that most of matter is empty space occupied by rapidly moving electrons creating the effect of a solid, with the nucleus only filling a tiny portion of the area at the center of the atom.

To clarify the purpose of indirect measurements employed by scientists, discuss how scientists are able to reach verifiable conclusions without using direct measurement techniques. In your discussion, highlight the indirect-measurement method by continually referring to the steps in the *Investigate*. Then ask students to explain the difference between direct and indirect measurements. Consider asking them why an atom or a virus cannot be measured with a ruler.

Discuss Rutherford's experiment and explain how the simulation in the *Investigate* helps them understand Rutherford's technique. Ask students to show a comparison between their experiment and Rutherford's. Students should describe what happens when alpha particles strike the thin gold foil and how Rutherford reached the conclusion that it was the nucleus that was deflecting the alpha particles.

Discuss Thomson's plum-pudding model and how Rutherford improved this model. While the calculations that Rutherford made to measure the size of 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!"

Rutherford's Experiment

Experimental setup

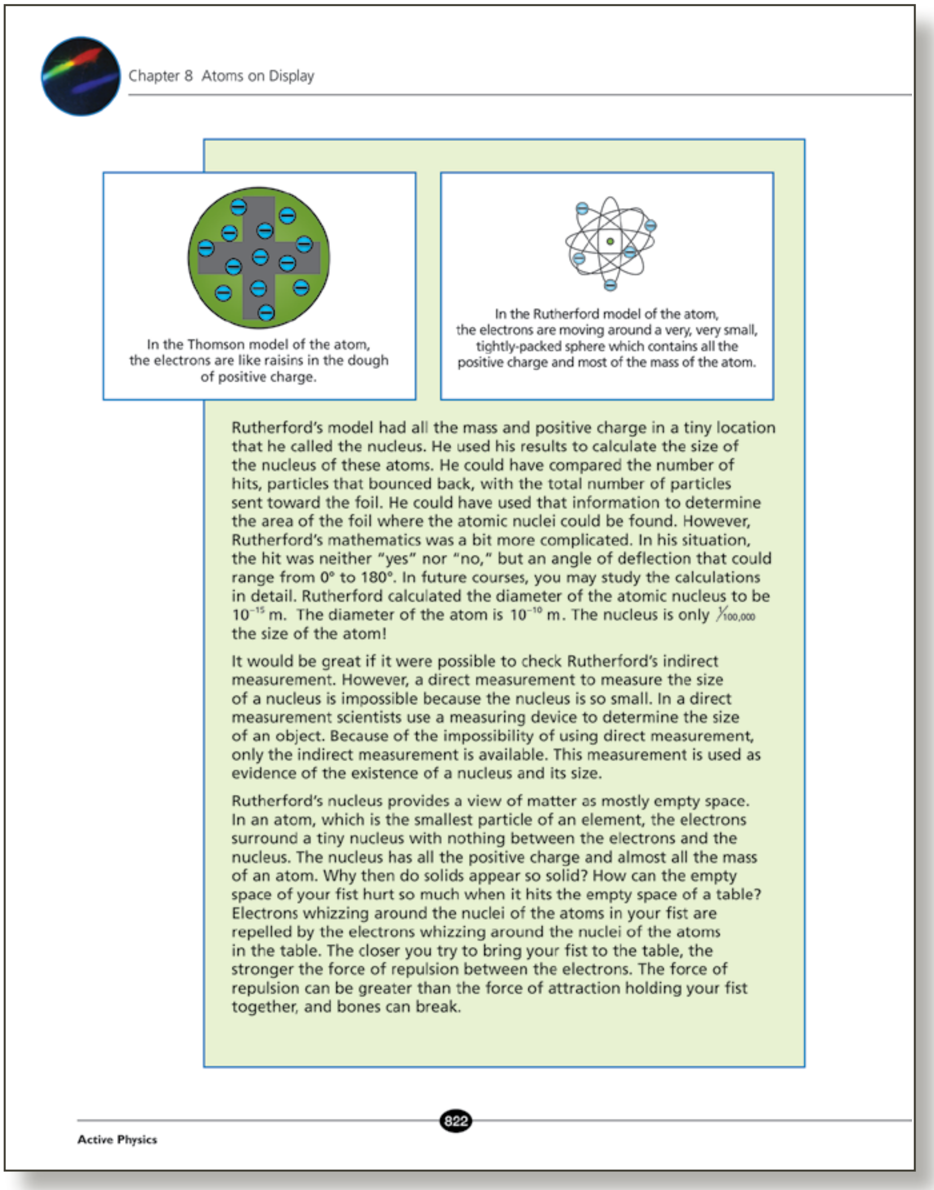
Observed results

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).

are beyond the scope of this section, you might want to ask students to think of a few ways in which Rutherford might have calculated the size of a nucleus. The thought of electrons whizzing around the nucleus creates quite a formidable picture in people's minds, and having students draw or sculpt the model of an atom to scale will lead them to appreciate its structure and the fine nuances that constitute the makeup of matter so remarkable.

8-3b Blackline Master



Chapter 8 Atoms on Display

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.

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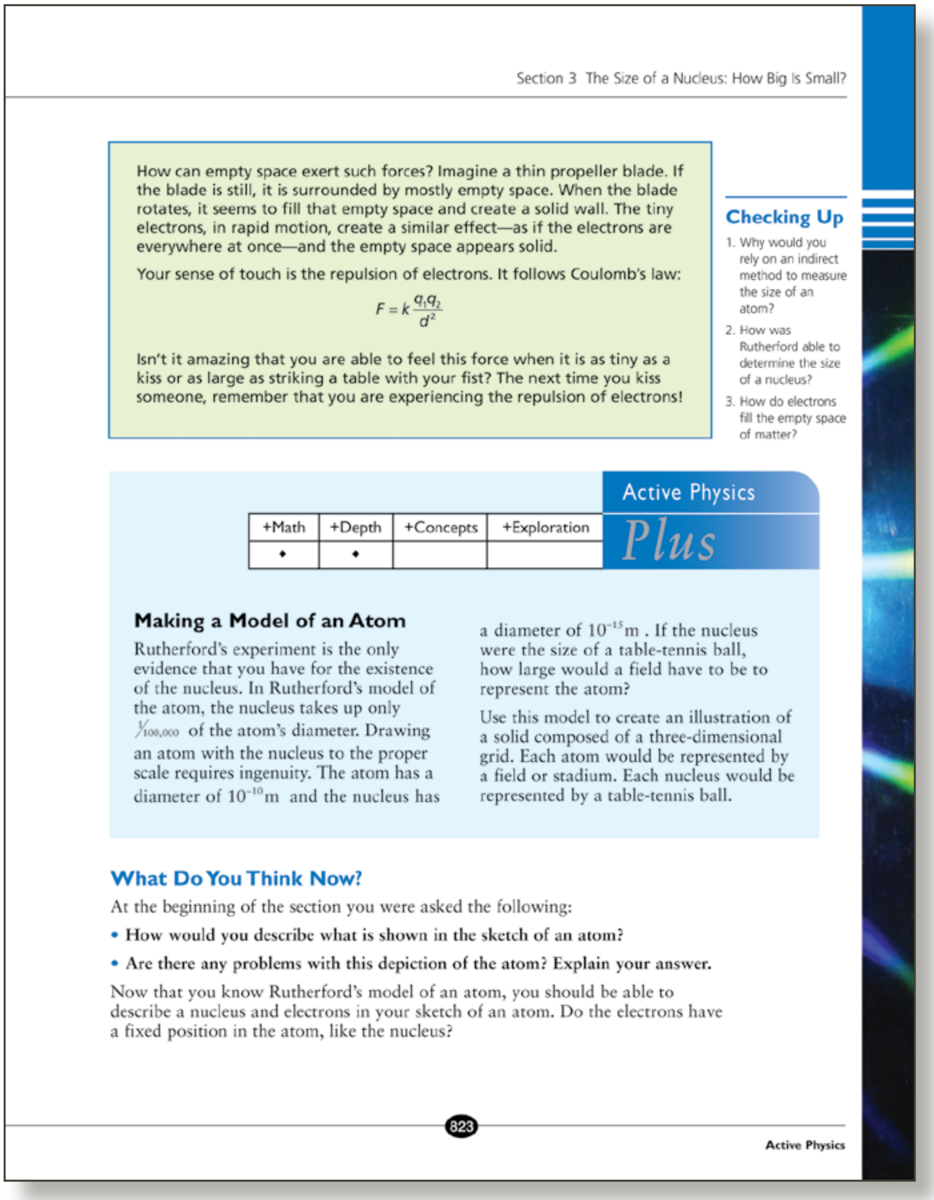

Section 3 The Size of a Nucleus: How Big Is Small?

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 *Plus*

+Math	+Depth	+Concepts	+Exploration
◆	◆		

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?

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Checking Up

1.

Because the size of an atom is so small, it is very difficult to measure the atom's size by direct methods such as using a ruler and your eye. An indirect method can often give equally good or better results than a direct method. The nucleus of the atom is much smaller, and can only be measured by indirect means.

2.

Rutherford's experiment was in some ways similar to the method used in this section's *Investigate*. However, Rutherford was also able to determine the energy of the bombarding alpha particles. From this energy and an understanding of the charge on the gold nucleus and Coulomb's law, he was able to make calculations to check the indirect method.

3.

Electrons fill the empty space of matter by orbiting around the nucleus and exerting a repulsive force on the electrons of other atoms. This repulsive force is what appears to give matter its "solid" form, even though most of the atom is empty space.

Active Physics Plus

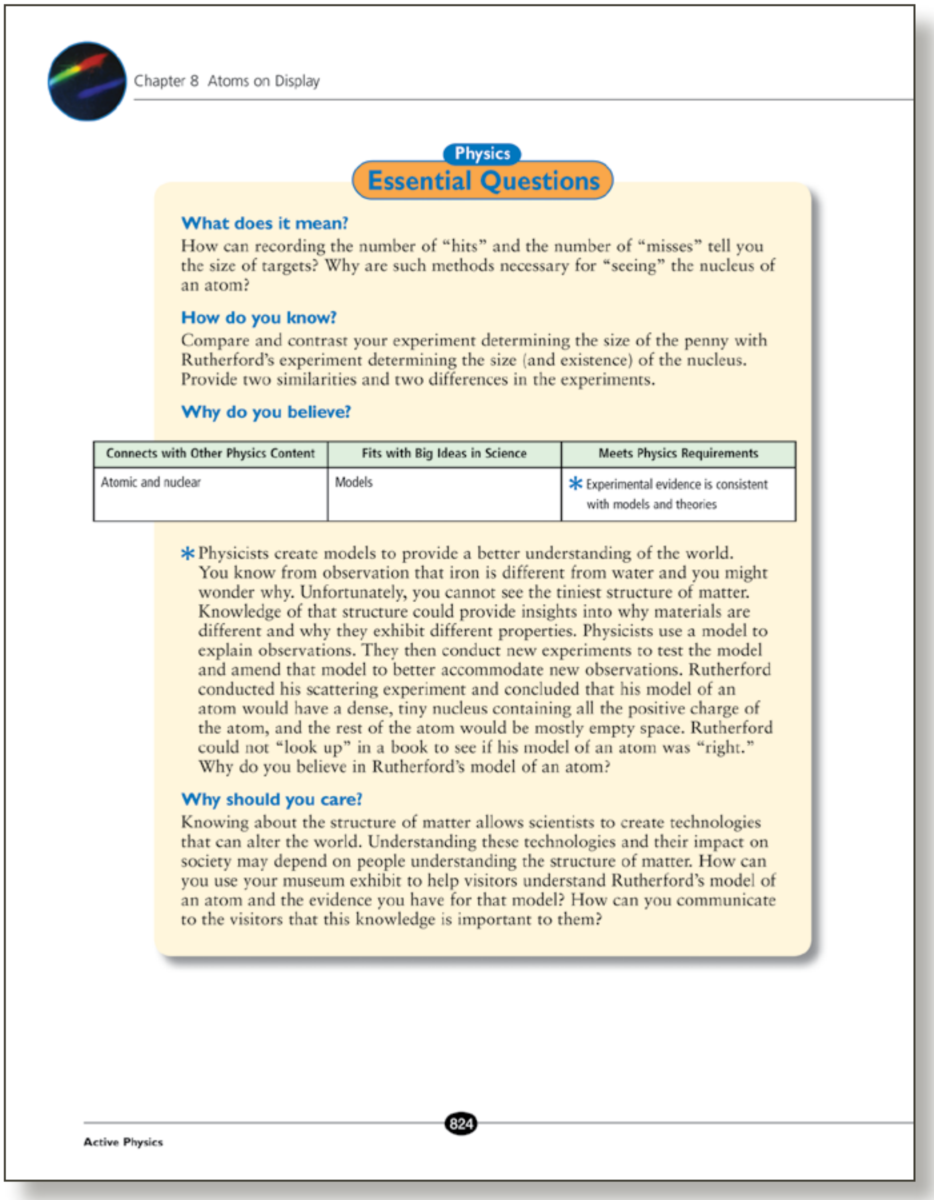
A table-tennis ball is 4 cm in diameter. If the table-tennis ball represents the nucleus, and the diameter of the atom is 10^5 times greater than the table-tennis ball, it must have a diameter of 4×10^5 cm or 4 km. The illustration showing this would have to employ landmarks outside the stadium to show the size of the atoms relative to the nucleus.

What Do You Think Now?

Students should be able to describe the structure of an atom and indicate the position of the nucleus and the electrons, and their relative sizes in their diagrams. Ask them to revise their earlier descriptions and how the sketch depicting the atom could be modified to present a more accurate picture. Provide students with answers to *A Physicist's Response* and encourage them to ask questions. Students should understand that the negative electrons orbit around the nucleus, which has all the positive charge. Revisiting the *What Do You See?* illustration will help students to understand the finer aspects of what the artist was trying to convey and how it applies to the model of the atom developed by Rutherford.

Reflecting on the Section and the Challenge

This section provides students the opportunity to reflect on Rutherford's experiment and how indirect measurement was useful in determining the structure of an atom. Consider asking students why probability may be used in measuring the size of the penny, and how this is similar to Rutherford's experiment when determining the size of the nucleus. Encourage students to start thinking of how they can use knowledge gained in this section toward their *Chapter Challenge*. Point out that they should start thinking of how they would be able to grab their visitors' attention in their museum display. Emphasize that in their model of an atom they should use Rutherford's model to show how it helps in determining the structure of an atom.



Chapter 8 Atoms on Display

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?

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Physics Essential Questions

What does it mean?

The number of hits will be directly proportional to the size of the target. This is based on the laws of probability. Because a nucleus is too small to measure directly you must use probability.

How do you know?

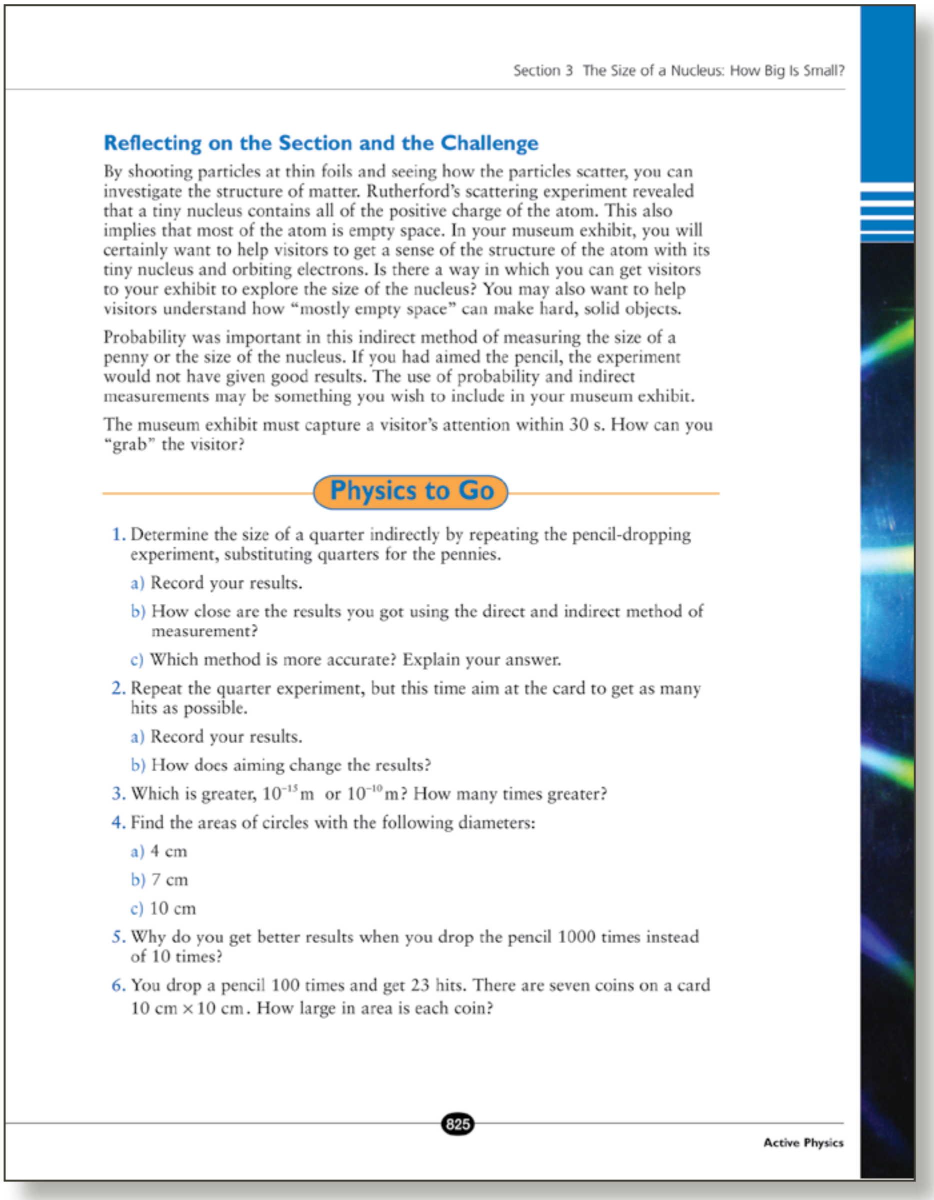
Both the penny lab and Rutherford's experiment used the concept of probability to determine the target size. In both experiments, you do not aim the object at the target. The penny lab and Rutherford's experiment are different because the penny lab is either a hit or a miss, while the alpha particle can be deflected by varying amounts. Another difference is that the repulsion in Rutherford's experiment is explained as the interaction between the positively charged alpha particle and the positively charged nucleus.

Why do you believe?

You believe in Rutherford's model of an atom because the existing evidence supports the explanation.

Why should you care?

You could relate the structure of the atom to our ability to use nanotechnologies.



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

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

Physics to Go

1.a)

Student results will vary.

1.b)

The direct method: radius of a quarter = 1.2 cm

$A = \pi r^2 = (3.14)(1.2\ \text{cm})^2 = 4.5\ \text{cm}^2$

1.c)

Both methods are accurate. If we increase the number of drops, the indirect method will eventually become more accurate.

2.a)

Student results will vary.

2.b)

By aiming at the card, students will skew the result so that the quarter calculations emerge as much too large (if they aim at the quarter) or much too small (if they aim away from the quarter).

3.

10^{-10} is 10^5 or 100,000 times larger than 10^{-15}.

4.a)

$A = \pi r^2 =$

$(3.14)(2\ \text{cm})^2 = 12.57\ \text{cm}^2$

4.b)

$A = \pi r^2 =$

$(3.14)(3.5\ \text{cm})^2 = 38.48\ \text{cm}^2$

4.c)

$A = \pi r^2 =$

$(3.14)(5\ \text{cm})^2 = 78.54\ \text{cm}^2$

5.

Any statistical variations (a lucky hit) will be averaged out with more drops.

6.

$$\frac{23\ \text{hits}}{100\ \text{drops}} = \frac{\text{area of all coins}}{100\ \text{cm}^2}$$

Area of all coins = 23 cm^2
With 7 coins on the card:
Area of one coin =
area of all coins/7 =
$23\ \text{cm}^2/7 = 3.3\ \text{cm}^2$

7.

Because the atom is 100,000 times $\left(10^5\right)$ as large as the nucleus, then the atom would be

$$100{,}000 \times 1 \text{ cm} = 1000 \text{ m} = 1 \text{ km}$$

diameter and the next nucleus would be twice this distance or 2 km away.

8.

As the positive alpha particles got closer to the positive nucleus, then the force would be larger and the deflection would be larger as well.

9.

All of the targets together cover $1/1000$ of the area A. Therefore the 10 atoms occupy area $A/1000$. Since this is the area covered by 10 atoms, the area per atom is $1/10$th of this, or $A/10{,}000$.

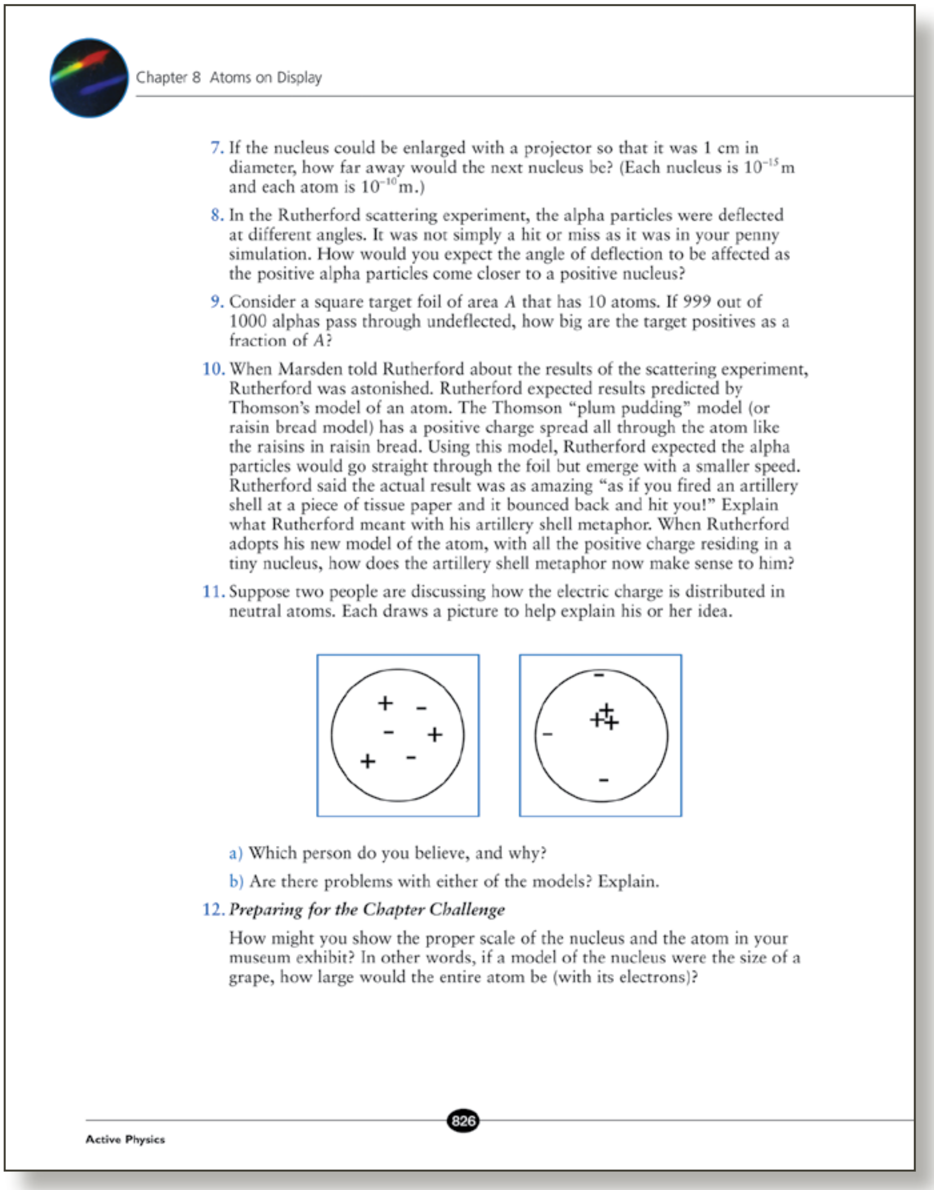
10.

Rutherford thought that the alpha particles had so much energy that when they collided with a bit of positive charge, like the positive charge on the alpha particle the difference in energy would be so great that the particle could never bounce back.

Once Rutherford realized all the mass of the atom could be concentrated into one very small part of the atom, it became the difference between striking a can of shaving cream rather than all of the foam spread out over many cubic meters.

11.a)

The drawing on the right is more indicative of the correct charge distribution.



Chapter 8 Atoms on Display

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)?

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11.b)

The drawing on the right is supported by Rutherford's experiment, where positive charges are centered in a tightly packed sphere and negative charges revolving around it.

12.

Preparing for the Chapter Challenge

Student answers will vary.

NOTES

SECTION 3 QUIZ

8-3c **Blackline Master**

1. In the Rutherford experiment, alpha particles were directed at a thin sheet of gold foil. Most of the alpha particles
   - a) were deflected at large angles.
   - b) were stopped by the gold foil.
   - c) passed right through the gold foil undeflected.
   - d) were captured by the gold atoms.

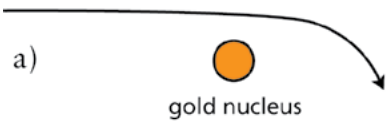
2. To determine the size of the atomic nucleus, Rutherford relied upon
   - a) direct measurement of the size, using the electron as a measuring scale.
   - b) direct measurement, using the alpha particles as a measuring scale.
   - c) indirect measurement, using electrons as a probe.
   - d) indirect measurement, using alpha particles as a probe.

3. In the Rutherford experiment, when some of the very energetic alpha particles were scattered back through large angles, Rutherford concluded
   - a) electrons have small masses.
   - b) electrons have quantized charges.
   - c) gold foil is the only material that can stop alpha particles.
   - d) the charge and mass of the atom must be concentrated in a very small volume.

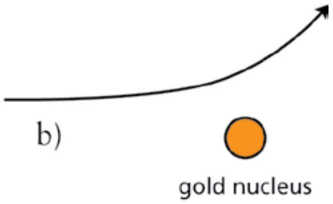
4. After directing alpha particles at gold foil, Rutherford concluded that most of the atom was empty space. He based his conclusion on the fact that
   - a) some of the alpha particles were deflected through large angles.
   - b) most of the alpha particles were not deflected.
   - c) the electron has only a small mass.
   - d) alpha particles hitting electrons are stopped.

5. Which diagram below best represents the path of an alpha particle as it comes near the nucleus of a gold atom?

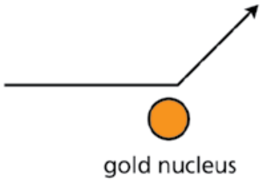
a)



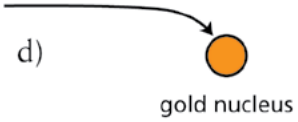
b)



c)



d)



SECTION 3 QUIZ ANSWERS

① c) passed right through the gold foil undeflected. Due to the very high energy of the alpha particles, most were able to pass right through the thin gold foil, since they only struck the electrons that circle the nucleus. The nucleus is such a small portion of the atom that a nuclear hit is very unlikely, and thus most alpha particles pass right through.

② d) indirect measurement, using alpha particles as a probe. Because of the extremely small size of the atom and the nucleus, Rutherford could not make a direct measurement, and thus had to rely on indirect methods and inference to determine the atomic structure.

③ d) the charge and mass of the atom must be concentrated in a very small volume. For a particle as energetic as the alphas that Rutherford was using to be deflected required an object that was much more massive than the alphas and was able to exert a large force. The mass and charge had to be concentrated in a small area to present a sufficiently large force to deflect the alphas, and not be moved by the alpha particles.

④ b) most of the alpha particles were not deflected.

⑤ b) As the positively charged alpha particle approaches the positively charged gold nuclease, it arcs away as the repellant forces increase.