SECTION 2

The Nature of Charge: Tiny and Indivisible

Section Overview

In a simulation of Millikan's oil-drop experiment, students develop a strategy to find the mass of a single penny by making a possible list of different masses of each container and containers filled with varying numbers of coins. They measure the mass of an empty container and also the masses of the other containers that have an unknown number of pennies inside to determine the mass of a single penny. They compare their values with members of other groups. The students then consider what would happen if they were to measure the weight of the containers with nickels in them, rather than pennies. By considering possible masses of the containers and assuming the mass of a nickel, students critique the accuracy of reported measurements and reasons for the differences between predicted and reported values without opening the container. Students relate their method of inquiry to the challenges faced by physicists when they have to determine the presence of something that cannot be directly seen. They then learn about the techniques employed by scientists to determine that electric charge is quantized.

Background Information

This section explains what it means for a quantity to be discrete (indivisible or "quantized"). The elementary particles of matter are discrete. This is illustrated using an analogy with pennies in a container to represent charges in an atom. Electric charge is quantized. There exists a smallest, fundamental unit of charge so that you can have one fundamental charge, two charges, three charges, etc., but you can never have fractional charges such as 1.4 charges or 2.7 charges. This is quite different from other quantities studied in physics. Mass does not seem to be quantized—any mass is permissible. Time does not seem to be quantized—any time is permissible.

Charge, however, comes in units that are multiples of 1.6×10^{-19} C. Robert Millikan found experimentally that charge was quantized by suspending a charged oil droplet within an electric field. The electric force up could be manipulated by varying the voltage between the plates of the capacitor. When the electric force was equal to the gravitational force, the oil drop would be at rest or would move up or down with a constant velocity. The gravitational force or weight of the oil droplet could be determined by watching it fall without an electrical force. When the droplet fell, it would acquire a terminal velocity that was dependent on its mass and properties of the air. The entire experiment had to be conducted through a microscope.

Quantum mechanics reveals that there are other qualities of the electron, in addition to charge, that are quantized. Energy levels in atoms are quantized, angular momentum is quantized and spin is quantized as well. The quantum numbers help define the electron configuration of atoms.

Crucial Physics

- All electric charge is quantized, and only comes in multiples of the fundamental charge on the proton and electron.
- The charge on the electron was obtained from the Millikan experiment. The charge on the electron is -1.6×10^{-19} Coulomb, and is equal and opposite to the charge on the proton ($+1.6 \times 10^{-19}$ Coulomb).
- Fractional charges of 1/3 and 2/3 that of the fundamental charge exist on quarks, but are never observed directly.

Learning Outcomes	Location in the Section	Evidence of Understanding
Detect the number of hidden pennies in a container without opening the container.	***Investigate*** Steps 1–2	Students find the mass of a single penny by making a list of possible masses of different containers that have an increasing number of pennies in them. They measure the mass of an empty container and use this to determine the number of pennies in each container as well the mass of a single penny.
Explain why the masses of containers with pennies can only have certain values.	***Investigate*** Steps 2–3	Students notice that the mass of each container varies at multiples of the same number. Therefore, they conclude that the mass of a penny can only have a certain value.
Describe the Millikan oil-drop experiment.	***Physics Talk*** ***Checking Up***	Students read and describe how Millikan suspended oil droplets between two charged plates to determine the charge on an electron.
Explain the meaning of quantization of charge.	***Physics Talk*** ***Checking Up*** ***Physics Essential Questions***	Students read and explain how the charge on electrons was determined to be in whole-number multiples of a single charge, and never in fractions.

CHAPTER 8

Section 2 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Film container, plastic (w/ top)	8 per group	
Scale, electronic, 0-1500 g, 0.1-g readability		4 per class
Pennies*		600 per class

*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

- Film canisters are no longer readily available due to the switch to digital photography, but may still be found in photography stores that develop film. Ask the proprietor well in advance to save as many of these as possible for you.
- If film canisters are not obtainable, any other small container of uniform mass may be substituted. If nothing is available, a bathroom paper cup could be used and sealed with a second cup on top. Do not add any tape or glue, as this would spoil the uniformity of the containers.
- If transparent film canisters are to be used, they should be lightly spray painted inside to make them opaque.
- If balances are not available, you will have to mass each canister and write it on a label for the students to read.
- Search the Internet to find a Web site that has an animation of the Millikan experiment to show the students.

Safety Requirements

- This *Investigate* has no particular safety requirements other than those consistent with good lab procedure.

NOTES

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Film container, plastic (w/ top)		8 per class
Scale, electronic, 0-1500 g, 0.1-g readability		4 per class
Pennies*		600 per class

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the teacher to do the *Investigate* portion of the section as a class demonstration, as well as complete the other parts of the section discussed in the *Plan B Pacing Guide*.

Teacher Preparation

- Film canisters are no longer readily available due to the switch to digital photography, but may still be found in photography stores that develop film. Ask the proprietor well in advance to save as many of these as possible for you.
- If film canisters are not obtainable, any other small container of uniform mass may be substituted. If nothing is available, a bathroom paper cup could be used and sealed with a second cup on top. Do not add any tape or glue, as this would spoil the uniformity of the containers.
- If transparent film canisters are to be used, they should be lightly spray painted inside to make them opaque.
- If balances are not available, you will have to mass each canister and write it on a label for the students to read.
- Recruit a student to record the data on a transparency or the board as you are weighing the canisters so the students may copy the data into their logs.
- Search the Internet to find a Web site that has an animation of the Millikan experiment to show the students.

Safety Requirements

- This *Investigate* has no particular safety requirements other than those consistent with good lab procedure.

CHAPTER 8

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Reading comprehension	***Physics Talk*** ***Checking Up*** ***Physics Essential Questions*** ***Physics to Go***	**Augmentation** • Understanding the text in *Physics Talk* is required to complete the rest of the questions in this section. Ask students to read the section one time individually. Then students should write down one thing they learned and one question they have about the section on a sticky note. Remind students to be as specific as possible. Next, students should reread the section with a partner and write down one new thing they have learned and one new question they have. Finally, lead a whole-group discussion during which students teach each other by sharing what they learned and trying to answer each other's questions. • Students could also collaborate during the group discussion to begin thinking about how their new knowledge and questions about Millikan's experiment could be used for the *Chapter Challenge*. Their questions will probably be the same questions that museum patrons will have. • Read *Physics Talk* aloud and provide direct instruction to teach and/or model Millikan's oil-drop experiment. **Accommodation** • Provide a reading guide that cues students into the key points in the text of this section.
Multiplying and dividing with exponents	***Active Physics Plus*** ***Physics to Go*** Questions 4–8	**Augmentation** • In order to find possible electric charges and coulomb equivalents for a certain number of electrons, students must be able to multiply and divide with exponents. Students could learn to do these calculations on their calculators, but they will probably need some practice and help to make sure they are using their calculators correctly. • It may also help students to review the skill of multiplying and dividing numbers with exponents. If students are required to use a manual method, some of them will also need to review how to add and subtract negative numbers.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Pronunciation	***Title***	Help students with the title of this section by modeling the pronunciation of both "quantization" and "indivisible." Students will encounter these terms, as well as the related terms "quantum," "quantize," and "indivisibility" throughout the section. Give them as many opportunities as possible to hear these words spoken properly and to speak these words aloud.
Higher order thinking	***Investigate*** Step 2.c)	Walk among students as they compare their value for the mass of a penny with the values determined by other groups. To begin a class discussion, ask the question put forth in the book: How does confidence in your value change as you compare it with more and more groups? Be sure students are able to explain *why* their confidence changes as it does. Expand the discussion to cover the text in the rest of *Step 2.c),* and challenge students to explain how scientific progress can be made when scientists use similar methods to conduct investigations and compare results. You may wish to expand the discussion further by asking how such sharing may lead scientists to conclude that more research is needed before any conclusions are drawn.
Writing skills	***Investigate*** Step 3.b)	Have as many ELL students as possible be the writers for their groups. To explain the fictitious lab group's error as well as possible, students should use appropriate vocabulary, write in complete sentences, and use correct grammar and punctuation. Have students hand in their explanations so that you can check their statements for scientific accuracy as well as for appropriate use of English.
Verbal skills	***Investigate*** Step 3.c)	Encourage ELL students to participate fully in the brainstorming discussions. All students may find it challenging to come up with three explanations for the 23-g mass. Encourage students to "think outside the box." They may not feel free to question the "facts" they were given about the canisters. Explain that their difficulty thinking creatively models one of the problems of progress in science. Often a paradigm shift is needed to accept that a set of observations cannot be explained by current theories. Another way of phrasing this is, "If you take everything you were told as absolute truth, then there can be no possible explanation. So something in your assumptions must be wrong." It could be experimental error, which would not necessitate a new theory, but there could also be other explanations that do require a new "theory of nickels."
Understanding concepts	***Physics Talk***	In the discussion of Millikan's oil-drop experiment, the penny—as the smallest unit of money—is used as an analogy to help explain the electric charge as something that cannot be further divided. To be sure students understand what an analogy is, challenge them to come up with analogies of their own. They can come up with another analogy for the indivisibility of electric charge, or they can formulate an analogy to explain anything they'd like. The only criterion is that they demonstrate understanding of the term "analogy."
Vocabulary comprehension	***Physics to Go*** Question 9	Students have learned that the atom, as small as it is, is made of even smaller parts, one of which is the electron. Challenge students to use that information to come up with a definition for "sub-atomic."
Writing skills	***Physics to Go*** Question 11	When students write a quote to explain the significance of the discovery of the electron, they should use related vocabulary where appropriate, and should try to present their quote as a complete, grammatically correct sentence.

SECTION 2

Teaching Suggestions and Sample Answers

What Do You See?

The classroom setting of this experiment should prompt students to respond to what students are engaged in finding. Initiate a class discussion on what is being recorded on the chart. Ask students how this visual would connect to what they are about to study. Remind them that they will have other opportunities to return to this illustration and reconnect with it. The purpose of the artist is to evoke students' curiosity and to elicit answers that you can refer to while explaining a concept. The student looking intently at the container on the weighing scale, another dropping coins into the container, or the coins scattered around the

Chapter 8 Atoms on Display

Section 2 The Nature of Charge: Tiny and Indivisible

What Do You See?

Learning Outcomes

In this section, you will

- **Detect** the number of hidden pennies in a container without opening the container.
- **Explain** why the masses of containers with pennies can only have certain values.
- **Describe** the Millikan oil-drop experiment.
- **Explain** the meaning of quantization of electric charge.

What Do You Think?

It's easy to share a box of popcorn with a friend at the movies. It is a bit tougher to share a slice of pizza equally, but it can be done with a knife. You can keep cutting it but each piece will still be pizza. However, at some point, you will separate the cheese from the crust and the pieces will no longer be pizza.

- Can you think of something that cannot be split into smaller pieces and retain its identity?

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

Investigate

In this *Investigate*, you will try to find the mass of a single penny in a closed container. The container may have one or more pennies but you will not have that information. You will find the mass of an empty container, using a balance, and the mass of the container with the pennies. You will then compare your results to those of the other groups.

808

Students' Prior Conceptions

There are excellent simulations and references to Millikan's oil-drop experiment in this section, and it is highly desirable for you to seek them out and to use them when presenting the nature of charge. When evaluating student explanations and dealing with the quantization of charge during brainstorming or discussion sessions, you will want to uncover the following prior conceptions:

1. Charge is continuous and can occur in any amount.

2. An electron is pure negative charge with no mass.

3. Oil drops are electrons.

4. Millikan measured the mass of the electron.

If time permits and students voice an interest in the discovery process and how ideas are explored in science, you may enjoy pursuing a discussion dealing with student preconceptions on the following topics:

1. The scientific method is pure and absolute.

2. Scientists always stumble on discoveries.

As students approach the *Mini-Challenge*, it is worthwhile for you to approach student ideas about how science is conducted and why they should care about input and output in the scientific process. What they observe while studying Millikan's oil-drop experiment directly influences their *Engineering Design Cycle*.

piggy bank are all images that students are likely to comment on. Encourage their responses and record a few, stating that their perceptions will gradually change as they move along in the section.

What Do You Think?

It will be interesting to see how students interpret the idea of divisible. Is a single egg divisible? Is an Oreo cookie divisible if one person gets the top half and crème and the other gets the bottom half? Is a penny divisible? The paragraph leading into the *What Do You Think?* question is designed to initiate students to think about the concept of an atom. Ask students if the smallest, indivisible piece of something that cannot be further divided challenges them to think of something that extends beyond their visual frame of reference. Point out to students that answering this question will prepare them for an inquiry-based investigation that would encourage them to link what they know to what they are in the process of finding out. Emphasize that recording responses is important, but wondering about the correctness of their response shouldn't be a concern at this stage. You might want to use an overhead of the *What Do You See*? illustration so that students can make further connections.

What Do You Think?

A Physicist's Response

The smallest piece of an element that cannot be split further and retains the identity of that element is an atom. The atom, however, has other internal parts; for instance, protons, neutrons, and electrons. The smallest parts of an atom are electrons that possess the smallest, indivisible unit of charge. The charge on the electron is said to be quantized; that is, it only comes in multiples of a specific value. Each electron has a charge of 1.6×10^{-19} C.

NOTES

Investigate

1.a)

Students should make a list of masses that include both the mass of the container and the mass of the pennies in the container. Possible masses are shown below:

Mass of container (g)	Number of pennies	Mass of pennies (g)	Total mass (g)
5	1	2	7
5	2	4	9
5	5	10	15
5	7	14	19
5	10	20	25
5	12	24	29
5	15	30	35
5	20	40	45
5	25	50	55
5	26	52	57

1.b)

Students could find the mass of a penny from the mass of the containers by looking for regular increases in the mass of the containers being measured. The mass should increase in uniform steps as the number of pennies increase, and the increases should correspond to the number of pennies added.

Teaching Tip

Film canisters often will have slight variations in mass that may make the incremental increase in mass more difficult for the students to detect. You may measure the mass of the each of the film canisters used, and then add a slight amount of sand to the lighter canisters to make them have a consistent mass with the heavier ones.

Teaching Tip

If a non digital balance such as a triple beam balance is used to weigh the film canisters with the pennies, inaccuracies in the balances may present difficulties for the students if the mass difference between canisters is small. To alleviate this problem, double the number of pennies in each canister so that students measure a mass difference that is twice as large, reducing the error. Then students can be told later that the difference in each can was always a multiple of 2 pennies rather than 1 penny.

2.a)

Students can follow the plan developed in *Step 1.b)*. The smallest increase in mass from container to container (not including slight variations in mass) will probably be the mass of a single penny. Students can test this hypothesis by looking at the changes in mass between containers to see if they are multiples of the mass of one penny.

2.b)

The mass of a penny is approximately 2.3 g, but results will vary from group to group depending upon how carefully the measurements are done.

2.c)

All student groups should have close to the same value, increasing their confidence in their value.

3.a)

The masses of the container plus the nickels would all be multiples of 5 g. Starting with a container with one nickel, the values could be 10 g, 15 g, etc., as shown in the table below

Mass of container (g)	Number of nickels	Mass of nickels (g)	Total mass (g)
5	2	10	15
5	5	25	30
5	7	35	40
5	12	60	65

3.b)

If the container is 5 g, then your nickels must have a mass of 23 g – 5 g = 18 g. If nickels are 5 g each, then the mass can be 15 g or 20 g, but not 18 g.

3.c)

One possibility is their container might only have a mass of 3 g. Other possibilities might include a penny accidentally being added to the container, rather than a nickel, a damaged nickel that is not whole, a nickel made of different metal, or perhaps from another country that has different composition and mass.

Section 2 The Nature of Charge: Tiny and Indivisible

1. Your teacher will provide you with a set of film canisters or other containers that contain pennies. Your goal is to determine the mass of a single penny.

   Do not open the containers. To develop a strategy, assume that each container has a mass of 5 g and each penny has a mass of 2 g.

   a) Make a list of possible masses of containers that have 1 penny, 2 pennies, 5 pennies, etc. Make this list for at least ten containers.

   b) Suppose you were given only the masses of the ten containers you calculated in *Step 1.a)* and not the mass of a penny. Describe how you could find the mass of a single penny.

2. Now, measure the mass of an empty container using a balance. Then measure the mass of each container, including the penny or pennies inside.

   a) Explain how you can find the mass of one penny using the measurements you are permitted to make. It is very possible that no container has only one penny. Write down your strategy.

   b) What do you determine the mass of a penny to be?

   c) Compare your value of the mass of a penny with that of another group. How does your confidence in your value change as you compare it with more and more groups? Scientists use similar methods to share and compare results with other scientists to make scientific progress.

3. Suppose you obtain a new set of containers with nickels in them. Suppose that each container is 5 g and each nickel is 5 g.

   a) What are some possible masses you would expect for four of the containers?

   b) A lab group stated that they measured the mass of a container of nickels and it was 23 g. Your lab group thinks that they must have made an error. Explain to the first group in writing why you think that there is a problem.

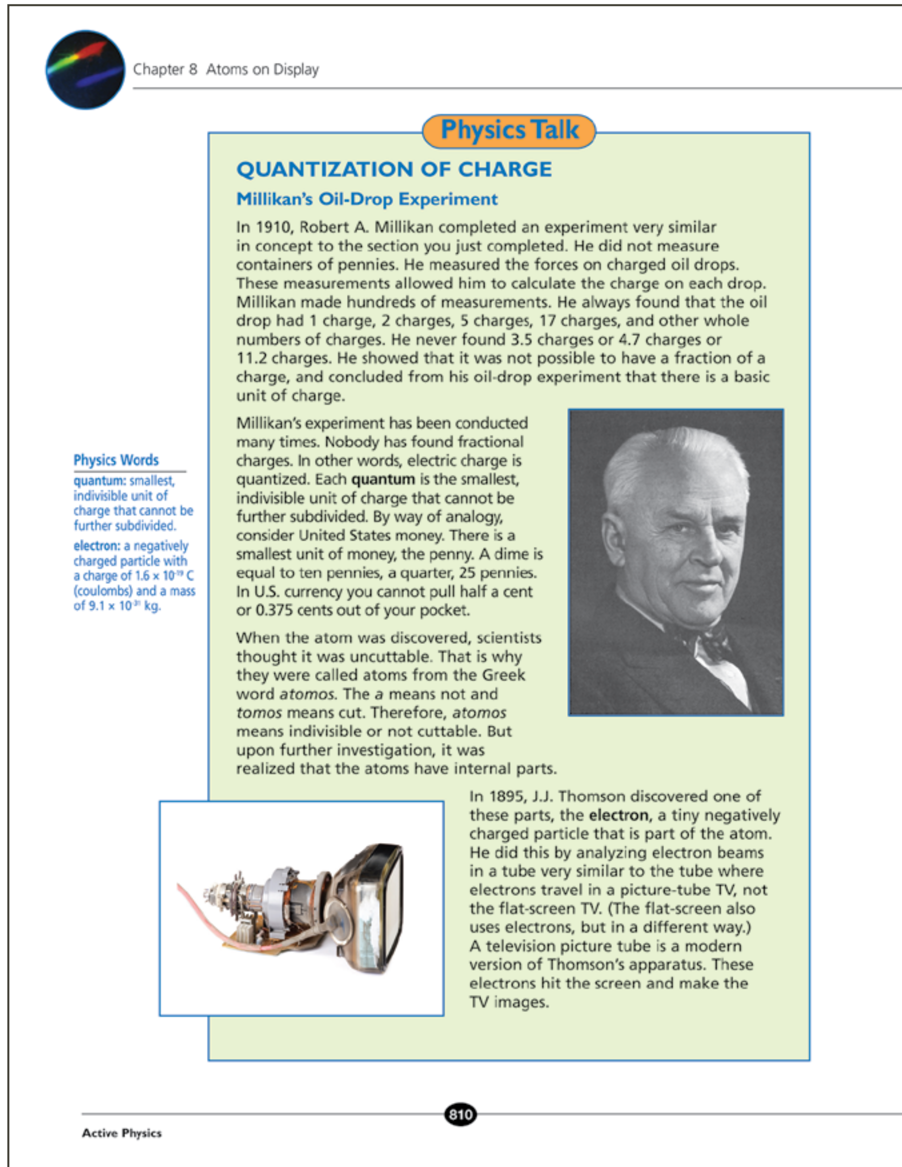
   c) When your lab group measured the mass of the container, you also found it to be 23 g. You now have a problem—a mystery—a puzzle. It is this kind of puzzle where calculations do not support the actual measurements that challenges and intrigues physicists. How could this be? It would be great to open up the container, but this may not be possible. Can you solve the puzzle? Suggest at least three different solutions to this puzzle.

Physics Talk

Students read how Robert Millikan concluded that charge is quantized. The smallest indivisible unit of charge is the charge found on a single electron. They are introduced to the concept of an electron and how Thompson first discovered these tiny, negatively charged particles. They learn how Millikan was able to determine the value of a charge through his oil-drop experiment and relate it to their experiment of finding the mass of the penny in the *Investigate*. Current theories of physics that suggest the existence of fractional charges are also discussed briefly.

As you and your class begin this section, ask students how their *Investigate* relates to Millikan's experiment. Consider asking them why Millikan determined that it was not possible to have a fraction of a charge and have them describe the analogy of the smallest unit of United States money. Discuss the definition of an atom and how Thomson analyzed electron beams, and then find out if students understand the comparison of the tube used in Thomson's apparatus to a television picture tube. You might want to ask students if they understand the relationship between quantized charge and electron.

Describe the challenges of Millikan's oil-drop experiment. It is important for students to understand the ingenuity of Millikan's experiment—and how he was able to determine how the smallest charges were found on an oil drop. Determine if students understand that the smallest unit of charge has the same value as that of an electron, and both concepts are interrelated. Discuss the theory of quarks and what conclusion Millikan's experiment draws in relation to quarks.


Chapter 8 Atoms on Display

Physics Talk

QUANTIZATION OF CHARGE

Millikan's Oil-Drop Experiment

In 1910, Robert A. Millikan completed an experiment very similar in concept to the section you just completed. He did not measure containers of pennies. He measured the forces on charged oil drops. These measurements allowed him to calculate the charge on each drop. Millikan made hundreds of measurements. He always found that the oil drop had 1 charge, 2 charges, 5 charges, 17 charges, and other whole numbers of charges. He never found 3.5 charges or 4.7 charges or 11.2 charges. He showed that it was not possible to have a fraction of a charge, and concluded from his oil-drop experiment that there is a basic unit of charge.

Millikan's experiment has been conducted many times. Nobody has found fractional charges. In other words, electric charge is quantized. Each **quantum** is the smallest, indivisible unit of charge that cannot be further subdivided. By way of analogy, consider United States money. There is a smallest unit of money, the penny. A dime is equal to ten pennies, a quarter, 25 pennies. In U.S. currency you cannot pull half a cent or 0.375 cents out of your pocket.

When the atom was discovered, scientists thought it was uncuttable. That is why they were called atoms from the Greek word *atomos*. The *a* means not and *tomos* means cut. Therefore, *atomos* means indivisible or not cuttable. But upon further investigation, it was realized that the atoms have internal parts.

In 1895, J.J. Thomson discovered one of these parts, the **electron**, a tiny negatively charged particle that is part of the atom. He did this by analyzing electron beams in a tube very similar to the tube where electrons travel in a picture-tube TV, not the flat-screen TV. (The flat-screen also uses electrons, but in a different way.) A television picture tube is a modern version of Thomson's apparatus. These electrons hit the screen and make the TV images.

Physics Words

quantum: smallest, indivisible unit of charge that cannot be further subdivided.

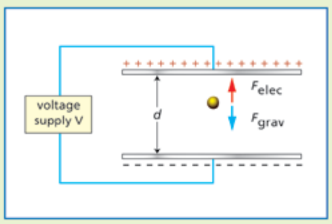
electron: a negatively charged particle with a charge of 1.6×10^{-19} C (coulombs) and a mass of 9.1×10^{-31} kg.

810

Active Physics

8-2a Blackline Master

Your penny lab was easy compared to Millikan's oil-drop experiment. The oil drops are so small that in Millikan's experiment he had to view them through a microscope. To find their mass required some ingenuity as well. Millikan sprayed the oil droplets between a positively charged plate and a negatively charged plate. If the oil drop had a negative charge, it would be repelled from the negative plate and attracted to the positive plate. If the positive plate were on top, the electric force would be pulling the drop up, while gravity would be pulling the drop down. If the two forces were equal, the drop would come to rest and remain suspended (or travel at a slow constant speed). By calculating the electrical force and the gravitational force, the charge on the oil drop (i.e., the charge of the electrons) could be found. Millikan won the Nobel Prize for this experiment.



The diagram above shows the oil drop, the electrical plates, and the battery voltage that provides the charge on the plates. The voltage is adjusted so that the oil drop is suspended or moves with a constant speed (no acceleration).

The weight of the oil drop (*mg*) can be found by observing the oil drop as it falls because of air resistance. You can calculate the electrical force from the voltage, charge, and distance between the plates. You can calculate the gravitational force from the mass and the acceleration due to gravity. The voltage of the power supply and the distance between the plates can be measured. Using the equations below, you can find the charge on the oil drops.

$$F_{elec} = F_{grav}$$

$$\frac{qV}{d} = mg$$

$$q = \frac{mgd}{V}$$

CHAPTER 8

Checking Up

1.

Millikan's experiment, in which he discovered that charges on objects only come in multiples of the fundamental unit of 1.6×10^{-19} C, led to the discovery that charge is quantized and only comes in whole-number multiples of the fundamental charge.

2.

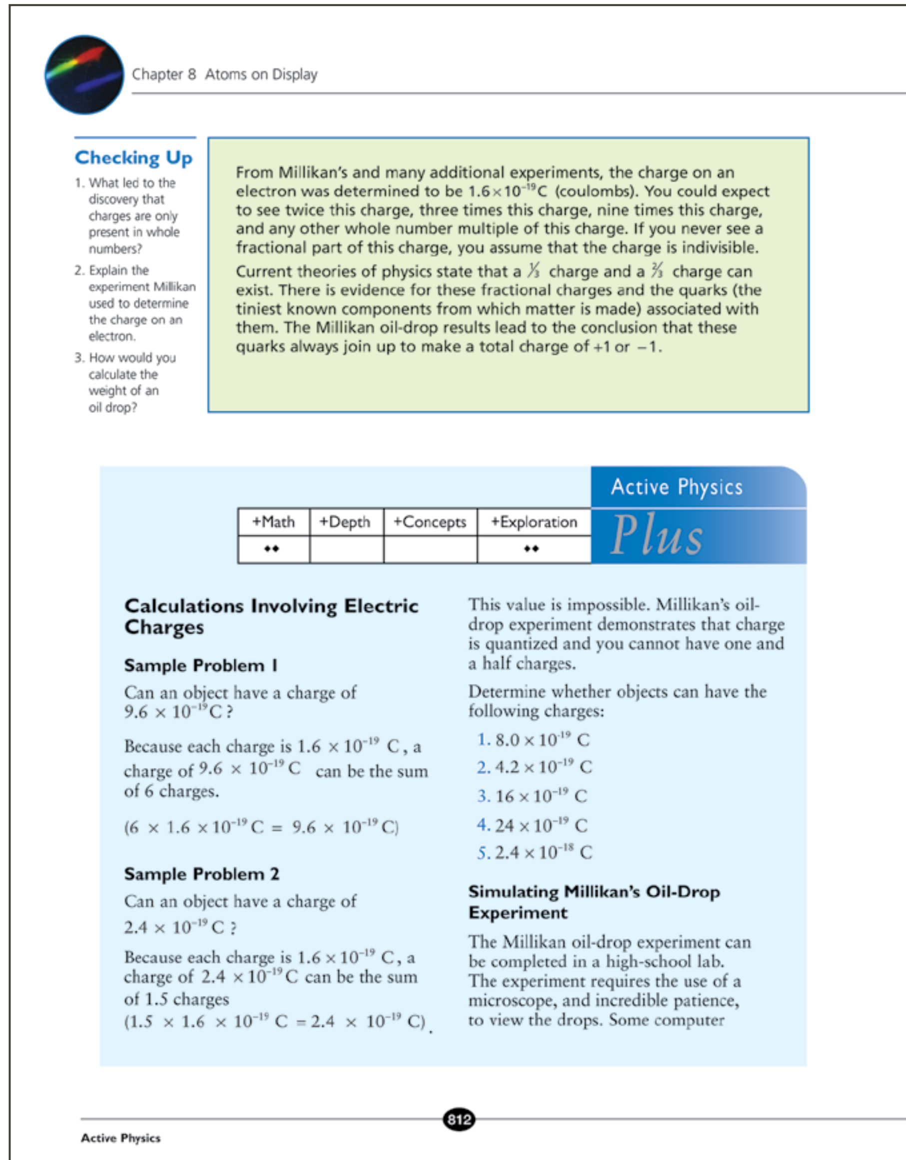
Millikan suspended oil droplets between two charged plates and adjusted the electric field between the plates so that the electric force on the oil droplet exactly balanced the force of gravity. After determining the mass of the oil droplet, he was able to use the balance of electric and gravitational forces to determine the charge on the oil droplet.

3.

If you know the volume and density of an oil droplet, you can calculate its weight using the relationship of $density = mass/volume$. Millikan was unable to calculate the mass in this manner, and had to determine it by the rate of fall of the droplet through air.

Active Physics Plus

Students determine through calculations that the basic unit of charge is 1.6×10^{-19} C and an object cannot have fractional values for a total charge. They also simulate Millikan's oil-drop experiment in their lab or design a computer game that works like Millikan's experiment.



Chapter 8 Atoms on Display

Checking Up

1. What led to the discovery that charges are only present in whole numbers?
2. Explain the experiment Millikan used to determine the charge on an electron.
3. How would you calculate the weight of an oil drop?

From Millikan's and many additional experiments, the charge on an electron was determined to be 1.6×10^{-19} C (coulombs). You could expect to see twice this charge, three times this charge, nine times this charge, and any other whole number multiple of this charge. If you never see a fractional part of this charge, you assume that the charge is indivisible. Current theories of physics state that a ⅓ charge and a ⅔ charge can exist. There is evidence for these fractional charges and the quarks (the tiniest known components from which matter is made) associated with them. The Millikan oil-drop results lead to the conclusion that these quarks always join up to make a total charge of +1 or −1.

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
••			••

Calculations Involving Electric Charges

Sample Problem 1

Can an object have a charge of 9.6×10^{-19} C?

Because each charge is 1.6×10^{-19} C, a charge of 9.6×10^{-19} C can be the sum of 6 charges.

$(6 \times 1.6 \times 10^{-19}\text{ C} = 9.6 \times 10^{-19}\text{ C})$

Sample Problem 2

Can an object have a charge of 2.4×10^{-19} C?

Because each charge is 1.6×10^{-19} C, a charge of 2.4×10^{-19} C can be the sum of 1.5 charges $(1.5 \times 1.6 \times 10^{-19}\text{ C} = 2.4 \times 10^{-19}\text{ C})$.

This value is impossible. Millikan's oil-drop experiment demonstrates that charge is quantized and you cannot have one and a half charges.

Determine whether objects can have the following charges:

1. 8.0×10^{-19} C
2. 4.2×10^{-19} C
3. 16×10^{-19} C
4. 24×10^{-19} C
5. 2.4×10^{-18} C

Simulating Millikan's Oil-Drop Experiment

The Millikan oil-drop experiment can be completed in a high-school lab. The experiment requires the use of a microscope, and incredible patience, to view the drops. Some computer

812

Active Physics

1.

Yes. $\dfrac{8 \times 10^{-19}\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} =$ 5 electrons

2.

No. $\dfrac{4.2 \times 10^{-19}\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} =$ 2.625 electrons

3.

Yes. $\dfrac{16 \times 10^{-19}\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} =$ 10 electrons

4.

Yes. $\dfrac{24 \times 10^{-19}\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} =$ 15 electrons

5.

Yes. $\dfrac{2.4 \times 10^{-18}\text{ C}}{1.6 \times 10^{-19}\text{ C/electron}} =$ 15 electrons simulations may be available on the Internet. You may decide to investigate using one of these or to design a computer simulation or game that works like the Millikan oil-drop experiment. Your created simulation should have the following features:

- The screen should look like the apparatus, with a variable power supply and oil drops between the plates.
- The drop should be able to get a new charge.
- The drop should be able to move.
- The voltage should be allowed to vary so that the net force on the drop is zero and the drop travels at constant velocity or is at rest.
- The velocity of the drop should be measurable to determine if it is traveling at a constant velocity.
- New drops should be able to be inserted between the plates.

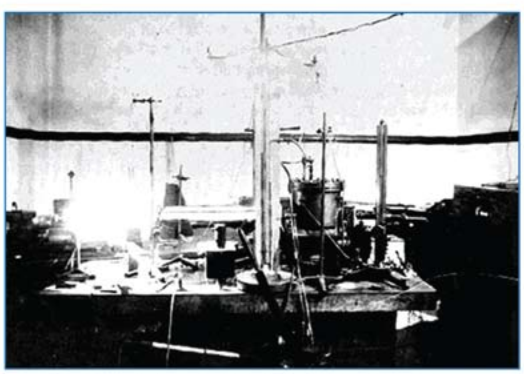
Map out a design for this computer simulation and if you can, create the simulation and test it with other students.

What Do You Think Now?

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

- **Can you think of something that cannot be split into smaller pieces and retain its identity?**

Review what you have learned about Millikan's oil-drop experiment. How do you know that the charge on an electron is quantized?



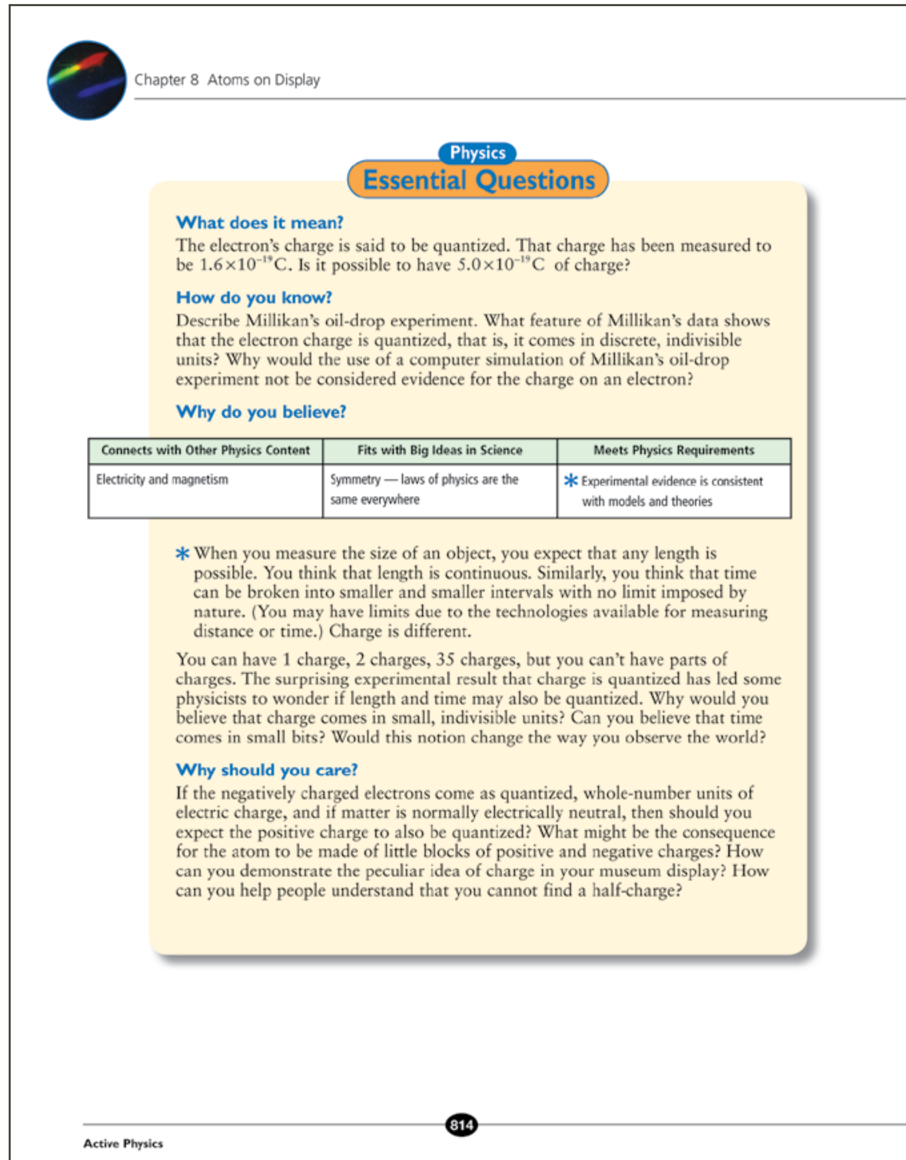
An early example of Robert Millikan's setup for the oil drop experiment.

What Do You Think Now?

Ask students to review what they have learned and update their previous responses to the *What Do You Think?* question. If they want clarification of a concept, ask them to review the *Investigate*, read the *Physics Talk*, or ask their classmates before providing an explanation. Share *A Physicist's Response* so that students can further modify their answers. Let students know that you expect a description of how Millikan's experiment relates to this question in their responses. Impress upon them that you will be assessing them through their answers as to whether they have understood the physics of electric charges.

Reflecting on the Section and the Challenge

Have a student volunteer read this section aloud and ask students to write a brief description of what they have learned about the atom so far. Ask them if electrons are indivisible, would the same be true for protons. Encourage students to connect what they learned about negative charges in *Section 1* to what they now know about the property of these negative charges. Point out that the presence of electrons in atoms and their indivisibility should be also be a part of their museum display. Also, query students about how they might include Millikan's experiment in their explanation of negative charge.



Physics
Essential Questions

What does it mean?

The electron's charge is said to be quantized. That charge has been measured to be 1.6×10^{-19}C. Is it possible to have 5.0×10^{-19}C of charge?

How do you know?

Describe Millikan's oil-drop experiment. What feature of Millikan's data shows that the electron charge is quantized, that is, it comes in discrete, indivisible units? Why would the use of a computer simulation of Millikan's oil-drop experiment not be considered evidence for the charge on an electron?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Electricity and magnetism	Symmetry — laws of physics are the same everywhere	* Experimental evidence is consistent with models and theories

* When you measure the size of an object, you expect that any length is possible. You think that length is continuous. Similarly, you think that time can be broken into smaller and smaller intervals with no limit imposed by nature. (You may have limits due to the technologies available for measuring distance or time.) Charge is different.

You can have 1 charge, 2 charges, 35 charges, but you can't have parts of charges. The surprising experimental result that charge is quantized has led some physicists to wonder if length and time may also be quantized. Why would you believe that charge comes in small, indivisible units? Can you believe that time comes in small bits? Would this notion change the way you observe the world?

Why should you care?

If the negatively charged electrons come as quantized, whole-number units of electric charge, and if matter is normally electrically neutral, then should you expect the positive charge to also be quantized? What might be the consequence for the atom to be made of little blocks of positive and negative charges? How can you demonstrate the peculiar idea of charge in your museum display? How can you help people understand that you cannot find a half-charge?

Physics Essential Questions

What does it mean?

It is not possible to have a charge of 5×10^{-19} C because it is not a multiple of 1.6×10^{-19} C, the charge of a single electron.

How do you know?

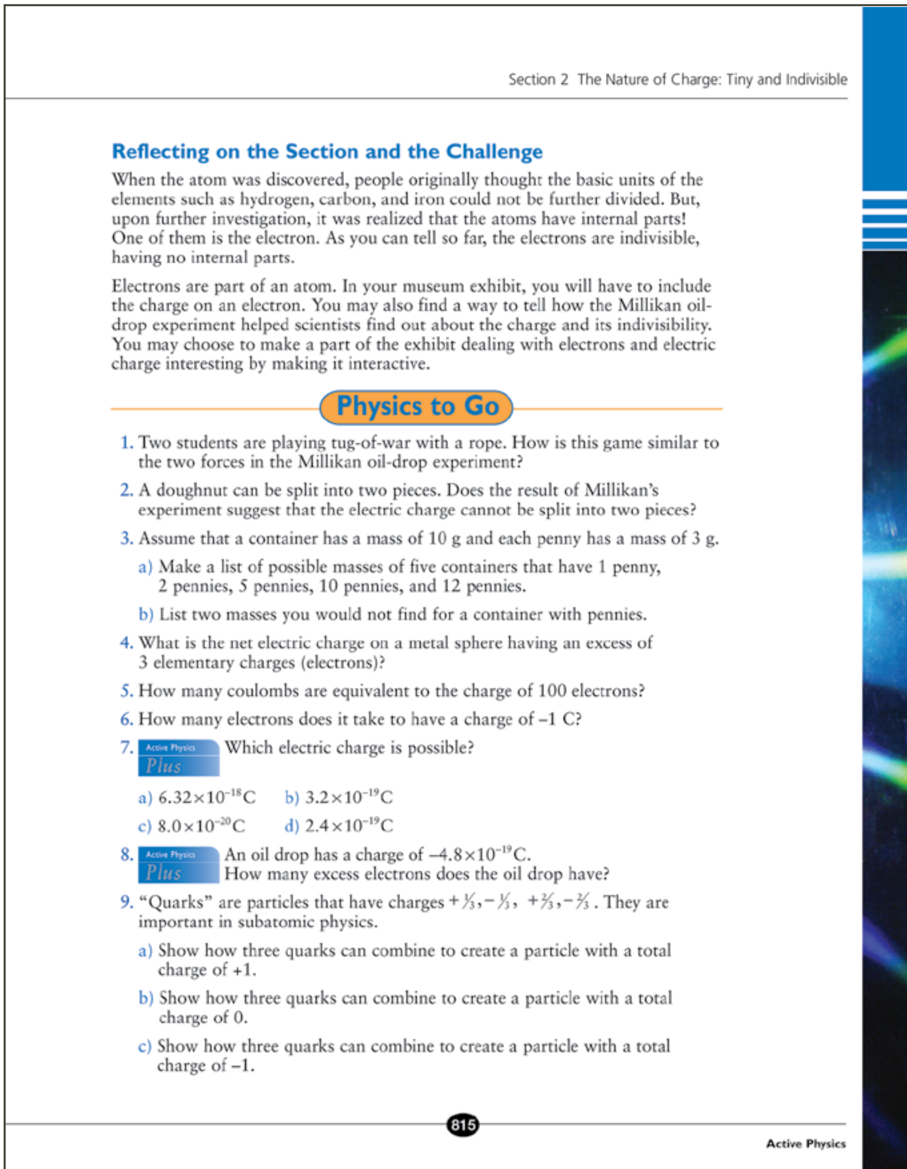
Millikan's oil-drop experiment captured charged oil droplets. The drops would be suspended. By comparing the weight with the electrical force, the charge on each oil drop was calculated. The values determined were always the multiple of 1.6×10^{-19} C. A computer simulation is not considered evidence; simulations can be programmed to show any values.

Why do you believe?

If time came in small units, then the idea of smooth transitions from one moment to the next would change. Our lives would be like frames of a movie that jump from one still to another (24/second).

Why should you care?

If matter can remain electrically neutral, then the positive and negative charges must be equal. If the negative charge is quantized, then the positive charge must be quantized. In a museum display, visitors can be asked to determine if matter is electrically neutral by counting "charges" and by seeing if matter attracts other matter.



Reflecting on the Section and the Challenge

When the atom was discovered, people originally thought the basic units of the elements such as hydrogen, carbon, and iron could not be further divided. But, upon further investigation, it was realized that the atoms have internal parts! One of them is the electron. As you can tell so far, the electrons are indivisible, having no internal parts.

Electrons are part of an atom. In your museum exhibit, you will have to include the charge on an electron. You may also find a way to tell how the Millikan oil-drop experiment helped scientists find out about the charge and its indivisibility. You may choose to make a part of the exhibit dealing with electrons and electric charge interesting by making it interactive.

Physics to Go

1. Two students are playing tug-of-war with a rope. How is this game similar to the two forces in the Millikan oil-drop experiment?
2. A doughnut can be split into two pieces. Does the result of Millikan's experiment suggest that the electric charge cannot be split into two pieces?
3. Assume that a container has a mass of 10 g and each penny has a mass of 3 g.
   a) Make a list of possible masses of five containers that have 1 penny, 2 pennies, 5 pennies, 10 pennies, and 12 pennies.
   b) List two masses you would not find for a container with pennies.
4. What is the net electric charge on a metal sphere having an excess of 3 elementary charges (electrons)?
5. How many coulombs are equivalent to the charge of 100 electrons?
6. How many electrons does it take to have a charge of –1 C?
7. Active Physics Plus Which electric charge is possible?
   a) 6.32×10^{-18}C b) 3.2×10^{-19}C
   c) 8.0×10^{-20}C d) 2.4×10^{-19}C
8. Active Physics Plus An oil drop has a charge of -4.8×10^{-19}C. How many excess electrons does the oil drop have?
9. "Quarks" are particles that have charges $+\frac{1}{3}, -\frac{1}{3}, +\frac{2}{3}, -\frac{2}{3}$. They are important in subatomic physics.
   a) Show how three quarks can combine to create a particle with a total charge of +1.
   b) Show how three quarks can combine to create a particle with a total charge of 0.
   c) Show how three quarks can combine to create a particle with a total charge of –1.

Physics to Go

1.

In the Millikan oil-drop experiment, the suspended oil drop has a gravitational force pulling it down and an electrical force pulling it up. When the two forces are equal, the drop remains still or moves with a constant speed. The two students are pulling the center of the rope. If the forces are equal, the center of the rope remains at rest or moves with a constant velocity.

2.

No, it does not prohibit it. Rather, it shows that experimentally, a fractional charge has never been observed.

3.a)

Mass of container (g)	Number of pennies	Mass of pennies (g)	Total mass (g)
10	1	3	13
10	2	6	16
10	5	15	25
10	10	30	40
10	12	36	46

3.b)

You could not find masses of 15 g or 26 g.

4.

$$(3 \text{ electrons}) \times (-1.6\times10^{-19} \text{ C/electron}) = -4.8\times10^{-19} \text{ C}$$

5.

$$(100 \text{ electrons}) \times (-1.6\times10^{-19} \text{ C/electron}) = -1.6\times10^{-17} \text{ C}$$

6.

6.25×10^{18} electrons

7.b)

Possible (2 charges), for a charge to be possible it must be a multiple of 1.6×10^{-19} C.

8.

$$\frac{-4.8\times10^{-19} \text{ C}}{-1.6\times10^{-19} \text{ C/electron}} = 3 \text{ electrons.}$$

9.a)

Possible answers are suggested.

$+1 = (+2/3, +2/3, -1/3)$
$+1 = (1/3, 1/3, 1/3)$

9.b)

$0 = (+2/3, -1/3, -1/3)$
$0 = (1/3, 1/3, -2/3)$

9.c)

$-1 = (-2/3, -2/3, +1/3)$
$-1 = (-1/3, -1/3, -1/3)$

CHAPTER 8

10.

Student answers will vary. Perhaps having people try to split a steel ball bearing with a piece of wood.

11.

Preparing for the Chapter Challenge

Student answers will vary. Do not limit their creativity by suggesting a possible answer.

Inquiring Further

a)

Assume the oil slick forms a circular patch on the pond surface one atom thick. This would form a right circular cylinder of $volume = area \times height$. Substituting into the formula the volume of $1\ \text{cm}^3$ or $\left(1 \times 10^{-6}\ \text{m}^3\right)$ and the area of $100\ \text{m}^2$ gives

$V = Ah$ or

$1 \times 10^{-6}\ \text{m}^3 = 100\ \text{m}^2(h)$

or $h = 1 \times 10^{-8}\ \text{m}$.

b)

Because you do not know if olive oil is made from one atom, its maximum size would be $1 \times 10^{-8}\ \text{m}$ if olive oil is made from a group of atoms together. The minimum size would be the number of atoms in the molecule divided into $1 \times 10^{8}\ \text{m}$ if the molecule was made of all equal-sized atoms in a row.

10. Describe how you could make Millikan's oil-drop experiment into an exciting interactive display.

11. *Preparing for the Chapter Challenge*

J.J. Thomson, the discoverer of the electron, tried to describe the significance of the discovery of this tiny particle: "Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen, which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science?" Create a quote of your own that captures the significance of the discovery of the electron. Perhaps the quote could be displayed near the entrance to your proposed museum exhibit.

Inquiring Further

Estimating the size of an atom

At one time, the atom was thought to be uncuttable. It is now recognized that the atom has internal parts, one of which is the electron. The electron seems to be uncuttable, but forms a tiny fraction of the atom's mass. The size and mass of an electron raises an interesting question that will be examined in upcoming sections: How big is an atom?

Here is a way to obtain a rough estimate of the size of an atom. One cubic centimeter of olive oil is poured onto the surface of a large pond. The oil spreads out into an oil slick. When it stops spreading, the area of the oil slick is measured to be 100 square meters.

a) Assuming the oil layer is one atom thick, what is the size of the atom?

b) Perhaps the "smallest bit" of olive oil is not a single atom, but combinations of atoms, called molecules. If you are not sure whether the oil layer is one atom thick, then the answer you obtained estimates the size of a molecule. Would that be a maximum or a minimum size for an atom?

NOTES

CHAPTER 8

SECTION 2 QUIZ

8-2b Blackline Master

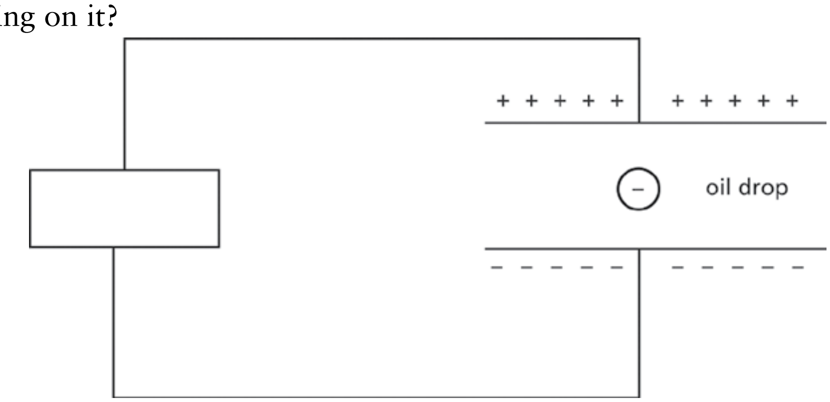
1. Which magnitude charge could not be found on an object?
   a) $+0.8 \times 10^{-19}$ C
   b) -1.6×10^{-19} C
   c) $+1.6 \times 10^{-19}$ C
   d) $+3.2 \times 10^{-19}$ C

2. Robert Millikan determined the charge on an electron by observing the motion of oil drops in the presence of
   a) sound waves.
   b) a magnetic field.
   c) standing waves.
   d) an electric field.

3. A sphere has a net excess charge of -4.8×10^{-19} C. The sphere must have an excess charge of
   a) 1 electron.
   b) 3 electrons.
   c) 4.8 electrons.
   d) 5 electrons.

4. After Millikan performed his oil-drop experiment he concluded
   a) there is a minimum amount of charge that an object can acquire.
   b) oil drops exhibit gravitational attraction for other oil drops.
   c) oil drops can only acquire negative charges.
   d) the mass of oil drops are always multiples of the smallest droplet.

5. The diagram below represents a negatively charged electron between two oppositely charged, parallel plates. If the oil drop is at rest, which statement below correctly describes the forces acting on it?



   a) The upward force of the positive plate equals the downward force of the negative plate.
   b) The upward force of the electric field equals the downward force of gravity.
   c) The downward force of the electric field balances the charge on the oil drop.
   d) No forces are acting on it—it is in equilibrium.

SECTION 2 QUIZ ANSWERS

1. a) $+0.8 \times 10^{-19}$ C. The Millikan experiment showed that the charge on an electron is quantized and equal to 1.6×10^{-19} C. No charge smaller than this is allowed, and the charge that exists on an object must always be an integral multiple of the electron charge. All the other answers are integral multiples of 1.6×10^{-19} C.

2. d) an electric field. Millikan could balance the downward gravitational force on the oil drop with an upward electric force due to the electric field between a pair of charged plates. A magnetic field is unable to do this, since it requires a moving charge to exert a force.

3. b) 3 electrons. Since the charge on an object must be an integral multiple of 1.6×10^{-19} C, dividing the charge on the object $(4.8 \times 10^{-19}\ \text{C})$ by the charge on the electron of 1.6×10^{-19} C/electron gives the answer of 3 electrons.

4. a) There is a minimum amount of charge that an object can acquire. Along with the quantization of charge, Millikan found there was a minimum charge an object could possess, that of on elementary charge $(1.6 \times 10^{-19}\ \text{C})$.

5. b) The upward force of the electric field equals the downward force of gravity. By Newton's first law, if the oil drop is at rest it must be in equilibrium. The only forces acting on the oil drop are gravity (acting downward) and the force of the electric field, which must be upward to counteract gravity.