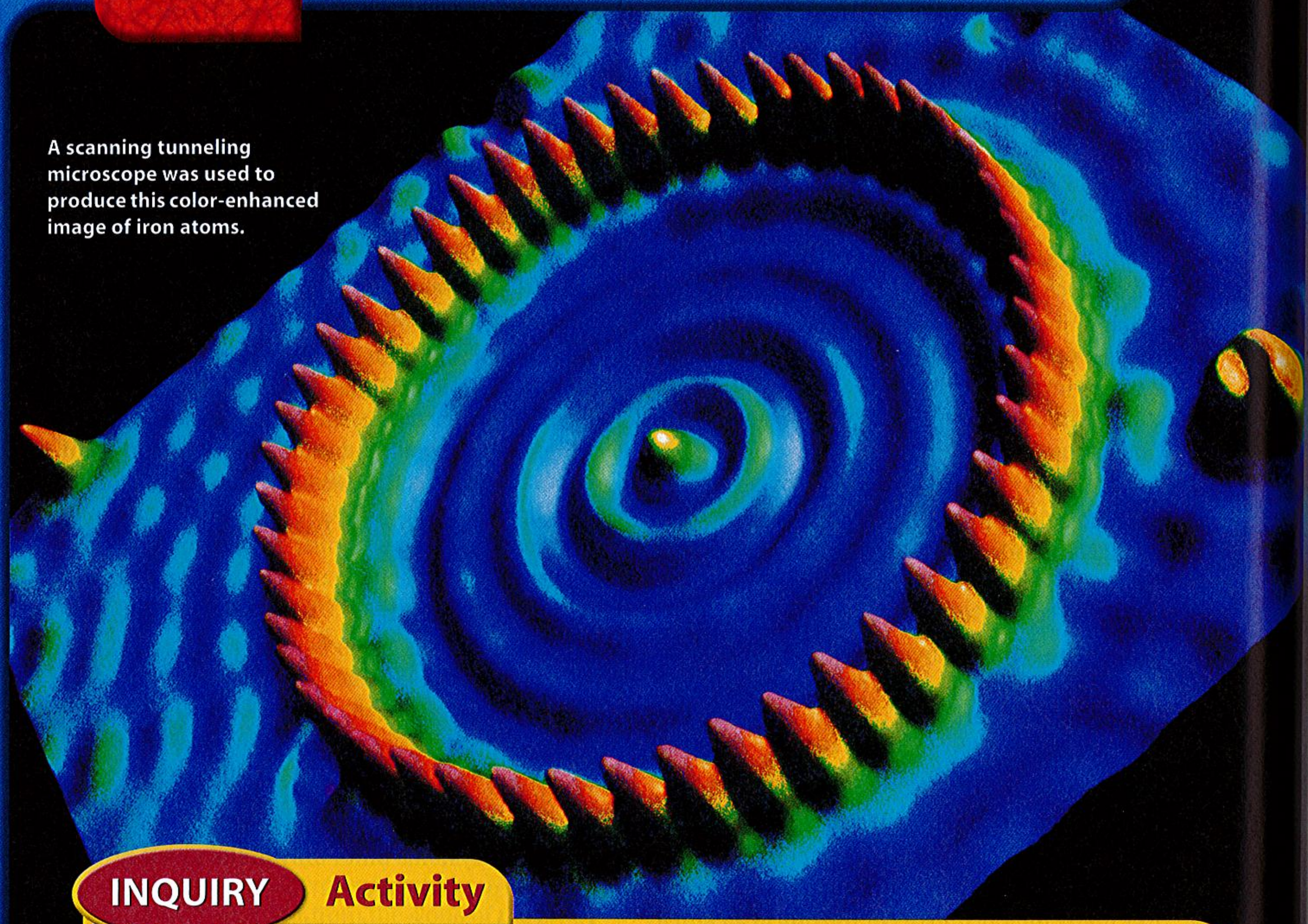
CHAPTER 4

Atomic Structure



A scanning tunneling microscope was used to produce this color-enhanced image of iron atoms.

INQUIRY Activity

Electric Charge

Materials

four 25-cm lengths of clear plastic tape and a metric ruler

Procedure

1. Firmly stick two of the 25-cm pieces of tape side-by-side, about 10 cm apart, on your desktop. Leave 2 to 3 cm of tape sticking over the edge of the desk. Grasp the free ends of the tapes and pull sharply upward to peel the tape pieces off of the desk. Slowly bring the pieces, which have similar charges, toward one another. Record your observations.
2. Pull the third and fourth pieces of tape between your thumb and forefinger several times, as if trying to clean each one. Slowly bring these two pieces of tape, which now have similar charges, toward one another. Record your observations.

Think About It

1. Predict what might happen if you brought a piece of tape pulled from your desktop close to a piece of tape pulled between your fingers. Try it, and see what happens. Explain your observations.
2. Do you think the pieces of tape used in Step 1 have the same charge as those used in Step 2? Explain.

4.1 Defining the Atom

Connecting to Your World It often helps to take a closer look. For example, you might walk up to a sign or a poster in order to make out the details. Or you might bring a set of binoculars to a sports stadium so that you can zoom in on the action. The lab technician shown here is using a magnifying lens to examine a bacterial culture in a petri dish. Scientists use many different devices that enhance their ability to see. However, scientists can't always see the details of what they study. In such cases, scientists try to obtain experimental data that helps fill in the picture.

Guide for Reading

Key Concepts

- How did Democritus describe atoms?
- How did John Dalton further Democritus's ideas on atoms?
- What instruments are used to observe individual atoms?

Vocabulary

atom

Dalton's atomic theory

Reading Strategy

Summarizing As you read about early atomic models, summarize the main ideas in the text that follow each red and blue heading.

Early Models of the Atom

Have you ever been asked to believe in something you couldn't see? Using your unaided eyes, you cannot see the tiny fundamental particles that make up matter. Yet all matter is composed of such particles, which are called atoms. An **atom** is the smallest particle of an element that retains its identity in a chemical reaction.

The concept of the atom intrigued a number of early scholars. Although these philosophers and scientists could not observe individual atoms, they still were able to propose ideas on the structure of atoms.

Democritus's Atomic Philosophy The Greek philosopher Democritus (460 B.C.–370 B.C.) was among the first to suggest the existence of atoms. **Democritus believed that atoms were indivisible and indestructible.** Although Democritus's ideas agreed with later scientific theory, they did not explain chemical behavior. They also lacked experimental support because Democritus's approach was not based on the scientific method.

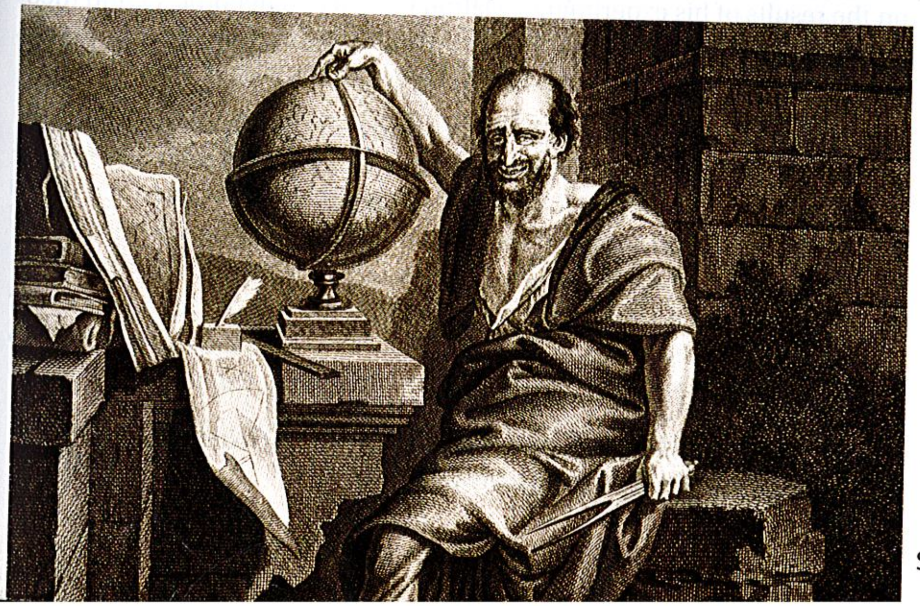
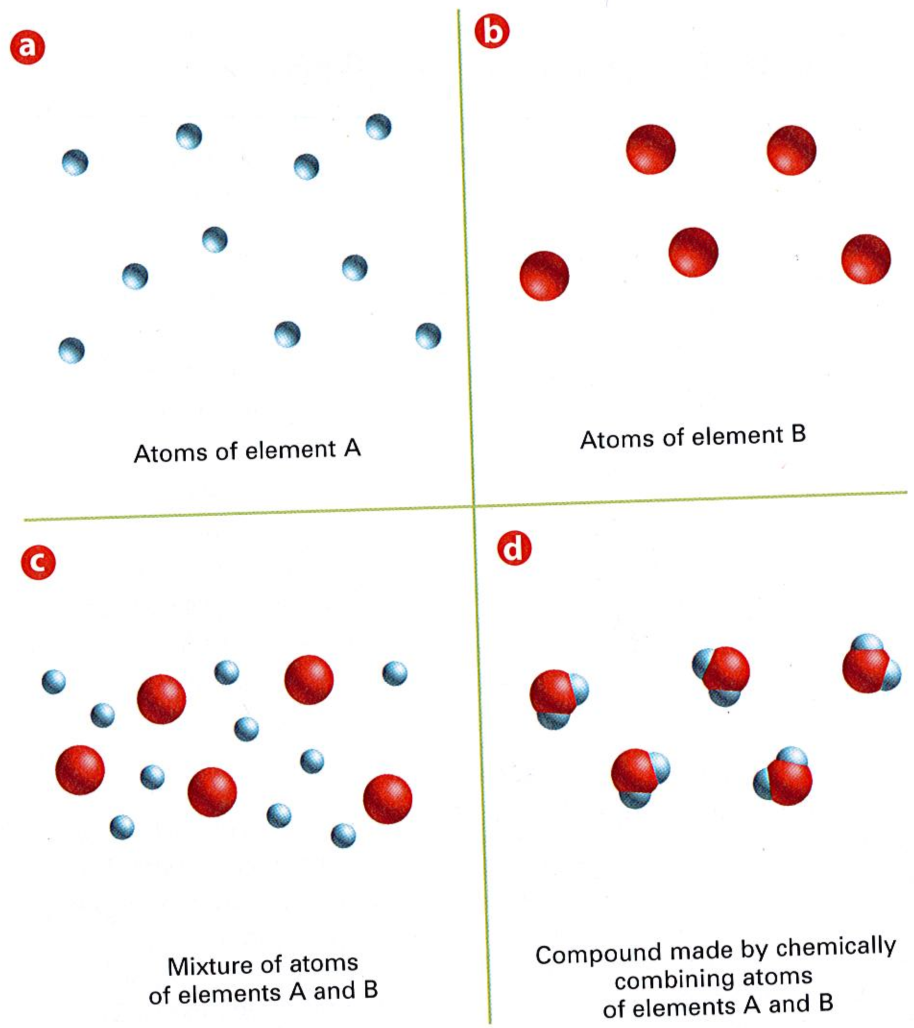


Figure 4.1 Democritus believed that matter consisted of tiny, indivisible, unchangeable particles called atoms. His ideas were later challenged by the Greek philosophers Plato and Aristotle.

Figure 4.2 According to Dalton's atomic theory, an element is composed of only one kind of atom, and a compound is composed of particles that are chemical combinations of different kinds of atoms. **a** Atoms of element A are identical. **b** Atoms of element B are identical, but differ from those of element A. **c** Atoms of elements A and B can physically mix together. **d** Atoms of elements A and B can chemically combine to form a compound.
Interpreting Diagrams ***How does a mixture of atoms of different elements differ from a compound?***



Word *Origins*

Atom comes from the Greek word *atomos,* meaning "indivisible." **If the suffix *-ize* means "to become like," what do you think the word *atomize* means?**

Dalton's Atomic Theory The real nature of atoms and the connection between observable changes and events at the atomic level were not established for more than 2000 years after Democritus. The modern process of discovery regarding atoms began with John Dalton (1766–1844), an English chemist and schoolteacher. **By using experimental methods, Dalton transformed Democritus's ideas on atoms into a scientific theory.** Dalton studied the ratios in which elements combine in chemical reactions. Based on the results of his experiments, Dalton formulated hypotheses and theories to explain his observations. The result was **Dalton's atomic theory,** which includes the ideas illustrated in Figure 4.2 and listed below.

1. All elements are composed of tiny indivisible particles called atoms.
2. Atoms of the same element are identical. The atoms of any one element are different from those of any other element.
3. Atoms of different elements can physically mix together or can chemically combine in simple whole-number ratios to form compounds.
4. Chemical reactions occur when atoms are separated, joined, or rearranged. Atoms of one element, however, are never changed into atoms of another element as a result of a chemical reaction.

Checkpoint ***What happens to atoms in a chemical reaction according to Dalton's atomic theory?***

Sizing up the Atom

A coin the size of a penny and composed of pure copper (Cu) illustrates Dalton's concept of the atom. Imagine grinding the copper coin into a fine dust. Each speck in the small pile of shiny red dust would still have the properties of copper. If by some means you could continue to make the copper dust particles smaller, you would eventually come upon a particle of copper that could no longer be divided and still have the chemical properties of copper. This final particle is an atom.

Copper atoms are very small. A pure copper coin the size of a penny contains about 2.4×10^{22} atoms. By comparison, Earth's population is only about 6×10^{9} people. There are about 4×10^{12} times as many atoms in the coin as there are people on Earth. If you could line up 100,000,000 copper atoms side by side, they would produce a line only 1 cm long!

The radii of most atoms fall within the range of 5×10^{-11} m to 2×10^{-10} m. Does seeing individual atoms seem impossible? **Despite their small size, individual atoms are observable with instruments such as scanning tunneling microscopes.** Figure 4.3 shows an image of iron atoms generated by a scanning tunneling microscope. Individual atoms can even be moved around and arranged in patterns. The ability to move individual atoms holds future promise for the creation of atomic-sized electronic devices, such as circuits and computer chips. This atomic-scale, or "nanoscale," technology could become essential to future applications in medicine, communications, solar energy, and space exploration.

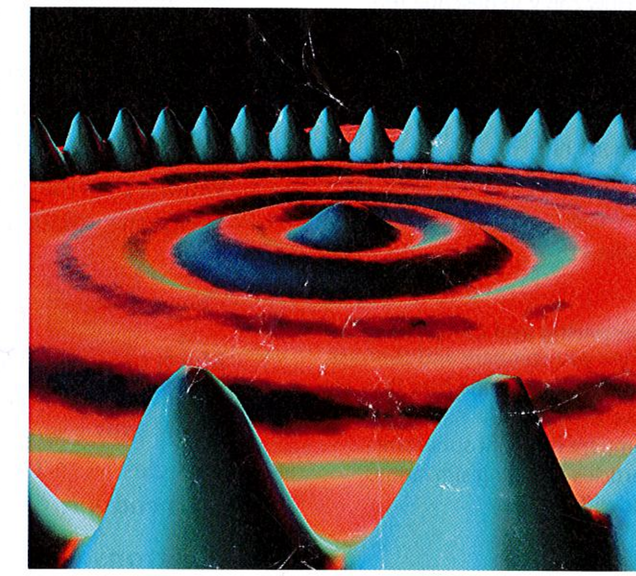


Figure 4.3 Scientists used a scanning tunneling microscope to generate this image of iron atoms, shown in blue. The radius of this circle of atoms is just 7.13×10^{-9} m.

4.1 Section Assessment

1. **Key Concept** How did Democritus characterize atoms?
2. **Key Concept** How did Dalton advance the atomic philosophy proposed by Democritus?
3. **Key Concept** What instrument can be used to observe individual atoms?
4. In your own words, state the main ideas of Dalton's atomic theory.
5. According to Dalton's theory, is it possible to convert atoms of one element into atoms of another? Explain.
6. Describe the range of the radii of most atoms in nanometers (nm).
7. A sample of copper with a mass of 63.5 g contains 6.02×10^{23} atoms. Calculate the mass of a single copper atom.

Connecting Concepts

Scientific Methods Reread the description of scientific methods in Section 1.3. Explain why the ideas on atoms proposed by Dalton constitute a theory, while the ideas proposed by Democritus do not.

Interactive Textbook

Assessment 4.1 Test yourself on the concepts in Section 4.1.

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4.2 Structure of the Nuclear Atom

Guide for Reading

Key Concepts
- What are three kinds of subatomic particles?
- How can you describe the structure of the nuclear atom?

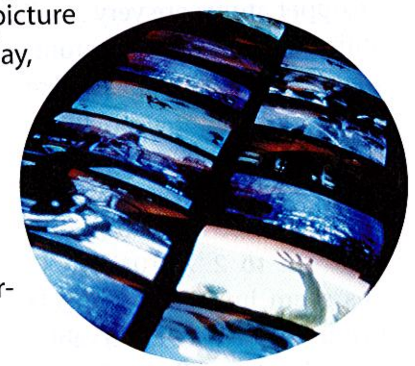
Vocabulary

electrons
cathode ray
protons
neutrons
nucleus

Reading Strategy

Comparing and Contrasting When you compare and contrast things, you examine how they are alike and different. As you read, compare different subatomic particles by listing similarities and differences.

Connecting to Your World A simple but important device first used by scientists in the late nineteenth century, the cathode-ray tube would achieve its greatest fame as the picture tube of the common television set. Today, cathode-ray tubes are found in TVs, computer monitors, and many other devices with electronic displays. But more than 100 years ago, scientists were the only ones staring into the glow of a cathode-ray tube. Their observations provided important evidence about the structure of atoms.



Subatomic Particles

Much of Dalton's atomic theory is accepted today. One important change, however, is that atoms are now known to be divisible. They can be broken down into even smaller, more fundamental particles, called subatomic particles. **Three kinds of subatomic particles are electrons, protons, and neutrons.**

Electrons In 1897, the English physicist J. J. Thomson (1856–1940) discovered the electron. **Electrons** are negatively charged subatomic particles. Thomson performed experiments that involved passing electric current through gases at low pressure. He sealed the gases in glass tubes fitted at both ends with metal disks called electrodes. The electrodes were connected to a source of electricity, as shown in Figure 4.4. One electrode, the anode, became positively charged. The other electrode, the cathode, became negatively charged. The result was a glowing beam, or **cathode ray,** that traveled from the cathode to the anode.

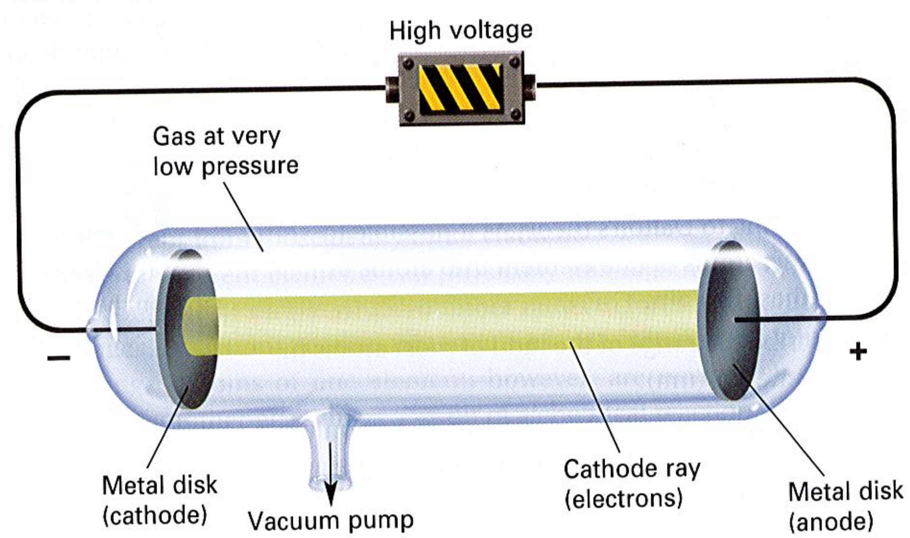


Figure 4.4 In a cathode-ray tube, electrons travel as a ray from the cathode (−) to the anode (+). A television tube is a specialized type of cathode-ray tube.

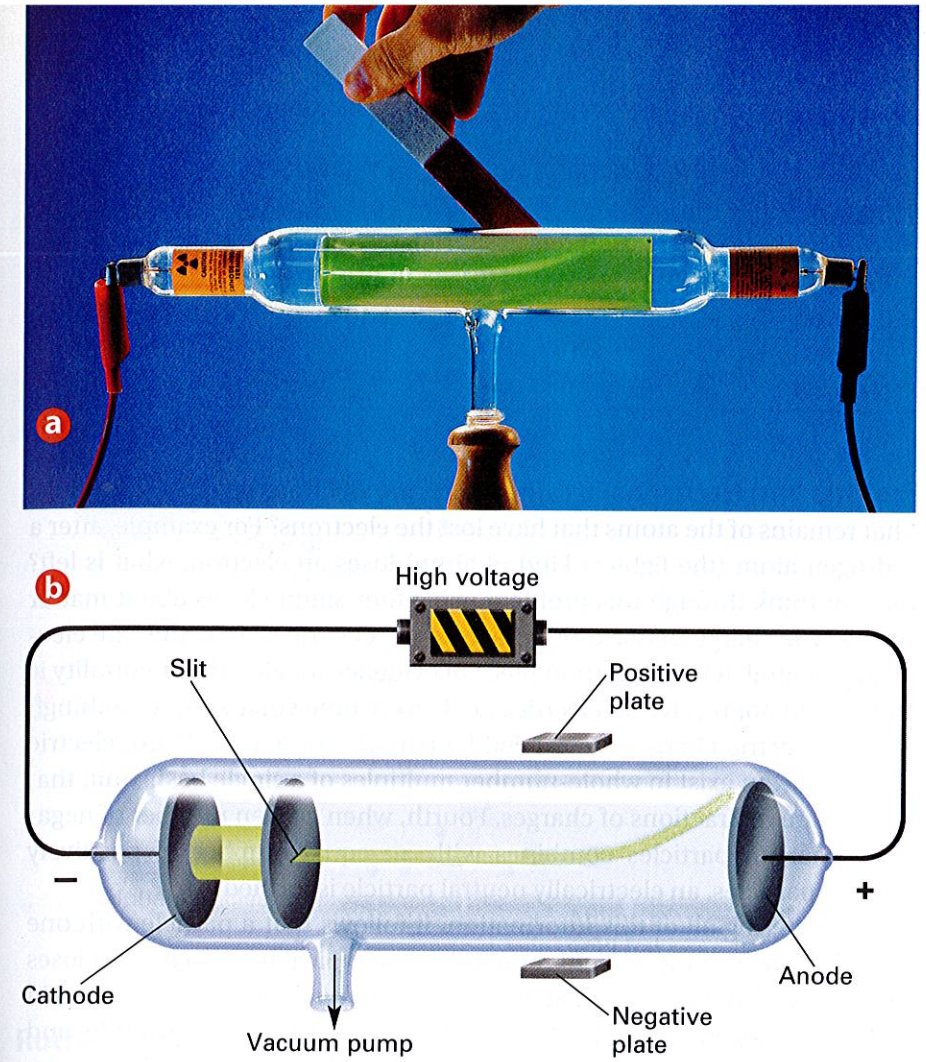


Figure 4.5 Thomson examined two ways that a cathode ray can be deflected: **a** by using a magnet, and **b** by using electrically charged plates.
Inferring ***If a cathode ray is attracted to a positively charged plate, what can you infer about the charge of the particles that make up the cathode ray?***

Figure 4.5a shows how a cathode ray is deflected by a magnet. A cathode ray is also deflected by electrically charged metal plates, as shown in Figure 4.5b. A positively charged plate attracts the cathode ray, while a negatively charged plate repels it. Thomson knew that opposite charges attract and like charges repel, so he hypothesized that a cathode ray is a stream of tiny negatively charged particles moving at high speed. Thomson called these particles corpuscles; later they were named electrons.

To test his hypothesis, Thomson set up an experiment to measure the ratio of the charge of an electron to its mass. He found this ratio to be constant. In addition, the charge-to-mass ratio of electrons did not depend on the kind of gas in the cathode-ray tube or the type of metal used for the electrodes. Thomson concluded that electrons must be parts of the atoms of all elements.

The U.S. physicist Robert A. Millikan (1868–1953) carried out experiments to find the quantity of charge carried by an electron. Using this value and the charge-to-mass ratio of an electron measured by Thomson, Millikan calculated the mass of the electron. Millikan's values for electron charge and mass, reported in 1916, are very similar to those accepted today. An electron carries exactly one unit of negative charge, and its mass is 1/1840 the mass of a hydrogen atom.

Checkpoint ***How do negatively charged plates affect the path of cathode rays?***

Go Online
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For: Links on J.J. Thomson
Visit: www.SciLinks.org
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Table 4.1

Properties of Subatomic Particles				
Particle	Symbol	Relative charge	Relative mass (mass of proton = 1)	Actual mass (g)
Electron	e^-	1−	1/1840	9.11×10^{-28}
Proton	p^+	1+	1	1.67×10^{-24}
Neutron	n^0	0	1	1.67×10^{-24}

Protons and Neutrons If cathode rays are electrons given off by atoms, what remains of the atoms that have lost the electrons? For example, after a hydrogen atom (the lightest kind of atom) loses an electron, what is left? You can think through this problem using four simple ideas about matter and electric charges. First, atoms have no net electric charge; they are electrically neutral. (One important piece of evidence for electrical neutrality is that you do not receive an electric shock every time you touch something!) Second, electric charges are carried by particles of matter. Third, electric charges always exist in whole-number multiples of a single basic unit; that is, there are no fractions of charges. Fourth, when a given number of negatively charged particles combines with an equal number of positively charged particles, an electrically neutral particle is formed.

Considering all of this information, it follows that a particle with one unit of positive charge should remain when a typical hydrogen atom loses an electron. Evidence for such a positively charged particle was found in 1886, when Eugen Goldstein (1850–1930) observed a cathode-ray tube and found rays traveling in the direction opposite to that of the cathode rays. He called these rays canal rays and concluded that they were composed of positive particles. Such positively charged subatomic particles are called **protons.** Each proton has a mass about 1840 times that of an electron.

In 1932, the English physicist James Chadwick (1891–1974) confirmed the existence of yet another subatomic particle: the neutron. **Neutrons** are subatomic particles with no charge but with a mass nearly equal to that of a proton. Table 4.1 summarizes the properties of these subatomic particles. Although protons and neutrons are exceedingly small, theoretical physicists believe that they are composed of yet smaller subnuclear particles called *quarks*.

Figure 4.6 Born in New Zealand, Ernest Rutherford was awarded the Nobel Prize for Chemistry in 1908. His portrait appears on the New Zealand $100 bill.

The Atomic Nucleus

When subatomic particles were discovered, scientists wondered how these particles were put together in an atom. This was a difficult question to answer, given how tiny atoms are. Most scientists—including J.J. Thomson, the discoverer of the electron—thought it likely that the electrons were evenly distributed throughout an atom filled uniformly with positively charged material. In Thomson's atomic model, known as the "plum-pudding model," electrons were stuck into a lump of positive charge, similar to raisins stuck in dough. This model of the atom turned out to be short-lived, however, due to the groundbreaking work of Ernest Rutherford (1871–1937), a former student of Thomson.

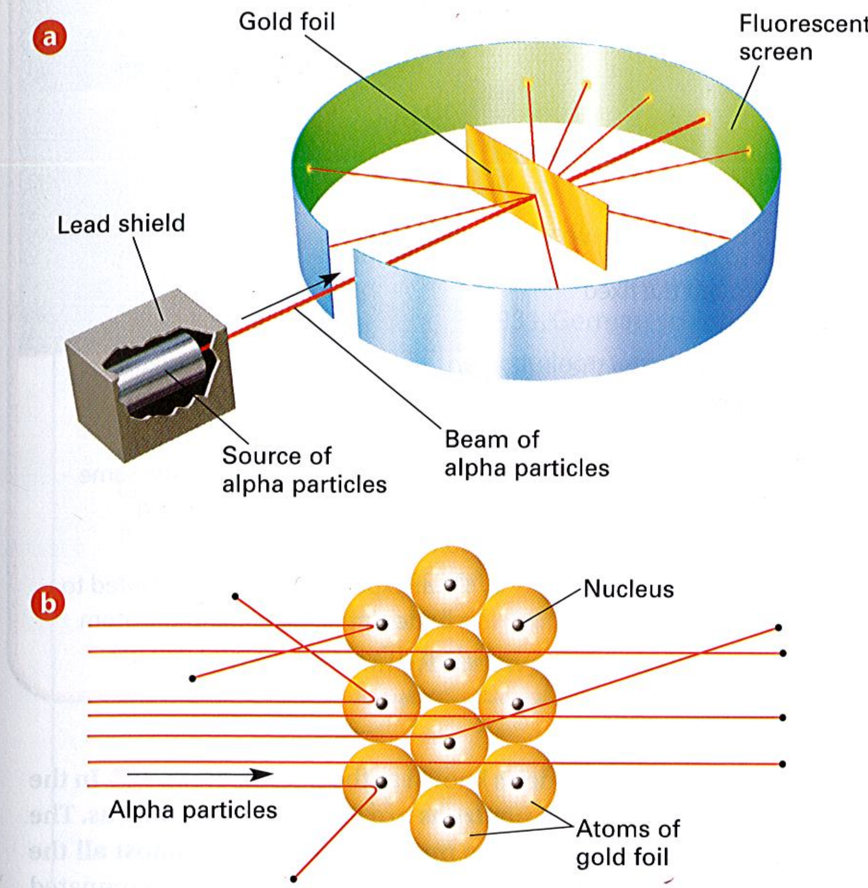

Figure 4.7 Rutherford's gold-foil experiment yielded evidence of the atomic nucleus. (a) Rutherford and his coworkers aimed a beam of alpha particles at a sheet of gold foil surrounded by a fluorescent screen. Most of the particles passed through the foil with no deflection at all. A few particles were greatly deflected. (b) Rutherford concluded that most of the alpha particles pass through the gold foil because the atom is mostly empty space. The mass and positive charge are concentrated in a small region of the atom. Rutherford called this region the nucleus. Particles that approach the nucleus closely are greatly deflected.

Rutherford's Gold-Foil Experiment In 1911, Rutherford and his coworkers at the University of Manchester, England, decided to test what was then the current theory of atomic structure. Their test used relatively massive alpha particles, which are helium atoms that have lost their two electrons and have a double positive charge because of the two remaining protons. In the experiment, illustrated in Figure 4.7, a narrow beam of alpha particles was directed at a very thin sheet of gold foil. According to the prevailing theory, the alpha particles should have passed easily through the gold, with only a slight deflection due to the positive charge thought to be spread out in the gold atoms.

To everyone's surprise, the great majority of alpha particles passed straight through the gold atoms, without deflection. Even more surprisingly, a small fraction of the alpha particles bounced off the gold foil at very large angles. Some even bounced straight back toward the source. Rutherford later recollected, "This is almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Interactive Textbook

Animation 4 Take a look at Rutherford's gold-foil experiment, its results, and its conclusions.

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The Rutherford Atomic Model Based on his experimental results, Rutherford suggested a new theory of the atom. He proposed that the atom is mostly empty space, thus explaining the lack of deflection of most of the alpha particles. He concluded that all the positive charge and almost all the mass are concentrated in a small region that has enough positive charge to account for the great deflection of some of the alpha particles. He called this region the nucleus. The **nucleus** is the tiny central core of an atom and is composed of protons and neutrons.

Quick LAB

Using Inference: The Black Box

Purpose

To determine the shape of a fixed object inside a sealed box without opening the box.

Materials

- box containing a regularly shaped object fixed in place and a loose marble

Procedure

1. Do not open the box.
2. Manipulate the box so that the marble moves around the fixed object.
3. Gather data (clues) that describe the movement of the marble.
4. Sketch a picture of the object in the box, showing its shape, size, and location within the box.
5. Repeat this activity with a different box containing a different object.

Analysis and Conclusions

1. Find a classmate who had the same lettered box that you had, and compare your findings.
2. What experiment that contributed to a better understanding of the atom does this activity remind you of?

The Rutherford atomic model is known as the nuclear atom. **In the nuclear atom, the protons and neutrons are located in the nucleus. The electrons are distributed around the nucleus and occupy almost all the volume of the atom.** According to this model, the nucleus is tiny compared with the atom as a whole. If an atom were the size of a football stadium, the nucleus would be about the size of a marble.

Although it was an improvement over Thomson's model of the atom, Rutherford's model turned out to be incomplete. In Chapter 5, you will learn how the Rutherford atomic model had to be revised in order to explain the chemical properties of elements.

4.2 Section Assessment

8. **Key Concept** What are three types of subatomic particles?
9. **Key Concept** How does the Rutherford model describe the structure of atoms?
10. What are the charges and relative masses of the three main subatomic particles?
11. Describe Thomson's and Millikan's contributions to atomic theory.
12. Compare Rutherford's expected outcome of the gold-foil experiment with the actual outcome.
13. What experimental evidence led Rutherford to conclude that an atom is mostly empty space?
14. How did Rutherford's model of the atom differ from Thomson's?

Writing Activity

Explanatory Paragraph Write a paragraph explaining how Rutherford's gold-foil experiment yielded new evidence about atomic structure. *Hint:* First describe the setup of the experiment. Then explain how Rutherford interpreted his experimental data.

Interactive Textbook

Assessment 4.2 Test yourself on the concepts in Section 4.2.

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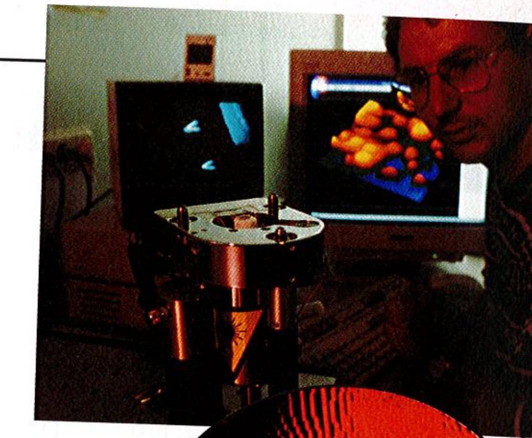
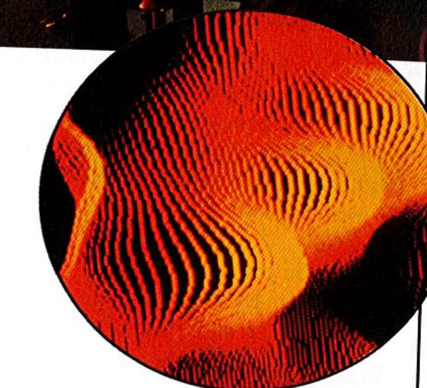
Technology & Society

Electron Microscopy

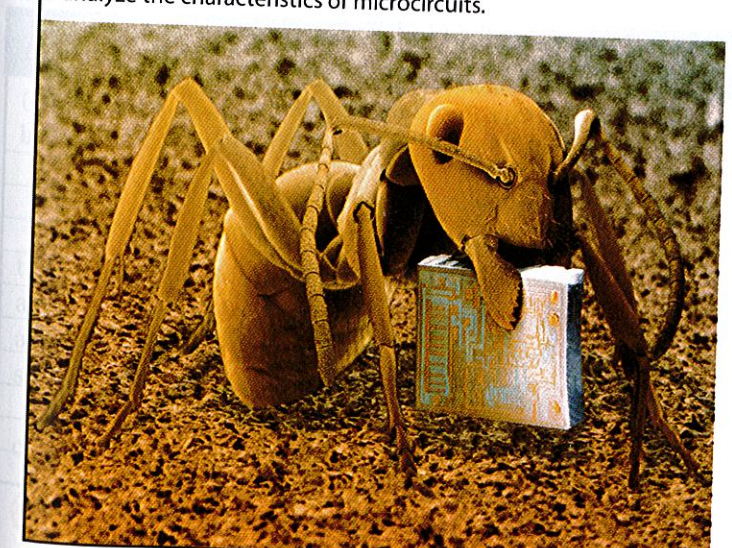
Within 30 years of J.J. Thomson's discovery of the electron, scientists were studying how to produce images of objects by using an electron beam. In 1931, German scientists Ernst Ruska and Max Knoll built the first electron microscope. While an ordinary light microscope uses a beam of light and lenses to magnify objects, an electron microscope uses an electron beam and "lenses" consisting of magnetic or electric fields. A typical light microscope is capable of magnifying an object 1000 times. An electron microscope can magnify an object over 100,000 times. **Interpreting Photographs** ***What characteristics of the images below provide the viewer with a sense of scale?***

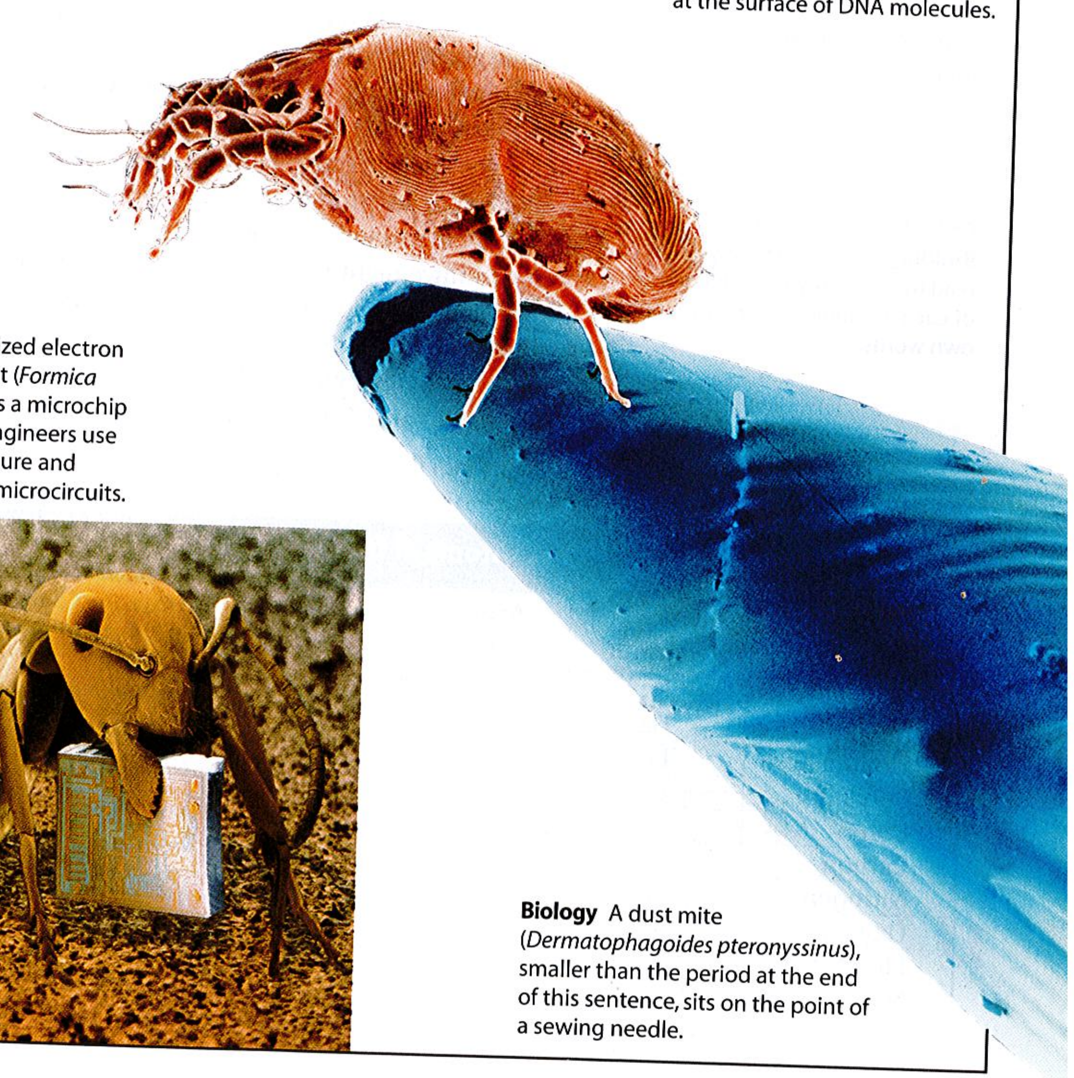




Biochemistry A scientist uses an electron microscope to look at the surface of DNA molecules.

Microelectronics In the colorized electron micrograph below, a wood ant (*Formica fusca*), about 5 mm long, holds a microchip in its jaws. Microelectronics engineers use electron microscopes to measure and analyze the characteristics of microcircuits.





Biology A dust mite (*Dermatophagoides pteronyssinus*), smaller than the period at the end of this sentence, sits on the point of a sewing needle.