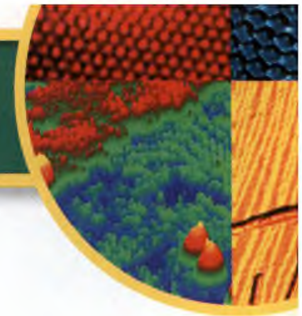
4.1 Studying Atoms



Reading Focus

Key Concepts

- What was Dalton's theory of the structure of matter?
- What contributions did Thomson and Rutherford make to the development of atomic theory?

Vocabulary

- nucleus

Reading Strategy

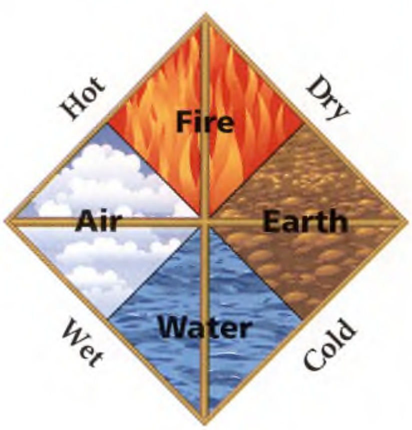
Summarizing Copy the table. As you read, complete the table about atomic models.

Scientist	Evidence	Model
a. ___?___	Ratio of masses in compounds	b. ___?___
c. ___?___	Deflected beam	d. ___?___
Rutherford	e. ___?___	Positive, dense nucleus

Studying the structure of atoms is a little like studying wind. Because you cannot see air, you must use indirect evidence to tell the direction of the wind. You might notice which way fallen leaves move as they are pushed by the wind, and infer that the leaves and wind are moving in the same direction.

Atoms pose a similar problem because they are extremely small. Even with a microscope, scientists cannot see the structure of an atom. In this chapter, you will find out how John Dalton, J. J. Thomson, Ernest Rutherford, Niels Bohr, and other scientists used evidence from experiments to develop models of atoms.

Figure 1 Aristotle thought that all substances were built up from only four elements—earth, air, fire, and water. These elements were a combination of four qualities—hot, cold, dry, and wet. Fire was a combination of hot and dry. Water was a combination of cold and wet.



Ancient Greek Models of Atoms

If you cut a piece of aluminum foil in half, you have two smaller pieces of the same shiny, flexible substance. You could cut the pieces again and again. Can you keep dividing the aluminum into smaller pieces? Greek philosophers debated a similar question about 2500 years ago.

The philosopher Democritus believed that all matter consisted of extremely small particles that could not be divided. He called these particles *atoms* from the Greek word *atomos,* which means "uncut" or "indivisible." He thought there were different types of atoms with specific sets of properties. The atoms in liquids, for example, were round and smooth, but the atoms in solids were rough and prickly.

Aristotle did not think there was a limit to the number of times matter could be divided. Figure 1 shows the model Aristotle used to describe matter. For many centuries, most people accepted Aristotle's views on the structure of matter. But by the 1800s, scientists had enough data from experiments to support an atomic model of matter.

Dalton's Atomic Theory

John Dalton was born in England in 1766. He was a teacher who spent his spare time doing scientific experiments. Because of his interest in predicting the weather, Dalton studied the behavior of gases in air. Based on the way gases exert pressure, Dalton correctly concluded that a gas consists of individual particles.

Figure 2 Magnesium reacts with oxygen to form the compound magnesium oxide. The ratio of magnesium to oxygen, by mass, in magnesium oxide is always about 3 : 2. **Observing** ***What color is magnesium oxide?***

Evidence for Atoms

Dalton gathered evidence for the existence of atoms by measuring the masses of elements that combine when compounds form. He noticed that all compounds have something in common. No matter how large or small the sample, the ratio of the masses of the elements in the compound is always the same. In other words, compounds have a fixed composition.

For example, when magnesium burns, as shown in Figure 2, it combines with oxygen. The product of this change is a white solid called magnesium oxide. A 100-gram sample of magnesium combines with 65.8 grams of oxygen. A 10-gram sample of magnesium combines with 6.58 grams of oxygen. The ratio of the mass of magnesium to the mass of oxygen is constant in magnesium oxide.

Dalton's Theory

Dalton developed a theory to explain why the elements in a compound always join in the same way. **Dalton proposed the theory that all matter is made up of individual particles called atoms, which cannot be divided.** The main points of Dalton's theory are as follows.

- All elements are composed of atoms.
- All atoms of the same element have the same mass, and atoms of different elements have different masses.
- Compounds contain atoms of more than one element.
- In a particular compound, atoms of different elements always combine in the same way.

Figure 3 Dalton made these wooden spheres to represent the atoms of different elements.

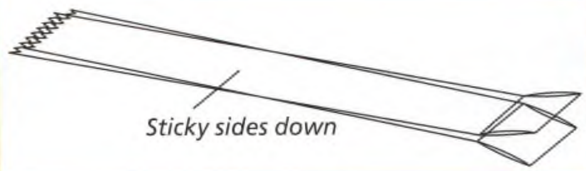
In the model of atoms based on Dalton's theory, the elements are pictured as solid spheres like those in Figure 3. Each type of atom is represented by a tiny, solid sphere with a different mass.

Recall that a theory must explain the data from many experiments. Because Dalton's atomic theory met that goal, the theory became widely accepted. Over time, scientists found that not all of Dalton's ideas about atoms were completely correct. But this did not cause later scientists to discard the atomic theory. Instead, they revised the theory to take into account new discoveries.

Reading Checkpoint ***What did Dalton notice that all compounds have in common?***

Quick Lab

Investigating Charged Objects



Materials

transparent tape, metric ruler, scissors

Procedure

1. Cut two 10-cm pieces of tape. Fold over 1 cm of tape at one end of each piece of tape to form a "handle."
2. Hold the pieces of tape by their folded ends so that they are hanging straight down. Then, without letting the pieces of tape touch, slowly bring their sticky sides close together. Record your observations.
3. Place one piece of tape on a clean surface with the sticky side facing down.
4. Place the second piece, sticky side down, directly over the first piece, as shown. Press down firmly so the pieces stick together.
5. Remove the joined strips from the table. Slowly peel the strips apart.
6. Bring the separated strips close together without touching. Record your observations.

Analyze and Conclude

1. **Drawing Conclusions** What can you conclude about the charges on the two pieces of tape after they are separated?
2. **Inferring** What other objects have you observed that became charged?

Figure 4 Amber is the hardened form of a sticky, viscous liquid that protects trees from insects and disease. If amber is rubbed with wool, it becomes charged and can attract a feather. **Predicting** ***What will happen to the feather if the amber loses its charge?***

Thomson's Model of the Atom

When some materials are rubbed, they gain the ability to attract or repel other materials. Glass and the amber in Figure 4 have this property. Based on their behavior, such materials are said to have either a positive or a negative electric charge. Objects with like charges repel, or push apart. Objects with opposite charges attract, or pull together.

Some charged particles can flow from one location to another. A flow of charged particles is called an electric current. When you turn on an appliance such as a hair dryer, a current flows from the wall socket through the appliance. Joseph John Thomson (1856–1940), better known as J. J. Thomson, used an electric current to learn more about atoms.

Thomson's Experiments Thomson used a device like the one shown in Figure 5A. At the center of the device is a sealed glass tube from which most of the air has been removed. There is a metal disk at each end of the tube. Wires connect the metal disks to a source of electric current. When the current is turned on, one disk becomes negatively charged and the other disk becomes positively charged. A glowing beam appears in the space between the disks.

Thomson hypothesized that the beam was a stream of charged particles that interacted with the air in the tube and caused the air to glow. In one experiment Thomson did to test his hypothesis, he placed a pair of charged metal plates on either side of the glass tube, as shown in Figure 5B. The plates caused the beam to deflect, or bend, from its straight path. Thomson observed that the beam was repelled by the negatively charged plate and attracted by the positively charged plate.

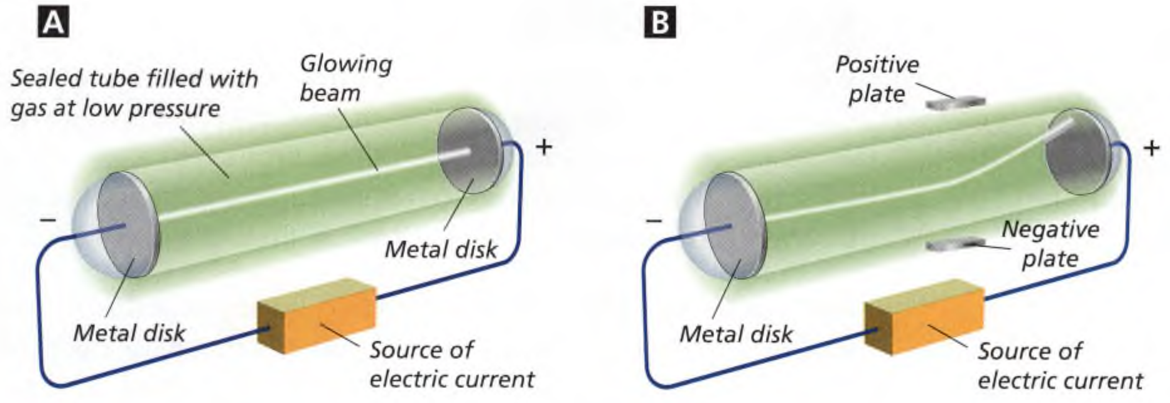


Figure 5 Thomson used a sealed tube of gas in his experiments. **A** When the current was on, the disks became charged and a glowing beam appeared in the tube. **B** The beam bent toward a positively charged plate placed outside the tube.
Inferring ***What was the charge on the particles in the beam?***

Evidence for Subatomic Particles

Thomson concluded that the particles in the beam had a negative charge because they were attracted to the positive plate. He hypothesized that the particles came from inside atoms. He had two pieces of evidence to support his hypothesis. No matter what metal Thomson used for the disk, the particles produced were identical. The particles had about $\frac{1}{2000}$ the mass of a hydrogen atom, the lightest atom.

Thomson's discovery changed how scientists thought about atoms. Before his experiments, the accepted model of the atom was a solid ball of matter that could not be divided into smaller parts. **Thomson's experiments provided the first evidence that atoms are made of even smaller particles.** Thomson revised Dalton's model to account for these subatomic particles.

Figure 6 A scoop of chocolate chip ice cream can represent Thomson's model of the atom. The chips represent negatively charged particles, which are spread evenly through a mass of positively charged matter—the vanilla ice cream.

Thomson's Model

An atom is neutral, meaning it has neither a negative nor a positive charge. How can an atom contain negative particles and still be neutral? There must be some positive charge in the atom. In Thomson's model of the atom, the negative charges were evenly scattered throughout an atom filled with a positively charged mass of matter. The model is called the "plum pudding" model, after a traditional English dessert.

You might prefer to think of Thomson's model as the "chocolate chip ice cream" model. Think of the chocolate chips in Figure 6 as the negative particles and the vanilla ice cream as the positively charged mass of matter. When the chocolate chips are spread evenly throughout the ice cream, their "negative charges" balance out the "positive charge" of the vanilla ice cream.

Reading Checkpoint ***How do objects with the same charge behave when they come close to one another?***

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For: Links on atomic theory
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Rutherford's Atomic Theory

When you try something new, you may have expectations about the outcome. Does the outcome always meet your expectations or are you sometimes surprised? Scientists can also be surprised by the results of their experiments, but unexpected results can lead to important discoveries. This is what happened to Ernest Rutherford (1871–1937).

Rutherford's Hypothesis In 1899, Ernest Rutherford discovered that uranium emits fast-moving particles that have a positive charge. He named them alpha particles. In 1909, Rutherford asked one of his students, Ernest Marsden, to find out what happens to alpha particles when they pass through a thin sheet of gold.

Recall that in Thomson's model of the atom, the mass and positive charge are evenly spread throughout an atom. Based on this model, Rutherford hypothesized that the mass and charge at any location in the gold would be too small to change the path of an alpha particle. He predicted that most particles would travel in a straight path from their source to a screen that lit up when struck. Those few that did not pass straight through would be deflected only slightly.

The Gold Foil Experiment Marsden used the equipment shown in Figure 7. He aimed a narrow beam of alpha particles at the gold. The screen around the gold was made of a material that produced a flash of light when struck by a fast-moving alpha particle. By observing the flash, Marsden could figure out the path of an alpha particle after it passed through the gold.

Some of the locations of the flashes on the screen did not support Rutherford's prediction. More particles were deflected than he expected. About one out of every 20,000 was deflected by more than 90 degrees. Some of the alpha particles behaved as though they had struck an object and bounced straight back.

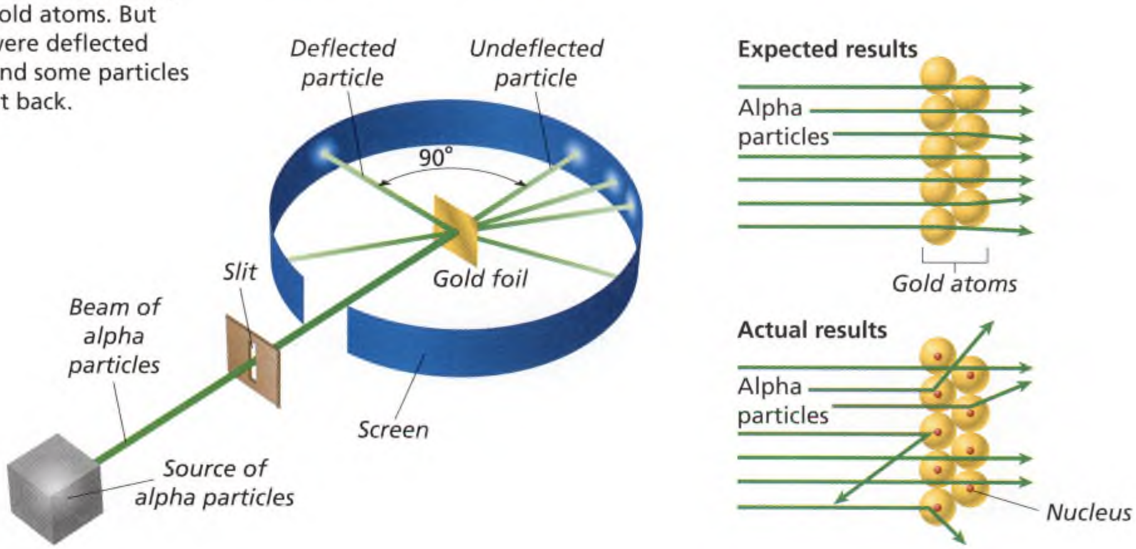


Figure 7 The path of an alpha particle can be detected by the location of a flash on a screen. Rutherford expected the paths of the positively charged alpha particles that were aimed at the thin gold foil to be affected only slightly by the gold atoms. But more particles were deflected than expected and some particles bounced straight back.

Discovery of the Nucleus The alpha particles whose paths were deflected must have come close to another charged object. The closer they came, the greater the deflection was. But many alpha particles passed through the gold without being deflected. From these results, Rutherford concluded that the positive charge of an atom is not evenly spread throughout the atom. It is concentrated in a very small, central area that Rutherford called the nucleus. The **nucleus** is a dense, positively charged mass located in the center of the atom. (The plural of *nucleus* is *nuclei.*)

Because Thomson's model no longer explained all the evidence, Rutherford proposed a new model. **According to Rutherford's model, all of an atom's positive charge is concentrated in its nucleus.** The alpha particles whose paths were deflected by more than 90 degrees came very close to a nucleus. The alpha particles whose paths were not bent moved through the space surrounding the nuclei without coming very close to any nucleus.

Figure 8 shows the inside of the Astrodome, a domed stadium in Houston, Texas. The roof of the stadium rises to a height of 202 feet above the center of the field. If an atom had the same volume as the stadium, its nucleus would have the volume of a marble. The total volume of an atom is about a trillion (10^{12}) times the volume of its nucleus.

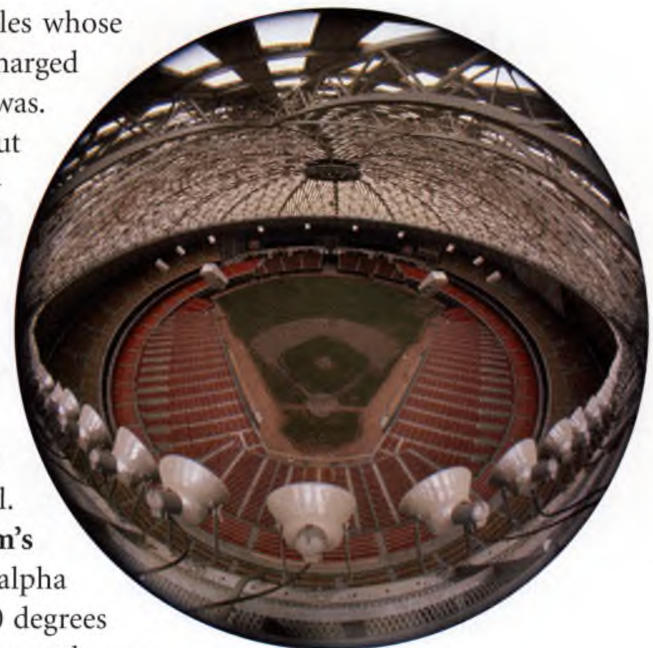


Figure 8 The Houston Astrodome occupies more than nine acres and seats 60,000 people. If the stadium were a model for an atom, a marble could represent its nucleus. **Using Analogies** ***In the model, where would the marble have to be located in the stadium to represent the nucleus?***

Section 4.1 Assessment

Reviewing Concepts

1. What theory did Dalton propose about the structure of matter?
2. What evidence did J. J. Thomson provide about the structure of an atom?
3. What did Rutherford discover about the structure of an atom?
4. What evidence did Thomson have that his glowing beam contained negative particles?
5. Why was Dalton's model of the atom changed after Thomson's experiment?

Critical Thinking

6. **Comparing and Contrasting** Explain why scientists accepted Dalton's atomic theory but not the idea of an atom proposed by the Greek philosophers.
7. **Drawing Conclusions** If you observed a beam of particles being bent toward a negatively charged plate, what might you conclude?
8. **Relating Cause and Effect** In the Rutherford experiment, why weren't all the alpha particles deflected?

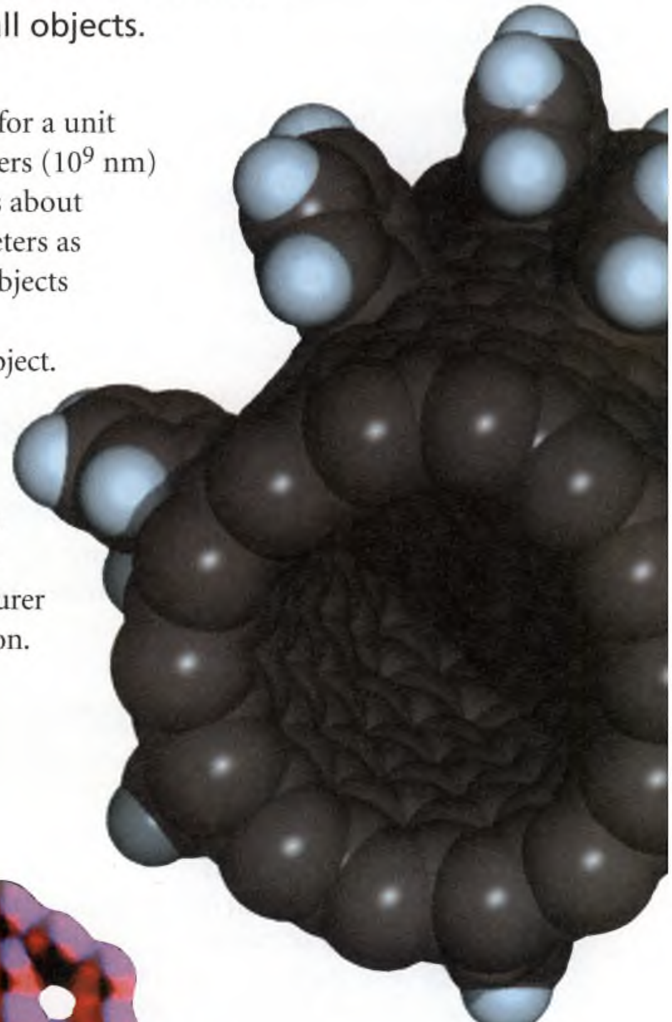
Writing in Science

Writing to Persuade Imagine you live in ancient Greece. Assume all you know about matter is what you can observe with your five senses. You have heard the views of both Democritus and Aristotle about matter. Write a paragraph supporting one of their views.

CONCEPTS in Action

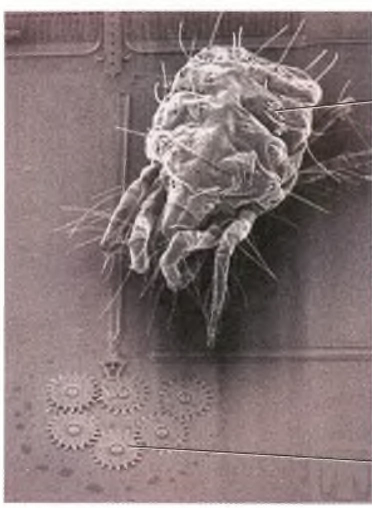
Small-Scale Construction

Some scientists and engineers think of atoms and molecules as construction materials for building very small objects.



The field of science called nanotechnology is named for a unit of measurement—the nanometer. A billion nanometers (10^9 nm) can fit in one meter. The diameter of a human hair is about 80,000 nm. Scientists and engineers who use nanometers as measuring units are building miniature versions of objects such as motors.

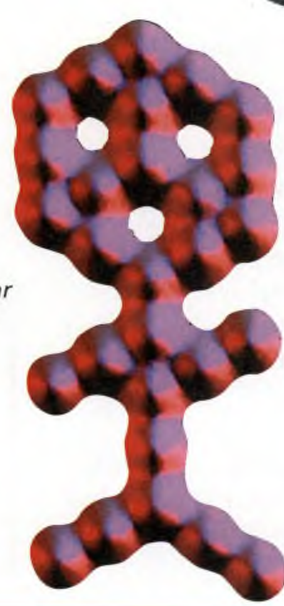
There are two general methods for building any object. You can start with more material than you need and shape the object by removing matter or you can build up the object from smaller pieces. When you shape your nails with an emery board, you are using a top-down construction method. When you see "some assembly required" on the side of a box, the manufacturer expects you to use a bottom-up method of construction.



Dust mite

Silicon gear assembly

Building from the top down
Gears are toothed disks that are designed to fit together so that the motion of one gear controls the motion of another. These silicon gears are among the smallest objects ever made from the top down.



Building from the bottom up
With a scanning tunneling microscope, it is possible to move individual atoms or molecules. This figure, made of linked carbon monoxide molecules, is just five nanometers (0.000005 mm) tall. In 1990, scientists built this figure to demonstrate bottom-up construction methods.

Futuristic model of a nanorobot performing surgery in a blood vessel.

The future of nanotechnology
Potential applications for nanotechnology include medical diagnostic tools and atomic-level electronic devices that assemble themselves. If such devices prove successful, perhaps someday the surgical robot will be built.

Sheet of carbon atoms rolled into a tube

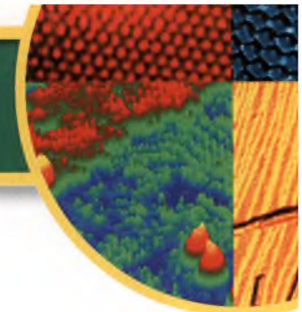
Ring of carbon atoms with hydrogen atoms attached

Nanogears
This image of nanogears was produced with a computer program designed to make models of molecules. Hollow tubes (nanotubes) made from sheets of carbon atoms do exist. So do the rings containing carbon and hydrogen atoms, which are used for the "teeth" of the gears. But researchers need to figure out how to get the "teeth" to attach to the tubes.

Going Further

- Research proposed uses of nanotechnology. Make a poster describing one proposed use. Explain the advantage of using small objects in this application. What problems must be solved before the application can be used?
- Take a Discovery Channel Video Field Trip by watching "Go For Gold."

Discovery Channel School Video Field Trip



4.2 The Structure of an Atom

Reading Focus

Key Concepts

- What are three subatomic particles?
- What properties can be used to compare protons, electrons, and neutrons?
- How are atoms of one element different from atoms of other elements?
- What is the difference between two isotopes of the same element?

Vocabulary

- proton
- electron
- neutron
- atomic number
- mass number
- isotopes

Reading Strategy

Monitoring Your Understanding Before you read, copy the table. List what you know about atoms and what you would like to learn. After you read, list what you have learned.

What I Know About Atoms	What I Would Like to Learn	What I Have Learned

Figure 9 This 45-foot-tall steel sculpture of a clothespin is in Philadelphia, Pennsylvania. Claes Oldenburg made the clothespin in 1976 from 10 tons of steel. If a proton had a mass of 10 tons, then an electron would have a mass of about 5 kilograms.

Beams like the ones Thomson produced create the images on many television screens. When a beam sweeps across the screen, spots on the screen light up in the same way the screen in the gold-foil experiment lit up when struck by an alpha particle. In a color television, there are three beams, one for each primary color of light—red, green, and blue. The particles in these beams are subatomic particles.

Properties of Subatomic Particles

By 1920, Rutherford had seen evidence for the existence of two subatomic particles and had predicted the existence of a third particle. **Protons, electrons, and neutrons are subatomic particles.**

Protons Based on experiments with elements other than gold, Rutherford concluded that the amount of positive charge varies among elements. Each nucleus must contain at least one particle with a positive charge. Rutherford called these particles protons. A **proton** is a positively charged subatomic particle that is found in the nucleus of an atom. Each proton is assigned a charge of 1+. Some nuclei contain more than 100 protons.

Electrons The particles that Thomson detected were later named electrons. *Electron* comes from a Greek word meaning "amber." An **electron** is a negatively charged subatomic particle that is found in the space outside the nucleus. Each electron has a charge of 1−.

Properties of Subatomic Particles					
Particle	Symbol	Relative Charge	Relative Mass (proton = 1)	Actual Mass (g)	Model
Electron	e^-	1−	$\frac{1}{1836}$	9.11×10^{-28}	
Proton	p^+	1+	1	1.674×10^{-24}	
Neutron	n	0	1	1.675×10^{-24}	

Figure 10 This table lists the symbol, the relative charge, the relative mass, and the actual mass of an electron, a proton, and a neutron. The Model column shows the colors used in this book to represent the subatomic particles. **Calculating** ***What is the difference in actual mass between a proton and a neutron?***

Neutrons In 1932, the English physicist James Chadwick designed an experiment to show that neutrons exist. Chadwick concluded that the particles he produced were neutral because a charged object did not deflect their paths. A **neutron** is a neutral subatomic particle that is found in the nucleus of an atom. It has a mass almost exactly equal to that of a proton.

Comparing Subatomic Particles

Figure 10 summarizes some properties of protons, electrons, and neutrons. **Protons, electrons, and neutrons can be distinguished by mass, charge, and location in an atom.** Protons and neutrons have almost the same mass. But the data in Figure 10 show that it would take about 2000 electrons to equal the mass of one proton. Electrons have a charge that is equal in size to, but the opposite of, the charge of a proton. Neutrons have no charge. Protons and neutrons are found in the nucleus, but electrons are found in the space outside the nucleus.

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Problem-Solving Activity

Designing an Atomic Exhibit

You work as a volunteer at the local science museum. You are asked to design an exhibit that compares the size of a lithium atom to the size of its nucleus. A lithium atom has a diameter of about 3×10^2 picometers. The nucleus of a lithium atom has a diameter of about 5×10^{-3} picometers. There are a trillion (10^{12}) picometers in a meter.

Defining the Problem State the problem in your own words. What decisions will you need to make before you can proceed?

Organizing Information How many times larger is the lithium atom than its nucleus? Find several objects that could represent the nucleus in your exhibit and measure their diameters.

Creating a Solution Pick one of the objects you measured to represent the nucleus in your atomic exhibit. Figure out how far away from the object you would have to place a marker so that people could visualize the relative sizes of the atom and the nucleus.

Presenting Your Plan Write a proposal to present to the committee that approves projects. Tell them where you would place the nucleus and where you would have to place the marker. Be prepared to explain why your exhibit needs the space you are requesting.

Everything scientists know about the nucleus and subatomic particles is based on how the particles behave. Scientists still do not have an instrument that can show the inside of an atom. But they do have microscopes that can show how atoms are arranged on the surface of a material. The How It Works box on page 111 describes one of those microscopes.

Reading Checkpoint *Which scientist demonstrated the existence of neutrons?*

Atomic Number and Mass Number

Dalton predicted that the atoms of any element are different from the atoms of all other elements. With the discovery of subatomic particles, scientists were able to describe those differences.

Atomic Number The atoms of any given element always have the same number of protons. For example, there is one proton in the nucleus of each and every hydrogen atom. Therefore, hydrogen is assigned the atomic number 1. The **atomic number** of an element equals the number of protons in an atom of that element.

Hydrogen atoms are the only atoms with a single proton. **Atoms of different elements have different numbers of protons.** The sulfur shown in Figure 11A is assigned atomic number 16 because a sulfur atom has 16 protons. You can use atomic numbers to refer to elements, like names and symbols, because each element has a unique atomic number.

Each positive charge in an atom is balanced by a negative charge because atoms are neutral. So the atomic number of an element also equals the number of electrons in an atom. Each hydrogen atom has one electron. Each sulfur atom has 16.

Figure 11 Each element has a different atomic number. **A** The atomic number of sulfur (S) is 16. **B** The atomic number of iron (Fe) is 26. **C** The atomic number of silver (Ag) is 47.
Applying Concepts ***How many protons are there in each atom of sulfur, iron, and silver?***

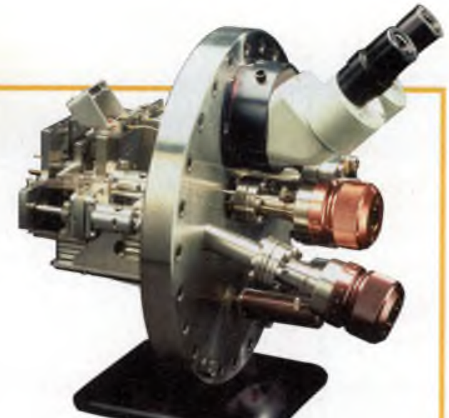
Mass Number The atomic number tells you the number of protons in an atom's nucleus. It does not give you any information about the number of neutrons in an atom. For that information, you need to know the atom's mass number. The **mass number** of an atom is the sum of the protons and neutrons in the nucleus of that atom. An atom of aluminum with 13 protons and 14 neutrons has a mass number of 27. If you know the atomic number and the mass number of an atom, you can find the number of neutrons by subtracting.

Number of Neutrons

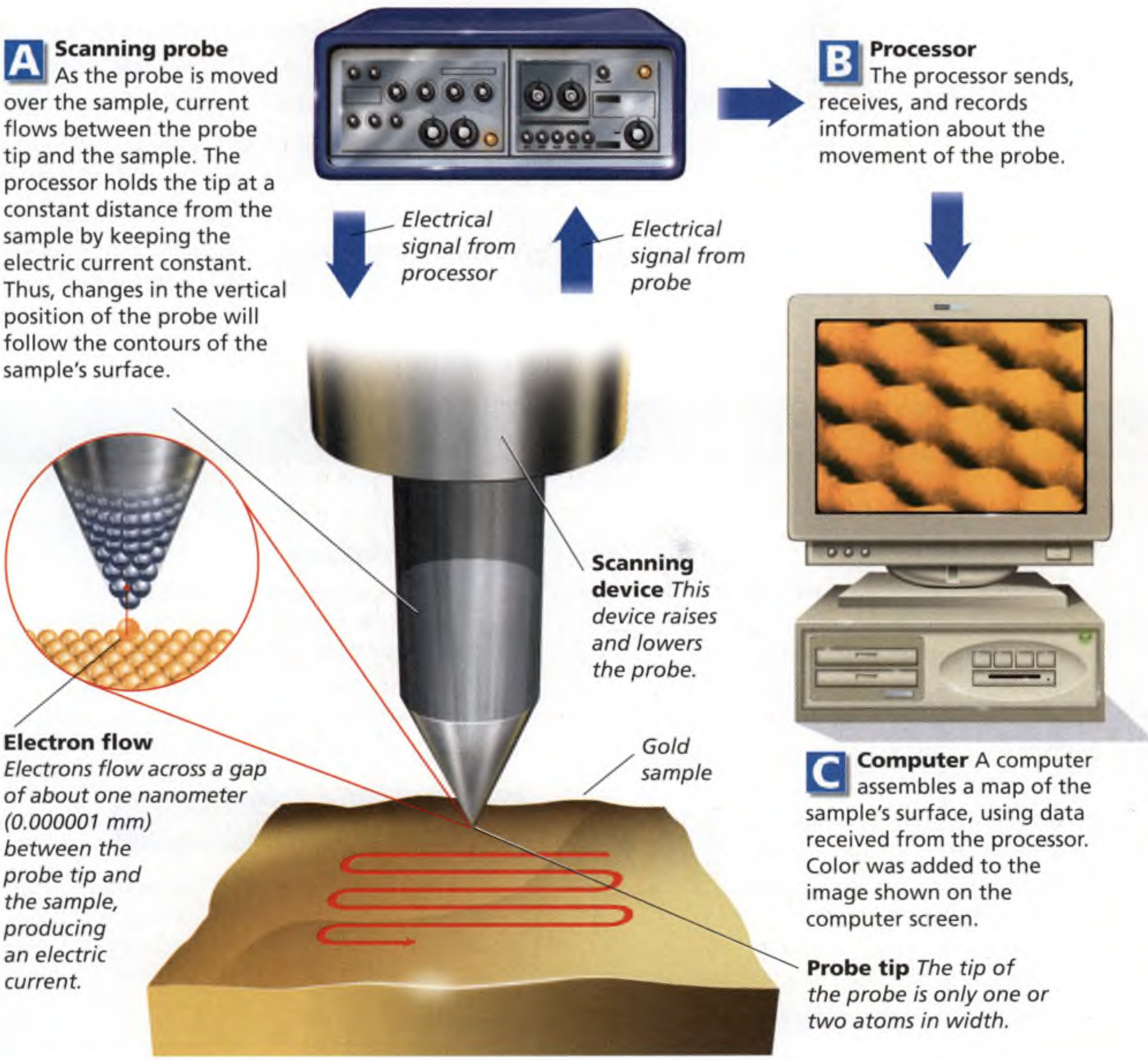
Number of neutrons = Mass number − Atomic number

Scanning Tunneling Microscope

A probe is moved back and forth across the surface of a sample. When electrons jump, or tunnel, across the gap between the sample and the probe, an electric current is produced. A computer uses data about changes in the probe's position to produce an image of the sample's surface. **Interpreting Diagrams** ***How is the distance between the probe tip and the sample kept constant?***



Scanning tunneling microscope
Modern scanning tunneling microscopes produce images of metal samples or biological specimens such as DNA.



A Scanning probe As the probe is moved over the sample, current flows between the probe tip and the sample. The processor holds the tip at a constant distance from the sample by keeping the electric current constant. Thus, changes in the vertical position of the probe will follow the contours of the sample's surface.

B Processor The processor sends, receives, and records information about the movement of the probe.

C Computer A computer assembles a map of the sample's surface, using data received from the processor. Color was added to the image shown on the computer screen.

Comparing Ordinary Water and Heavy Water		
Property	**Ordinary Water**	**Heavy Water**
Melting point	0.00°C	3.81°C
Boiling point	100.00°C	101.42°C
Density (at 25°C)	0.99701 g/cm^3	1.1044 g/cm^3

Figure 12 Heavy water contains hydrogen-2 atoms, which have twice the mass of hydrogen-1 atoms. **Using Tables** ***At what temperature would a sample of heavy water freeze?***

Isotopes

In Dalton's atomic theory, all the atoms of a given element are identical. Every atom of a given element *does* have the same number of protons and electrons. But every atom of a given element *does not* have the same number of neutrons. **Isotopes** are atoms of the same element that have different numbers of neutrons and different mass numbers. **Isotopes of an element have the same atomic number but different mass numbers because they have different numbers of neutrons.**

For example, every atom of oxygen has 8 protons. Some oxygen atoms have 8 neutrons and a mass number of 16. Some oxygen atoms have 9 neutrons and a mass number of 17. Some oxygen atoms have 10 neutrons and a mass number of 18. When it is important to distinguish one oxygen isotope from another, the isotopes are referred to as oxygen-16, oxygen-17, and oxygen-18. All three oxygen isotopes can react with hydrogen to form water or combine with iron to form rust.

With most elements, it is hard to notice any differences in the physical or chemical properties of their isotopes. Hydrogen is an exception. Hydrogen-1 has no neutrons. (Almost all hydrogen is hydrogen-1.) Hydrogen-2 has one neutron, and hydrogen-3 has two neutrons. Because a hydrogen-1 atom has only one proton, adding a neutron doubles its mass. Water that contains hydrogen-2 atoms in place of hydrogen-1 atoms is called heavy water. Figure 12 compares some physical properties of ordinary water and heavy water.

Section 4.2 Assessment

Reviewing Concepts

1. Name three subatomic particles.
2. Name three properties you could use to distinguish a proton from an electron.
3. Which characteristic of an atom always varies among atoms of different elements?
4. How are the isotopes of an element different from one another?
5. What do neutrons and protons have in common? How are they different?
6. How can atoms be neutral if they contain charged particles?
7. What is the difference between atoms of oxygen-16 and oxygen-17?

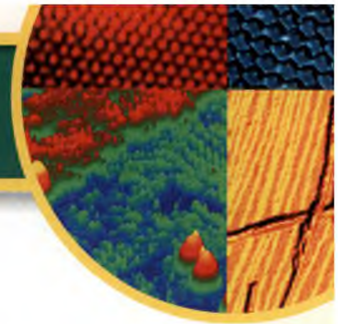
Critical Thinking

8. **Comparing and Contrasting** What property do protons and electrons have that neutrons do not?
9. **Applying Concepts** Explain why it isn't possible for an atom to have a mass number of 10 and an atomic number of 12.

Connecting Concepts

Elements In Section 2.1, you were told that elements contain only one type of atom. How would you define "type of atom" to account for the existence of isotopes?

4.3 Modern Atomic Theory



Reading Focus

Key Concepts

- What can happen to electrons when atoms gain or lose energy?
- What model do scientists use to describe how electrons behave in atoms?
- What is the most stable configuration of electrons in an atom?

Vocabulary

- energy levels
- electron cloud
- orbital
- electron configuration
- ground state

Reading Strategy

Sequencing Copy the flowchart. After you read, complete the description of how a gain or loss of energy affects atoms.

Electrons and Energy Levels

a. ? → Excited state → b. ? → Emits energy

Have you ever wondered what produces the different colors in a fireworks display? Why does one explosion produce red light and another explosion produce green light? The people who make fireworks know that certain compounds will produce certain colors of light when they are heated. For example, compounds containing the element strontium produce red light when they are heated. Compounds containing barium produce green light.

You have seen two things that can happen when atoms absorb energy—an increase in kinetic energy or a phase change. But there is another possibility. The energy may be temporarily absorbed by the atom and then emitted as light. The colors in a fireworks display are a clue to how electrons are arranged in atoms.

Bohr's Model of the Atom

You may have seen diagrams of an atom that look like a solar system with planets revolving around a sun. These diagrams are based on a model of the atom that was developed by Niels Bohr (1885–1962), a Danish physicist who worked for a while with Rutherford. Bohr agreed with Rutherford's model of a nucleus surrounded by a large volume of space. But Bohr's model did something that Rutherford's model did not do. It focused on the electrons. A description of the arrangement of electrons in an atom is the centerpiece of the modern atomic model.

Figure 13 Fireworks are often displayed above the Lincoln Memorial in Washington, D.C. The red light was produced by a strontium compound.

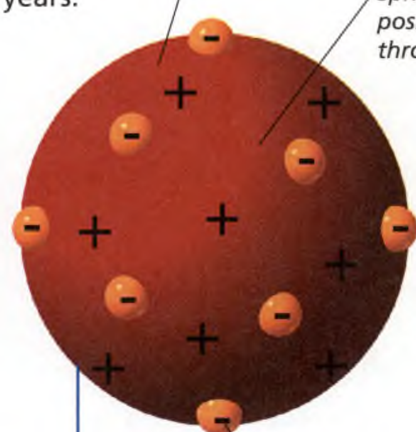
Energy Levels In Bohr's model, electrons move with constant speed in fixed orbits around the nucleus, like planets around a sun. Each electron in an atom has a specific amount of energy. If an atom gains or loses energy, the energy of an electron can change. The possible energies that electrons in an atom can have are called **energy levels.**

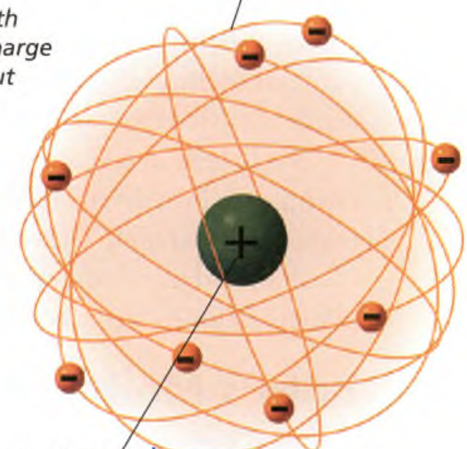
To understand energy levels, picture them as steps in a staircase. As you move up or down the staircase, you can measure how your position changes by counting the number of steps you take. You might take one step up, or you might jump two steps down. Whether you are going up or down, you can move only in whole-step increments. Just as you cannot stand between steps on a staircase, an electron cannot exist between energy levels.

SCIENCE and History

Models of the Atom

The development of scientific ideas on the structure of atoms has passed several key milestones during the last 200 years.





1803 John Dalton pictures atoms as tiny, indestructible particles, with no internal structure.

1897 J. J. Thomson, a British scientist, discovers the electron, leading to his "plum-pudding" model. He pictures electrons embedded in a sphere of positive electric charge.

1904 Hantaro Nagaoka, a Japanese physicist, suggests that an atom has a central nucleus. Electrons move in orbits like the rings around Saturn.

1911 New Zealander Ernest Rutherford states that an atom has a dense, positively charged nucleus. Electrons move randomly in the space around the nucleus.

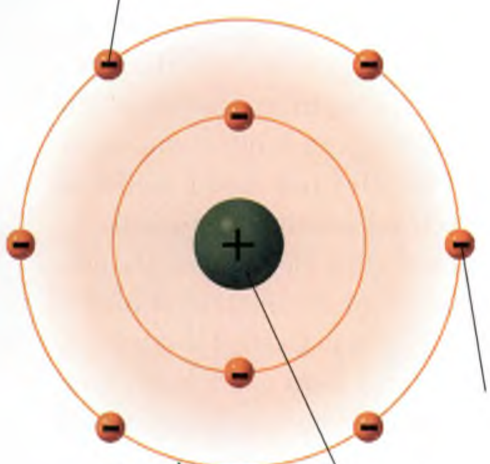
1800 | 1805 | 1895 | 1900 | 1905 | 1910

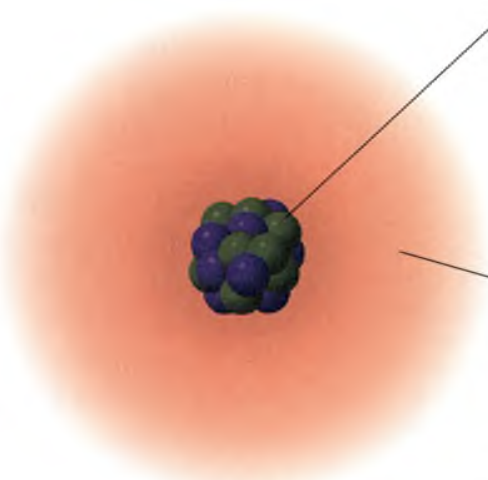
The landing at the bottom of the staircase is like the lowest energy level in an atom. Each step up represents a higher energy level. The distance between two steps represents the difference in energy between two energy levels. To continue the analogy, there would need to be a different staircase for each element because no two elements have the same set of energy levels.

An electron in an atom can move from one energy level to another when the atom gains or loses energy. An electron may move up two energy levels if it gains the right amount of energy. An electron in a higher energy level may move down two energy levels if it loses the right amount of energy. The size of the jump between energy levels determines the amount of energy gained or lost.

Writing in Science

Summary Select a scientist mentioned on the time line. Research and write a paragraph about the scientist's early years. What experiences led to his interest in science? Was he the first in his family to be interested in science? What subjects did he study at school?





1913 In Niels Bohr's model, the electrons move in spherical orbits at fixed distances from the nucleus.

1924 Frenchman Louis de Broglie proposes that moving particles like electrons have some properties of waves. Within a few years, evidence is collected to support this idea.

1926 Erwin Schrödinger develops mathematical equations to describe the motion of electrons in atoms. His work leads to the electron cloud model.

1932 James Chadwick, a British physicist, confirms the existence of neutrons, which have no charge. Atomic nuclei contain neutrons and positively charged protons.

1915 | 1920 | 1925 | 1930 | 1935

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Evidence for Energy Levels What evidence is there that electrons can move from one energy level to another? Scientists can measure the energy gained when electrons absorb energy and move to a higher energy level. They can measure the energy released when the electron returns to a lower energy level.

The movement of electrons between energy levels explains the light you see when fireworks explode. Light is a form of energy. Heat produced by the explosion causes some electrons to move to higher energy levels. When those electrons move back to lower energy levels, they emit energy. Some of that energy is released as visible light. Because no two elements have the same set of energy levels, different elements emit different colors of light.

Reading Checkpoint ***What determines the amount of energy gained or lost when an electron moves between energy levels?***

Electron Cloud Model

Like earlier models, Bohr's model was improved as scientists made further discoveries. Bohr was correct in assigning energy levels to electrons. But he was incorrect in assuming that electrons moved like planets in a solar system. Today, scientists know that electrons move in a less predictable way.

Scientists must deal with probability when trying to predict the locations and motions of electrons in atoms. An **electron cloud** is a visual model of the most likely locations for electrons in an atom. The cloud is denser at those locations where the probability of finding an electron is high. **Scientists use the electron cloud model to describe the possible locations of electrons around the nucleus.**

Figure 14 provides an analogy for an electron cloud. When the propeller of an airplane is at rest, you can count the number of blades. When the propeller is moving, the blades spin so fast that you see only a blur. You know that the blades are located somewhere in the blur, but at any specific moment in time you can't be exactly sure where each blade is located.

Figure 14 When the propeller of an airplane is at rest, you can see the locations of the blades. When the propeller is moving, you see only a blur that is similar to a drawing of an electron cloud. **Comparing and Contrasting** ***Describe one difference between the motion of a propeller and the motion of an electron.***

Quick Lab

Comparing Excited States

Materials

fluorescent ("neon") markers, glow-in-the-dark toy, ultraviolet (UV) lamp

Procedure

1. Use the fluorescent markers to draw a picture on a piece of paper.
2. With the room darkened, observe your drawing under a UV lamp. **CAUTION** *Do not look directly at the light.* Remove the drawing from under the UV light and observe it again. Record your observations.
3. Observe the glow-in-the-dark toy under the UV light. Remove the toy from the light and observe it again. Record your observations.

Analyze and Conclude

1. **Observing** How did the glow of the toy differ from the glow of your drawing?
2. **Formulating Hypotheses** Use the concepts of ground and excited states to explain how UV light caused your drawing and the toy to glow.
3. **Drawing Conclusions** In which object, your drawing or the toy, do the atoms have excited states that are more stable, or less likely to change? Explain your answer.

Atomic Orbitals

The electron cloud represents all the orbitals in an atom. An **orbital** is a region of space around the nucleus where an electron is likely to be found. To understand the concept of an orbital, imagine a map of your school. Suppose you mark your exact location with a dot once every 10 minutes over a period of one week. The places you visit the most—such as your classrooms, the cafeteria, and the area near your locker—would have the highest concentration of dots. The places you visit the least would have the lowest concentration of dots.

The dots on your map are a model of your "orbital." They describe your most likely locations. There are some locations in your orbital that you may not visit every week—such as the principal's office or the auditorium. These locations may not be represented by a dot on your map. Despite such omissions, the dots on your map are a good model of how you usually behave in your orbital. **An electron cloud is a good approximation of how electrons behave in their orbitals.**

The level in which an electron has the least energy—the lowest energy level—has only one orbital. Higher energy levels have more than one orbital. Figure 15 shows the number of orbitals in the first four energy levels of an atom. Notice that the maximum number of electrons in an energy level is twice the number of orbitals. Each orbital can contain two electrons at most.

Figure 15 The table lists the number of orbitals in the first four energy levels of an atom. It also lists the maximum number of electrons in each energy level. **Inferring** ***How many electrons can be in each orbital?***

Energy Levels, Orbitals, and Electrons

Energy Level	Number of Orbitals	Maximum Number of Electrons
1	1	2
2	4	8
3	9	18
4	16	32

Figure 16 A gymnast on a balance beam is like an atom in an excited state—not very stable.

Electron Configurations

How are the seats in your classroom arranged? Are they lined up neatly in rows, or are they grouped in clusters? A configuration is an arrangement of objects in a given space. Some configurations are more stable than others, meaning that they are less likely to change. The position of the gymnast on the balance beam in Figure 16 is not very stable because the beam is only 10 centimeters wide.

An **electron configuration** is the arrangement of electrons in the orbitals of an atom. **The most stable electron configuration is the one in which the electrons are in orbitals with the lowest possible energies.** When all the electrons in an atom have the lowest possible energies, the atom is said to be in its **ground state.**

For example, lithium is a silvery-white metal with an atomic number of 3, which means that a lithium atom has three electrons. In the ground state, two of the lithium electrons are in the orbital of the first energy level. The third electron is in an orbital of the second energy level.

If a lithium atom absorbs enough energy, one of its electrons can move to an orbital with a higher energy. This configuration is referred to as an excited state. An excited state is less stable than the ground state. Eventually, the electron that was promoted to a higher energy level loses energy, and the atom returns to the ground state. Helium, neon, argon, krypton, and xenon atoms returning from excited states to the ground state emit the light you see in "neon" lights.

Section 4.3 Assessment

Reviewing Concepts

1. When is an electron in an atom likely to move from one energy level to another?
2. What model do scientists use to describe how electrons move around the nucleus?
3. Describe the most stable configuration of the electrons in an atom.
4. What did Bohr contribute to modern atomic theory?
5. What does an electron cloud represent?

Critical Thinking

6. **Comparing and Contrasting** A boron atom has two electrons in the first energy level and three in the second energy level. Compare the relative energies of the electrons in these two energy levels.
7. **Making Judgments** Was Rutherford's model of an atom incorrect or incomplete? Explain your answer.
8. **Posing Questions** Apply what you know about charged particles to the modern model of the atom. Is there anything about the behavior of electrons in atoms that is unexpected? Explain your answer.

Writing in Science

Describing Energy Levels Use a bookcase as an analogy for the energy levels in an atom. Use the analogy to write a paragraph about electrons and energy levels. (*Hint:* Reread the staircase analogy on pages 114 and 115.)

Forensics Lab

Using Flame Tests

Forensic scientists use various approaches to distinguish different substances. In this lab, you will observe the flame colors of several substances and use the data to determine the identity of an unknown substance.

Problem

How can the color of a flame be used to distinguish substances?

Materials

- solutions of calcium chloride, boric acid, potassium chloride, copper(II) sulfate, sodium chloride, and an unknown
- Bunsen burner
- nichrome wire loop
- dilute solution of hydrochloric acid
- wash bottle with distilled water

Skills

Observing, Predicting, Using Data Tables

Procedure

Part A: Observing Flame Colors

1. Make a copy of the data table shown.

Data Table	
Solution	Flame Color
Calcium chloride	
Potassium chloride	
Boric acid	
Copper(II) sulfate	
Sodium chloride	
Unknown	
Identity of Unknown	

2. Light the Bunsen burner. **CAUTION** *Put on safety goggles and a lab apron. Tie back loose hair and clothing before working with a flame.*
3. Dip the wire loop into the calcium chloride solution and then place the loop in the flame as shown. Observe and record the color of the flame.
4. Clean the loop by dipping it into hydrochloric acid. Then, while holding the loop over a sink, rinse away the acid with distilled water. **CAUTION** *Keep hydrochloric acid away from your skin and clothing. Do not breathe in its vapor.*
5. Repeat Steps 3 and 4 with each of the other solutions. Be careful not to transfer any solution from one container to another. **CAUTION** *These chemicals are poisonous. Do not let them get on your skin.*

Part B: Examining an Unknown Solution

6. Obtain the unknown solution from your teacher.
7. Repeat Steps 3 and 4 using the unknown solution. Compare your observations with the other data you recorded to identify the unknown. **CAUTION** *Wash your hands thoroughly before leaving the laboratory.*

Analyze and Conclude

1. **Comparing and Contrasting** Is there a relationship between the color of the flame and the color of the solution?
2. **Formulating Hypotheses** How do these substances produce light of different colors?
3. **Drawing Conclusions** A forensic scientist does a flame test on a substance that was found at a crime scene. What might the scientist conclude if the flame turns green?

Go Further There is another test that you can use to distinguish elements by color. With your teacher supervising, dip a wire loop in borax. Heat the loop in a flame until the borax melts. Remove the loop from the flame and let the borax cool. It will form a clear glass bead. Dip the bead in a tiny sample of solid copper sulfate and return the loop to the flame for a few seconds. Remove the loop and observe the color of the bead as it cools.

CHAPTER 4

Study Guide

4.1 Studying Atoms

Key Concepts

- Dalton proposed the theory that all matter is made up of individual particles called atoms, which cannot be divided.
- Thomson's experiments provided the first evidence that atoms are made of even smaller particles.
- According to Rutherford's model, all of an atom's positive charge is concentrated in its nucleus.

Vocabulary

nucleus, *p. 105*

4.2 The Structure of an Atom

Key Concepts

- Protons, electrons. and neutrons are subatomic particles.
- Protons, electrons, and neutrons can be distinguished by mass, charge, and location in an atom.
- Atoms of different elements have different numbers of protons.
- Isotopes of an element have the same atomic number but different mass numbers because they have different numbers of neutrons.

Vocabulary

proton, *p. 108*
electron, *p. 108*
neutron, *p. 109*
atomic number, *p. 110*
mass number, *p. 110*
isotopes, *p. 112*

4.3 Modern Atomic Theory

Key Concepts

- An electron in an atom can move from one energy level to another when the atom gains or loses energy.
- Scientists use the electron cloud model to describe the possible locations of electrons around the nucleus.
- An electron cloud is a good approximation of how electrons behave in their orbitals.
- The most stable electron configuration is the one in which the electrons are in orbitals with the lowest possible energies.

Vocabulary

energy levels, *p. 114*
electron cloud, *p. 116*
orbital, *p. 117*
electron configuration, *p. 118*
ground state, *p. 118*

Thinking Visually

Table of Properties Use information from the chapter to complete the table below.

Particle	Proton	Electron	Neutron
Symbol	a. ?	e^-	n
Relative charge	1+	b. ?	c. ?
Relative mass	d. ?	$\frac{1}{1836}$	e. ?

CHAPTER 4

Assessment

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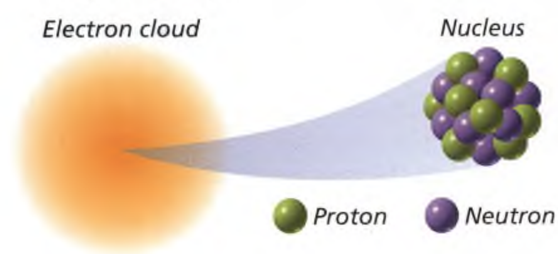
Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. One of the first people to state that matter is made up of atoms was
   a. Democritus. b. Aristotle.
   c. Dalton. d. Rutherford.
2. Dalton's model of an atom is best described as
   a. a solar system. b. a solid sphere.
   c. a plum pudding. d. an electron cloud.
3. Who provided the first evidence that atoms contain subatomic particles?
   a. Dalton b. Rutherford
   c. Thomson d. Bohr
4. Almost all the mass of an atom is located in its
   a. protons. b. electrons.
   c. electron cloud. d. nucleus.
5. An electron is a particle with
   a. a negative charge, found in the nucleus.
   b. a positive charge, found in the nucleus.
   c. no charge, found outside the nucleus.
   d. a negative charge, found outside the nucleus.
6. Which particle is the least massive?
   a. proton b. electron
   c. neutron d. nucleus
7. All atoms of an element have the same
   a. mass number. b. number of isotopes.
   c. atomic number. d. number of neutrons.
8. The number of neutrons in an atom equals the
   a. mass number minus atomic number.
   b. atomic number plus number of electrons.
   c. mass number plus atomic number.
   d. atomic number minus mass number.
9. The atomic number of sulfur is 16. How many electrons are there in an atom of sulfur-34?
   a. 16 b. 34
   c. 18 d. 50
10. Atoms emit energy as light when
    a. electrons move to a higher energy level.
    b. electrons move to a lower energy level.
    c. protons move to a higher energy level.
    d. protons move to a lower energy level.

Understanding Concepts

11. Why must indirect evidence be used to study the structure of atoms?
12. What evidence convinced Dalton that elements must be made of individual particles called atoms?
13. In Thomson's experiment, why was the glowing beam repelled by a negatively charged plate?
14. What evidence supported Thomson's hypothesis that the negative particles he observed came from inside atoms?
15. Compare the mass and volume of the nucleus to the total mass and volume of an atom.
16. Compare the relative masses of protons, neutrons, and electrons in an atom.
17. What is the difference between the atomic number of an atom and its mass number?
18. If the atomic number of an atom is 11, how many electrons does the atom have? Explain.
19. If an atom has an atomic number of 6 and a mass number of 14, how many protons, electrons, and neutrons are in the atom?
20. What part of Dalton's theory was modified after the discovery of isotopes?
21. Which isotope of oxygen is represented by the drawing—oxygen-16, oxygen-17, or oxygen-18? Assume that all the protons and neutrons in the nucleus are visible in the drawing. Give a reason for your answer.



22. What is the main difference between Bohr's model of the atom and the atomic theory that is currently accepted?
23. What does it mean to say that an atom is in an excited state?

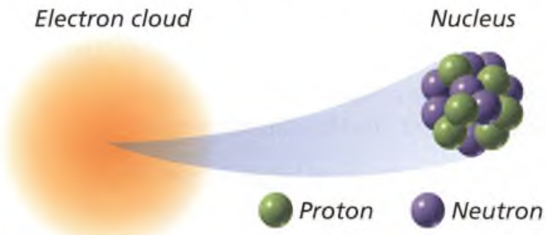
Assessment *(continued)*

Critical Thinking

24. **Controlling Variables** Look at the drawing of the experimental setup in Figure 5A. Explain how the setup is a control for the setup in Figure 5B.

25. **Predicting** How would the results of Thomson's experiment change if the beam were a stream of neutrons instead of a stream of electrons?

26. **Interpreting Diagrams** The atomic number of carbon is 6. The atomic number of nitrogen is 7. The atomic number of oxygen is 8. Name the isotope represented by the drawing.



27. **Hypothesizing** Why were the proton and electron discovered before the neutron?

28. **Applying Concepts** Explain why a neutral atom cannot have one proton, one neutron, and two electrons.

29. **Classifying** The nucleus of an atom contains six neutrons and six protons. The nucleus of a second atom contains six neutrons and five protons. Are they atoms of different elements or isotopes of the same element? Explain your answer.

Math Skills

30. **Calculating** The atomic number for iron is 26. How many neutrons are in the nucleus of an iron atom with a mass number of 57? How many electrons does the iron atom have?

31. **Applying Concepts** If a potassium atom has an atomic number of 19 and a mass number of 39, how many protons, electrons, and neutrons are in the atom?

32. **Applying Concepts** A helium-4 atom has twice as many protons as a hydrogen atom. How many protons and how many neutrons are in the nucleus of a helium-4 atom?

Concepts in Action

33. **Comparing and Contrasting** The compound in blood that carries oxygen to cells throughout the body contains iron. Iron has an atomic number of 26. Iron-59 is used to diagnose disorders in the blood. How is iron-59 different from all other isotopes of iron? How is it the same?

34. **Using Analogies** Scientists working in the field of nanotechnology use either a top-down or bottom-up approach to construct tiny objects. Give an example of a visible structure that was made using the bottom-up approach and one that was made using the top-down approach.

35. **Inferring** If you see a green color when fireworks explode, can you be certain that the fireworks contained a barium compound? Give a reason for your answer.

36. **Relating Cause and Effect** Brightly colored neon lights consist of tubes filled with a gas. When an electric current passes through the tubes, different colors are emitted. Why might you conclude that the tubes in a multicolored display contain more than one element?

37. **Writing in Science** Better technology leads to an increase in scientific knowledge. An increase in knowledge allows for the invention of new technology. Write a paragraph discussing these statements. Use a scanning tunneling microscope as your example.

Performance-Based Assessment

Preparing a Survey Write ten questions you could ask to find out what people know about the modern model of an atom. Figure out the best order for the questions to test someone's knowledge fairly. Be prepared to explain your choices.

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Standardized Test Prep

Test-Taking Tip

Using Data Tables

When presented with a question that is related to a data table, read the title of the table to see what type of data it contains. Then look at the headings of the columns and rows to see how the data are organized. The table below lists properties for subatomic particles. There is a row for each particle and a column for each property. Read the question to find out which data you will need to answer the question. In this case, you will need the data on relative charge.

Properties of Subatomic Particles

Particle	Symbol	Relative Charge	Relative Mass (proton = 1)
Electron	e^-	1−	$\frac{1}{1836}$
Proton	p^+	1+	1
Neutron	n	0	1

Which of the following statements is true?

(A) The charge on a proton is larger than the charge on an electron.
(B) The charge on a proton is smaller than the charge on an electron.
(C) The charge on a proton is identical to the charge on an electron
(D) The charge on a proton is equal in size but opposite to the charge on an electron.
(E) A proton is a neutral particle.

(Answer: D)

Choose the letter that best answers the question or completes the statement.

1. J. J. Thomson demonstrated that electrons
(A) have a negative electric charge.
(B) have a positive electric charge.
(C) are repelled by a positively charged object.
(D) are attracted to a negatively charged object.
(E) do not have an electric charge.

2. According to Dalton's atomic theory, an atom is
(A) made of smaller particles.
(B) a particle with a positive charge.
(C) the smallest particle of an element.
(D) in constant motion.
(E) a particle with a negative charge.

3. Electrons in the first energy level of an atom
(A) have no energy.
(B) have the lowest possible energy.
(C) have the highest possible energy.
(D) are in an excited state.
(E) are in an unstable state.

4. Most alpha particles pass through a thin layer of gold without deflection because gold atoms
(A) are filled with positively charged matter.
(B) have no overall charge.
(C) have a negatively charged nucleus.
(D) do not have a nucleus.
(E) have a dense nucleus surrounded by space.

Use the data table to answer Question 5.

Comparison of Oxygen Isotopes

Property	Oxygen-16	Oxygen-18
Protons	8	8
Neutrons	8	10
Electrons	8	8
Percentage in nature	99.757	0.205

5. What is the mass number of oxygen-18?
(A) 8
(B) 10
(C) 16
(D) 18
(E) 0.205

6. An electron configuration describes
(A) regions of space around the nucleus of an atom.
(B) possible energies that an electron can have.
(C) the arrangement of electrons in an atom.
(D) the emission of light from an excited atom.
(E) the number of possible orbitals in an atom.