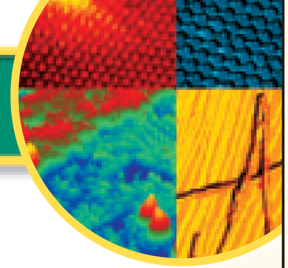
4.3 Modern Atomic Theory



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.

Section 4.3

1 FOCUS

Objectives

4.3.1 **Describe** Bohr's model of the atom and the evidence for energy levels.

4.3.2 **Explain** how the electron cloud model represents the behavior and locations of electrons in atoms.

4.3.3 **Distinguish** the ground state from excited states of an atom based on electron configurations.

Reading Focus

Build Vocabulary L2

LINCS Have students use the LINCS strategy to learn the terms *energy levels, electron cloud, orbital, electron configuration,* and *ground state.* In LINCS exercises, students **L**ist what they know about each term, **I**magine a picture that describes the term, **N**ote a reminding "sound-alike" word, **C**onnect the terms to the sound-alike word by making up a short story, and then perform a brief **S**elf-test.

Reading Strategy L2

a. Electron moves to higher energy level.
b. Electron moves to lower energy level.

2 INSTRUCT

Bohr's Model of the Atom

Build Reading Literacy L1

Relate Text and Visuals Refer to page **190D** in **Chapter 7**, which provides the guidelines for relating text and visuals.

Have students read Bohr's Model of the Atom on pp. 113–116. Then, have students examine the diagram of Bohr's model in the time line on p. 115. Ask, **What do the circles around the nucleus represent?** *(They represent energy levels.)*
Visual

Section Resources

Print

- ***Laboratory Manual,*** Investigations 4A and 4B
- ***Reading and Study Workbook With Math Support,*** Section 4.3
- ***Transparencies,*** Section 4.3

Technology

- ***Interactive Textbook,*** Section 4.3
- ***Presentation Pro CD-ROM,*** Section 4.3
- ***Go Online,*** NSTA SciLinks, Energy levels

Address Misconceptions L2

Students may think that electrons travel around the nucleus in fixed orbits, like planets orbiting the sun. Challenge this misconception by having students compare Bohr's model and the electron cloud model. Explain that Bohr's model correctly introduced the concept of energy levels, but energy levels cannot be used to describe the actual location of an electron. The electron cloud model can be used to model the probability that an electron is in a certain location. The exact speed and location of a single electron cannot be determined.
Verbal

FYI

The usefulness of Bohr's model was limited. The model could be used to describe the behavior of the single electron in a hydrogen atom quite accurately. However, this model could not be applied to atoms with multiple electrons.

Integrate Space Science L2

Planets in the solar system travel in fixed orbits around the sun. Because most of the orbits are nearly circular, the difference between the distance to the sun when a planet is closest and when it is farthest away is not great (given the magnitude of distances in space). Pluto is an exception. Its orbit is so elliptical that there are times during Pluto's journey around the sun (249 Earth days) when it is closer to the sun than Neptune is. This switch in order of proximity to the sun lasts 20 years. It last happened between 1979 and 1999. Have students research when it will happen again.
Logical

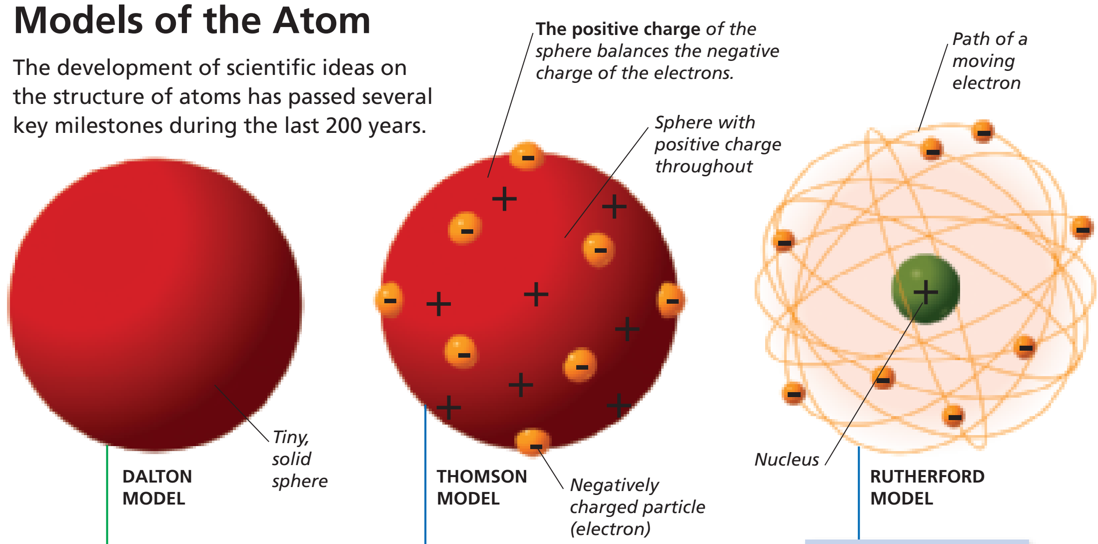
Energy Levels In Bohr's model, electrons move with constant speed in fixed orbits around the nucleus, like planets around a sun. Each electron in an atom has a specific amount of energy. If an atom gains or loses energy, the energy of an electron can change. The possible energies that electrons in an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

DK 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

Customize for English Language Learners

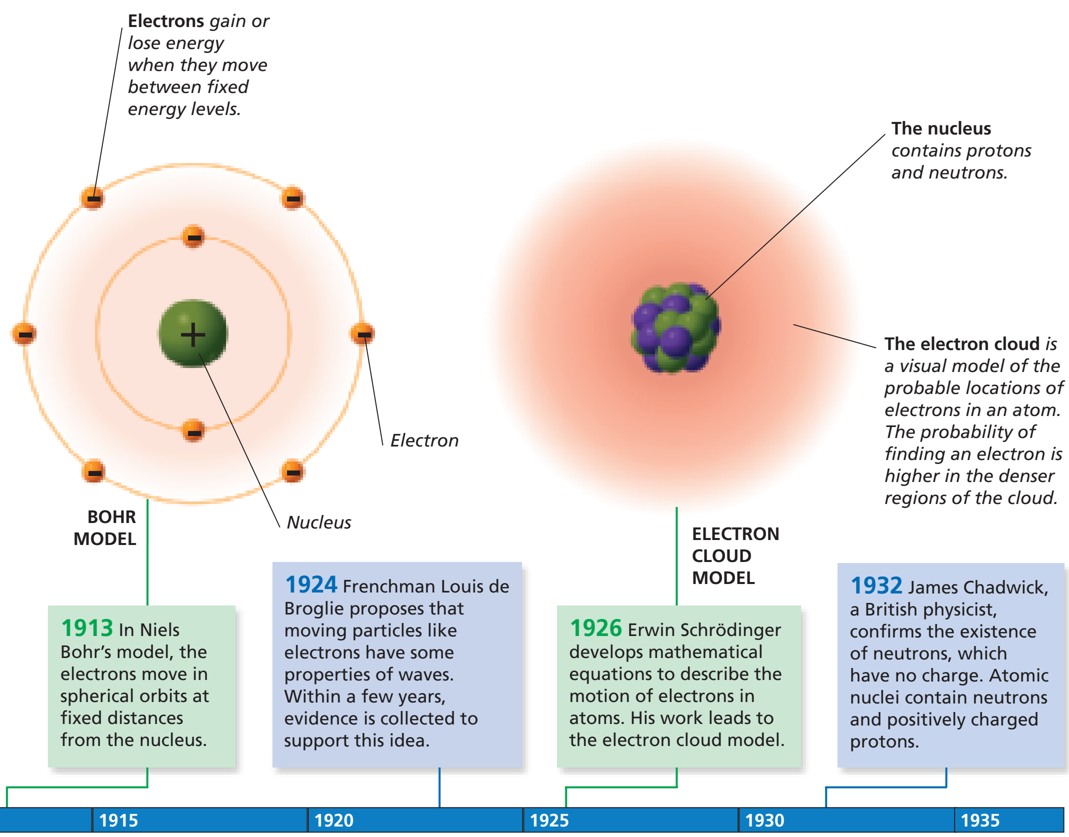
Think-Pair-Share
Have students work in pairs to think of structures that can serve as analogies for energy levels. Examples include rungs of a ladder, guitar frets, and the series of holes on a belt or shoe strap. Note, however, that in all of these models, the intervals are equal, which is not true of the intervals between energy levels. Provide pictures of dressers that have drawers of different sizes or bookshelves that have adjustable shelves, which might better model the intervals of energy levels. Strengthen discussion skills by having students share their examples with the class.

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.

Facts and Figures

De Broglie and Schrödinger In 1924, Louis de Broglie, a French graduate student, derived an equation that describes the wavelength of a moving particle. Using de Broglie's equation, an electron has a wavelength of about 2×10^{-10} cm. In 1926, Erwin Schrödinger, an Austrian physicist, wrote a mathematical equation to describe the location and energy of the electron in a hydrogen atom. When the equation is solved (using advanced calculus), it produces a series of wave functions that describe the behavior of electrons. The quantum mechanical model of atoms is based on these wave functions. Atomic physicists define an orbital as the space-dependent part of the Schrödinger wave function of an electron in an atom or molecule.

FYI

In Section 6.1, students will learn that electrons sometimes gain enough energy to escape from an atom.

SCIENCE and History

Models of the Atom L2

Have groups of students build or draw models that represent the changes over time in scientists' understanding of atomic structure. Have them make a three-dimensional version of the time line shown and display it as a mobile or diorama. Have students note the time scale on the time line. Explain that the break between 1805 and 1895 allows the milestone in 1803 to be included.
Group, Visual

Writing in Science

There will be more information for some scientists than for others. The exercise focuses on early experiences because students will not understand most of what is written about the careers of these scientists. By pooling their research, students will see that scientists can emerge from diverse backgrounds.

Students may learn that Dalton was the son of a weaver and de Broglie was the son of a duke; that Dalton began his teaching career at the age of 12; that Schrödinger was an only child, but Rutherford had 11 siblings; or that Chadwick was shy and Rutherford charming.
Verbal

Use Community Resources L2

Have a female scientist visit the class to discuss the experiences that led to her interest in science. Have students prepare questions similar to those asked in the Writing in Science feature.
Interpersonal, Visual

Electron Cloud Model

Build Science Skills L2

Using Models Have students examine the windmill in Figure 14. Ask, **How are the windmill blades similar to an electron cloud?** *(You cannot be sure at any specific moment where the windmill blades or electrons are located. However, the central part of the blades and the nucleus of an atom are in fixed locations.)* **What other examples can you think of that could model the concept of an electron cloud?** *(Acceptable answers include a ceiling fan, or moths flying around a light bulb.)*
Visual

Teacher Demo

Electron Cloud Model L2

Purpose Students will use a model to describe the probable position of electrons.

Materials small, round balloon; large, round balloon; 10 beads with 4-mm diameter; 5 beads with 2-mm diameter

Procedure Put the 4-mm beads into the small balloon. Tell students that the small balloon represents the nucleus of a boron atom (five neutrons, five protons). Put the 2-mm beads into the large balloon. Explain that the beads represent electrons and the balloon represents the electron cloud. Slightly inflate the small balloon and push it completely into the large balloon. Inflate the large balloon and tie the end. Agitate the balloon so that the small beads are in constant motion.

Expected Outcome The precise location of a bead at a specific time is unknown, but the probability that it is in the large balloon is quite high.
Kinesthetic

Go Online NSTA SciLinks

Download a worksheet on energy levels for students to complete, and find additional teacher support from NSTA SciLinks.

Go Online NSTA SciLinks

For: Links on energy levels
Visit: www.SciLinks.org
Web Code: ccn-1043

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.**

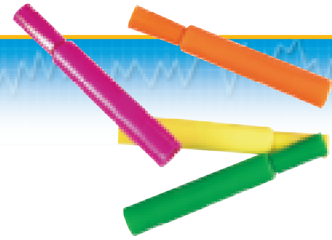
Figure 14 provides an analogy for an electron cloud. When the blades of a windmill are at rest, you can count the number of blades. When they are moving, the blades spin so fast that you see only a blur. You know that the blades are located somewhere in the blur, but at any specific moment in time you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

Figure 14 When the blades of a windmill are at rest, you can see their locations. When the blades are spinning, 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 windmill blades and the motion of an electron.***

Facts and Figures

Emission and Absorption Spectra When the energy gained or lost by an atom is light energy, each frequency (or wavelength) of light corresponds to a movement of an electron between two energy levels in the atom. An element can be identified by the frequencies of light that are absorbed or emitted by its atoms because no two elements have the same set of energy levels. For example, the element helium was discovered on the sun in 1868 before it was discovered on Earth. The spectrum of light emitted by gases on the surface of the sun contained a yellow line that did not match a known element.

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

FYI

According to the quantum mechanical model, an orbital is the mathematical function that describes the behavior of an electron in space.

Atomic Orbitals

Quick Lab

Comparing Excited States L2

Objective
After completing this activity, students will be able to
- explain how UV light causes objects to glow.
- use the persistence of light to compare excited states.

Skills Focus **Observing, Formulating Hypotheses**

Prep Time 5 minutes

Class Time 15 minutes

Safety Check the MSDS for the markers to make sure that they are low in VOCs (volatile organic compounds). Students should not look directly at UV light, which is harmful to the eyes. Demonstrate safe use of the UV lamps before allowing students to use them.

Teaching Tips
- Do this lab only after you teach ground state and excited states.

Expected Outcome Fluorescent ink will emit brilliant visible light under UV light. This fluorescence will instantly cease when the UV light is removed. Phosphorescent (glow-in-the-dark) objects will continue to emit visible light even after the UV light is removed.

Analyze and Conclude
1. The toy still glowed after the UV light was removed. The drawing did not.
2. The drawing and the toy absorbed energy from the UV light. When electrons moved to higher energy levels, the atoms were in an excited state. When electrons returned to lower energy levels, energy was released as visible light.
3. The fact that the toy's glow persisted suggests that the excited state of atoms in the toy was more stable than the excited state of atoms in the drawing.
Visual, Kinesthetic

Answer to . . .

Figure 14 *The windmill blades have a single, set path, and the blades stop moving when the wind stops blowing.*

Figure 15 *Two*

Reading Checkpoint *The size of the jump between energy levels*

Section 4.3 (continued)

Electron Configurations

Use Visuals L1

Figure 16 Extend the analogy of the gymnast on the balance beam by having students consider a gymnast doing an entire routine on equipment such as a balance beam, a pommel horse, parallel bars, or uneven bars. **In the analogy, when is the configuration of the gymnast like an atom in an excited state?** *(When the gymnast is in a precarious position, such as when the gymnast is not in direct contact with the equipment)* **In the analogy, when is the gymnast most like an atom in its ground state?** *(The gymnast is in her most stable position when she is standing on the floor.)*
Logical

3 ASSESS

Evaluate Understanding L2

Have students draw and label a diagram that represents Bohr's model of an atom. Then, have students explain how the electron cloud model differs from Bohr's model.

Reteach L1

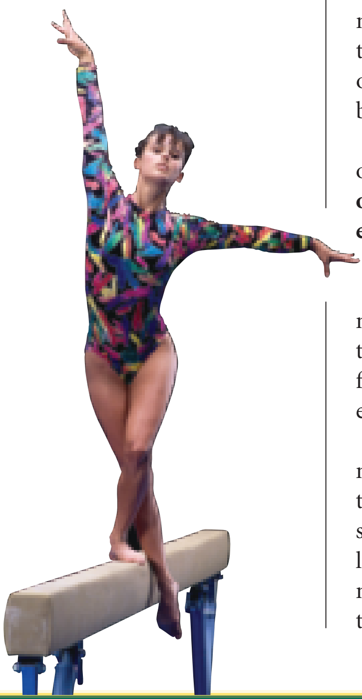
Use the diagrams on p. 115 in the Science and History feature to review Bohr's model, energy levels, and electron clouds.

Writing in Science

The shelves in a bookcase can represent energy levels in an atom. If students know about potential energy, they may compare what happens to the energy of a book as it is moved between shelves to the difference in energy between electrons in different energy levels.

Interactive Textbook If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 4.3.

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.)

Section 4.3 Assessment

1. Electrons are likely to move from one energy level to another when atoms gain or lose energy.
2. The electron cloud model
3. The most stable configuration is the one in which the electrons are in orbitals with the lowest possible energy.
4. Bohr contributed the idea that electrons have energy levels with specific amounts of energy.
5. An electron cloud represents the most probable locations of an electron in an atom.
6. The electrons in the second energy level will have more energy than the electrons in the first energy level.
7. Rutherford's description of an atom was correct, but incomplete. It did not provide as much information about the behavior of the electrons as later models.
8. Students may ask why the negatively charged electrons are not drawn into the nucleus by the positively charged protons.