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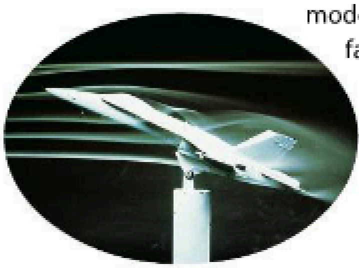
5.1 Models of the Atom

1 ***Connecting to Your World*** Aeronautical engineers use wind tunnels and scale models to simulate and test the forces from the moving air on each proposed design. The scale model shown is a physical model. However, not all models are physical. In fact, several theoretical models of the atom have been developed over the last few hundred years. In this section, you will learn about the currently accepted model of how electrons behave in atoms.



Guide for Reading

Key Concepts

- What was inadequate about Rutherford's atomic model?
- What was the new proposal in the Bohr model of the atom?
- What does the quantum mechanical model determine about the electrons in an atom?
- How do sublevels of principal energy levels differ?

Vocabulary

energy levels
quantum
quantum mechanical model
atomic orbital

Reading Strategy

Using Prior Knowledge Before you read, jot down three things you already know about atoms. As you read the section, explain how what you already knew helped you learn something new.

2 The Development of Atomic Models

So far in this textbook, the model for the atom consisted of protons and neutrons making up a nucleus surrounded by electrons. After discovering the atomic nucleus, Rutherford used existing ideas about the atom and proposed an atomic model in which the electrons move around the nucleus, like the planets move around the sun. Rutherford's model explained only a few simple properties of atoms. It could not explain, for example, why metals or compounds of metals give off characteristic colors when heated in a flame, or why objects—when heated to higher and higher temperatures—first glow dull red, then yellow, then white, as shown in Figure 5.1. **Rutherford's atomic model could not explain the chemical properties of elements.** Explaining what leads to the chemical properties of elements requires a model that better describes the behavior of electrons within atoms.

Figure 5.1 Rutherford's model fails to explain why objects change color when heated. As the temperature of this horseshoe is increased, it first appears black, then red, then yellow, and then white. The observed behavior could be explained only if the atoms in the iron gave off light in specific amounts of energy. A better atomic model was needed to explain this observation.

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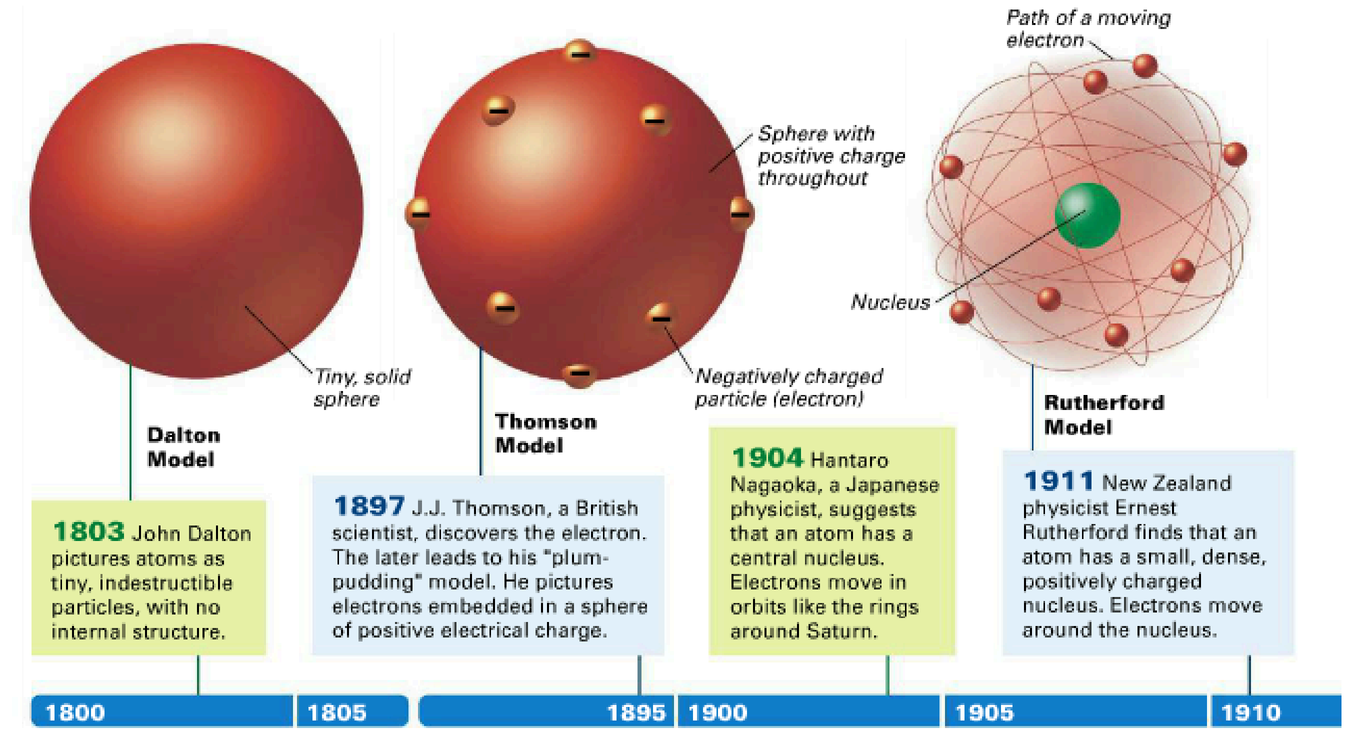

Figure 5.2 These illustrations show how the atomic model has changed as scientists learned more about the atom's structure.

The Bohr Model

Niels Bohr (1885–1962), a young Danish physicist and a student of Rutherford, believed Rutherford's model needed improvement. In 1913 Bohr changed Rutherford's model to include newer discoveries about how the energy of an atom changes when it absorbs or emits light. He considered the simplest atom, hydrogen, which has one electron. **Bohr proposed that an electron is found only in specific circular paths, or orbits, around the nucleus.** The timeline in Figure 5.2 shows the development of atomic models from 1800 to 1935. 3

Each possible electron orbit in Bohr's model has a fixed energy. The fixed energies an electron can have are called **energy levels.** The fixed energy levels of electrons are somewhat like the rungs of the ladder in Figure 5.3a. The lowest rung of the ladder corresponds to the lowest energy level. A person can climb up or down a ladder by going from rung to rung. Similarly, an electron can jump from one energy level to another. A person on a ladder cannot stand between the rungs. Similarly, the electrons in an atom cannot be between energy levels. To move from one rung to another, a person climbing a ladder must move just the right distance. To move from one energy level to another, an electron must gain or lose just the right amount of energy. In general, the higher an electron is on the energy ladder, the farther it is from the nucleus. 4

A **quantum** of energy is the amount of energy required to move an electron from one energy level to another energy level. The energy of an electron is said to be quantized. You have probably heard the term *quantum leap* used to describe an abrupt change. The term originates from the ideas found in the Bohr model of the atom. 5

Word *Origins*

Quantum comes from the Latin word *quantus,* meaning "how much." **What other commonly used English word comes from this root?**

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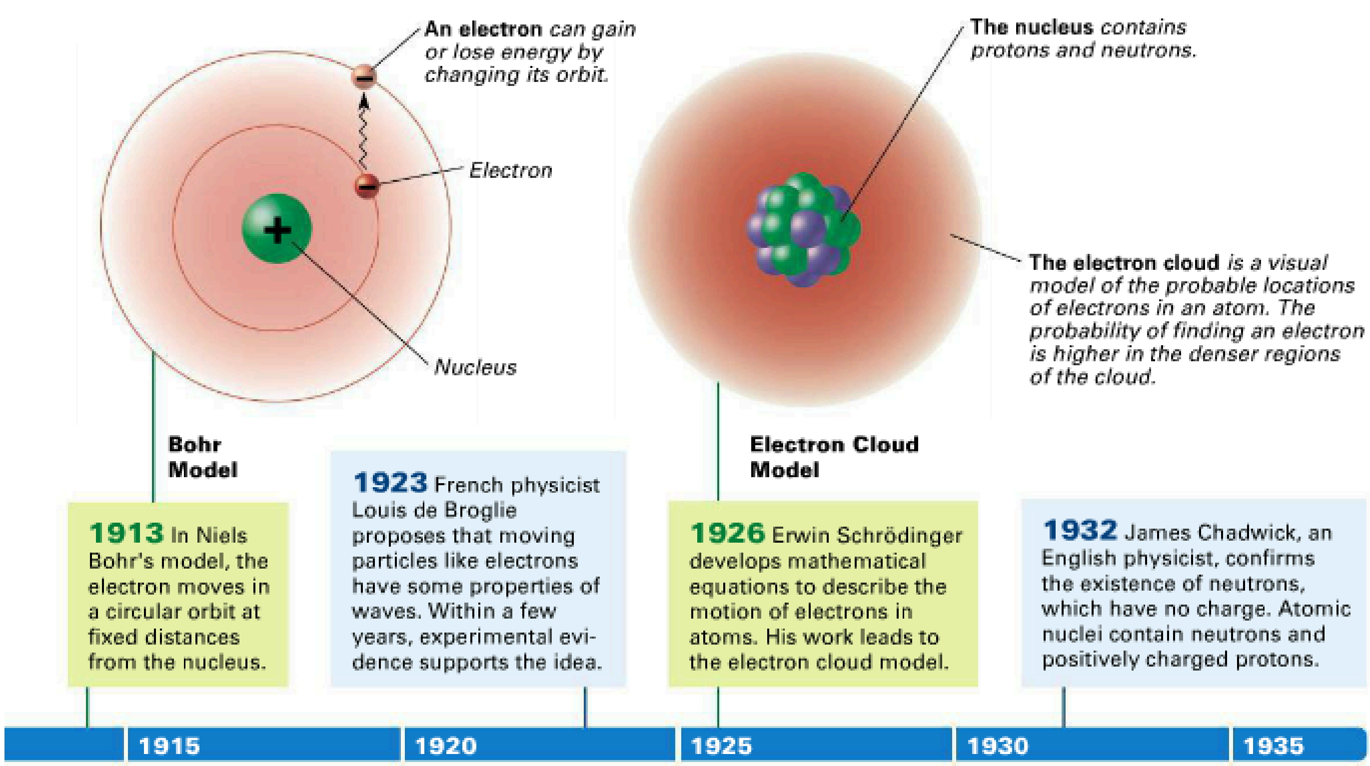

6 The amount of energy an electron gains or loses in an atom is not always the same. Like the rungs of the strange ladder in Figure 5.3b, the energy levels in an atom are not equally spaced. The higher energy levels are closer together. It takes less energy to climb from one rung to another near the top of the ladder in Figure 5.3b, where the rungs are closer. Similarly, the higher the energy level occupied by an electron, the less energy it takes to move from that energy level to the next higher energy level.

7 The Bohr model gave results in agreement with experiment for the hydrogen atom. However, it still failed in many ways to explain the energies absorbed and emitted by atoms with more than one electron.

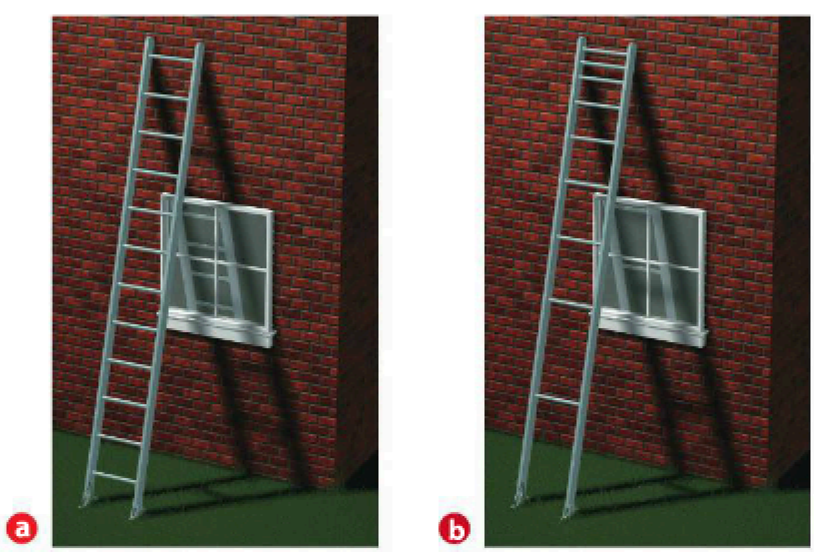

Figure 5.3 These ladder steps are somewhat like energy levels. **a** In an ordinary ladder, the rungs are equally spaced. **b** The energy levels in atoms are unequally spaced, like the rungs in this ladder. The higher energy levels are closer together.

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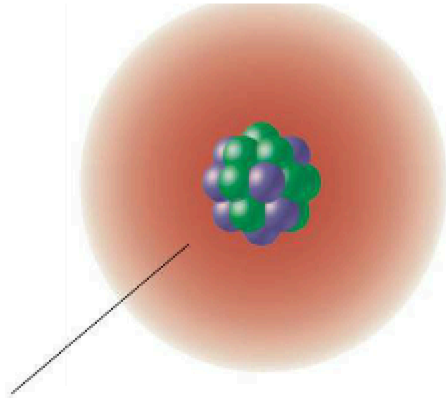

Figure 5.4 The electron cloud of an atom is compared here to photographs of a spinning airplane propeller. (a) The airplane propeller is somewhere in the blurry region it produces in this picture, but the picture does not tell you its exact position at any instant. (b) Similarly, the electron cloud of an atom represents the locations where an electron is likely to be found.

The Quantum Mechanical Model

The Rutherford planetary model and the Bohr model of the atom are based on describing paths of moving electrons as you would describe the path of a large moving object. New theoretical calculations and experimental results were inconsistent with describing electron motion this way. In 1926, the Austrian physicist Erwin Schrödinger (1887–1961) used these new results to devise and solve a mathematical equation describing the behavior of the electron in a hydrogen atom. The modern description of the electrons in atoms, the **quantum mechanical model,** comes from the mathematical solutions to the Schrödinger equation. 8

Like the Bohr model, the quantum mechanical model of the atom restricts the energy of electrons to certain values. Unlike the Bohr model, however, the quantum mechanical model does not involve an exact path the electron takes around the nucleus. **The quantum mechanical model determines the allowed energies an electron can have and how likely it is to find the electron in various locations around the nucleus.** 9

How likely it is to find the electron in a particular location is described by probability. If you place three red marbles and one green marble into a box and then pick a marble without looking, the probability of picking the green marble is one in four, or 25%. This means that if you put the four marbles in a box and picked one, and repeated this a great many times, you would pick a green marble in 25% of your tries. 10

The quantum mechanical model description of how the electron moving around the nucleus is similar to the motion of a rotating propeller blade. Figure 5.4a shows that the propeller blade has the same probability of being anywhere in the blurry region it produces in the picture, but you cannot tell its precise location at any instant. Similarly, in the quantum mechanical model of the atom, the probability of finding an electron within a certain volume of space surrounding the nucleus can be represented as a fuzzy cloud. The cloud is more dense where the probability of finding the electron is high. The cloud is less dense where the probability of finding the electron is low. Though it is unclear where the cloud ends, there is at least a slight chance of finding the electron at a considerable distance from the nucleus. Therefore, attempts to show probabilities as a fuzzy cloud are usually limited to the volume in which the electron is found 90% of the time. To visualize an electron probability cloud, imagine that you could mold a sack around the cloud so that the electron was inside the sack 90% of the time. The shape of the sack would then give you a useful picture of the shape of the cloud. 11

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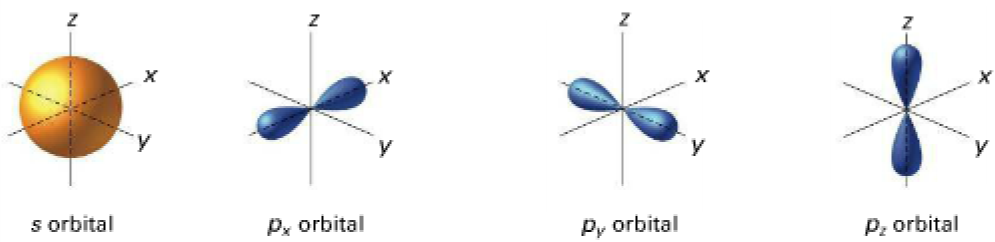

Figure 5.5 The electron clouds for the *s* orbital and the *p* orbitals are shown here.

Atomic Orbitals

12 Solving the Schrödinger equation gives the energies an electron can have. These are its energy levels. For each energy level, the Schrödinger equation also leads to a mathematical expression, called an atomic orbital, describing the probability of finding an electron at various locations around the nucleus. An **atomic orbital** is often thought of as a region of space in which there is a high probability of finding an electron.

The energy levels of electrons in the quantum mechanical model are
13 labeled by principal quantum numbers (n). These are assigned the values $n = 1, 2, 3, 4$, and so forth. For each principal energy level, there may be several orbitals with different shapes and at different energy levels. These energy levels within a principal energy level constitute energy sublevels. **Each energy sublevel corresponds to an orbital of a different shape, which describes where the electron is likely to be found.**

14 Different atomic orbitals are denoted by letters. As shown in Figure 5.5, *s* orbitals are spherical, and *p* orbitals are dumbbell-shaped. Because of the spherical shape of an *s* orbital, the probability of finding an electron at a given distance from the nucleus in an *s* orbital does not depend on direction. The three kinds of *p* orbitals have different orientations in space.

Checkpoint ***How do s and p orbitals differ?***

Interactive Textbook

Animation 5 Observe the characteristics of atomic orbitals.

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Table 5.1

Summary of Principal Energy Levels, Sublevels, and Orbitals

Principal energy level	Number of sublevels	Type of sublevel
$n = 1$	1	1*s* (1 orbital)
$n = 2$	2	2*s* (1 orbital), 2*p* (3 orbitals)
$n = 3$	3	3*s* (1 orbital), 3*p* (3 orbitals), 3*d* (5 orbitals)
$n = 4$	4	4*s* (1 orbital), 4*p* (3 orbitals), 4*d* (5 orbitals), 4*f* (7 orbitals)

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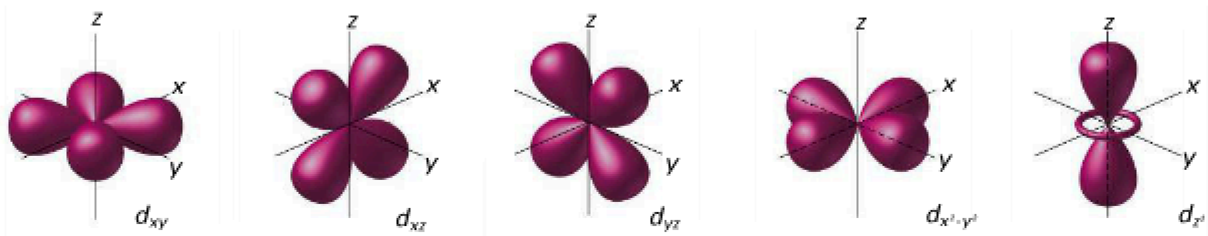

Figure 5.6 The *d* orbitals are illustrated here. Four of the five *d* orbitals have the same shape but different orientations in space.
Interpreting Diagrams ***How are the orientations of the d_{xy} and $d_{x^2-y^2}$ orbitals similar? How are they different?***

Figure 5.6 shows the shapes of *d* orbitals. Four of the five kinds of *d* orbitals have clover leaf shapes. The shapes of *f* orbitals are more complicated than for *d* orbitals. 15

The numbers and kinds of atomic orbitals depend on the energy sublevel. The lowest principal energy level ($n = 1$) has only one sublevel, called 1*s*. 16

The second principal energy level ($n = 2$) has two sublevels, 2*s* and 2*p*. 17
The 2*p* sublevel is of higher energy than the 2*s* and consists of three *p* orbitals of equal energy. The long axis of each dumbbell-shaped *p* orbital is perpendicular to the other two. It is convenient to label these orbitals $2p_x$, $2p_y$, and $2p_z$. Thus the second principal energy level has four orbitals: 2*s*, $2p_x$, $2p_y$, and $2p_z$.

The third principal energy level ($n = 3$) has three sublevels. These are 18
called 3*s*, 3*p*, and 3*d*. As shown in Figure 5.6, the 3*d* sublevel consists of five *d* orbitals of equal energy. Thus the third principal energy level has nine orbitals (one 3*s*, three 3*p*, and five 3*d* orbitals).

The fourth principal energy level ($n = 4$) has four sublevels, called 4*s*,
4*p*, 4*d*, and 4*f*. The 4*f* sublevel consists of seven *f* orbitals of equal energy. 19
The fourth principal energy level, then, has 16 orbitals (one 4*s*, three 4*p*, five 4*d*, and seven 4*f* orbitals).

As mentioned, the principal quantum number always equals the number of sublevels within that principal energy level. The maximum number 20
of electrons that can occupy a principal energy level is given by the formula $2n^2$, where n is the principal quantum number. The number of electrons allowed in each of the first four energy levels is shown in Table 5.2.

Table 5.2
Maximum Numbers of Electrons

Energy level *n*	Maximum number of electrons
1	2
2	8
3	18
4	32

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5.1 Section Assessment

1. **Key Concept** Why did Rutherford's atomic model need to be replaced?
2. **Key Concept** What was the basic new proposal in the Bohr model of the atom?
3. **Key Concept** What does the quantum mechanical model determine about electrons in atoms?
4. **Key Concept** How do two sublevels of the same principal energy level differ from each other?
5. How can electrons in an atom move from one energy level to another?
6. The energies of electrons are said to be quantized. Explain what this means.
7. How many orbitals are in the following sublevels?
   a. 3*p* sublevel **b.** 2*s* sublevel **c.** 4*p* sublevel
   d. 3*d* sublevel **e.** 4*f* sublevel

Connecting Concepts

Reread the materials on the quantum mechanical model of the atom. Describe how the quantum mechanical model differs from Dalton's model, from Thomson's model, and from Rutherford's model.

Interactive Textbook

Assessment 5.1 Test yourself on the concepts in Section 5.1.

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