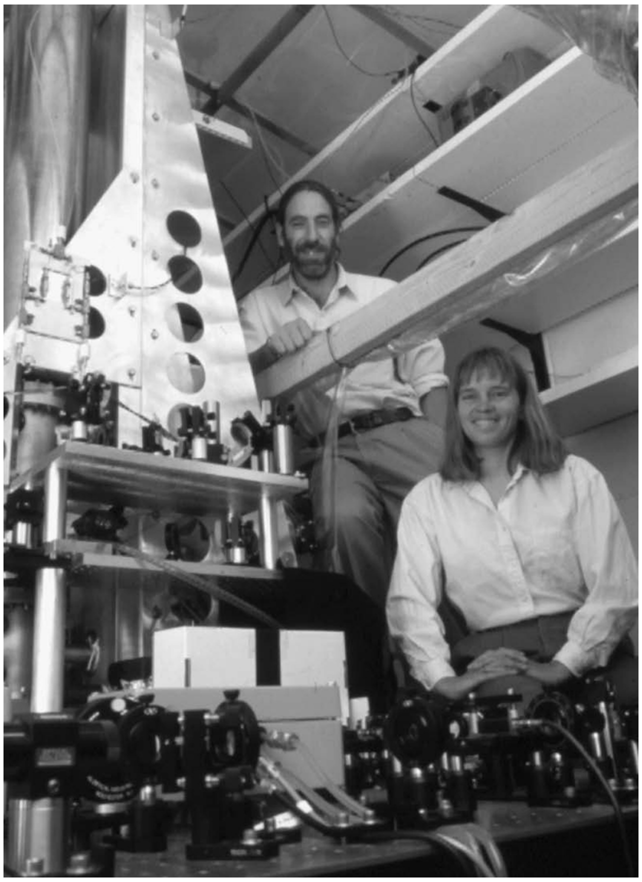
9

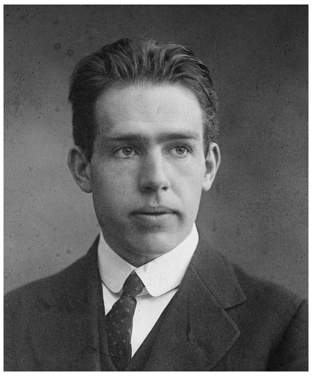
Quantum Physics of Atoms and Materials

The first postulate enunciates the existence of stationary states of an atomic system. The second postulate states that the transition of the system from one stationary state to another is … accompanied by the emission of one quantum of … radiation.

Niels Bohr
(1913)



Physicists Dawn Meekhof and Steve Jefferts with their atomic clock, which would neither gain nor lose 1 sec in 60 million years! Their clock uses the quantum properties of cesium atoms to provide its extreme stability. (Courtesy of the National Institute of Standards and Technology. Copyright Geoffrey Wheeler, 1999.)



Niels Bohr, Danish physicist who in 1913 discovered the quantum model of the atom and the relation of an atom's change in energy to the light emitted or absorbed by it.

9.1 ATOMS, CRYSTALS, AND COMPUTERS

Modern computers are made with semiconductor-based electronic circuits, which can act as switches, enabling binary data to be stored and logic operations to be performed. Semiconductor-based circuits are made of silicon ***crystals*** with small amounts of other elements added to control their electrical properties. Engineers invented modern computers using an understanding of how electrons flow in crystals. This required an understanding of the basic properties of atoms and how they combine to form crystals. Gaining a proper understanding of atoms and crystals requires us to learn more about the properties of electrons.

In Chapter 5, we discussed the origins of magnetic forces, which, according to Ampère's law, arise solely from moving electric charges. We learned that magnetic data-recording materials such as iron contain many tiny magnetic regions, called ***domains***. If these domains are all aligned and kept in a common direction, the iron becomes a magnet, allowing us to store a data bit value. A question remained, however: Why is each microscopic domain a permanent magnet itself? The answer lies in atomic physics, namely in the motion of electrons within atoms.

Between 1900 and 1930, there was a rapid and incredibly important advance in scientists' understanding of the properties and behavior of electrons. They discovered, through careful analysis of experiments, a set of quantum physics principles describing the behavior of microscopic objects—in particular, electrons in atoms. They found that the physics rules for the behavior of microscopic objects are in some ways radically different from those expounded in the nineteenth century by Newton to explain the behavior of large objects such as baseballs or the Moon. They found that microscopic objects obey different laws of motion than do macroscopic ones. This discovery rather shocked them, so much so that some of the founding fathers of the then-new principles—including Einstein—never completely accepted them as correct. Nevertheless, physicists persisted and confirmed that the then-new quantum principles are indeed correct. From the results of many experiments, combined with clever mathematics, physicists developed a theory that allows us to understand and predict electrons' properties very accurately. Without using mathematics, we can state the main principles in words and illustrate them using pictures. This will allow us to build up a set of rules and guidelines that provide a mental picture of how electrons behave in atoms.

We will learn how to read the Periodic Table of the Elements, which summarizes the structure and properties of atoms—the building blocks of matter. We will see how atoms combine to form crystals, and how the atomic structure of each type of crystal determines its electrical properties, that is, whether it is a good electric-current conductor, insulator, or in between. In the following chapters, we will develop models for the operation of semiconductor devices and see how semiconductor computer logic works.

To start at the beginning, let us consider the surprising properties of electrons, and how their behavior leads to understanding the structure of atoms.

9.2 THE QUANTUM NATURE OF ELECTRONS AND ATOMS

Before we discuss the structure and behavior of atoms, we need to review a few descriptive facts.

- A ***proton*** is a tiny object having a small mass and positive (+) electric charge.
- A ***neutron*** is a tiny neutral object (zero electric charge) having approximately the same mass as a proton.

- An ***electron*** is an even tinier object having negative (–) charge and mass about 1/(2000) that of a proton or neutron.
- A ***nucleus*** is made of protons and neutrons bound tightly together by so-called nuclear forces, which we will not discuss in this text.
- An ***atom*** consists of a nucleus and one or more electrons moving around it.
- An ***element*** is a substance made of a single kind of atom.

As we discussed in Chapter 5, the net charge of an object equals the sum of the charges of all particles making up the object. This means, for example, that the net charge on a nucleus equals the number of protons in that nucleus, because the other particles in the nucleus—the neutrons—have zero charge. Normally, atoms are neutral: they have zero net charge. This means that the number of electrons surrounding the nucleus equals the number of protons in the nucleus.

Many of us have a mental picture of an atom—a small, hard nucleus at the center, with electrons orbiting around the nucleus like wee planets orbiting around a tiny sun. We can think crudely of the electrons as particles moving in an ***orbit*** around the nucleus, as shown in **Figure 9.1** for the case of a helium atom. This picture of the atom is somewhat naive and is not entirely correct. In fact, no one has a truly satisfactory mental picture of exactly how electrons behave, although we do have a good mathematical theory describing their behavior.

By studying how atoms absorb and emit light of different colors, and how electrons travel through electric and magnetic fields, scientists discovered after 1900 that atoms and electrons do not obey the classical principles of mechanics that were put forth by Newton and described in Chapter 3. Scientists of the time could not understand how the basic “laws of motion,” which were so successful in describing the motions of typical large objects, could fail when applied to atoms.

Perhaps, with hindsight, it is not so surprising that electrons don’t follow Newton’s laws. The objects that we can see directly—those at the human scale—do obey Newton’s laws. By *human scale* we mean the scale of baseballs, racing cars, and space shuttles. Newton’s theory is extremely accurate for large, slow-moving objects, but fails when the object is on the scale of electrons and atoms; that is, roughly a billion–billion times less massive than a baseball. Newton did not take into account the behavior of such tiny objects when he formulated his laws, because at that time nothing was known about such objects. Any successful theory of atoms must take such behaviors into account.

One of the limitations of the naive Newtonian view of the atom was the faulty assumption that an electron is actually a ***particle***, as illustrated by the dots in Figure 9.1. What is meant here by “particle”? A particle is an entity or thing with mass, a definite location in space, and a definite speed. Surprisingly, this description does not apply to electrons. It is not simply that we lack information about where an electron is at a particular moment. Rather, the very concepts of location and speed are not strictly appropriate to electrons. It is as if the electron is spread or smeared throughout some region in space, rather than being at a specific place. This is one of the mysterious properties referred

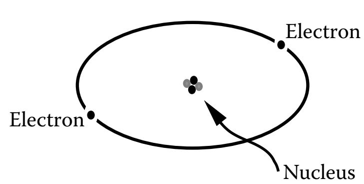


FIGURE 9.1 Naïve picture of a helium atom, showing two electrons orbiting around a nucleus, comprised of two protons (black) and two neutrons (gray). The drawing of the atom is not drawn to scale.

to as the "quantum nature of electrons," which distinguishes them from the classical concept of particles used by Newton and his followers. We can crudely represent the spread-out nature of electrons by drawing a fuzzy region as in **Figure 9.2**.

Although we need to keep this spread-out picture in mind, it is cumbersome to draw it in this way, especially when there are many fuzzy orbits that need to be drawn. So we will use the simpler style of drawing shown in Figure 9.2a to symbolically represent the more accurate picture in Figure 9.2b.

We should wonder what the spread-out picture of an electron really represents. The mathematics of ***quantum theory***, which we will not study here, shows that a spread-out electron behaves in some ways like a ***wave***. A wave—such as waves in the ocean—is not located at a particular position. A water wave is made of many separate water (H_2O) molecules, moving in an organized pattern. In contrast, the electron wave is associated with only one electron. We believe in the validity of this wavelike description because the mathematics that goes along with it is in excellent agreement with all of the experimental observations on electrons.

This description of an electron might seem strange, but physicists have an interpretation of the meaning of the electron's wave. The wave's amplitude in a region of space tells us the likelihood that the electron will be found in that region. In Figure 9.2b, the darker shaded regions are the places with higher likelihood for the electron to be located. Before we make the measurement, the electron is not at a definite location, but the very act of measuring causes the electron to appear at a definite location.

To further develop the water-wave analogy for the electron in an atom, consider the surface of water in a drinking cup. The wave is confined within the cup. The pattern illustrated in **Figure 9.3** is a circular wave, rotating counterclockwise as time goes on. In the example shown, there are eight wave peaks around the edge of the circular

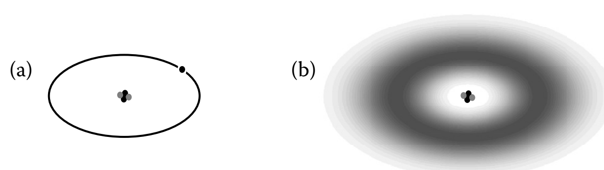


FIGURE 9.2 (a) Naïve classical picture of an electron orbit as a localized particle traveling around a localized path. (b) Quantum picture of an electron orbit as a spread out region in space. The darker the shading, the more likely it is to find the electron at that location.

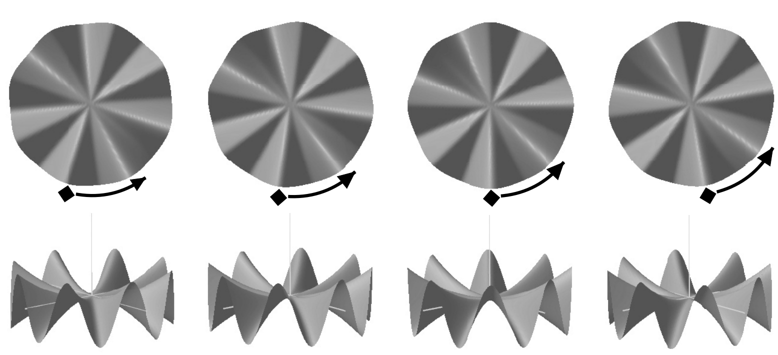


FIGURE 9.3 Frames (left to right) showing a rotating circular wave, in top view and side view. The diamond labels a particular spot on the wave, showing how it rotates in time. In this simple model of an electron's wave, the likelihood that the electron is in some region is highest at the edges of the circular region, where the amplitude is greatest.

pattern. This means that the wavelength along the edge equals one-eighth of the circumference of the circular edge of the pattern.

THINK AGAIN

When you think of a wave, such as a water wave, you usually think of many particles (H_2O molecules) moving in an organized pattern. However, the wave describing an electron corresponds to only a single electron. This is very different from the idea of a wave in classical physics.

An analogy that is simpler to visualize is that of a water wave traveling around a circular canal, as in **Figure 9.4**. In this example, the wave travels around the canal in the clockwise direction and has 16 wavelengths fitting precisely around the circular length of the canal. This leads to constructive interference of the wave when it goes around once and meets up with its "tail." This reinforces and makes a stable wave.

The condition for stability of an electron wave is shown in **Figure 9.5**. For a wave moving in a circular path to be stable, there must be an integer number of wavelengths exactly fitting around the edge circumference. If instead the wavelength equaled, for example, 1/(8.5) of the edge circumference, as shown in the middle of Figure 9.5, the wave would not constructively reinforce itself; rather it would tend to cancel, leading to an unstable wave. This means that only certain discrete wavelengths are allowed for stable circular waves of a given circumference. (*Discrete* means distinct or unconnected.) The figure also shows a wave with 20 wavelengths fitting around a somewhat larger circumference; this is also a stable wave.

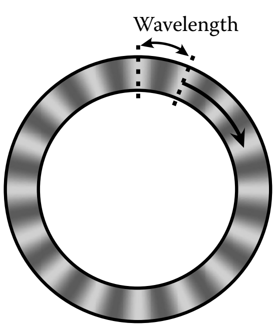


FIGURE 9.4 A water wave traveling around a circular canal. The circumference of the canal must equal an integer number of wavelengths (in this example, 16), otherwise the wave cannot be continuous and stable.

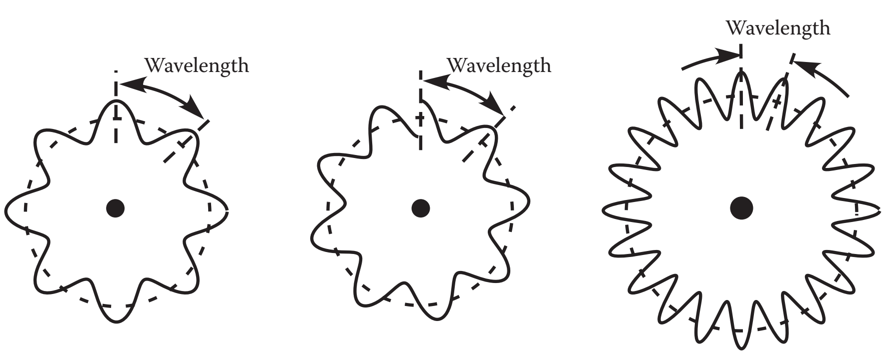


FIGURE 9.5 Constructive interference of electron waves. The circumference of the edge of an orbit must be an integer number of electron wavelengths, otherwise the wave cannot be continuous and stable.

Niels Bohr, in the chapter-opening quote, called these stable conditions stationary states. We refer to the discreteness of wavelengths by saying that the values of the wavelengths are "quantized." This is the origin of the term quantum physics. The quantized nature of a wave's wavelength is a result of its being confined to a small region—in the water case, the region of the cup. In the case of atoms, the electron is confined to the small region around the nucleus.

The electron's wave has a frequency as well as a wavelength. For the simple model in Figure 9.5, the wave's frequency could be observed by sitting at a fixed point on the outer edge and counting the number of oscillations of the passing wave's displacement during a certain time interval. As for any wave, a decreased wavelength means an increased frequency, although the precise relation depends on the type of wave and the shape of the small volume to which it is confined. Because the electron's wavelength in an atom is quantized, its possible frequency values are also quantized.

According to quantum theory, an electron's wavelike motion determines its energy. When an electron is confined to the volume of an atom, this motion is quantized, and therefore the electron's energy is quantized. This means that when an electron is confined to the volume of an atom, its energy can take on only certain discrete values. This behavior is quite unlike a moon orbiting around a planet. Such a moon can have any energy as it flies, depending on how fast it moves; that is, the energy of an orbiting moon is not quantized. The mathematics of quantum theory makes it possible to create accurate pictures of the electron's wave within a hydrogen atom. A few examples of electron waves of different energies are shown in **Figure 9.6**.

The ***quantization*** of an electron's energy, first proposed by Niels Bohr in 1913, is a remarkable property, totally outside the realm of classical, Newtonian physics. Its discovery led to a revolution in our understanding of the nature of atoms, molecules, and crystals and paved the way for developing computer technology. It was arrived at—not by purely intellectual reasoning—but by thinking hard about how to understand the results of experiments carried out around 1900. Next we review some of those experiments.

THINK AGAIN

When we say that the electron behaves in a discrete manner, we do not mean that its position is discrete (that would be more like a particle than a wave). We mean that the electron's energy is discrete, or quantized.

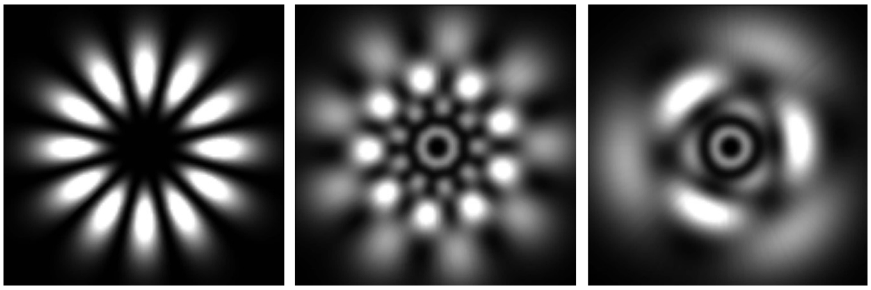


FIGURE 9.6 Realistic computer-generated images of electron waves in a hydrogen atom. (Created using *Atom in a Box,* http://daugerresearch.com/orbitals. With permission of Dauger Research, Inc.)

9.3 THE EXPERIMENTS BEHIND QUANTUM THEORY

How do we know that these claims about electron behavior are true? Three crucial experiments that were carried out around 1900 paved the way for the discovery of the quantum nature of electrons and other particles.

9.3.1 The Spectrum of Light Emitted by a Hot Object

When a piece of any material, such as a ***metal*** light-bulb filament, is heated to a high temperature, it glows and emits light. When it is not very hot, it emits mostly red and infrared light. The hotter it is, the more yellow and blue is the light. When heated to very high temperatures, it emits light of all colors, so it looks white. Light can be analyzed for the different colors it contains, using a prism or other device to spread out the colors into a ***spectrum***. As shown in **Figure 9.7**, light from an incandescent light bulb is passed through a narrow slit in an opaque screen to make a narrow beam of light, and then is spread out by a prism. A smooth, continuous spectrum is observed.

In 1900 Max Planck, a German scientist, found that the prediction for this spectrum based on the theories of Newton and Maxwell did not agree with experiments. It did not correctly predict the relative amounts of light at different colors in the spectrum illustrated in Figure 9.7. Those theories predicted blue light that was far too intense relative to the intensity or brightness of the red light. Resolving this discrepancy led to a revolution in our understanding of the physics of the universe. Max Planck found that he could alter the theory of Newton and Maxwell by making a radical assumption about how light behaves. He hypothesized that light cannot exist in continuous amounts of energy, but rather comes only in indivisible, discrete bundles of ***electromagnetic*** (EM) energy. We call these energy bundles ***photons***, as will be described in more detail in Chapter 12. Planck found that by making this alteration to the old ("classical") theories, he could derive a formula that accurately predicts the relative intensity of each color in the spectrum of light emitted by a hot object.

Planck was on to something, but he did not know precisely what. In fact, he spent the next couple of decades trying to wriggle out of his 1900 hypothesis, thinking that it was simply an accident of the mathematics. That is, he looked hard for an alternative, less radical explanation for the spectrum of colors that did not use the idea of light energy bundles. His hard work failed. Since then, thousands of physicists have looked for convincing alternative theories, but they have also failed. Their failure greatly strengthens

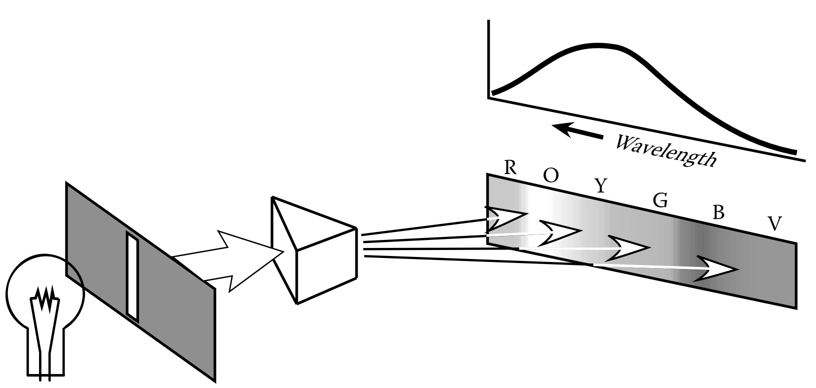


FIGURE 9.7 The spectrum of light from a hot metal filament in an incandescent light bulb is made up of smooth, continuous bands of colors: red, orange, yellow, green, blue, and violet.

physicists' confidence that no other satisfactory explanation exists. It seems that we are stuck with the idea of photons, that is, the idea that the energy in light comes in little indivisible amounts, lumps, or bundles. This means that light cannot simply be described as a wave of EM fields, as we implied in earlier chapters. The classical wave picture of light is not completely wrong, but it did need to be refined with the quantum theory.

9.3.2 Sharp-Line Atomic Lamp Spectra

In contrast to the case of an incandescent light bulb, if we analyze light emitted by an atomic-vapor lamp, such as those in a neon display light or a yellow sodium streetlamp, we observe sharp, discrete lines of color. We discussed atomic-vapor lamps in In-Depth Look 5.2. The experiment showing the discrete lines of color is shown in **Figure 9.8**. Linelike spectra of this type were observed as early as 1885 by Jakob Balmer, a science teacher in a Swiss girls' school. He found a mathematical formula that matched the pattern of the line positions in the spectrum, but he had no explanation for why this pattern arose. This effect was a mystery to scientists at the time. The theories of the time, based on Newton's theory and Maxwell's theory, predicted a smooth, continuous spectrum, such as that seen in Figure 9.7.

In 1913 Niels Bohr proposed that these sharp lines of color were associated with light given off by an atom when it suddenly loses energy, accompanied by a "jump" of the electron from a high-energy orbit to a low-energy one. His ideas are summarized in the quote at the beginning of this chapter. There he talked about the stationary states, or orbits. These are analogous to the stable circular waves illustrated in Figure 9.5. Bohr hypothesized that, if the possible states have discrete energies, then the light given off when an electron jumps from one state to another would have discrete colors. The colored light is given off in bundles called photons, as postulated earlier by Planck. Bohr reasoned that one could learn about the nature of the electron orbits by analyzing the pattern of the colored lines that Balmer had studied earlier.

The principal difference between an atomic-vapor lamp and an incandescent lamp, discussed in the previous section, is that in the vapor lamp all atoms are moving freely as individual particles in the vapor. Their light emission is therefore characteristic of isolated atomic properties. In contrast, in an incandescent lamp, the atoms make up a solid metal, with properties quite different from those of isolated atoms.

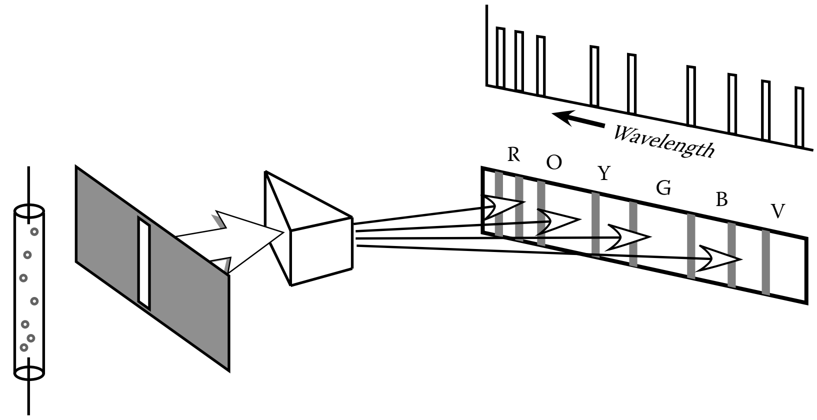


FIGURE 9.8 The spectrum of light emitted by an atomic-vapor lamp is made up of discrete lines of color.

IN-DEPTH LOOK 9.1: SPECTRUM OF HYDROGEN ATOMS

An important part of the scientific process is using mathematical formulas to represent the results of physical observations. By using such formulas, scientists can better recognize regular patterns in a seemingly complex collection of observed data. As a consequence, a mathematical theory can often be devised to summarize the results. In the case of the spectrum of the hydrogen atom, this procedure led to a whole new type of science—quantum physics—along with its remarkable implications for science and technology.

When a glass tube containing hydrogen atoms is used as an atomic vapor lamp, as in Figure 9.8, sharply defined colors are emitted, rather than a continuous spectrum as with a hot-filament lamp. Many of these sharp color lines are illustrated in **Figure 9.9**, along with the value of the wavelength associated with each "color" of EM radiation. Recall that the visible region of the spectrum is roughly 400–800 nm, and only about four of the hydrogen lines fall in this range. The rest are in the infrared or ultraviolet regions.

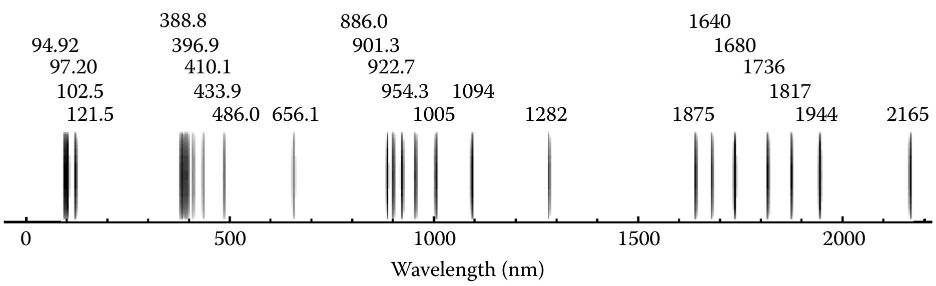


FIGURE 9.9 Sharp lines of color appearing in the spectrum of light emitted by hydrogen.

In 1890, a Swedish physicist, Johannes Rydberg, found that he could represent all of the wavelengths shown in the figure by a single, simple formula:

$$\lambda = \frac{91.12671\text{ nm}}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)}$$

In this formula, 91.12671 nm is called the Rydberg constant. The variables m and n take on integer values (i.e., $m = 1,2,3\ldots$, and $n = 1,2,3\ldots$), but with the restriction that n is always greater than m. The first four wavelengths are calculated as:

$$\lambda = \frac{91.12671\text{ nm}}{\left(\frac{1}{1^2} - \frac{1}{5^2}\right)} = 94.92\text{ nm}, \quad \lambda = \frac{91.12671\text{ nm}}{\left(\frac{1}{1^2} - \frac{1}{4^2}\right)} = 97.20\text{ nm}$$

$$\lambda = \frac{91.12671\text{ nm}}{\left(\frac{1}{1^2} - \frac{1}{3^2}\right)} = 102.5\text{ nm}, \quad \lambda = \frac{91.12671\text{ nm}}{\left(\frac{1}{1^2} - \frac{1}{2^2}\right)} = 121.5\text{ nm}$$

It is remarkable that such a simple formula can be used to calculate precisely the spectrum lines of hydrogen, and this fact provided a powerful clue to the physics "sleuths" of the time about the nature of atoms. Niels Bohr used this clue to create the quantum theory of electron motion in atoms. He and others formulated the quantum principles, described in the following sections, specifically to create a theoretical model that could explain the reasons behind Rydberg's simple formula.

9.3.3 Electron Scattering from Crystals

A third piece of evidence for the wavelike properties of electrons was found in 1927, when two American physicists working at AT&T Bell Telephone Laboratories, Clinton Davisson and Lester Germer, observed an astounding effect in their laboratory. They fired a beam of electrons (similar to the electron beam that we still sometimes use to create images on a television cathode-ray tube) at a crystal of nickel. A crystal is a regular array of atoms, analogous to a regular array of slits. (Recall the discussion about wave interference in Section 7.11.) They found, as expected, that some of the electrons bounced off (scattered) from the nickel atoms. They measured the pattern made by the scattered electrons. If electrons were tiny particles, one would anticipate that the observed pattern would be easily explained by Newton's theory of forces and acceleration. Instead, they found a pattern of scattered electrons that looked completely different from this expectation. The pattern they saw looked like a wave-interference pattern.

In the same year, George P. Thomson in England sent a beam of electrons into a very thin foil of aluminum (Al), and observed interference patterns where the transmitted electrons hit a screen. The circular-shaped interference patterns that Thomson recorded are shown in **Figure 9.10**, which also shows interference patterns produced when x-rays were passed through a similar Al foil. It was well established by then that x-rays

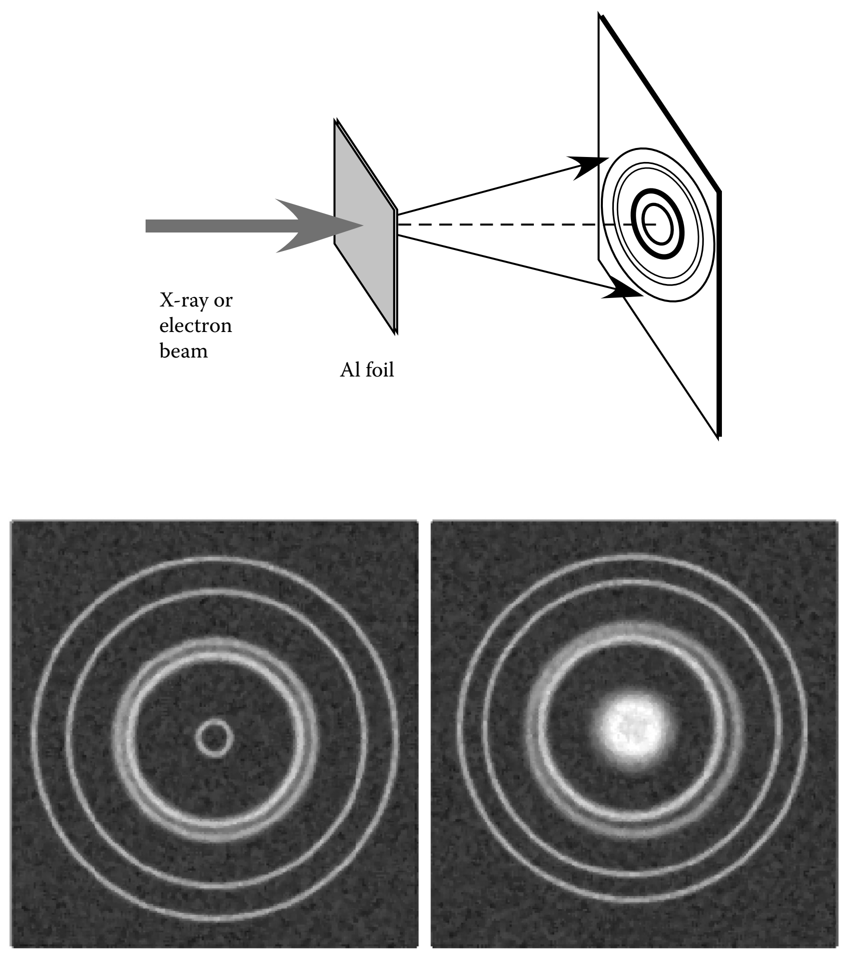


FIGURE 9.10 Top: Experimental setup. Bottom: Artist's rendering of G. P. Thomson's 1927 recordings of interference, or diffraction, patterns observed when x-rays (left) or electrons (right) pass through thin aluminum foil.

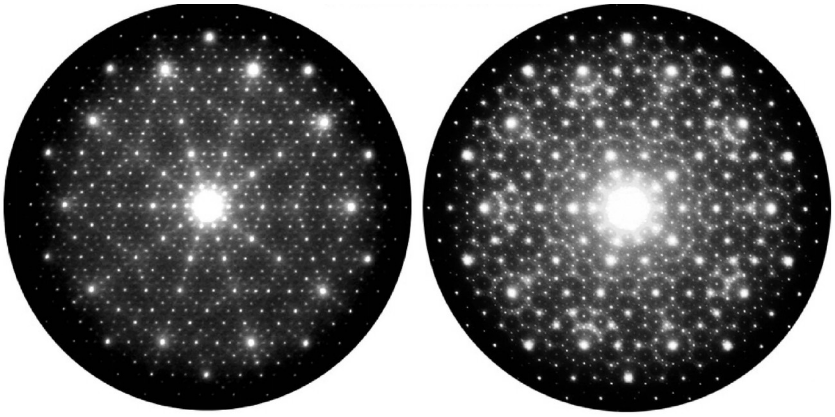


FIGURE 9.11 Electron interference patterns observed when electrons pass through two types of AlCoNi crystals. In both cases 5-fold symmetry of the intensity distribution may be observed. (Courtesy of Conradin Beeli, Swiss Federal Institute of Technology. With permission.)

are EM waves, so it was not surprising to see interference with them. In contrast, it was astonishing to see interference with the electron beam. It seemed that the electrons interacted with the crystal as if they were waves, or as if they were being guided by a wave. The phenomenon of interference that occurs when a wave passes through a material is called diffraction.

The experimenters learned that 3 years earlier, in 1924, a young French physicist, Louis de Broglie, had precisely predicted the behavior of electrons that the Americans and British had observed. De Broglie had hypothesized that electrons simultaneously have properties of both particles (called corpuscles) and waves. As de Broglie said some years later, in his Nobel Prize address, "the existence of corpuscles accompanied by waves has to be assumed in all cases." This hypothesis, which has since been proven true, opened the gates to a mathematical formulation of quantum theory. In 1926, Austrian physicist Erwin Schrödinger developed a mathematical theory that updated the venerable theory of Isaac Newton. With Schrödinger's theory and with Davisson's and Thomson's experiments, the quantum revolution had arrived.

Since it was discovered in 1927, electron diffraction has been an important tool for studying the structure of crystals. The internal structure of the crystal lattice is revealed by diffraction patterns, sometimes strikingly beautiful, as those shown in **Figure 9.11**.

9.4 THE SPINNING OF ELECTRONS

Let us return to our solar-system model of a helium atom with two electrons orbiting around the nucleus-like planets orbiting around a sun, shown in more detail in **Figure 9.12**. As the Earth orbits around the Sun, it also spins around its north-south axis. In analogous fashion, an electron spins around its axis as it travels around the atom's nucleus. Each electron can spin either clockwise or counterclockwise. We cannot literally describe electrons as particles that spin around their axis. Such a picture is the best we can do in describing electrons without using the full mathematical methods.

The spin of electrons plays an important role in determining the structure of the various kinds of atoms. We will discuss how this works after introducing the principles of quantum physics in the next section.

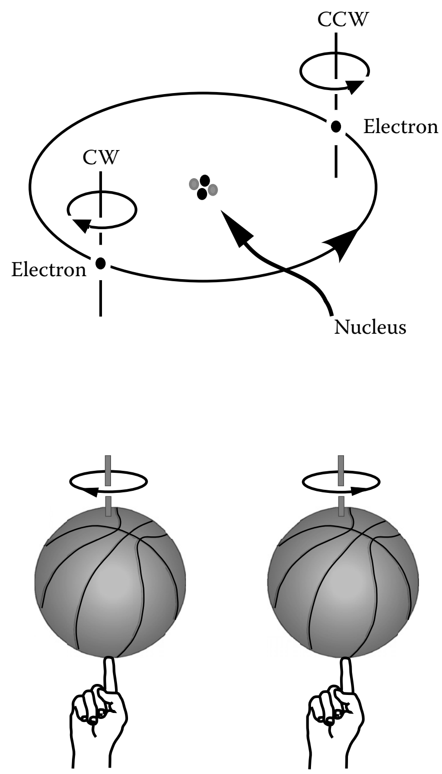


FIGURE 9.12 Naïve model of a helium atom, with two electrons orbiting around a nucleus. The vertical lines indicate the axis of internal rotation or spin for the electrons, which are shown spinning in opposite directions—one clockwise (cw) and the other counterclockwise (ccw). The spin of an electron is roughly analogous to the spin of a basketball.

9.5 THE PRINCIPLES OF QUANTUM PHYSICS

To summarize the above discussions, experiments confirmed that electrons, which were classically thought of as particles, actually have properties of particles *and* waves. In addition, light cannot be thought of simply as a wave (as it was in earlier, classical times), but is comprised of bundles of energy. Clearly, these entities cannot properly be called particles or waves. Some people jokingly call them *wavicles*. For our discussions, we will continue to use the terms particles and waves, keeping in mind that these terms are being used loosely.

To explain the observed behaviors of electrons and photons, scientists found a set of rules that describe objects at the atomic scale. These rules are the principles of quantum physics. They form the basis of quantum theory, which is an extremely successful physical theory. By using the theory, scientists can predict with incredible accuracy the outcome of virtually any experiment that can be done with electrons and atoms. This is despite the fact that the theory is so counterintuitive. The mathematics of quantum theory was developed in the 1920s and 1930s by Niels Bohr in Denmark (opening photo), Erwin Schrödinger in Austria, Wolfgang Pauli and Werner Heisenberg in Germany, Paul Dirac in England, and others. It later underwent refinements by Richard Feynman and Julian Schwinger in the United States, Shin-Ichiro Tomonaga in Japan, and others. All of these received the Nobel Prize in physics for their contributions to quantum theory. Here we will not use the mathematical quantum theory to get a basic understanding of electrons and atoms. We will instead work with a set of principles that can be stated in words. Please realize, however, that it is only through the detailed study of the mathematical predictions and corresponding experiments that we know these principles to be correct.

In all, we will introduce six quantum principles. The first three, stated here, deal with the properties of electrons in atoms. We have already discussed the concepts behind the first two principles.

Quantum Physics Principles (i–iii)

(i) **The wave nature of electrons:** An electron is a small entity or "thing" that cannot be thought of as a tiny particle, because it cannot be said to have a definite location and a definite speed. Although an electron has mass—a particle-like property— it also has wavelike properties, with the amplitude of the electron wave determining the likelihood of finding the electron in a certain region.
(ii) **Quantization of energy:** An electron in an atom can have only certain discrete energies; that is, its energy is quantized. The wave patterns associated with the electron's stable motion in the atom are called stationary or stable orbits.
(iii) **Exclusion Principle:** At most two electrons can occupy the same orbit. Furthermore, for two electrons to occupy the same orbit, they must be spinning in opposite directions around their axes.

The meaning of the third principle—the Exclusion Principle—can be understood by referring to Figure 9.12, which shows each electron spinning around its own vertical axis, in opposite directions. Two electrons in the same orbit simply cannot be spinning in the same direction. That is "forbidden" by the laws of physics, meaning simply that we do not ever observe it. This is different from two moons orbiting a planet, which could be in the same orbit and be spinning in the same direction. An electron's spinning behavior is not easy to grasp intuitively, because an electron is not really a particle, like a tiny basketball. Nevertheless, we draw the spinning electron as if it were a tiny particle to give us some picture to visualize. The Exclusion Principle is known to be correct from examining the structure of the atoms or elements in the Periodic Table, as we shall do in the following section. In fact, it was hypothesized by its discoverer, Wolfgang Pauli, for this very purpose—to explain the nature of the elements using quantum theory.

An important concept is the ***state*** of an electron. The word *state* means *condition*, or "how something is." The state of an electron is determined by which orbit it is in and in which direction it is spinning. For example, in the lowest-energy orbit, there are two possible electron states—each corresponding to the same orbit but distinct spin directions. Using the language of electron states, we can rephrase the Exclusion Principle as: *No two electrons can have (be in) the same state.*

We can draw pictures to illustrate and explore the consequences of the three principles. Let us use the naïve, easy way of drawing electron orbits, as shown in Figure 9.1. Here we also draw the nucleus as a single dot for simplicity. **Figure 9.13a** shows two electrons moving around a nucleus in the same orbit, with opposite spin directions—clockwise (cw) or counterclockwise (ccw) with respect to a vertical axis of rotation. These two electrons have the same energy—the lowest energy allowed for an electron in an atom. This lowest-energy orbit makes up what is called the first ***energy shell***.

Figure 9.13b shows four electrons within an atom. Two are in the lowest-energy shell, and two are in the next-to-lowest shell, with a larger orbit diameter, which we call the second energy shell. Only one of the four orbits in the second shell contains

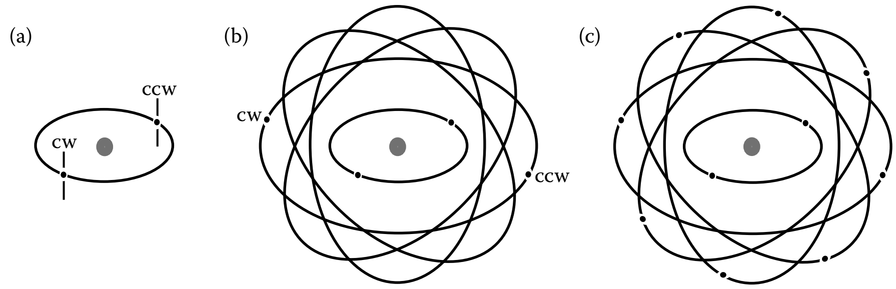


FIGURE 9.13 Electron orbits in an atom. (a) Two electrons in the lowest-energy (first) shell. (b) Four electrons, filling the first shell and partially filling the second shell. (c) Ten electrons, completely filling the first and second shells.

electrons—the other orbits are empty. Although the fourth electron is shown as being in the same orbit occupied by the third electron, this need not be the case. It can go into one of the other unoccupied orbits in the second shell, all of which have about the same energy. This is not an important distinction for our purposes. As always, any two electrons in the same orbit necessarily have opposite spin directions. Figure 9.13c shows ten electrons within an atom. Again, two (the maximum number) are in the lowest-energy shell, and eight are in the second energy shell. The second shell has four distinct orbits, which have equal energies but are distinguished by the details of their orbit shapes, which are represented here simply by different orientations.

Remember that the actual orbit shapes are complicated three-dimensional patterns. Although the drawings are shown as flat, two-dimensional pictures, the actual orbits are three-dimensional. They can be visualized as filling a sphere, as in **Figure 9.14**.

The first three quantum principles, along with some advanced mathematics that we will not discuss, correctly predict how many orbits are within each shell.

- The lowest-energy shell has one orbit (two states). So, according to the Exclusion Principle, this shell can contain at most two electrons (one per state).
- The second-lowest-energy shell has four orbits (eight states). So this shell can contain at most eight electrons.

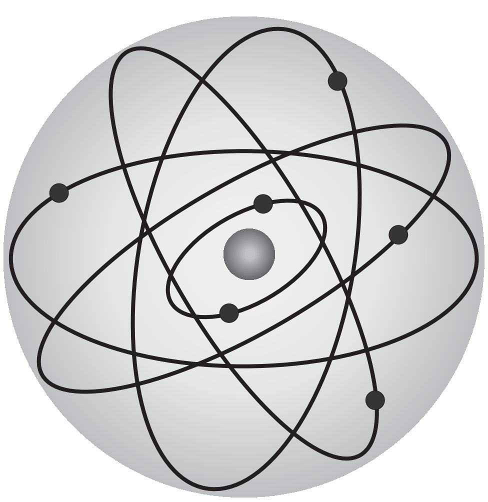


FIGURE 9.14 Three-dimensional drawing of electron orbits in an atom.

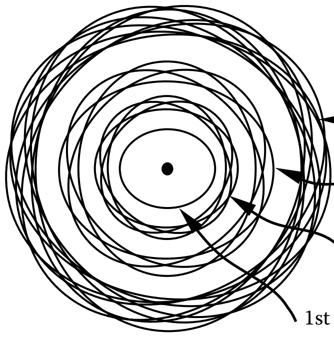


FIGURE 9.15 Naïve representation of all possible electron orbits in the first four energy shells.

- The third-lowest-energy shell also has four orbits (eight states). So this shell can contain at most eight electrons.[1]
- The fourth- and fifth-lowest-energy shells each have nine orbits (eighteen states). So these shells can contain at most eighteen electrons each.

The first four shells are illustrated in **Figure 9.15**. Orbits within the same shell have equal, or nearly equal, energies. Shells with lower energies and smaller orbits are called *inner shells*, and those with higher energy and larger orbits are called *outer shells*.

QUICK QUESTION 9.1

An atom has 37 electrons. How many protons does it have, assuming the atom is overall neutral?

9.6 BUILDING UP THE ATOMS

One of the early triumphs of quantum theory was its ability to explain the structures of the known atoms and to explain why each element appears where it does in the periodic table of the elements, which is shown in **Table 9.1**. Chemists had previously constructed this table on the basis of how different elements combine in chemical reactions. Each element in the Periodic Table is identified as a different atom (hydrogen, carbon, silicon, gold, etc.). Now we know that, for neutral atoms, the number of electrons and the number of protons is equal. This number is called the ***atomic number***, and is denoted by N. In the Periodic Table, N is given directly above each element's name. The atoms are listed in order of increasing mass per atom, with hydrogen (H) being the lightest. The number below each element's name gives the atom's mass in units called atomic mass units. One atomic mass unit is approximately equal to the mass of one proton.[2] The H atom has one electron and one proton and no neutrons, so its mass (1.008) very nearly equals that of one proton. The carbon atom has six electrons, six protons, and six neutrons, and its mass (12.01) approximately equals that of twelve protons.

The key to determining the structure of atoms is the following two rules:

1. Electrons will occupy one of the lowest-energy orbits available (i.e., not fully occupied).
2. If an orbit is already occupied by two electrons (with opposite spin directions), then another cannot join them in that orbit.

The first rule is consistent with common experience that normally objects will move to the lowest energy they can reach. This is a rather general property of nature. An analogy is a ball rolling down a grassy hill to the lowest level. The second rule is again the Exclusion Principle.

[1] Standard texts use the term *shell* in a different manner than used here, but for our purposes our usage is fine.
[2] More precisely, one proton has mass equal to 1.007 atomic mass units.

TABLE 9.1
Periodic Table of the Elements

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 --- ()	111 --- ()	112 --- ()		114 --- ()		116 --- ()		118 --- ()
Lanthanide series			58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (147)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0		
Actinide series			90 Th 232.0	91 Pa (231)	92 U (238)	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)		

Source: Adapted from Los Alamos National Laboratory's Chemistry Division. In the online version, each element symbol links to a web page with more information. http://pearl1.lanl.gov/periodic/default.htm.

TABLE 9.2
Some of the Low-Atomic-Number Elements

Atomic Number *N*	Symbol	Name	Number of Electrons in Shells 1	2	3	4	5	Common Pure Form
1	H	Hydrogen	1					Gas (molecular)
2	He	Helium	2					Gas (atomic)
3	Li	Lithium	2	1				Metal
4	Be	Beryllium	2	2				Metal
5	B	Boron	2	3				Metal
6	C	Carbon	2	4				Various
7	N	Nitrogen	2	5				Gas (molecular)
8	O	Oxygen	2	6				Gas (molecular)
9	F	Fluorine	2	7				Gas (molecular)
10	Ne	Neon	2	8				Gas (atomic)
11	Na	Sodium	2	8	1			Metal
12	Mg	Magnesium	2	8	2			Metal
13	Al	Aluminum	2	8	3			Metal
14	Si	Silicon	2	8	4			Semiconductor
15	P	Phosphorus	2	8	5			Various
16	S	Sulfur	2	8	6			Crystal
17	Cl	Chlorine	2	8	7			Gas (molecular)
18	Ar	Argon	2	8	8			Gas (atomic)
19	K	Potassium	2	8	8	1		Metal
20	Ca	Calcium	2	8	8	2		Metal
21	Sc	Scandium	2	8	8	3		Metal
22	Ti	Titanium	2	8	8	4		Metal
31	Ga	Gallium	2	8	8	13		Metal
32	Ge	Germanium	2	8	8	14		Semiconductor
33	As	Arsenic	2	8	8	15		Various
34	Se	Selenium	2	8	8	16		Various
35	Br	Bromine	2	8	8	17		Various
36	Kr	Krypton	2	8	8	18		Gas (atomic)

The numbers of states in each of the shells—described in the previous section—give the order of the elements in the Periodic Table. A list of examples is given in **Table 9.2**. The first (lowest-energy) shell corresponds to the hydrogen (H) atom, which has one electron, and helium (He), which has two electrons. These are illustrated in **Figure 9.16**.

Hydrogen and helium appear in the top row of the Periodic Table. The second row contains atoms having the second-lowest shell partially or completely occupied. This row therefore has eight different atoms (elements): lithium (Li), with three electrons, through neon (Ne) with ten electrons. The neon atom has two electrons in the first shell and eight electrons in the second shell, making these shells filled. For the next element—sodium (Na)—the eleventh electron must be in the third shell. By the time we reach argon (Ar) the third shell is filled for a total of $2 + 8 + 8 = 18$ electrons. Notice that the atomic number, N, of argon is 18 in the table. This number tells us how many electrons (and protons) each atom has. The number of neutrons is less important for our purposes—in the lighter elements there are roughly equal numbers of neutrons and protons, whereas in the heavier elements there are more neutrons than protons.

QUICK QUESTION 9.2

An atom has five electrons. Give the name of this atom and draw its orbit picture analogous to those in Figure 9.16.

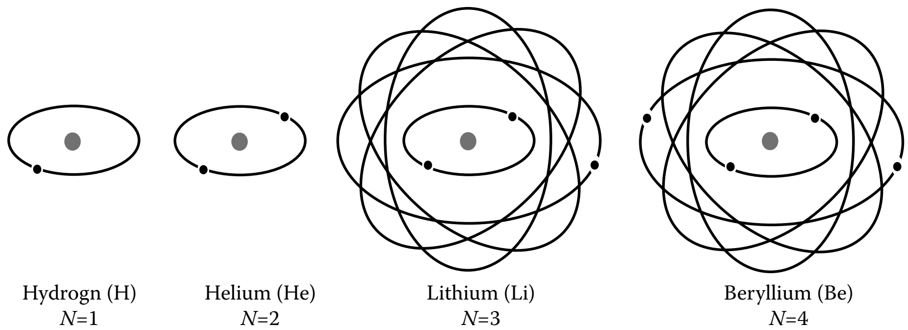


FIGURE 9.16 The atoms hydrogen, helium, lithium, and beryllium have one, two, three, and four electrons, respectively. Each electron added goes into the lowest-energy shell that is not fully occupied.

A type of diagram that we will use extensively in our study of semiconductors is the atomic energy level diagram. This is made by drawing a scale (like on a ruler) in the vertical direction indicating the total (kinetic plus potential) energy of the electron states. The horizontal axis or direction has no meaning, just as it has no meaning on a ruler. As shown in **Figure 9.17**, the lowest-energy shell has two states with nearly equal energies, then there is an ***energy gap***, a range of energies in which electrons are forbidden. At higher energy, above the gap, is the second shell with eight states having nearly equal energies, followed by another gap. At still higher energies is the third shell with eight more states having nearly equal energies.

A good way to think of this diagram is that it portrays a staircase, as in **Figure 9.18**. To increase its energy, an electron must "jump" up a full step. An electron is not allowed to be between steps. The concept of energy and the fact of its conservation are key ingredients in the quantum theory. These concepts are among the few that carried over from the classical, Newtonian theory to the quantum setting.

We can use the energy-level diagram to represent the structure of different atoms, as in **Figure 9.19**. Hydrogen has atomic number $N = 1$, meaning it has one electron, shown as the dark dot in the lowest-energy state. Helium has $N = 2$, meaning it has two electrons, shown as two dots, one in each of the two lowest-energy states. Lithium has $N = 3$, and its third electron must have an energy much higher than the lowest two, because there is a large gap in the energy level diagram above the second lowest state. Boron has $N = 5$, and its fourth and fifth electrons have energies only slightly higher

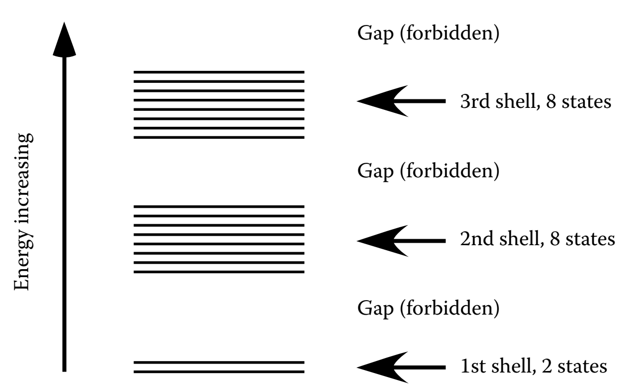


FIGURE 9.17 Energy-level diagram for the total (kinetic plus potential) energies of electrons within atoms. Energy increases in the vertical direction.

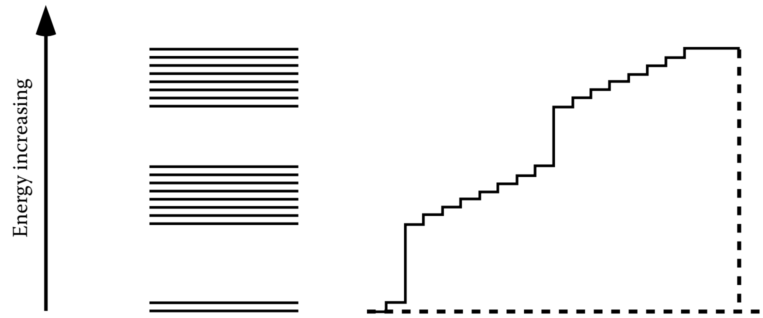


FIGURE 9.18 Energy levels of an atom viewed as a staircase of increasing total energy.

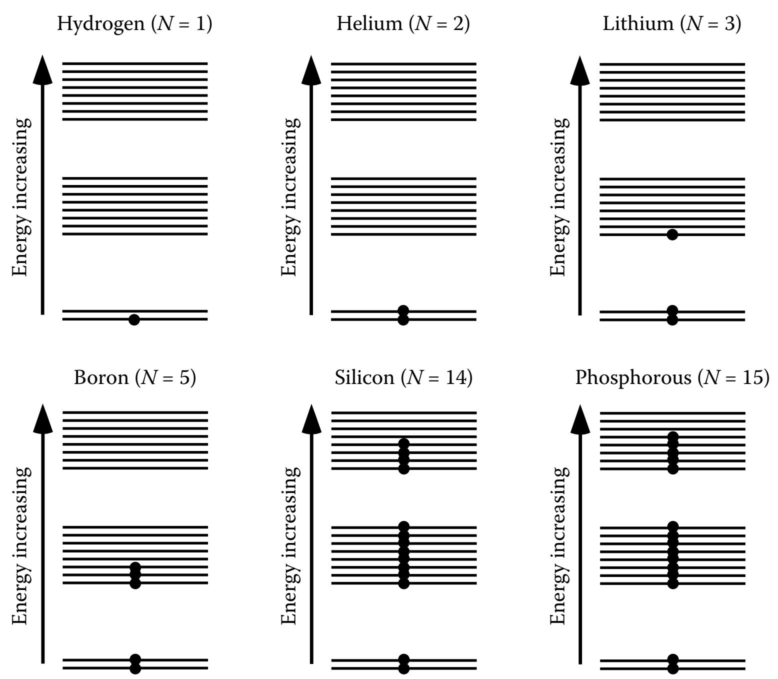


FIGURE 9.19 Energy-level diagrams for some atoms. Although each diagram is drawn with the same spacing between energy levels, there are actually different spacings for different atoms.

than its third electron. Silicon ($N = 14$) and phosphorous ($N = 15$) are important atoms for semiconductors, and their highest-energy electrons are in the third energy shell. A way to think of each diagram in Figure 9.19 is as a high-rise building: each level is a floor of the building, which may be occupied or not, as indicated by a room light viewed from outside.

What are typical values of the energies of the atomic levels? This will be useful later when we discuss lasers and light detectors in the context of optical communication. As an example, in hydrogen, the difference of energies between the lowest shell and the second-lowest shell is about 1.6×10^{-18} joules (J), or 1.6 attojoules (aJ). According to the metric system, 1 aJ equals 10^{-18} J. This is a very small energy, reflecting the fact that atoms are microscopic objects. It seems astonishing that even differences between such small energies can be easily observed (e.g., in the colors of light in the spectrum of a hydrogen lamp).

REAL-WORLD EXAMPLE 9.1: FLUORESCENT LAMPS

The liquid-crystal display (LCD) screen in a laptop computer is illuminated from within the computer. What type of light source is inside, and why is this particular source used? Laptop designers want a light source that is efficient, consumes (or converts) little electrical energy from the battery, and generates as little heat as possible. Two types of light sources could satisfy these requirements—light-emitting diodes (LEDs) and fluorescent lamps. At present, most laptops use fluorescent lamps, because these are cheaper than LEDs to produce. This is a much better choice than incandescent bulbs, which heat up and waste a lot of energy, generating invisible infrared radiation rather than visible light.

A fluorescent lamp is closely related to the atomic-vapor lamps that we discussed earlier in In-Depth Look 5.2. **Figure 9.20** shows an oscillating voltage source, which causes electric current to flow through a gas mixture containing several types of atoms, typically mercury and argon. The electrons making up the current collide with the mercury atoms, exciting the electrons inside these atoms to higher-energy shells. After a brief time, those electrons drop down to a lower energy level, giving off light of various sharply defined colors, primarily ultraviolet (UV). To alter the atomic lamp so that it gives off white light, the manufacturer coats the inner walls of the glass tube with a special substance called a phosphor. This substance is the same as glow-in-the-dark, or fluorescent, paint. The phosphor absorbs the UV light, and re-emits this energy as white light, that is, light containing all visible colors. Fluorescent lamps are typically about 5 times more efficient than incandescent bulbs in converting electrical energy into visible light energy.

How does electric current flow through a gas? Normally the atoms in a gas, such as air, are electrically neutral; that is, each atom has zero net charge and there are no electrons roaming freely around in the gas. In such a situation, a gas is a very good insulator—if a moderate voltage is applied across a region of gas, no current will flow. To make a gas into a conductor, it must be ionized. This means that many of the atoms must be converted into ions by removing one or more electrons from each atom, leaving it positively charged. Ionized gas is called a plasma. The electrons that were removed can flow freely through the plasma if a voltage is applied across it. The positively charged atomic ions can also move—in the direction opposite to that of the electrons—and thereby can also carry current. Finally, any electrons that are newly introduced into the plasma from a negatively charged metal electrode can flow through the gas to another positively charged electrode.

Before a fluorescent lamp is turned on, the gas is neutral, so even a medium-sized voltage would not create the current needed to light the bulb. Therefore, when the lamp is first turned on, a control circuit applies a very high voltage (several hundred volts) for a

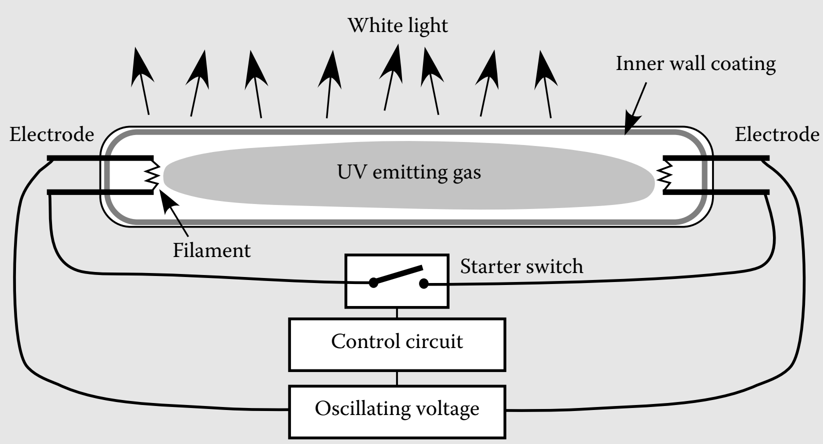


FIGURE 9.20 Fluorescent lamp.

brief instant to the electrodes, ionizing the gas and making a plasma, which then conducts current. The control circuit also momentarily closes a starter switch, which causes current to flow through thin wire filaments, which form the two electrodes. The filaments heat to very high temperature, aiding the emission of electrons from the filaments into the plasma. Once the lamp has been started, the starter switch is opened, because the plasma can now sustain itself without external heating of the filaments. This type of operation is used for room lighting, where fairly high powers are needed.

Most laptop computers use a thin, straight fluorescent lamp to illuminate the LCD screen from behind, in an arrangement called backlighting. The operation of LCDs was discussed in Real-World Example 7.3. To avoid generating too much heat in the laptop, a so-called cold cathode lamp is used. That is, without heating the filament to a high temperature, small lamps can be operated at sufficient power to illuminate an LCD screen.

9.7 ELECTRICAL PROPERTIES OF MATERIALS

The physical properties of atoms are what make the elements useful for different purposes. Iron is a strong metal that rusts easily, gold is a weak metal that resists rust, copper is an excellent electrical conductor, and magnesium is a soft metal that burns easily. The number and arrangement of the outer-shell electrons determine the physical properties of the elements. The inner-shell electrons are tightly bound to the nucleus and can do little.

For our purposes in discussing the basis of computers, the most important property is ***electrical conductivity***. Recall from Chapter 5 that electrical conductivity is the ability for electrons to flow through a certain material when pushed by an electric force associated with a voltage. Materials are classified as one of the following:

- ***Conductors*** (metals)—materials with high conductivity
- ***Insulators*** (diamond, quartz, glass, some ceramics)—materials with nearly zero conductivity
- ***Semiconductors*** (silicon)—materials with small conductivity, which is controllable

To understand why high electrical conductivity arises in some materials but not others, we need to understand the nature of the electron energy states in crystals and other solids. The behavior of electrons in crystals is quite different than in isolated atoms, in that each electron moves near several nuclei, rather than near just one nucleus.

A crystal is composed of a regular three-dimensional array of atoms. **Figure 9.21** shows a small region of a lithium ($N = 3$) crystal, with each small circle representing a

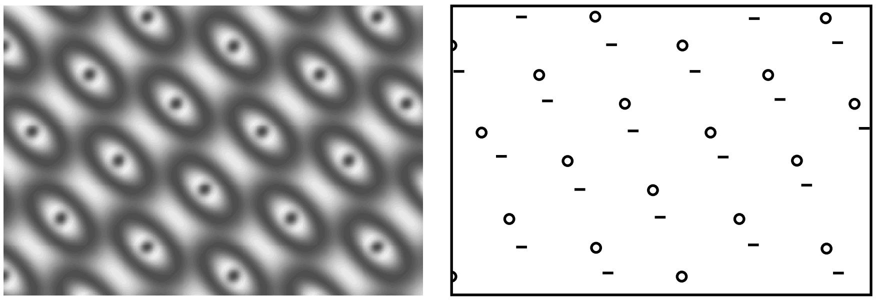


FIGURE 9.21 Crystal structure with nuclei plus inner electrons (circles), and electrons (dashes).

nucleus along with its two inner electrons. Each oval-shaped cloud represents an outer-shell electron in a smeared-out orbit. We are only concerned with the electrons in the outermost shell, because they determine the electrical properties. In the right side of the figure, for simplicity, we represent each nucleus with its two inner electrons by a small circle and each outer-shell electron by a dash, or minus sign.

In Chapter 5, it was stated that electrons move easily between objects, whereas protons do not. The reason for this is that the protons are within the atomic nuclei, and these are bound tightly by the chemical bonding that holds the crystal together. In contrast, the outer-shell electrons are spread out in the crystal, with overlapping orbits, and in some materials can move through the crystal.

When a large number (N_A) of atoms assemble into a crystal, the number of electron states, (i.e., energy levels) is N_A times larger than for a single atom. In a typical crystal 1 centimeter on a side, the number of atoms is about 10^{22}. This is ten-thousand billion-billion atoms. In this crystal, each atom provides one set of states of the type shown above in Figure 9.18. Therefore, the crystal as a whole has 2×10^{22} states that correspond to the first shell. Likewise, the crystal has 8×10^{22} states that correspond to the second shell, etc. For each shell, the number of states is 10^{22} times larger than for a single atom. Imagine trying to draw an energy-level diagram with this many states. The states are so close together, that we can cannot draw a separate line for each; we can only draw continuous "bands" of energy. An ***energy band*** is a region of very closely spaced energy levels that are allowable for an electron in a crystal. For energies outside of the bands, electrons are forbidden; these regions are the ***energy gaps***.

Figure 9.22 shows the energy-level diagram for crystalline lithium. Energy bands are shown as boxes. Because there are far more electrons than we can draw, we use a schematic drawing using connected dots to represent electrons. In this way we can indicate if an energy band is filled or only partially filled. Each dot in this example represents 10^{22} electrons. The figure also shows on the right a cartoon picture of the energy bands, indicating that the energy within a band increases smoothly and continuously, but in the gaps no energy levels exist. An electron simply cannot have energy in one of the gaps. As before, there is no meaning to the horizontal axis.

THINK AGAIN

In Figure 9.22, which of the Quantum Principles explains that the electron in the second shell cannot lose energy and fall into the first shell?

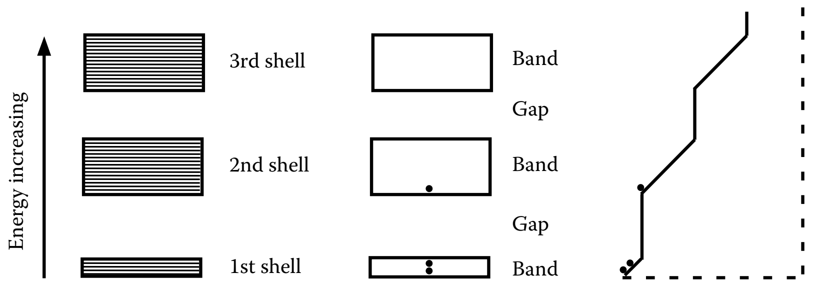


FIGURE 9.22 Energy-level diagram of crystalline lithium ($N = 3$). Each dot represents a large number (for example, 10^{22}) of electrons. The lowest-energy band is filled (completely occupied) with electrons, and the second band is partially filled, making solid lithium a metal. The right side illustrates that the energy of the electron states is continuously increasing, like a ramp as opposed to a staircase.

9.7.1 Conductors

Crystalline lithium is a metal. Recall that this means it has high electrical conductivity, which means that electrons can easily flow through it when pushed by a voltage. It is a conductor. Why is lithium, with three electrons per atom, a conductor? It is because the second lowest band is partially empty. Crystals that have partially empty energy bands are metals, and have high electrical conductivity, as we now explain.

Consider attaching two wires to either end of a solid piece of lithium and attaching the wires to a battery, as shown in **Figure 9.23**. Electrons will flow from one side of the crystal to the other because lithium is highly conducting. Under the influence of the battery's voltage, electrons feel a force, and they accelerate; their speed increases and they move through the crystal to the other side. To do this, each electron must gain some energy when it accelerates. Recall that an electron at rest has zero kinetic energy, whereas a moving electron has nonzero kinetic energy. Notice that the crystal remains neutral at all times, because for each electron that enters it at the negative side, one departs from the positive side. There is no buildup of extra electrons.

In terms of the energy-level diagram, the acceleration is visualized as follows. Each electron in the partially empty band can gradually gain some energy, upon which it gradually goes "up" the vertical energy axis in the diagram, as indicated by the arrow in **Figure 9.24**. In contrast, the voltage cannot accelerate electrons that are in the lower, filled band. This is because the small voltages used (up to about 100 V) cannot impart enough energy for them to "jump the gap" and go into the second shell. The point is

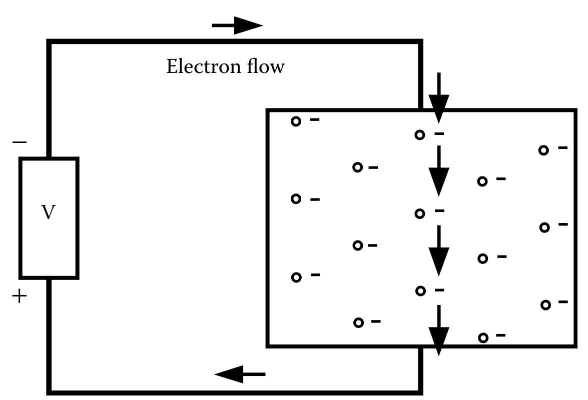


FIGURE 9.23 Electrons accelerating and moving through a lithium crystal.

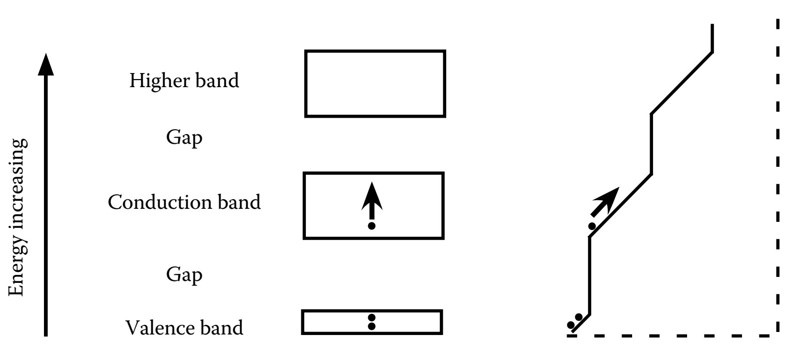


FIGURE 9.24 Outer-shell electrons in a metal accelerating under the influence of a small voltage. Inner-shell electrons (those in the lower, filled band) cannot accelerate.

that electrons cannot accelerate gradually through the forbidden gap energies. They cannot gradually gain energy and are therefore fixed with the energy they originally had. Also, electrons cannot accelerate within the lowest band. The Exclusion Principle prevents this, because if acceleration were to occur, there would be more than one electron in some of the states in the lower band. Electrons also repel one another by the electric force, but this is not the fundamental reason that no two electrons can be in the same state. Rather, it is a fundamental property of electrons. The Exclusion Principle "blocks" electrons from accelerating in a completely filled band. Physicists use the term ***valence band*** for the highest-energy band that is completely filled, and ***conduction band*** for the band just above the valence band. In the case of a metal, the conduction band is partially filled. Electrons in the conduction band are free to move, whereas electrons in the valance band are not.

THINK AGAIN

When explaining why a metal is a conductor, we should not say it is because there is a lot of unoccupied space for the electrons to flow; it is because there are many unoccupied energy levels into which the electrons can be accelerated.

THINK AGAIN

When current flows in a conductor, there are no extra electrons in the metal. If there were, the metal would have negative net charge, which it does not. Rather, electrons that are already in the metal before the voltage is connected are made to move through and out of the crystal by the voltage while being replenished by new electrons from the battery.

It is important to realize that we are looking at two different types of diagrams. Figure 9.21 is a drawing of the actual crystal in space, like a photograph taken through a very powerful microscope. An example of such an image of a real silicon crystal is shown in **Figure 9.25**. On the other hand, the energy-band diagrams, such as Figure 9.24, are not pictures in space. They are graphs showing the energies of electrons. Recall the comparison to a high-rise building, shown here in Figure 9.25. In these diagrams, the vertical location of each dot tells us the energy of each electron in the atom, just as the vertical position of a lighted window in the building could tell us what floor level a person is on.

9.7.2 Insulators

~~Diamond~~, quartz, and glass are insulators, meaning they have very low electrical conductivity. This arises from the way the energy bands are filled, or not filled, in these materials. Insulators have energy-level diagrams as shown in **Figure 9.26**. The two lower-energy bands are completely occupied with electrons. There is a large gap between the highest filled band and the next empty band. By large, we mean approximately 0.5 aJ or larger. When a voltage (not too great) is applied across an insulator, electrons cannot accelerate, because there are no empty energy levels immediately above the highest occupied energy level. Therefore no electrons can move or flow. Again, the Exclusion Principle "blocks" the electrons from accelerating in a completely

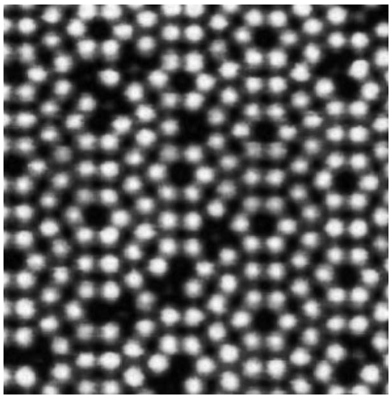
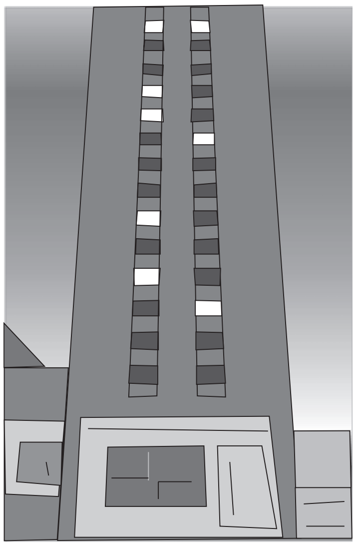



FIGURE 9.25 A laboratory image of the surface of a silicon crystal, revealing atoms forming a regular pattern, along with some "defects" where atoms are missing. This image is taken, not with a regular microscope, but by slowly dragging the tip of a tiny needle across the crystal's surface and recording the force felt at each location. Lights in the windows of a high-rise building indicate which floors are occupied. (Silicon image by Juergen Koeble. Courtesy of Omicron NanoTechnology, Germany.)

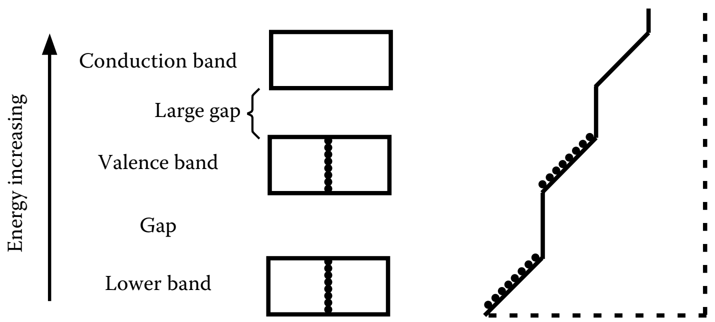


FIGURE 9.26 Every energy band of an electrical insulator is either all filled or all empty. Electrons cannot accelerate when voltage is applied.

filled band. Note that if too large a voltage (e.g., greater than 10^6 V) is put across an insulator, the crystal structure can be damaged, allowing current to flow. This "breakdown" behavior is normally not useful for operating electronics.

Diamond and quartz are crystals. Although glass is a noncrystalline solid, its energy diagram looks similar to that shown in the figure, explaining why it also is an insulator.

9.7.3 Semiconductors

The most useful semiconductor is the silicon crystal. **Figure 9.27** shows the structure of a silicon (Si) crystal. Each circle represents a Si atom nucleus plus all inner-shell electrons. As we can see by referring to Figure 9.19, the Si atom has four outer-shell electrons. In Figure 9.27, these electrons are shown as four minus signs, pointing away from each Si nucleus. Because the atoms are close together, the orbits on different atoms overlap, and there are eight electrons close to each atom.

A Si crystal is a semiconductor, meaning it has low, but not zero, electrical conductivity. A semiconductor has small conductivity because it has a small energy gap just

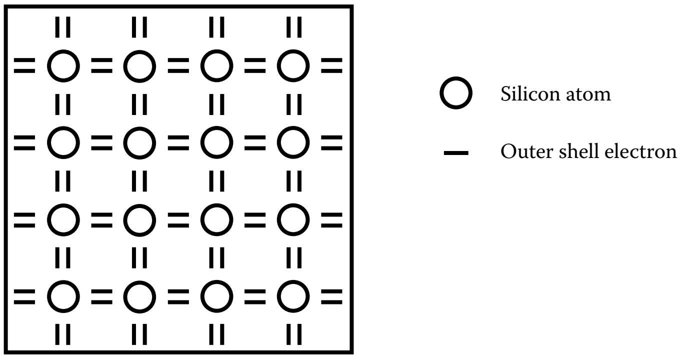


FIGURE 9.27 A silicon crystal is made of a regular array of Si atoms, each with four outer-shell electrons. Each outer-shell electron is indicated by a dash (minus sign).

above the highest filled band, as shown in **Figure 9.28**. The values of semiconductor band gaps fall in the range of 0.01–0.5 aJ. By looking at the energy-level diagram for a single Si atom in Figure 9.19, one would not expect that such a gap would be present in the Si crystal, but experiments show that there is a small gap, nevertheless. Although the gap is correctly predicted by quantum theory, for our purposes the existence of the small gap is more important than the cause of the gap. In-Depth Look 9.2 explains the physical origin of the gap.

IN-DEPTH LOOK 9.2: ORIGIN OF THE ENERGY GAP IN SILICON CRYSTALS

The small energy gap in Si crystals is explained as follows. As shown in Figure 9.27, in a crystal the atoms are packed closely together, so the orbits on different atoms overlap. This means that there are eight electrons close to each atom. Therefore, from the point of view of each Si atom, it "feels" as though its third energy shell is filled with the maximum eight electrons. If any extra electrons are put into the crystal, they have a hard time finding a "place" to go, because it seems as though all orbits are filled. For this reason, it takes a somewhat higher energy to place an additional electron into the Si crystal than would be required to place the same electron into an isolated Si atom. Therefore, if a small voltage is applied across the crystal, electrons are not able to move freely and there is no conduction (at low temperature). This fact is reflected by the existence of a small energy gap, as shown in Figure 9.28. The overlapping of electron orbits, which gives rise to the small energy gap, also causes chemical bonding, which holds the Si crystal tightly together.

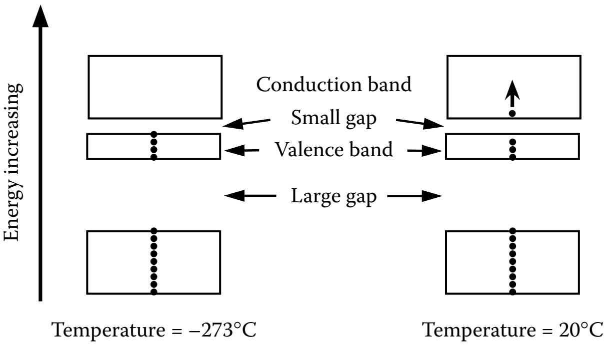


FIGURE 9.28 At absolute zero temperature (–273°C), the energy bands of a semiconductor are either completely filled or completely empty. Electrons cannot accelerate when a voltage is applied. At room temperature (20°C), the thermal energy in the crystal raises some electrons to the band above the small gap, making the crystal a conductor.

When a voltage is put across a semiconductor at room temperature, a small current flows. Why? It might appear that no electrons could be accelerated, because of the presence of the gap. This would be true at extremely low temperatures near absolute zero (–273°C, or 0 K). No electron would have enough energy to jump the gap. But, because the gap is small, if the crystal is at room temperature there are a few electrons that are not in the lowest possible energy levels. This is because the thermal-energy in the crystal gives some of the electrons enough energy to jump the gap and go into the previously unoccupied upper band. It is interesting that thermal energy can cause an electron to jump the gap and go to a higher energy band, but voltage from an applied battery cannot do this. We will clarify this in Chapter 12. (It turns out that thermal energy can also produce infrared light, and it is this that actually causes the electrons to jump the gap.)

With this insight, we can update the rule given earlier in the chapter as:

State occupation in rule: At very low temperature, an electron goes into the lowest unoccupied state available. At higher temperatures, such as room temperature, a relatively small number of electrons can gain enough thermal energy to go into a higher energy state, or band.

The important difference between an insulator and a semiconductor is the size of the gap separating the highest-energy filled band (valence band) and the next higher band (conduction band). Because this gap is quite small in a semiconductor, there is a small temperature-induced current. The smallness of the gap also gives us the opportunity to modify the properties of semiconductors by adding small amounts of other elements into the crystal. This is a crucial technique for making electronic circuits with semiconductors, and is the topic of the next chapter.

THINK AGAIN

When explaining why a warm semiconductor can conduct electrical current, we should not say it is because there is a lot of unoccupied “space” for the electrons to flow; it is because there are many unoccupied *energy levels*, into which the electrons can be accelerated.

THINK AGAIN

Keep in mind that some crystals are conductors (e.g., gold and copper), whereas other crystals are insulators (diamond, quartz). In addition, some noncrystalline solids are insulators (glass), whereas some other noncrystalline solids are conductors (some specialized plastics).

IN-DEPTH LOOK 9.3: ATOMIC NATURE OF MAGNETIC DOMAINS

In Chapter 5 we discussed magnetic materials. In a magnetized piece of iron are small magnetic domains, which act like tiny permanent magnets. If you take any piece of nonmagnetized iron and grind it into small microscopic grains, you will find that each grain is a tiny magnet. They will be attracted to any nonmagnetic piece of iron by the induced-magnetization effect described in In-Depth Look 5.4.

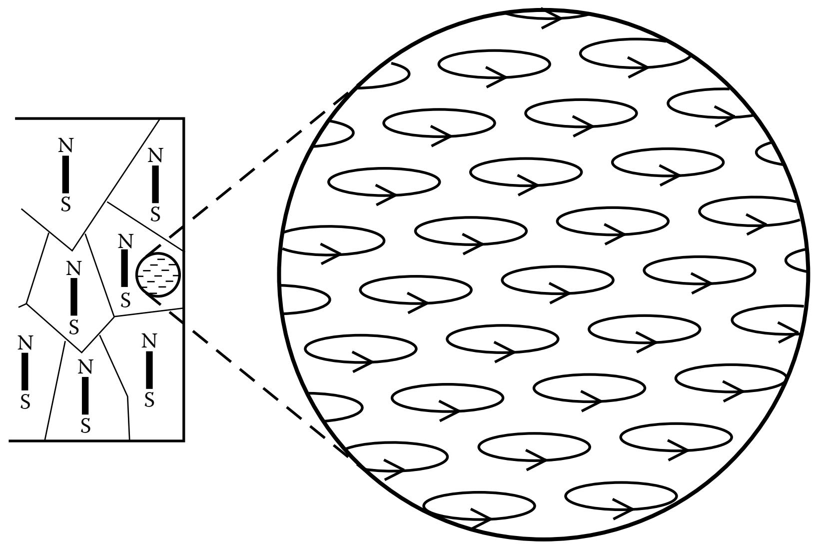


FIGURE 9.29 Magnified view of the interior of a single domain of iron. Each atom is represented as a tiny current loop.

Consider a domain made up of a million atoms. You might wonder, "Why is this tiny piece of metal a magnet?" If you keep grinding this tiny speck of metal smaller and smaller, so you end up with individual atoms, you will find that each iron atom is by itself a magnet! This is not true of, say, aluminum atoms; there is something special about iron. Each iron atom can be viewed as containing an atom-sized current loop. **Figure 9.29** shows an imagined blow-up of the interior of a domain of iron. Each atom is represented as a tiny current loop. This is a reasonable picture, because atoms are made of electrons orbiting around a central point. The electrons carry an electric current around a loop-shaped path. According to Ampère's law, electric current moving around a loop creates a magnetic field. Because all of the atomic current loops are aligned in same direction, their summation creates a stronger magnetic field than would otherwise be the case.

SUMMARY AND LOOK FORWARD

Atoms are nature's building blocks, and their internal structure determines the properties of conductors, insulators, and semiconductors—the materials in computer circuits. Surprisingly, when physicists discovered the physics of atoms and electrons in the early twentieth century, they found that atom-sized objects obey different physical laws than do large objects. They found that electrons cannot correctly be thought of as tiny particles, because they have wave-like as well as particle-like properties. An electron has no definite location. It is more meaningful to talk about the likelihood of finding the electron in various selected regions than to talk about its actual position. As a consequence of its wave-like properties, an electron in an atom must have certain discrete energies, described by groups of orbits organized into energy shells. The energy is quantized.

Each element has a distinct number of electrons—its atomic number, *N*. The Exclusion Principle says that at most two electrons can occupy any orbit, and if two electrons share an orbit, they must have opposite directions of spin. Each electron energy shell has a maximum number of electrons that it can house (2, 8, 8, 18, 18, etc.).

The electrons in the outer shells of each atom in crystals and other solids are close to neighboring atoms. The number of electrons in the highest-energy occupied shell determines the physical properties of solids. Electrical conductivity is the ability for electrons to flow through a material when pushed by an electric force associated with a voltage. Materials are classified as one of the following: insulators, semiconductors, or conductors, depending on how well they conduct. Using the quantum principles, we can predict which crystalline elements are conducting or insulating.

- Metals are crystals that have their highest-energy occupied band partially empty. This makes them electrical conductors, since the electrons can be accelerated by an externally applied voltage.
- Insulators are crystals that have all of their occupied shells completely filled, with a large energy gap between the highest filled shell and the next lowest shell. They do not conduct electrical current, because the Exclusion Principle prevents electrons from accelerating into already-occupied energy levels.
- Semiconductors are crystals that have all of the occupied shells completely filled, with a small energy gap between the highest filled shell and the next higher shell. At low temperature semiconductors do not conduct electrical current, because the Exclusion Principle prevents electrons from accelerating into already-occupied energy levels. At room temperature they can conduct, because some electrons are boosted into higher, non-filled shells by thermal energy in the crystal.

Where is this discussion leading in our quest to understand computers and the Internet? We know vastly more about electrons and atoms than was understood only four generations ago. In parallel with this intense scientific effort, engineers have made astounding progress in applying the discovered basic knowledge to building electronic circuitry that is small, fast, and energy efficient. Our next step will be to study how the atomic nature of crystals is used to build electronic switches and other devices that make up computer logic circuits and electronic memory.

SOCIAL IMPACTS: SCIENCE, MYSTICISM, AND PSEUDO-SCIENCE

> We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.
>
> **Isaac Newton (1687)**

> Man seeks to form for himself, in whatever manner is suitable for him, a simplified and lucid image of the world, and so to overcome the world of experience.
>
> **Albert Einstein (1937)**

> What evidence would it take to prove your beliefs wrong?
>
> **Steven Dutch (2007)**

Some years ago, a man came to my office at the university and announced that he had invented a machine that produced energy using no fuel or other external source of energy. He said it involved "chaos" and extracted energy from the rotations of magnets in some mechanical contraption, and he wanted to discuss the physics behind it. I politely said that if it were real, then I would like to see it and try to confirm its operation. I was not much worried that he would take up my offer; he replied that it was in his barn in another town, and in any case, he needed to keep the details secret. I said in that case, "I can't help you." He left. I believe that this man was practicing pseudo-science. He used scientific terms such as energy, magnetism, and chaos and said he had done experiments that supported his claims. Maybe he had, maybe he had not. Without independent testing, there is no way to know.

Pseudo-science means *fake science*. It is defined as any kind of intellectual or experimental exploration that is claimed to be scientific but actually does not follow the widely agreed upon methods of science. In Chapter 1, Section 1.4 we discussed the scientific method, which is the process by which repeated observations of physical events allow people to discover regular rules, laws, or principles about such events. The scientific method necessarily involves making quantitative measurements to represent the results of the observations being reported. A "good" scientific theory is a theory about physical events that has been well tested and is seen not to make false predictions.

To be believable, the results of observations must be repeatable. Any person following the procedure described should be able to observe the same or similar results. Therefore, if a person refuses to tell anybody else what procedure he or she used, then the results probably should not be called scientific. This applies to my office visitor.

An additional requirement is that for any theory to be scientific it must be testable. As well put by geologist Steven Dutch, "Refutability is one of the classic determinants of whether a theory can be called scientific." [1] That is, if there is no possible test or evidence that would convince a believer that his or her favorite hypothesis is wrong, then that idea can not be called scientific.

It is difficult to mark precisely the boundary between science and pseudo-science. This is called the demarcation problem in the philosophy of science. For example, it seems possible to apply the scientific method to the question of unidentified "flying" objects, or UFOs. There are certainly some researchers (mostly amateur) who do apply the scientific method to this question. But, it is apparent that no definitive conclusions that could be called laws or principles have emerged to help us understand why so many people report unidentified objects and to what these observations correspond. Pseudo-science enters at this point—in the absence of any confirmed scientific results—and exploits the gullibility of some people who cannot distinguish, or do not want to distinguish, between real science and pseudo-science.

Peoples' gullibility perhaps comes from their need, which all people have, as Einstein says above, to "form for himself, in whatever manner is suitable for him, a simplified and lucid image of the world, and so to overcome the world of experience." That is, to be human is to be curious and to try to understand. The need to understand can lead to self-delusion. A goal of science is to help people avoid gullibility and self-delusion. (This discussion has nothing to do with whether one has religious or spiritual beliefs, which are independent of science, according to many careful thinkers. If, on the other hand, people try to invoke scientific methods to address fundamental religious questions, then most likely it turns into pseudo-science.)

Although there may be no sharp line between science and pseudo-science, various thinkers have drawn up lists of "warning signs," which indicate a high likelihood that pseudo-science is being presented. Most pseudo-science claims do not suffer from all or even most of these, but when you see more than one cropping up, beware.

Ten Warning Signs for Detecting Pseudo-Science

1. Pseudo-science usually begins with an idea based on wishful thinking, and then claims to have found evidence supporting it. (Would it not be great if there were a source of unlimited, free energy?)
2. Pseudo-scientists usually ignore all evidence that might refute their claims.
3. Pseudo-scientists do not believe they need to give examples of testable predictions that logically follow from their claims.
4. Pseudo-scientists do not carry out careful, repeatable experiments and share the results in a way that would enable others to repeat them as a further test.
5. Pseudo-science is often based on a claim that certain tenets of established science are wrong, not realizing that if the claim being made were true, it would undermine hundreds of other well established laws and tested theories. Established science is an interconnected web of knowledge, and changing major pillars of it is not so easy.
6. Pseudo-scientists often work alone or in isolation, with no one to check their work.
7. Pseudo-scientists often claim that some powerful organization, such as the government or the auto industry, is trying to suppress or unfairly criticize their work.
8. Pseudo-scientists often use technical-sounding words like energy or vibration, without clearly defining what they mean.
9. Pseudo-scientists often cite alleged "experts," who turn out either to be pseudo-scientists themselves or legitimate scientists with no expertise in the field that is most relevant.
10. Pseudo-scientists often use an argument that appeals to the "unknown," rather than to known scientific laws and principles. They might argue that because no one has explained some phenomenon (such as the origin of life on Earth), their harebrained ideas may be valid.

Of course, scientists can be wrong, too. In fact, admitting that one is wrong when evidence points in that direction is a hallmark of a good scientist—but not of a pseudo-scientist.

Unfortunately, the media often report stories about pseudo-science as if it were real science. This should be intolerable, but, "Hey! —It sells advertising space." Rather than laughing it off, educated readers would do us a favor by writing rebuttals to nonsense when it appears in legitimate media.

An example of a broad area of pseudo-science is the purported connection between quantum physics and spirituality or mysticism. As a subject of "pop-philosophical" speculation, "quantum spirituality" can be a lot of fun, but at its worst, it exploits an appeal to the unknown, rather than to known scientific laws and principles (see warning 10 above). Claims made that spirituality and quantum physics are somehow connected miseducates the public about the fascinating subject of quantum physics. The following quote sets the stage for some of the present confusion:

> The discovery of quantum mechanics is one of the greatest achievements of the human race, but it is also one of the most difficult for the human mind to grasp … It violates our intuition—or rather, our intuition has been built up in a way that ignores quantum-mechanical behavior.
>
> **—Murray Gell-Mann (1994)**

Gell-Mann is a Nobel-winning physicist and yet even he finds some of quantum physics hard to grasp and in a sense mysterious. Pseudo-scientists will point out that consciousness and spirituality are also hard to grasp and mysterious. Therefore, they will argue, "Ah-hah! These topics must be talking about the same thing!" This, of course, is a fallacy. Two mysteries need not be related. In particular, no repeatable, verifiable experiments have been conducted that convince the scientific mainstream that there is any connection in this case. Although I feel that it would be nice if there were a connection, I must recognize that science is plodding, and it slowly arrives at deep and true insights. One cannot take shortcuts via wishful thinking. This is well explained in an article in *What is Enlightenment* magazine [2].

It seems that the majority of quantum physicists see no need for the injection of human consciousness into the mathematical formalisms that form the basis of their science. As Ken Wilber pointed out 20 years ago, even the founding fathers of quantum physics/mechanics—Max Planck, Niels Bohr, Werner Heisenberg, Erwin Schrodinger, Sir Arthur Eddington, etc. (who were all self-proclaimed mystics) strongly rejected the notion that mysticism and physics were describing the same realm. The attempt to unify them is, in the words of Planck, "founded on a misunderstanding, or, more precisely, on a confusion of the images of religion with scientific statements."

By the way, the man who came to my university office 18 years ago never returned, and the world never did hear of his self-proclaimed revolutionary energy-creating "chaos" device.

REFERENCES

1. S. Dutch, at the University of Wisconsin-Green Bay, http://www.uwgb.edu/DutchS/index.html. He also writes, "There is no single Scientific Method. Rather, I believe we must think of a battery of methods that have proven useful. Testing of scientific ideas can include the classical experimental method, replication, attempted refutation, prediction, modeling, inference, deduction, induction and logical analysis."
2. Huston, Tom. "Taking the Quantum Leap... Too Far? Not Just a Movie Review of What the Bleep Do We Know!?" *What is Enlightenment*, October–December, 2004.

SOURCES

The following sources discuss how to distinguish pseudo-science from science:

Coker, Rory. "Distinguishing Science and Pseudoscience," *Quackwatch* (2001). http://www.quackwatch.org/01QuackeryRelatedTopics/pseudo.html.

Gardner, Martin. *Did Adam and Eve Have Navels?: Discourses on Reflexology, Numerology, Urine Therapy, and Other Dubious Subjects.* New York: W.W. Norton & Company, 2000.

Hines, Terence. *Pseudoscience and the Paranormal.* Amherst, MA: Prometheus, 1988.

Park, Robert L. *The Seven Warning Signs of Bogus Science* (January 31, 2003). *The Chronicle Review*, 49, no. 21, B20. http://chronicle.com/free/v49/i21/21b02001.htm.

Sagan, Carl. *The Demon-Haunted World—Science as a Candle in the Dark.* New York: Random House, 1995.

Schick, Theodore, Jr., Lewis Vaughn. *How to Think about Weird Things: Critical Thinking for a New Age.* Mountain View, CA: Mayfield, 1995.

Shermer, Michael. *The Borderlands of Science: Where Sense Meets Nonsense.* Oxford, UK: Oxford University Press, 2001.

Simanek, Donald E. "What is Science? What is Pseudoscience?" (2005). http://www.lhup.edu/~dsimanek/pseudo/scipseud.htm.

Wilber, Ken. *Quantum Questions.* Boston: Shambhala, 2001.

The image in Figure 9.11 appeared in Ritsch, S., et al., *Philosophical Magazine Letters,* 78, 67–75, 1998. With permission of Taylor & Francis.

SUGGESTED READING

Popular-level discussions of the experiments carried out during 1900–1927 that led to our present understanding of quantum theory are given in:

Asimov, Isaac. *The History of Physics*. New York: Walker, 1984.
Gribbon, John. *In Search of Schrödinger's Cat*. New York: Bantam, 1984.
Motz, L., and J. H. Weaver. *The Story of Physics.* New York: Avon Books, 1989.

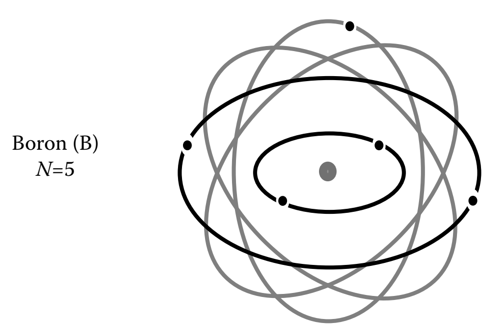
KEY TERMS

Atom
Atomic number
Conduction band
Conductor
Crystal
Domain
Electrical conductivity
Electromagnetic
Electron
Element
Energy band
Energy gap
Energy shell
Exclusion Principle
Glass
Insulator
Metal
Neutron
Nucleus
Orbit
Particle
Photon
Proton
Quantization
Quantum theory
Semiconductor
Spectrum
State
Valence band
Wave

ANSWERS TO QUICK QUESTIONS

Q9.1 A neutral atom with 37 protons also has 37 electrons.

Q9.2 The boron atom has $N = 5$. The fifth electron goes into one of the unoccupied orbits having the lowest energy in the second shell.



EXERCISES AND PROBLEMS

Exercises

E9.1 Explain the various ways in which real atoms are different from a model analogous to the solar system (planets orbiting the Sun). What behaviors of electrons are similar to and/or different from human-scale objects such as baseballs or planets?

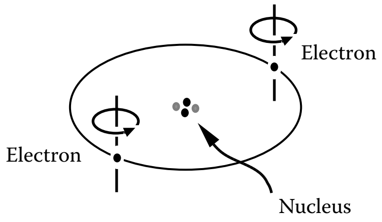
E9.2 Explain the concept of a particle in physics. Give examples of physical entities that can be considered particles and examples of physical entities that cannot.

E9.3 An element has 33 electrons. How many protons does it have, assuming the atom is overall neutral? What element is this? What is the mass of one atom of this element? What can you say about the number of neutrons the atom has?

E9.4 If extra electrons are added to or removed from a neutral atom, it is then called an ion. If two of the electrons are removed from the atom in E9.3, what will be the net charge of the remaining ion?

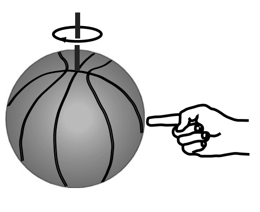
E9.5 If two ions of the type described in E9.4 come near each other, will there be a repulsive or an attractive force between them?

E9.6 What is wrong in this picture of an atom?



E9.7 Go online to http://nobelprize.org and transcribe the citation for Niels Bohr's Nobel Prize. From his biography there, to what three countries did he flee during the Nazi occupation of his home country, Denmark?

E9.8 A basketball is rotating (spinning) at 3 revolutions per second around the axis shown as a black line. In 5 sec, how many black seam lines pass a fixed point indicated by the pointing finger? What is the frequency of seam lines per second passing the pointing finger? Discuss a possible analogy between the basketball and the electron wave in an atom.



E9.9 Think of three everyday examples of physical quantities (not mentioned in the text) that are quantized and three quantities that are continuous.

E9.10 Think of an amusing analogy to illustrate the Exclusion Principle that could be used for teaching the concept to middle school students.

E9.11 (a) Draw the occupied orbits (as circles or ellipses) for the oxygen atom, showing the distinctions between shell radii and the direction of spin of each electron.
(b) Draw the occupied orbits for the scandium (Sc) atom.

E9.12 (a) Draw the energy-level diagrams for the following elements: carbon (C), nitrogen (N), oxygen (O), sodium (Na), and aluminum (Al).
(b) What prevents the highest-energy electron in a sodium atom from being in the second energy shell?

E9.13 There exists a minimum energy level in an atom, below which an electron's energy cannot be. Explain why this fact is incompatible with the classical theory based on Newton's and Maxwell's theories. *Hint*: An oscillating electric charge always emits or radiates EM waves. What would this energy emission do to the orbit of an electron according to classical concepts?

E9.14 How is the concept of an electron state related to the concepts of orbit and of spin?

E9.15 (a) Use and cite some of the quantum principles to explain in some detail why solid beryllium (Be) is a metal and why it conducts current when a small voltage is applied. Draw sketches of the energy bands and explain where (in energy, not location) the electrons are in these bands and the effect of an applied voltage.
(b) Likewise, use some of the quantum principles, plus a drawing of the bands, to explain in some detail why solid Argon (Ar) is an insulator.

E9.16 The following solids have band gap values given in parentheses. Determine whether each solid is a conductor, a semiconductor, or an insulator.

(a) SiO_2 (1.44 aJ) [glass]
(b) C (0.86 aJ) [diamond]
(c) Si_3N_4 (0.80 aJ) [silicon nitride]
(d) GaAs (0.23 aJ) [gallium arsenide]
(e) Si (0.18 aJ) [silicon]
(f) InN (0.11 aJ) [indium nitride]
(g) Ge (0.10 aJ) [germanium]
(h) Al (0.0 aJ) [aluminum]
(i) Cu (0.0 aJ) [copper]

Problems

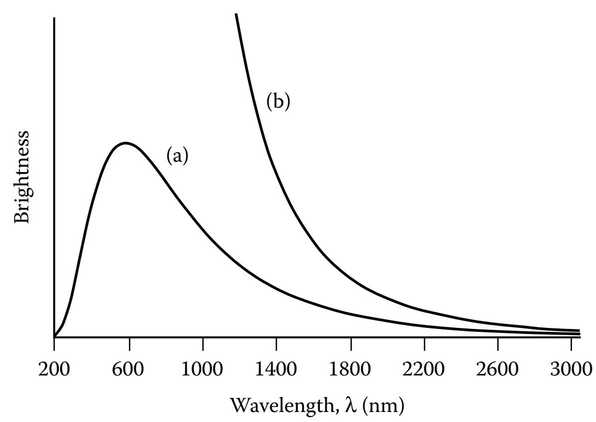
P9.1 Jakob Balmer's observations of the spectrum of light emitted by a hot hydrogen gas led him to a practical formula for calculating the frequencies of light corresponding to the spectral lines observed.

$$f_{Balmer} = (3.28992 \times 10^{15}\ \text{Hz}) \times \left(\frac{1}{4} - \frac{1}{n^2}\right)$$

The symbol n can equal any integer greater than or equal to 3; that is, $n = 3,4,5,\ldots$

Use Balmer's formula to calculate the frequency and the wavelength (in vacuum) of each of the spectral lines corresponding to $n = 3,4,5$. What part of the visible spectrum (i.e., what color) does each line fall into? Check your results against the spectrum of hydrogen shown in In-Depth Look 9.1.

P9.2 The figure below shows two graphs of the emission spectrum of light versus wavelength from a hot metal object at temperature 5,000K. One is the experimentally observed brightness or intensity of light colors. The other is an incorrect prediction based on Newton's and Maxwell's theories. From the discussion in the chapter, determine which curve is which, and explain your reasoning.



P9.3 Find a heavy rope or flexible chain and with one hand, hold it dangling down toward the ground. Whirl your hand around in a horizontal, circular motion to make the rope or chain whirl around. Observe that at certain rotation frequencies, distinct patterns occur on the rope. Describe in words and sketches at least three of these patterns and how they depend on the frequency at which you rotate the upper end. How is this analogous to quantization of electron waves?

P9.4 Bohr's theory, which we have not derived here, gives a formula for the energies of the electron shells in the H atom:

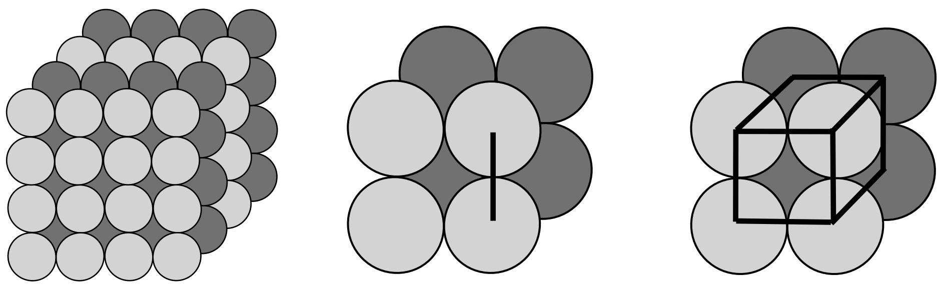
$$E_n = R \times \left(1 - \frac{1}{n^2}\right), \quad R = 2.1799 \times 10^{-18}\ \text{J}$$

R is a constant, and n is an integer labeling each energy shell. The lowest-energy shell (with energy defined to be zero) has $n = 1$, the second-lowest-energy shell has $n = 2$, etc. Calculate the energies of the first four energy shells in H, and give your answers in units of Joules and in attojoules.

P9.5 (a) Table 9.2 indicates that gallium (Ga) is a metal. Explain why.
(b) At very low temperature, argon (Ar) becomes a crystalline solid. Explain what would be the electrical conductivity (high, medium, or low) for solid argon and why.

P9.6 Not every crystal can be easily classified as a conductor, semiconductor, or insulator only on the basis of its atomic number and the number of electrons occupying its highest occupied shell. For example, diamond is a form of carbon, with four electrons in its outer shell, in which there is space in each atom for more electrons. Nevertheless, diamond is an insulator. Explain this behavior of diamond. *Hint*: Study the explanation in this chapter for why silicon crystals are semiconductors. There is a similar effect in diamond, only much stronger. Each carbon atom is bonded to four other carbons.

P9.7 The polonium (Po) atom has atomic number 84, and a mass 3.472×10^{-25}kg. The density of a particular crystal form, alpha-polonium, is 9,230 kg/m^3. The structure of this crystal is the simplest possible—the simple cubic lattice, shown below at left. In this arrangement, the atoms are stacked vertically and horizontally in square patterns. Assuming the atoms are tightly packed, so they are "touching," we conclude that each atom's diameter equals the distance between two adjacent atoms' centers, shown by the bold bars in the magnified drawings. The centers of any eight adjacent atoms form a cube, whose side length equals the single atom's diameter. Each atom can be circumscribed by one of these cubes. From this information, calculate the diameter of a polonium atom. Give your answer in both meters and in nanometers.



P9.8 At room temperature, a typical electron in a solid has an average energy of 0.004 aJ. In a silicon crystal, the band gap is 0.18 aJ. Explain, in light of these numbers but without any calculation, how room-temperature silicon (Si) can act as a weak conductor.

P9.9 (a) Use the Bohr formula given in P9.4 to write the formula for the difference of energies of the shell labeled by integer n_1 and another shell labeled by integer n_2.

(b) Compare your result to Balmer's formula given in P9.1. What does this comparison tell you about the relation between the energy difference between two levels and the frequencies of light emitted by the H atom?