CHAPTER 4
MODERN ATOMIC THEORY

> *To see a World in a Grain of Sand*
> *And a Heaven in a Wild Flower*
> *Hold Infinity in the palm of your hand*
> *And Eternity in an hour*
>
> William Blake (1757-1827)
>
> *Auguries of Innocence*

Scientists' attempts to understand the atom have led them into the unfamiliar world of the unimaginably small, where the rules of physics seem to be different from the rules in the world we can see and touch. Scientists explore this world through the use of mathematics. Perhaps this is similar to the way a writer uses poetry to express ideas and feelings beyond the reach of everyday language. Mathematics allows the scientist to explore beyond the boundaries of the world we can experience directly. Just as scholars then try to analyze the poems and share ideas about them in everyday language, scientists try to translate the mathematical description of the atom into words that more of us can understand. Although both kinds of translation are fated to fall short of capturing the fundamental truths of human nature and the physical world, the attempt is worthwhile for the occasional glimpse of those truths that it provides.

This chapter offers a brief, qualitative introduction to the mathematical description of electrons and describes the highly utilitarian model of atomic structure that chemists have constructed from it. Because we are reaching beyond the world of our senses, we should not be surprised that the model we create is uncertain and, when described in normal language, a bit vague. In spite of these limitations, however, you will return from your journey into the strange, new world of the extremely small with a useful tool for explaining and predicting the behavior of matter.

Because the modern description of the atom is closely tied to the concept of energy, we begin this chapter with an introduction to energy and its different forms.

Chemists try to "see" the structure of matter even more closely than can be seen in any photograph.

Review Skills

The presentation of information in this chapter assumes that you can already perform the tasks listed below. You can test your readiness to proceed by answering the Review Questions at the end of the chapter. This might also be a good time to read the Chapter Objectives, which precede the Review Questions.

- Describe the relationship between temperature and motion. (Section 3.1)
- Describe the nuclear model of the atom. (Section 3.4)

- Describe the similarities and differences between solids, liquids, and gases with reference to the particle nature of matter, the degree of motion of the particles, and the degree of attraction between the particles. (Section 3.1)

4.1 Energy

Energy…it makes things happen. To get an idea of the role energy plays in our lives, let's spend some time with John, a college student in one of the coastal towns in California. He wakes up in the morning to a beautiful sunny day and decides to take his chemistry book to the beach. Before leaving, he fries up some scrambled eggs, burns some toast, and pops a cup of day-old coffee in the microwave oven. After finishing his breakfast, he shoves his chemistry textbook into his backpack and jumps on his bike for the short ride to the seashore. Once at the beach, he reads two pages of his chemistry assignment, and despite the fascinating topic, gets drowsy and drops off to sleep. When he wakes up an hour later, he's real sorry that he forgot to put on his sunscreen. His painful sunburn drives him off the beach and back to his apartment to spend the rest of the day inside.
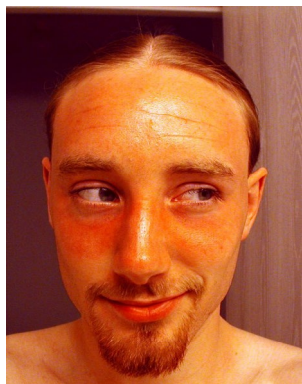
Radiant energy from the sun causes sunburn

All of John's actions required energy. It took energy to get out of bed, make breakfast, pedal to the beach, and (as you well know) read his chemistry book. John gets that energy from the chemical changes that his body induces in the food he eats. It took heat energy to cook his eggs and burn his toast. The radiant energy from microwaves raised the temperature of his coffee, and the radiant energy from the sun caused his sunburn.

All chemical changes are accompanied by energy changes. Some reactions, such as the combustion of methane (a component of natural gas) release energy. This is why natural gas can be used to heat our homes. Other reactions absorb energy. For example, when energy from the sun strikes oxygen molecules, O_2, in the Earth's atmosphere, some of the energy is absorbed by the molecules, causing them to break apart into separate atoms (Figure 4.1).

Figure 4.1
Some reactions absorb energy.

Energy from the sun

Some reactions absorb energy.

$$O_2(g) + energy \longrightarrow 2O(g)$$
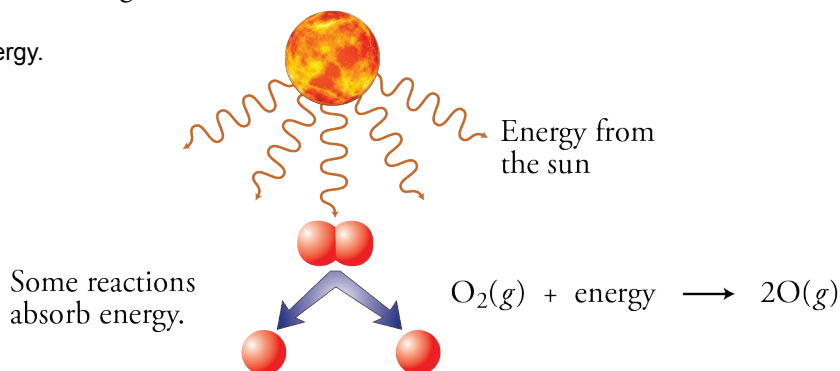
Before we can begin to explain the role that energy plays in these and other chemical reactions, we need to get a better understanding of what energy is and the different forms it can take.

You probably have a general sense of what energy is. When you get up in the morning after a good night's sleep, you feel that you have plenty of energy to get your day's work done. After a long day of studying chemistry, you might feel like you hardly have the energy necessary to drag yourself to bed. The main goal of this section is to give you a more specific, scientific understanding of energy.

The simplest definition of **energy** is that it is the capacity to do work. Work, in this context, may be defined as what is done to move an object against some sort of resistance. For example, when you push this book across a table, the work you do overcomes the resistance caused by the contact between the book and the table.

Likewise, when you lift this book, you do work to overcome the gravitational attraction that causes the book and the earth to resist being separated. When two oxygen atoms are linked together in a covalent bond, work must be done to separate them. Anything that has the capacity to do such work must, by definition, have energy (Figure 4.2).

Figure 4.2
Energy: the Capacity to Do Work
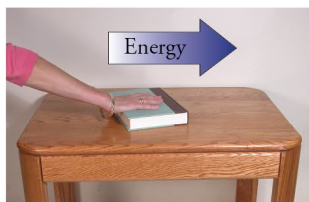
Energy is required to push a book across a table and overcome the resistance to movement due to friction.
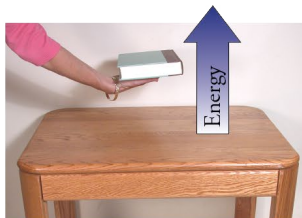
Energy is required to lift a book and overcome the resistance to movement due to gravity.
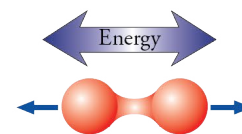
Energy is required to separate two atoms in a molecule and overcome the resistance to movement due to the chemical bond between them.

Kinetic Energy

It takes work to move a brick wall. A bulldozer moving at 20 miles per hour has the capacity to do this work, but when the same bulldozer is sitting still, it's not going to get the work done. The movement of the bulldozer gives it the capacity to do work, so this movement must be a form of energy. Any object that is in motion can collide with another object and move it, so any object in motion has the capacity to do work. This capacity to do work resulting from the motion of an object is called **kinetic energy, KE**.

The amount of an object's kinetic energy is related to its mass and its velocity. If two objects are moving at the same velocity, the one with the greater mass will have a greater capacity to do work and thus a greater kinetic energy. For example, a bulldozer moving at 20 miles per hour can do more work than a scooter moving at the same velocity. If these two objects were to collide with a brick wall, the bulldozer would do more of the work of moving the wall than the scooter.
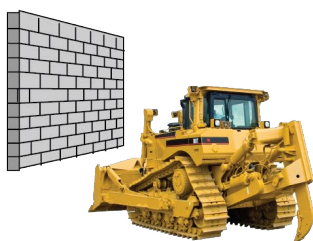
OBJECTIVE 2

If two objects have equal mass but different velocities, the one with the greater velocity has the greater kinetic energy. A bulldozer moving at 20 miles per hour can do more work than an identical bulldozer moving at 5 miles per hour (Figure 4.3).

OBJECTIVE 3

Figure 4.3
Factors that Affect Kinetic Energy
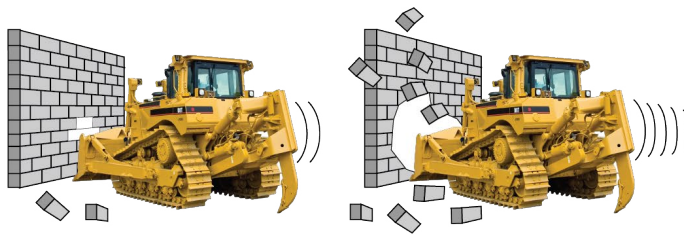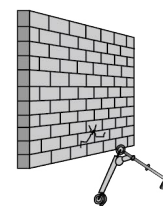
OBJECTIVE 2   OBJECTIVE 3

A stationary bulldozer does not have the capacity to do the work of moving a wall.

The faster moving bulldozer does more of the work of moving the wall. The faster an object moves, the more work it can do, and the more kinetic energy it has.

A scooter moving at the same velocity as a bulldozer will do less work and therefore has less energy.
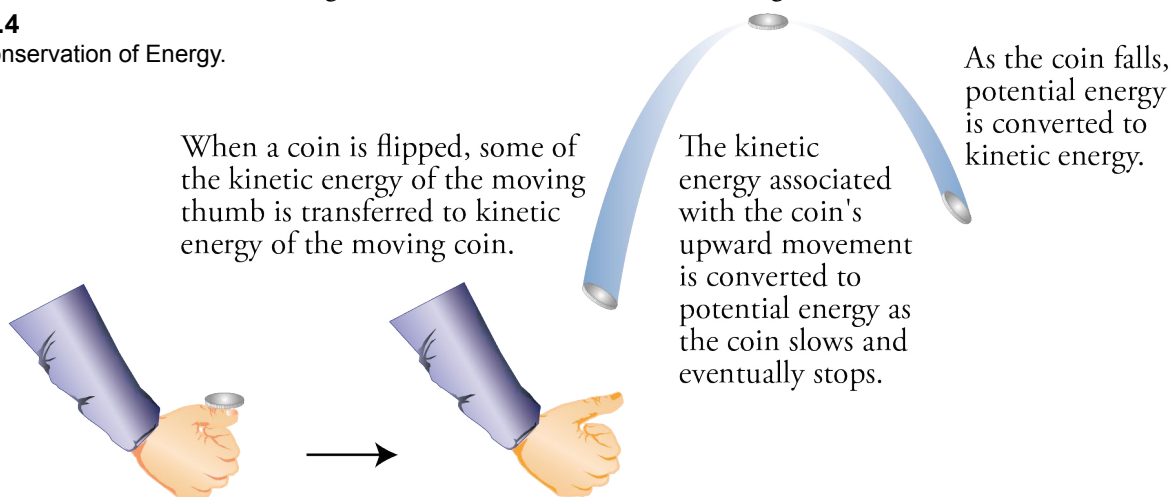
Potential Energy

Energy can be transferred from one object to another. Picture the coin-toss that precedes a football game. A coin starts out resting in the referee's hand. After he flips it, sending it moving up into the air, it has some kinetic energy that it did not have before it was flipped. Where did the coin get this energy? From the referee's moving thumb. When scientists analyze such energy transfers, they find that all of the energy still exists. The **Law of Conservation of Energy** states that energy can be neither created nor destroyed, but it can be transferred from one system to another and changed from one form to another.[1]

OBJECTIVE 4

As the coin rises, it slows down and eventually stops. At this point, the kinetic energy it got from the referee's moving thumb is gone, but the Law of Conservation of Energy says that energy cannot be destroyed. Where did the kinetic energy go? Although some of it has been transferred to the air particles it bumps into on its flight, most of the energy is still there in the coin in a form called **potential energy (PE)**, which is the retrievable, stored form of energy an object possesses by virtue of its position or state. We get evidence of this transformation when the coin falls back down toward the grass on the field. The potential energy it had at the peak of its flight is converted into kinetic energy of its downward movement, and this kinetic energy does the work of flattening a few blades of grass when the coin hits the field (Figure 4.4).

Figure 4.4
Law of Conservation of Energy.

When a coin is flipped, some of the kinetic energy of the moving thumb is transferred to kinetic energy of the moving coin.

The kinetic energy associated with the coin's upward movement is converted to potential energy as the coin slows and eventually stops.

As the coin falls, potential energy is converted to kinetic energy.

There are many kinds of potential energy. An alkaline battery contains potential energy that can be used to move a toy car. A plate of pasta provides potential energy to allow your body to move. Knowing the relationships between potential energy and stability can help you to recognize changes in potential energy and to decide whether the potential energy has increased or decreased as a result of each change.
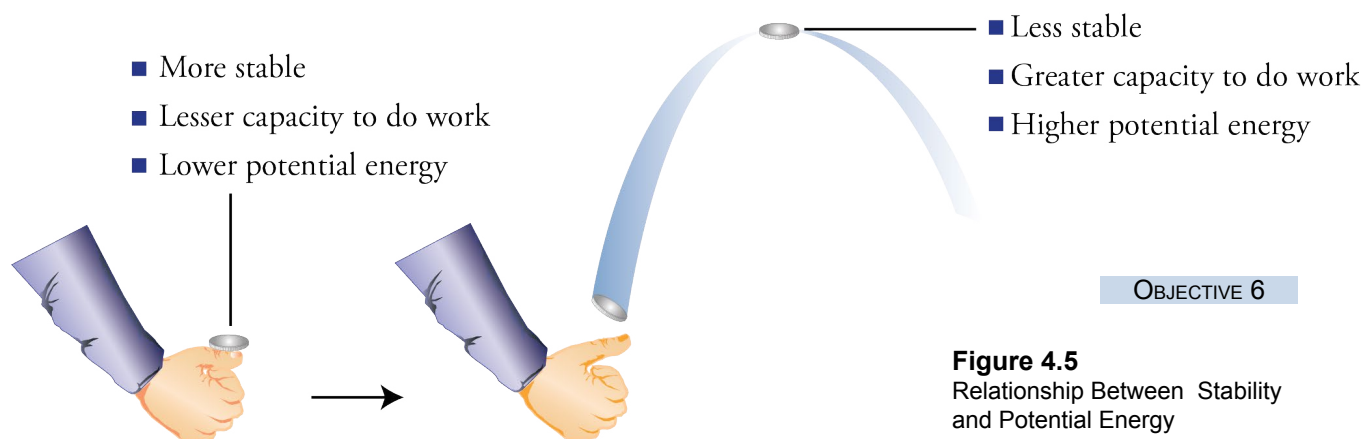
OBJECTIVE 5

Let's look at the relationship between potential energy and stability. A system's stability is a measure of its tendency to change. A more stable system is less likely to change than a less stable system. As an object moves from a less stable state to a more stable state, it can do work. Thus, as an object becomes less stable, it gains a greater capacity to do work and, therefore, a greater potential energy. For example, a coin in your hand is less likely to move than a flipped coin at the peak of its flight, so we say that the coin in the hand is more stable than the coin in the air. As the coin moves

OBJECTIVE 6

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[1] Although chemists recognize that matter can be converted into energy and energy into matter, this matter-energy conversion is small enough to be disregarded.

from its less stable state in the air to a more stable state on the ground, it collides with and moves particles in the air and blades of grass. Therefore, the coin at the peak of its flight has a greater capacity to do the work of moving the objects, and, therefore, a greater potential energy than the more stable coin in the hand (Figure 4.5). *Any time a system shifts from a more stable state to a less stable state, the potential energy of the system increases.* We have already seen that kinetic energy is converted into potential energy as the coin is moved from the more stable position in the hand to the less stable position in the air.
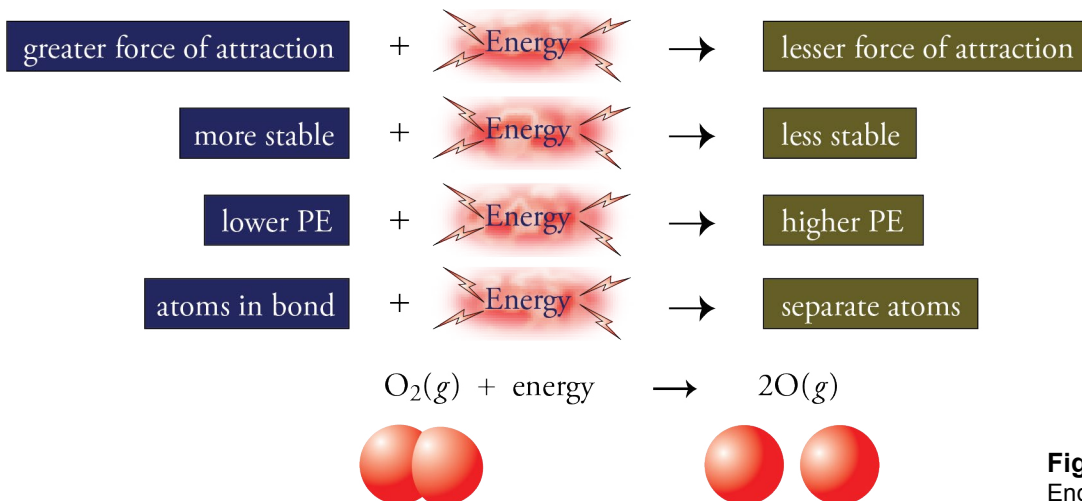
OBJECTIVE 5

more stable + **energy** → less stable system

lesser capacity to do work + **energy** → greater capacity to do work

lower PE + **energy** → higher PE

coin in hand + **energy** → coin in air above hand

- Less stable
- Greater capacity to do work
- Higher potential energy

- More stable
- Lesser capacity to do work
- Lower potential energy

OBJECTIVE 6

Figure 4.5
Relationship Between Stability and Potential Energy

OBJECTIVE 7

Just as energy is needed to propel a coin into the air and increase its potential energy, energy is also necessary to separate two atoms being held together by mutual attraction in a chemical bond. The energy supplied increases the potential energy of the less stable separate atoms compared to the more stable atoms in the bond. For example, the first step in the formation of ozone in the earth's atmosphere is the breaking of the oxygen-oxygen covalent bonds in more stable oxygen molecules, O_2, to form less stable separate oxygen atoms. This change could not occur without an input of considerable energy, in this case, radiant energy from the sun. We call changes that absorb energy **endergonic** (or endogonic) changes (Figure 4.6).

greater force of attraction + Energy → lesser force of attraction

more stable + Energy → less stable

OBJECTIVE 7

lower PE + Energy → higher PE

atoms in bond + Energy → separate atoms

$$O_2(g) + energy \longrightarrow 2O(g)$$

Figure 4.6
Endergonic Change

The attraction between the separated atoms makes it possible that they will change from their less stable separated state to the more stable bonded state. As they move together, they could bump into and move something (such as another atom), so the separated atoms have a greater capacity to do work and a greater potential energy than the atoms in the bond. This is why energy must be supplied to break chemical bonds.

When objects shift from less stable states to more stable states, energy is released. For example, when a coin moves from the less stable peak of its flight to the more stable position on the ground, potential energy is released as kinetic energy. Likewise, energy is released when separate atoms come together to form a chemical bond. Because the less stable separate atoms have higher potential energy than the more stable atoms that participate in a bond, the change from separate atoms to atoms in a bond corresponds to a decrease in potential energy. Ozone, O_3, forms in the stratosphere when an oxygen atom, O, and an oxygen molecule, O_2, collide. The energy released in this change comes from the formation of a new O–O bond in ozone, O_3. We call changes that release energy **exergonic** (or exogonic) changes (Figure 4.7).

Figure 4.7
Exergonic Change

$$O(g) \quad + \quad O_2(g) \quad \longrightarrow \quad O_3(g) \quad + \quad energy$$
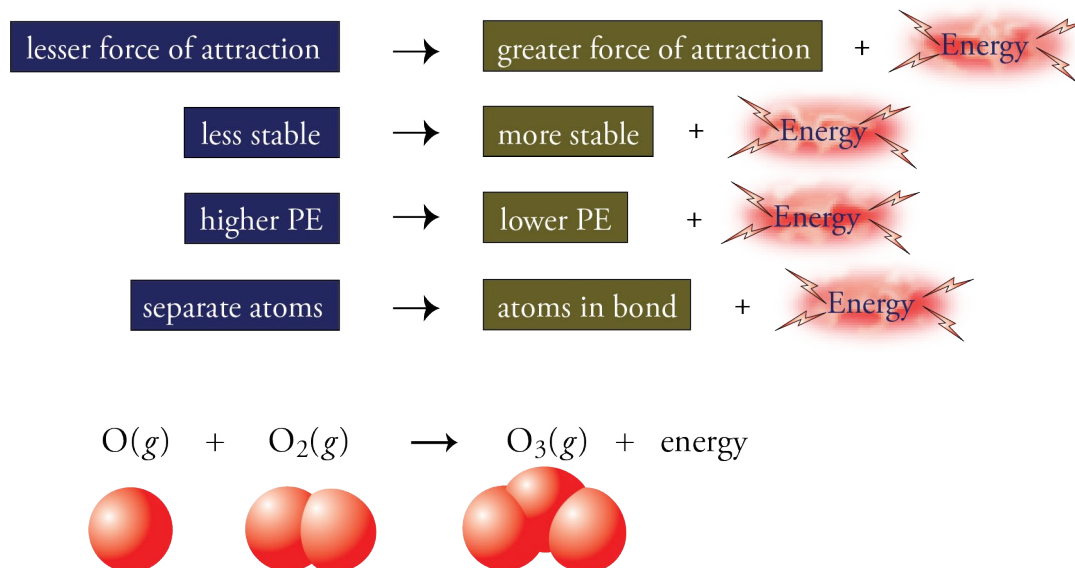
Some bonds are more stable than others. The products of the chemical reactions that take place in an alkaline battery, and in our bodies when the chemicals in pasta are converted into other substances, have more stable chemical bonds between their atoms than the reactants do. Therefore, in each case, the potential energy of the products is lower than that of the reactants, and the lost potential energy supplies the energy to move a toy car across the carpet and propel a four-year-old along behind it.

EXAMPLE 4.1 - Energy

For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 5

a. Incandescent light bulbs burn out because their tungsten filament gradually evaporates, weakening until it breaks. Argon gas is added to these bulbs to reduce the rate of evaporation. Which has greater energy, (1) an argon atom, Ar, with a velocity of 428 m/s or (2) the same atom moving with a velocity of 456 m/s? (These are the average velocities of argon atoms at 20 °C and 60 °C.)

b. Krypton, Kr, gas does a better job than argon of reducing the rate of evaporation of the tungsten filament in an incandescent light bulb. Because of its higher cost, however, krypton is only used when longer life is worth the extra cost. Which has higher energy, (1) an argon atom with a velocity of 428 m/s or (2) a krypton atom moving at the same velocity?

c. According to our model for ionic solids, the ions at the surface of the crystal are constantly moving out and away from the other ions and then being attracted back to the surface. Which has more energy, (1) a stationary sodium ion well separated from the chloride ions at the surface of a sodium chloride crystal or (2) a stationary sodium ion located quite close to the chloride ions on the surface of the crystal?

d. The chemical reactions that lead to the formation of polyvinyl chloride (PVC), which is used to make rigid plastic pipes, are initiated by the decomposition of peroxides. The general reaction is shown below. The simplest peroxide is hydrogen peroxide, H_2O_2 or HOOH. Which has more energy, (1) a hydrogen peroxide molecule or (2) two separate HO molecules that form when the relatively weak O–O bond in an HOOH molecule is broken?

$$HOOH \rightarrow 2HO$$
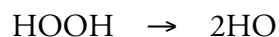
e. Hydrogen atoms react with oxygen molecules in the earth's upper atmosphere to form HO_2 molecules. Which has higher energy, (1) a separate H atom and O_2 molecule or (2) an HO_2 molecule?

$$H(g) + O_2(g) \rightarrow HO_2(g)$$
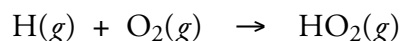
f. Dry ice—solid carbon dioxide—sublimes, which means that it changes directly from solid to gas. Assuming that the temperature of the system remains constant, which has higher energy, (1) the dry ice or (2) the gaseous carbon dioxide?

Solution

a. Any object in motion can collide with another object and move it, so any object in motion has the capacity to do work. This capacity to do work resulting from the motion of an object is called kinetic energy, KE. The particle with the higher velocity will move another object (such as another atom) farther, so it can do more work. It must therefore have more energy. In short, an **argon atom with a velocity of 456 m/s has greater kinetic energy** than the same atom with a velocity of 428 m/s.

b. The moving particle with the higher mass can move another object (such as another molecule) farther, so it can do more work and must therefore have more energy. Thus the **more massive krypton atoms moving at 428 m/s have greater kinetic energy** than the less massive argon atoms with the same velocity.

c. Separated ions are less stable than atoms in an ionic bond, so the **separated sodium and chloride ions have higher potential energy** than the ions that are closer together. The attraction between the separated sodium cation and the chloride anion pulls them together; as they approach each other, they could conceivably bump into another object, move it, and do work.

d. Separated atoms are less stable and have higher potential energy than atoms in a chemical bond, so energy is required to break a chemical bond. Thus energy is required to separate the two oxygen atoms of HOOH being held together by mutual attraction in a chemical bond. The energy supplied is represented in the higher potential energy of separate HO molecules compared to the HOOH molecule. If the bond were reformed, the potential energy would be converted into a form of energy that could be used to do work. In short, **two HO molecules have higher potential energy** than an HOOH molecule.

e. Atoms in a chemical bond are more stable and have lower potential energy than separated atoms, so energy is released when chemical bonds form. When H and O_2 are converted into an HO_2 molecule, a new bond is formed, and some of the potential energy of the separate particles is released. The energy could be used to do some work.

$$H(g) \; + \; O_2(g) \;\; \rightarrow \;\; HO_2(g)$$
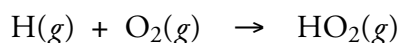
Therefore, **separated hydrogen atoms and oxygen molecules have higher potential energy** than the HO_2 molecules that they form.

f. When carbon dioxide sublimes, the attractions that link the CO_2 molecules together are broken. The energy that the dry ice must absorb to break these attractions goes to increase the potential energy of the CO_2 as a gas. If the CO_2 returns to the solid form, attractions are reformed, and the potential energy is converted into a form of energy that could be used to do work. Therefore, **gaseous CO_2 has higher potential energy** than solid CO_2.

EXERCISE 4.1 - Energy

For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

a. Nitric acid molecules, HNO_3, in the upper atmosphere decompose to form HO molecules and NO_2 molecules by the breaking of a bond between the nitrogen atom and one of the oxygen atoms. Which has higher energy, (1) a nitric acid molecule or (2) the HO molecule and NO_2 molecule that come from its decomposition?

b. Nitrogen oxides, $NO(g)$ and $NO_2(g)$, are released into the atmosphere in the exhaust of our cars. Which has higher energy, (1) a NO_2 molecule moving at 439 m/s or (2) the same NO_2 molecule moving at 399 m/s. (These are the average velocities of NO_2 molecules at 80 °C and 20 °C, respectively.)

c. Which has higher energy, (1) a nitrogen monoxide molecule, NO, emitted from your car's tailpipe at 450 m/s or (2) a nitrogen dioxide molecule, NO_2, moving at the same velocity?

d. Liquid nitrogen is used for a number of purposes, including the removal (by freezing) of warts. Assuming that the temperature remains constant, which has higher energy, (1) liquid nitrogen or (2) gaseous nitrogen?

e. Halons, such as halon-1301 (CF_3Br) and halon-1211 (CF_2ClBr), which have been used as fire extinguishing agents, are a potential threat to the Earth's protective ozone layer, partly because they lead to the production of $BrONO_2$, which is created from the combination of BrO and NO_2. Which has higher energy, (1) separate BrO and NO_2 molecules or (2) the $BrONO_2$ that they form?

f. The so-called alpha particles released by large radioactive elements such as uranium are helium nuclei consisting of two protons and two neutrons. Which has higher energy, (1) an uncharged helium atom or (2) an alpha particle and two separate electrons?

Units of Energy

The accepted SI unit for energy is the **joule (J)**, but another common unit is the **calorie (cal)**. The calorie has been defined in several different ways. One early definition described it as the energy necessary to increase the temperature of 1 gram of water from 14.5 °C to 15.5 °C. There are 4.186 J/cal according to this definition. Today, however, the U.S. National Institute of Standards and Technology defines the calorie as 4.184 joules:

$$4.184 \text{ J} = 1 \text{ cal} \quad \text{or} \quad 4.184 \text{ kJ} = 1 \text{ kcal}$$

The "calories" spoken of in the context of dietary energy—the energy supplied by food—are actually kilocalories, kcal, equivalent to 4184 J or 4.184 kJ. This dietary calorie is often written **Calorie** (using an uppercase C) and abbreviated Cal.

$$4184 \text{ J} = 1 \text{ Cal} \quad \text{or} \quad 4.184 \text{ kJ} = 1 \text{ Cal}$$

A meal of about 1000 dietary calories (Calories) provides about 4184 kJ of energy. Table 4.1 shows the energy provided by various foods. We will use joules

and kilojoules to describe energy in this text. Figure 4.8 shows some approximate values in kilojoules for the energy represented by various events.

Table 4.1 Approximate Energy Provided by Various Foods

Food	Dietary Calories (kcal)	kilojoules (kJ)	Food	Dietary Calories (kcal)	kilojoules (kJ)
Cheese pizza (12 inch diameter)	1180	4940	Unsweetened apple juice (1 cup)	120	500
Roasted cashew nuts (1 cup)	780	3260	Butter (1 tablespoon)	100	420
White granular sugar (1 cup)	770	3220	Raw apple (medium sized)	100	420
Dry rice (1 cup)	680	2850	Chicken's egg (extra large)	90	380
Wheat flour (1 cup)	400	1670	Cheddar cheese (1 inch cube)	70	290
Ice cream - 10% fat (1 cup)	260	1090	Whole wheat bread (1 slice)	60	250
Raw broccoli (1 pound)	140	590	Black coffee (6 fl oz cup)	2	8

Figure 4.8

Approximate Energy of Various Events   (The relative sizes of these measurements cannot be shown on such a small page. The wedge and the numbers of increasing size are to remind you that each numbered measurement on the scale represents 10,000,000,000 times the magnitude of the preceding numbered measurement.)
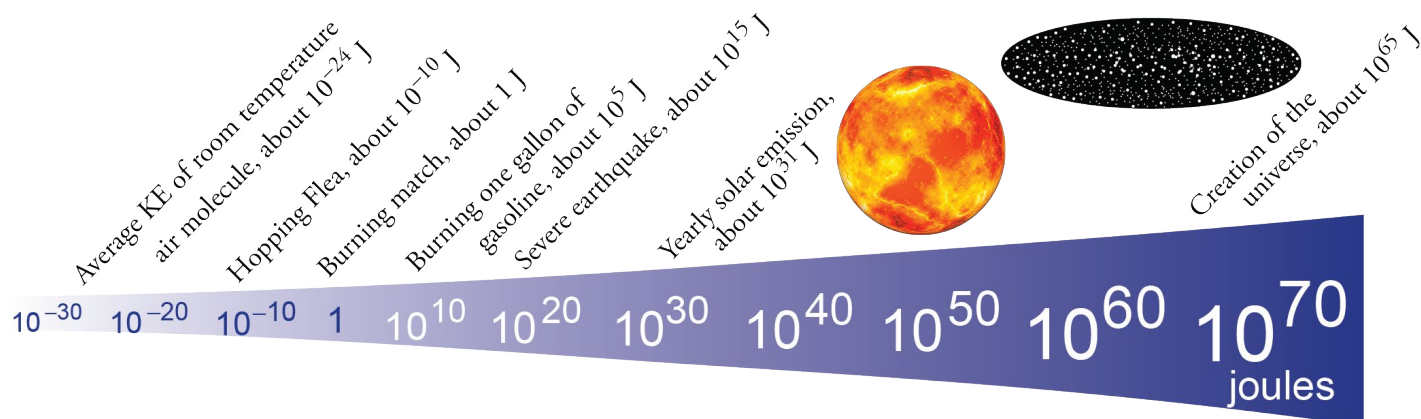
Kinetic Energy and Heat

OBJECTIVE 11

An object's kinetic energy can be classified as internal or external. For example, a falling coin has a certain external kinetic energy that is related to its overall mass and to its velocity as it falls. The coin is also composed of particles that, like all particles, are moving in a random way, independent of the overall motion (or position) of the coin. The particles in the coin are constantly moving, colliding, changing direction, and changing their velocities. The energy associated with this internal motion is called **internal kinetic energy** (Figure 4.9).
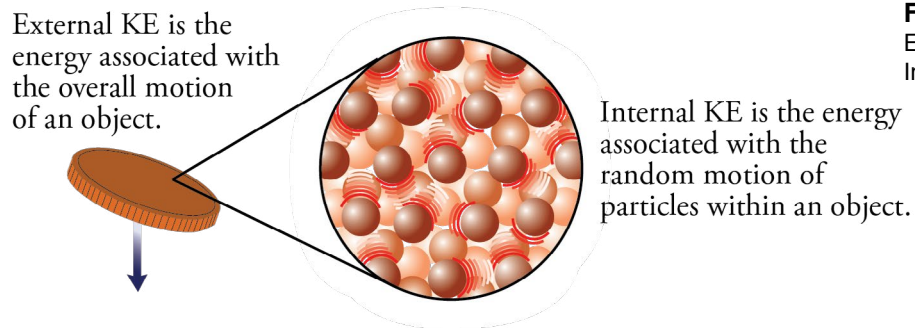
External KE is the energy associated with the overall motion of an object.

Internal KE is the energy associated with the random motion of particles within an object.

Figure 4.9
External Kinetic Energy and Internal Kinetic Energy

OBJECTIVE 11

The amount of internal kinetic energy in an object can be increased in three general ways. The first way is to rub, compress, or distort the object. For example, after a good snowball fight, you can warm your hands by rubbing them together. Likewise, if you beat on metal with a hammer, it will get hot.

OBJECTIVE 12

The second way to increase the internal kinetic energy of an object is to put it in contact with another object at a higher temperature. **Temperature** is proportional to the average internal kinetic energy of an object, so higher temperature means a greater average internal energy for the particles within the object. The particles in a higher-temperature object collide with other particles with greater average force than the particles of a lower-temperature object. Thus collisions between the particles of two objects at different temperatures cause the particles of the lower-temperature object to speed up, increasing the object's energy, and cause the particles of the higher-temperature object to slow down, decreasing this object's energy. In this way, energy is transferred from the higher-temperature object to the lower-temperature object. We call energy that is transferred in this way heat. The energy that is transferred through an object, as from the bottom of a cooking pan to its handle, is also called heat. **Heat** is the energy that is transferred from a region of higher temperature to a region of lower temperature as a consequence of the collisions of particles (Figure 4.10).
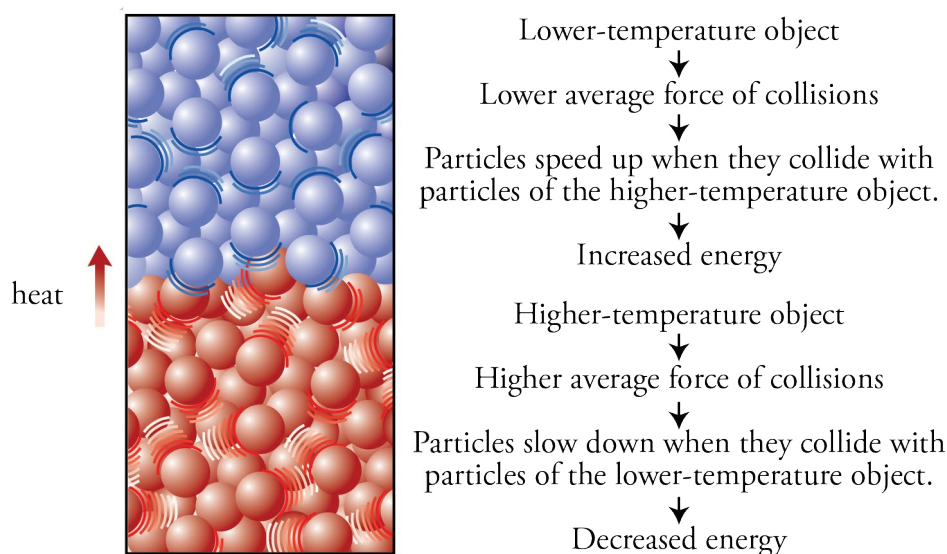
OBJECTIVE 13

OBJECTIVE 14

heat

Lower-temperature object
↓
Lower average force of collisions
↓
Particles speed up when they collide with particles of the higher-temperature object.
↓
Increased energy

Higher-temperature object
↓
Higher average force of collisions
↓
Particles slow down when they collide with particles of the lower-temperature object.
↓
Decreased energy

Figure 4.10
Heat Transfer

OBJECTIVE 14

The third way an object's internal kinetic energy is increased is by exposure to radiant energy, such as the energy coming from the sun. The radiant energy is converted to kinetic energy of the particles in the object. This is why we get hot in the sun.

Radiant Energy

Gamma rays, X rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio and TV waves are all examples of radiant energy. Although we know a great deal about radiant energy, we still have trouble describing what it is. For example, it seems to have a dual nature, with both particle and wave characteristics. It is difficult to visualize both of these two aspects of radiant energy at the same time, so sometimes we focus on its particle nature and sometimes on its wave character, depending on which is more suitable in a given context. Accordingly, we can describe the light that comes from a typical flashlight either as a flow of about 10^{17} particles of energy leaving the bulb per second or as waves of a certain length.

OBJECTIVE 15

In the particle view, radiant energy is a stream of tiny, massless packets of energy called **photons**. The light from the flashlight contains photons of many different energies, so you might try to picture the beam as a stream of photons of many different sizes. (It is difficult to picture a particle without mass, but that is just one of the problems we have in describing what light is.)
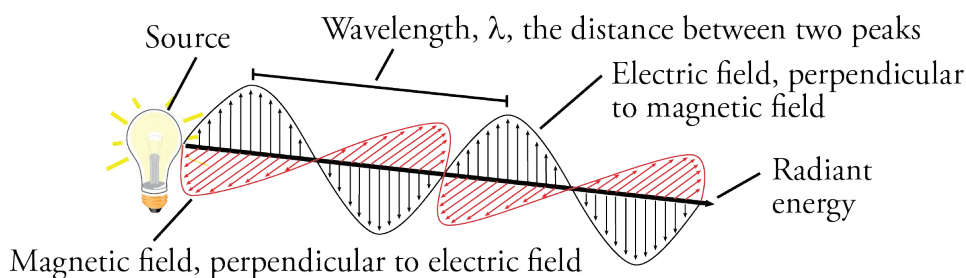
OBJECTIVE 16

The wave view says that as radiant energy moves away from its source, it has an effect on the space around it that can be described as a wave consisting of an oscillating electric field perpendicular to an oscillating magnetic field (Figure 4.11).

Because radiant energy seems to have both wave and particle characteristics, some experts have suggested that it is probably neither a wave nor a stream of particles. Perhaps the simplest model that includes both aspects of radiant energy says that as the photons travel, they somehow affect the space around them in such a way as to create the electric and magnetic fields.

Radiant energy, then, is energy that can be described in terms of oscillating electric and magnetic fields or in terms of photons. It is often called **electromagnetic radiation**. Because all forms of radiant energy have these qualities, we can distinguish one form of radiant energy from another either by the energy of its photons or the characteristics of its waves. The energies of the photons of radiant energy range from about 10^{-8} J per photon for the very high-energy gamma rays released in radioactive decay to about 10^{-31} J per photon or even smaller for low-energy radio waves. The different forms of radiant energy are listed in Figure 4.12 on the next page.

One distinguishing characteristic of the waves of radiant energy is wavelength, λ, the distance between two peaks on the wave of electromagnetic radiation. A more specific definition of **wavelength** is the distance in space over which a wave completes one cycle of its repeated form. Between two successive peaks, the wave has gone through all of its possible combinations of magnitude and direction and has begun to repeat the cycle again (Figure 4.11).

**Figure 4.11**
A Light Wave's Electric and Magnetic Fields

OBJECTIVE 16

Source

Wavelength, λ, the distance between two peaks

Electric field, perpendicular to magnetic field

Radiant energy

Magnetic field, perpendicular to electric field

Gamma rays, with very high-energy photons, have very short wavelengths (Figure 4.12), on the order of 10^{-14} meters (or 10^{-5} nm). Short wavelengths are often described with nanometers, nm, which are 10^{-9} m. In contrast, the radio waves on the low-energy end of the AM radio spectrum have wavelengths of about 500 m (about one-third of a mile). If you look at the energy and wavelength scales in Figure 4.12, you will see that longer wavelength corresponds to lower-energy photons. The shorter the wavelength of a wave of electromagnetic radiation, the greater the energy of its photons. In other words, the energy, ε, of a photon is inversely proportional to the radiation's wavelength, λ. (The symbol ε is a lower case Greek epsilon, and the λ is a lowercase Greek lambda.)

OBJECTIVE 17

$$\varepsilon \propto \frac{1}{\lambda}$$

As Figure 4.12 illustrates, all forms of radiant energy are part of a continuum with no precise dividing lines between one form and the next. In fact, there is some overlap between categories. Note that visible light is only a small portion of the radiant energy spectrum. The different colors of visible light are due to different photon energies and associated wavelengths.

Figure 4.12
Radiant-Energy Spectrum
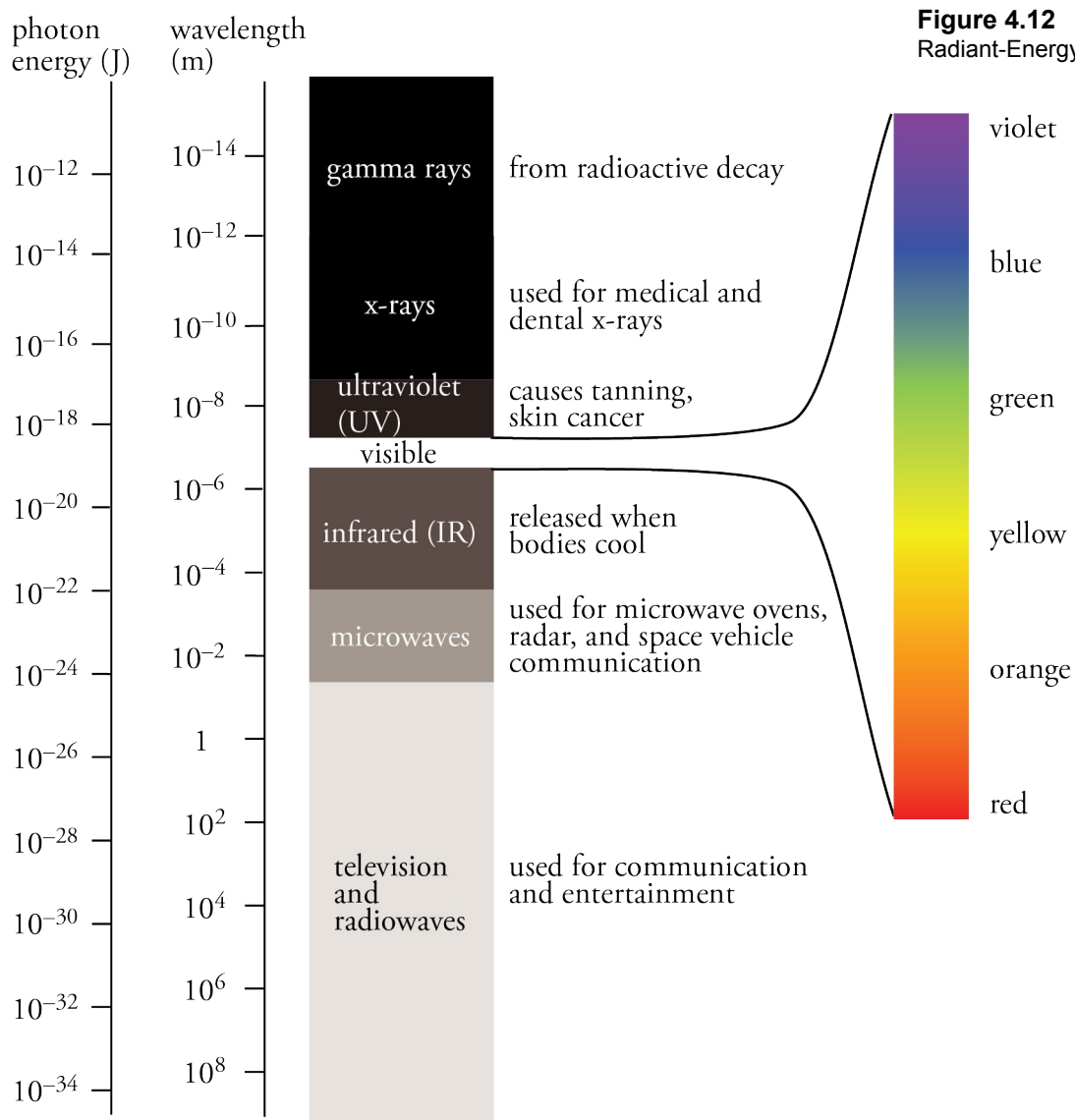
OBJECTIVE 18
OBJECTIVE 19

4.2 The Mysterious Electron

Where there is an open mind, there will always be a frontier.

Charles F. Kettering (1876-1958)
American engineer and inventor

Scientists have known for a long time that it is incorrect to think of electrons as tiny particles orbiting the nucleus like planets around the sun. Nevertheless, nonscientists have become used to picturing them in this way. In some circumstances, this "solar system" model of the atom may be useful, but you should know that the electron is much more unusual than that model suggests. The electron is extremely tiny, and modern physics tells us that strange things happen in the realm of the very, very small.

The modern description of the electron is based on complex mathematics and on the discoveries of modern physics. The mathematical complexity alone makes an accurate verbal portrayal of the electron challenging, but our difficulty in describing the electron goes beyond complexity. Modern physics tells us that it is impossible to know exactly where an electron is and what it is doing. As your mathematical and scientific knowledge increases, you will be able to understand more sophisticated descriptions of the electron, but the problem of describing exactly where the electron is and what it is doing never goes away. It is a problem fundamental to very tiny objects. Thus complete confidence in our description of the nature of the electron is beyond our reach.

There are two ways that scientists deal with the problems associated with the complexity and fundamental uncertainty of the modern description of the electron:

Analogies   In order to communicate something of the nature of the electron, scientists often use analogies, comparing the electron to objects with which we are more familiar. For example, in this chapter we will be looking at the ways in which electrons are like vibrating guitar strings.
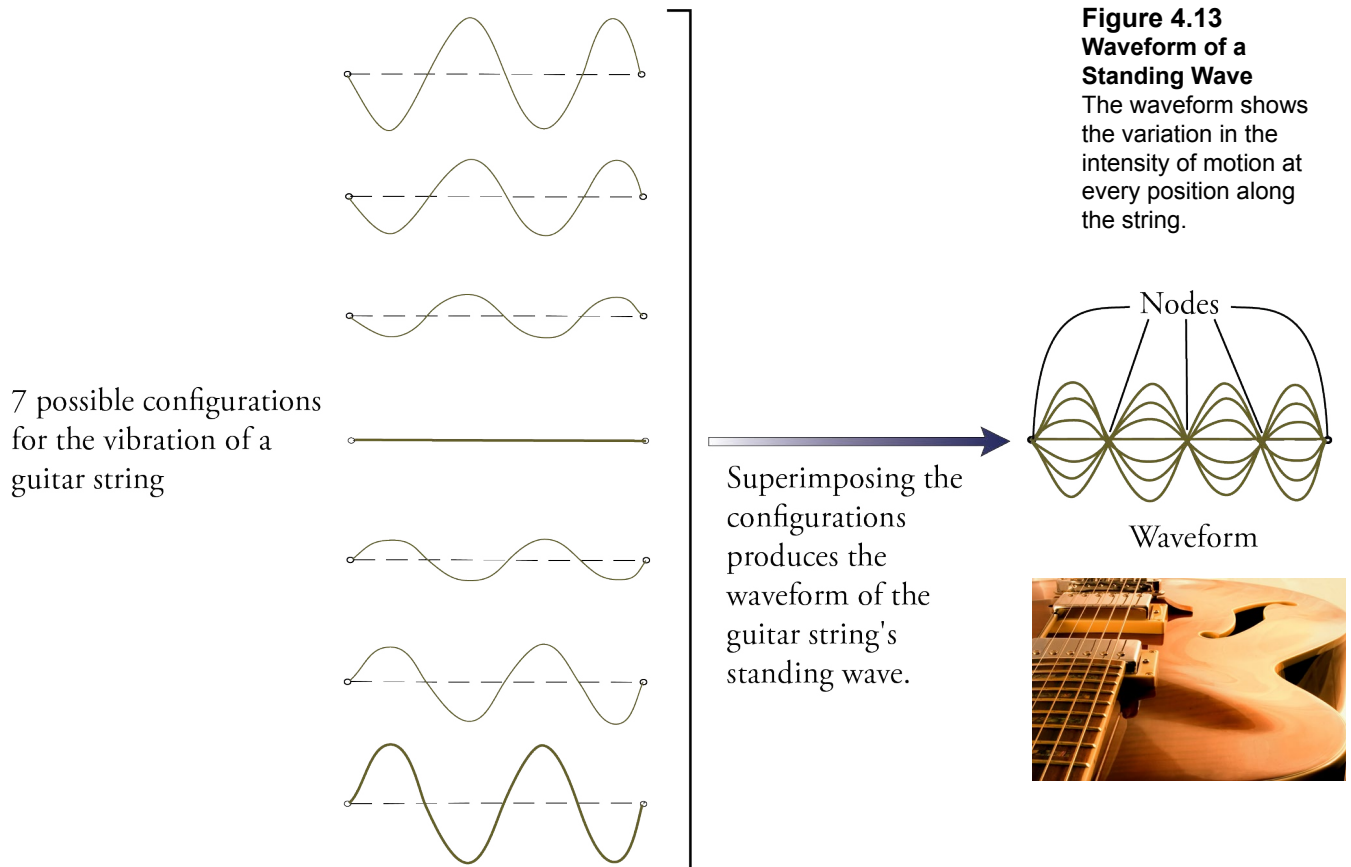
Probabilities   In order to accommodate the uncertainty of the electron's position and motion, scientists talk about where the electron probably is within the atom, instead of where it definitely is.

Through the use of analogies and a discussion of probabilities, this chapter attempts to give you a glimpse of what scientists are learning about the electron's character.

Standing Waves and Guitar Strings

Like radiant energy, each electron seems to have a dual nature in which both particle and wave characteristics are apparent. It is difficult to describe these two aspects of an electron at the same time, so sometimes we focus on its particle nature and sometimes on its wave character, depending on which is more suitable in a given context. In the particle view, electrons are tiny, negatively charged particles with a mass of about 9.1096×10^{-28} grams. In the wave view, an electron has an effect on the space around it that can be described as a wave of varying negative charge intensity. To gain a better understanding of this electron-wave character, let's compare it to the wave character of guitar strings. Because a guitar string is easier to visualize than an electron, its vibrations serve as a useful analogy of the wave character of electrons.

When a guitar string is plucked, the string vibrates up and down in a wave pattern. Figure 4.13 shows one way that it can vibrate; the seven images on the left represent the position of the string at various isolated moments, and the final image on the right shows all those positions combined. If you squint a bit while looking at a vibrating guitar string, what you see is a blur with a shape determined by the varying intensity of the vibration along the string. This blur, which we will call the **waveform**, appears to be stationary. Although the string is constantly moving, the waveform is not, so this wave pattern is called a standing or stationary wave. Note that as your eye moves along the string, the intensity, or amount, of the string's movement varies. The points in the waveform where there is no motion are called **nodes**.

7 possible configurations for the vibration of a guitar string

Superimposing the configurations produces the waveform of the guitar string's standing wave.

Nodes

Waveform

Figure 4.13
Waveform of a Standing Wave
The waveform shows the variation in the intensity of motion at every position along the string.

Although many waveforms are possible, the possibilities are limited by the fact that the string is tied down and cannot move at the ends. In theory, there are an infinite number of possible waveforms, but they all allow the string to remain stationary at the ends. Figure 4.14 shows various allowed waveforms.
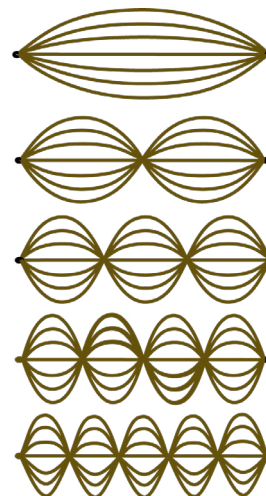

Figure 4.14
Some Possible Waveforms for a Vibrating Guitar String

OBJECTIVE 20

Electrons as Standing Waves

OBJECTIVE 21

The wave character of the guitar string is represented by the movement of the string. We can focus our attention on the blur of the waveform and forget the material the string is made of. The waveform describes the motion of the string over time, not the string itself.

In a similar way, the wave character of the electron is represented by the waveform of its negative charge, on which we can focus without concerning ourselves about the electron's particle nature. This frees us from asking questions about where the electrons are in the atom and how they are moving—questions that we are unable to answer. The waveforms for electrons in an atom describe the variation in intensity of negative charge within the atom, with respect to the location of the nucleus. This can be described without mentioning the positions and motion of the electron particle itself.

The following statements represent the core of the modern description of the wave character of the electron:

- Just as the intensity of the movement of a guitar string can vary, so can the intensity of the negative charge of the electron vary at different positions outside the nucleus.
- The variation in the intensity of the electron charge can be described in terms of a three-dimensional standing wave like the standing wave of the guitar string.
- As in the case of the guitar string, only certain waveforms are possible for the electron in an atom.
- We can focus our attention on the waveform of varying charge intensity without having to think about the actual physical nature of the electron.

Waveforms for Hydrogen Atoms

Most of the general descriptions of electrons found in the rest of this chapter are based on the wave mathematics for the one electron in a hydrogen atom. The comparable calculations for other elements are too difficult to lead to useful results, so as you will see in the next section, the information calculated for the hydrogen electron is used to describe the other elements as well. Fortunately, this approximation works quite well.

The wave equation for the one electron of a hydrogen atom predicts waveforms for the electron that are similar to the allowed waveforms for a vibrating guitar string. For example, the simplest allowed waveform for the guitar string looks something like
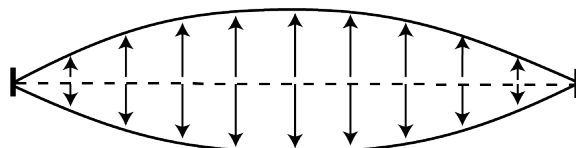
OBJECTIVE 22

The simplest allowed waveform for an electron in a hydrogen atom looks like the image in Figure 4.15. The cloud that you see surrounds the nucleus and represents the variation in the intensity of the negative charge at different positions outside the nucleus. The negative charge is most intense at the nucleus and diminishes with increasing distance from the nucleus. The variation in charge intensity for this waveform is the same in all directions, so the waveform is a sphere. The allowed waveforms for

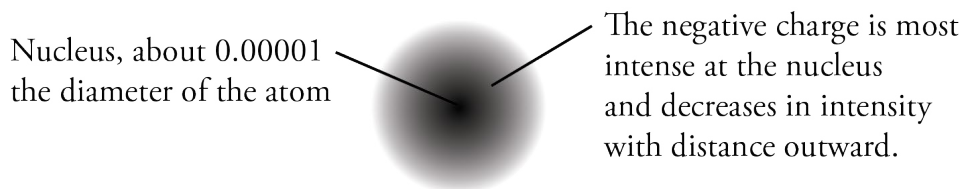the electron are also called **orbitals**. The orbital shown in Figure 4.15 is called the 1*s* orbital.

Nucleus, about 0.00001 the diameter of the atom

The negative charge is most intense at the nucleus and decreases in intensity with distance outward.

Theoretically, the charge intensity depicted in Figure 4.15 decreases toward zero as the distance from the nucleus approaches infinity. This suggests the amusing possibility that some of the negative charge created by an electron in a hydrogen atom is felt an infinite distance from the atom's nucleus. The more practical approach taken by chemists, however, is to specify a volume that contains most of the electron charge and focus their attention on that, forgetting about the small negative charge felt outside the specified volume. For example, we can focus on a sphere containing 90% of the charge of the 1*s* electron. If we wanted to include more of the electron charge, we enlarge the sphere so that it encloses 99% (or 99.9%) of the electron charge (Figure 4.16). This leads us to another definition of **orbital** as the volume that contains a given high percentage of the electron charge.

Most of the pictures you will see of orbitals represent the hypothetical surfaces that surround a high percentage of the negative charge of an electron of a given waveform. The 1*s* orbital, for example, can either be represented by a fuzzy sphere depicting the varying intensity of the negative charge (Figure 4.15) or by a smooth spherical surface depicting the boundary within which most of the charge is to be found (Figure 4.16).

OBJECTIVE 22

Almost all of the electron's charge lies within a spherical shell with the diameter of this circle.
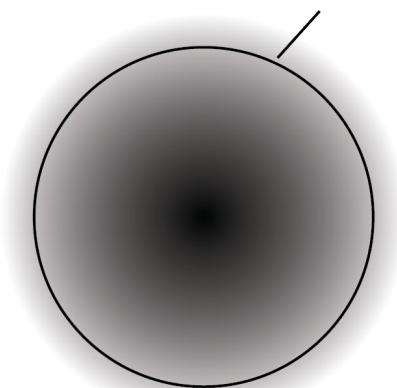
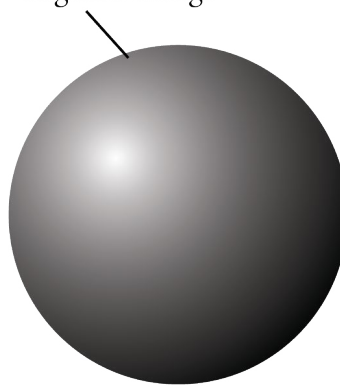Sphere enclosing almost all of the electron's negative charge

Is the sphere in Figure 4.15 the 1*s* electron? This is like asking if the guitar string is the blur that you see when the string vibrates. When we describe the standing wave that represents the motion of a guitar string, we generally do not refer to the material composition of the string. The situation is very similar for the electron. We are able to describe the variation in intensity of the negative charge created by the electron without thinking too much about what the electron is and what it is doing.
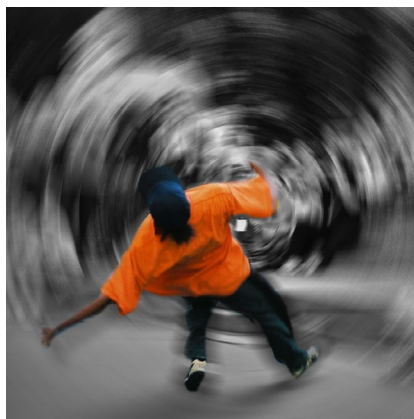
Particle Interpretation of the Wave Character of the Electron

OBJECTIVE 23

So, where is the electron and what is it doing? We do not really know, and modern physics tells us that we never will know with 100% certainty. However, with information derived from wave mathematics for an electron, we can predict where the electron probably is. According to the particle interpretation of the wave character of the electron, the surface that surrounds 90% of an electron's charge is the surface within which we have a 90% probability of finding the electron. We could say that the electron spends 90% of its time within the space enclosed by that surface. Thus an **orbital** can also be defined as the volume within which an electron has a high probability of being found.

It is not difficult to visualize a reasonable path for an electron in a 1s orbital, but as you will see later in this section, the shapes of orbitals get much more complex than the simple sphere of the 1s orbital. For this reason, we do not attempt to visualize the path an electron follows in an orbital.

How should we picture the electron? Perhaps the best image is the one we used in Chapter 3: a cloud. Our interpretation of the nature of the electron cloud will differ, however, depending on whether we are considering the charge of the electron or its particle nature.

If we wish to consider the charge of the electron, the electron cloud represents the continuous variation in the intensity of the negative charge; it is stronger near the nucleus and weaker with increasing distance away from the nucleus, like the fuzzy sphere pictured in Figure 4.15.

In the particle view, the electron cloud can be compared to a multiple-exposure photograph of the electron. (Once again, we must resort to an analogy to describe electron behavior.) If we were able to take a series of sharply focused photos of an electron over a period of time without advancing the film, our final picture would look like Figure 4.17. We would find a high density of dots near the nucleus and a decrease in density with increasing distance from the nucleus (because there is a higher probability of finding the electron in a volume near the nucleus than in the same volume farther away). This arrangement of dots would illustrate the wave equation's prediction of the probability of finding the electron at any given distance from the nucleus.

If enough photos of this dancer are combined, we see a blur instead of an individual dancer. This dancer-blur is like an electron cloud.

OBJECTIVE 22
OBJECTIVE 23

A multiple exposure picture of the electron in a 1s orbital of a hydrogen atom might look like this.

Figure 4.17
Particle Interpretation of a 1s Orbital

Other Important Orbitals

Just like the guitar string can have different waveforms, the one electron in a hydrogen atom can also have different waveforms, or orbitals. The shapes and sizes for these orbitals are predicted by the mathematics associated with the wave character of the hydrogen electron. Figure 4.18 shows some of them.
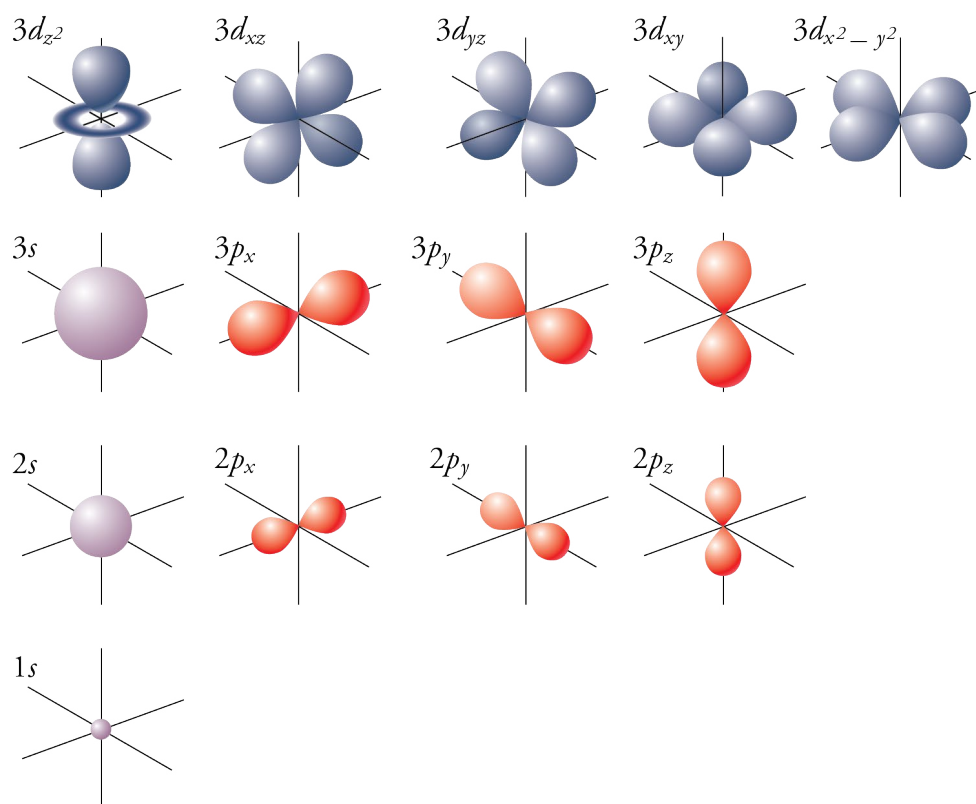
$3d_{z^2}$ $3d_{xz}$ $3d_{yz}$ $3d_{xy}$ $3d_{x^2-y^2}$

$3s$ $3p_x$ $3p_y$ $3p_z$

$2s$ $2p_x$ $2p_y$ $2p_z$

$1s$

Figure 4.18
Some Possible Waveforms, or Orbitals, for an Electron in a Hydrogen Atom

Before considering the second possible orbital for the electron of a hydrogen atom, let's look at another of the possible ways a guitar string can vibrate. The guitar string waveform below has a node in the center where there is no movement of the string.

Node
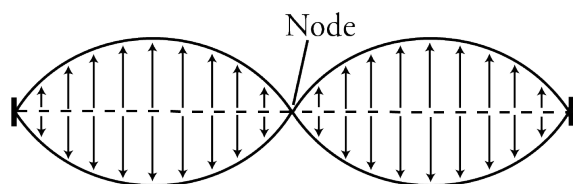
The electron-wave calculations predict that an electron in a hydrogen atom can have a waveform called the 2s orbital that is analogous to the guitar string waveform above. The 2s orbital for an electron in a hydrogen atom is spherical like the 1s orbital, but it is a larger sphere. All spherical electron waveforms are called *s* orbitals. For an electron in the 2s orbital, the charge is most intense at the nucleus. With increasing distance from the nucleus, the charge diminishes in intensity until it reaches a minimum at a certain distance from the nucleus; it then increases again to a maximum, and finally it

OBJECTIVE 24

diminishes again. The region within the 2*s* orbital where the charge intensity decreases to zero is called a node. Figure 4.19 shows cutaway, quarter-section views of the 1*s* and 2*s* orbitals.

Figure 4.19
Quarter Sections of the 1*s* and 2*s* Orbitals

OBJECTIVE **24**

1s

The 2s orbital is larger and has a node.
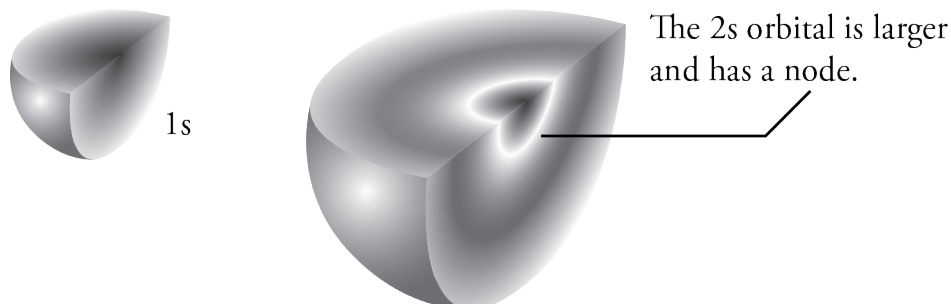
OBJECTIVE **25**   The average distance between the positive charge of the nucleus and the negative charge of a 2*s* electron cloud is greater than the average distance between the nucleus and the charge of a 1*s* electron cloud. Because the strength of the attraction between positive and negative charges decreases with increasing distance between the charges, an electron is more strongly attracted to the nucleus and therefore is more stable when it has the smaller 1*s* waveform than when it has the larger 2*s* waveform. As you discovered in Section 4.1, increased stability is associated with decreased potential energy, so a 1*s* electron has lower potential energy than a 2*s* electron. We describe this energy difference by saying the 1*s* electron is in the first principal energy level, and the 2*s* electron is in the second principal energy level. All of the orbitals that have the same potential energy for a hydrogen atom are said to be in the same **principal energy level**. The principal energy levels are often called shells. The 1 in 1*s* and the 2 in 2*s* show the principal energy levels, or shells, for these orbitals.

Chemists sometimes draw orbital diagrams, such as the following, with lines to represent the orbitals in an atom and arrows (which we will be adding later) to represent electrons:

2*s* ___

1*s* ___

The line representing the 2*s* orbital is higher on the page to indicate its higher potential energy.

Because electrons seek the lowest energy level possible, we expect the electron in a hydrogen atom to have the 1*s* waveform, or electron cloud. We say that the electron is in the 1*s* orbital. But the electron in a hydrogen atom does not need to stay in the 1*s* orbital at all times. Just as an input of energy (a little arm work on our part) can lift a book resting on a table and raise it to a position that has greater potential energy, so can the waveform of an electron in a hydrogen atom be changed from the 1*s* shape to the 2*s* shape by the addition of energy to the atom. We say that the electron can be excited from the 1*s* orbital to the 2*s* orbital. Hydrogen atoms with their electron in the 1*s* orbital are said to be in their **ground state**. A hydrogen atom with its electron in the 2*s* orbital is in an **excited state**.

If you lift a book from a table to above the table and then release it, it falls back down to its lower-energy position on the table. The same is true for the electron. After the electron is excited from the 1s orbital to the 2s orbital, it spontaneously returns to its lower-energy 1s form.

An electron in a hydrogen atom can be excited to orbitals other than the 2s. For example, an electron in a hydrogen atom can be excited from the 1s to a 2p orbital. There are actually three possible 2p orbitals. They are identical in shape and size, but each lies at a 90° angle to the other two. Because they can be viewed as lying on the x, y and z axes of a three-dimensional coordinate system, they are often called the 2p_x, 2p_y, and 2p_z orbitals. An electron with a 2p waveform has its negative charge distributed in two lobes on opposite sides of the nucleus. Figure 4.20 shows the shape of a 2p_z orbital.

In order to more easily show how the 2p orbitals fit together, they are often drawn in a more elongated and stylized form (Figures 4.21 and 4.22).

The energy generated by the explosives in fireworks supplies the energy to excite electrons to higher energy levels. When the electrons return to their ground state, they give off energy in the form of light.
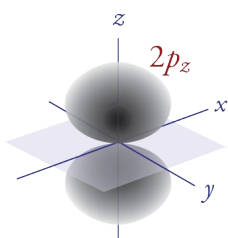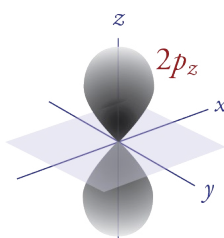
Figure 4.20
Realistic View of a
2p_z Orbital

Figure 4.21
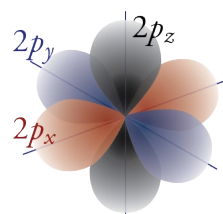Stylized View of a
2p_z Orbital

Figure 4.22
Stylized View of a
2p_x, 2p_y, and 2p_z
Orbitals Combined

OBJECTIVE 26

In a hydrogen atom, the average distance between the negative charge of a 2p electron cloud and the nucleus is the same as for a 2s electron cloud. Therefore, an electron in a hydrogen atom has the same attraction to the nucleus and the same stability when it has a 2p form as when it has the 2s form. Therefore, a 2s electron has the same potential energy as a 2p electron . These orbitals are in the same principal energy level.

Because the shapes of the 2s and 2p electron clouds are different, we distinguish between them by saying that an electron with the 2s waveform is in the 2s sublevel, and an electron with any of the three 2p waveforms is in the 2p sublevel. Orbitals that have the same potential energy, the same size, and the same shape are in the same **sublevel**. The sublevels are sometimes called **subshells**. Thus there is one orbital in the 1s sublevel, one orbital in the 2s sublevel, and three orbitals in the 2p sublevel. The following orbital diagram shows these orbitals and sublevels.

$2s$ ____ $2p$ ____ ____ ____
$1s$ ____
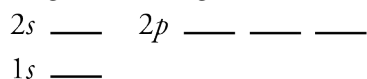
The lines for the 2s and 2p orbitals are drawn side by side to show that they have the same potential energy for the one electron in a hydrogen atom. You will see in the next section that the 2s and 2p orbitals have different potential energies for atoms larger than hydrogen atoms.

In the third principal energy level, there are nine possible waveforms for an electron, in three different sublevels (Figure 4.18). The 3s sublevel has one orbital that has a spherical shape, like the 1s and the 2s, but it has a larger average radius and two nodes. Its greater average distance from the positive charge of the nucleus makes it less stable and higher in energy than the 1s or 2s orbitals. The calculations predict that the third principal energy level has a 3p sublevel, with three 3p orbitals. They have the same general shape as the 2p orbitals, but they are larger, which leads to less attraction to the nucleus, less stability, and higher potential energy than for a 2p orbital. The third principal energy level also has a 3d sublevel, with five 3d orbitals. Four of these orbitals have four lobes whose shape is similar to the lobes of a 3p orbital. We will call these "double dumbbells." An electron in a 3d orbital has its negative charge spread out in these four lobes. The fifth 3d orbital has a different shape, as shown in Figure 4.23.

Four of the five 3d orbitals have a double dumbbell shape like this one.
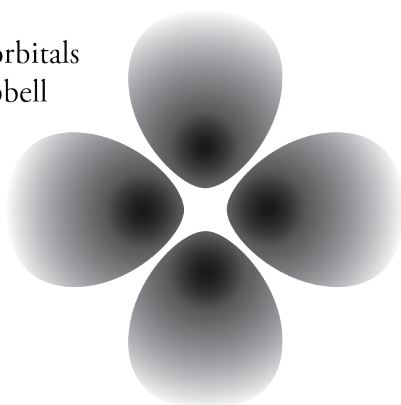
The fifth 3d orbital is shaped like a dumbell and a donut.
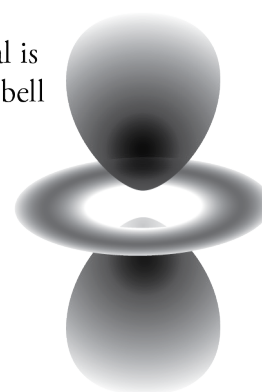
Figure 4.23
3d Orbitals

When an electron in a hydrogen atom is excited to the fourth principal energy level, it can be in any one of four sublevels: 4s, 4p, 4d, or 4f. There is one 4s orbital, with a spherical shape and a larger volume than the 3s. There are three 4p orbitals, similar in shape to the 3p orbitals but with a larger volume than the 3p orbitals. There are five 4d orbitals, similar to but larger than the 3d orbitals. The 4f sublevel has seven possible orbitals.

Overall Organization of Principal Energy Levels, Sublevels, and Orbitals

Table 4.2 shows all the orbitals predicted for the first seven principal energy levels. Notice that the first principal energy level has one sublevel, the second has two sublevels, the third has three sublevels, and the fourth has four. If n is the number associated with the principal energy level, each principal energy level has n sublevels. Thus there are five sublevels on the fifth principal energy level: 5s, 5p, 5d, 5f, and 5g. The 5s, 5p, 5d, and 5f orbitals have shapes similar to the 4s, 4p, 4d, and 4f orbitals, but they are larger and have higher potential energy.

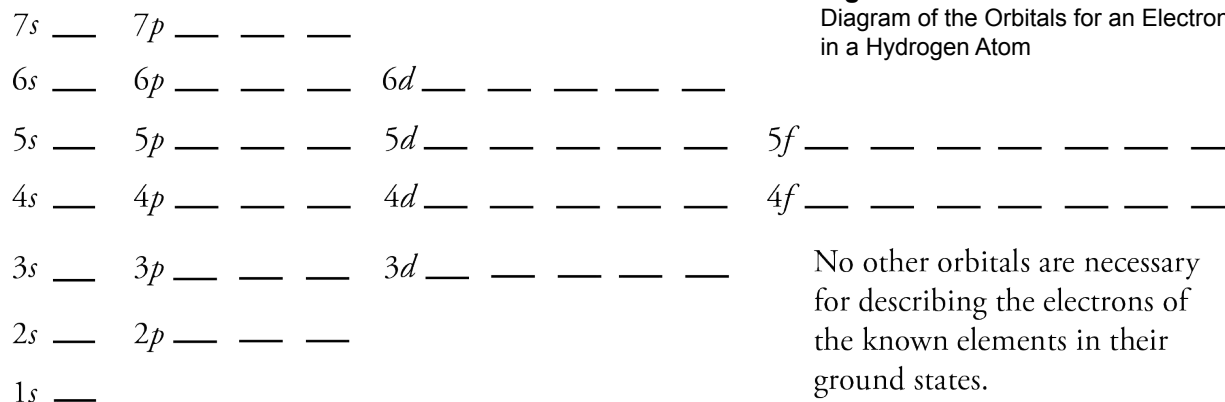Each s sublevel has one orbital, each p sublevel has three orbitals, each d has five orbitals, and each f sublevel has seven orbitals. Thus there are one 5s orbital, three 5p orbitals, five 5d orbitals, and seven 5f orbitals. The trend of increasing the number of orbitals by two for each succeeding sublevel continues for 5g and beyond. There are nine 5g orbitals with shapes more complex than the shapes of the 4f orbitals.

Table 4.2 Possible Sublevels and Orbitals for the First Seven Principal Energy Levels (The sublevels in parentheses are not necessary for describing any of the known elements.)

Sublevels (subshells)	Number of orbitals	Sublevels (subshells)	Number of orbitals
1s	1	6s	1
2s	1	6p	3
2p	3	6d	5
3s	1	(6f)	7
3p	3	(6g)	9
3d	5	(6h)	11
4s	1	7s	1
4p	3	7p	3
4d	5	(7d)	5
4f	7	(7f)	7
5s	1	(7g)	9
5p	3	(7h)	11
5d	5	(7i)	13
5f	7		
(5g)	9		

In the next section, where we use the orbitals predicted for hydrogen to describe atoms of other elements, you will see that none of the known elements has electrons in the 5g sublevel for their most stable state (ground state). Thus we are not very interested in describing the 5g orbitals. Likewise, although the sixth principal energy level has six sublevels and the seventh has seven, only the 6s, 6p, 6d, 7s, and 7p are important for describing the ground states of the known elements. The reason for this will be explained in the next section.

None of the known elements in its ground state has any electrons in a principal energy level higher than the seventh, so we are not concerned with the principal energy levels above seven. The orbital diagram in Figure 4.24 shows only the sublevels (or subshells) and orbitals that are necessary for describing the ground states of the known elements.

Figure 4.24
Diagram of the Orbitals for an Electron in a Hydrogen Atom

7s __   7p __ __ __

6s __   6p __ __ __   6d __ __ __ __ __

5s __   5p __ __ __   5d __ __ __ __ __   5f __ __ __ __ __ __ __

4s __   4p __ __ __   4d __ __ __ __ __   4f __ __ __ __ __ __ __

3s __   3p __ __ __   3d __ __ __ __ __

2s __   2p __ __ __

1s __

No other orbitals are necessary for describing the electrons of the known elements in their ground states.

4.3 Multi-Electron Atoms

It is possible to solve the wave equation and determine the shapes and sizes of electron orbitals for the hydrogen atom and for any one electron ion (for example He^+ or Li^{2+}), but the calculations for any atom with two or more electrons are extremely complex. Fortunately, scientists have found that when they take the information derived from solving the wave equation for hydrogen atoms and apply it to other atoms, the resulting descriptions are sufficiently accurate to explain many of the chemical characteristics of those elements. Thus the following assumption lies at the core of the modern description of atoms other than hydrogen. *All of the elements have the same set of possible principal energy levels, sublevels, and orbitals that has been calculated for hydrogen.* In other words, we assume that all atoms can have the sublevels and orbitals listed on Table 4.2. Now let us look at how the electrons of elements other than hydrogen are distributed in those hydrogen-like orbitals.

Helium and Electron Spin

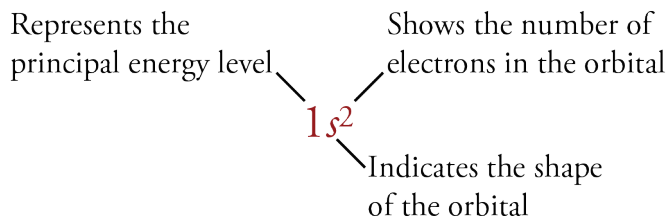OBJECTIVE 28

Figure 4.25
Electron Spin
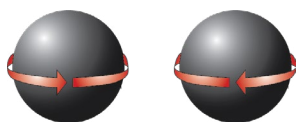
Helium, with atomic number 2 and two electrons, is the next element after hydrogen in the periodic table. Both of helium's electrons are in the $1s$ orbital. This allows them to be as close to the positive charge of the nucleus as possible. Even though the two electron charge clouds occupy the same space, the two electrons are not identical. The property in which they differ is called electron spin. Although the true nature of electron spin is uncertain, it is useful to think of it as if electrons can spin on their axis. We can visualize the two electrons in a helium atom as spinning in opposite directions (Figure 4.25).

Arrows are added to an **orbital diagram** to show the distribution of electrons in the possible orbitals and the relative spin of each electron. The following is an orbital diagram for a helium atom.

$1s$ ↑↓

The orbital distribution of electrons can also be described with a shorthand notation that describes the arrangement of electrons in the sublevels without reference to their spin. This shorthand for helium's configuration is written $1s^2$ and is commonly called an electron configuration. The 1 represents the first principal energy level, the s indicates an electron cloud with a spherical shape, and the 2 shows that there are two electrons in that $1s$ sublevel.

Represents the
principal energy level

Shows the number of
electrons in the orbital

$1s^2$
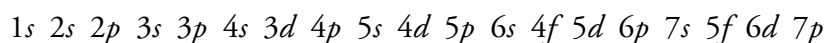
OBJECTIVE 29

Indicates the shape
of the orbital

In the broadest sense, an **electron configuration** is any description of the complete distribution of electrons in atomic orbitals. Although this can mean either an orbital diagram or the shorthand notation, this text will follow the common convention of referring to only the shorthand notation as an **electron configuration**. For example,

if you are asked for an electron configuration for helium, you will write $1s^2$. If you are expected to describe the orbitals with lines and the electrons with arrows, you will be asked to draw an orbital diagram.

The Second Period Elements

Electrons do not fill the available sublevels in the order we might expect. Thus, to predict the electron configurations of elements larger than helium, we need a way of remembering the actual order of sublevel filling. Probably the *least* reliable method is to memorize the following list that shows the order of filling of all the orbitals necessary for describing the ground state electron configurations of all of the known elements.

1s 2s 2p 3s 3p 4s 3d 4p 5s 4d 5p 6s 4f 5d 6p 7s 5f 6d 7p

OBJECTIVE 29

Instead of relying on memorization, you can use the memory aid shown in Figure 4.26 to remind you of the correct order of filling of the sublevels. The following steps explain how to write it and use it yourself.

- Write the possible sublevels for each energy level in organized rows and columns like in Figure 4.26. To do this, you need to remember that there is one sublevel on the first principal energy level, two on the second, three on the third, etc. Every principal energy level has an *s* orbital. The second principal energy and all higher energy levels have a *p* sublevel. The *d* sublevels start on the third principal energy level, the *f* sublevels start on the fourth principal energy level, etc.
- Draw arrows like those you see in Figure 4.26.
- Starting with the top arrow, follow the arrows one by one in the direction they point, listing the sublevels as you pass through them.

The sublevels that are not needed for describing the known elements are enclosed in parentheses in Figure 4.26. Later in this section, you will see how to determine the order of filling of the sublevels using a periodic table.

Start here and move along the arrows one by one.

1s

2s   2p

3s   3p   3d

4s   4p   4d   4f

5s   5p   5d   5f   (5g)

6s   6p   6d   (6f   6g   6h)

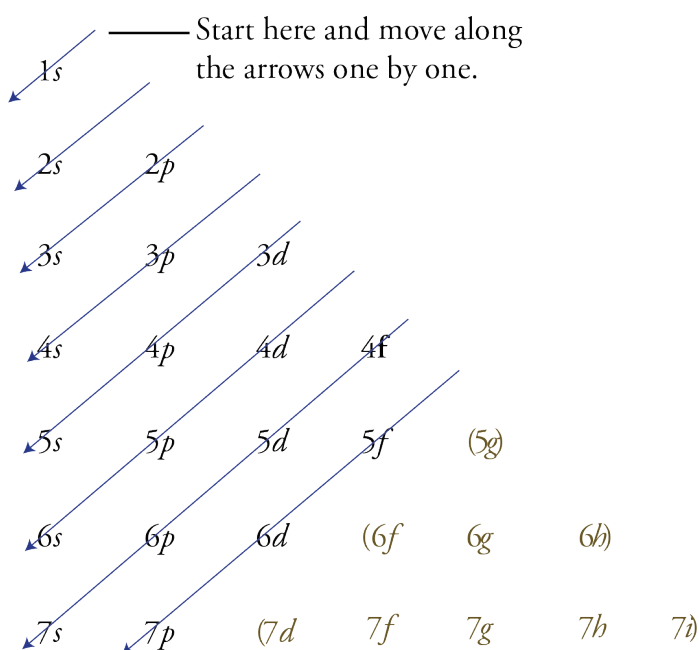7s   7p   (7d   7f   7g   7h   7i)

Figure 4.26
Aid for Remembering the Order
of Sublevel Filling

OBJECTIVE 29

An atomic orbital may contain two electrons at most, and the electrons must have different spins. Because each s sublevel has one orbital and each orbital contains a maximum of two electrons, each s sublevel contains a maximum of two electrons. Because each p sublevel has three orbitals and each orbital contains a maximum of two electrons, each p sublevel contains a maximum of six electrons. Using similar reasoning, we can determine that each d sublevel contains a maximum of ten electrons, and each f sublevel contains a maximum of 14 electrons (Table 4.3).

Table 4.3   General Information About Sublevels

Type of Sublevel	Number of Orbitals	Maximum Number of Electrons
s	1	2
p	3	6
d	5	10
f	7	14

We can now predict the electron configurations and orbital diagrams for the ground state of lithium, which has three electrons, and beryllium, which has four electrons:

Lithium $1s^2\ 2s^1$ Beryllium $1s^2\ 2s^2$

$2s\ \uparrow$ $2s\ \uparrow\downarrow$

$1s\ \uparrow\downarrow$ $1s\ \uparrow\downarrow$

OBJECTIVE 29
OBJECTIVE 30

A boron atom has five electrons. The first four fill the $1s$ and $2s$ orbitals, and the fifth electron goes into a $2p$ orbital. The electron configuration and orbital diagram for the ground state of boron atoms are below. Even though only one of three possible $2p$ orbitals contains an electron, we show all three $2p$ orbitals in the orbital diagram. The lines for the $2p$ orbitals are drawn higher on the page than the line for the $2s$ orbital to show that electrons in the $2p$ orbitals have a higher potential energy than electrons in the $2s$ orbital of the same atom.[2]

Boron $1s^2\ 2s^2\ 2p^1$

$2p\ \uparrow\ \underline{\quad}\ \underline{\quad}$

$2s\ \uparrow\downarrow$

$1s\ \uparrow\downarrow$
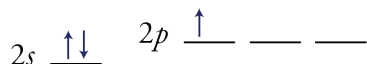
OBJECTIVE 29
OBJECTIVE 30

When electrons are filling orbitals of the same energy, they enter orbitals in such a way as to maximize the number of unpaired electrons, all with the same spin. In other words, they enter empty orbitals first, and all electrons in half filled orbitals have the same spin. The orbital diagram for the ground state of carbon atoms is

$2p\ \uparrow\ \uparrow\ \underline{\quad}$

$2s\ \uparrow\downarrow$

$1s\ \uparrow\downarrow$
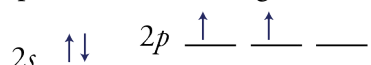
OBJECTIVE 30

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[2] The $2s$ and $2p$ orbitals available for the one electron of a hydrogen atom have the same potential energy. However, for reasons that are beyond the scope of this discussion, when an atom has more than one electron, the $2s$ orbital is lower in potential energy than the $2p$ orbitals.

There are two ways to write the electron configuration of carbon atoms. One way emphasizes that the two electrons in the $2p$ sublevel are in different orbitals:

$$1s^2\ 2s^2\ 2p_x{}^1\ 2p_y{}^1$$
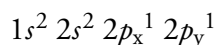
OBJECTIVE 29

Often, however, the arrangement of the $2p$ electrons is taken for granted, and the following notation is used:

$$1s^2\ 2s^2\ 2p^2$$

OBJECTIVE 29

Unless you are told otherwise, you may assume that a "complete electron configuration" means a configuration written in the second form, without the subscripts x, y, and z.
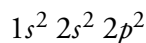
The electron configurations and orbital diagrams for the rest of the elements of the second period show the sequential filling of the $2p$ orbitals:

Nitrogen $1s^2\ 2s^2\ 2p^3$

Oxygen $1s^2\ 2s^2\ 2p^4$

OBJECTIVE 29
OBJECTIVE 30

Fluorine $1s^2\ 2s^2\ 2p^5$

Neon $1s^2\ 2s^2\ 2p^6$
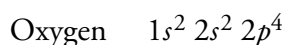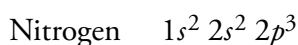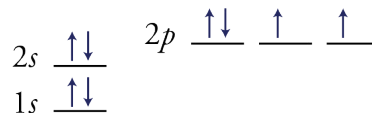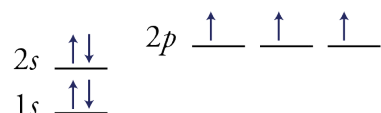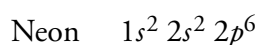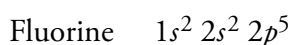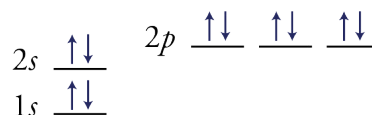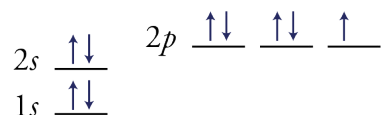
OBJECTIVE 29
OBJECTIVE 30

Figure 4.27 shows how the electron clouds for the electrons of the atoms of first and second period elements are envisioned. Note that the electron charge waveforms for the electrons in different orbitals of each atom are all superimposed on each other.

Figure 4.27
Electron Configurations and Orbital Models for the First Ten Elements

The Periodic Table and the Modern Model of the Atom

The periodic table itself can be used as a guide for predicting the electron configurations of most of the elements. Conversely, the electron configurations of the elements can be used to explain the table's structure and the similarities and differences that were the basis for the table's creation.

The organization of the periodic table reflects the modern model of the atom. For example, the highest-energy electrons for all of the elements in groups 1 (1A) and 2 (2A)

Figure 4.28
The Periodic Table and the Modern Model of the Atom

in the periodic table are in *s* orbitals. That is, the highest-energy electrons for lithium, Li, and beryllium, Be, atoms are in the 2*s* orbital, and the highest-energy electrons for sodium, Na, and magnesium, Mg, atoms are in the 3*s* orbital. This continues down to francium, Fr, and radium, Ra, which have their highest-energy electrons in the 7*s* orbital. Therefore, the first two columns on the periodic table are called the *s* block. Because hydrogen and helium have their electrons in the 1*s* orbital, they belong in the *s* block too (Figure 4.28).

All of the elements in the block with boron, B, neon, Ne, thallium, Tl, and radon, Rn, at the corners have their highest energy electrons in *p* orbitals, so this is called the *p* block (Figure 4.28). The second principal energy level is the first to contain *p* orbitals, so atoms of elements in the first row of the *p* block have their highest-energy electrons in the 2*p* sublevel. The highest-energy electrons for elements in the second row of the *p* block are in the 3*p* sublevel. This trend continues, so we can predict that the 81st through the 86th electrons for the elements thallium, Tl, through radon, Rn, are added to the 6*p* sublevel. Moreover, we can predict that the new elements that have been made with atoms larger than element 112 have their highest-energy electrons in the 7*p* sublevel.

The last electrons to be added to an orbital diagram for the atoms of the transition metal elements go into *d* orbitals. For example, the last electrons added to atoms of scandium, Sc, through zinc, Zn, are added to 3*d* orbitals. The elements yttrium, Y, through cadmium, Cd, have their highest-energy electrons in the 4*d* sublevel. The elements directly below them in rows 6 and 7 add electrons to the 5*d* and 6*d* orbitals. The transition metals can be called the *d* block. (Figure 4.28).

The section of the periodic table that contains the inner transition metals is called the *f* block. Thus we can predict that the last electrons added to the orbital diagrams of elements with atomic numbers 57 through 70 would go into the 4*f* sublevel. Elements 89 through 102 are in the second row of the *f* block. Because the fourth principal energy level is the first to have an *f* sublevel, we can predict that the highest energy electrons for these elements go to the 5*f* sublevel.

We can also use the block organization of the periodic table, as shown in Figure 4.28, to remind us of the order in which sublevels are filled. To do this, we move through the elements in the order of increasing atomic number, listing new sublevels as we come to them. The type of sublevel (*s*, *p*, *d*, or *f*) is determined from the block in which the atomic number is found. The number for the principal energy level (for example, the 3 in 3*p*) is determined from the row in which the element is found and the knowledge that the *s* sublevels start on the first principal energy level, the *p* sublevels start on the second principal energy level, the *d* sublevels start on the third principal energy level, and the *f* sublevels start on the fourth principal energy level.

■ We know that the first two electrons added to an atom go to the 1*s* sublevel.
■ Atomic numbers 3 and 4 are in the second row of the *s* block (look for them in the bottom half of Figure 4.28), signifying that the 3rd and 4th electrons are in the 2*s* sublevel.

- Atomic numbers 5 through 10 are in the first row of the *p* block, and the *p* sublevels start on the second energy level. Therefore, the 5ᵗʰ through 10ᵗʰ electrons go into the 2*p* sublevel.
- Atomic numbers 11 and 12 are in the third row of the *s* block, so the 11ᵗʰ and 12ᵗʰ electrons go into the 3*s* sublevel.
- Because atomic numbers 13 through 18 are in the *p* block, we know they go into a *p* sublevel. Because the *p* sublevels begin on the second principal energy level and atomic numbers 13 through l8 are in the second row of the *p* block, the 13ᵗʰ through 18ᵗʰ electrons must go into the 3*p* sublevel.
- The position of atomic numbers 19 and 20 in the fourth row of the *s* block and the position of atomic numbers 21 through 30 in the first row of the *d* block show that the 4*s* sublevel fills before the 3*d* sublevel.

Moving through the periodic table in this fashion produces the following order of sublevels up through 6*s*:

1*s* 2*s* 2*p* 3*s* 3*p* 4*s* 3*d* 4*p* 5*s* 4*d* 5*p* 6*s*
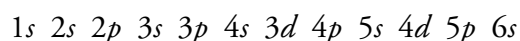
Note that atomic numbers 57 through 70 on the periodic table in Figure 4.28 are in the 4*f* portion of the table. It is a common mistake to forget that the 4*f* sublevel is filled after the 6*s* sublevel and before the 5*d* sublevel. In order to make the overall shape of the table more compact and convenient to display, scientists have adopted the convention of removing the elements with atomic number 57 through 70 and 89 through 102 (the latter being the 5*f* portion of the table) from their natural position between the *s* and *d* blocks and placing them at the bottom of the table. Electrons go into the 5*f* sublevel after the 7*s* sublevel and before the 6*d* sublevel. The periodic table in Figure 4.29 shows how the blocks on the periodic table would fit together if the inner transition metals—the *f* block—were left in their natural position.

Figure 4.29
Periodic Table with the Inner Transition Metals in Their Natural Position

The following sample study sheet shows the general steps for writing complete electron configurations and orbital diagrams for uncharged atoms.

Sample Study
Sheet 4.1

Writing
Complete
Electron
Configurations
and Orbital
Diagrams for
Uncharged
Atoms

OBJECTIVE 29
OBJECTIVE 30

TIP-OFF   If you are asked to write a complete electron configuration or an orbital diagram, you can use the following guidelines.

GENERAL STEPS

To write a complete electron configuration for an uncharged atom:

STEP 1 Determine the number of electrons in the atom from its atomic number.

STEP 2 Add electrons to the sublevels in the correct order of filling. Add two electrons to each *s* sublevel, 6 to each *p* sublevel, 10 to each *d* sublevel, and 14 to each *f* sublevel.

STEP 3 To check your complete electron configuration, look to see whether the location of the last electron added corresponds to the element's position on the periodic table. (See Example 4.2.)

To draw an orbital diagram for an uncharged atom,

STEP 1 Write the complete electron configuration for the atom. (This step is not absolutely necessary, but it can help guide you to the correct orbital diagram.)

STEP 2 Draw a line for each orbital of each sublevel mentioned in the complete electron configuration.

Draw one line for each s sublevel, three lines for each *p* sublevel, five lines for each *d* sublevel, and seven lines for each *f* sublevel.

As a guide to the order of filling, draw your lines so that the orbitals that fill first are lower on the page than the orbitals that fill later.

Label each sublevel.

STEP 3 For orbitals containing two electrons, draw one arrow up and one arrow down to indicate the electrons' opposite spin.

STEP 2 For unfilled sublevels, add electrons to empty orbitals whenever possible, giving them the same spin.

The arrows for the first three electrons to enter a *p* sublevel should each be placed pointing up in different orbitals. The fourth, fifth, and sixth are then placed, pointing down, in the same sequence, so as to fill these orbitals.

The first five electrons to enter a *d* sublevel should be drawn pointing up in different orbitals. The next five electrons are drawn as arrows pointing down and fill these orbitals (again, following the same sequence as the first five *d* electrons).

The first seven electrons to enter an *f* sublevel should be drawn as arrows pointing up in different orbitals. The next seven electrons are paired with the first seven (in the same order of filling) and are drawn as arrows pointing down.

EXAMPLE   See Example 4.2.

EXAMPLE 4.2 - Electron Configurations and Orbital Diagrams

Write the complete electron configuration and draw an orbital diagram for iron, Fe.

Solution

We follow the steps described in Study Sheet 4.1 to write the complete electron configuration:

Determine the number of electrons in the atom from its atomic number.

The periodic table shows us that iron, Fe, has an atomic number of 26, so an uncharged atom of iron has 26 electrons.

Add electrons to the sublevels in the correct order of filling.

We can determine the order of filling by either memorizing it, figuring it out from the memory aid shown in Figure 4.26, or using the periodic table and our knowledge of *s*, *p*, *d*, and *f* blocks. The order of filling is

$$1s\ 2s\ 2p\ 3s\ 3p\ 4s\ 3d\ 4p\ 5s\ 4d\ 5p\ 6s\ 4f\ 5d\ 6p\ 7s\ 5f\ 6d\ 7p$$
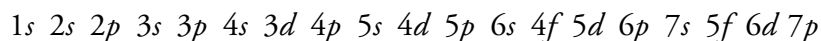
Next, we fill the orbitals according to this sequence, putting two electrons in each s sublevel, six in each *p* sublevel, 10 in each *d* sublevel, and 14 in each *f* sublevel until we reach the desired number of electrons. For iron, we get the following complete electron configuration:
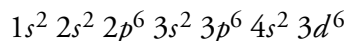
$$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^6$$

To check your complete electron configuration, look to see whether the location of the last electron added corresponds to the element's position on the periodic table.

Because it is fairly easy to forget a sublevel or miscount the number of electrons added, it is a good idea to quickly check your complete electron configuration by looking to see if the last electrons added correspond to the element's location on the periodic table. The symbol for iron, Fe, is found in the sixth column of the *d* block. This shows that there are six electrons in a *d* sublevel. Because iron is in the first row of the *d* block, and because the *d* sublevels begin on the third principal energy level, these six electrons are correctly described as $3d^6$.

To draw the orbital diagram, we draw a line for each orbital of each sublevel mentioned in the complete electron configuration above. For orbitals containing two electrons, we draw one arrow up and one arrow down to indicate the electrons' opposite spin. For unfilled sublevels, we add electrons to empty orbitals first with the same spin. The orbital diagram for iron atoms is displayed below. Note that four of the six electrons in the 3*d* sublevel are in different orbitals and have the same spin.

3*d* ↑↓ ↑ ↑ ↑ ↑

4*s* ↑↓

3*s* ↑↓   3*p* ↑↓ ↑↓ ↑↓

2*s* ↑↓   2*p* ↑↓ ↑↓ ↑↓

1*s* ↑↓
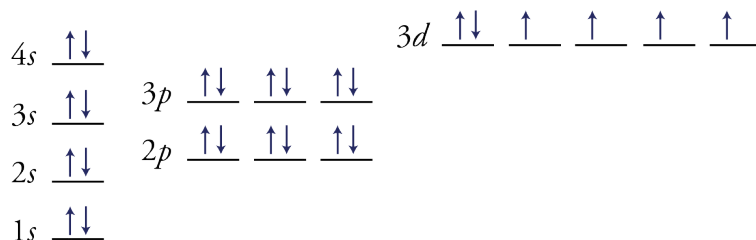
EXERCISE 4.2 - Electron Configurations and Orbital Diagrams

Write the complete electron configuration and draw an orbital diagram for antimony, Sb.

Abbreviated Electron Configurations

We learned in Chapter 3 that the noble gases rarely form chemical bonds. This can now be explained in terms of the stability of their electron configurations. The formation of chemical bonds requires atoms to gain, lose, or share electrons, and the electron configurations of the noble gases (displayed below) are so stable that their atoms do not easily undergo any of those changes.

He $1s^2$

Ne $1s^2\, 2s^2\, 2p^6$

Ar $1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6$

Kr $1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6\, 4s^2\, 3d^{10}\, 4p^6$

Xe $1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6\, 4s^2\, 3d^{10}\, 4p^6\, 5s^2\, 4d^{10}\, 5p^6$

Rn $1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6\, 4s^2\, 3d^{10}\, 4p^6\, 5s^2\, 4d^{10}\, 5p^6\, 6s^2\, 4f^{14}\, 5d^{10}\, 6p^6$
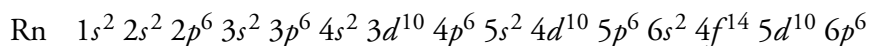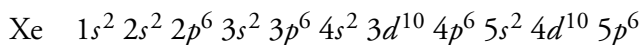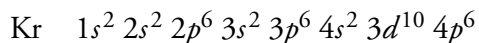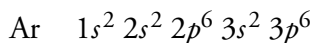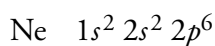
The atoms of other elements (other than hydrogen) contain noble gas configurations as part of their own electron configurations. For example, the configuration of a sodium atom is the same as neon's configuration with the addition of one more electron to the 3s orbital.

Ne $1s^2\, 2s^2\, 2p^6$

Na $1s^2\, 2s^2\, 2p^6\, 3s^1$
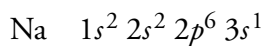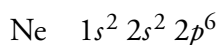
The 3s electron of sodium is much more important in the description of sodium's chemical reactions than the other electrons are. There are two reasons why this is true. We know from the stability of neon atoms that the $1s^2\, 2s^2\, 2p^6$ configuration is very stable, so these electrons are not lost or shared in chemical reactions involving sodium. These electrons are called the noble gas inner core of sodium. Another reason is that an electron in the larger 3s orbital is less strongly attracted to the nuclear charge than electrons in smaller orbitals in the first and second principal energy levels. As a result, the 3s electron is easier to remove.

Because we are not as interested in the noble gas inner core of electrons for sodium atoms as we are in the 3s electron, sodium atoms are often described with the following abbreviated electron configuration, in which [Ne] represents the electron configuration of neon:

Na   [Ne] $3s^1$

Sometimes the symbol for the noble gas is left out of abbreviated electron configurations, but in this text, all abbreviated electron configurations will consist of the symbol, in brackets, for the noble gas element at the end of the previous row, followed by the electron configuration of the remaining electrons (Figure 4.30).

Abbreviated electron configurations are especially useful for describing the chemistry of larger atoms. For example, atoms of cesium, Cs, have one more electron than xenon, Xe. Therefore, the 55th electron of a cesium atom is the only electron that is likely to participate in the formation of chemical bonds. Because atomic number 55 is in the sixth horizontal row of the *s* block, the 55th electron must be in the $6s$ sublevel, making the abbreviated electron configuration for cesium atoms

Cs $[Xe]\ 6s^1$
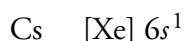
This is much easier to determine and much less time consuming to write than the complete electron configuration:

$$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^1$$
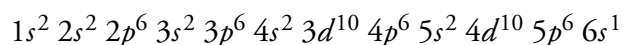
Figure 4.30
Group 1 Abbreviated Electron
Configurations
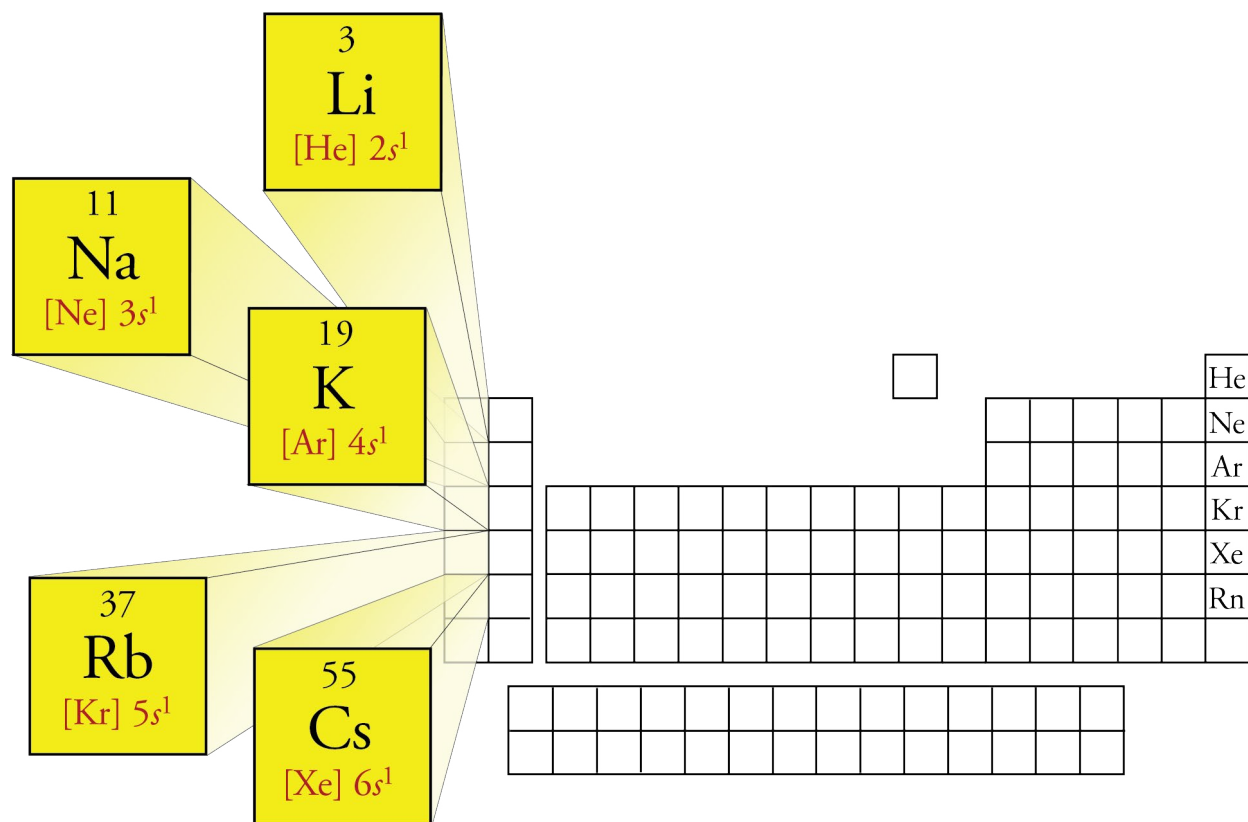
The following sample study sheet shows the steps for writing abbreviated electron configurations.

TIP-OFF   If you are asked to write an abbreviated electron configuration, you can use the following steps.

GENERAL STEPS

STEP 1   Find the symbol for the element on a periodic table.

For example, to write an abbreviated electron configuration for zinc atoms, we first find Zn on the periodic table (Figure 4.31).

STEP 2   Write the symbol in brackets for the noble gas located at the far right of the preceding horizontal row on the table.

For zinc, we move up to the third period and across to Ar (Figure 4.31). To describe the first 18 electrons of a zinc atom, we write

[Ar]

STEP 3   Move back down a row (to the row containing the element you wish to describe) and to the far left. Following the elements in the row from left to right, write the outer-electron configuration associated with each column until you reach the element you are describing.

For zinc, we need to describe the 19th through the 30th electrons. The atomic numbers 19 and 20 are in the fourth row of the s block, so the 19th and 20th electrons for each zinc atom enter the $4s^2$ sublevel. The atomic numbers 21 through 30 are in the first row of the d block, so the 21st to the 30th electrons for each zinc atom fill the $3d$ sublevel (Figure 4.31). Zinc, with atomic number 30, has the abbreviated configuration

[Ar] $4s^2\ 3d^{10}$

EXAMPLE   See Example 4.3.

Sample Study Sheet 4.2

Abbreviated Electron Configurations

OBJECTIVE 31

Step 1   Find the symbol for the element (zinc).

Step 2   Write the symbol in brackets for the nearest, smaller noble gas.

Step 3   Write the outer electron configuration for the remaining electrons.

[Ar] $4s^2\ 3d^{10}$

[Ar]

Figure 4.31
Steps for Writing Abbreviated Electron Configurations for a Zinc Atom

EXAMPLE 4.3 - Abbreviated Electron Configurations

Write abbreviated electron configurations for (a) strontium, Sr, (b) germanium, Ge, and (c) thallium, Tl.

Solution

a. With an atomic number of 38, strontium has 38 electrons. The noble gas element at the end of the previous row is krypton, so putting Kr in brackets describes strontium's first 36 electrons. The atomic numbers 37 and 38 are in the fifth row of the s block, indicating that the 37th and 38th electrons enter and fill the $5s$ sublevel.

$$[\text{Kr}]\ 5s^2$$
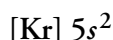
b. With an atomic number of 32, germanium has 32 electrons. The noble gas element at the end of the previous row is argon, so putting Ar in brackets describes germanium's first 18 electrons. The atomic numbers 19 and 20 are in the fourth row of the s block, so the 19th and 20th electrons enter the $4s$ sublevel. The atomic numbers 21 through 30 are in the first row of the d block. Because the d sublevels start on the third principal energy level, the 21st through 30th electrons are in the $3d$ sublevel. The atomic numbers 31 and 32 are in the third row of the p block, or the $4p$ sublevel (because the p sublevels start on the second principal energy level). Thus the last two electrons for a germanium atom are in the $4p$ sublevel.

$$[\text{Ar}]\ 4s^2\ 3d^{10}\ 4p^2$$

c. With an atomic number of 81, thallium has 81 electrons. Its noble gas inner core of electrons has the xenon, Xe, configuration, and its 55th and the 56th electrons are in the $6s$ sublevel. The atomic numbers 57 through 70 are in the first row of the f block, so the next 14 electrons are in the $4f$ sublevel. (Remember that the sixth and seventh rows contain an f sublevel; this is commonly forgotten.) Electrons 71 through 80 are in the $5d$ sublevel. The atomic number 81 is in the fifth row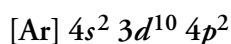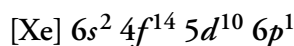 of the p block, or the $6p$ sublevel (because the p sublevels start on the second principal energy level). Thus the 81st electron is in a $6p$ orbital.

$$[\text{Xe}]\ 6s^2\ 4f^{14}\ 5d^{10}\ 6p^1$$

EXERCISE 4.3 - Electron Configurations and Orbital Diagrams

Write abbreviated electron configurations for (a) rubidium, Rb, (b) nickel, Ni, and (c) bismuth, Bi.

Some of the elements have electron configurations that differ slightly from what our general procedure would lead us to predict. You can read more about these at the textbook's Web site. The Web site also shows you how to predict charges on monatomic ions and how to write their electron configurations.

Now that you have learned something about the elements' electron configurations (even though you cannot say precisely what an electron is), Chapter 5 will show you how the configurations can be used to explain patterns of bonding and the structure of molecules.

SPECIAL TOPIC 4.1   Why Does Matter Exist, and Why Should We Care About This Question?

A great deal of money, time, and scientific expertise are spent on trying to answer questions such as, "*What is the nature of matter, and why does it exist?*" When it comes time for lawmakers to distribute tax money and for executives in industry or academia to plan their research goals, it is natural for them, in turn, to wonder, "*Shouldn't we direct our energies and money toward more practical goals? Isn't it much more important to develop procedures for early diagnosis and treatment of Alzheimer's disease rather than spend our limited resources on understanding how the universe came to be?*" These sorts of questions are at the core of an on-going debate between people who believe strongly in basic research, the seeking of knowledge for its own sake without a specific application in mind, and those who prefer to focus on applied research, the attempt to develop a specific procedure or product.

Often, basic research leads to unforeseen practical applications. Quantum mechanics, the wave mathematics used to predict the shapes and sizes of atomic orbitals, provides an example. In 1931 Paul Adrien Dirac, one of the pioneers of quantum mechanics, found an unexpected minus sign in the equations he was developing to describe the nature of matter. He could have ignored this problem in the hope that it would disappear with further refinement of the equations, but Dirac took a much bolder approach instead. He suggested that the minus sign indicated the existence of a particle identical to the electron except that it has a positive charge instead of a negative charge. This "anti-electron," which was detected in the laboratory by Carl Anderson in 1932, came to be called a positron, e^+.

Apparently, every particle has a twin antiparticle, and they are formed together from very concentrated energy. In 1955 and 1956, antiprotons and antineutrons were created and detected. The general name for antiparticles is antimatter. As the terminology suggests, when a particle meets its antimatter counterpart, they annihilate each other, leaving pure energy in their place. For example, when a positron collides with an electron, they both disappear, sending out two gamma ray photons (γ-ray) in opposite directions.
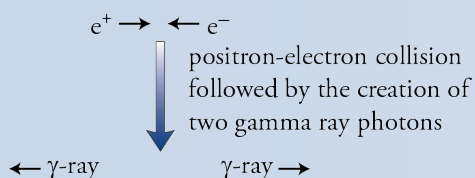
Originally, there was no practical application for the discovery of antimatter, although its existence suggested possible answers to some very big questions. Perhaps the universe was originally created from the conversion of some extremely concentrated energy source into matter and antimatter. However, while some scientists continue to do basic research on the nature of matter and antimatter, others are using the knowledge and techniques developed through this basic research to actively seek practical applications. One use of the antimatter created in the laboratory is called positron emission tomography (PET). With the help of a large team of scientists and computer experts, physicians use PET to scan the brain in search of biochemical abnormalities that signal the presence of Alzheimer's disease, schizophrenia, epilepsy, brain tumors, and other brain disorders.

In PET, radioactive substances that emit positrons are introduced into a patient's bloodstream. As the radioactive atoms decay, the positrons they emit collide with electrons, producing gamma rays that escape from the body and are detected by an array of instruments surrounding the patient. Computer analysis of the amount and direction of gamma ray production, and comparison of the data collected for people with and without certain brain disorders provides doctors with valuable information. For example, PET scans of the brain have been used to study the movement of the medication L-dopa in the brains of people suffering from Parkinson's disease. In these procedures, fluorine-18 atoms are attached to L-dopa molecules, which are then injected into a patient. Each flourine-18 decays and emits a positron that generates gamma rays when it meets an electron.

Similar experiments are providing information about physiological processes such as glucose metabolism, the effects of opiate drugs, and the mechanisms of memory retrieval. Without the basic research, PET technology could never have been imagined, and it is just one of the many reasons why we should continue to ask fundamental questions such as, "*Why are we here?*" and "*How do things work?*"

$$e^+ \rightarrow \quad \leftarrow e^-$$

positron-electron collision
followed by the creation of
two gamma ray photons

$\leftarrow$ γ-ray   γ-ray $\rightarrow$

Chapter Glossary

Energy   The capacity to do work.

Kinetic energy   The capacity to do work due to the motion of an object.

Law of Conservation of Energy   Energy can neither be created nor destroyed, but it can be transferred from one system to another and changed from one form to another.

Potential energy   A retrievable, stored form of energy an object possesses by virtue of its position or state.

Endergonic (endogonic) change   Change that absorbs energy.

Exergonic (exogonic) change   Change that releases energy.

Joule (J)   The accepted international unit for energy.

calorie (with a lowercase c)   A common energy unit. There are 4.184 joules per calorie (abbreviated *cal*).

Calorie (with an upper case C)   The dietary calorie (abbreviated Cal). In fact, it is a kilocalorie, the equivalent of 4184 joules.

Internal kinetic energy   The energy associated with the random motion of particles.

Temperature   A measure of the average internal kinetic energy of an object.

Heat   The energy transferred from a region of higher temperature to a region of lower temperature due to collisions between particles.

Radiant energy or electromagnetic radiation   Energy that can be described in terms of either oscillating electric and magnetic fields or in terms of a stream of tiny packets of energy with no mass.

Photons   Tiny packets or particles of radiant energy.

Wavelength (λ)   The distance in space over which a wave completes one cycle of its repeated form.

Waveform   A representation of the shape of a wave.

Nodes   The locations in a waveform where the intensity of the wave is always zero.

Orbitals   The allowed waveforms for the electron. This term can also be defined as a volume that contains a high percentage of the electron charge or as a volume within which an electron has a high probability of being found.

Principal energy level or shell   A collection of orbitals that have the same potential energy for a hydrogen atom, except for the first (lowest) principal energy level, which contains only one orbital (1*s*). For example, the 2*s* and 2*p* orbitals are in the second principal energy level.

Ground state   The condition of an atom whose electrons are in the orbitals that give it the lowest possible potential energy.

Excited state   The condition of an atom that has at least one of its electrons in orbitals that do not represent the lowest possible potential energy.

Sublevel or Subshell   One or more orbitals that have the same potential energy, the same size, and the same shape. For example, the second principal energy level contains a 2*s* sublevel (with one spherical orbital) and a 2*p* sublevel (with three dumbbell-shaped orbitals).

Orbital diagram   A drawing that uses lines or squares to show the distribution of electrons in orbitals and arrows to show the relative spin of each electron.

Electron configuration   A description of the complete distribution of an element's electrons in atomic orbitals. Although a configuration can be described either with an orbital diagram or with its shorthand notation, this text will follow the common convention of referring to the shorthand notation that describes the distribution of electrons in sublevels without reference to the spin of the electrons as an electron configuration.

> **You can test yourself on the glossary terms at the textbook's Web site.**

Chapter Objectives

The goal of this chapter is to teach you to do the following.

1. Define all of the terms in the Chapter Glossary.

Section 4.1 Energy

2. Explain why a more massive object, such as a bulldozer, has a more energy than a less massive object, such as a scooter, moving at the same velocity.
3. Explain why an object, such as a bulldozer, has more energy when it is moving at a higher velocity than the same object moving at a lower velocity.
4. State the Law of Conservation of Energy.
5. Describe the relationship between stability, capacity to do work, and potential energy.
6. Explain why an object, such as a coin, gains potential energy as it moves farther from the earth.
7. Explain why energy must be absorbed to break a chemical bond.
8. Explain why energy is released when a chemical bond is formed.
9. Convert between the names and abbreviations for joule (J), calorie (cal), and dietary calorie (Calorie or Cal).
10. Write or identify the relative sizes of the joule, calorie, and dietary calorie (Calorie).
11. Explain the difference between external kinetic energy and internal kinetic energy.
12. List the three ways that an object's internal kinetic energy can be increased.
13. Write or identify what is meant in terms of average internal kinetic energy when we say that one object has a higher temperature than another object.
14. Describe the changes that take place during heat transfer between objects at different temperatures.
15. Write a brief description of radiant energy in terms of its particle nature.
16. Write a brief description of radiant energy in terms of its wave nature.
17. Write or identify the relationship between the wavelength of radiant energy and the energy of its photons.
18. Write or identify the relative energies and wavelengths of the following forms of radiant energy: gamma rays, X rays, ultraviolet (UV), visible, infrared (IR), microwaves, and radio waves.
19. Write or identify the relative energies and wavelengths of the following colors of visible light: violet, blue, green, yellow, orange, and red.

Section 4.2 The Mysterious Electron

20. Explain why, in theory, a guitar string can vibrate with an infinite number of possible waveforms, but why not all waveforms are possible.

21. Describe how electrons are like vibrating guitar strings.
22. Describe the 1*s* orbital in a hydrogen atom in terms of negative charge and in terms of the electron as a particle.
23. Explain why electrons in atoms are often described in terms of electron clouds.
24. Describe a 2*s* orbital for a hydrogen atom.
25. Explain why an electron in a hydrogen atom has lower potential energy in the 1*s* orbital than the 2*s* orbital.
26. Describe the three 2*p* orbitals for a hydrogen atom.
27. Draw, describe, or recognize descriptions or representations of the 3*s*, 3*p*, and 3*d* orbitals.

Section 4.3 Multi-Electron Atoms

28. Describe the difference between any two electrons in the same atomic orbital.
29. Write complete electron configurations for all of the elements on the periodic table that follow the normal order of filling of the sublevels.
30. Draw orbital diagrams for all of the elements on the periodic table that follow the normal order of filling of the sublevels.
31. Write abbreviated electron configurations for all of the elements on the periodic table that follow the normal order of filling of the sublevels.

Review Questions

For questions 1 and 2, illustrate your answers with simple drawings of the particles that form the structures of the substances mentioned. You do not need to be specific about the nature of the particles. Think of them as simple spheres, and draw them as circles. Provide a general description of the arrangement of the particles, the degree of interaction between them, and their freedom of movement.

1. A pressurized can of a commercial product used to blow the dust off computer components contains tetrafluoroethane. At room temperature, this substance is a liquid at pressures slightly above normal pressure and a gas at normal pressures. Although most of the tetrafluoroethane in the can is in the liquid form evaporates rapidly, resulting in a significant amount of vapor above the liquid. When the valve on the top of the can is pushed, the tetrafluoroethane gas rushes out, blowing dust off the computer. When the valve closes, more of the liquid evaporates to replace the vapor released. If the can is heated, the liquid evaporates more quickly, and the increase in gas causes the pressure to build up to possibly dangerous levels.
   a. Describe the general structure of liquids, such as liquid tetrafluoroethane.
   b. Describe the general structure of gases, such as gaseous tetrafluoroethane.
   c. Describe the process by which particles move from liquid to gas.
   d. Describe the changes that take place in the liquid when it is heated, and explain why these changes lead to a greater rate of evaporation of the liquid.
2. Sodium metal can be made by running an electric current through molten sodium chloride.
   a. Describe the changes that take place when the temperature of sodium chloride solid increases.
   b. Describe the changes that take place when sodium chloride melts.
3. Describe the nuclear model of the atom.

Complete the following statements by writing one of these words or phrases in each blank.

4.184	motion
analogies	motion
average	*n*
calculated for hydrogen	negative charge
calorie	nine
change	other elements
changed	*p* block
cloud	particle
collisions	particle
created	particle interpretation
cycle	peaks
d	position or state
decrease	positions
decreased	possible
definitely	potential
destroyed	principal
diminishes	probabilities
electric	probably
electron configuration	resistance
energy	retrievable, stored
exactly	*s* orbitals
external	seven
five	seventh
greater	shorter
high percentage	spherical
hydrogen	spinning
impossible	spins
increases	spontaneously returns
inner transition metals	strange
intense	strength
intensity of the movement	sublevel
intensity of the negative charge	three
internal kinetic	three-dimensional
joule	transferred
less	two
magnetic	unpaired
mass	volume
massless	wave
mathematics	wave
modern physics	waveforms
more	

4. The simplest definition of _____ is that it is the capacity to do work. Work, in this context, may be defined as what is done to move an object against some sort of _____.

5. The capacity to do work resulting from the _____ of an object is called kinetic energy, KE.

6. If two objects are moving at the same velocity, the one with the greater _____ will have a greater capacity to do work and thus a greater kinetic energy.

7. If two objects have equal mass but different velocities, the one with the greater velocity has the _____ kinetic energy.

8. The Law of Conservation of Energy states that energy can be neither _____ nor _____, but it can be _____ from one system to another and _____ from one form to another.

9. Potential energy (PE) is a(n) _____ form of energy an object possesses by virtue of its _____.

10. A system's stability is a measure of its tendency to _____.

11. As an object moves from a(n) _____ stable state to a(n) _____ stable state, it can do work.

12. Any time a system shifts from a more stable state to a less stable state, the potential energy of the system _____.

13. Energy is necessary to separate two atoms being held together by mutual attraction in a chemical bond. The energy supplied increases the _____ energy of the less stable separate atoms compared to the more stable atoms in the bond.

14. Because less stable separate atoms have higher potential energy than the more stable atoms that participate in a bond, the change from separate atoms to atoms in a bond corresponds to a(n) _____ in potential energy.

15. The accepted SI unit for energy is the _____, but another common unit is the _____.

16. The U.S. National Institute of Standards and Technology defines the calorie as _____ joules.

17. A falling coin has a certain _____ kinetic energy that is related to its overall mass and to its velocity as it falls.

18. The energy associated with internal motion of particles that compose an object can be called _____ energy.

19. Temperature is a measure of the _____ internal kinetic energy of an object.

20. Heat is the energy that is transferred from a region of higher temperature to a region of lower temperature as a consequence of the _____ of particles.

21. Radiant energy seems to have a dual nature, with both _____ and _____ characteristics.

22. Radiant energy can be viewed as a stream of tiny, _____ packets of energy called photons.

23. The wave view says that as radiant energy moves away from its source, it has an effect on the space around it that can be described as a wave consisting of an oscillating _____ field perpendicular to an oscillating _____ field.

24. One distinguishing characteristic of the waves of radiant energy is wavelength, λ, the distance between two _____ on the wave of electromagnetic radiation. A more specific definition of wavelength is the distance in space over which a wave completes one _____ of its repeated form.

25. The _____ the wavelength of a wave of electromagnetic radiation, the greater the energy of its photons.

26. The electron is extremely tiny, and modern physics tells us that _____ things happen in the realm of the very, very small.

27. The modern description of the electron is based on complex _____ and on the discoveries of _____.

28. Modern physics tells us that it is _____ to know _____ where an electron is and what it is doing.

29. There are two ways in which scientists deal with the problems associated with the complexity and fundamental uncertainty of the modern description of the electron, _____ and _____.

30. In order to accommodate the uncertainty of the electron's position and motion, scientists talk about where the electron _____ is within the atom, instead of where it _____ is.

31. Each electron seems to have a dual nature in which both _____ and _____ characteristics are apparent.

32. In the wave view, an electron has an effect on the space around it that can be described as a wave of _____ varying in its intensity.

33. The _____ for electrons in an atom describe the variation in intensity of negative charge within the atom, with respect to the location of the nucleus. This can be described without mentioning the _____ and _____ of the electron particle itself.

34. Just as the _____ of a guitar string can vary, so can the _____ of the electron vary at different positions outside the nucleus.

35. The variation in the intensity of the electron charge can be described in terms of a(n) _____ standing wave like the standing wave of the guitar string.

36. As in the case of the guitar string, only certain waveforms are _____ for the electron in an atom.

37. Most of the general descriptions of electrons found in this chapter are based on the wave mathematics for the one electron in a(n) _____ atom.

38. The information calculated for the hydrogen electron is used to describe the _____ as well.

39. For the 1s orbital, the negative charge is most _____ at the nucleus and _____ with increasing distance from the nucleus.

40. The allowed waveforms for the electron are also called orbitals. Another definition of orbital is as the volume that contains a given _____ of the electron charge. An orbital can also be defined as the _____ within which an electron has a high probability of being found.

41. According to the _____ of the wave character of the electron, the surface that surrounds 90% of an electron's charge is the surface within which we have a 90% probability of finding the electron.

42. In the particle view, the electron _____ can be compared to a multiple exposure photograph of the electron.

43. All _____ electron waveforms are called *s* orbitals.

44. Because the _____ of the attraction between positive and negative charges decreases with increasing distance between the charges, an electron is more strongly attracted to the nucleus and therefore is more stable when it has the smaller 1*s* waveform than when it has the larger 2*s* waveform. Increased stability is associated with _____ potential energy, so a 1*s* electron has lower potential energy than a 2*s* electron.

45. All of the orbitals that have the same potential energy for a hydrogen atom are said to be in the same _____ energy level.

46. After the electron is excited from the 1*s* orbital to the 2*s* orbital, it _____ to its lower-energy 1*s* form.

47. There are _____ possible 2*p* orbitals.

48. Orbitals that have the same potential energy, the same size, and the same shape are in the same _____.

49. In the third principal energy level, there are _____ possible orbitals for an electron, in three different sublevels.

50. Note that the first principal energy level has one sublevel, the second has two, the third has three, and the fourth has four. If _____ is the number associated with the principal energy level, each principal energy level has *n* sublevels.

51. Each *s* sublevel has one orbital, each *p* sublevel has three orbitals, each *d* sublevel has _____ orbitals, and each *f* sublevel has _____ orbitals.

52. None of the known elements in its ground state has any electrons in a principal energy level higher than the _____.

53. Scientists assume that all of the elements have the same set of possible principal energy levels, sublevels, and orbitals that has been _____.

54. We can visualize the two electrons in a helium atom as _____ in opposite directions.

55. In the broadest sense, a(n) _____ is any description of the complete distribution of electrons in atomic orbitals.

56. An atomic orbital may contain _____ electrons at most, and the electrons must have different _____.

57. When electrons are filling orbitals of the same energy, they enter orbitals in such a way as to maximize the number of _____ electrons, all with the same spin. In other words, they enter empty orbitals first, and all electrons in half-filled orbitals have the same spin.

58. The highest-energy electrons for all of the elements in groups 1 (1A) and 2 (2A) in the periodic table are in _____.

59. All of the elements in the block with boron, B, neon, Ne, thallium, Tl, and radon, Rn, at the corners have their highest-energy electrons in *p* orbitals, so this is called the _____.

60. The last electrons to be added to an orbital diagram for the atoms of the transition metal elements go into _____ orbitals.

61. The section of the periodic table that contains the _____ is called the *f* block.

Section 4.1 Energy

62. For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 5

   a. (1) An ozone molecule, O_3, with a velocity of 393 m/s or (2) the same molecule moving with a velocity of 410 m/s. (These are the average velocities of ozone molecules at 25 °C and 50 °C.)
   b. (1) An ozone molecule, O_3, moving at 300 m/s or (2) an oxygen molecule, O_2, moving at the same velocity.
   c. (1) A proton and an electron close together or (2) a proton and an electron farther apart.
   d. (1) An HOCl molecule or (2) an OH molecule and a chlorine atom formed from breaking the chlorine-oxygen bond in the HOCl molecule. (The conversion of HOCl into Cl and OH takes place in the stratosphere.)
   e. (1) Two separate chlorine atoms in the stratosphere or (2) a chlorine molecule, Cl_2, that can form when they collide.
   f. (1) Water in the liquid form or (2) water in the gaseous form. (Assume that the two systems are at the same temperature.)

63. For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 5

   a. (1) A methane molecule, CH_4, in the stratosphere or (2) a CH_3 molecule and a hydrogen atom formed from breaking one of the carbon-hydrogen bonds in a CH_4 molecule.
   b. (1) A water molecule moving at 1.63×10^3 mi/h or (2) the same water molecule moving at 1.81×10^3 mi/h. (These are the average velocities of water molecules at 110 °C and 200 °C.)
   c. (1) Iodine solid or (2) iodine gas. (Assume that the two systems are at the same temperature.)
   d. (1) A nitrogen monoxide, NO, molecule and an oxygen atom in the stratosphere or (2) the NO_2 molecule that can form when they collide.
   e. (1) Two bar magnets pushed together with the north pole of one magnet almost touching the south pole of the other magnet or (2) the same magnets farther apart.
   f. (1) A water molecule moving at 1.63×10^3 mi/h or (2) a uranium hexafluoride, UF_6, molecule moving at the same velocity.

64. At 20 °C, ozone molecules, O_3, have an average velocity of 390 m/s, and oxygen molecules, O_2, have an average velocity of 478 m/s. If these gases are at the same temperature, they have the same average kinetic energy. Explain in qualitative terms how these gases could have the same average kinetic energy but different average velocities.

65. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)

    a. A brick on the top of a tall building

    b. A stretched rubber band

    c. Alcohol molecules added to gasoline

66. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)

    a. A paper clip an inch away from a magnet

    b. A candy bar

    c. A baseball popped up to the catcher at the peak of its flight.

67. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)

    a. An archer pulls back a bow with the arrow in place.

    b. The archer releases the arrow, and it speeds toward the target.

68. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)

    a. A car in an old wooden roller coaster is slowly dragged up a steep incline to the top of the first big drop.

    b. After the car passes the peak of the first hill, it falls down the backside at high speed.

    c. As it goes down the hill, the car makes the whole wooden structure shake.

    d. By the time the car reaches the bottom of the first drop, it is moving fast enough to go up to the top of the next smaller hill on its own.

69. When a child swings on a swing, energy is constantly being converted back and forth between kinetic energy and potential energy. At what point (or points) in the child's motion is the potential energy at a maximum? At what point (or points) is the kinetic energy at a maximum? If a parent stops pushing a swinging child, why does the child eventually stop? Where has the energy of the swinging child gone?

OBJECTIVE 7
OBJECTIVE 8

70. Methyl bromide is an agricultural soil fumigant that can make its way into the stratosphere, where bromine atoms are stripped away by radiant energy from the sun. The bromine atoms react with ozone molecules (thus diminishing the earth's protective ozone layer) to produce BrO, which in turn reacts with nitrogen dioxide , NO_2, to form $BrONO_2$. For each of these reactions, identify whether energy would be absorbed or released. Explain why. Describe how energy is conserved in each reaction.

    a. $CH_3Br(g) \rightarrow CH_3(g) + Br(g)$

    b. $BrO(g) + NO_2(g) \rightarrow BrONO_2(g)$

71. The following chemical changes take place in the air over sunny industrial cities, such as Los Angeles. Identify whether energy would be absorbed or released in each reaction. Explain why. Describe how energy is conserved in each reaction.

    a. $2O(g) \rightarrow O_2(g)$

    b. $NO_2(g) \rightarrow NO(g) + O(g)$

72. A silver bullet speeding toward a vampire's heart has both external kinetic energy and internal kinetic energy. Explain the difference between the two.

73. Describe three different ways to increase the internal kinetic energy of your skin.

74. When a room-temperature thermometer is placed in a beaker of boiling water, heat is transferred from the hot water to the glass of the thermometer and then to the liquid mercury inside the thermometer. With reference to the motion of the particles in the water, glass, and mercury, describe the changes that are taking place during this heat transfer. What changes in total energy and average internal kinetic energy are happening for each substance? Why do you think the mercury moves up the thermometer?

75. With reference to both their particle and their wave nature, describe the similarities and differences between visible light and ultraviolet radiation.

76. With reference to both their particle and their wave nature, describe the similarities and differences between red light and blue light.

77. Consider the following forms of radiant energy: microwaves, infrared, ultraviolet, X rays, visible light, radio waves, and gamma rays.

    a. List them in order of increasing energy.

    b. List them in order of increasing wavelength.

78. Consider the following colors of visible light: green, yellow, violet, red, blue, and orange.

    a. List these in order of increasing energy.

    b. List these in order of increasing wavelength.

Section 4.2 The Mysterious Electron

79. Explain why, in theory, a guitar string can vibrate with an infinite number of possible waveforms, but why not all waveforms are possible.

80. Describe how electrons are like vibrating guitar strings.

81. Describe the 1s orbital in a hydrogen atom in terms of negative charge and in terms of the electron as a particle.

82. Explain why electrons in atoms are often described in terms of electron clouds.

83. Describe a 2s orbital for a hydrogen atom.

84. Explain why an electron has lower potential energy in the 1s orbital than the 2s orbital for a hydrogen atom.

85. Which is larger, a 2p orbital or a 3p orbital? Would the one electron in a hydrogen atom be more strongly attracted to the nucleus in a 2p orbital or in a 3p orbital? Would the electron be more stable in a 2p orbital or in a 3p orbital? Would the electron have higher potential energy when it is in a 2p orbital or a 3p orbital?

86. Which is larger, a 3d orbital or a 4d orbital? Would the one electron in a hydrogen atom be more strongly attracted to the nucleus in a 3d orbital or in a 4d orbital? Would the electron be more stable in a 3d orbital or in a 4d orbital? Would the electron have higher potential energy when it is in a 3d orbital or a 4d orbital?

OBJECTIVE 26

87. Describe the three 2*p* orbitals for a hydrogen atom.

OBJECTIVE 27

88. Write descriptions of the 3*s*, 3*p*, and 3*d* orbitals.

89. How many sublevels are in the fourth principal energy level for the hydrogen atom? What is the shorthand notation used to describe them? (For example, there is one sublevel in the first principal energy level, and it is described as 1*s*.)

90. How many orbitals are there in the 3*p* sublevel for the hydrogen atom?

91. How many orbitals are there in the 4*d* sublevel for the hydrogen atom?

92. How many orbitals are there in the third principal energy level for the hydrogen atom?

93. How many orbitals are there in the fourth principal energy level for the hydrogen atom?

94. Which of the following sublevels do not exist?

    a. 5*p*   b. 2*s*   c. 3*f*   d. 6*d*

95. Which of the following sublevels do not exist?

    a. 1*p*   b. 5*d*   c. 6*f*   d. 1*s*

Section 4.3 Multi Electron Atoms

OBJECTIVE 28

96. Describe the difference between any two electrons in the same atomic orbital.

97. What is the maximum number of electrons that can be placed in a 3*p* orbital?… in a 3*d* orbital?

98. What is the maximum number of electrons that can be placed in a 5*s* orbital?…in a 5*f* orbital?

99. What is the maximum number of electrons that can be placed in a 3*p* sublevel?… in a 3*d* sublevel?

100. What is the maximum number of electrons that can be placed in a 5*s* sublevel?…in a 5*f* sublevel?

101. What is the maximum number of electrons that can be placed in the third principal energy level?

102. What is the maximum number of electrons that can be placed in the fourth principal energy level?

103. For each of the following pairs, identify the sublevel that is filled first.

    a. 2*s* or 3*s*   b. 3*p* or 3*s*   c. 3*d* or 4*s*   d. 4*f* or 6*s*

104. For each of the following pairs, identify the sublevel that is filled first.

    a. 2*p* or 3*p*   b. 5*s* or 5*d*   c. 4*d* or 5*s*   d. 4*f* or 5*d*

OBJECTIVE 29
OBJECTIVE 30

105. Write the complete electron configuration and orbital diagram for each of the following.

    a. carbon, C

    b. phosphorus, P

    c. vanadium, V

    d. iodine, I

    e. mercury, Hg

106. Write the complete electron configuration and orbital diagram for each of the following.

   a. oxygen, O
   b. sulfur, S
   c. manganese, Mn
   d. tellurium, Te
   e. radon, Rn

107. Which element is associated with each of the ground state electron configurations listed below?

   a. $1s^2\,2s^2$
   b. $1s^2\,2s^2\,2p^6\,3s^1$
   c. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^5$
   d. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^6\,5s^2\,4d^{10}\,5p^6\,6s^2\,4f^{14}\,5d^{10}\,6p^2$

108. Which element is associated with each of the ground state electron configurations listed below?

   a. $1s^2\,2s^2\,2p^3$
   b. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6$
   c. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}$
   d. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^6\,5s^2\,4d^{10}\,5p^6\,6s^2$

109. Would the following electron configurations represent ground states or excited states?

   a. $1s^2\,2s^1\,2p^5$
   b. $1s^2\,2s^2\,2p^4$
   c. $1s^2\,2s^2\,2p^4\,3s^1$
   d. $1s^2\,2s^2\,2p^5$

110. Would the following electron configurations represent ground states or excited states?

   a. $1s^2\,2s^2\,2p^6\,3s^2$
   b. $1s^2\,2s^2\,2p^6\,3s^1\,3p^1$
   c. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^8\,4p^1$
   d. $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^9$

111. Write the abbreviated electron configurations for each of the following.

   a. fluorine, F
   b. silicon, Si
   c. cobalt, Co
   d. indium, In
   e. polonium, Po
   f. palladium, Pd

112. Write the abbreviated electron configurations for each of the following.

   a. chlorine, Cl
   b. boron, B
   c. scandium, Sc
   d. yttrium, Y
   e. astatine, At

Additional Problems

113. Which sublevel contains:
   a. the highest-energy electron for francium, Fr?
   b. the 25$^{\text{th}}$ electron added to an orbital diagram for elements larger than chromium, Cr?
   c. the 93$^{\text{rd}}$ electron added to an orbital diagram for elements larger than uranium, U?
   d. the 82$^{\text{nd}}$ electron added to an orbital diagram for elements larger than lead, Pb?

114. Which sublevel contains:
   a. the highest-energy electron for strontium, Sr?
   b. the 63$^{\text{rd}}$ electron added to an orbital diagram for elements larger than samarium, Sm?
   c. the 33$^{\text{rd}}$ electron added to an orbital diagram for elements larger than germanium, Ge?
   d. the 75$^{\text{th}}$ electron added to an orbital diagram for elements larger than tungsten, W?

115. What is the first element on the periodic table to have
   a. an electron in the $3p$ sublevel.
   b. a filled $4s$ sublevel.
   c. a half-filled $3d$ sublevel.

116. What is the first element on the periodic table to have
   a. an electron in the $5s$ sublevel.
   b. a filled $4d$ sublevel.
   c. a half-filled $6p$ sublevel.

117. Which pair of the following ground-state, abbreviated electron configurations corresponds to elements in the same group on the periodic table? What elements are they? What is the name of the group to which they belong?
   a. [Ne] $3s^2$
   b. [Ar] $4s^2\, 3d^{10}$
   c. [Kr] $5s^2$
   d. [Xe] $6s^2\, 4f^{14}\, 5d^{10}\, 6p^1$

118. Which pair of the following ground-state, abbreviated electron configurations corresponds to elements in the same group on the periodic table? What elements are they? What is the name of the group to which they belong?
   a. [Ar] $4s^2\, 3d^{10}\, 4p^3$
   b. [Ne] $3s^2\, 3p^5$
   c. [Xe] $6s^2$
   d. [Kr] $5s^2\, 4d^{10}\, 5p^5$

119. What is the maximum number of electrons in each of the following?
   a. the $8j$ sublevel
   b. a $6h$ orbital
   c. the $n = 8$ principal energy level

120. What is the maximum number of electrons in each of the following?
   a. the $9k$ sublevel
   b. a $12n$ orbital
   c. the $n = 9$ principal energy level

121. Draw a sketch of how the orbitals for the electron clouds for all of the electrons in a phosphorus atom are superimposed on each other.

122. Write the expected abbreviated electron configuration for the as-yet-undiscovered element with an atomic number of 121. Use Uuo for the symbol of the noble gas below xenon, Xe. (Hint: See Figure 4.29.)

123. Write the expected abbreviated electron configuration for the as-yet-undiscovered element with an atomic number of 139. Use Uuo for the symbol of the noble gas below xenon, Xe. (Hint: See Figure 4.29.)

124. Draw a periodic table like the one in Figure 4.29 but showing the 5*g* sublevel in its correct position.

Discussion Topics

125. You know that the Law of Conservation of Energy states that energy is conserved. When you put on the brakes of a car to stop it, where does the energy associated with the moving car go?

126. Only a fraction of the energy released in the combustion of gasoline is converted into kinetic energy of the moving car. Where does the rest go?

127. Do you think electrons are more like baseballs or guitar strings?

128. What do you think of the following statement? "*We will never know about the true nature of the electron.*"

129. Do you think that there is some understanding of nature that is just beyond our ability to attain? What do you think about the following statement? "*Just as all dogs have a limit to their ability to understand things, humans also have a limit.*"

130. With which of the following two statements do you most agree?
"*The main criterion for accepting a scientific model, such as our model for the electron, is whether or not it is* **true**."
"*The main criterion for accepting a scientific model, such as our model for the electron, is whether or not it is* **useful**."