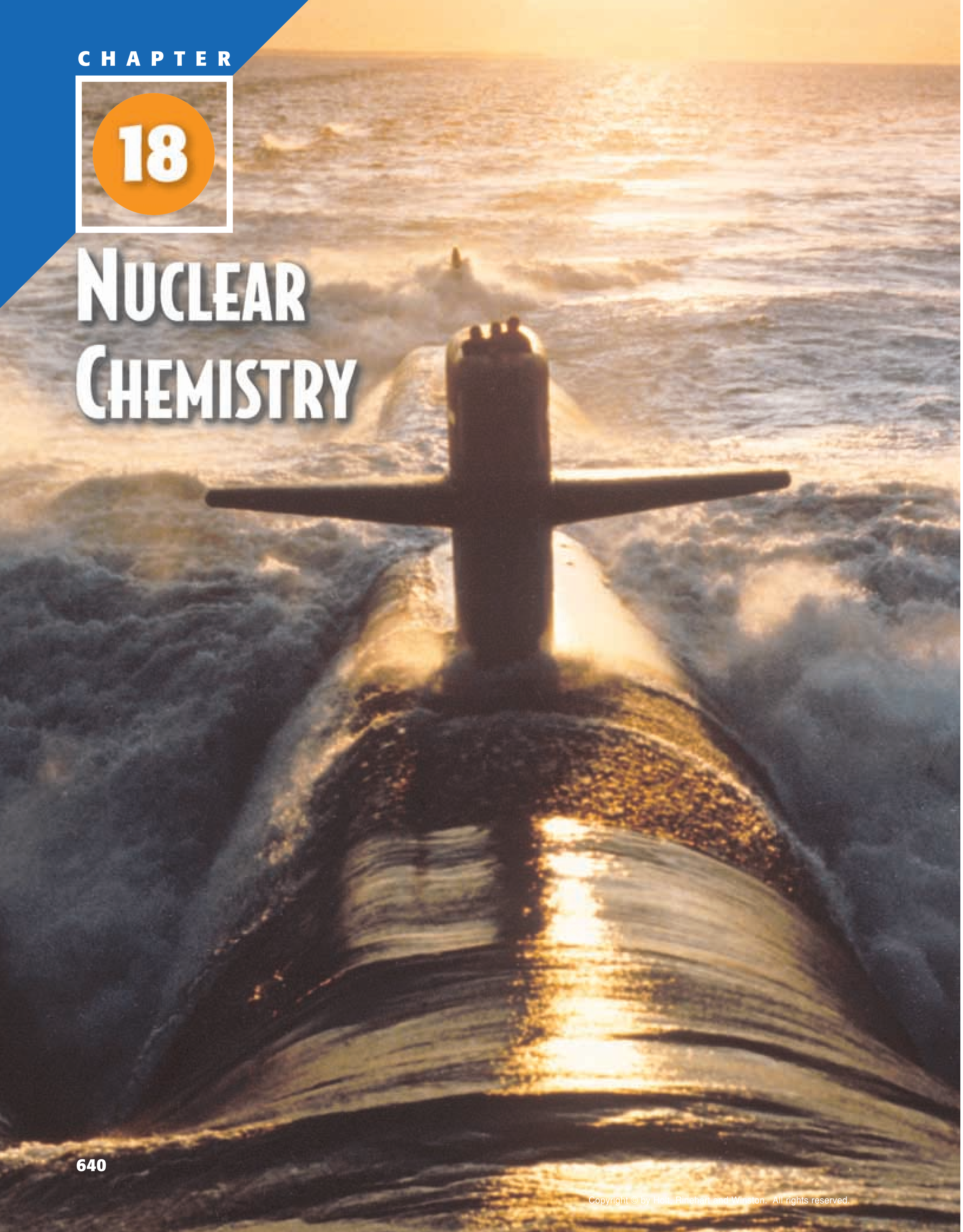
CHAPTER 18

Nuclear Chemistry



Before nuclear power was used, submarines could stay submerged for only a brief period of time. A diesel-powered submarine had to surface regularly to recharge its batteries and refuel. But with a lump of nuclear fuel about the size of a golf ball, the first nuclear-powered submarine could remain underwater for months and travel about 97 000 km (about 60 000 mi). Today, nuclear power enables submarines to refuel only once every nine years.

START-UP ACTIVITY

SAFETY PRECAUTIONS

Half-Lives and Pennies

PROCEDURE

1. Make a data table with two columns. Label the first column "Trials." Label the second column "Number of pennies." Count the **pennies** your teacher has given you, and record this number in the table. Also, record "0" in the column labeled "Trials."
2. Place the pennies in a **plastic cup.** Cover the cup with one hand, and gently shake it for several seconds.
3. Pour the pennies on your desk or laboratory table. Remove all the pennies that are heads up. Count the remaining pennies, and record this number in column two. In the first column, record the number of times you performed step 2.
4. Repeat steps 2 and 3 until you have no pennies to place in your cup.
5. Plot your data on **graph paper.** Label the *x*-axis "Trial," and label the *y*-axis "Number of pennies."

ANALYSIS

1. What does your graph look like?
2. Describe any trend that your data display.

Pre-Reading Questions

1. **What particles make up an atom?**
2. **Name some types of radiation that compose the electromagnetic spectrum.**
3. **Can energy be created? Explain.**
4. **What quantities are conserved in a chemical reaction?**

CONTENTS 18

SECTION 1

Atomic Nuclei and Nuclear Stability

KEY TERMS

- **nucleons**
- **nuclide**
- **strong force**
- **mass defect**

OBJECTIVES

1. **Describe** how the strong force attracts nucleons.
2. **Relate** binding energy and mass defect.
3. **Predict** the stability of a nucleus by considering factors such as nuclear size, binding energy, and the ratio of neutrons to protons in the nucleus.

Nuclear Forces

Topic Link

Refer to the "Atoms and Moles" chapter for a discussion of Rutherford's experiment.

In 1911, Ernest Rutherford's famous gold-foil experiment determined the distribution of charge and mass in an atom. Rutherford's results showed that all of an atom's positive charge and almost all of its mass are contained in an extremely small nucleus.

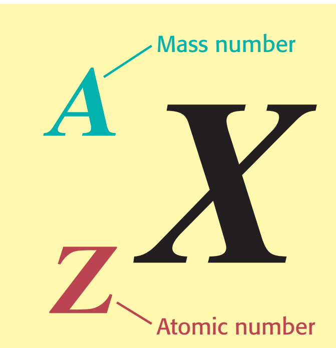
Other scientists later determined more details about the nuclei of atoms. Atomic nuclei are composed of protons. The nuclei of all atoms except hydrogen also are composed of neutrons. The number of protons is the atomic number, Z, and the total number of protons and neutrons is the mass number, A. The general symbol for the nucleus of an atom of element X is shown in **Figure 1.**

nucleon
a proton or a neutron

nuclide
an atom that is identified by the number of protons and neutrons in its nucleus

The protons and neutrons of a nucleus are called **nucleons.** A **nuclide** is a general term applied to a specific nucleus with a given number of protons and neutrons. Nuclides can be represented in two ways. One way, shown in **Figure 1,** shows an element's symbol with its atomic number and mass number. A second way is to represent the nuclide by writing the element's name followed by its mass number, such as radium-228 or einsteinium-253. It is not essential to include the atomic number when showing a nuclide because all nuclides of an element have the same atomic number.

Figure 1
In this figure, X represents the element, Z represents the atom's atomic number, and A represents the element's mass number.



Recall that isotopes are atoms that have the same atomic number but different mass numbers. So, isotopes are nuclides that have the same number of protons but different numbers of neutrons. The following symbols represent nuclei of isotopes of tellurium.

$$^{122}_{52}\text{Te} \quad ^{124}_{52}\text{Te} \quad ^{128}_{52}\text{Te}$$

These three isotopes of tellurium are stable. So, their nuclei do not break down spontaneously. Yet, each of these nuclei are composed of 52 protons. How can these positive charges exist so close together? Protons repel each other because of their like charges. So, why don't nuclei fall apart? There must be some attraction in the nucleus that is stronger than the repulsion due to the positive charges on protons.

The Strong Force Holds the Nucleus Together

In 1935, the Japanese physicist Hideki Yukawa proposed that a force between protons that is stronger than the electrostatic repulsion can exist between protons. Later research showed a similar attraction between two neutrons and between a proton and a neutron. This force is called the **strong force** and is exerted by nucleons only when they are very close to each other. All the protons and neutrons of a stable nucleus are held together by this strong force.

Although the strong force is much stronger than electrostatic repulsion, the strong force acts only over very short distances. Examine the nuclei shown in **Figure 2.** The nucleons are close enough for each nucleon to attract all the others by the strong force. In larger nuclei, some nucleons are too far apart to attract each other by the strong force. Although forces due to charges are weaker, they can act over greater distances. If the repulsion due to charges is not balanced by the strong force in a nucleus, the nucleus will break apart.

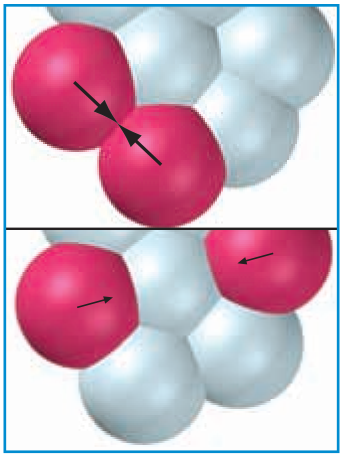


Figure 2
In the nucleus, the nuclear force acts only over a distance of a few nucleon diameters. Arrows describe magnitudes of the strong force acting on the protons.

strong force
the interaction that binds nucleons together in a nucleus

Protons and Neutrons Are Made of Quarks

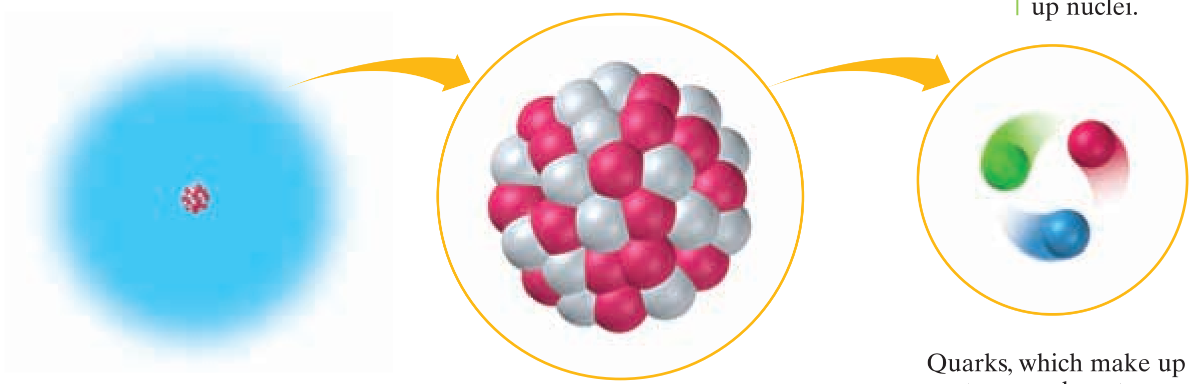
In the early 1800s, John Dalton suggested that atoms could not be broken down. However, the discovery of electrons, protons, and neutrons showed that this part of his atomic theory is not correct. So, scientists changed the atomic theory to state that these subatomic particles were indivisible and were the basic building blocks of all matter. However, the atomic theory had to change again when scientists discovered in the 1960s that protons and neutrons are made of even smaller particles called *quarks,* as shown in **Figure 3.**

Quarks were first identified by observing the products formed in high-energy nuclear collisions. Six types of quarks are recognized. Each quark type is known as a flavor. The six flavors are up, down, top, bottom, strange, and charm. Only two of these—the up and down quarks—compose protons and neutrons. A proton is made up of two up quarks and one down quark, while a neutron consists of one up quark and two down quarks. The other four types of quarks exist only in unstable particles that spontaneously break down during a fraction of a second.

Topic Link

Refer to the "Atoms and Moles" chapter for a discussion of protons, neutrons, and Dalton's theory.

Figure 3
Protons and neutrons, which are made of quarks, make up nuclei.



Atom, which has a nucleus

Nucleus, which is made of protons and neutrons

Quarks, which make up protrons and neutrons

Binding Energy and Nuclear Stability

When protons and neutrons that are far apart come together and form a nucleus, energy is released. As a result, a nucleus is at a lower energy state than the separate nucleons were. A system is always more stable when it reaches a lower energy state. One way to describe this reaction is as follows:

$$\text{separate nucleons} \longrightarrow \text{nucleus} + \text{energy}$$

The energy released in this reaction is enormous compared with the energy changes that take place during chemical reactions. The energy released when nucleons come together is called *nuclear binding energy*. Where does this enormous quantity of energy come from? The answer can be found by comparing the total mass of the nucleons with the nucleus they form.

mass defect

the difference between the mass of an atom and the sum of the masses of the atom's protons, neutrons, and electrons

The mass of any atom is less than the combined masses of its separated parts. This difference in mass is known as the **mass defect,** also called *mass loss.* Electrons have masses so small that they can be left out of mass defect calculations. For helium, ${}^{4}_{2}\text{He}$, the mass of the nucleus is about 99.25% of the total mass of two protons and two neutrons. According to the equation $E = mc^2$, energy can be converted into mass, and mass can be converted into energy. So, a small quantity of mass is converted into an enormous quantity of energy when a nucleus forms.

Binding Energy Can Be Calculated for Each Nucleus

As **Figure 4** shows, the mass defect for one ${}^{4}_{2}\text{He}$ nucleus is 0.0304 amu. The equation $E = mc^2$ can be used to calculate the binding energy for this nucleus. Remember to first convert the mass defect, which has units of amu to kilograms, to match the unit for energy which is joules ($\text{kg}\cdot\text{m}^2/\text{s}^2$).

$$0.0304\ \cancel{\text{amu}} \times \frac{1.6605 \times 10^{-27}\ \text{kg}}{1\ \cancel{\text{amu}}} = 5.05 \times 10^{-29}\ \text{kg}$$

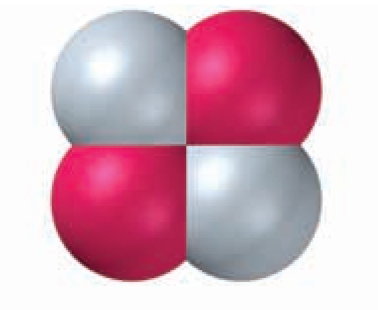
The binding energy for one ${}^{4}_{2}\text{He}$ nucleus can now be calculated.

$$E = (5.05 \times 10^{-29}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2 = 4.54 \times 10^{-12}\ \text{J}$$

This quantity of energy may seem rather small, but remember that 4.54×10^{-12} J is released for every ${}^{4}_{2}\text{He}$ nucleus that forms. The binding energy for 1 mol of ${}^{4}_{2}\text{He}$ nuclei is much more significant.

$$4.54 \times 10^{-12} \frac{\text{J}}{\cancel{\text{He nucleus}}} \times 6.022 \times 10^{23} \frac{\cancel{\text{He nuclei}}}{\text{mol}} =$$
$$2.73 \times 10^{12}\ \text{J/mol}$$

Figure 4
The mass defect represents the difference in mass between the helium nucleus and the total mass of the separated nucleons.



Helium nucleus

$$\begin{aligned}
{}^{4}_{2}\text{He nucleus} &= 2(\text{mass of proton}) + 2(\text{mass of neutron})\\
&= 2(1.007\ 276\ 47\ \text{amu}) + 2(1.008\ 664\ 90\ \text{amu})\\
&= 4.031\ 882\ 74\ \text{amu}\\
\text{mass defect} &= (\text{total mass of separate nucleons}) - (\text{mass of helium nucleus})\\
&= 4.031\ 882\ 74\ \text{amu} - 4.001\ 474\ \ 92\ \text{amu}\\
&= 0.030\ 407\ 82\ \text{amu per nucleus of } {}^{4}_{2}\text{He}
\end{aligned}$$

Binding Energy Is One Indicator of Nuclear Stability

A system's stability depends on the amount of energy released as the system is established. When 16 g of oxygen nuclei is formed, 1.23×10^{13} J of binding energy is released. This amount of energy is about equal to the energy needed to heat 4.6×10^{6} L of liquid water from 0°C to 100°C and to boil the water away completely.

The binding energy of a selenium nucleus, $^{80}_{34}Se$, is much greater than that of an $^{16}_{8}O$ nucleus. Does this difference in energy mean that the $^{80}_{34}Se$ nucleus is more stable than the $^{16}_{8}O$ nucleus? Not necessarily. After all, $^{80}_{34}Se$ contains 64 more nucleons than $^{16}_{8}O$ does. To make a good comparison of these nuclei, you must look at the binding energy per nucleon. Examine the graph in **Figure 5.** Notice that the binding energy per nucleon rises rapidly among the lighter nuclei. The greater the binding energy per nucleon is, the more stable the nucleus is.

In the graph, the binding energy per nucleon levels off when the mass number is approximately 60. The curve reaches a maximum when the mass number is around 55. Therefore, the most stable nuclei are $^{56}_{26}Fe$ and $^{58}_{28}Ni$. These isotopes are relatively abundant in the universe in comparison to other heavy metals, and they are the major components of Earth's core.

Atoms that have larger mass numbers than $^{56}_{26}Fe$ and $^{58}_{28}Ni$ have nuclei too large to have larger binding energies per nucleon than these iron and nickel isotopes. In these cases, the net attractive force on a proton is reduced because of the increased distance of the neighboring protons. So, the repulsion between protons results in a decrease in the binding energy per nucleon. Nuclei that have mass numbers greater than 209 and atomic numbers greater than 83 are never stable.

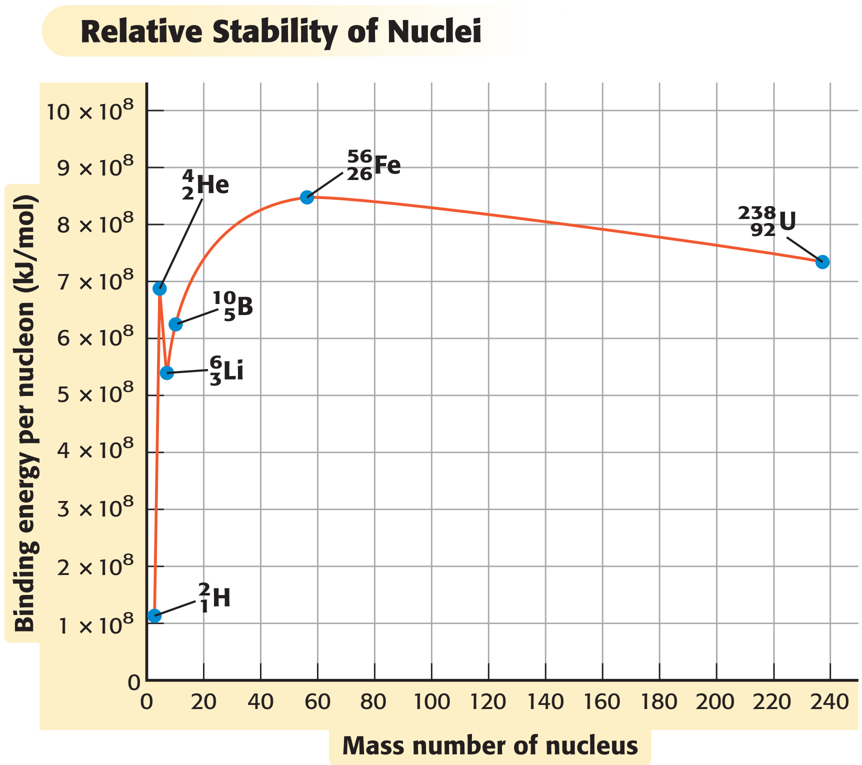


Figure 5
This graph indicates the relative stability of nuclei. Isotopes that have a high binding energy per nucleon are more stable. The most stable nucleus is $^{56}_{26}Fe$.

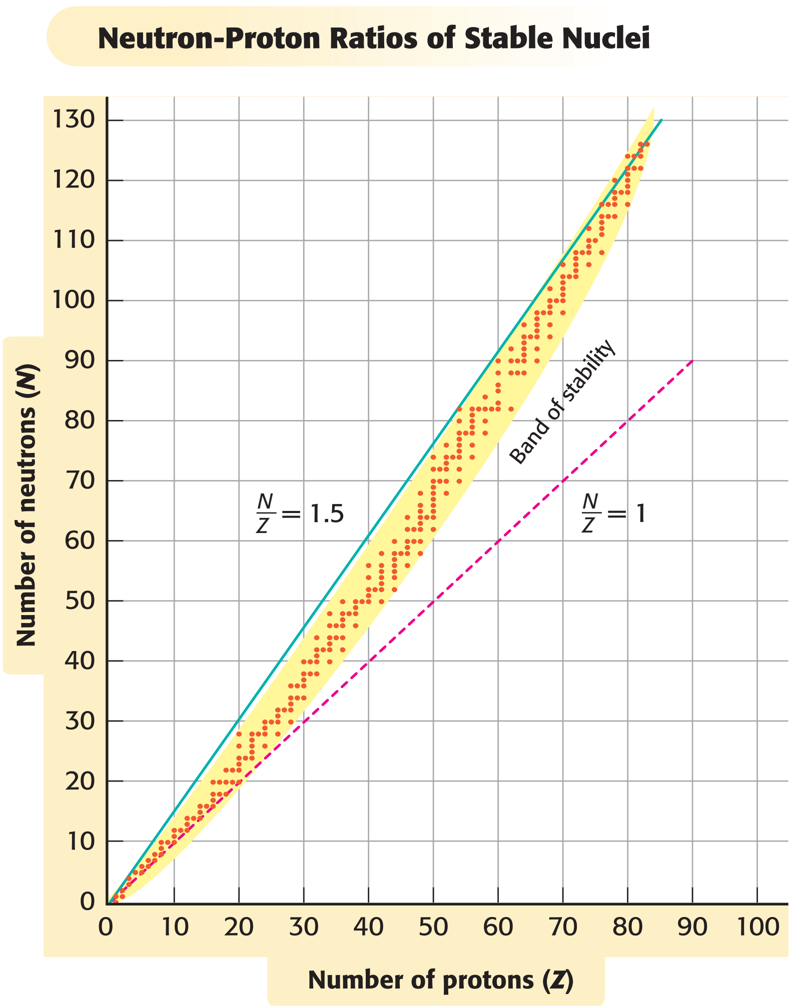
Predicting Nuclear Stability

Finding the binding energy per nucleon for an atom is one way to predict a nucleus's stability. Another way is to compare the number of neutrons with the number of protons of a nucleus. Examine the graph in **Figure 6.** The number of neutrons, N, is plotted against the number of protons, Z, of each stable nucleus. All known stable nuclei are shown as red dots.

The maroon line shows where the data lie for $N/Z = 1$. For elements that have small atomic numbers, the most stable nuclei are those for which $N/Z = 1$. Notice in **Figure 6** that the dots that represent elements that have small atomic numbers are clustered near the line that represents $N/Z = 1$. The green line shows where the data would lie for $N/Z = 1.5$. For elements that have large atomic numbers, the most stable nuclei are those where $N/Z = 1.5$. The reason for the larger N/Z number is that neutrons are needed to stabilize the nuclei of heavier atoms. Notice in **Figure 6** that the dots that represent elements with large atomic numbers are clustered near the line $N/Z = 1.5$.

The dots representing 256 known stable nuclei cluster over a range of neutron-proton ratios, which are referred to as a *band of stability*. This band of stability is shown in yellow in **Figure 6.**

Figure 6
The graph shows the ratio of protons to neutrons for 256 of the known stable nuclei.



Some Rules to Help You Predict Nuclear Stability

You probably see that the graph in **Figure 6** shows several trends. The following rules for predicting nuclear stability are based on this graph.

1. Except for $^{1}_{1}H$ and $^{3}_{2}He$, all stable nuclei have a number of neutrons that is equal to or greater than the number of protons.

2. A nucleus that has an *N/Z* number that is too large or too small is unstable. For small atoms, *N/Z* is very close to 1. As the nuclei get larger, this number increases gradually until the number is near 1.5 for the largest nuclei.

3. Nuclei with even numbers of neutrons and protons are more stable. Almost 60% of all stable nuclei have even numbers of protons and even numbers of neutrons.

4. Nuclei that have so-called magic numbers of protons and neutrons tend to be more stable than others. These numbers—2, 8, 20, 28, 50, 82, and 126—apply to the number of protons or the number of neutrons. Notice in **Figure 5** the large binding energy of $^{4}_{2}He$. This nucleus is very small and has two protons and two neutrons. Such "extra stability" also is true of the element calcium, which has six stable isotopes that range from $^{40}_{20}Ca$ to $^{48}_{20}Ca$, all of which have 20 protons. Tin, having the magic number of 50 protons, has 10 stable isotopes, the largest number of any element. The heaviest stable element, bismuth, having only one stable isotope, has the magic number of 126 neutrons in $^{209}_{83}Bi$.

5. No atoms that have atomic numbers larger than 83 and mass numbers larger than 209 are stable. The nuclei of these atoms are too large to be stable.

1 Section Review

UNDERSTANDING KEY IDEAS

1. What are the nucleons of an atom?
2. What role does the strong force play in the structure of an atom?
3. What is the band of stability?
4. What is mass defect?
5. Explain what happens to the mass that is lost when a nucleus forms.
6. How do the nuclides $^{16}_{8}O$ and $^{15}_{8}O$ differ?
7. Why is bismuth, $^{209}_{83}Bi$, stable?
8. Which are more stable, nuclei that have an even number of nucleons or nuclei that have an odd number of nucleons?

CRITICAL THINKING

9. Which is generally more stable, a small nucleus or a large nucleus? Explain.
10. How does nuclear binding energy relate to the stability of an atom?
11. Which is expected to be more stable, $^{6}_{3}Li$ or $^{9}_{3}Li$? Explain.
12. Use **Figure 6** and the rules for predicting nuclear stability to determine which of the following isotopes are stable and which are unstable.
    - **a.** $^{32}_{15}P$
    - **b.** $^{14}_{6}C$
    - **c.** $^{51}_{23}V$
    - **d.** $^{24}_{12}Mg$
    - **e.** $^{97}_{43}Tc$

SECTION

2 Nuclear Change

KEY TERMS

- **radioactivity**
- **beta particle**
- **gamma ray**
- **nuclear fission**
- **chain reaction**
- **critical mass**
- **nuclear fusion**

OBJECTIVES

1. **Predict** the particles and electromagnetic waves produced by different types of radioactive decay, and write equations for nuclear decays.
2. **Identify** examples of nuclear fission, and describe potential benefits and hazards of its use.
3. **Describe** nuclear fusion and its potential as an energy source.

Radioactive Decay

Nuclear changes can be easier to understand than chemical changes because only a few types of nuclear changes occur. One type is the spontaneous change of an unstable nucleus to form a more stable one. This change involves the release of particles, electromagnetic waves, or both and is generally called **radioactivity** or radioactive decay. Specifically, radioactivity is the spontaneous breakdown of unstable nuclei to produce particles or energy. **Table 1** summarizes the properties of both the particles and the energy released by radioactive decay.

radioactivity

the process by which an unstable nucleus emits one or more particles or energy in the form of electromagnetic radiation

Table 1 Characteristics of Nuclear Particles and Rays

Particle	Mass (amu)	Charge	Symbol	Stopped by
Proton	1.007 276 47	+1	$p, p^+, {}^{1}_{+1}p, {}^{1}_{1}\mathrm{H}$	a few sheets of paper
Neutron	1.008 664 90	0	$n, n^0, {}^{1}_{0}n$	a few centimeters of lead
β particle (electron)	0.000 548 580	–1	$\beta, \beta^-, {}^{0}_{-1}e$*	a few sheets of aluminum foil
Positron†	0.000 548 580	+1	$\beta^+, {}^{0}_{+1}e$*	same as electron
α particle (He-4 nucleus)	4.001 474 92	+2	$\alpha, \alpha^{2+}, {}^{4}_{2}\mathrm{He}$	skin or one sheet of paper
Gamma ray	0	0	γ	several centimeters of lead

*The superscript zero in the symbols for electron and positron does not mean that they have zero mass. It means their mass number is zero.

†The positron is the antiparticle of the electron. Each particle has an antiparticle, but only the positron is frequently involved in nuclear changes.

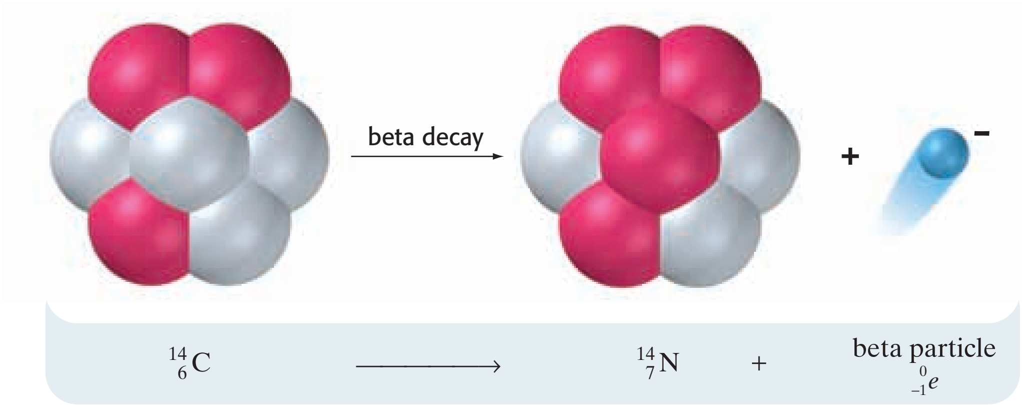


Figure 7
When the unstable carbon-14 nucleus emits a beta particle, the carbon-14 nucleus changes into a nitrogen-14 nucleus.

Stabilizing Nuclei by Converting Neutrons into Protons

Recall that the stability of a nucleus depends on the ratio of neutrons to protons, or the *N/Z* number. If a particular isotope has a large *N/Z* number or too many neutrons, the nucleus will decay and emit radiation.

A neutron in an unstable nucleus may emit a high-energy electron, called a **beta particle** (β particle), and change to a proton. This process is called *beta decay*. This process often occurs in unstable nuclei that have large *N/Z* numbers.

beta particle
a charged electron emitted during a certain type of radioactive decay, such as beta decay

gamma ray
the high-energy photon emitted by a nucleus during fisson and radioactive decay

$$^{1}_{0}n \xrightarrow{\text{beta decay}} {}^{1}_{+1}p + {}^{0}_{-1}e$$

Because this process changes a neutron into a proton, the atomic number of the nucleus increases by one, as you can see in **Figure 7.** As a result of beta decay, carbon becomes a different element, nitrogen. However, the mass number does not change because the total number of nucleons does not change as shown by the following equation.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

Stabilizing Nuclei by Converting Protons into Neutrons

One way that a nucleus that has too many protons can become more stable is by a process called *electron capture*. In this process, the nucleus merely absorbs one of the atom's electrons, usually from the 1*s* orbital. This process changes a proton into a neutron and decreases the atomic number by one. The mass number stays the same.

$$^{1}_{+1}p + {}^{0}_{-1}e \xrightarrow{\text{electron capture}} {}^{1}_{0}n$$

A typical nucleus that decays by this process is chromium-51.

$$^{51}_{24}Cr + {}^{0}_{-1}e \xrightarrow{\text{electron capture}} {}^{51}_{23}V + \gamma$$

The final symbol in the equation, γ, indicates the release of **gamma rays.** Many nuclear changes leave a nucleus in an energetic or excited state. When the nucleus stabilizes, it releases energy in the form of gamma rays. **Figure 8** shows a thunderstorm during which gamma rays may also be produced.

Figure 8
Thunderstorms may produce terrestrial gamma-ray flashes (TGFs).

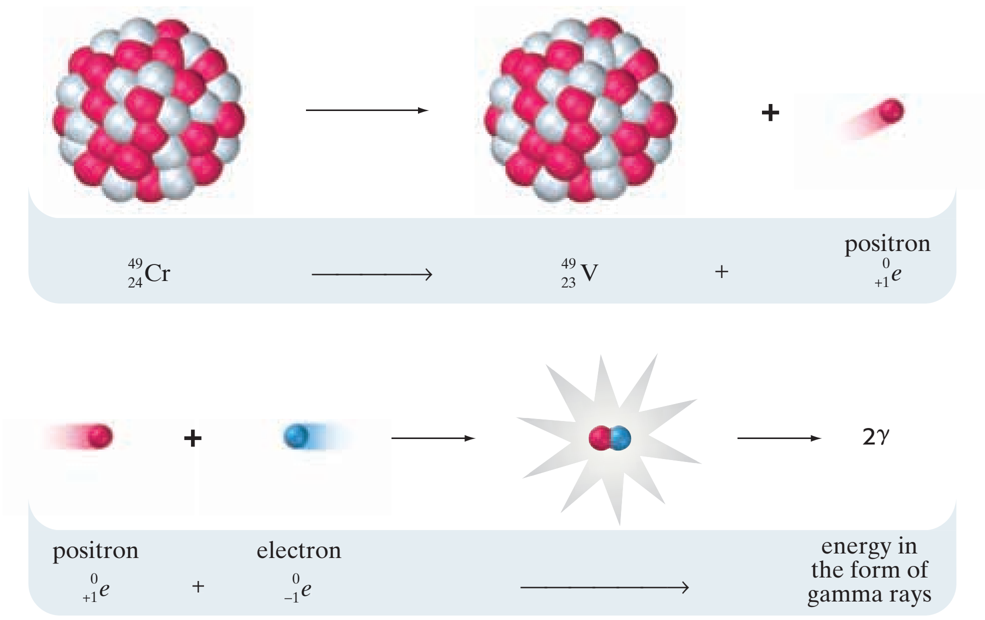


Figure 9
Nuclei can release positrons to form new nuclei. Matter is then converted into energy when positrons and electrons collide and are converted into gamma rays.

Gamma Rays Are Also Emitted in Positron Emission

Some nuclei that have too many protons can become stable by emitting positrons, which are the antiparticles of electrons. The process is similar to electron capture in that a proton is changed into a neutron. However, in *positron emission,* a proton emits a positron.

$$^{1}_{+1}p \xrightarrow{\text{positron emission}} {}^{1}_{0}n + {}^{0}_{+1}e$$

Topic Link

Refer to the "Atoms and Moles" chapter for a discussion of electromagnetic waves.

Notice that when a proton changes into a neutron by emitting a positron, the mass number stays the same, but the atomic number decreases by one. The isotope chromium-49 decays by this process, as shown by the model in **Figure 9.**

$$^{49}_{24}Cr \longrightarrow {}^{49}_{23}V + {}^{0}_{+1}e$$

Another example of an unstable nucleus that emits a positron is potassium-38, which changes into argon-38.

$$^{38}_{19}K \longrightarrow {}^{38}_{18}Ar + {}^{0}_{+1}e$$

The positron is the opposite of an electron. Unlike a beta particle, a positron seldom makes it into the surroundings. Instead, the positron usually collides with an electron, its antiparticle. Any time a particle collides with its antiparticle, all of the masses of the two particles are converted entirely into electromagnetic energy or gamma rays. This process is called *annihilation of matter,* which is illustrated in **Figure 9.**

$$^{0}_{-1}e + {}^{0}_{+1}e \xrightarrow{\text{annihilation}} 2\gamma$$

The gamma rays from electron-positron annihilation have a characteristic wavelength; therefore, these rays can be used to identify nuclei that decay by positron emission. Such gamma rays have been detected coming from the center of the Milky Way galaxy.

Stabilizing Nuclei by Losing Alpha Particles

An unstable nucleus that has an *N/Z* number that is much larger than 1 can decay by emitting an alpha particle. In addition, none of the elements that have atomic numbers greater than 83 and mass numbers greater than 209 have stable isotopes. So, many of these unstable isotopes decay by emitting alpha particles, as well as by electron capture or beta decay. Uranium-238 is one example.

$$^{238}_{92}\text{U} \xrightarrow{\text{alpha decay}} {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

Notice that the atomic number in the equation decreases by two while the mass number decreases by four. Alpha particles have very low penetrating ability because they are large and soon collide with other matter. Exposure to external sources of alpha radiation is usually harmless. However, if substances that undergo alpha decay are ingested or inhaled, the radiation can be quite damaging to the body's internal organs.

Many heavy nuclei go through a series of reactions called a decay series before they reach a stable state. The decay series for uranium-238 is shown in **Figure 10.** After the $^{238}_{92}$U nucleus decays to $^{234}_{90}$Th, the nucleus is still unstable because it has a large *N/Z* number. This nucleus undergoes beta decay to produce $^{234}_{91}$Pa. By another beta decay, $^{234}_{91}$Pa changes to $^{234}_{92}$U. After a number of other decays (taking millions of years), the nucleus finally becomes a stable isotope, $^{206}_{82}$Pb.

Topic Link

Refer to the "Atoms and Moles" chapter for a discussion of alpha particles.

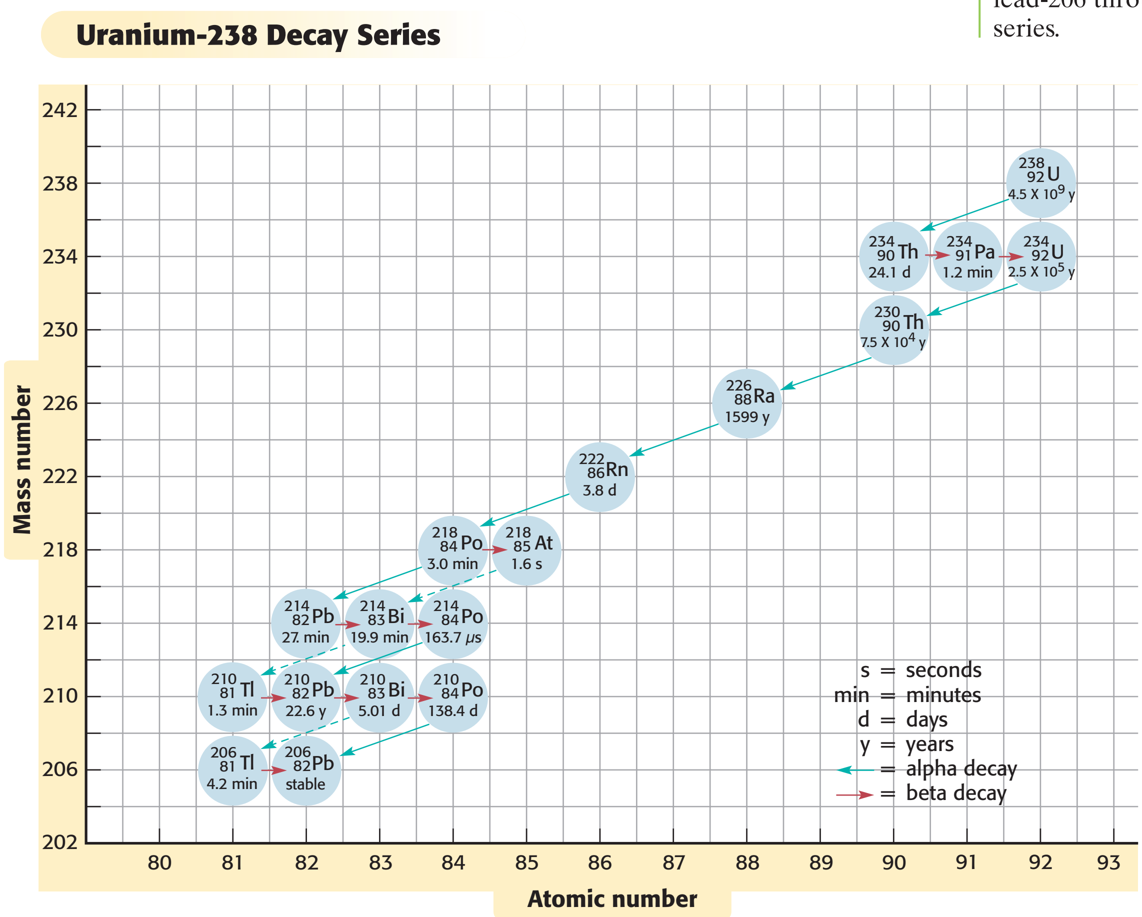


Figure 10
Uranium-238 decays to lead-206 through a decay series.

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Nuclear Equations Must Be Balanced

Look back at all of the nuclear equations that have appeared so far in this chapter. Notice that the sum of the mass numbers (superscripts) on one side of the equation always equals the sum of the mass numbers on the other side of the equation. Likewise, the sums of the atomic numbers (subscripts) on each side of the equation are equal. Look at the following nuclear equations, and notice that they balance in terms of both mass and nuclear charge.

$$^{238}_{92}\text{U} \longrightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} \quad \begin{matrix}[238 = 234 + 4 \text{ mass balance}]\\ [92 = 90 + 2 \text{ charge balance}]\end{matrix}$$

$$^{234}_{90}\text{Th} \longrightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}e \quad \begin{matrix}[234 = 234 + 0 \text{ mass balance}]\\ [90 = 91 + (-1) \text{ charge balance}]\end{matrix}$$

Remember that whenever the atomic number changes, the identity of the element changes. In the above examples, uranium changes into thorium, and thorium changes into protactinium.

1 SKILLS Toolkit

Balancing Nuclear Equations

The following rules are helpful for balancing a nuclear equation and for identifying a reactant or a product in a nuclear reaction.

1. Check mass and atomic numbers.

- The total of the mass numbers must be the same on both sides of the equation.
- The total of the atomic numbers must be the same on both sides of the equation. In other words, the nuclear charges must balance.
- If the atomic number of an element changes, the identity of the element also changes.

2. Determine how nuclear reactions change mass and atomic numbers.

- If a beta particle, ${}^{0}_{-1}e$, is released, the mass number does not change but the atomic number increases by one.
- If a positron, ${}^{0}_{+1}e$ is released, the mass number does not change but the atomic number decreases by one.
- If a neutron, ${}^{1}_{0}n$, is released, the mass number decreases by one and the atomic number does not change.
- Electron capture does not change the mass number but decreases the atomic number by one.
- Emission of an alpha particle, ${}^{4}_{2}\text{He}$, decreases the mass number by four and decreases the atomic number by two.
- When a positron and an electron collide, energy in the form of gamma rays is generated.

SAMPLE PROBLEM A

Balancing a Nuclear Equation

Identify the product formed when polonium-212 emits an alpha particle.

1 Gather information.

- Check the periodic table to write the symbol for polonium-212: $^{212}_{84}\text{Po}$.
- Write the symbol for an alpha particle: $^{4}_{2}\text{He}$.

2 Plan your work.

- Set up the nuclear equation.

$$^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + ?$$

3 Calculate.

- The sums of the mass numbers must be the same on both sides of the equation: $212 = 4 + A$; $A = 212 - 4 = 208$

$$^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + {}^{208}?$$

- The sums of the atomic numbers must be the same on both sides of the equation: $84 = 2 + Z$; $Z = 84 - 2 = 82$

$$^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + {}^{208}_{82}?$$

- Check the periodic table to identify the element that has an atomic number of 82, and complete the nuclear equation.

$$^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + {}^{208}_{82}\text{Pb}$$

4 Verify your results.

- Emission of an alpha particle does decrease the atomic number by two (from 84 to 82) and does decrease the mass number by four (from 212 to 208).

PRACTICE HINT

Unlike a chemical equation, the elements are usually different on each side of a balanced nuclear equation.

PRACTICE

Write balanced equations for the following nuclear equations.

1. $^{218}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + ?$
2. $^{142}_{61}\text{Pm} + ? \longrightarrow {}^{142}_{60}\text{Nd}$
3. $^{253}_{99}\text{Es} + {}^{4}_{2}\text{He} \longrightarrow {}^{1}_{0}n + ?$
4. Write the balanced nuclear equation that shows how sodium-22 changes into neon-22.

PROBLEM SOLVING SKILL

Nuclear Fission

nuclear fission

the splitting of the nucleus of a large atom into two or more fragments, a process that produces additional neutrons and a lot of energy

chain reaction

a reaction in which a change in a single molecule makes many molecules change until a stable compound forms

critical mass

the minimum mass of a fissionable isotope that provides the number of neutrons needed to sustain a chain reaction

So far, you have learned about one class of nuclear change in which a nucleus decays by adding or losing particles. Another class of nuclear change is called **nuclear fission.** Nuclear fission occurs when a very heavy nucleus splits into two smaller nuclei, each more stable than the original nucleus. Some nuclei undergo fission without added energy. A very small fraction of naturally occurring uranium nuclei is of the isotope $^{235}_{92}U$, which undergoes spontaneous fission. However, most fission reactions happen artificially by bombarding nuclei with neutrons.

Figure 11 shows what happens when an atom of uranium-235 is bombarded with a neutron. The following equation represents the first reaction shown in **Figure 11.**

$$^{235}_{92}U + {}^{1}_{0}n \xrightarrow{\text{nuclear fission}} {}^{93}_{36}Kr + {}^{140}_{56}Ba + 3\,{}^{1}_{0}n$$

Notice that the products include Kr-93, Ba-140, and three neutrons.

As shown in **Figure 11,** each of the three neutrons emitted by the fission of one nucleus can cause the fission of another uranium-235 nucleus. Again, more neutrons are emitted. These reactions continue one after another as long as enough uranium-235 remains. This process is called a **chain reaction.** One characteristic of a chain reaction is that the particle that starts the reaction, in this case a neutron, is also produced from the reaction. A minimum quantity of radioactive material, called **critical mass,** is needed to keep a chain reaction going.

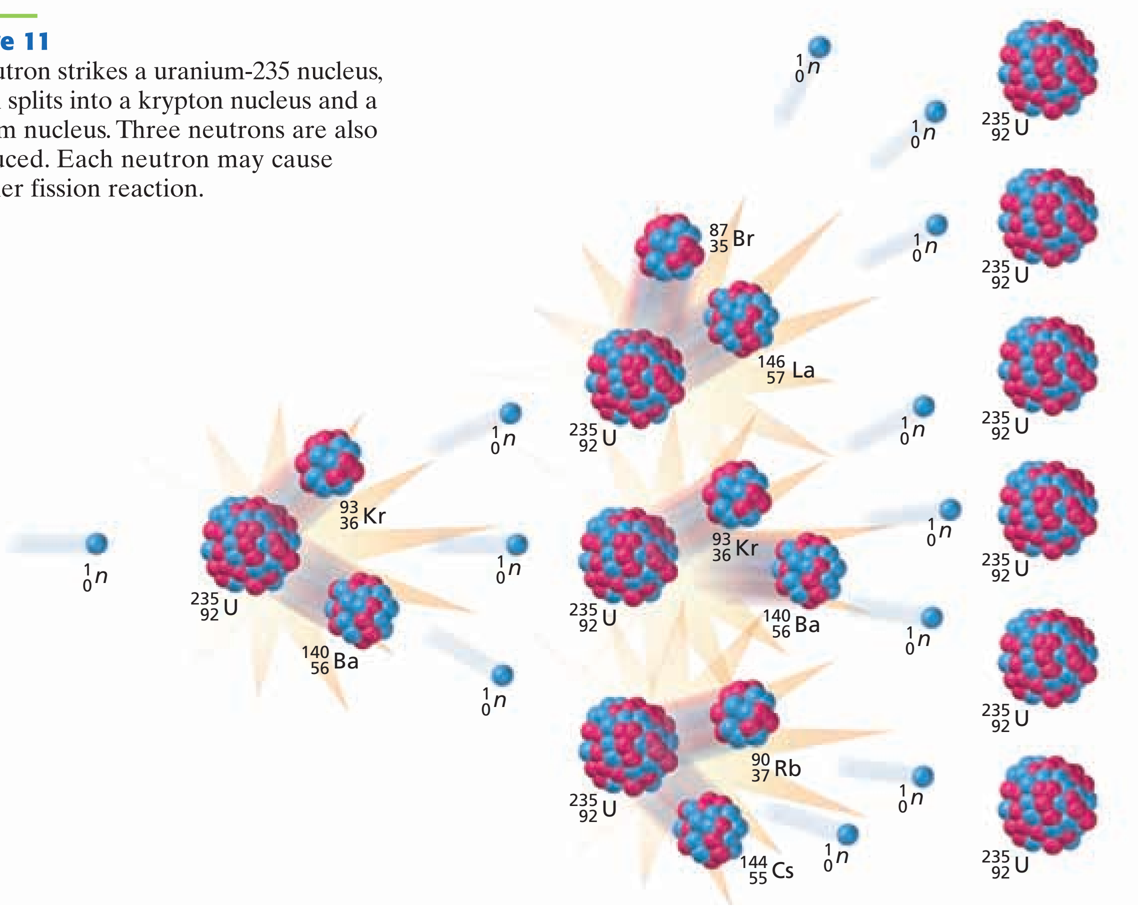

Figure 11
A neutron strikes a uranium-235 nucleus, which splits into a krypton nucleus and a barium nucleus. Three neutrons are also produced. Each neutron may cause another fission reaction.

Chain Reactions Occur in Nuclear Reactors

Fission reactions can produce a large amount of energy. For example, the fission of 1 g of uranium-235 generates as much energy as the combustion of 2700 kg of coal. Fission reactions are used to generate electrical energy in nuclear power plants. Uranium-235 and plutonium-239 are the main radioactive isotopes used in these reactors.

In a nuclear reactor, represented in **Figure 12,** the fuel rods are surrounded by a moderator. The moderator is a substance that slows down neutrons. Control rods are used to adjust the rate of the chain reactions. These rods absorb some of the free neutrons produced by fission. Moving these rods into and out of the reactor can control the number of neutrons that are available to continue the chain reaction. Chain reactions that occur in reactors can be very dangerous if they are not controlled. An example of the danger that nuclear reactors can create is the accident that happened at the Chernobyl reactor in the Ukraine in 1986. This accident occurred when technicians briefly removed most of the reactor's control rods during a safety test. However, most nuclear reactors have mechanisms that can prevent most accidents.

As shown in **Figure 12,** water is heated by the energy released from the controlled fission of U-235 and changed into steam. The steam drives a turbine to produce electrical energy. The steam then passes into a condenser and is cooled by a river or lake's water. Notice that water heated by the reactor or changed into steam is isolated. Only water used to condense the steam is gotten from and is returned to the environment.

Figure 12
This model shows a pressurized, light-water nuclear reactor, the type most often used to generate electrical energy in the United States. Note that each of the three water systems is isolated from the others for safety reasons.

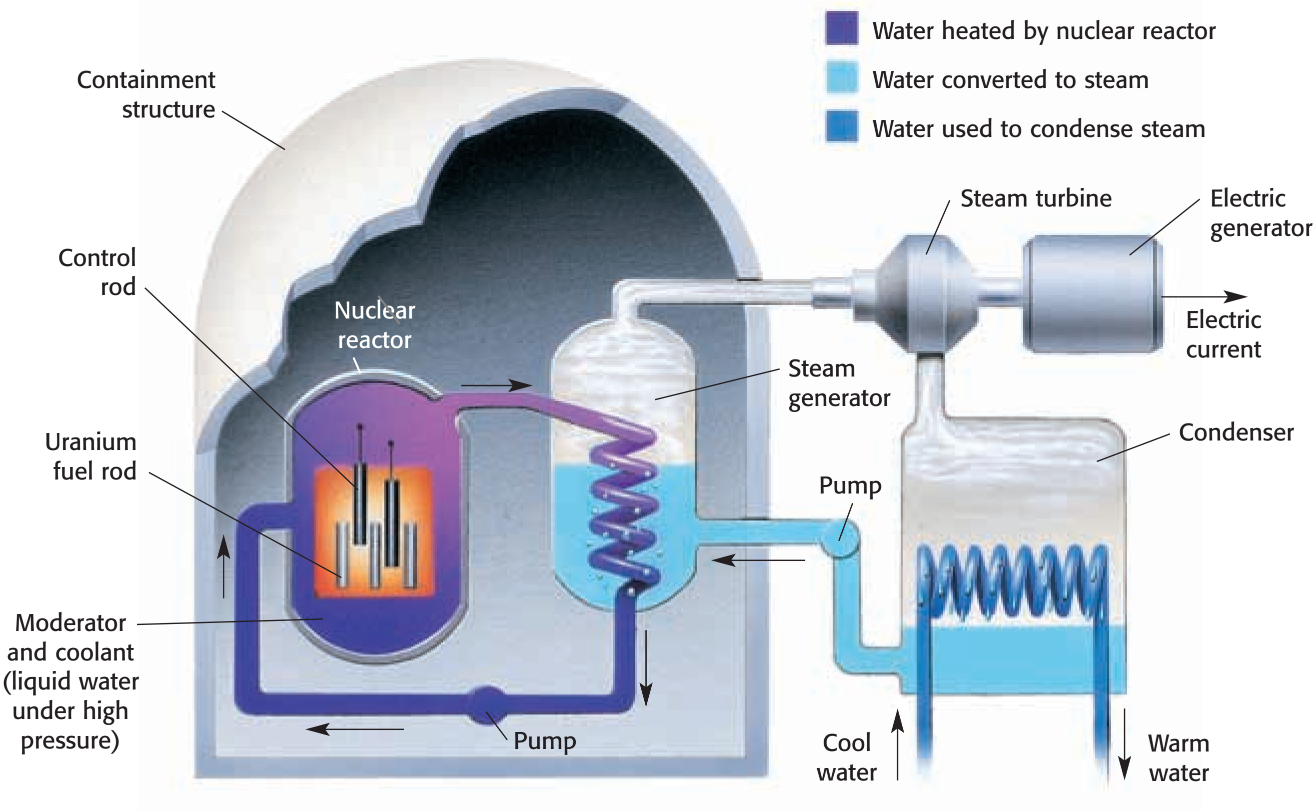

Figure 13
In the stars of this galaxy, four hydrogen nuclei fuse to form a single $^{4}_{2}He$ nucleus.

Nuclear Fusion

nuclear fusion

the combination of the nuclei of small atoms to form a larger nucleus, a process that releases energy

Nuclear fusion, which is when small nuclei combine, or fuse, to form a larger, more stable nucleus, is still another type of nuclear change. The new nucleus has a higher binding energy per nucleon than each of the smaller nuclei does, and energy is released as the new nucleus forms. In fact, fusion releases greater amounts of energy than fission for the same mass of starting material. Fusion is the process by which stars, including our sun, generate energy. In the sun, the net reaction involves four hydrogen nuclei fusing to form a single $^{4}_{2}He$ nucleus.

$$4^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e$$

The reaction above is a net reaction. Very high temperatures are required to bring the nuclei together. The temperature of the sun's core, where some of the fusion reactions occur, is about 1.5×10^{7}°C. When the hydrogen nuclei are fused, some mass is converted to energy.

Fusion Reactions Are Hard to Maintain

Scientists are investigating ways to control fusion reactions so that they may be used for both energy generation and research. One problem is that starting a fusion reaction takes a lot of energy. So far, researchers need just as much energy to start a fusion reaction as is released by the reaction. As a result, fusion is not a practical source of energy.

Another challenge is finding a suitable place for a fusion reaction. In fusion reactions, the reactants are in the form of a plasma, a random mixture of positive nuclei and electrons. Because no form of solid matter can withstand the tremendous temperatures required for fusion to occur, this plasma is hard to contain. Scientists currently use extremely strong magnetic fields to suspend the charged plasma particles. In this way, the plasma can be kept from contacting the container walls. Scientists have also experimented with high-powered laser light to start the fusion process.

Topic Link

Refer to the "Periodic Table" chapter for a discussion of nuclear fusion.

Nuclear Energy and Waste

The United States depends on nuclear power to generate electrical energy. In fact, about 100 nuclear reactors generate 20% of electrical energy needs in the United States. Nuclear power also generates waste like many other sources of energy, such as fossil fuels. Nuclear waste is "spent fuel" that can no longer be used to create energy. But this material is still radioactive and dangerous and must be disposed of with care.

Nuclear waste is often stored in "spent-fuel pools" that cover the spent fuel with at least 6 m of water. This amount of water prevents radiation from the waste from harming people. Nuclear waste can also be stored in a tightly sealed steel container. These containers have inert gases that surround the waste. These containers can also be surrounded by steel or concrete. Most of the nuclear waste that is put into a container has first been put in a spent-fuel pool to cool for about one year.

Some isotopes from the spent fuel can be extracted and used again as reactor fuel. However, this process is not currently done on a large scale in the United States.

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2 Section Review

UNDERSTANDING KEY IDEAS

1. What is the name of a high-energy electron that is emitted from an unstable nucleus?
2. How are nuclear fission and nuclear fusion similar? How are they different?
3. Describe what happens when a positron and an electron collide.
4. How is critical mass related to a chain reaction?

PRACTICE PROBLEMS

5. Write the balanced equations for the following nuclear reactions.
   a. Uranium-233 undergoes alpha decay.
   b. Copper-66 undergoes beta decay.
   c. Beryllium-9 and an alpha particle combine to form carbon-13. The carbon-13 nucleus then emits a neutron.
   d. Uranium-238 absorbs a neutron. The product then undergoes successive beta emissions to become plutonium-239.
6. A fusion reaction that takes place in the sun is the combination of two helium-3 nuclei to form two hydrogen nuclei and one other nucleus. Write the balanced nuclear equation for this fusion reaction. Be sure to include both products that are formed.

CRITICAL THINKING

7. In electron capture, why is the electron that is absorbed by the nucleus usually taken from the 1*s* orbital?
8. Can annihilation of matter occur between a positron and a neutron? Explain your answer.
9. Why do the nuclear reactions in a decay series eventually stop?
10. Cobalt-59 is bombarded with neutrons to produce cobalt-60, which is then used to treat certain cancers. The nuclear equation for this reaction shows the gamma rays that are released when cobalt-60 is produced.

$$^{59}_{27}\mathrm{Co} + ^{1}_{0}n \longrightarrow ^{60}_{27}\mathrm{Co} + \gamma$$

Is this an example of a nuclear change that involves the creation of a nucleus of another element? Explain your answer.

SECTION

3 Uses of Nuclear Chemistry

KEY TERMS

- half-life

OBJECTIVES

1. **Define** the half-life of a radioactive nuclide, and explain how it can be used to determine an object's age.
2. **Describe** some of the uses of nuclear chemistry.
3. **Compare** acute and chronic exposures to radiation.

Half-Life

The start-up activity for this chapter involved shaking pennies and then removing those that landed heads up after they were poured out of the cup. Each time you repeated this step, you should have found that about half the pennies were removed. Therefore, if you started with 100 pennies, about 50 should have been removed after the first shake. After the second shake, about 25 should have been removed, and so on. So, half of the amount of pennies remained after each step. This process is similar to what happens to radioactive materials that undergo nuclear decay. A radioactive sample decays at a constant rate. This rate of decay is measured in terms of its **half-life.**

half-life

the time required for half of a sample of a radioactive substance to disintegrate by radioactive decay or natural processes

Constant Rates of Decay Are Key to Radioactive Dating

The half-life of a radioactive isotope is a constant value and is not influenced by any external conditions, such as temperature and pressure. The use of radioactive isotopes to determine the age of an object, such as the one shown in **Figure 14,** is called *radioactive dating.* The radioactive isotope carbon-14 is often used in radioactive dating.

Figure 14
Using radioactive-dating techniques, scientists determined this Egyptian cat was made between 950–342 BCE.

Nearly all of the carbon on Earth is present as the stable isotope carbon-12. A very small percentage of the carbon in Earth's crust is carbon-14. Carbon-14 undergoes decay to form nitrogen-14. Because carbon-12 and carbon-14 have the same electron configuration, they react chemically in the same way. Both of these carbon isotopes are in carbon dioxide, which is used by plants in photosynthesis.

As a result, all animals that eat plants contain the same ratio of carbon-14 to carbon-12 as the plants do. Other animals eat those animals, and so on up the food chain. So all animals and plants have the same ratio of carbon-14 to carbon-12 throughout their lives. Any carbon-14 that decays while the organism is alive is replaced through photosynthesis or eating. But when a plant or animal dies, it stops taking in carbon-containing substances, so the carbon-14 that decays is not replaced.

TABLE 2 Half-Lives of Some Radioactive Isotopes

Isotope	Half-life	Radiation emitted	Isotope formed
Carbon-14	5.715×10^3 y	β^-, γ	nitrogen-14
Iodine-131	8.02 days	β^-, γ	xenon-131
Potassium-40	1.28×10^9 y	β^+, γ	argon-40
Radon-222	3.82 days	α, γ	polonium-218
Radium-226	1.60×10^3 y	α, γ	radon-222
Thorium-230	7.54×10^4 y	α, γ	radium-226
Thorium-234	24.10 days	β^-, γ	protactinium-234
Uranium-235	7.04×10^8 y	α, γ	thorium-231
Uranium-238	4.47×10^9 y	α, γ	thorium-234
Plutonium-239	2.41×10^4 y	α, γ	uranium-235

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Table 2 shows that the half-life of carbon-14 is 5715 years. After that interval, only half of the original amount of carbon-14 will remain. In another 5715 years, half of the remaining carbon-14 atoms will have decayed and leave one-fourth of the original amount.

Once amounts of carbon-12 and carbon-14 are measured in an object, the ratio of carbon-14 to carbon-12 is compared with the ratio of these isotopes in a sample of similar material whose age is known. Using radioactive dating, with carbon-14, scientists can estimate the age of the object.

A frozen body that was found in 1991 in the Alps between Austria and Italy was dated using C-14. The body is known as the Iceman. A small copper ax was found with the Iceman's body, which shows that the Iceman lived during the Age of copper (4000 to 2200 BCE). Radioactive dating with C-14 revealed that the Iceman lived between 3500 and 3000 BCE and is the oldest prehistoric human found in Europe.

Generally, the more unstable a nuclide is, the shorter its half-life is and the faster it decays. **Figure 15** shows the radioactive decay of iodine-131, which is a very unstable isotope that has a short half-life.

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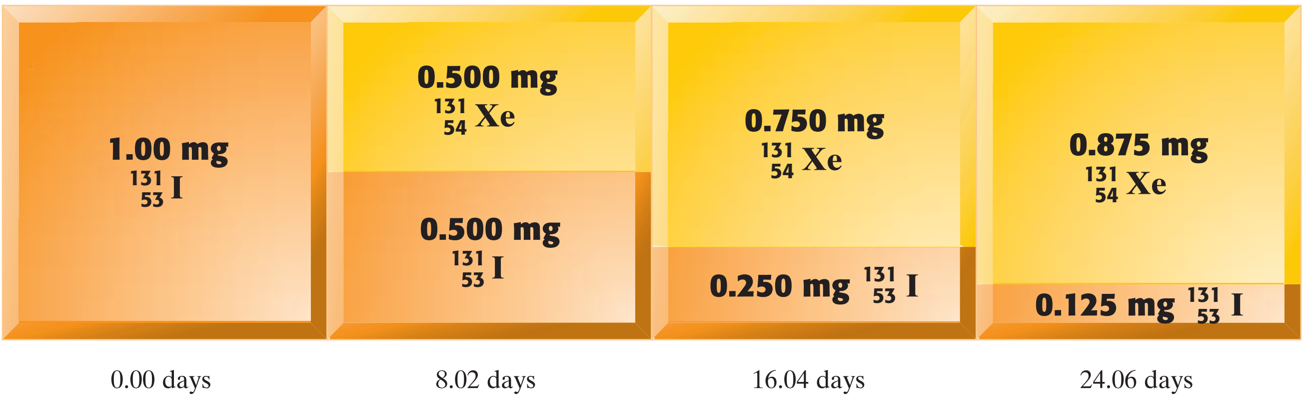

Figure 15
The radioactive isotope $^{131}_{53}I$ has a half-life of 8.02 days. In each successive 8.02-day period, half the atoms of $^{131}_{53}I$ in the original sample decay to $^{131}_{54}Xe$.

SAMPLE PROBLEM B

Determining the Age of an Artifact or Sample

An ancient artifact is found to have a ratio of carbon-14 to carbon-12 that is one-eighth of the ratio of carbon-14 to carbon-12 found in a similar object today. How old is this artifact?

1 Gather information.

- The half-life of carbon-14 is 5715 years.
- The artifact has a ratio of carbon-14 to carbon-12 that is one-eighth of the ratio of carbon-14 to carbon-12 found in a modern-day object.

2 Plan your work.

- First, determine the number of half-lives that the carbon-14 in the artifact has undergone.
- Next, find the age of the artifact by multiplying the number of half-lives by 5715 y.

3 Calculate.

- For an artifact to have one-eighth of the ratio of carbon-14 to carbon-12 found in a modern-day object, three half-lives must have passed.

$$\frac{1}{8} = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$$

- To find the age of the artifact, multiply the half-life of carbon-14 three times for the three half-lives that have elapsed.

$$3 \times 5715 \text{ y} = 17\,145 \text{ y}$$

4 Verify your results.

- Start with your answer, and work backward through the solution to be sure you get the information found in the problem.

$$\frac{17\,145 \text{ y}}{3} = 5715 \text{ y}$$

PRACTICE HINT

Make a diagram that shows how much of the original sample is left to solve half-life problems.

$1 \longrightarrow 1/2 \longrightarrow 1/4 \longrightarrow 1/8 \longrightarrow 1/16 \longrightarrow 1/32 \longrightarrow$ etc.

Each arrow represents one half-life.

PRACTICE

PROBLEM SOLVING SKILL

1. Assuming a half-life of 1599 y, how many years will be needed for the decay of 15/16 of a given amount of radium-226?
2. The half-life of radon-222 is 3.824 days. How much time must pass for one-fourth of a given amount of radon to remain?
3. The half-life of polonium-218 is 3.0 min. If you start with 16 mg of polonium-218, how much time must pass for only 1.0 mg to remain?

Figure 16
Scientists determined that this cave painting at Lascaux, called *Chinese Horse*, was created approximately 13 000 BCE.

Some Isotopes Are Used for Geologic Dating

By analyzing organic materials in the paints, scientists used carbon-14 to date the cave painting shown in **Figure 16.** Two factors limit dating with carbon-14. The first limitation is that C-14 cannot be used to date objects that are completely composed of materials that were never alive, such as rocks or clay. The second limitation is that after four half-lives, the amount of radioactive C-14 remaining in an object is often too small to give reliable data. Consequently, C-14 is not useful for dating specimens that are more than about 50 000 years old. Anything older must be dated on the basis of a radioactive isotope that has a half-life longer than that of carbon-14. One such isotope is potassium-40.

Potassium-40, which has a half-life of 1.28 billion years, represents only about 0.012% of the potassium present in Earth today. Potassium-40 is useful for dating ancient rocks and minerals. Potassium-40 produces two different isotopes in its radioactive decay. About 11% of the potassium-40 in a mineral decays to argon-40 by emitting a positron.

$$^{40}_{19}\text{K} \longrightarrow {}^{40}_{18}\text{Ar} + {}^{0}_{+1}e$$

The argon-40 may remain in the sample. The remaining 89% of the potassium-40 decays to calcium-40 by emitting a beta particle.

$$^{40}_{19}\text{K} \longrightarrow {}^{40}_{20}\text{Ca} + {}^{0}_{-1}e$$

The calcium-40 is not useful for radioactive dating because it cannot be distinguished from other calcium in the rock. The argon-40, however, can be measured. **Figure 17** shows the decay of potassium-40 through four half-lives.

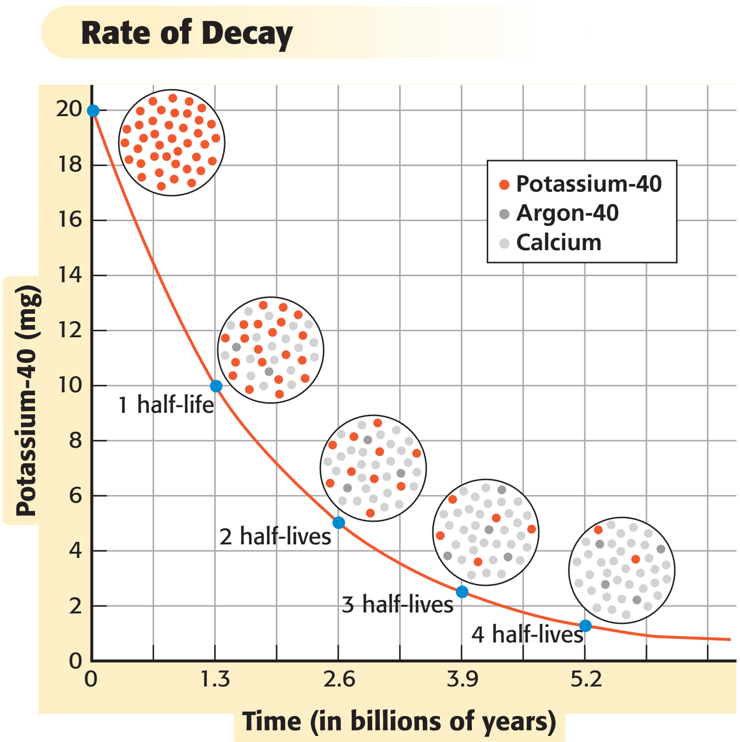

Figure 17
Potassium-40 decays to argon-40 and calcium-40, but scientists monitor only the ratio of potassium-40 to argon-40 to determine the age of the object.

SAMPLE PROBLEM C

Determining the Original Mass of a Sample

A rock is found to contain 4.3 mg of potassium-40. The rock is dated to be 3.84 billion years old. How much potassium-40 was originally present in this rock?

1 Gather information.

- The rock is 3.84 billion years old and contains 4.3 mg of $^{40}_{19}K$.
- The half-life of potassium-40 is 1.28 billion years.

2 Plan your work.

- Find the number of half-lives that the $^{40}_{19}K$ in the rock has undergone.
- Next, find the mass of the $^{40}_{19}K$ that was originally in the rock. Double the present amount for every half-life that the isotope has undergone.

3 Calculate.

- Divide the age of the rock by the half-life of the isotope to find the number of half-lives.

$$\frac{3.84 \text{ billion y}}{1.28 \text{ billion y}} = 3 \text{ half-lives have elapsed}$$

- The mass of the original potassium-40 sample is calculated by doubling 4.3 mg three times.

$4.3 \text{ mg} \times 2 = 8.6 \text{ mg}$ were present in the rock 1 half-life ago

$8.6 \text{ mg} \times 2 = 17 \text{ mg}$ were present in the rock 2 half-lives ago

$17 \text{ mg} \times 2 = 34 \text{ mg}$ were present in the rock 3 half-lives ago

4 Verify your results.

After three half-lives, one-eighth of the original $^{40}_{19}K$ remains. So, $8 \times 4.3 = 34$ mg.

PRACTICE HINT

Remember to double the amount of radioactive isotope each time you go back one half-life.

PRACTICE

PROBLEM SOLVING SKILL

1. The half-life of polonium-210 is 138.4 days. How many milligrams of polonium-210 remain after 415.2 days if you start with 2.0 mg of the isotope?
2. After 4797 y, how much of an original 0.250 g sample of radium-226 remains? Its half-life is 1599 y.
3. The half-life of radium-224 is 3.66 days. What was the original mass of radium-224 if 0.0800 g remains after 7.32 days?

Other Uses of Nuclear Chemistry

Scientists create new elements by using nuclear reactions. But the use of nuclear reactions has extended beyond laboratories. Today, nuclear reactions have become part of our lives. Nuclear reactions that protect your life may be happening in your home.

Smoke Detectors Contain Sources of Alpha Particles

Smoke detectors depend on nuclear reactions to sound an alarm when a fire starts. Many smoke detectors contain a small amount of americium-241, which decays to form neptunium-237 and alpha particles.

$$^{241}_{95}\text{Am} \longrightarrow \, ^{237}_{93}\text{Np} + \, ^{4}_{2}\text{He}$$

The alpha particles cannot penetrate the plastic cover and can travel only a short distance. When alpha particles travel through the air, they ionize gas molecules in the air, which change the molecules into ions. These ions conduct an electric current. Smoke particles reduce this current when they mix with the ionized molecules. In response, the smoke detector sets off an alarm.

Detecting Art Forgeries with Neutron Activation Analysis

Nuclear reactions can be used to help museum directors detect whether an artwork, such as the one shown in **Figure 18,** is a fake. The process is called *neutron activation analysis.* A tiny sample from the suspected forgery is placed in a machine. A nuclear reactor in the machine bombards the sample with neutrons. Some of the atoms in the sample absorb neutrons and become radioactive isotopes. These isotopes emit gamma rays as they decay.

Scientists can identify each element in the sample by the characteristic pattern of gamma rays that each element emits.

Figure 18
Neutron activation analysis can be used to determine if this artwork is real.

Scientists can then determine the exact proportions of the elements present. This method gives scientists a "fingerprint" of the elements in the sample. If the fingerprint matches materials that were not available when the work was supposedly created, then the artwork is a fake.

Nuclear Reactions Are Used in Medicine

The use of nuclear reactions by doctors has grown to the point where a whole field known as nuclear medicine has developed. Nuclear medicine includes the use of nuclear reactions both to diagnose certain conditions and to treat a variety of diseases, especially certain types of cancer.

For years, doctors have used a variety of devices, such as X-ray imaging, to get a view inside a person's body. Nuclear reactions have enabled them to get a much more detailed view of the body. For example, doctors can take a close look at a person's heart by using a thallium stress test. The person is given an intravenous injection of thallium-201, which acts chemically like calcium and collects in the heart muscle. As the thallium-201 decays, low-energy gamma rays are emitted and are detected by a special camera that produces images, such as the one shown in **Figure 19.**

The radioactive isotope most widely used in nuclear medicine is technetium-99, which has a short half-life and emits low-energy gamma rays. This radioactive isotope is used in bone scans. Bone repairs occur when there is a fracture, infection, arthritis, or an invading cancer. Bones that are repairing themselves take in minerals and absorb the technetium at the same time. If an area of bone has an unusual amount of repair, the technetium will gather there. Cameras detect the gamma rays that result from its decay.

Another medical procedure that uses nuclear reactions is called *positron emission tomography* (PET), which is shown in **Figure 20.** PET uses radioactive isotopes that have short half-lives. An unstable isotope that contains too many protons is injected into the person.

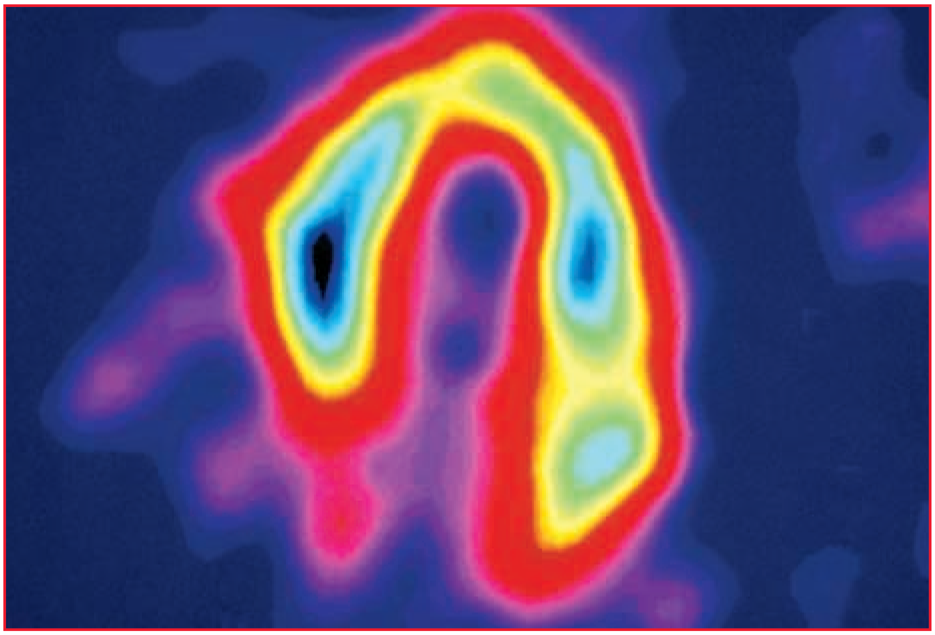

Figure 19
This image reveals the size of the heart, how well the chambers are pumping, and whether there is any scarring of muscle from previous heart attacks.

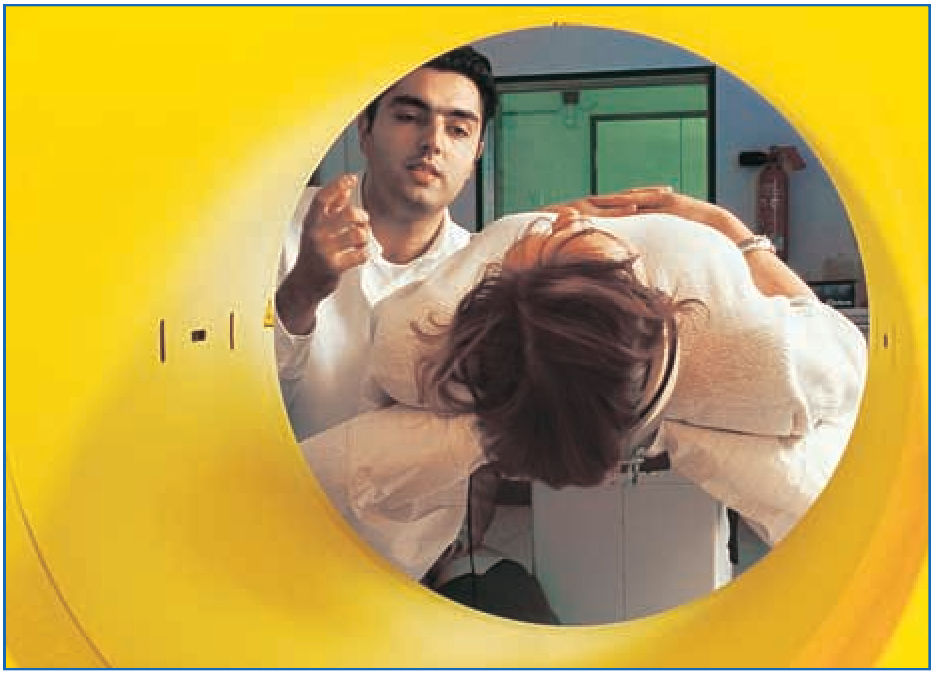

Figure 20
This person is undergoing a PET scan. The scan will provide information about how well oxygen is being used by the person's brain.

As this isotope decays, positrons are emitted. Recall that when a positron collides with an electron, both are annihilated, and two gamma rays are produced. These gamma rays leave the body and are detected by a scanner. A computer converts the images into a detailed three-dimensional picture of the person's organs.

Exposure to Radiation Must Be Checked

Table 3 shows how radiation can affect a person's health using the unit *rem*, which expresses the biological effect of an absorbed dose of radiation in humans. People who work with radioactivity wear a film badge to monitor the amount of radiation to which they are exposed. Radioactivity was discovered when sealed photographic plates exposed to radiation became fogged. A film badge works on the same principle. Any darkening of the film indicates that the badge wearer was exposed to radiation, and the degree of darkening indicates the total exposure.

Table 3 Effect of Whole-Body Exposure to a Single Dose of Radiation

Dose (rem)	Probable effect
0–25	no observable effect
25–50	slight decrease in white blood cell count
50–100	marked decrease in white blood cell count
100–200	nausea, loss of hair
200–500	ulcers, internal bleeding
> 500	death

Table 4 Units Used in Measurements of Radioactivity

Units	Measurements
Curie (C)	radioactive decay
Becquerel (Bq)	radioactive decay
Roentgens (R)	exposure to ionizing radiation
Rad (rad)	energy absorption caused by ionizing radiation
Rem (rem)	biological effect of the absorbed dose in humans

Single and Repeated Exposures Have Impact

As shown in **Table 3,** the biological effect of exposure to nuclear radiation can be expressed in rem. Healthcare professionals are advised to limit their exposure to 5 rem per year. This exposure is 1000 times higher than the recommended exposure level for most people, including you. Other units of radiation measurement can be seen in **Table 4.**

People exposed to a single large dose or a few large doses of radiation in a short period of time are said to have experienced an acute radiation exposure. More than 230 people suffered acute radiation sickness and 28 died when a meltdown occurred in 1986 at the Chernobyl nuclear power plant in the Ukraine.

The effects of nuclear radiation on the body can add up over time. Exposure to small doses of radiation over a long period of time can be as dangerous as a single large dose if the total radiation received is equal. Chronic radiation exposure occurs when people get many low doses of radiation over a long period of time. Some scientific studies have shown a correlation between chronic radiation exposure and certain types of cancer.

3 Section Review

UNDERSTANDING KEY IDEAS

1. What is meant by the *half-life* of a radioactive nuclide?
2. Explain how carbon-14 dating is used to determine the age of an object.
3. Why is potassium-40 used to date objects older than 50 000 years old?
4. Identify three practical applications of nuclear chemistry.

PRACTICE PROBLEMS

5. What fraction of an original sample of a radioactive isotope remains after three half-lives have passed?
6. How many half-lives of radon-222 have passed in 11.46 days? If 5.2×10^{-8} g of radon-222 remain in a sealed box after 11.46 days, how much was present in the box initially? Refer to **Table 2.**
7. The half-life of protactinium-234 in its ground state is 6.69 h. What fraction of a given amount remains after 26.76 h?
8. The half-life of thorium-227 is 18.72 days. How many days are required for three-fourths of a given amount to decay?

CRITICAL THINKING

9. Someone tells you that neutron activation analysis can reveal whether a famous painter or a rival living at the same time created a painting. What is wrong with this reasoning?
10. Why are isotopes that have relatively short half-lives the only ones used in medical diagnostic tests?
11. A practical rule is that a radioactive nuclide is essentially gone after 10 half-lives. What percentage of the original radioactive nuclide is left after 10 half-lives? How long will it take for 10 half-lives to pass for plutonium-239? Refer to **Table 2.**

1
H
Hydrogen
1.007 94
1*s*

Where Is H?

Earth's crust
0.9 by mass

Universe
approximately 93% of all atoms

Element Spotlight

Hydrogen Is an Element unto Itself

Hydrogen is a unique element in many respects. Its scarcity on Earth is partially due to the low density of hydrogen gas. The low density permits hydrogen molecules to escape Earth's gravitational pull and drift into space.

Hydrogen does not fit precisely anywhere in the periodic table. It could be placed in Group 1 because it has a single valence electron. But it could also be placed with the halogens in Group 17 because it needs only one electron to get a full outer shell.

Liquid hydrogen is used as fuel for some rockets.

Industrial Uses

- Hydrogen gas is prepared industrially by the thermal decomposition of hydrocarbons, such as natural gas, oil-refinery gas, gasoline, fuel oil, and crude oil.
- Most of the hydrogen gas produced is used for synthesizing ammonia.
- Hydrogen is used in the hydrogenation of unsaturated vegetable oils to make solid fats.
- Liquid hydrogen is a clear, colorless liquid that has a boiling point of –252.87°C, the lowest boiling point of any known liquid other than liquid helium. Because of its low temperature, liquid hydrogen is used to cool superconducting materials.
- Liquid hydrogen is used to fuel rockets, satellites, and spacecrafts.

Real-World Connection Nuclear fusion, in which hydrogen atoms form helium atoms, occurs in our sun.

A Brief History

1600 — 1700 — 1800 — 1900

1660: Robert Boyle prepares hydrogen from a reaction between iron and sulfuric acid.

1766: Henry Cavendish prepares a pure sample of hydrogen and distinguishes it from other gases. He names it "inflammable air."

1783: Jacques Charles fills a balloon with hydrogen and flies in a basket over the French countryside.

1898: James Dewar produces liquid hydrogen and develops a glass vacuum flask to hold it.

1931: Harold Urey discovers deuterium, an isotope of hydrogen, in water.

1934: Ernest Rutherford, Marcus Oliphant, and Paul Harteck discover tritium.

1937: The Hindenburg, a hydrogen-filled dirigible, explodes during a landing in Lakehurst, New Jersey.

1996: Scientists at Lawrence Livermore National Laboratory succeed in making solid, metallic hydrogen.

Questions

1. Research how hydrogen is used to fuel rockets and spacecrafts.

2. Write a paragraph about stars and fusion.

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18 CHAPTER HIGHLIGHTS

KEY IDEAS

SECTION ONE Atomic Nuclei and Nuclear Stability

- The strong force overcomes the repulsive force between protons to keep a nucleus intact.
- The mass that is converted to energy when nucleons form a nucleus is known as the mass defect.
- If the mass defect is known, the nuclear binding energy can be calculated by using the equation $E = mc^2$.
- The ratio of neutrons to protons defines a band of stability that includes the stable nuclei.

KEY TERMS

nucleons
nuclide
strong force
mass defect

SECTION TWO Nuclear Change

- Unstable nuclei are radioactive and can emit radiation in the form of alpha particles, beta particles, and gamma rays.
- Unstable nuclei that have large N/Z usually emit beta particles.
- Unstable nuclei that have small N/Z or have too few neutrons can undergo either electron capture or positron emission, emitting gamma rays in the process.
- Large nuclei that have large N/Z frequently emit alpha particles.
- Nuclear equations are balanced in terms of mass and nuclear charge.
- In nuclear fission, a heavy nucleus splits into two smaller nuclei; in nuclear fusion, two or more smaller nuclei combine to form one larger nucleus.
- Nuclear fission reactions that cause other fissions are chain reactions. Chain reactions must be controlled to generate usable energy.

KEY TERMS

radioactivity
beta particle
gamma ray
nuclear fission
chain reaction
critical mass
nuclear fusion

SECTION THREE Uses of Nuclear Chemistry

- Half-life is the time required for one half of the mass of a radioactive isotope to decay.
- The half-life of the carbon-14 isotope can be used to date organic material that is up to 50 000 years old. Other radioactive isotopes are used to date older rock and mineral formations.
- Radioactive isotopes have a number of practical applications in industry, medicine, and chemical analysis.

KEY TERMS

half-life

KEY SKILLS

Balancing a Nuclear Equation
Skills Toolkit 1 p. 652
Sample Problem A p. 653

Determining the Age of an Artifact or Sample
Sample Problem B p. 660

Determining the Original Mass of a Sample
Sample Problem C p. 662

CHAPTER REVIEW 18

USING KEY TERMS

1. What is the energy emitted when a nucleus forms?
2. What is a nucleon?
3. What is the high-energy electromagnetic radiation produced by decaying nuclei?
4. What nuclear reaction happens when two small nuclei combine?
5. Explain the difference between fission and fusion.
6. Name the process that describes an unstable nucleus that emits particles and energy.
7. Define *critical mass.*
8. Define *half-life.*
9. What is the combination of neutrons and protons in a nucleus known as?
10. Name two types of nuclear changes.

UNDERSTANDING KEY IDEAS

Atomic Nuclei and Nuclear Stability

11. Explain how the strong force holds a nucleus together despite the repulsive forces between protons.
12. Describe what happens to unstable nuclei.
13. **a.** What is the relationship among the number of protons, the number of neutrons, and the stability of the nucleus for small atoms?

    b. What is the relationship among number of protons, the number of neutrons, and the stability of the nucleus for large atoms?
14. What is the relationship between binding energy and the formation of a nucleus from protons and neutrons?
15. What is the relationship between mass defect and binding energy?
16. Why is nuclear stability better indicated by binding energy per nucleon than by total binding energy per nucleus?
17. What is a quark?

Nuclear Change

18. What is the relationship between an alpha particle and a helium nucleus?
19. Compare the penetrating powers of alpha particles, beta particles, and gamma rays.
20. Is the decay of an unstable isotope into a stable isotope always a one-step process? Explain.
21. **a.** What role does a neutron serve in starting a nuclear chain reaction and in keeping it going?

    b. Why must neutrons in a chain reaction be controlled?

    c. Why must there be a minimum mass of material in order to sustain a chain reaction?
22. Under what conditions does fusion occur?
23. Why do positron emission and electron capture have the same effect on a nucleus?

Uses of Nuclear Chemistry

24. Explain why nuclei that emit alpha particles, such as americium-241, are safe to use in smoke detectors.

25. How does acute radiation exposure differ from chronic radiation exposure?

26. Why do animals contain the same ratio of carbon-14 to carbon-12 as plants do?

27. What type of radioactive nuclide is injected into a person who is about to undergo a PET scan?

28. Describe how nuclear chemistry can be used to detect an art forgery.

29. What does the unit *rem* describe?

PRACTICE PROBLEMS

PROBLEM SOLVING SKILL

Sample Problem A Balancing a Nuclear Equation

30. The decay of uranium-238 results in the spontaneous ejection of an alpha particle. Write the nuclear equation that describes this process.

31. What type of radiation is emitted in the decay described by the following equation?

$$^{43}_{19}\text{K} \longrightarrow {}^{43}_{20}\text{Ca} + ?$$

32. When a radon-222 nucleus decays, an alpha particle is emitted. Write the nuclear equation to show what happens when a radon-222 nucleus decays. What is the other product that forms?

33. One radioactive decay series that begins with uranium-235 and ends with lead-207 shows the partial sequence of emissions: alpha, beta, alpha, beta, alpha, alpha, alpha, alpha, beta, beta, and alpha. Write an equation for each reaction in the series.

34. Balance the following nuclear reactions.

    a. $^{239}_{93}\text{Np} \longrightarrow {}^{0}_{-1}e + ?$

    b. $^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \longrightarrow ?$

    c. $^{32}_{15}\text{P} + ? \longrightarrow {}^{33}_{15}\text{P}$

    d. $^{236}_{92}\text{U} \longrightarrow {}^{94}_{36}\text{Kr} + ? + 3{}^{1}_{0}n$

35. Complete and balance the following nuclear equations:

    a. $^{187}_{75}\text{Re} + ? \longrightarrow {}^{188}_{75}\text{Re} + {}^{1}_{1}\text{H}$

    b. $^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \longrightarrow ? + {}^{1}_{0}n$

    c. $^{22}_{11}\text{Na} + ? \longrightarrow {}^{22}_{10}\text{Ne}$

36. Write the nuclear equation for the release of a positron by $^{117}_{54}\text{Xe}$.

Sample Problem B Determining the Age of an Artifact or Sample

37. Copper-64 is used to study brain tumors. Assume that the original mass of a sample of copper-64 is 26.00 g. After 64 hours, all that remains is 0.8125 g of copper-64. What is the half-life of this radioactive isotope?

38. The half-life of thorium-234 is 24.10 days. How many days until only one-sixteenth of a 52.0 g sample of thorium-234 remains?

39. The half-life of carbon-14 is 5715 y. How long will it be until only half of the carbon-14 in a sample remains?

Sample Problem C Determining the Original Mass of a Sample

40. The half-life of one radon isotope is 3.8 days. If a sample of gas contains 4.38 g of radon-222, how much radon will remain in the sample after 15.2 days?

41. After 4797 y, how much of an original 0.450 g of radium-226 remains? The half-life of radium-226 is 1599 y.

42. The half-life of cobalt-60 is 10.47 min. How many milligrams of Co-60 remain after 104.7 min if you start with 10.0 mg of Co-60?

MIXED REVIEW

43. Calculate the neutron-proton ratios for the following nuclides, and determine where they lie in relation to the band of stability.

    a. $^{235}_{92}\text{U}$

    b. $^{16}_{8}\text{O}$

    c. $^{56}_{26}\text{Fe}$

    d. $^{156}_{60}\text{Nd}$

44. Calculate the binding energy per nucleon of $^{238}_{92}U$ in joules. The atomic mass of a $^{238}_{92}U$ nucleus is 238.050 784 amu.

45. The energy released by the formation of a nucleus of $^{56}_{26}Fe$ is 7.89×10^{-11} J. Use Einstein's equation, $E = mc^2$, to determine how much mass is lost (in kilograms) in this process.

46. What nuclear process is occuring in the sun shown? Also, write a nuclear reaction that describes this process.

47. The radiation given off by iodine-131 in the form of beta particles is used to treat cancer of the thyroid gland. Write the nuclear equation to describe the decay of an iodine-131 nucleus.

48. The parent nuclide of the thorium decay series is $^{232}_{90}Th$. The first four decays are as follows: alpha emission, beta emission, beta emission, and alpha emission. Write the nuclear equations for this series of emissions.

49. The half-life of radium-224 is 3.66 days. What was the original mass of radium-224 if 0.0500 g remains after 7.32 days?

50. How many milligrams remain of a 15.0 mg sample of radium-226 after 6396 y? The half-life of this isotope is 1599 y.

51. The mass of a $^{7}_{3}Li$ atom is 7.016 00 amu. Calculate its mass defect.

52. Determine whether each of the following nuclear reactions involves alpha decay, beta decay, positron emission, or electron capture.

a. $^{234}_{90}Th \longrightarrow {}^{0}_{-1}e + {}^{234}_{91}Pa$

b. $^{238}_{92}U \longrightarrow {}^{4}_{2}He + {}^{234}_{90}Th$

c. $^{15}_{8}O \longrightarrow {}^{0}_{+1}e + {}^{15}_{7}N$

53. Uranium-238 decays through alpha decay with a half-life of 4.46×10^9 y. How long would it take for seven-eighths of a sample of uranium-238 to decay?

54. Write the nuclear equation for the release of an alpha particle by $^{157}_{70}Yb$.

55. The half-life of iodine-131 is 8.02 days. What percentage of an iodine-131 sample will remain after 40.2 days?

56. The mass of a $^{20}_{10}Ne$ atom is 19.992 44 amu. Calculate its mass defect.

57. Calculate the nuclear binding energy of one lithium-6 atom. The measured atomic mass of lithium-6 is 6.015 amu.

58. Write the nuclear equation for the release of a beta particle by $^{210}_{82}Pb$.

59. The half-life of an element X is 5.25 y. How many days are required for one-fourth of a given amount of X to decay?

60. Complete the following nuclear reactions.

a. $^{12}_{5}B \longrightarrow {}^{12}_{6}C + ?$

b. $^{225}_{89}Ac \longrightarrow {}^{221}_{87}Fr + ?$

c. $^{63}_{28}Ni \longrightarrow ? + {}^{0}_{-1}e$

d. $^{212}_{83}Bi \longrightarrow ? + {}^{4}_{2}He$

61. Actinium-217 decays by releasing an alpha particle. Write an equation for this decay process, and determine what element is formed.

62. Indicate if the following equations represent fission reactions or fusion reactions.

a. $^{1}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + \gamma$

b. $^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 3{}^{1}_{0}n$

c. $^{21}_{10}Ne + {}^{4}_{2}He \longrightarrow {}^{24}_{12}Mg + {}^{1}_{0}n$

d. $^{208}_{82}Pb + {}^{58}_{26}Fe \longrightarrow {}^{265}_{108}Hs + {}^{1}_{0}n$

63. Predict whether the total mass of the 26 protons and neutrons that make up the iron nucleus will be more, less, or equal to 55.845 amu, the mass of an iron atom from the periodic table. If it is not equal, explain why not.

64. A sample of francium-212 will decay to one-sixteenth its original amount after 80 min. What is the half-life of francium-212?

65. Identify which of the four common types of nuclear radiation (beta, neutron, alpha, or gamma) correspond to the following descriptions:
a. an electron
b. uncharged particle
c. can be stopped by a piece of paper
d. high-energy light

66. Calculate the time required for three-fourths of a sample of cesium-138 to decay given that its half-life is 32.2 min.

67. Calculate that half-life of cesium-135 if seven-eighths of a sample decays in 6×10^6 y.

68. An archaeologist discovers a wooden mask whose carbon-14 to carbon-12 ratio is one-sixteenth the ratio measured in a newly fallen tree. How old does the wooden mask seem to be, given this evidence?

69. The half-life of tritium, ${}^{3}_{1}H$, is 12.3 y. How long will it take for seven-eighths of the sample to decay?

70. It takes about 10^6 y for just half the samarium-149 in nature to decay by alpha-particle emission. Write the decay equation, and find the isotope that is produced by the reaction.

71. Describe some of the similarities and differences between atomic electrons and beta particles.

CRITICAL THINKING

72. Medium-mass nuclei have larger binding energies per nucleon than heavier nuclei do. What can you conclude from this fact?

73. Why are elevated temperatures necessary to initiate fusion reactions but not fission reactions?

74. Why is the constant rate of decay of radioactive nuclei so important in radioactive dating?

75. Why would someone working around radioactive waste in a landfill use a radiation monitor instead of a watch to determine when the workday is over? At what point would that person decide to stop working?

76. Explain why charged particles do not penetrate matter deeply.

ALTERNATIVE ASSESSMENTS

77. Research some important historical findings that have been validated through radioactive dating. Report your findings to the class.

78. Design an experiment that illustrates the concept of half-life.

79. Research and evaluate environmental issues regarding the storage, containment, and disposal of nuclear wastes.

80. Suppose you are an energy consultant who has been asked to evaluate a proposal to build a power plant in a remote area of the desert. Research the requirements for each of the following types of power plant: nuclear-fission power plant, coal-burning power plant, solar-energy farm. Decide which of these power plants would be best for its surroundings, and write a paragraph supporting your decision.

CONCEPT MAPPING

concept map

81. Use the following terms to complete the concept map below: *critical mass, chain reaction, nuclear fission,* and *nucleon.*

FOCUS ON GRAPHING

Study the graph below, and answer the questions that follow.
For help in interpreting graphs, see Appendix B, "Study Skills for Chemistry."

82. Do stable nuclei that have *N/Z* numbers approximately equal to 1 have small or large atomic numbers?

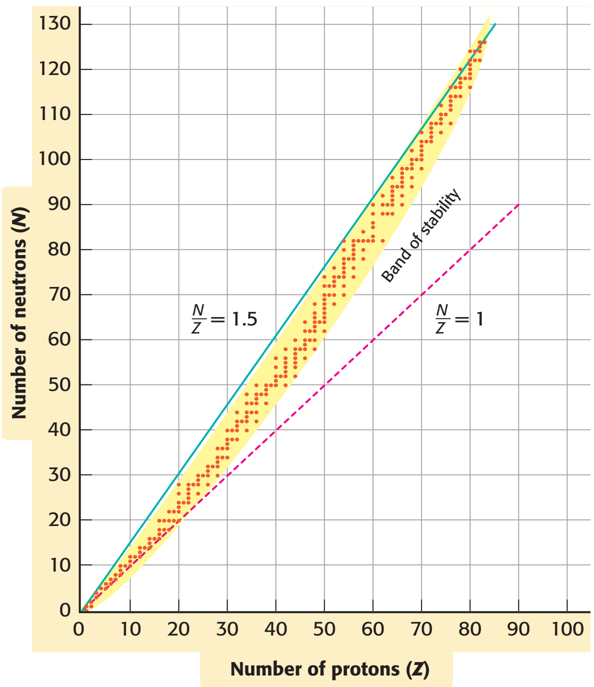
83. Do stable nuclei that have *N/Z* numbers approximately equal to 1.5 have small or large atomic numbers?

84. Calculate the *N/Z* number for a nucleus A that has 70 neutrons and 50 protons.

85. Calculate the *N/Z* number for a nucleus B that has 90 neutrons and 60 protons.

86. Does nucleus A or nucleus B have an *N/Z* number closer to 1.5?

Neutron-Proton Ratios of Stable Nuclei



TECHNOLOGY AND LEARNING

87. Graphing Calculator

Calculating the Amount of Radioactive Material

The graphing calculator can run a program that graphs the relationship between the amount of radioactive material and elapsed time. Given the half-life of the radioactive material and the initial amount of material in grams, you will graph the relationship between the amount of radioactive material and the elapsed time. Then, with the elapsed time, you will trace the graph to calculate the amount of radioactive material.

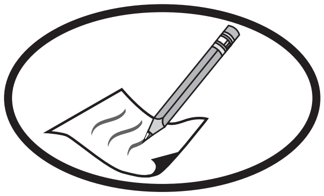
Go to Appendix C. If you are using a TI-83 Plus, you can download the program RADIOACT and run the application as directed. If you are using another calculator, your teacher will provide you with keystrokes and data sets to use. After you have run the program, answer these questions.

a. Determine the amount of neptunium-235 left after 2.0 years, given the half-life of neptunium-235 is 1.08 years and the initial amount was 8.00 g.

b. Determine the amount of neptunium-235 left after 5.0 years, given the half-life of neptunium-235 is 1.08 years and the initial amount was 8.00 g.

c. Determine the amount of uranium-232 left after 100 years, given the half-life of uranium-232 is 69 years and the initial amount was 10.0 g.

18 STANDARDIZED TEST PREP



UNDERSTANDING CONCEPTS

***Directions (1–3):* For *each* question, write on a separate sheet of paper the letter of the correct answer.**

1 Which of the following changes occurs when a nucleus is formed?

A. Mass is gained.
B. Energy is absorbed.
C. Mass is converted to energy.
D. Electrons and protons combine to form neutrons.

2 Why doesn't the electrical repulsion between protons cause all nuclei larger than hydrogen to break apart?

F. The atom's electrons neutralize the charge on the protons.
G. The protons are separated by enough distance to withstand the repulsive force.
H. All nuclei do break apart but most have a long enough half-life so it is not detected.
I. The protons and neutrons are held together by a force that is stronger than the repulsion.

3 When an atom emits a beta particle, how does its mass change?

A. -4
B. -1
C. 0
D. $+1$

***Directions (4–6):* For *each* question, write a short response.**

4 Use binding energy to explain why lighter elements, such as hydrogen and helium, are much more likely than heavier elements to undergo nuclear fusion.

5 A sample of strontium-90 is found to have decayed to one-eighth its original amount after 87.3 years. What is its half-life?

6 Explain the function of control rods in a nuclear reactor.

READING SKILLS

***Directions (7–9):* Read the passage below. Then answer the questions.**

Radioactive isotopes are often used as "tracers" to follow the path of an element through a chemical reaction. For example, using radiotracers chemists have determined that the oxygen atoms in O_2 that are produced by a green plant during photosynthesis come from the oxygen in water and not the oxygen in carbon dioxide.

7 Which of the following is a reason that radioactive isotopes can be used as radiotracers to monitor reactions?

F. The chemical reactions of radioisotopes are different from those of other isotopes.
G. Molecules containing radioisotopes can easily separate from molecules through chemical separation techniques.
H. Radioisotopes are expensive to isolate from nature or to produce.
I. Radiation can pass through cell walls and other materials, so it can be monitored in plant and animal tissues.

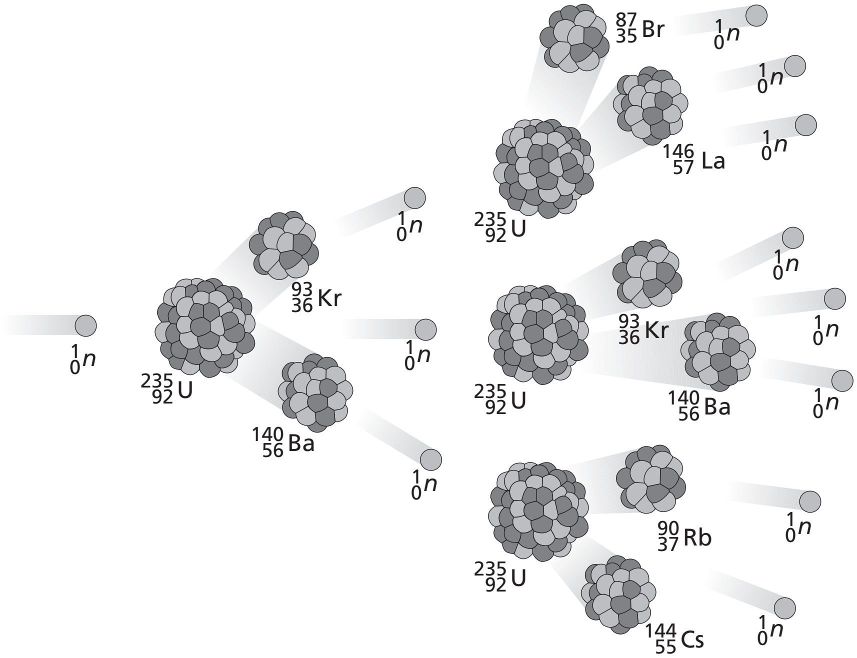
8 How could you design an experiment to determine which molecule is the source of the oxygen produced by photosynthesis?

9 Why would scientists want to determine which molecule contributes the oxygen atoms that form oxygen molecules during photosynthesis?

INTERPRETING GRAPHICS

Directions (10–12): **For *each* question below, record the correct answer on a separate sheet of paper.**

The diagram below shows what happens when a neutron strikes a uranium-235 nucleus. Use it to answer questions 10 through 12.



10 The chain reaction shown here generates a large amount of energy. What is the source of the energy produced?

A. destruction of neutrons

B. lost mass that is converted to energy

C. electrical repulsion between the nuclei produced by fission

D. decrease in binding energy per nucleon as the uranium nucleus breaks apart

11 Which of the following is a way to control this nuclear chain reaction?

F. Add an element, such as cadmium, that absorbs neutrons.

G. Enclose the critical mass of uranium inside a container made of a dense metal such as lead.

H. Increase the concentration of the reaction products to shift the equilibrium toward the reactants.

I. Compress the uranium into a very small volume so that most of the neutrons escape without hitting a nucleus.

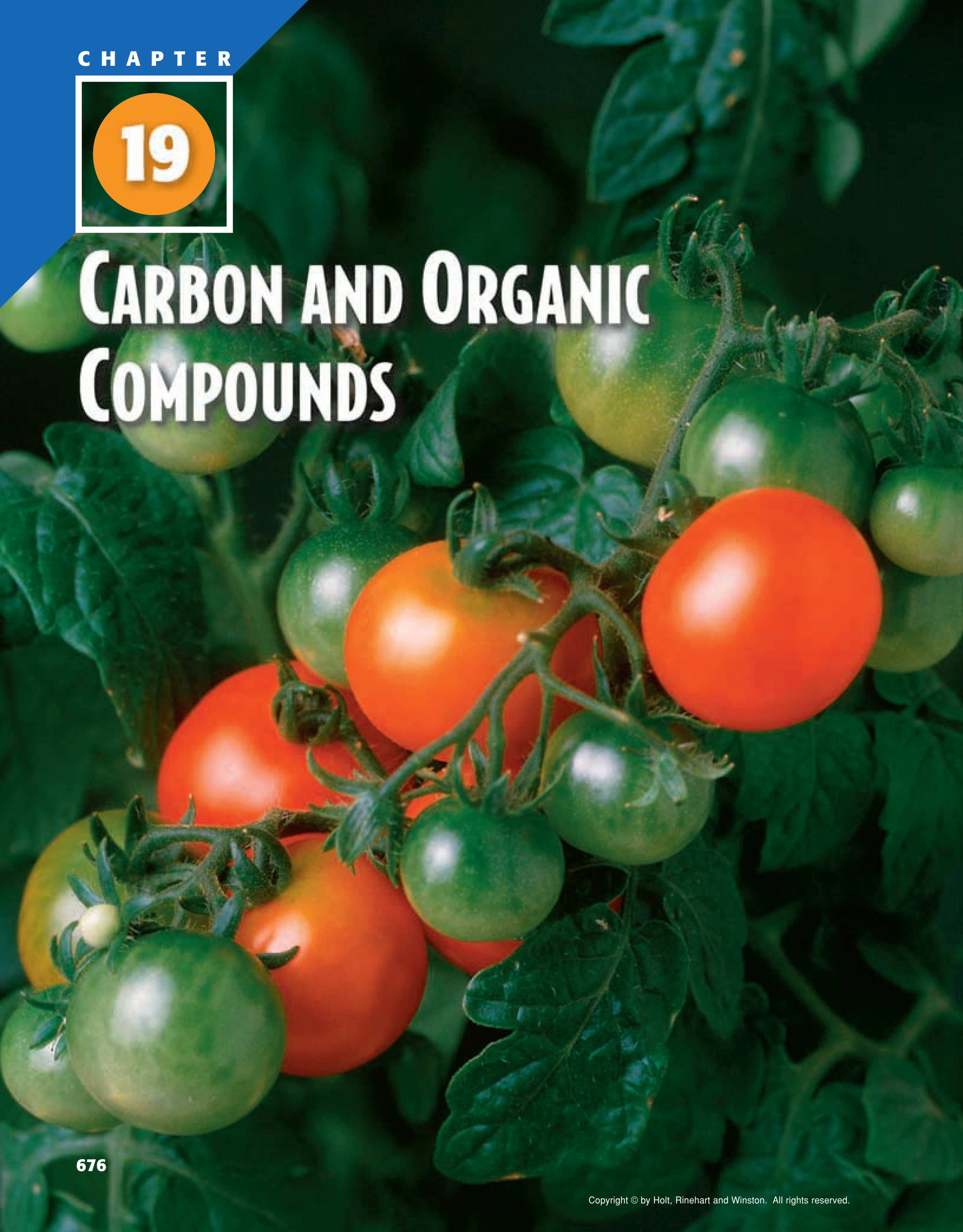
12 Write a balanced equation for the nuclear reaction that produces krypton-93 and barium-140 from uranium-235.

Test TIP

Test questions may not be arranged in order of increasing difficulty. If you are unable to answer a question, mark it and move on to another question.

CHAPTER 19

CARBON AND ORGANIC COMPOUNDS



Tomatoes contain many compounds of carbon, including some that have properties that help people stay healthy. Two of these compounds are lycopene and beta-carotene. Lycopene gives tomatoes their red color and is believed to help prevent heart disease and some forms of cancer. In the human body, beta-carotene is converted to vitamin A, an essential nutrient .

Like the vine that supports the tomatoes in this picture, carbon forms the backbone for the chemicals that make up living organisms. In this chapter, you will learn about the nature of carbon and its many compounds.

START-UP ACTIVITY

Testing Plastics

PROCEDURE

1. Examine **two plastic samples** with a **magnifying lens** to look for any structural differences.
2. To test the rigidity of each sample, try to bend both pieces.
3. To test the hardness of each sample, press into each sample with your fingernail and try to make a permanent mark.
4. To test the strength of each sample, try tearing each plastic piece.

ANALYSIS

1. Which plastic sample would you use to hold liquids?
2. What physical differences did you observe between the two samples?
3. Why do you think most communities recycle only one of these plastics?

CONTENTS 19

Pre-Reading Questions

1. **How many covalent bonds can a carbon atom form?**
2. **How does the structure of a compound affect its chemical reactivity?**
3. **What are two possible ways to show the structure of CH_4?**

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Topic: Organic Compounds
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SECTION 1

Compounds of Carbon

KEY TERMS

- hydrocarbon
- alkane
- alkene
- alkyne
- aromatic hydrocarbon
- functional group
- isomer

OBJECTIVES

1. **Explain** the unique properties of carbon that make the formation of organic molecules possible.
2. **Relate** the structures of diamond, graphite, and other allotropes of carbon to their properties.
3. **Describe** the nature of the bonds formed by carbon in alkanes, alkenes, alkynes, aromatic compounds, and cyclic compounds.
4. **Classify** organic compounds such as alcohols, esters, and ketones by their functional groups.
5. **Explain** how the structural difference between isomers is related to the difference in their properties.

Properties of Carbon

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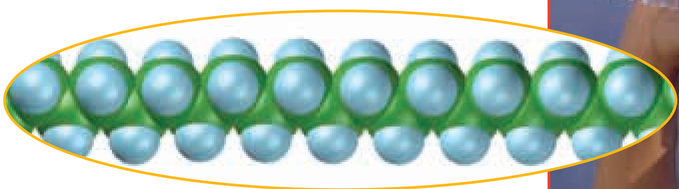
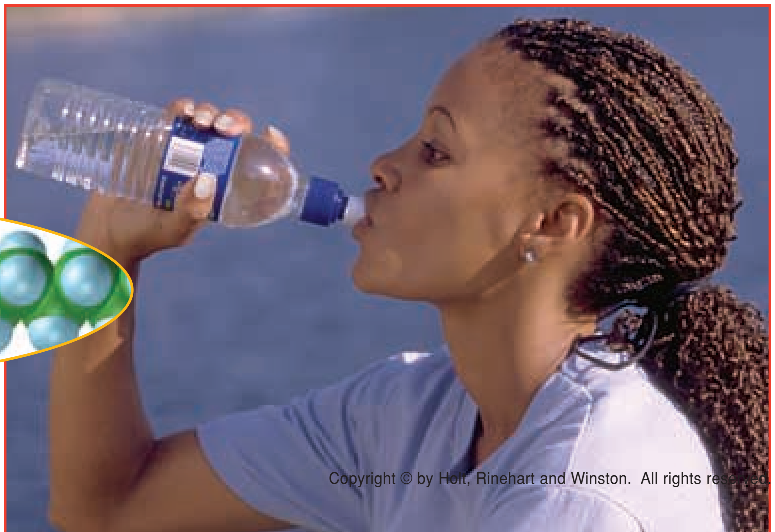
The water bottle shown in **Figure 1** is made of a strong but flexible plastic. These properties result from the bonds formed by the carbon atoms that make up the plastic. Carbon atoms nearly always form covalent bonds. Three factors make the bonds that carbon atoms form with each other unique.

First, even a single covalent bond between two carbon atoms is quite strong. In contrast, the single covalent bond that forms between two oxygen atoms, such as in hydrogen peroxide (HO—OH), is so weak that this compound decomposes at room temperature. Second, carbon compounds are not extremely reactive under ordinary conditions. Butane, C_4H_{10}, is stable in air, but tetrasilane, Si_4H_{10}, catches fire spontaneously in air. Third, because carbon can form up to four single covalent bonds, a wide variety of compounds is possible.

Figure 1
Carbon-carbon bonds within long-chained molecules, such as the polyethylene used to make water bottles, are very strong.





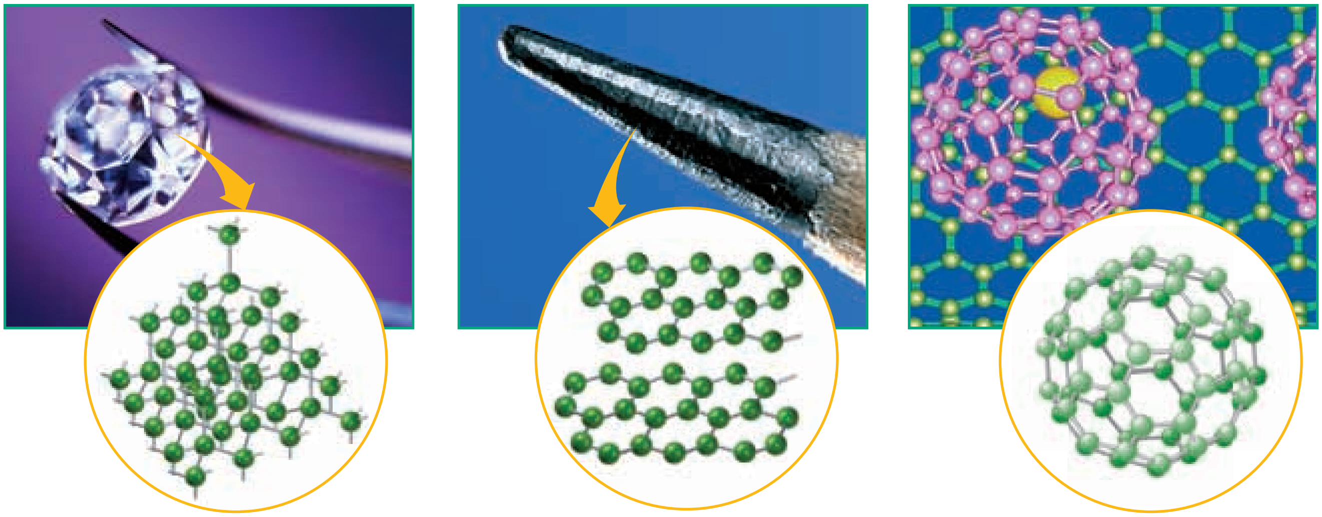


Figure 2
a Diamond is a carbon allotrope in which the atoms are densely packed in a tetrahedral arrangement.
b Graphite is a carbon allotrope in which the atoms form separate layers that can slide past one another.
c Buckminsterfullerene is a carbon allotrope in which 60 carbon atoms form a sphere.

Carbon Exists in Different Allotropes

As an element, carbon atoms can form different bonding arrangements, or *allotropes*. Three carbon allotropes are illustrated in **Figure 2.** As shown in **Figure 2a,** a diamond contains an enormous number of carbon atoms that form an extremely strong, tetrahedral network, which makes diamond the hardest known substance.

In contrast, graphite, another allotrope of carbon, is very soft. As illustrated in **Figure 2b,** the carbon atoms in graphite are bonded in a hexagonal pattern and lie in planes. The covalent bonds in each plane are very strong. However, weaker forces hold the planes together so that the planes can slip past each other. The sliding layers make graphite useful as a lubricant and as pencil lead. As you write with a pencil, the graphite layers slide apart, leaving a trail of graphite on the paper.

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Topic: Allotropes
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Other Carbon Allotropes Include Fullerenes and Nanotubes

In the mid-1980s, another type of carbon allotrope, the fullerene, was discovered. As illustrated in **Figure 2c,** fullerenes consist of near-spherical cages of carbon atoms. The most stable of these structures is C_{60}, which is formed by 60 carbon atoms arranged in interconnecting rings. The discoverers of these allotropes named C_{60} *buckminsterfullerene* in honor of the architect and designer Buckminster Fuller, whose geodesic domes had a similar shape. These allotropes can be found in the soot that forms when carbon-containing materials burn with limited oxygen.

In 1991, yet another carbon allotrope was discovered. Hexagons of carbon atoms were made to form a hollow cylinder known as a *nanotube*. A nanotube has a diameter about 10 000 times smaller than a human hair. Despite its thinness, a single nanotube is between 10 and 100 times stronger than steel by weight. Scientists are currently experimenting to find ways in technology and industry to use the unique properties of nanotubes.

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Topic: Diamond/Graphite
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Organic Compounds

Most compounds of carbon are referred to as *organic compounds*. Organic compounds contain carbon, of course, and most also contain atoms of hydrogen.

In addition to hydrogen, many other elements can bond to carbon. These elements include oxygen, nitrogen, sulfur, phosphorus, and the halogens. These bonded atoms are found in the different types of organic compounds found in living things, including proteins, carbohydrates, lipids (fats), and nucleic acids. In addition, these atoms are used to make a wide variety of synthetic organic compounds including plastics, fabrics, rubber, and pharmaceutical drugs. **Figure 3** shows examples of some natural and synthetic organic compounds.

More than 12 million organic compounds are known, and thousands of new ones are discovered or synthesized each year. There are more known compounds of carbon than compounds of all the other elements combined. To make the study of these many organic compounds easier, chemists group those with similar characteristics. The simplest class of organic compounds are those that contain only carbon and hydrogen and are known as **hydrocarbons.** Hydrocarbons can be classified into three categories based on the type of bonding between the carbon atoms.

hydrocarbon

an organic compound composed only of carbon and hydrogen

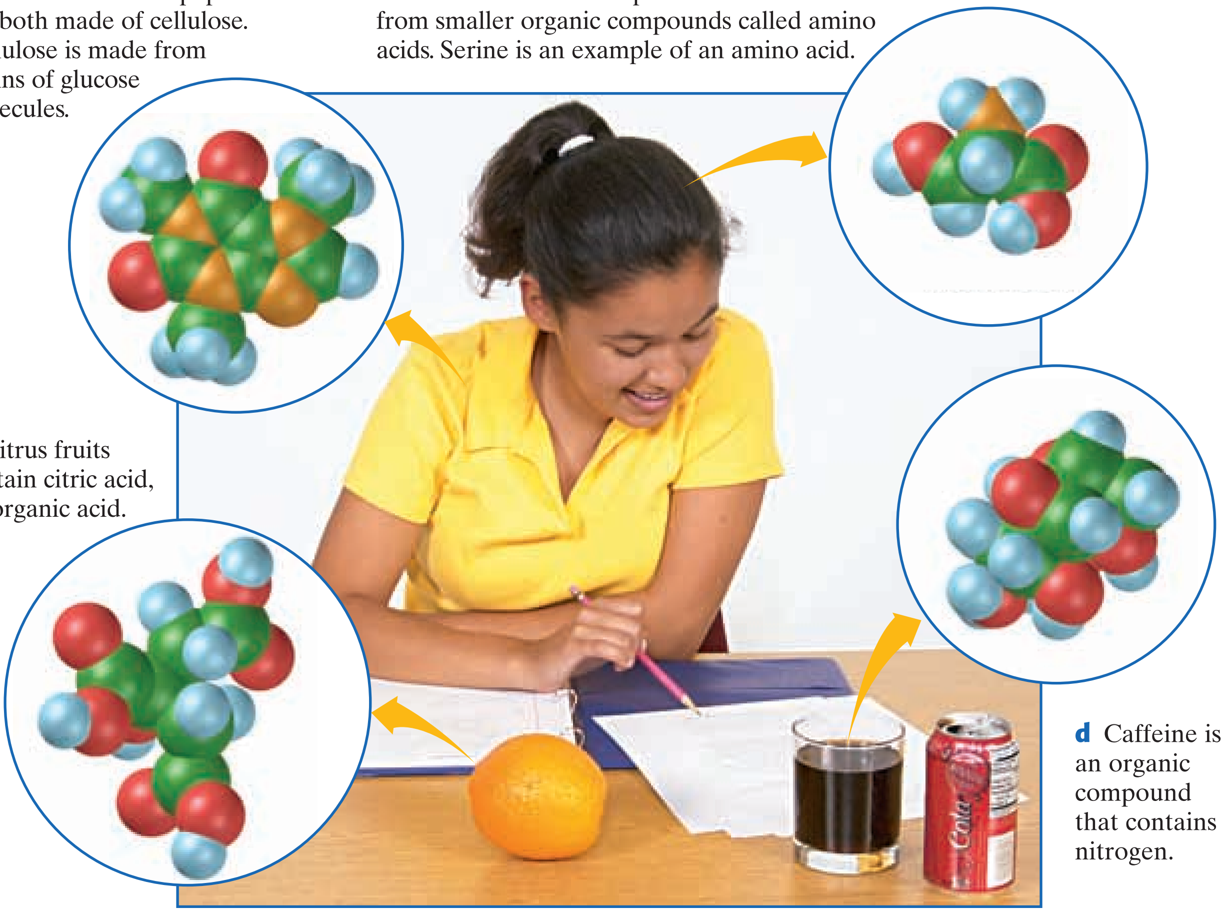


Figure 3

a This shirt and the paper are both made of cellulose. Cellulose is made from chains of glucose molecules.

b Your hair is made of proteins that are made from smaller organic compounds called amino acids. Serine is an example of an amino acid.

c Citrus fruits contain citric acid, an organic acid.

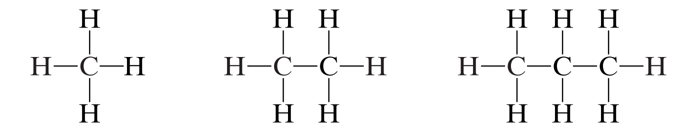
d Caffeine is an organic compound that contains nitrogen.

Alkanes Are the Simplest Hydrocarbons

The simplest hydrocarbons, **alkanes,** have carbon atoms that are connected only by single bonds. Three examples include methane, ethane, and propane. The structural formulas for each of these alkanes are drawn as follows.

alkane

a hydrocarbon characterized by a straight or branched carbon chain that contains only single bonds



methane, CH_4 ethane, C_2H_6 propane, C_3H_8

If you examine the structural formulas for these three alkanes, you will notice that each member of the series differs from the one before by one carbon atom and two hydrogen atoms. This difference is more obvious when you compare the molecular formulas of each compound. The molecular formulas of the alkanes fit the general formula C_nH_{2n+2}, where n represents the number of carbon atoms. If the alkane contains 30 carbon atoms, then its formula is $C_{30}H_{62}$.

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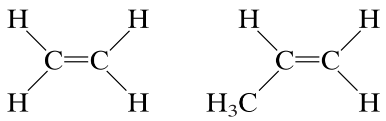
Many Hydrocarbons Have Multiple Bonds

The second class of hydrocarbons is the **alkenes,** which contain at least one double bond between two carbon atoms. The structural formulas for two alkenes are drawn as follows.

alkene

a hydrocarbon that contains one or more double bonds



ethene propene

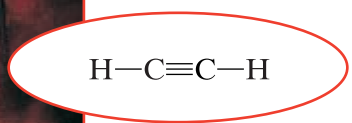
Because alkenes with one double bond have twice as many hydrogen atoms as carbon atoms, their general formula is written C_nH_{2n}.

The third class of hydrocarbons is the **alkynes,** which contain at least one triple bond between two carbon atoms. The simplest alkyne is ethyne, C_2H_2, which is shown in **Figure 4.** The general formula for an alkyne with one triple bond is C_nH_{2n-2}.

alkyne

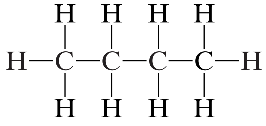
a hydrocarbon that contains one or more triple bonds

Figure 4
Ethyne, commonly called *acetylene,* is one of the very few alkynes that are of practical importance. This welder is using an acetylene torch.

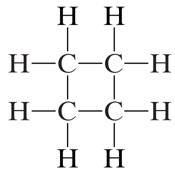


Carbon Atoms Can Form Rings

Carbon atoms that form covalent bonds with one another can be arranged in a straight line or in a ring structure. They can also be branched. For example, 4 carbon atoms and 10 hydrogen atoms can be arranged to form butane, C_4H_{10}, which has a linear structure. Four carbon atoms can also form a compound called cyclobutane, C_4H_8, which has a ring structure.



butane



cyclobutane

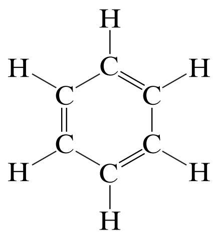
Notice that the prefix *cyclo-* is added to the name of the alkane to indicate that it has a ring structure.

Benzene Is an Important Ring Compound

aromatic hydrocarbon

a member of the class of hydrocarbons (of which benzene is the first member) that consists of assemblages of cyclic conjugated carbon atoms and that is characterized by large resonance energies

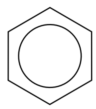
A most important organic ring compound is the hydrocarbon benzene, C_6H_6. Benzene is the simplest member of a class of organic compounds known as **aromatic hydrocarbons.** These compounds have a variety of practical uses from insecticides to artificial flavorings. Benzene can be drawn as a six-carbon ring with three double bonds, as shown below.



Topic Link

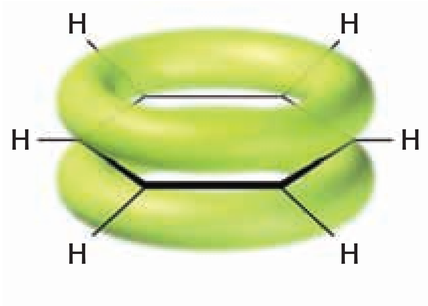
Refer to the "Covalent Compounds" chapter for a discussion of resonance structures.

However, experiments show that all the carbon-carbon bonds in benzene are the same. In other words, benzene is a molecule with resonance structures. **Figure 5** illustrates how the electron orbitals in benzene overlap to form continuous molecular orbitals known as delocalized clouds. The following structural formula is often used to show the ring structure of benzene.



The hexagon represents the six carbon atoms, while the circle represents the delocalized electron clouds. The hydrogen atoms are not shown in this simplified structural formula.

Figure 5
Electron orbitals in benzene overlap to form continuous orbitals that allow the delocalized electrons to spread uniformly over the entire ring.



Other Organic Compounds

Hydrocarbons are only one class of organic compounds. The other classes of organic compounds include other atoms such as oxygen, nitrogen, sulfur, phosphorus, and the halogens along with carbon (and usually hydrogen).

Less than 200 years ago, scientists believed that organic compounds could be made only by living things. The word *organic* that is used to describe these compounds comes from this belief. Then in 1828 a German chemist named Friedrich Wöhler synthesized urea, an organic compound, from inorganic substances.

Many Compounds Contain Functional Groups

Like most organic compounds, urea contains a group of atoms that is responsible for its chemical properties. Such a group of atoms is known as a **functional group.** Many common organic functional groups can be seen in **Figure 6.** Because single bonds between carbon atoms are rarely involved in most chemical reactions, functional groups, which contain bonds between carbon atoms and atoms of other elements, are often responsible for how an organic compound reacts. Organic compounds are commonly classified by the functional groups they contain. **Table 1** on the next page provides an overview of some common classes of organic compounds and their functional groups.

functional group
the portion of a molecule that is active in a chemical reaction and that determines the properties of many organic compounds

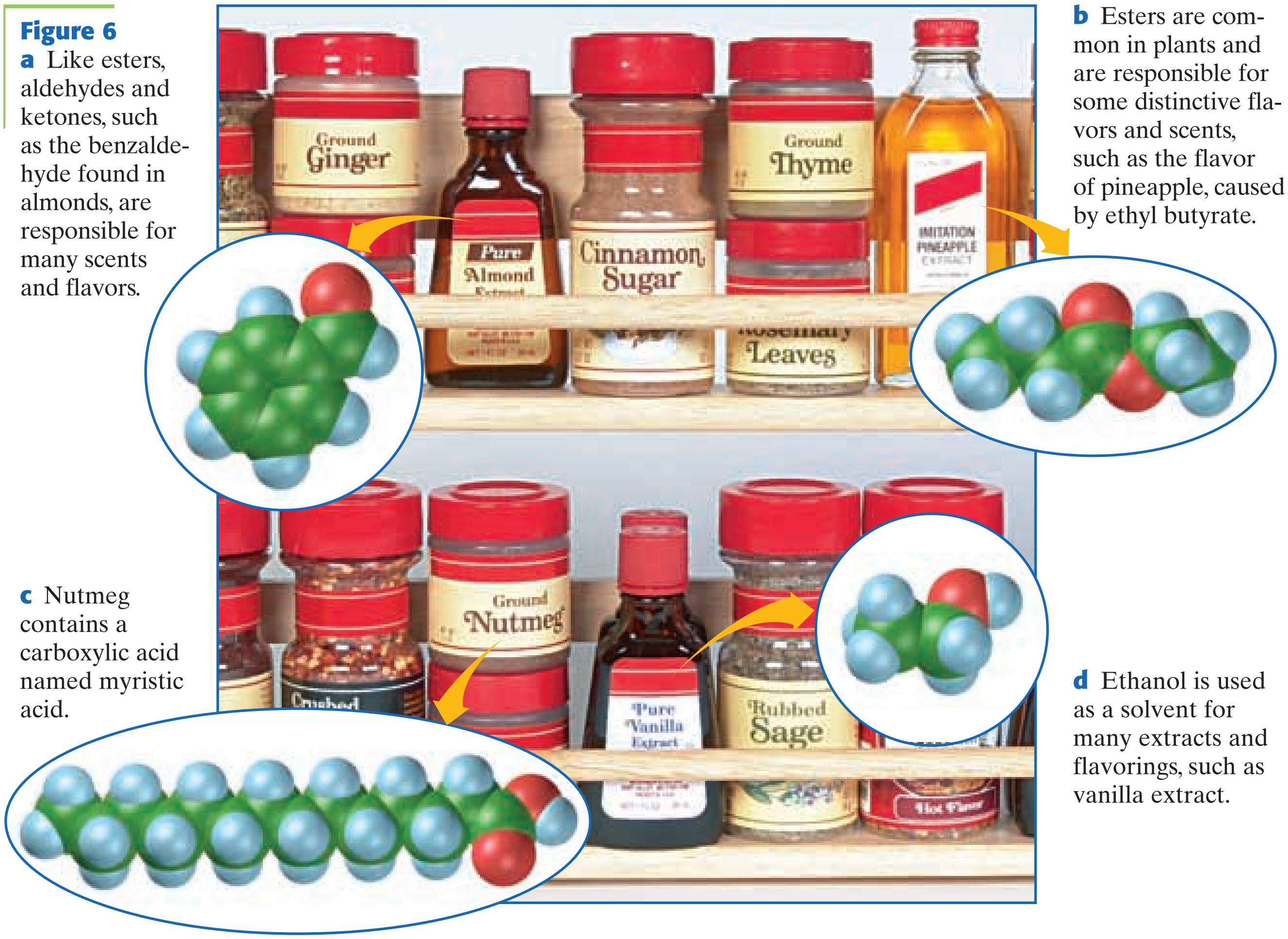


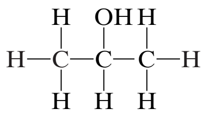
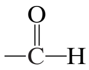
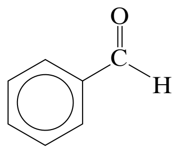
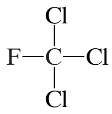
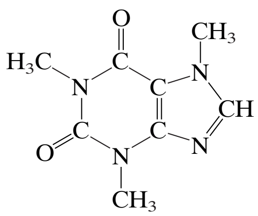
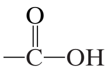
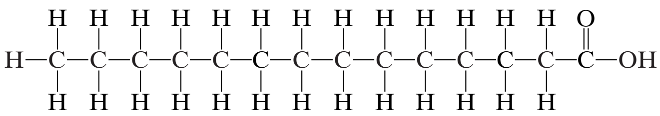
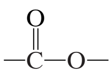
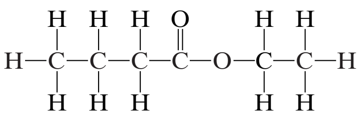
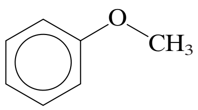
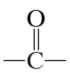
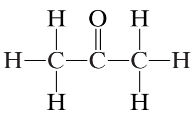
Figure 6
a Like esters, aldehydes and ketones, such as the benzaldehyde found in almonds, are responsible for many scents and flavors.

b Esters are common in plants and are responsible for some distinctive flavors and scents, such as the flavor of pineapple, caused by ethyl butyrate.

c Nutmeg contains a carboxylic acid named myristic acid.

d Ethanol is used as a solvent for many extracts and flavorings, such as vanilla extract.

Table 1 Classes of Organic Compounds

Class	Functional group	Example	Use
Alcohol	—OH	 2-propanol	disinfectant
Aldehyde		 benzaldehyde	almond flavor
Halide	—F, Cl, Br, I	 trichlorofluoromethane (Freon-11)	refrigerant
Amine		 caffeine	beverage ingredient
Carboxylic acid		 tetradecanoic acid (myristic acid)	soap-making ingredient
Ester		 ethyl butanoate	perfume ingredient
Ether	—O—	 methyl phenyl ether (anisole)	perfume ingredient
Ketone		 propanone (acetone)	solvent in nail-polish remover

Functional Groups Determine Properties

The presence of a functional group in an organic compound causes the compound to have properties that differ greatly from those of the corresponding hydrocarbon. In fact, while molecules of very different sizes with the same functional group will have similar properties, molecules of similar sizes with different functional groups will have very different properties.

Compare the structural formulas of the molecules shown in **Table 2.** Notice that each of these molecules consists of four carbon atoms joined to one another by a single bond and arranged in a linear fashion. Notice, however, that each molecule, with the exception of butane, has a different functional group attached to one or more of these carbon atoms. As a result, each molecule has properties that differ greatly from butane.

For example, compare the boiling point of butane with those of the other compounds in **Table 2.** Butane is a gas at room temperature. Because of the symmetrical arrangement of the atoms, butane is nonpolar. Because the intermolecular forces between butane molecules are weak, butane has very low boiling and melting points and a lower density than the other four-carbon molecules.

Next compare the structural formulas of butane and 1-butanol in **Table 2.** Notice that the only difference between these two molecules is the presence of the functional group —OH on one of the carbon atoms in 1-butanol. The presence of this functional group causes 1-butanol to exist as a liquid at room temperature with much higher melting and boiling points and a significantly greater density than butane.

Table 2 Comparing Classes of Organic Compounds

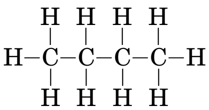
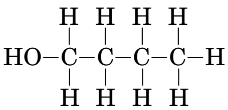
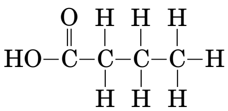
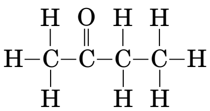
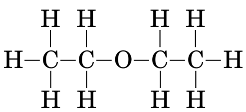
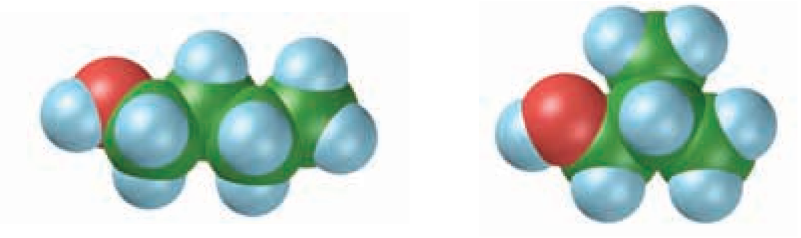
Name	Structural formula	Melting point (°C)	Boiling point (°C)	Density (g/mL)
Butane		–138.4	–0.5	0.5788
1-butanol		–89.5	117.2	0.8098
Butanoic acid		–4.5	163.5	0.9577
2-butanone		–86.3	79.6	0.8054
Diethyl ether		–116.2	34.5	0.7138

Figure 7
Both of these molecules are alcohols. They are isomers of each other because they both have the molecular formula $C_4H_{10}O$.



1-butanol

2-methyl-1-propanol (isobutyl alcohol)

Different Isomers Have Different Properties

isomer
one of two or more compounds that have the same chemical composition but different structures

Examine the two molecules shown in **Figure 7.** Both have the same molecular formula: $C_4H_{10}O$. They differ, however, in the way in which their atoms are arranged. These two molecules are known as **isomers.** Isomers are compounds that have the same formula but differ in their chemical and physical properties because of the difference in the arrangement of their atoms. The greater the structural difference between two isomers, the more significant is the difference in their properties. Because the structural difference between the two isomers shown in **Figure 7** is minor, both molecules have similar boiling points and densities.

1 Section Review

UNDERSTANDING KEY IDEAS

1. List the three factors that make the bonding of carbon atoms unique.

2. What are allotropes?

3. How are alkanes, alkenes, and alkynes similar? How are they different from each other?

4. Draw the simplified representation of the resonance structure for benzene.

5. List four elements other than carbon and hydrogen that can bond to carbon in organic compounds.

6. What is an aromatic compound?

7. What is a functional group?

8. What is an isomer? What do two molecules that are isomers of each other have in common?

CRITICAL THINKING

9. Draw a structural formula for the straight-chain hydrocarbon with the molecular formula C_3H_6. Is this an alkane, alkene, or alkyne?

10. Can molecules with molecular formulas C_4H_{10} and $C_4H_{10}O$ be isomers of one another? Why or why not?

11. Draw a structural formula for an alkyne that contains seven carbon atoms.

12. Draw the structural formulas for two isomers of C_4H_{10}.

13. Why is benzene not considered a cycloalkene even though double bonds exist between the carbon atoms that are arranged in a ring structure?

14. Write the molecular formulas for an alkane, alkene, and alkyne with 5 carbon atoms each. Why are these three hydrocarbons not considered isomers?

15. Draw C_4H_6 as a cycloalkene.

SECTION

2 Names and Structures of Organic Compounds

KEY TERMS

- **saturated hydrocarbon**
- **unsaturated hydrocarbon**

OBJECTIVES

1. **Name** simple hydrocarbons from their structural formulas.
2. **Name** branched hydrocarbons from their structural formulas.
3. **Identify** functional groups from a structural formula, and assign names to compounds containing functional groups.
4. **Draw** and interpret structural formulas and skeletal structures for common organic compounds.

Naming Straight-Chain Hydrocarbons

Inorganic carbon compounds, such as carbon dioxide, are named by using a system of prefixes and suffixes. Organic compounds have their own naming scheme, which includes prefixes and suffixes that denote the class of organic compound. Learning just a few rules will help you decipher the names of most common organic compounds.

For example, the names of all alkanes end with the suffix *-ane*. The simplest alkane is methane, CH_4, the main component of natural gas. **Table 3** lists the names and formulas for the first 10 straight-chain alkanes. For alkanes that consist of five or more carbon atoms, the prefix comes from a Latin word that indicates the number of carbon atoms in the chain.

Table 3 Straight-Chain Alkane Nomenclature

Number of carbon atoms	Name	Formula
1	methane	CH_4
2	ethane	$CH_3—CH_3$
3	propane	$CH_3—CH_2—CH_3$
4	butane	$CH_3—CH_2—CH_2—CH_3$
5	pentane	$CH_3—CH_2—CH_2—CH_2—CH_3$
6	hexane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_3$
7	heptane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
8	octane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
9	nonane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$
10	decane	$CH_3—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_2—CH_3$

Naming Short-Chain Alkenes and Alkynes

The scheme used to name straight-chain hydrocarbons applies to both saturated and unsaturated compounds. A **saturated hydrocarbon** is a hydrocarbon in which each carbon atom forms four single covalent bonds with other atoms. The alkanes are saturated hydrocarbons. An **unsaturated hydrocarbon** is a hydrocarbon in which not all carbon atoms have four single covalent bonds. The alkenes and alkynes are unsaturated hydrocarbons.

saturated hydrocarbon

an organic compound formed only by carbon and hydrogen linked by single bonds

unsaturated hydrocarbon

a hydrocarbon that has available valence bonds, usually from double or triple bonds with carbon

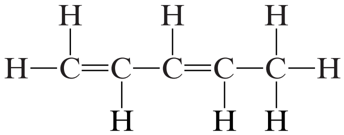
The rules for naming an unsaturated hydrocarbon with fewer than four carbon atoms are similar to those for naming alkanes. A two-carbon alkene is named *ethene,* with the suffix *-ene* indicating that the molecule is an alkene. A three-carbon alkyne is named *propyne,* with the suffix *-yne* indicating that the molecule is an alkyne.

Naming Long-Chain Alkenes and Alkynes

The name for an unsaturated hydrocarbon containing four or more carbon atoms must indicate the position of the double or triple bond within the molecule. First number the carbon atoms in the chain so that the first carbon atom in the double bond has the lowest number. Examine **Figure 8,** which shows structural formulas for two alkenes with five carbon atoms.

The correct name for the alkene shown on the left in **Figure 8** is *1-pentene*. The molecule is correctly numbered from left to right because the first carbon atom with the double bond must have the lowest number. The name *1-pentene* indicates that the double bond is present between the first and second carbon atoms. The alkene shown on the right in **Figure 8** is correctly named *2-pentene,* indicating that the double bond is present between the second and third carbon atoms. Note that 1-pentene and 2-pentene are the only possible pentenes, because 3-pentene would be the same molecule as 2-pentene and the lower numbering is preferred.

If there is more than one multiple bond in a molecule, number the position of each multiple bond, and use a prefix to indicate the number of multiple bonds. For example, the following molecule is called *1,3-pentadiene*. (Note the placement of the prefix *di-*.)



STUDY TIP

Preparing for Year-End Evaluations

As you approach the completion of your study of chemistry, you should start preparing for any final exams or standardized tests that you will be taking. The best way to begin is by developing a schedule for the remainder of the school year. Map out a schedule that involves spending more time on topics that you studied early in the course or ones that you found more difficult.

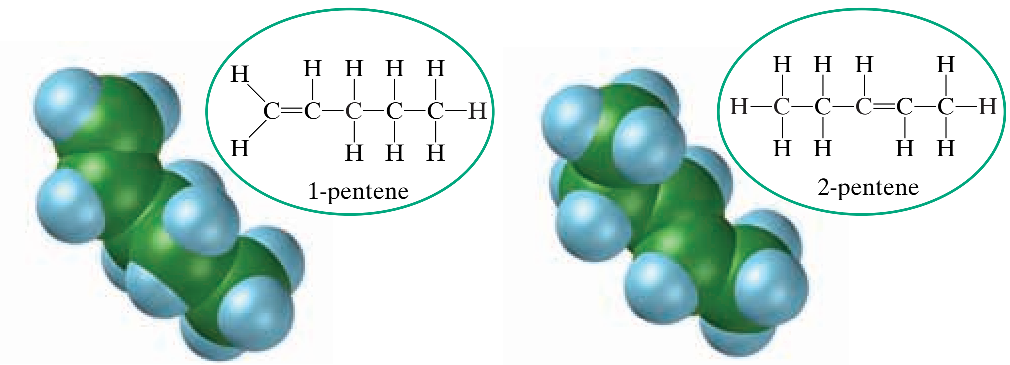
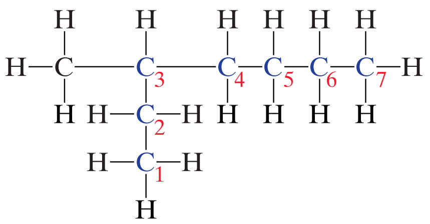


Figure 8
Both the names and structural formulas indicate the position of the double bond in each alkene. Notice that you cannot tell from the space-filling models where the double bond is located.

Naming Branched Hydrocarbons

When naming a hydrocarbon that is not a simple straight chain, first determine the number of carbon atoms in the longest chain. It can be named based on the corresponding alkane in **Table 3.** The longest chain may not appear straight in a structural formula, as in the example below.



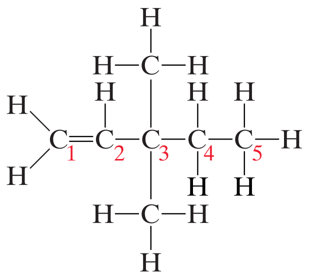
The "parent" chain in the compound shown above contains seven carbon atoms, so it is heptane. Next, number the carbon atoms on the parent chain so that any branches on the chain have the lowest numbers possible.

Name the Attached Groups and Indicate Their Positions

In the structural formula above, all the numbered carbon atoms, with one exception, are bonded only to hydrogen atoms. The one exception is the third carbon atom, which has a $—CH_3$ group attached. This group is known as a *methyl group,* because it is similar to a methane molecule, but with one less hydrogen atom. Because the methyl group is attached to the third carbon, the complete name for this branched alkane is *3-methylheptane*.

You can omit the numbers if there is no possibility of ambiguity. For example, a propane chain can have a methyl group only on its second carbon (if the methyl group were on the first or third carbon of propane, the molecule would be butane). So, what you might want to call *2-methylpropane* would be called *methylpropane.*

With unsaturated hydrocarbons that have attached groups, the longest chain containing the double bond is considered the parent compound. In addition, if more than one group is attached to the longest chain, the position of attachment of each group is given. Prefixes are used if the same group is attached more than once. Examine the following structural formula for a branched alkene.

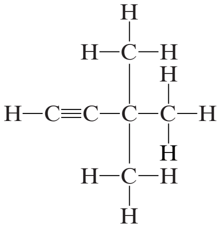


The chain containing the double bond has five carbon atoms. Therefore, the compound is a pentene. Notice that the first carbon atom has a double bond, making the chain 1-pentene. Because two methyl groups are attached to the third carbon atom, the correct name for this branched alkene is *3,3-dimethyl-1-pentene*.

SAMPLE PROBLEM A

Naming a Branched Hydrocarbon

Name the following hydrocarbon.



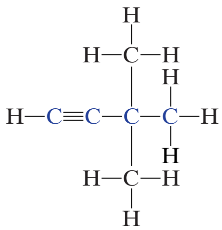
1 Gather information.

- The triple bond makes the branched hydrocarbon an alkyne.

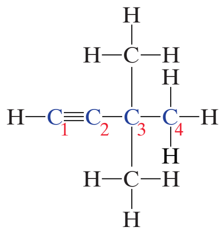
2 Plan your work.

- Identify the longest continuous chain (the "parent" chain), and name it.
- Number the parent chain so that the triple bond is attached to the carbon atom with the lowest possible number.
- Name the groups that make up the branches.
- Identify the positions that the branches occupy on the longest chain.

3 Name the structure.



- The longest continuous chain has four carbon atoms.
- The parent chain is butyne.
- The numbering begins with the triple bond.
- Two methyl, —CH_3, groups are present.
- Both methyl groups are attached to the third carbon atom.
- The name of this branched hydrocarbon is *3, 3-dimethyl-1-butyne*.



4 Verify your results.

- The parent name *butyne* indicates that four carbon atoms are present in the longest chain. The *1-butyne* indicates that the first carbon atom has a triple bond. The *3,3-dimethyl-* indicates that two methyl groups, —CH_3, are attached to the third carbon atom in the longest chain.

PRACTICE HINT

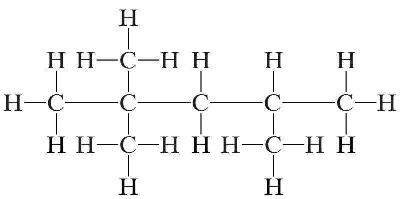
Many organic structural formulas look quite confusing, but keep in mind that the name will be based on one of the simple alkane names listed in **Table 3**.

PRACTICE

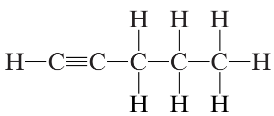
PROBLEM SOLVING SKILL

Name the following branched hydrocarbons.

1 a.

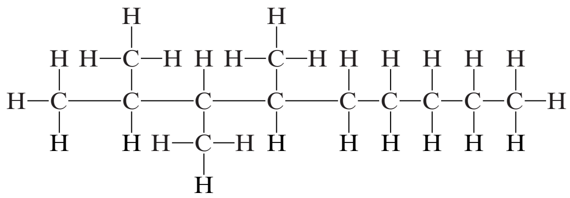


b.

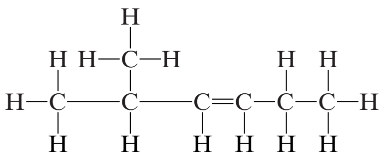


PRACTICE

1 c.

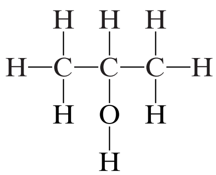


d.



Names of Compounds Reflect Functional Groups

Names for organic compounds with functional groups are based on the same system used for hydrocarbons with branched chains. First, the longest chain is named. Then a prefix or suffix indicating the functional group is added to the hydrocarbon name. **Table 4** lists the prefixes and suffixes for various functional groups. When necessary, the position of the functional group is noted in the same way that the position of hydrocarbon branches is noted. Consider the following structural formula.



Because the longest chain consists of three carbon atoms, the name for this compound is based on propane. From **Table 1,** you can see that the presence of the —OH functional group classifies this compound as an alcohol. Therefore, as indicated by **Table 4,** the name for this compound is *propanol,* whose suffix *-ol* indicates that this molecule is an alcohol. Because the functional group is attached to the second carbon atom, the correct name for this compound is *2-propanol*. A number of organic compounds are often referred to by their common names, even by chemists. The common name for 2-propanol is *isopropyl alcohol*.

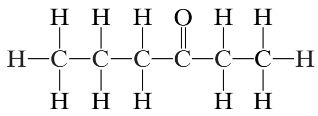
Table 4 Naming Compounds with Functional Groups

Class of compound	Suffix or prefix	Example
Alcohol	*-ol*	propanol
Aldehyde	*-al*	butanal
Amine	*-amine* or *amino-*	methylamine
Carboxylic acid	*-oic acid*	ethanoic acid
Ketone	*-one*	propanone

SAMPLE PROBLEM B

Naming a Compound with a Functional Group

Name the following organic compound.



1 Gather information.

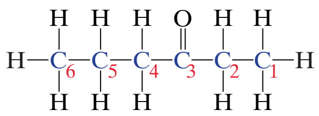
- Notice that the functional group indicates that this compound is a ketone.

2 Plan your work.

- Identify the longest continuous chain (the "parent" chain), and name it.
- Number the parent chain so that the functional group is attached to the carbon atom with the lowest possible number.
- Identify the position that the functional group occupies on the longest chain.
- Name the organic compound.

3 Name the structure.

- The longest continuous chain has six carbon atoms: the parent chain is hexane.
- The carbon atoms are numbered from right to left to give the ketone functional group the lowest number.



- The name of this organic compound is *3-hexanone*.

4 Verify your results.

- The name *3-hexanone* indicates that six carbon atoms are present in the parent chain. The suffix *-one* indicates that this compound is a ketone. The *3-* indicates that the functional group is attached to the third carbon atom in the parent chain.

PRACTICE HINT

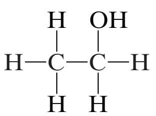
The steps to follow for naming organic compounds with functional groups are similar to those for naming branched hydrocarbons.

PRACTICE

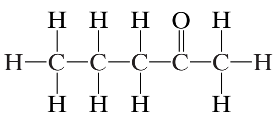
Name the following organic compounds.

PROBLEM SOLVING SKILL

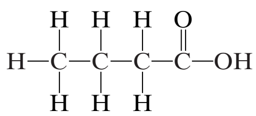
1 **a.**



b.



c.



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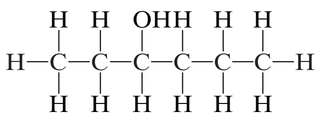


Representing Organic Molecules

Table 5 shows four ways of representing the organic molecule cyclohexane. Each type of model used to represent an organic compound has both advantages and disadvantages. Each one highlights a different feature of the molecule, from the number and kinds of atoms in a chemical formula to the three-dimensional shape of the space-filling model. Keep in mind that a picture or model cannot fully convey the true three-dimensional shape of a molecule or show the motion within a molecule caused by the atoms' constant vibration.

Structural Formulas Can Be Simplified

Structural formulas are sometimes represented by what are called *skeletal structures,* which show bonds, but leave out some or even all of the carbon and hydrogen atoms. You have already seen the skeletal structure for benzene, which is a hexagon with a ring inside it.

A skeletal structure usually shows the carbon framework of a molecule only as lines representing bonds. These lines are often drawn in a zigzag pattern to indicate the tetrahedral arrangement of bonds between a carbon atom and other atoms. Carbon atoms are understood to be at each bond along with enough hydrogen atoms so that each carbon atom has four bonds. Atoms other than carbon and hydrogen are always shown, which highlights any functional groups present.

Table 5 Types of Molecular Models

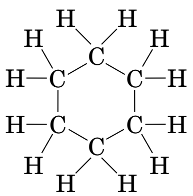
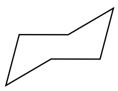
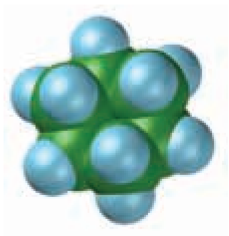
Type of model	Example	Advantages	Disadvantages
Chemical formula	C_6H_{12}	shows number of atoms in a molecule	does not show bonds, atom sizes, or shape
Structural formula		shows arrangement of all atoms and bonds in a molecule	does not show actual shape of molecule or atom sizes; larger molecules can be too complicated to draw easily
Skeletal structure		shows arrangements of carbon atoms; is simple	does not show actual shape or atom sizes; does not show all atoms or bonds
Space-filling model		shows three-dimensional shape of molecule; shows most of the space taken by electrons	uses false colors to differentiate between elements; bonds are not clearly indicated; parts of large molecules may be hidden

Figure 9
a The chemical name for aspirin is acetylsalicylic acid.

b Because the complete structural formula of acetylsalicylic acid is complex . . .

c . . . chemists usually draw its skeletal structure instead. The presence of a benzene ring indicates that it is an aromatic compound.

SAMPLE PROBLEM C

Drawing Structural and Skeletal Formulas

Draw both the structural formula and the skeletal structure for 1,2,3-propanetriol.

1 Gather information.

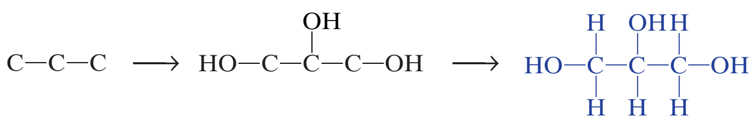
- The name *propanetriol* indicates that the molecule is an alcohol that consists of three carbon atoms making up the parent chain.
- The suffix *-triol* indicates that three alcohol groups are present.
- The *1,2,3-* prefix indicates that an alcohol group is attached to the first, second, and third carbon atoms.

2 Plan your work.

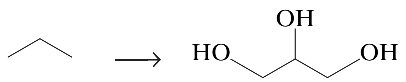
- Draw the carbon framework showing the parent chain.
- Add the alcohol groups to the appropriate carbon atoms.
- Add enough hydrogen atoms so that each carbon atom has four bonds.
- Show the carbon framework as a zigzag line.
- Include the functional groups as part of the skeletal structure.

3 Draw the structures.

Structural formula:



Skeletal formula:



4 Verify your results.

- The structural formula should show all bonds and atoms in the compound 1, 2, 3-propanetriol.
- The skeletal formula should show only carbon-carbon bonds plus any functional groups present in the molecule.

PRACTICE HINT

Unless it is a part of a functional group, hydrogen is not shown in a skeletal structure. In the sample, the hydrogens shown are part of the alcohol functional group. The other hydrogen atoms bonded to carbon are not shown.