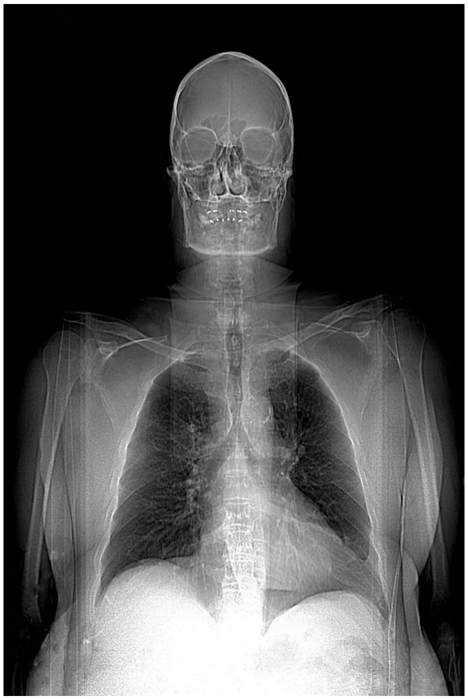
Chapter 16
Nuclear Chemistry

Stan is going to visit his son Fred at the radiology department of a local research hospital, where Fred has been recording the brain activity of kids with learning differences and comparing it to the brain activity of kids who excel in normal school environments. To pursue this research, Fred uses imaging technology developed through the science of **nuclear chemistry**, the study of changes that occur within the nuclei of atoms. But even before getting into his car to go see Fred, Stan is already surrounded by substances undergoing nuclear reactions. In fact, nuclear reactions accompany Stan wherever he goes. He has strontium-90 in his bones and iodine-131 in his thyroid, and both substances are constantly undergoing nuclear reactions of a type known as beta emission. Stan is not unique in this respect. All of our bodies contain these substances and others like them.

Stan is surrounded by nuclear changes that take place outside his body, as well. The soil under his house contains a small amount of uranium-238, which undergoes a type of nuclear reaction called alpha emission. A series of changes in the nucleus of the uranium-238 leads to an even smaller amount of radon-222, which is a gas that he inhales in every breath he takes at home. Subsequently, radon-222 undergoes a nuclear reaction very similar to the reaction for uranium-238.



PET scans and MRI scans (like the one above) use changes in the nuclei of atoms to create an image of the soft tissues of the body.

On Stan's way to the hospital, he passes a nuclear power plant that generates electricity for the homes and businesses in his city by means of yet another kind of nuclear reaction. When Stan gets to the hospital, Fred shows him the equipment he is using in his research. It is a positron emission tomography (PET) machine that allows Fred to generate images showing which parts of a child's brain are being used when the child does certain tasks. Positron emission is another type of nuclear change described in this chapter.

There are good reasons why, in the preceding seventeen chapters, our exploration of chemistry has focused largely on the behavior of electrons. Chemistry is the study of the structure and behavior of matter, and most of our understanding of such phenomena comes from studying the gain, loss, and sharing of electrons. At the same time, however, we have neglected the properties of the nuclei of atoms and the changes that some nuclei can undergo. In this chapter, we turn our attention toward the center of the atom to learn what is meant by nuclear stability and to understand the various kinds of nuclear reactions.

Review Skills

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

- Describe the nuclear model of the atom, including the general location of the protons, neutrons, and electrons, the relative size of the nucleus compared to the size of the atom, and the modern description of the electron. (Section 3.4)
- Write the definitions for isotope, atomic number, and mass number. (Chapter 3 Glossary)
- Write or identify a description of the Law of Conservation of Energy. (Section 4.1)
- Describe the relationship between stability, capacity to do work, and potential energy. (Section 4.1)
- Write a brief description of radiant energy in terms of its particle and wave nature. (Section 4.1)
- Write or identify the relative energies and wavelengths of the following forms of radiant energy: gamma rays, X rays, ultraviolet (UV) rays, visible light, infrared (IR) rays, microwaves, and radio waves. (Section 4.1)
- Write the definitions for energy, kinetic energy, potential energy, excited state and ground state. (Chapter 4 Glossary)

16.1 The Nucleus and Radioactivity

Our journey into the center of the atom begins with a brief review. You learned in Chapter 3 that the protons and neutrons in each atom are found in a tiny, central nucleus that measures about 1/100,000 the diameter of the atom itself. You also learned that the atoms of each element are not necessarily identical; they can differ with respect to the number of neutrons in their nuclei. When an element has two or more species of atoms, each with the same number of protons but a different number of neutrons, the different species are called isotopes. Different isotopes of the same element have the same atomic number, but they have a different mass number, which is the sum of the numbers of protons and neutrons in the nucleus. In the context of nuclear science, protons and neutrons are called **nucleons**, because they reside in the nucleus. The atom's mass number is often called the **nucleon number**, and a particular type of nucleus, characterized by a specific atomic number and nucleon number, is called a **nuclide**. Nuclides are represented in chemical notation by a subscript atomic number (Z) and superscript nucleon number (A) on the left side of the element's symbol (X):

Objective 2

Mass number (nucleon number)

$${}^{A}_{Z}X$$

Atomic number   Element symbol

For example, the most abundant nuclide of uranium has 92 protons and 146 neutrons, so its atomic number is 92, its nucleon number is 238 (92 + 146), and its symbol is $^{238}_{92}U$. Often, the atomic number is left off of the symbol. Nuclides can also be described with the name of the element followed by the nucleon number. Therefore, $^{238}_{92}U$ is commonly described as ^{238}U or uranium-238. Examples 16.1 and 16.2 provide practice in writing and interpreting nuclide symbols.

Objective 3
Objective 4

Example 16.1 - Nuclide Symbols

Objective 2
Objective 3
Objective 4

A nuclide that has 26 protons and 33 neutrons is used to study blood chemistry. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to represent this nuclide.

Solution

Because this nuclide has 26 protons, its atomic number, Z, is 26, identifying the element as iron, Fe. This nuclide of iron has 59 total nucleons (26 protons + 33 neutrons), so its nucleon number, A, is 59.

$^{59}_{26}Fe$ or ^{59}Fe or iron-59

Exercise 16.1 - Nuclide Symbols

Objective 2
Objective 3
Objective 4

One of the nuclides used in radiation therapy for the treatment of cancer has 39 protons and 51 neutrons. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to represent this nuclide.

Example 16.2 - Nuclide Symbols

Objective 2
Objective 3
Objective 4

Physicians can assess a patient's lung function with the help of krypton-81. What is this nuclide's atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.

Solution

The periodic table shows us that the atomic number for krypton is 36, so each krypton atom has 36 protons. The number following the element name in krypton-81 is this nuclide's mass number. The difference between the mass number (the sum of the numbers of protons and neutrons) and the atomic number (the number of protons) is equal to the number of neutrons, so krypton-81 has 45 neutrons (81 – 36).

atomic number = 36; mass number = 81; 36 protons and 45 neutrons

$^{81}_{36}Kr$ ^{81}Kr

Exercise 16.2 - Nuclide Symbols

Objective 2
Objective 3
Objective 4

A nuclide with the symbol ^{201}Tl can be used to assess a patient's heart in a stress test. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.

Nuclear Stability

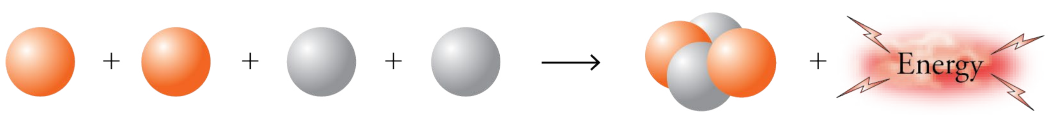
OBJECTIVE 5

Two forces act upon the particles within the nucleus to produce the nuclear structure. One, called the **electrostatic force** (or electromagnetic force), is the force that causes opposite electrical charges to attract each other and like charges to repel each other. The positively charged protons in the nucleus of an atom have an electrostatic force pushing them apart. The other force within the nucleus, called the **strong force**, holds nucleons (protons and neutrons) together.

OBJECTIVE 5

If one proton were to encounter another, the electrostatic force pushing them apart would be greater than the strong force pulling them together, and the two protons would fly in separate directions. Therefore, nuclei that contain more than one proton and no neutrons do not exist. Neutrons can be described as the nuclear glue that allows protons to stay together in the nucleus. Because neutrons are uncharged, there are no electrostatic repulsions between them and other particles. At the same time, each neutron in the nucleus of an atom is attracted to other neutrons and to protons by the strong force. Therefore, adding neutrons to a nucleus increases the attractive forces holding the particles of the nucleus together without increasing the amount of repulsion between those particles. As a result, although a nucleus that consists of only two protons is unstable, a helium nucleus that consists of two protons and two neutrons is very stable. The increased stability is reflected in the significant amount of energy released when two protons and two neutrons combine to form a helium nucleus.

$$\mathrm{p} + \mathrm{p} + \mathrm{n} + \mathrm{n} \longrightarrow {}^{4}_{2}\mathrm{He}^{2+}$$



OBJECTIVE 5

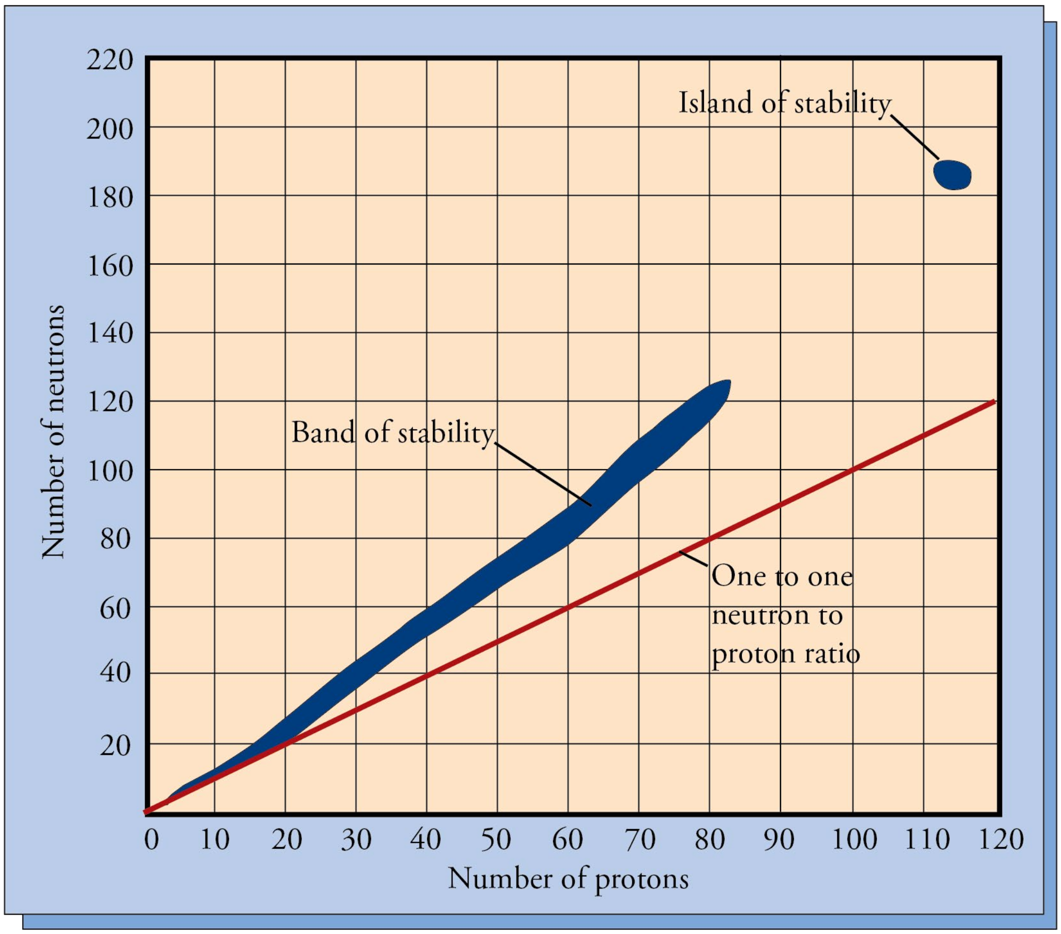
For many of the lighter elements, the possession of an equal number of protons and neutrons leads to stable atoms. For example, carbon-12 atoms, ${}^{12}_{6}\mathrm{C}$, with six protons and six neutrons, and oxygen-16 atoms, ${}^{16}_{8}\mathrm{O}$, with eight protons and eight neutrons, are both very stable. Larger atoms with more protons in their nuclei require a higher ratio of neutrons to protons to balance the increased electrostatic repulsion between protons. Table 16.1 shows the steady increase in the neutron-to-proton ratios of the most abundant isotopes of the elements in group 15 on the periodic table.

Table 16.1
Neutron-to-Proton Ratio for the Most Abundant Isotopes of the Group 15 Elements

Element	Number of neutrons	Number of protons	Neutron-to-proton ratio
nitrogen, N	7	7	1 to 1
phosphorus, P	16	15	1.07 to 1
arsenic, As	42	33	1.27 to 1
antimony, Sb	70	51	1.37 to 1
bismuth, Bi	126	83	1.52 to 1

There are 264 stable nuclides found in nature. The graph in Figure 16.1 shows the neutron-to-proton ratios of these stable nuclides. Collectively, these nuclides fall within what is known as the **band of stability**.

Figure 16.1
The Band of Stability



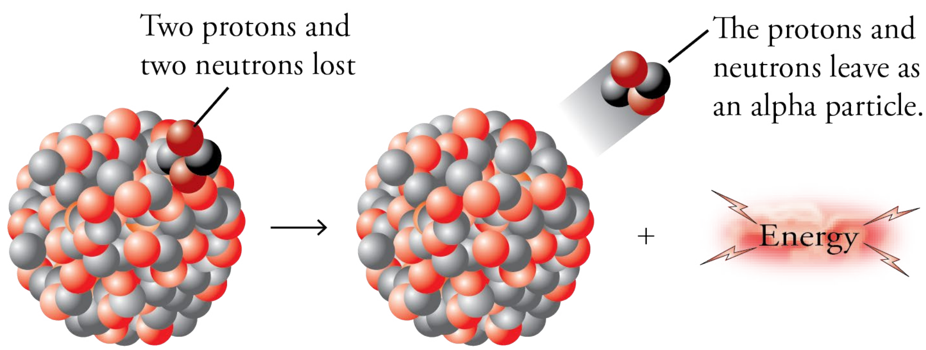
A nuclide containing numbers of protons and neutrons that place it outside this band of stability will be unstable until it undergoes one or more nuclear reactions that take it into the band of stability. We call these unstable atoms **radioactive nuclides**, and the changes they undergo to reach stability are called **radioactive decay**. Note that the band of stability stops at 83 protons. All of the known nuclides with more than 83 protons are radioactive, but scientists have postulated that there should be a small island of stability around the point representing 114 protons and 184 neutrons. The relative stability of the heaviest atoms that have so far been synthesized in the laboratory suggests that this is true. (See Special Topic 3.1: *Why Create New Elements*.).

Types of Radioactive Emissions

Objective 6

One of the ways that nuclides with more than 83 protons change to reach the band of stability is to release two protons and two neutrons in the form of a helium nucleus, which in this context is called an **alpha particle**. Natural uranium, which is found in many rock formations on earth, has three isotopes that all experience **alpha emission**, the release of alpha particles. The isotope composition of natural uranium is 99.27% uranium-238, 0.72% uranium-235, and a trace of uranium-234. The nuclear equation for the alpha emission of uranium-238, the most abundant isotope, is

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



Objective 7

In nuclear equations for alpha emission, the alpha particle is written as either α or $^{4}_{2}\text{He}$. Note that in alpha emission, the radioactive nuclide changes into a different element, with an atomic number that is lower by 2 and a mass number that is lower by 4.

Objective 6
Objective 8

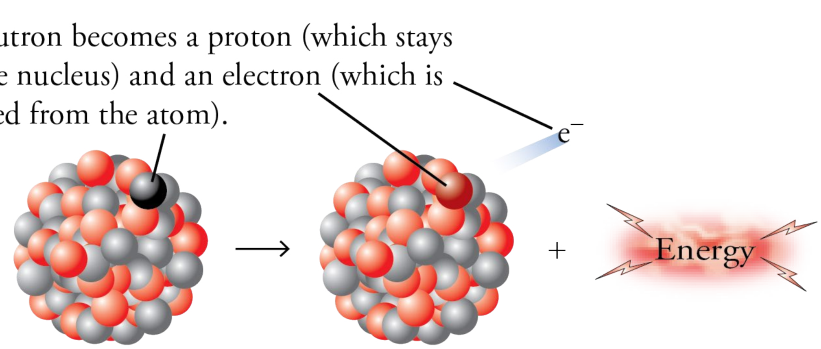
Some radioactive nuclides have a neutron-to-proton ratio that is too high, placing them above the band of stability. To reach a more stable state they undergo **beta emission** (β^-). In this process, a neutron becomes a proton and an electron. The proton stays in the nucleus, and the electron, which is called a **beta particle** in this context, is ejected from the atom.

$$\text{n} \rightarrow \text{p} + \text{e}^-$$

Objective 7

In nuclear equations for beta emission, the electron is written as either β, β^-, or $^{0}_{-1}\text{e}$. Iodine-131, which has several medical uses, including the measurement of iodine uptake by the thyroid, is a beta emitter:

$$^{131}_{53}\text{I} \longrightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e}$$



Note that in beta emission, the radioactive nuclide changes into a different element, with an atomic number that is higher by 1 but the same mass number.

Objective 6
Objective 8

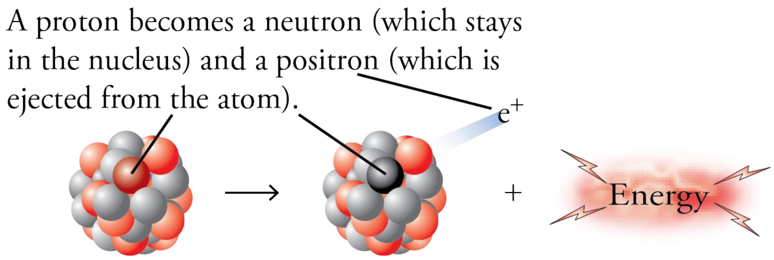
If a radioactive nuclide has a neutron-to-proton ratio that is too low, placing it below the band of stability, it can move toward stability in one of two ways, positron emission or electron capture. **Positron emission** (β^+) is similar to beta emission, but in this case, a proton becomes a neutron and an anti-matter electron, or anti-electron.[1] The latter is also called a **positron** because, although it resembles an electron in most ways, it has a positive charge. The neutron stays in the nucleus, and the positron speeds out of the nucleus at high velocity.

$$p \rightarrow n + e^+$$

Objective 7

In nuclear equations for positron emission, the electron is written as either β^+, ${}^{0}_{+1}e$, or ${}^{0}_{1}e$. Potassium-40, which is important in geologic dating, undergoes positron emission:

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



Note that in positron emission, the radioactive nuclide changes into a different element, with an atomic number that is lower by 1 but the same mass number.

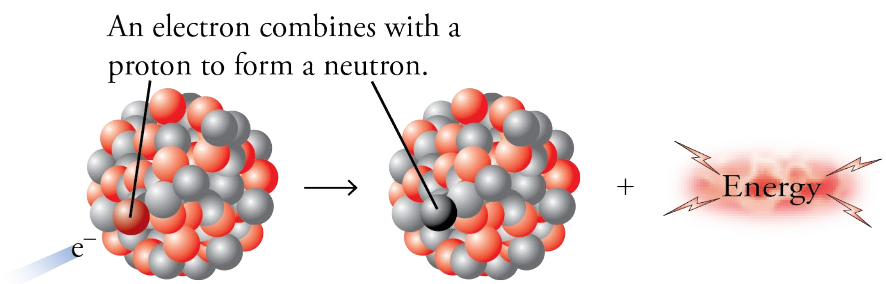
Objective 6
Objective 8

The second way that an atom with an excessively low neutron-to-proton ratio can reach a more stable state is for a proton in its nucleus to capture one of the atom's electrons. In this process, called **electron capture**, the electron combines with the proton to form a neutron.

$$e^- + p \rightarrow n$$

Iodine-125, which is used to determine blood hormone levels, moves toward stability through electron capture.

$$ {}^{0}_{-1}e + {}^{125}_{53}I \longrightarrow {}^{125}_{52}Te $$



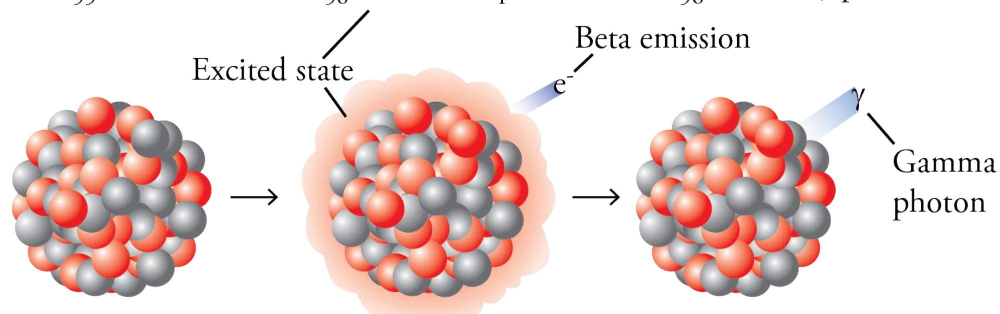
Like positron emission, electron capture causes the radioactive nuclide to change to a new element, with an atomic number that is lower by 1 but with the same mass number.

[1] Special Topic 4.1 describes anti-particles, such as anti-electrons (positrons). Every particle has a twin anti-particle that formed along with it from very concentrated energy. When a particle meets an antimatter counterpart, they annihilate each other, leaving pure energy in their place. For example, when a positron collides with an electron, they both disappear, sending out two gamma (γ) photons in opposite directions.

OBJECTIVE 9

Because radioactive decay leads to more stable products, it always releases energy. Some of this energy is released in the form of kinetic energy, adding to the motion of the product particles, but often some of it is given off as the form of radiant energy called gamma rays. **Gamma rays** can be viewed as streams of high energy photons. For example, cesium-137 is a beta emitter that also releases gamma radiation. The energy released in the beta emission leaves the product element, barium-137, in an excited state. When the barium-137 descends to its ground state, it gives off photons in the gamma ray region of the radiant energy spectrum. (See Section 4.1 for a review of the different forms of radiant energy.)

$$^{137}_{55}Cs \longrightarrow\ ^{137}_{56}Ba^{*} +\ ^{0}_{-1}e \longrightarrow\ ^{137}_{56}Ba + \gamma\text{-photon}$$



Nuclear Reactions and Nuclear Equations

OBJECTIVE 10

Now that we have seen some examples of nuclear reactions, let's look more closely at how they differ from the chemical reactions we have studied in the rest of this text.

- **Nuclear reactions** involve changes in the nucleus, whereas chemical reactions involve the loss, gain, and sharing of electrons.
- Different isotopes of the same element may undergo very different nuclear reactions, even though an element's isotopes all share the same chemical characteristics.
- Unlike chemical reactions, the rates of nuclear reactions are unaffected by temperature, pressure, and the presence of other atoms to which the radioactive atom may be bonded.
- Nuclear reactions, in general, give off much more energy than chemical reactions.

OBJECTIVE 11

The equations that describe nuclear reactions are different from those that describe chemical reactions because in nuclear equations charge is disregarded. If you study the nuclear changes for alpha, beta, and positron emission already described in this section, you will see that the products must be charged. For example, when an alpha particle is released from a uranium-238 nucleus, two positively charged protons are lost. Assuming that the uranium atom was uncharged initially, the thorium atom formed would have a −2 charge. Because the alpha particle is composed of two positively charged protons and two uncharged neutrons (and no electrons), it has a +2 overall charge.

$$^{238}_{92}U \rightarrow\ ^{234}_{90}Th^{2-} +\ ^{4}_{2}He^{2+}$$

The ions lose their charges quickly by exchanging electrons with other particles. Because we are usually not concerned about charges for nuclear reactions, and because these charges do not last very long, they are not usually mentioned in nuclear equations.

Objective 12

Scientists may not be interested in the charges on the products of nuclear reactions, but they are very interested in the changes that take place in the nuclei of the initial and final particles. Therefore, **nuclear equations** must clearly show the changes in the atomic numbers of the nuclides (the number of protons) and the changes in their mass numbers (the sum of the numbers of protons and neutrons). Note that in each of the following equations, the sum of the superscripts (mass numbers, A) for the reactants is equal to the sum of the superscripts for the products. Likewise, the sum of the subscripts (atomic numbers, Z) for the reactants is equal to the sum of the subscripts for the products. To show this to be true, beta particles are described as ${}^{0}_{-1}e$, and positrons are described as ${}^{0}_{+1}e$.

Objective 12

Alpha emission

$$\begin{array}{lccccccc}
\text{mass number} & 238 & & 234 & + & 4 & = & 238 \\
 & {}^{238}_{92}\text{U} & \longrightarrow & {}^{234}_{90}\text{Th} & + & {}^{4}_{2}\text{He} & & \\
\text{atomic number} & 92 & & 90 & + & 2 & = & 92
\end{array}$$

Beta emission

$$\begin{array}{lccccccc}
\text{mass number} & 131 & & 131 & + & 0 & = & 131 \\
 & {}^{131}_{53}\text{I} & \longrightarrow & {}^{131}_{54}\text{Xe} & + & {}^{0}_{-1}\text{e} & & \\
\text{atomic number} & 53 & & 54 & + & (-1) & = & 53
\end{array}$$

Positron emission

$$\begin{array}{lccccccc}
\text{mass number} & 40 & & 40 & + & 0 & = & 40 \\
 & {}^{40}_{19}\text{K} & \longrightarrow & {}^{40}_{18}\text{Ar} & + & {}^{0}_{+1}\text{e} & & \\
\text{atomic number} & 19 & & 18 & + & 1 & = & 19
\end{array}$$

Electron capture

$$\begin{array}{lcccccccc}
\text{mass number} & 0 & + & 125 & = & 125 & & 125 \\
 & {}^{0}_{-1}\text{e} & + & {}^{125}_{53}\text{I} & & & \longrightarrow & {}^{125}_{52}\text{Te} \\
\text{atomic number} & -1 & + & 53 & = & 52 & & 52
\end{array}$$

Objective 12

The following general equations describe these nuclear changes:

Alpha emission $\quad {}^{A}_{Z}\text{X} \longrightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\text{He}$

Beta emission $\quad {}^{A}_{Z}\text{X} \longrightarrow {}^{A}_{Z+1}\text{Y} + {}^{0}_{-1}\text{e}$

Positron emission $\quad {}^{A}_{Z}\text{X} \longrightarrow {}^{A}_{Z-1}\text{Y} + {}^{0}_{+1}\text{e}$

Electron capture $\quad {}^{0}_{-1}\text{e} + {}^{A}_{Z}\text{X} \longrightarrow {}^{A}_{Z-1}\text{Y}$

Table 16.2 on the next page summarizes the nuclear changes described in this section.

Table 16.2
Nuclear Changes

Objective 12

Type of change	Symbol	Change in protons (atomic number, Z)	Change in neutrons	Change in mass number, A
Alpha emission	α or ${}^{4}_{2}He$	−2	−2	4
Beta emission	β, β^-, or ${}^{0}_{-1}e$	+1	−1	0
Positron emission	β^+, ${}^{0}_{+1}e$, or ${}^{0}_{1}e$	−1	+1	0
Electron capture	E. C.	−1	+1	0
Gamma emission	γ or ${}^{0}_{0}\gamma$	0	0	0

Example 16.3 provides practice in writing nuclear equations for alpha emission, beta emission, positron emission, and electron capture.

Example 16.3 - Nuclear Equations

Objective 12

Write nuclear equations for (a) alpha emission by polonium-210, used in radiation therapy, (b) beta emission by gold-198, used to assess kidney activity, (c) positron emission by nitrogen-13, used in making brain, heart, and liver images, and (d) electron capture by gallium-67, used to do whole body scans for tumors.

Solution

a. The symbol for polonium-210 is ${}^{210}_{84}Po$, and the symbol for an alpha particle is ${}^{4}_{2}He$. Therefore, the beginning of our equation is

$${}^{210}_{84}Po \rightarrow \underline{\qquad} + {}^{4}_{2}He$$

The first step in completing this equation is to determine the subscript for the missing formula by asking what number would make the sum of the subscripts on the right of the arrow equal to the subscript on the left. That number gives us the atomic number of the missing nuclide. We then consult the periodic table to find out what element the missing nuclide represents. In this particular equation, the subscripts on the right must add up to 84, so the subscript for the missing nuclide must be 82. This is the atomic number of lead, so the symbol for the product nuclide is Pb. We next determine the superscript for the missing formula by asking what number would make the sum of the superscripts on the right of the equation equal to the superscript on the left. The mass number for the product nuclide must be 206.

$$\mathbf{{}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He}$$

b. The symbol for gold-198 is ${}^{198}_{79}Au$, and the symbol for a beta particle is ${}^{0}_{-1}e$. Therefore, the beginning of our equation is

$${}^{198}_{79}Au \rightarrow \underline{\qquad} + {}^{0}_{-1}e$$

To make the subscripts balance in our equation, the subscript for the missing nuclide must be 80, indicating that the symbol for the product nuclide should be Hg, for mercury. The mass number stays the same in beta emission, so we write 198.

$$\mathbf{{}^{198}_{79}Au \rightarrow {}^{198}_{80}Hg + {}^{0}_{-1}e}$$

c. The symbol for nitrogen-13 is $^{13}_{7}\text{N}$, and the symbol for a positron is $^{0}_{+1}\text{e}$. Therefore, the beginning of our equation is

$$^{13}_{7}\text{N} \rightarrow \underline{\qquad} + {}^{0}_{+1}\text{e}$$

To make the subscripts balance, the subscript for the missing nuclide must be 6, so the symbol for the product nuclide is C, for carbon. The mass number stays the same in positron emission, so we write 13.

$$\mathbf{^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{+1}e}$$

d. The symbol for gallium-67 is $^{67}_{31}\text{Ga}$, and the symbol for an electron is $^{0}_{-1}\text{e}$. Therefore, the beginning of our equation is

$$^{67}_{31}\text{Ga} + {}^{0}_{-1}\text{e} \rightarrow \underline{\qquad}$$

To balance the subscripts, the atomic number for our missing nuclide must be 30, so the symbol for the product nuclide is Zn, for zinc. The mass number stays the same in electron capture, so we write 67.

$$\mathbf{^{67}_{31}Ga + {}^{0}_{-1}e \rightarrow {}^{67}_{30}Zn}$$

Exercise 16.3 - Nuclear Equations

Objective 12

Write nuclear equations for (a) alpha emission by plutonium-239, one of the substances formed in nuclear power plants, (b) beta emission by sodium-24, used to detect blood clots, (c) positron emission by oxygen-15, used to assess the efficiency of the lungs, and (d) electron capture by copper-64, used to diagnose lung disease.

Example 16.4 shows how you can complete a nuclear equation when one of the symbols for a particle is missing.

Example 16.4 - Nuclear Equations

Objective 13

Glenn Seaborg and his team of scientists at the Lawrence Laboratory at the University of California, Berkeley, created a number of new elements, some of which—berkelium, californium, lawrencium—have been named in honor of their work. Complete the following nuclear equations that describe the processes used to create these elements.

a. $^{244}_{96}\text{Cm} + {}^{4}_{2}\text{He} \rightarrow \underline{\qquad} + {}^{1}_{1}\text{H} + 2{}^{1}_{0}\text{n}$

b. $^{238}_{92}\text{U} + \underline{\qquad} \rightarrow {}^{246}_{98}\text{Cf} + 4{}^{1}_{0}\text{n}$

c. $\underline{\qquad} + {}^{10}_{5}\text{B} \rightarrow {}^{257}_{103}\text{Lr} + 5{}^{1}_{0}\text{n}$

Solution

First, determine the subscript for the missing formula by asking what number would make the sum of the subscripts on the left of the arrow equal the sum of the subscripts on the right. That number is the atomic number of the missing nuclide and leads us to the element symbol for that nuclide. Next, determine the superscript for the missing formula by asking what number would make the sum of the superscripts on the left of the arrow equal to the sum of the superscripts on the right.

a. $^{244}_{96}\text{Cm} + {}^{4}_{2}\text{He} \rightarrow \mathbf{^{245}_{97}Bk} + {}^{1}_{1}\text{H} + 2{}^{1}_{0}\text{n}$

b. $^{238}_{92}\text{U} + \mathbf{^{12}_{6}C} \rightarrow {}^{246}_{98}\text{Cf} + 4{}^{1}_{0}\text{n}$

c. $\mathbf{^{252}_{98}Cf} + {}^{10}_{5}\text{B} \rightarrow {}^{257}_{103}\text{Lr} + 5{}^{1}_{0}\text{n}$

Exercise 16.4 - Nuclear Equations

Objective 13

Complete the following nuclear equations.

a. ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow$ _____ $+ {}^{1}_{1}H$

b. ${}^{238}_{92}U +$ _____ $\rightarrow {}^{247}_{99}Es + 5{}^{1}_{0}n$

c. _____ $+ {}^{2}_{1}H \rightarrow {}^{239}_{93}Np + {}^{1}_{0}n$

Rates of Radioactive Decay

Because the different radioactive nuclides have different stabilities, the rates at which they decay differ as well. These rates are described in terms of a nuclide's **half-life**, the time it takes for one-half of a sample to disappear. For example, radioactive carbon-14, which decays to form nitrogen-14 by emitting a beta particle, has a half-life of 5730 years. After 5730 years, one-half of a sample remains, and one-half has become nitrogen-14. After 11,460 years (two half-lives), half of that remainder will have decayed to form nitrogen-14, bringing the sample down to one-fourth of its original amount. After 17,190 years (three half-lives), half of what remained after 11,460 years will have decayed to form nitrogen-14, so one-eighth of the original sample will remain. This continues, with one-half of the sample decaying each half-life.

Imagine having a pie and being told that you are only allowed to eat one-half of whatever amount is on the plate each day. The first day you eat one-half of the pie. The next day you eat half of what is there, but that's only one-fourth of a pie ($\frac{1}{2} \times \frac{1}{2}$). The next day you can only eat one-eighth of the original pie ($\frac{1}{2} \times \frac{1}{4}$ or $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$), and on the next day one-sixteenth ($\frac{1}{2} \times \frac{1}{8}$ or $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$). On the fifth day (after five half-lives), the piece you eat is only $\frac{1}{32}$ of the original pie ($\frac{1}{2} \times \frac{1}{16}$ or $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$). The process continues until there is not enough pie to bother eating any. It's a similar situation with radioactive nuclides. One-half of their amount disappears each half-life until there's no significant amount left. The length of time necessary for a radioactive sample to dwindle to insignificance depends on its half-life and the amount that was present to begin with (Figure 16.2).

In subsequent chemistry or physics courses, you might learn a general technique for using a nuclide's half-life to predict the length of time required for any given percentage of a sample to decay. Example 16.5 gives you a glimpse of this procedure by showing how to predict the length of time required for a specific radioactive nuclide (with a given half-life) to decay to $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$, or $\frac{1}{32}$ of its original amount. Example 16.6 shows how you can predict what fraction of a sample will remain after one, two, three, four, or five half-lives.

Figure 16.2
Half-life and Radioactive Decay

Objective 14

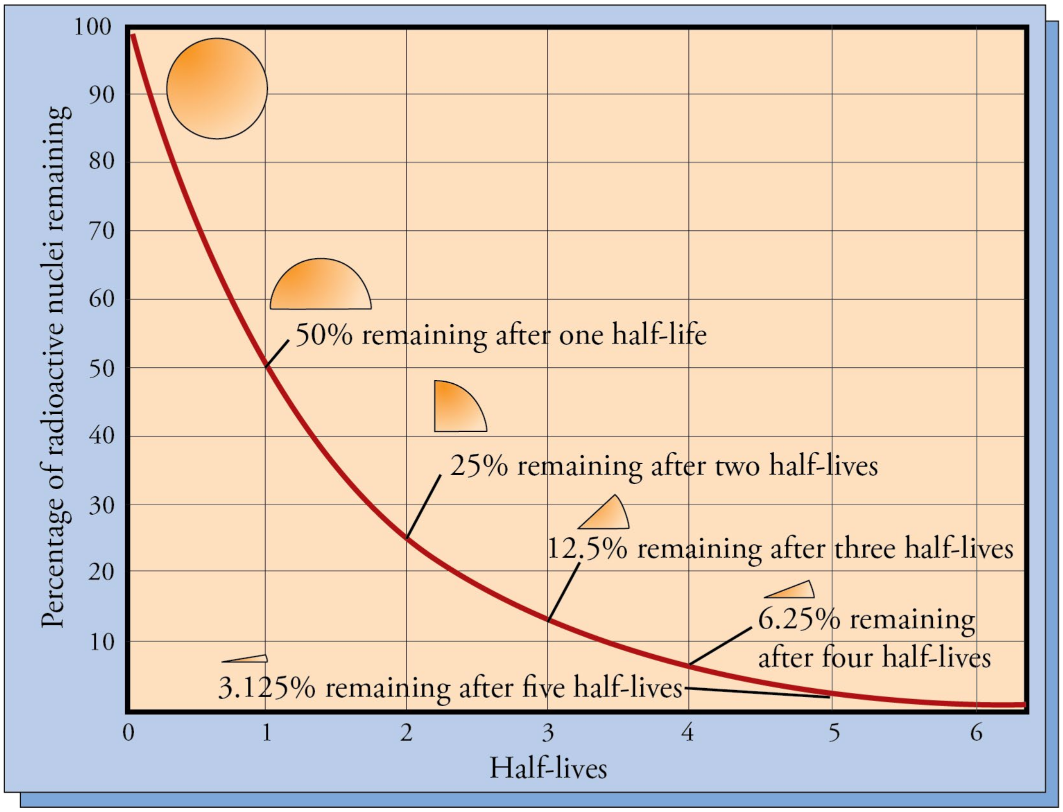


Table 16.3
Half-Lives of Common Radioactive Isotopes

Nuclide	Half-life	Type of change	Nuclide	Half-life	Type of change
rubidium-87	5.7×10^{10} years	beta	iron-59	45 days	beta
thorium-232	1.39×10^{10} years	alpha	phosphorus-32	14.3 days	beta
uranium-238	4.51×10^{9} years	alpha	barium-131	11.6 days	electron capture and positron
uranium-235	7.13×10^{9} years	alpha	iodine-131	8.06 days	beta
plutonium-239	2.44×10^{4} years	alpha	radon-222	3.82 days	alpha
carbon-14	5730 years	beta	gold-198	2.70 days	beta
radium-226	1622 years	alpha	krypton-79	34.5 hours	electron capture and positron
cesium-133	30 years	beta	carbon-11	20.4 min	positron
strontium-90	29 years	beta	fluorine-17	66 s	positron
hydrogen-3	12.26 years	beta	polonium-213	4.2×10^{-6} s	alpha
cobalt-60	5.26 years	beta	beryllium-8	1×10^{-16} s	alpha

Example 16.5 - Half-Life

Objective 14

Radon-222, which is found in the air inside houses built over soil containing uranium, has a half-life of 3.82 days. How long before a sample decreases to $\frac{1}{32}$ of the original amount?

Solution

In each half-life of a radioactive nuclide, the amount diminishes by one-half. The fraction $\frac{1}{32}$ is $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$, so five half-lives are needed to reduce the sample to that extent. For radon-222, five half-lives are 19.1 days (5 × 3.82 days).

Exercise 16.5 - Half-Life

Objective 14

One of the radioactive nuclides formed in nuclear power plants is hydrogen-3, called tritium, which has a half-life of 12.26 years. How long before a sample decreases to $\frac{1}{8}$ of its original amount?

Example 16.6 - Half-Life

Objective 15

One of the problems associated with the storage of radioactive wastes from nuclear power plants is that some of the nuclides remain radioactive for a very long time. An example is plutonium-239, which has a half-life of 2.44×10^4 years. What fraction of plutonium-239 is left after 9.76×10^4 years?

Solution

The length of time divided by the half-life yields the number of half-lives:

$$\frac{9.76 \times 10^4 \text{ years}}{2.44 \times 10^4 \text{ years}} = 4 \text{ half-lives}$$

In each half-life of a radioactive nuclide, the amount diminishes by one-half, so the fraction remaining would be $\frac{1}{16}$ ($\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$).

Exercise 16.6 - Half-Life

Objective 15

Uranium-238 is one of the radioactive nuclides sometimes found in soil. It has a half-life of 4.51×10^9 years. What fraction of a sample is left after 9.02×10^9 years?

Radioactive Decay Series

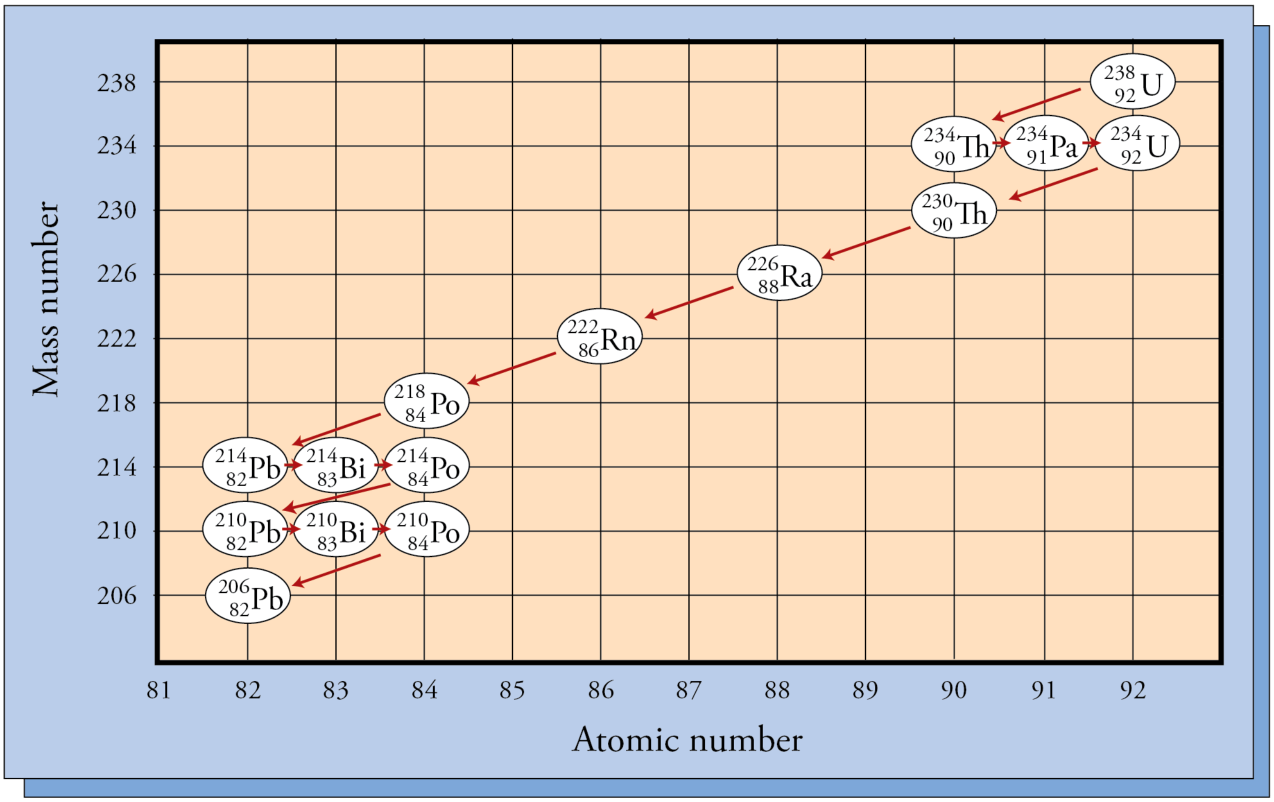
Objective 16

Many of the naturally-occurring radioactive nuclides have relatively short half-lives. Radon-222, which according to U.S. Environmental Protection Agency estimates causes between 5000 and 20,000 deaths per year from lung cancer, has a half-life of only 3.82 days. With such a short half-life, why are this and other short-lived nuclides still around? The answer is that although they disappear relatively quickly once they form, these nuclides are constantly being replenished because they are products of other radioactive decays.

Three relatively abundant and long-lived radioactive nuclides are responsible for producing many of the other natural radioactive isotopes on earth. One of them is uranium-238, with a half-life of 4.51 billion years, which changes to lead-206 in a series of eight alpha decays and six beta decays (Figure 16.3). Chemists call such a sequence a **nuclear decay series**. Because this sequence of decays is happening constantly in soil and rocks containing uranium, all of the radioactive intermediates between uranium-238 and lead-206 are constantly being formed and are therefore still found in nature.

Objective 16

Figure 16.3
Uranium-238 Decay Series



You can see in Figure 16.3 that one of the products of the uranium-238 decay series is radium-226. This nuclide, with a half-life of 1622 years, is thought to be the second leading cause of lung cancer, after smoking. The next step in this same decay series forms radon-222. Radon-222 is also thought to cause cancer, but it does not do so directly. Radon-222 is a gas, and enters our lungs through the air. Then, because of its fairly short half-life, a significant amount of it decays to form polonium-218 while still in our lungs. Polonium and all of the radioactive nuclides that follow it in the decay series are solids that stay in the lining of the lungs, emitting alpha particles, beta particles, and gamma rays. Houses built above earth that contains uranium can harbor significant concentrations of radon, so commercial test kits have been developed to detect it. Radon is a bigger problem in colder climates and at colder times of the year because it accumulates inside houses that are sealed up tight to trap warm air.

Objective 17

Objective 18

Radon Test Kit

The other two important decay series are the one in which uranium-235 (with a half-life of 7.13×10^8 years) decays in eleven steps to lead-207 and the one in which thorium-232 (which has a half-life of 1.39×10^{10} years) decays in ten steps to lead-208.

The Effect of Radiation on the Body

Alpha particles, beta particles, and gamma photons are often called **ionizing radiation**, because as they travel through a substance, they strip electrons from its atoms, leaving a trail of ions in their wake. Let's explore why this happens and take a look at the effects that ionizing radiation has on our bodies.

Objective 19
Objective 20

Picture an alpha particle moving through living tissue at up to 10% the speed of light. Remember that alpha particles are helium nuclei, so they each have a +2 charge. As such a particle moves past, say, an uncharged water molecule (a large percentage of our body is water), it attracts the molecule's electrons. One of the electrons might be pulled toward the passing alpha particle enough to escape from the water molecule, but it might not be able to catch up to the fast-moving alpha particle. Instead, the electron is quickly incorporated into another atom or molecule, forming an anion, while the water molecule that lost the electron becomes positively charged. The alpha particle continues on its way, creating many ions before slowing down enough for electrons to catch up with it and neutralize its charge. When a neutral water molecule, which has all of its electrons paired, loses one electron, the cation that is formed has an unpaired electron. Particles with unpaired electrons are called **free radicals**.

Free radical

$$H_2O \xrightarrow{\alpha\text{-particle}} H_2O^{\bullet +} + e^-$$

Objective 19

In beta radiation, the repulsion between the beta particles' negative charges and the electrons on the atoms and molecules of our tissue causes electrons to be pushed off the uncharged particles, creating ions like the ones created by alpha particles. Gamma photons produce their damage by exciting electrons enough to actually remove them from atoms.

The water cations, $H_2O^{\bullet +}$, and free electrons produced by ionizing radiation react with uncharged water molecules to form other ions and free radicals.

Objective 20

$$H_2O^{\bullet +} + H_2O \rightarrow H_3O^+ + {}^{\bullet}OH$$
$$H_2O + e^- \rightarrow H^{\bullet} + OH^-$$

Objective 21

These very reactive ions and free radicals then react with important substances in the body, leading to immediate tissue damage and to delayed problems, such as cancer. The cells that reproduce most rapidly are the ones most vulnerable to harm, because they are the sites of greatest chemical activity. This is why nuclear emissions have a greater effect on children, who have larger numbers of rapidly reproducing cells, than on adults. The degree of damage is, of course, related to the length of exposure, but it is also dependent on the kind of radiation and whether the source is inside or outside the body.

Objective 22

Some radioactive nuclides are especially damaging because they tend to concentrate in particular parts of the body. For example, because both strontium and calcium are alkaline earth metals in group 2 on the periodic table, they combine with other elements in similar ways. Therefore, if radioactive strontium-90 is ingested, it concentrates in the bones in substances that would normally contain calcium. This can lead to bone cancer or leukemia. For similar reasons, radioactive cesium-137 can enter the cells of the body in place of its fellow alkali metal potassium, leading to tissue damage. Non-radioactive iodine and radioactive iodine-131 are both absorbed by thyroid glands. Because iodine-131 is one of the radioactive nuclides produced in nuclear power plants, the

Chernobyl accident released large quantities of it. To reduce the likelihood of thyroid damage, people were directed to take large quantities of salt containing non-radioactive iodine-127. This flooding of the thyroid glands with the non-damaging form of iodine made it less likely that the iodine-131 would be absorbed.

Objective 23

Because alpha particles are relatively large and slow moving compared to other emissions from radioactive atoms, it is harder for them to slip between the atoms in the matter through which they pass. Alpha particles are blocked by 0.02 mm to 0.04 mm of water or about 0.05 mm of human tissue. Therefore, alpha particles that strike the outside of the body enter no further than the top layer of skin. Because beta particles are much smaller, and can move up to 90% the speed of light, they are about 100 times as penetrating as alpha particles. Thus beta particles are stopped by 2 mm to 4 mm of water or by 5 mm to 10 mm of human tissue. Beta particles from a source outside the body may penetrate to the lower layers of skin, but they will be stopped before they reach the vital organs. Gamma photons are much more penetrating, so gamma radiation from outside the body can do damage to internal organs.

Objective 24

Although alpha and beta radiation are less damaging to us than gamma rays when emitted from external sources, both forms of radiation can do significant damage when emitted from within the body (by a source that has been eaten or inhaled). Because they lose all of their energy over a very short distance, alpha or beta particles can do more damage to localized areas in the body than the same number of gamma photons would.

16.2 Uses for Radioactive Substances

As you saw in the last section, radioactive substances can be damaging to our bodies, but scientists have figured out ways to use some of their properties for our benefit. For example, radioactive nuclides are employed to diagnose lung and liver disease, to treat thyroid problems and cancer, and to determine the ages of archaeological finds. Let's examine some of these beneficial uses.

Medical Uses

Objective 25

Cobalt-60 emits ionizing radiation in the form of beta particles and gamma photons. You saw in the last section that gamma photons, which penetrate the body and damage the tissues, do more damage to rapidly reproducing cells than to others. This characteristic coupled with the fact that cancer cells reproduce very rapidly underlies the strategy of using radiation to treat cancer. Typically, a focused beam of gamma photons from cobalt-60 is directed at a cancerous tumor. The ions and free radicals that the gamma photons produce inside the tumor damage its cells and cause the tumor to shrink.

Like many other radioactive nuclides used in medicine, cobalt-60 is made by bombarding atoms of another element (in this case iron) with neutrons. The iron contains a small percentage of iron-58, which forms cobalt-60 in the following steps:

$${}^{58}_{26}\text{Fe} + {}^{1}_{0}\text{n} \rightarrow {}^{59}_{26}\text{Fe}$$

$${}^{59}_{26}\text{Fe} \rightarrow {}^{59}_{27}\text{Co} + {}^{0}_{-1}\text{e}$$

$${}^{59}_{27}\text{Co} + {}^{1}_{0}\text{n} \rightarrow {}^{60}_{27}\text{Co}$$

Objective 26

One of the most significant advances in medicine in recent years is the development of computer imaging techniques. One such technique that relies on the characteristics of atomic nuclei is called magnetic resonance imaging (MRI). The patient is placed in a strong magnetic field and exposed to radio wave radiation, which is absorbed and re-emitted in different ways by different tissues in the body. Computer analysis of the re-emitted radio waves yields an image of the tissues of the body.

Objective 26

A simplified description of how MRI works begins with the fact that protons act like tiny magnets. When patients are put in the strong magnetic field, the proton magnets in the hydrogen atoms in their bodies line up either with or against the field (these orientations are called parallel and anti-parallel, respectively). The anti-parallel arrangement is slightly higher in energy than the parallel position, and the energy difference is equivalent to the energy of photons in the radio wave range of the radiant energy spectrum. As a result, when radio waves are directed at the patient, they are absorbed by protons in the parallel orientation and excite the protons into the anti-parallel orientation. As the protons return to the more stable parallel orientation, they re-emit energy, which can be detected by scanners placed around the patient's body.

proton parallel to field + absorbed energy → proton anti-parallel to field

proton anti-parallel to field → proton parallel to field + emitted energy

Objective 26

Because the soft tissues of the body contain a lot of water (with a lot of hydrogen atoms) and bones do not, the MRI process is especially useful for creating images of the soft tissues of the body. Hydrogen atoms absorb and re-emit radio wave photons in different ways depending on their molecular environment, so the computer analysis of the data leads to detailed images of the soft tissues.

Objective 27

Special Topic 4.1: *Why does matter exist, and why should we care about answering this question?* describes positron emission tomography (PET), which is another computer-imaging diagnostic technique. In this technique, a solution containing a positron-emitting substance is introduced into the body. The positrons collide with electrons, and the two species annihilate each other, creating two gamma photons that move apart in opposite directions.

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

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

$\leftarrow \gamma\text{-ray} \qquad \gamma\text{-ray} \rightarrow$

Objective 27

Objective 28

These photons can be detected and the data can be analyzed by a computer to yield images showing where in the body the radioactive substances collected. Different nuclides are used to study different parts of the body. For example, fluorine-18 containing substances collect in the bones, so that nuclide is used in bone scanning. Glucose molecules are used throughout the body, but are especially concentrated in the brain, so glucose constructed with carbon-11 can be used to study brain function. PET scans reveal which parts of the brain use glucose most actively during different activities. This ability to study dynamic processes in the body, such as brain activity or blood flow, makes the PET scan a valued research and diagnostic tool.

The nuclides used for PET scans have half-lives that range from about two minutes to about 110 minutes, so one of the challenges in refining this technology has been to find ways to quickly incorporate the positron emitters into the substances, such as glucose, that will be introduced into the body.

Carbon-14 Dating

[If not for radiocarbon dating,] we would still be floundering in a sea of imprecisions sometimes bred of inspired guesswork but more often of imaginative speculations.

Desmond Clark, Anthropologist

As anthropologists, such as Desmond Clark, attempt to piece together the strands of human history, they often call on other scientists for help. One important contribution that nuclear science has made in this area is the ability to determine the age of ancient artifacts. There are several techniques for doing this, but the most common process for dating objects of up to about 50,000 years is called **radiocarbon dating**.

Objective 29

Natural carbon is composed of three isotopes. It is 98.89% carbon-12, 1.11% carbon-13, and 0.00000000010% carbon-14. The last of these, carbon-14, is most important in radiocarbon dating. Carbon-14 atoms are constantly being produced in our upper atmosphere through neutron bombardment of nitrogen atoms.

$$^{14}_{7}\text{N} + {}^{1}_{0}\text{n} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$$

Objective 29

Once formed, the carbon-14 is quickly oxidized to produce carbon dioxide, CO_2, which is then converted into many different substances in plants. When animals eat the plants, the carbon-14 becomes part of the animals too. For these reasons, carbon-14 is found in all living things. This radioactive isotope is a beta emitter with a half-life of 5730 years (±40 years), so as soon as it becomes part of a plant or animal, it begins to disappear.

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

Objective 29

As long as a plant or animal remains alive, its intake of carbon-14 balances the isotope's continuous decay, so that the ratio of ^{14}C to ^{12}C in living tissues remains constant at about 1 in 1,000,000,000,000. When the plant or animal dies, it stops taking in fresh carbon, but the carbon-14 it contains continues to decay. Thus the ratio of ^{14}C to ^{12}C drops steadily. Therefore, to date an artifact, a portion of it is analyzed to determine the $^{14}C/^{12}C$ ratio, which is then used to calculate its age.

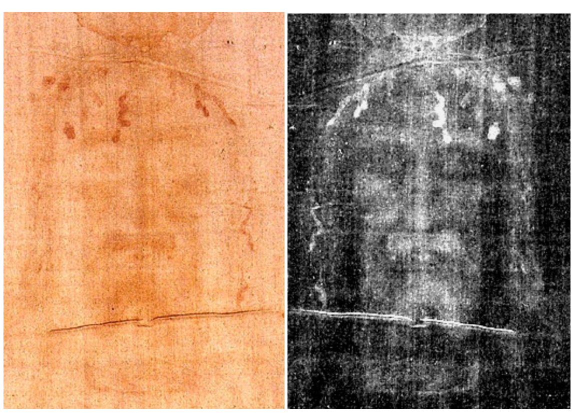
Objective 29

Initially, researchers expected that once the $^{14}C/^{12}C$ ratio was known, calculating an object's age would be simple. For example, if the $^{14}C/^{12}C$ ratio had dropped to one-half of the ratio found in the air today, the object would have been described as about 5730 years old. A $^{14}C/^{12}C$ ratio of one-fourth of the ratio found in the air today would date it as 11,460 years old (2 half-lives). This only works if we can assume that the $^{14}C/^{12}C$ ratio in the air was the same when the object died as it is now, and scientists have discovered that this is not strictly true. For example, it is now believed that the large quantities of carbon periodically released into the atmosphere by volcanoes have in many cases been isolated from the air for so long that they have much lower than average levels of carbon-14. The levels of cosmic radiation also fluctuate, and lower levels of neutron bombardment produce lower levels of carbon-14.

Information derived from Bristlecone pines in California has helped scientists to date artifacts.

By checking the $^{14}C/^{12}C$ ratio of the wood in tree rings (which are formed once a year), scientists discovered that the ratio has varied by about ±5% over the last 1500 years. Further study of very old trees, such as the bristlecone pines in California, has allowed researchers to develop calibration curves for radiocarbon dating that go back about 10,000 years. These calibration curves are now used to get more precise dates for objects.

Radiocarbon dating has been used to date charcoal from ancient fires, fragments of bone, shells from the ocean, hair, insect remains, paper, cloth, and many other carbon-containing substances. Two of the most famous artifacts that have been dated by this technique are the Shroud of Turin and the Dead Sea Scrolls. Because these objects are very precious, they were only dated after techniques had been developed for testing very small amounts of substance (as little as 100 mg of material). The Dead Sea Scrolls are a collection of about 600 Hebrew and Aramaic manuscripts discovered in caves near Khirbat Qumrân in Jordan, near the Dead Sea. Carbon-14 dating confirmed the age that had already predicted from other clues, such as the kinds of handwriting on the scrolls and the materials used to make them. These scrolls, which contain hymn books, biblical commentaries, and parts of every book in the Old Testament except Esther, are thought to have been written between 200 BC and AD 68, making them about 1000 years older than any other surviving biblical transcripts.



Left, a regular photo of the Shroud of Turin. Right, a photo-negative of one portion of the Shroud of Turin. The Shroud of Turin has been dated by the carbon-14 process.

The dating of the Shroud of Turin in 1988 has been more controversial. The shroud is a linen cloth with a faint image of an adult who seems to have been crucified. Some people believe it to be the burial shroud of Jesus of Nazareth, but the results of radiocarbon dating suggest that the shroud is only about 600 years old. If these results are correct, they rule out the possibility of the shroud's having been used to bury Jesus.

The development of more sensitive ways to measure levels of radioactive substances has allowed scientists to take advantage of the decay of nuclides other than carbon-14. For example, chlorine-36 can be used to date ground water, marine sediments can be dated by measuring levels of beryllium-11 and aluminum-26, and krypton-81 has been used to estimate the age of glacial ice.

Other Uses for Radioactive Nuclides

There are many other uses for radioactive nuclides. For example, some smoke detectors contain the alpha emitter americium-241. The alpha particles it releases ionize the air in the detector's interior, allowing an electric current to pass through. When particles of smoke enter the detector, they block the alpha particles, thus decreasing the number of ions in the air, reducing the electric current, and triggering the alarm. Objective 30

Iridium-192 is used to check for faulty connections in pipes. Film is wrapped around the outside of a welded junction and then a radioactive substance is run through the pipe. If there is a crack in the connection, radiation leaks out and exposes the film. Objective 31

One of the more controversial uses of radioactive nuclides is in food irradiation. Gamma ray beams, X rays, and electron beams have been directed at food for a variety of purposes. Radiation inhibits the sprouting of potatoes and onions, retards the growth of mold on strawberries, and kills bacteria in poultry and fish. Cobalt-60 and cesium-137 have been used for these purposes. The controversy lies in whether the radiation causes changes in the food that could have adverse health consequences. Although the food is not any more radioactive after the treatment than before, the radiation does create ions and free radicals in the food. Most of these recombine to form harmless substances, such as water, but some form other, more worrisome chemicals, such as H_2O_2. Cooking and pasteurization also form substances in food that would not be there otherwise, so the formation of new substances, in and of itself, is not necessarily unusual or bad. Researchers have been attempting to identify the new substances in each situation and consider what problems, if any, they might create. Because people in certain parts of the world lose up to 50% of their food to spoilage, questions about the safety of using radiation to preserve food are of major importance. At this point, the scientific consensus is that the benefits of irradiating certain foods outweigh the potential dangers. Objective 32

Unstable nuclides have also been used as **radioactive tracers** in scientific research. For example, scientists have used carbon-14 to study many aspects of photosynthesis. Because the radiation emitted from carbon-14 atoms can be detected outside of the system into which the carbon-14-containing molecules have been placed, the location of changes involving carbon can be traced. Likewise, phosphorus-32 atoms can be used to trace phosphorus-containing chemicals as they move from the soil into plants. Carbon-14, hydrogen-3, and sulfur-35 have been used to trace the biochemical changes that take place in our bodies. Objective 33

Table 16.4 on the next page lists many other uses for radioactive nuclides.

Table 16.4

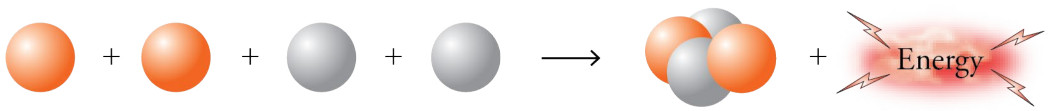
Uses for Radioactive Nuclides (Remember that gamma emission often accompanies other forms of radioactive decay.)

Nuclide	Nuclear change	Application
argon-41	beta emission	Measure flow of gases from smokestacks
barium-131	electron capture	Detect bone tumors
carbon-11	positron emission	PET brain scan
carbon-14	beta emission	Archaeological dating
cesium-133	beta emission	Radiation therapy
cobalt-60	beta emission	Cancer therapy
copper-64	beta emission, positron emission, electron capture	Lung and liver disease diagnosis
chromium-51	electron capture	Determine blood volume and red blood cell lifetime; diagnose gastrointestinal disorders
fluorine-18	beta emission, positron emission, electron capture	Bone scanning; study of cerebral sugar metabolism
gallium-67	electron capture	Diagnosis of lymphoma and Hodgkin disease; whole body scan for tumors
gold-198	beta emission	Assess kidney activity
hydrogen-3	beta emission	Biochemical tracer; measurement of the water content of the body
indium-111	gamma emission	Label blood platelets
iodine-125	electron capture	Determination of blood hormone levels
iodine-131	beta emission	Measure thyroid uptake of iodine
iron-59	beta emission	Assessment of blood iron metabolism and diagnosis of anemia
krypton-79	positron emission and electron capture	Assess cardiovascular function
nitrogen-13	positron emission	Brain, heart, and liver imaging
oxygen-15	positron emission	Lung function test
phosphorus-32	beta emission	Leukemia therapy, detection of eye tumors, radiation therapy, and detection breast carcinoma
polonium-210	alpha emission	Radiation therapy
potassium-40	beta emission	Geological dating
radium-226	alpha emission	Radiation therapy
selenium-75	beta emission and electron capture	Measure size and shape of pancreas
sodium-24	beta emission	Blood studies and detection of blood clots
technetium-99	gamma emission	Bone scans and detection of blood clots
xenon-133	beta emission	Lung capacity measurement

16.3 Nuclear Energy

In Section 16.1, we saw that energy is released when nucleons (protons and neutrons) combine to form nuclei.

$$p + p + n + n \longrightarrow {}^{4}_{2}He^{2+}$$



Let's look more closely at this energy.

Objective 34

The amount of energy released when a nucleus is formed is a reflection of the strength with which the nucleons are bound. This amount is therefore called the atom's **binding energy**. The alpha particle whose creation is illustrated above has a binding energy of 4.54×10^{-12} J, a small amount that scientists often prefer to describe in terms of the more convenient **electron volt**, which is equivalent to 1.6×10^{-19} joules. The binding energy of the alpha particle is 28.4 MeV (million electron volts). Small as this amount may be, it is still significantly larger than the energies associated with electrons. It takes about 10,000 times as much energy to remove a proton or a neutron from the nucleus of a hydrogen-2 atom as to remove its one electron.

Objective 35

Objective 36

One way of comparing the relative stabilities of different nuclei is to look at their binding energies in terms of the binding energy per nucleon, that is, the nuclide's binding energy divided by the number of nucleons. A higher binding energy per nucleon means more stable and more tightly bound nucleons in the nucleus. The binding energy per nucleon for the helium nucleus is 7.10 MeV (28.4 MeV total binding energy divided by 4 nucleons). The chart in Figure 16.4 on the next page shows that the binding energy per nucleon varies for different nuclei, suggesting that the stabilities of nuclei vary. The binding energy (and therefore stability) starts low for hydrogen-2, rises (with some exceptions) with atomic mass for mass numbers up to around 56, and then drops again for larger atoms.

Objective 37

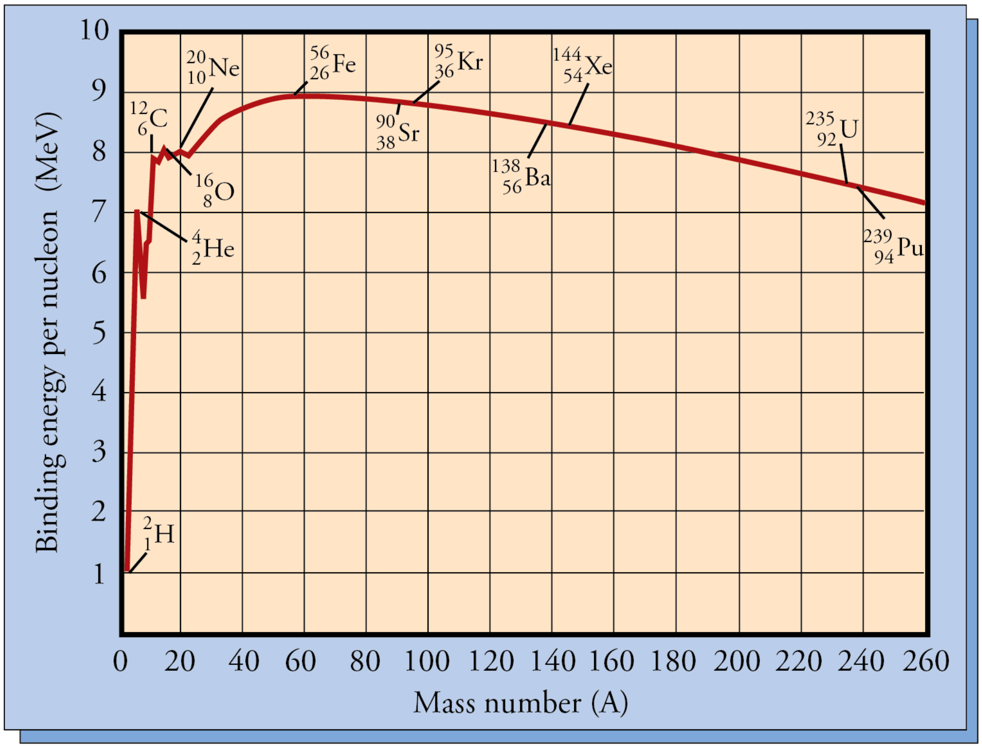
There are several important conclusions that we can draw from Figure 16.4. First, it shows that certain nuclides are more stable than we might have expected them to be if the trend for the change in binding energy per nucleon were smooth. The stabilities of ${}^{4}_{2}He$, ${}^{12}_{6}C$, ${}^{16}_{8}O$, and ${}^{20}_{10}Ne$ are all high. This is explained by the fact that they each have an even number of protons and an even number of neutrons. In short, paired nucleons (like paired electrons) are more stable than unpaired ones. Thus, of the 264 stable isotopes in nature, 160 of them have an even number of protons and an even number of neutrons, 50 have an even number of protons and an odd number of neutrons, 50 have an odd number of protons and an even number of neutrons, and only 4 (${}^{2}_{1}H$, ${}^{6}_{3}Li$, ${}^{10}_{5}B$, and ${}^{14}_{7}N$) have an odd number of protons and an odd number of neutrons.

Objective 38

In Chapter 4, we found that there was something special about having the same number of electrons as the noble gases (2, 10, 18, 36, 54, and 86). There also appears to be something stable about having 2, 8, 20, 28, 50, 82, or 126 protons or neutrons. The stability of nuclides with double magic numbers (the aforementioned numbers of protons and neutrons are often called "magic numbers") is very high. For example, ${}^{4}_{2}He$, ${}^{16}_{8}O$, ${}^{40}_{20}Ca$, and ${}^{208}_{82}Pb$ are especially stable.

Figure 16.4
Binding Energy per Nucleon Versus Mass Number

OBJECTIVE 36



OBJECTIVE 36

Note that initially, as we read left to right along the curve in Figure 16.4, the binding energy per nucleon generally increases. This means that more energy is released per nucleon to form a nucleus approaching the size of the iron-56 nucleus than to form a nucleus that is smaller. Thus, as a rule, when atoms are much smaller than iron-56, energy is released when they combine to form larger atoms. As we will see, this process of combining smaller atoms to make larger ones (called **fusion**) is the process that fuels the sun. Likewise, the chart shows that when atoms are larger than iron-56, splitting them to form more stable, smaller atoms should also release energy. This process, called **fission**, is the process that fuels nuclear reactors used to make electricity.

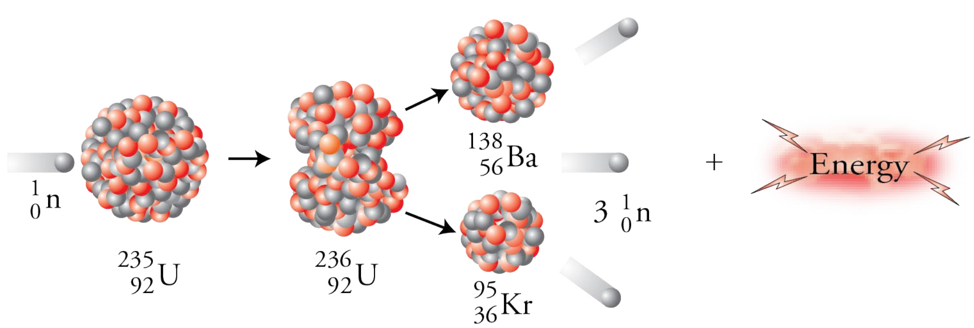
Nuclear Fission and Electric Power Plants

OBJECTIVE 39

In a typical nuclear fission process, a neutron collides with a large atom, such as uranium-235, and forms a much less stable nuclide that spontaneously decomposes into two medium sized atoms and 2 or 3 neutrons. For example, when uranium-235 atoms are bombarded with neutrons, they form uranium-236 atoms, which decompose to form atoms such as krypton-95 and barium-138 as well as neutrons.

neutron + large nuclide → unstable nuclide

unstable nuclide → 2 medium sized nuclides + 2 or 3 neutrons



Objective 39

The nuclides produced in the reaction pictured above are only two of many possible fission products of uranium-235. More than 200 different nuclides form, representing 35 different elements. Two possible reactions are

$$ {}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{95}_{36}\text{Kr} + {}^{138}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} $$

$$ {}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{144}_{54}\text{Xe} + {}^{90}_{38}\text{Sr} + 3\,{}^{1}_{0}\text{n} $$

Nuclear reactions such as these are used to power electrical generating plants.

Objective 40

The nuclear reactor in a nuclear power plant is really just a big furnace whose job is to generate heat and thus convert liquid water to steam in order to turn a steam turbine generator that produces electricity. The electricity-generating portion of a nuclear power plant is typically no different than the electricity-generating portion of a plant that generates heat from burning fossil fuels. Therefore, instead of describing that part of the power plant's setup, we will focus exclusively on how the fission process generates heat.

Objective 39

Figure 16.4 shows that energy is released when larger nuclides with lower binding energy per nucleon are converted to medium-sized nuclides with a higher binding energy per nucleon. The reason the fission of uranium-235 can generate a lot of energy in a short period of time is that under the right circumstances, it can initiate a **chain reaction**, a process in which one of the products of a reaction initiates another identical reaction. In the fission of uranium-235, one or more of the neutrons formed in the reaction can collide with another uranium-235 atom and cause it to fission too (Figure 16.5).

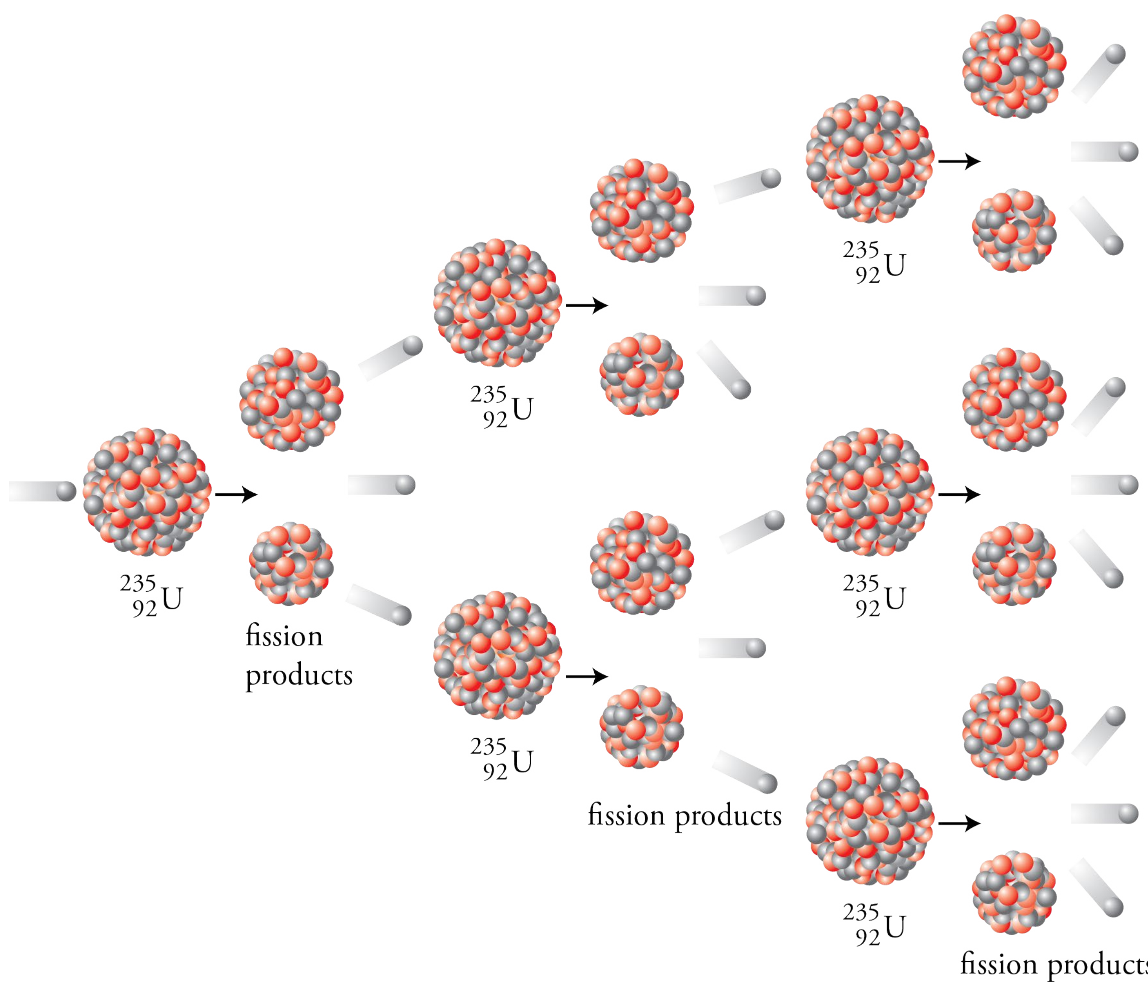


Figure 16.5
Uranium-235 Chain Reaction

Objective 39

Objective 41

To sustain a chain reaction for the fission of uranium-235, an average of about one of the neutrons generated in each reaction must go on to cause another reaction. If this does not occur, the series of reactions slows down and eventually stops. When natural uranium is bombarded by neutrons, the chain reaction cannot be sustained. Too many neutrons are absorbed by other entities without leading to fission. To see why, we need to look again at the natural composition of uranium, described earlier in the chapter as 99.27% uranium-238, 0.72% uranium-235, and a trace of uranium-234. The only one of these isotopes that undergoes fission is uranium-235. Uranium-238 does absorb neutrons, but the uranium-239 that then forms reacts by beta emission rather than nuclear fission.

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U}$$
$$^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e}$$
$$^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}$$

Objective 41
Objective 40

When natural uranium is bombarded by neutrons, the uranium-238 absorbs so many of the neutrons released in the fission reactions of uranium-235 that a chain reaction cannot be sustained. One part of the solution to this problem for nuclear power plants is to create a uranium mixture that is enriched in uranium-235 (to about 3%). A typical 1000-megawatt power plant will have from 90,000 to 100,000 kilograms of this enriched fuel packed in 100 to 200 zirconium rods about 4 meters long (Figure 16.6).

Objective 42

There is another way to increase the likelihood that neutrons will be absorbed by uranium-235 instead of uranium-238. Both uranium-235 and uranium-238 absorb fast neutrons, but if the neutrons are slowed down, they are much more likely to be absorbed by uranium-235 atoms. Therefore, in a nuclear reactor, the fuel rods are surrounded by a substance called a **moderator** that slows the neutrons as they pass through it. Several substances have been used as moderators, but normal water is most common (Figure 16.6).

Objective 40

Objective 43

Another problem associated with the absorption of neutrons by uranium-238 is that it leads to the creation of plutonium-239 (look again at the series of equations presented above). This is a cause for concern because plutonium-239 undergoes nuclear fission easier than uranium-235, and is thus a possible nuclear weapon fuel. Moreover, plutonium has a relatively long half-life, so the radioactive wastes from nuclear reactors (which contain many other unstable nuclides besides plutonium) must be carefully isolated from the environment for a very long time.

Objective 44

An efficient nuclear reactor needs to sustain the chain reaction but should not allow the fission reactions to take place too rapidly. For this reason, nuclear power plants have **control rods** containing substances such as cadmium or boron, which are efficient neutron absorbers. At the first sign of trouble, these control rods are inserted between the fuel rods, absorbing the neutrons that would have passed from one fuel rod to another and preventing them from causing more fission reactions. The deployment of the control rods stops the chain reaction.

Objective 44

The control rods serve another purpose in the normal operation of the power plant. When fresh fuels rods are introduced, the control rods are partially inserted to absorb some of the neutrons released. As the uranium-235 reacts and its percentage of the total mixture in the fuel rods decreases, the control rods are progressively withdrawn. In this way, a constant rate of fission can be maintained, even as the percentage of the fissionable uranium-235 diminishes (Figure 16.6).

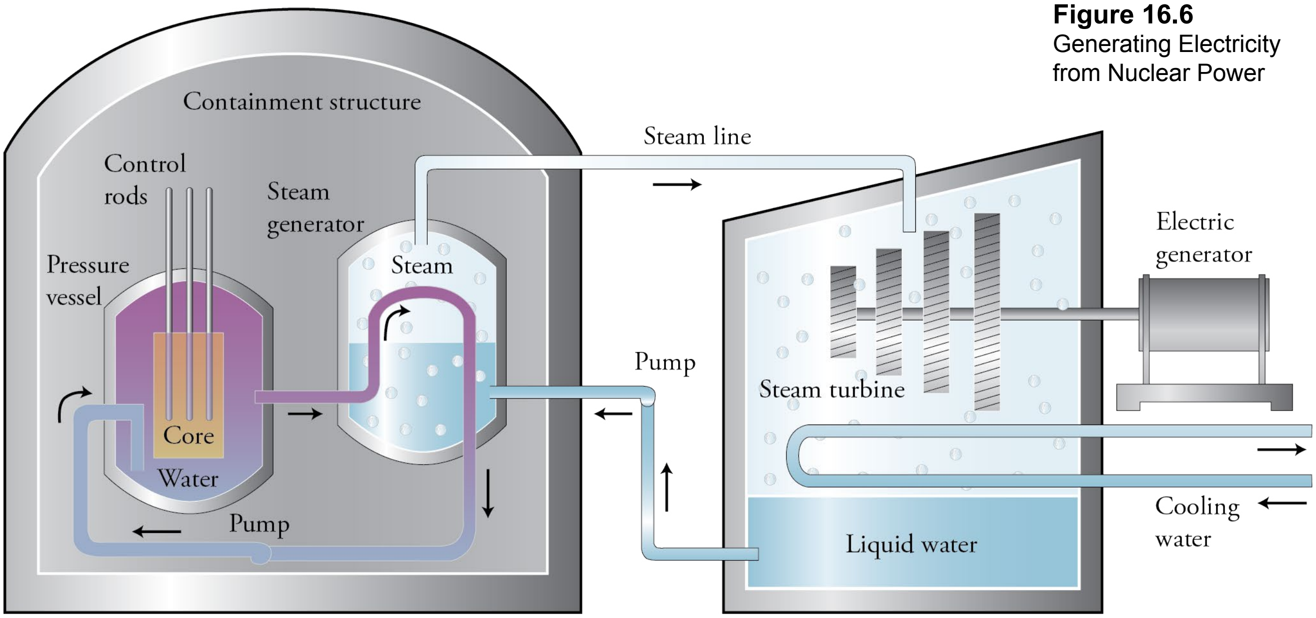


Figure 16.6
Generating Electricity from Nuclear Power

Nuclear power is a major source of energy for electrical generation worldwide. In March 2012, nuclear power plants were found in 30 countries and generated about 13% of the world's electricity. France got about 77% of its electricity from nuclear power, and the United States got about 19%. Special Topic 16.1: *A New Treatment for Brain Cancer* describes another use for a fission reaction.

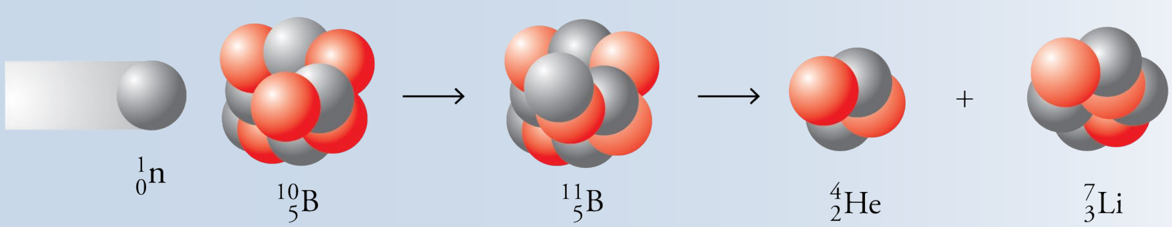
Special Topic 16.1 A New Treatment for Brain Cancer

A promising new experimental treatment for brain tumors makes use of the fission reaction of boron-10, an isotope representing 19.9% of natural boron. The patient is given a boron-containing compound that is selectively absorbed by the tumor cells, after which a low-energy neutron beam from a nuclear reactor or linear accelerator is directed toward the tumor. Most of the neutrons pass through normal cells without affecting them, but when they strike a boron-10 atom in a tumor cell, the atom absorbs the neutron to form an unstable boron-11 atom, which then splits in two to form a helium-4 atom and a lithium-7 atom. These products rush away from each other at a very high velocity, doing serious damage to the tumor cell as they go.

$$^{1}_{0}n + ^{10}_{5}B \rightarrow ^{11}_{5}B \rightarrow ^{4}_{2}He + ^{7}_{3}Li + \text{energy}$$

The diameter of a tumor cell is about 10 μm, and the helium and lithium atoms lose the energy derived from their creation in about 5 μm to 8 μm. Therefore, the product atoms do most of their damage to the cell in which they were produced. If the normal cells do not absorb a significant amount of the boron-containing compound, they do not incur a significant amount of damage. The chemist's primary role in the development of this treatment is to design boron-containing compounds that deliver more boron to tumor cells and as little as possible to normal ones.

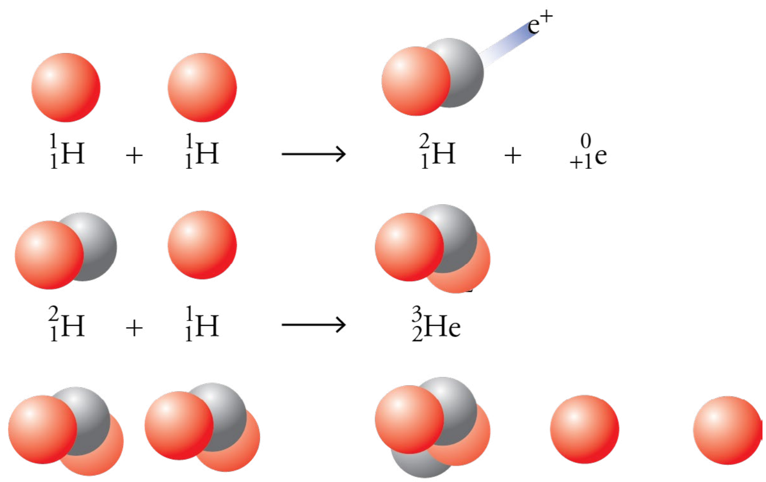
This treatment is still experimental, but the clinical trials that have been done in several places in the world seem promising for the treatment of glioma, a form of brain cancer that has low survival rates. Tests are also being done to see if this treatment could be used for other cancers, such as oral cancer and thyroid cancer, and for other medical problems, such as rheumatoid arthritis.



Nuclear Fusion and the Sun

Objective 45

Whereas nuclear fission reactions yield energy by splitting large nuclei to form medium-sized ones, nuclear fusion reactions release energy by combining small nuclei into larger and more stable species. For example, the sun releases energy at a rate of about 3.8×10^{26} J/s from the fusion of hydrogen nuclei to form helium. This is equivalent to burning 3×10^{18} gallons of gasoline per second. The change takes place in three steps:



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

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

$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

It seems fitting that the end of this text should take us back to the creation of the elements, which is the very beginning of chemistry. Special Topic 16.2: *The Origin of the Elements* describes how scientists believe the chemical elements were made. You will see that fusion played a major role in this process.

Special Topic 16.2 The Origin of the Elements

Scientists believe that nuclear fusion played an important role in the creation of the chemical elements. To get a rough idea of what they think occurred, we have to begin with the beginning of the universe.

The standard model for the origin of the universe suggests that it all started about 15 billion years ago with a tremendous explosion called the Big Bang. About one second after the Big Bang, the universe is thought to have consisted of an expanding sea of light and elementary particles, including electrons, protons, and neutrons. The model describes three ways in which different elements formed.

The first of these processes took place in the first minutes following the Big Bang. The expanding cloud cooled enough for hydrogen atoms to form and for a series of nuclear reactions to occur. In each of these reactions, very high-velocity particles collided and fused to produce a new and larger nucleus:

$$^{1}_{1}H + ^{1}_{0}n \rightarrow ^{2}_{1}H + \text{energy}$$

$$^{2}_{1}H + ^{1}_{0}n \rightarrow ^{3}_{1}H + \text{energy}$$

$$^{3}_{1}H + ^{1}_{1}H \rightarrow ^{4}_{2}He + \text{energy}$$

$$^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \text{energy}$$

$$^{3}_{2}He + ^{1}_{0}n \rightarrow ^{4}_{2}He + \text{energy}$$

$$^{3}_{2}He + ^{4}_{2}He \rightarrow ^{7}_{4}Be + \text{energy}$$

$$^{7}_{4}Be + ^{0}_{-1}e \rightarrow ^{7}_{3}Li + \text{energy}$$

After this first phase of element synthesis, the universe consisted mostly of hydrogen and helium with extremely small amounts of lithium and beryllium. Even today about 90% of the atoms and 75% of the mass of the universe is hydrogen, and most of the rest is helium.

By chance, the material of the expanding universe was unevenly distributed. In the regions of higher concentrations of matter, gravity pulled the particles even closer together, and stars began to form. As the cosmic dust was compressed, the material in the core of the forming stars began to heat up, providing the energy for hydrogen atoms to fuse and form helium atoms. In the extremely high temperatures of a star's core, colliding atoms attain enough speed to overcome the repulsion between their positive nuclei and approach each other closely enough for the nuclear attraction to fuse the nuclei together. This is the second way elements have formed: by fusion reactions occurring in the cores of stars. Because the heat released in the fusion reactions would normally cause the gases to expand, it counteracts the gravitational force that would otherwise cause the star to collapse. When the two forces balance, the star finds a stable size.

Eventually much of the hydrogen in the core of a young star is converted into helium, so that the star chiefly consists of a helium core and a hydrogen outer shell. The ultimate fate of a star depends on its size. If the star is relatively small, it will simply burn out when the hydrogen in the core is depleted, and it will become a white dwarf star. The situation is different for a very large star. When there is no longer enough hydrogen to convert to helium and supply the heat that keeps the star from imploding, the star begins to collapse, becoming what astronomers call a "red giant." The increased velocity of the particles as they rush toward the center of the star means an increase in the temperature of the gases. This change supplies the heat necessary for a new set of fusion reactions to occur that form carbon and oxygen. If the star is large enough and if its fusion reactions produce enough energy, other elements (up to the size of iron) are also formed.

A star whose mass is over ten times the mass of our sun can reach a stage where the reactions in its core cannot overcome gravity. At that point, the star collapses very rapidly, heating to tremendous temperatures as a result, and then explodes as a supernova. During the explosion—which can take place in a matter of seconds—elements larger than iron are thought to be formed very rapidly. The explosion also launches these atoms far out into space.

In the last of the three ways that elements are thought to have been formed, high-energy hydrogen or helium atoms participate in fusion reactions with gas and dust in the space between stars.

Because the heavier elements are formed in localized areas of the universe, the distribution of these elements is uneven. The elemental composition of the earth, for example, is very different from most of the rest of the universe. Table 16.5 lists the percent abundance of elements in the earth's crust, waters, and atmosphere. Note that eleven elements make up over 99% of the planet's mass. Some elements that play major roles in our culture and technology—such as copper, tin, zinc and gold—are actually very rare.

Table 16.5
Percent Abundance of the Elements in the Earth's Crust, Waters, and Atmosphere

Element	% Abundance	Element	% Abundance
Oxygen	49.20	Chlorine	0.19
Silicon	25.70	Phosphorus	0.11
Aluminum	7.50	Manganese	0.09
Iron	4.71	Carbon	0.08
Calcium	3.39	Sulfur	0.06
Sodium	2.63	Barium	0.04
Potassium	2.40	Nitrogen	0.03
Magnesium	1.93	Fluorine	0.03
Hydrogen	0.87	All others	0.49
Titanium	0.58		

Chapter Glossary

Nuclear chemistry The study of the properties and behavior of atomic nuclei.

Nucleons The particles that reside in the nucleus of atoms (protons and neutrons).

Nucleon number The sum of the numbers of protons and neutrons (nucleons) in the nucleus of an atom. It is also called the mass number.

Nuclide A particular type of nucleus that is characterized by a specific atomic number (Z) and nucleon number (A).

Electrostatic force (or **electromagnetic force**) The force between electrically charged particles.

Strong force The force that draws nucleons (protons and neutrons) together.

Band of stability On a graph of the numbers of neutrons versus protons in the nuclei of atoms, the portion that represents stable nuclides.

Radioactive nuclide An unstable nuclide whose numbers of protons and neutrons place it outside the band of stability.

Radioactive decay One of several processes that transform a radioactive nuclide into a more stable product or products.

Alpha particle The emission from radioactive nuclides that is composed of two protons and two neutrons in the form of a helium nucleus.

Alpha emission The process of releasing an alpha particle by atoms that have too many protons to be stable.

Beta emission The conversion of a neutron to a proton, which stays in the nucleus, and an electron, called a beta particle in this context, which is ejected from the atom.

Beta particle A high-velocity electron released from radioactive nuclides that have too many neutrons.

Positron emission In radioactive nuclides that have too few neutrons, the conversion of a proton to a neutron, which stays in the nucleus, and a positron, which is ejected from the nucleus.

Positron A high-velocity anti-electron released from radioactive nuclides that have too few neutrons.

Electron capture In radioactive nuclides that have too few neutrons, the combination of an electron with a proton to form a neutron, which stays in the nucleus.

Gamma ray A stream of high-energy photons.

Nuclear reaction A process that results in a change in an atomic nucleus (as opposed to a chemical reaction, which involves the loss, gain, or sharing of electrons).

Nuclear equation The shorthand notation that describes nuclear reactions. It shows changes in the participating nuclides' atomic numbers (the number of protons) and mass numbers (the sum of the numbers of protons and neutrons).

Half-life The time it takes for one-half of a sample to disappear.

Nuclear decay series A series of radioactive decays that lead from a large unstable nuclide, such as uranium-238, to a stable nuclide, such as lead-206.

Ionizing radiation Alpha particles, beta particles, and gamma photons, which are all able to strip electrons from atoms as they move through matter, leaving ions in their wake.

Free radicals Particles with unpaired electrons.

Radiocarbon (or carbon-14) dating The process of determining the age of an artifact that contains material from formerly living plants or animals by comparing the ratio of carbon-14 to carbon-12 in the object to the ratio thought to have been in living organisms when the object was originally produced.

Radioactive tracer A radioactive nuclide that is incorporated into substances that can then be tracked through detection of the nuclide's emissions.

Binding energy The amount of energy released when a nucleus is formed.

Electron volt An energy unit equivalent to 1.6×10^{-19} joules. It is often used to describe the energy associated with nuclear changes.

Fusion Nuclear reaction that yields energy by combining smaller atoms to make larger, more stable ones.

Fission Nuclear reaction that yields energy by splitting larger atoms to form more stable, smaller atoms.

Chain reaction A process in which one of the products of a reaction initiates another identical reaction.

Moderator A substance in a nuclear reactor that slows neutrons as they pass through it.

Control rods Rods containing substances such as cadmium or boron (which are efficient neutron absorbers), used to regulate the rate of nuclear fission in a power plant and to stop the fission process if necessary.

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

Chapter Objectives

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

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

Section 16.1 The Nucleus and Radioactivity

2. Given a symbol for a nuclide, identify its atomic number and mass number (nucleon number).
3. Given a symbol for a nuclide, identify the numbers of protons and neutrons that its nucleus contains, or given the numbers of protons and neutrons that its nucleus contains, write its symbol.
4. Given one of the following ways to describe nuclides, write the other two:

   (element name)-(mass number)

   $^{\text{mass number}}_{\text{atomic number}}$(element symbol)

   $^{\text{mass number}}$(element symbol)

   For example, one of the nuclides of uranium can be described as uranium-238, $^{238}_{92}U$, or ^{238}U.
5. Describe the two opposing forces between particles in the nucleus, and with reference to these forces, explain why the optimum ratio of neutrons to protons (for the stability of the nuclide) increases with increasing atomic number.
6. Write descriptions of alpha emission, beta emission, positron emission, and electron capture.
7. Write the symbols used for alpha particles, beta particles, positrons, and gamma photons.

8. Given the symbols for three nuclides of the same element—one that is stable and non-radioactive, one that is radioactive and has a lower mass number than the stable nuclide, and one that is radioactive and has a higher mass number than the stable nuclide—predict which of the radioactive nuclides would be more likely to undergo beta emission and which would be more likely to undergo positron emission (or electron capture).
9. Explain why gamma rays often accompany alpha emission, beta emission, positron emission, and electron capture.
10. Describe the differences between nuclear reactions and chemical reactions.
11. Describe the difference between nuclear equations and chemical equations.
12. Given a description of a radioactive nuclide and whether it undergoes alpha emission, beta emission, positron emission, or electron capture, write a nuclear equation for the reaction.
13. Given an incomplete nuclear equation, write the symbol for the missing component.
14. Given the half-life for a radioactive nuclide, predict how long before a sample decreases to $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$, or $\frac{1}{32}$ of its original amount.
15. Given the half-life for a radioactive nuclide, predict the fraction that will remain of the initial amount after 1, 2, 3, 4, or 5 half-lives.
16. Explain why short-lived radioactive nuclides are found in nature.
17. Describe the source of radium-226 and radon-222 found in nature, and describe the problems that these nuclides cause.
18. Explain why radon-222 is considered an indirect rather than a direct cause of cancer.
19. Explain why alpha particles, beta particles, and gamma photons are all considered ionizing radiation.
20. Describe how alpha particles, beta particles, and gamma photons interact with water to form ions and free radicals, and explain why these products can do damage to the body.
21. Describe the types of tissues that are most sensitive to damage from radioactive emission, and explain why radiation treatments do more damage to cancer cells than to regular cells and why children are more affected by radiation than adults are.
22. Explain how strontium-90 atoms can cause bone cancer or leukemia, how cesium-137 atoms can cause tissue damage, and how iodine-131 can damage thyroid glands.
23. Describe the relative penetrating ability of alpha particles, beta particles, and gamma photons, and use this description to explain why gamma photons emitted outside the body can do damage to internal organs but alpha and beta emitters must be ingested to do damage.
24. Explain why alpha particles from a source inside the body do more damage to tissues than the same number of gamma photons.

Section 16.2 Uses of Radioactive Substances

25. Describe how cobalt-60 is used to treat cancer.
26. Explain how MRI produces images of the soft tissues of the body.

27. Explain how PET scans can show dynamic processes in the body, such as brain activity and blood flow.
28. Explain how fluorine-18 is used to study bones and how carbon-11 is used to study brain activity.
29. Describe how carbon-14 (radiocarbon) dating of artifacts is done.
30. Explain how smoke detectors containing americium-241 work.
31. Describe how iridium-192 can be used to find leaks in welded pipe joints.
32. Describe the pros and cons of food irradiation.
33. Explain how scientists use radioactive tracers.

Section 16.3 Nuclear Energy

34. Explain how the binding energy of a nucleus reflects its stability.
35. Explain how the binding energy per nucleon for a nuclide can be used to compare its stability to that of other nuclides.
36. Describe the general trend in the variation in binding energy per nucleon for the natural nuclides, and use it to explain how energy is released in both nuclear fusion and nuclear fission.
37. Explain why ${}^{4}_{2}He$, ${}^{12}_{6}C$, ${}^{16}_{8}O$, and ${}^{20}_{10}Ne$ are especially stable.
38. Explain why ${}^{40}_{20}Ca$ and ${}^{208}_{82}Pb$ are especially stable.
39. Describe the fission reaction of uranium-235, and explain how it can lead to a chain reaction.
40. Describe how heat is generated in a nuclear power plant.
41. Explain why uranium must be enriched in uranium-235 before it can be used as fuel in a typical nuclear reactor.
42. Describe the role of the moderator in a nuclear reactor.
43. Describe the problems associated with the production of plutonium-239 in nuclear reactors.
44. Describe the role of the control rods in a nuclear reactor.
45. Describe how energy is generated in the sun.

Review Questions

1. Describe the nuclear model of the atom, including the general location of the protons, neutrons, and electrons, the relative size of the nucleus compared to the size of the atom, and the modern description of the electron.
2. With reference to both their particle and their wave nature, describe the similarities and differences between gamma radiation and radio waves. Which has higher energy?

Complete the following statements by writing the word or phrase in each blank that best completes the thought.

3. Atoms that have the same number of protons but different numbers of neutrons are called ______________. They have the same atomic number but different mass numbers.
4. The ______________ for an atom is equal to the number of protons in an atom's nucleus. It establishes the element's identity.
5. The ______________ for an atom is equal to the sum of the numbers of protons and neutrons in an atom's nucleus.
6. ______________ is the capacity to do work.

7. ______________ is the capacity to do work due to the motion of an object.
8. The ______________ states that energy can neither be created nor destroyed, but it can be transferred from one system to another and changed from one form to another.
9. ______________ is a retrievable, stored form of energy an object possesses by virtue of its position or state.
10. The more stable a system is, the ______________ (higher or lower) its potential energy.
11. When a system shifts from a less stable to a more stable state, energy is ______________ (absorbed or released).
12. The ______________ of an atom is the condition in which its electrons are in the orbitals that give it the lowest possible potential energy.
13. The ______________ of an atom is the condition in which one or more of its electrons are in orbitals that do not represent the lowest possible potential energy.

Key Ideas

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

35	neutrons
83 protons	nitrogen
100	nucleus
200	one-half
10,000	one lower
A	photons
alpha	protons
attractions	pull
binding energy per nucleon	pushed
$^{14}C/^{12}C$ ratio	rapidly reproducing
charge	ratio
different	released
double magic numbers	releases
electrostatic	repulsion
energy	skin
excite	smaller than
furnace	strong
glue	too high
identical	too low
internal organs	unaffected
ionizing	Z
larger than	

14. Because ______________ and ______________ reside in the nucleus of atoms, they are called nucleons.
15. The symbols used for nucleons have the atomic number (______________) as a subscript in front of the element symbol and the nucleon number (______________) as a superscript above the atomic number.

16. There are two forces among the particles within the nucleus. The first, called the ____________ force, is the force between electrically charged particles. The second force, called the ____________ force, holds nucleons (protons and neutrons) together.
17. You can think of neutrons as the nuclear ____________ that allows protons to stay together in the nucleus. Adding neutrons to a nucleus leads to more ____________ holding the particles of the nucleus together without causing increased ____________ between those particles.
18. Larger atoms with more protons in their nuclei require a greater ____________ of neutrons to protons to balance the increased repulsion between protons.
19. If a nucleus contains more than ____________, the nucleus cannot be made completely stable no matter how many neutrons are added.
20. One of the ways that heavy nuclides change to move back into the band of stability is to release two protons and two neutrons in the form of a helium nucleus, called a(n) ____________ particle.
21. When a radioactive nuclide has a neutron-to-proton ratio that is ____________, it undergoes beta emission (β^-). In this process, a neutron becomes a proton and an electron. The proton stays in the nucleus, and the electron, which is called a beta particle in this context, is ejected from the atom.
22. When a radioactive nuclide has a neutron-to-proton ratio that is ____________, it can move toward stability in one of two ways, positron emission or electron capture. In positron emission (β^+), a proton becomes a neutron and a positron. The neutron stays in the nucleus, and the positron speeds out of the nucleus at high velocity.
23. In electron capture, an electron combines with the proton to form a neutron. Like positron emission, electron capture causes the radioactive nuclide to change to a new element with an atomic number that is ____________ but with the same mass number.
24. Because radioactive decay leads to more stable products, it always ____________ energy, some in the form of kinetic energy of the moving product particles, and some in the form of gamma rays. Gamma rays can be viewed as a stream of high-energy ____________.
25. Nuclear reactions involve changes in the ____________, whereas chemical reactions involve the loss, gain, and sharing of electrons.
26. Different isotopes of the same element, which share the same chemical characteristics, often undergo very ____________ nuclear reactions.
27. Unlike chemical reactions, the rates of nuclear reactions are ____________ by temperature, pressure, and the other atoms to which the radioactive atom is bonded.
28. Nuclear reactions, in general, give off a lot more ____________ than chemical reactions.
29. The equations that describe nuclear reactions are different than those that describe chemical reactions because in nuclear equations ____________ is disregarded.
30. Rates of radioactive decay are described in terms of half-life, the time it takes for ____________ of a sample to disappear.

31. Alpha particles, beta particles, and gamma photons are often called ______________ radiation, because they are all able to strip electrons from atoms as they move through matter, leaving ions in their wake.
32. As alpha particles, which move at up to 10% the speed of light, move through the tissues of our bodies, they ______________ electrons away from the tissue's atoms.
33. The repulsion between negatively-charged beta particles and the electrons on atoms and molecules of our tissues leads to electrons being ______________ off the uncharged particles.
34. Gamma photons are ionizing radiation, because they can ______________ electrons enough to actually remove them from atoms.
35. Alpha particles that strike the outside of the body are stopped by the top layer of ______________.
36. Because beta particles are smaller than alpha particles, and because they can move up to 90% the speed of light, they are about ______________ times as penetrating as alpha particles.
37. Gamma photons are much more penetrating than alpha and beta particles, so gamma radiation from outside the body can do damage to ______________.
38. Gamma photons that penetrate the body do more damage to ______________ cells than to others.
39. Carbon-14 atoms are constantly being produced in our upper atmosphere through neutron bombardment of ______________ atoms.
40. To date an artifact, a portion of it is analyzed to determine the ______________, which can be used to determine its age.
41. Because the amount of energy ______________ when a nucleus is formed is a reflection of the strength with which nucleons are bound, it is called the atom's binding energy.
42. It takes about ______________ times as much energy to remove a proton or a neutron from the nucleus of a hydrogen-2 atom as to remove its one electron.
43. A higher ______________ reflects more stable and more tightly bound nucleons in their nucleus.
44. There appears to be something stable about having 2, 8, 20, 28, 50, 82, or 126 protons or neutrons. The nuclides with ______________ have very high stability.
45. For atoms ______________ iron-56, energy is released when smaller atoms combine to form larger ones.
46. For atoms ______________ iron-56, splitting larger atoms to form more stable, smaller atoms releases energy.
47. The fission reactions of uranium-235 yield more than ______________ different nuclides of ______________ different elements.
48. The nuclear reactor in a nuclear power plant is really just a big ______________ that generates heat to convert liquid water to steam that turns a steam turbine generator to produce electricity.
49. A chain reaction is a process in which one of the products of the reaction initiates another ______________ reaction.

Chapter Problems

Section 16.1 The Nucleus and Radioactivity

50. A radioactive nuclide that has an atomic number of 88 and a mass (nucleon) number of 226 is used in radiation therapy. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to represent this nuclide. OBJECTIVE 4

51. A radioactive nuclide that has an atomic number of 54 and a mass (nucleon) number of 133 is used to determine lung capacity. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to represent this nuclide. OBJECTIVE 3 OBJECTIVE 4

52. A radioactive nuclide that has six protons and five neutrons is used to generate positron emission tomography (PET) brain scans. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to represent this nuclide. OBJECTIVE 3 OBJECTIVE 4

53. A radioactive nuclide that has 29 protons and 35 neutrons is used to diagnose liver disease. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to represent this nuclide. OBJECTIVE 3 OBJECTIVE 4

54. A radioactive nuclide with the symbol ${}^{40}_{19}K$ is used for geologic dating. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 4

55. A radioactive nuclide with the symbol ${}^{198}_{79}Au$ is used in the measurement of kidney activity. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 4

56. A radioactive nuclide with the symbol ${}^{111}_{49}In$ is used to label blood platelets. How many protons and how many neutrons does each atom have? Write two other ways to represent this nuclide. OBJECTIVE 3 OBJECTIVE 4

57. A radioactive nuclide with the symbol ${}^{18}_{9}F$ is used in bone scans. How many protons and how many neutrons does each atom have? Write two other ways to represent this nuclide. OBJECTIVE 3 OBJECTIVE 4

58. Barium-131 is used to detect bone tumors. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 3 OBJECTIVE 4

59. Polonium-210 is used in radiation therapy. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 3 OBJECTIVE 4

60. The radioactive nuclide with the symbol ${}^{75}Se$ is used to measure the shape of the pancreas. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 3 OBJECTIVE 4

61. The radioactive nuclide with the symbol ${}^{125}I$ is used to measure blood hormone levels. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide. OBJECTIVE 2 OBJECTIVE 3 OBJECTIVE 4

62. Describe the two opposing forces between particles in the nucleus, and with reference to these forces, explain why the ratio of neutrons to protons required for a stable nuclide increases as the number of protons in a nucleus increases. OBJECTIVE 5

63. Explain why the ${}^{2}_{2}He$ nuclide does not exist.

Objective 6
Objective 7

64. Write a general description of the changes that take place in alpha emission. Write the two symbols used for an alpha particle. Write the general equation for alpha emission, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number.

Objective 6
Objective 7

65. Write a general description of the changes that take place in beta emission. Write the three symbols used for a beta particle. Write the general equation for beta emission, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number.

Objective 6
Objective 7

66. Write a general description of the changes that take place in positron emission. Write the three symbols used for a positron. Write the general equation for positron emission, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number.

Objective 6
Objective 7

67. Write a general description of the changes that take place in electron capture. Write the general equation for electron capture, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number.

Objective 8

68. Consider three isotopes of bismuth: ${}^{202}_{83}Bi$, ${}^{209}_{83}Bi$, and ${}^{215}_{83}Bi$. Bismuth-209 is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes electron capture. Identify the isotope that makes each of these changes, and explain your choices.

Objective 8

69. Consider three isotopes of nitrogen: ${}^{13}_{7}N$, ${}^{14}_{7}N$, and ${}^{16}_{7}N$. Nitrogen-14 is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes positron emission. Identify the isotope that makes each of these changes, and explain your choices.

Objective 9

70. Explain why gamma rays often accompany alpha emission, beta emission, positron emission, and electron capture.

Objective 6

71. What nuclear process or processes lead to each of the results listed below? The possibilities are alpha emission, beta emission, positron emission, electron capture, and gamma emission.

a. Atomic number increases by 1.
b. Mass number decreases by 4
c. No change in atomic number or mass number.
d. The number of protons decreases by 1.
e. The number of neutrons decreases by 1.
f. The number of protons decreases by 2.

Objective 6

72. What nuclear process or processes lead to each of the results listed below? The possibilities are alpha emission, beta emission, positron emission, electron capture, and gamma emission.

a. The number of neutrons increases by 1.
b. Atomic number decreases by 2.
c. The number of neutrons decreases by 2.
d. Atomic number decreases by 1.
e. The number of protons increases by 1.
f. No change in the number of protons and neutrons.

Objective 10

73. Describe the differences between nuclear reactions and chemical reactions.

74. Explain why ${}^{38}_{17}Cl$ and ${}^{38}_{17}Cl^{-}$ are very different chemically and why they each undergo identical nuclear reactions.

75. Describe the difference between nuclear equations and chemical equations. OBJECTIVE 11

76. Marie Curie won the Nobel Prize for physics in 1903 for her study of radioactive nuclides, including polonium-218 (which was named after her native country, Poland). Polonium-218 undergoes alpha emission. Write the nuclear equation for this change. OBJECTIVE 12

77. Americium-243 is an alpha emitter used in smoke detectors. Write the nuclear equation for its alpha emission. OBJECTIVE 12

78. Cobalt-60, which is the most common nuclide used in radiation therapy for cancer, undergoes beta emission. Write the nuclear equation for this reaction. OBJECTIVE 12

79. Radioactive iron-59, which is used to assess blood iron changes, shifts toward stability by emitting beta particles. Write the nuclear equation for this reaction. OBJECTIVE 12

80. Carbon-11 is used in PET brain scans because it emits positrons. Write the nuclear equation for the positron emission of carbon-11. OBJECTIVE 12

81. Oxygen-13 atoms undergo positron emission, so they can be used to generate PET scans. Write the nuclear equation for this reaction. OBJECTIVE 12

82. Mercury-197 was used in the past for brain scans. Its decay can be detected, because this nuclide undergoes electron capture, which forms an excited atom that then releases a gamma photon that escapes the body and strikes a detector. Write the nuclear equation for the electron capture by mercury-197. OBJECTIVE 12

83. Your cardiovascular system can be assessed using krypton-79, which shifts to a more stable nuclide by electron capture. Write an equation that describes this change. OBJECTIVE 12

84. Complete the following nuclear equations. OBJECTIVE 13

a. ${}^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + \_\_\_\_$

b. ${}^{17}_{9}\mathrm{F} \rightarrow {}^{17}_{8}\mathrm{O} + \_\_\_\_$

c. ${}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + \_\_\_\_$

d. ${}^{18}_{9}\mathrm{F} + \_\_\_\_ \rightarrow {}^{18}_{8}\mathrm{O}$

e. ${}^{235}_{92}\mathrm{U} \rightarrow \_\_\_\_ + {}^{4}_{2}\mathrm{He}$

f. ${}^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\mathrm{e} \rightarrow \_\_\_\_$

g. ${}^{52}_{26}\mathrm{Fe} \rightarrow \_\_\_\_ + {}^{0}_{+1}\mathrm{e}$

h. ${}^{3}_{1}\mathrm{H} \rightarrow \_\_\_\_ + {}^{0}_{-1}\mathrm{e}$

i. $\_\_\_\_ \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$

j. $\_\_\_\_ \rightarrow {}^{118}_{53}\mathrm{I} + {}^{0}_{+1}\mathrm{e}$

k. $\_\_\_\_ + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{204}_{83}\mathrm{Bi}$

l. $\_\_\_\_ \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

OBJECTIVE 13

85. Complete the following nuclear equations.

a. $\_\_\_\_\_ \rightarrow {}^{18}_{8}O + {}^{0}_{+1}e$

b. ${}^{26}_{13}Al \rightarrow {}^{26}_{14}Si + \_\_\_\_\_$

c. $\_\_\_\_\_ + {}^{0}_{-1}e \rightarrow {}^{58}_{26}Fe$

d. ${}^{242}_{96}Cm \rightarrow {}^{238}_{94}Pu + \_\_\_\_\_$

e. $\_\_\_\_\_ \rightarrow {}^{210}_{88}Ra + {}^{4}_{2}He$

f. ${}^{210}_{84}Po \rightarrow \_\_\_\_\_ + {}^{4}_{2}He$

g. ${}^{30}_{15}P \rightarrow \_\_\_\_\_ + {}^{0}_{+1}e$

h. ${}^{104}_{43}Tc \rightarrow {}^{104}_{44}Ru + \_\_\_\_\_$

i. ${}^{44}_{22}Ti + {}^{0}_{-1}e \rightarrow \_\_\_\_\_$

j. ${}^{137}_{55}Cs \rightarrow \_\_\_\_\_ + {}^{0}_{-1}e$

k. $\_\_\_\_\_ \rightarrow {}^{32}_{16}S + {}^{0}_{-1}e$

l. ${}^{64}_{29}Cu + \_\_\_\_\_ \rightarrow {}^{64}_{28}Ni$

86. Silver-117 atoms undergo three beta emissions before they reach a stable nuclide. What is the final product?

87. Molybdenum-105 atoms undergo four beta emissions before they reach a stable nuclide. What is the final product?

88. Tellurium-116 atoms undergo two electron captures before they reach a stable nuclide. What is the final product?

89. Cesium-127 atoms undergo two electron captures before they reach a stable nuclide. What is the final product?

90. Samarium-142 atoms undergo two positron emissions before they reach a stable nuclide. What is the final product?

91. Indium-107 atoms undergo a positron emission and an electron capture before they reach a stable nuclide. What is the final product?

92. Bismuth-211 atoms undergo an alpha emission and beta emission before they reach a stable nuclide. What is the final product?

93. Polonium-214 atoms undergo an alpha emission, two beta emissions, and another alpha emission before they reach a stable nuclide. What is the final product?

OBJECTIVE 13

94. Complete the following nuclear equations describing the changes that led to the formation of previously undiscovered nuclides.

a. ${}^{246}_{96}Cm + {}^{12}_{6}C \rightarrow \_\_\_\_\_ + 6{}^{1}_{0}n$

b. $\_\_\_\_\_ + {}^{16}_{8}O \rightarrow {}^{263}_{106}Sg + 2{}^{1}_{0}n$

c. ${}^{240}_{95}Am + {}^{4}_{2}He \rightarrow {}^{243}_{97}Bk + \_\_\_\_\_$

d. ${}^{252}_{98}Cf + \_\_\_\_\_ \rightarrow {}^{257}_{103}Lr + 5{}^{1}_{0}n$

OBJECTIVE 13

95. Complete the following nuclear equations describing the changes that led to the formation of previously undiscovered nuclides.

a. ${}^{238}_{92}U + {}^{12}_{6}C \rightarrow \_\_\_\_\_ + 6{}^{1}_{0}n$

b. $\_\_\_\_\_ + {}^{16}_{8}O \rightarrow {}^{252}_{102}No + 5{}^{1}_{0}n$

c. ${}^{253}_{99}Es + {}^{4}_{2}He \rightarrow {}^{256}_{102}Md + \_\_\_\_\_$

d. ${}^{246}_{96}Cm + \_\_\_\_\_ \rightarrow {}^{254}_{102}No + 5{}^{1}_{0}n$

96. In February 1981, the first atoms of the element Bohrium-262, $^{262}_{107}Bh$, were made from the bombardment of bismuth-209 atoms by chromium-54 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.) Objective 13

97. In December 1994, the nuclide roentgenium-272, $^{272}_{111}Rg$, was made from the bombardment of bismuth-209 atoms with nickel-64 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.)

98. Cesium-133, which is used in radiation therapy, has a half-life of 30 years. How long before a sample decreases to $\frac{1}{4}$ of what was originally there? Objective 14

99. Gold-198, which is used to assess kidney function, has a half-life of 2.70 days. How long before a sample decreases to $\frac{1}{16}$ of what was originally there? Objective 14

100. Phosphorus-32, which is used for leukemia therapy, has a half-life of 14.3 days. What fraction of a sample is left in 42.9 days? Objective 15

101. Cobalt-60, which is used in radiation therapy, has a half-life of 5.26 years. What fraction of a sample is left in 26.3 years? Objective 15

102. Explain why short-lived radioactive nuclides are found in nature. Objective 16

103. Describe the source of radium-226 and radon-222 found in nature. What problems do these nuclides cause? Objective 17

104. Explain why radon-222 is considered an indirect rather than a direct cause of cancer. Objective 18

105. The first six steps of the decay series for uranium-235 consist of the changes alpha emission, beta emission, alpha emission, beta emission, alpha emission, and alpha emission. Write the products formed after each of these six steps.

106. The last five steps of the decay series for uranium-235 consist of alpha emission from $^{219}_{86}Rn$ followed by alpha emission, beta emission, beta emission, and alpha emission. Write the products formed after each of these steps.

107. In the first five steps of the decay series for thorium-232, the products are $^{228}_{88}Ra$, $^{228}_{89}Ac$, $^{228}_{90}Th$, $^{224}_{88}Ra$, and $^{220}_{86}Rn$. Identify each of these steps as alpha emissions or beta emissions.

108. The last five steps of the decay series for thorium-232 start with $^{220}_{86}Rn$, and the products are $^{216}_{84}Po$, $^{212}_{82}Pb$, $^{212}_{83}Bi$, $^{212}_{84}Po$, and $^{208}_{82}Pb$. Identify each of these steps as alpha emissions or beta emissions.

109. Explain why alpha particles are considered ionizing radiation. Objective 19

110. Explain why beta particles are considered ionizing radiation. Objective 19

111. Explain why gamma photons are considered ionizing radiation. Objective 19

112. Describe how alpha particles, beta particles, and gamma photons interact with water to form ions and free radicals, and explain why these products can do damage to the body. Objective 20

113. What types of tissues are most sensitive to emission from radioactive nuclides? Why do radiation treatments do more damage to cancer cells than to regular cells? Why are children more affected by radiation than adults are? Objective 21

114. Explain how strontium-90 atoms can cause bone cancer or leukemia, how cesium-137 atoms can cause tissue damage, and how iodine-131 can damage thyroid glands. Objective 22

115. Why do you think radium-226 concentrates in our bones?

Objective 23
116. Describe the relative penetrating ability of alpha particles, beta particles, and gamma photons, and use this description to explain why gamma photons emitted outside the body can do damage to internal organs but alpha and beta emitters must be inside the body to do damage.

Objective 24
117. Why are alpha particles more damaging to tissues when the source is ingested than the same number of gamma photons would be?

Section 16.2: Uses of Radioactive Substances

Objective 25
118. Describe how cobalt-60 is used to treat cancer.

Objective 26
119. Explain how MRI produces images of the soft tissues of the body.

Objective 27
120. Explain how PET can show dynamic processes in the body, such as brain activity and blood flow.

Objective 28
121. Explain how fluorine-18 is used to study bones and how carbon-11 is used to study brain activity.

Objective 29
122. Describe how carbon-14 (radiocarbon) dating of artifacts is done.

Objective 30
123. Explain how smoke detectors containing americium-241 work.

Objective 31
124. Describe how iridium-192 can be used to find leaks in welded pipe joints.

Objective 32
125. Describe the pros and cons of food irradiation.

Objective 33
126. Explain how scientists use radioactive tracers.

Section 16.3: Nuclear Energy

Objective 34
127. Explain how the binding energy of a nucleus reflects its stability.

Objective 35
128. Explain how the binding energy per nucleon can be used to compare the stability of nuclides.

Objective 36
129. Describe the general trend in binding energy per nucleon for the natural nuclides, and use it to explain how energy is released in both nuclear fusion and nuclear fission.

Objective 37
130. Explain why ${}^{4}_{2}He$, ${}^{12}_{6}C$, ${}^{16}_{8}O$, and ${}^{20}_{10}Ne$ are especially stable.

Objective 38
131. Explain why ${}^{40}_{20}Ca$ and ${}^{208}_{82}Pb$ are especially stable.

132. Give two reasons why ${}^{16}_{8}O$ is more stable than ${}^{15}_{8}O$.

Objective 39
133. Describe the fission reaction of uranium-235, and explain how it can lead to a chain reaction.

Objective 40
134. Describe how heat is generated in a nuclear power plant.

Objective 41
135. Explain why uranium must be enriched in uranium-235 before it can be used as fuel in a typical nuclear reactor.

Objective 42
136. Describe the role of the moderator in a nuclear reactor.

Objective 43
137. Describe the problems associated with the production of plutonium-239 in nuclear reactors.

138. The reason that nuclear wastes must be isolated from the environment for a very long time is that they contain relatively long-lived radioactive nuclides, such as technetium-99 with a half-life of over 2.1×10^5 years. One proposed solution is to bombard the waste with neutrons so as to convert the long lived nuclides into nuclides that decay more quickly. When technetium-99 absorbs a neutron, it forms technetium-100, which has a half-life of 16 seconds and forms stable ruthenium-100 by emitting a beta particle. Write the nuclear equations for these two changes.

Objective 44
139. Describe the role of the control rods in a nuclear reactor.

140. Describe how energy is generated in the sun. OBJECTIVE 45

Additional Problems

141. A radioactive nuclide that has an atomic number of 53 and a mass (nucleon) number of 131 is used to measure thyroid function. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to symbolize this nuclide.
142. A radioactive nuclide that has an atomic number of 6 and a mass (nucleon) number of 14 is used to determine the age of artifacts. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to symbolize this nuclide.
143. A radioactive nuclide that has 11 protons and 13 neutrons is used to detect blood clots. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to symbolize this nuclide.
144. A radioactive nuclide that has 43 protons and 56 neutrons is used in bone scans. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to symbolize this nuclide.
145. A radioactive nuclide with the symbol $^{133}_{55}Cs$ is used in radiation therapy. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide.
146. A radioactive nuclide with the symbol $^{79}_{36}Kr$ is used to assess cardiovascular function. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide.
147. A radioactive nuclide with the symbol $^{51}_{24}Cr$ is used to determine blood volume. How many protons and neutrons does each atom have? Write two other ways to represent this nuclide.
148. A radioactive nuclide with the symbol $^{15}_{8}O$ is used to test lung function. How many protons and neutrons does each atom have? Write two other ways to represent this nuclide.
149. Gallium-67 is used to diagnose lymphoma. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.
150. Nitrogen-13 is used in heart imaging. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.
151. The radioactive nuclide with the symbol ^{32}P is used to detect eye tumors. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.
152. The radioactive nuclide with the symbol ^{41}Ar is used to measure the flow of gases from smokestacks. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide.
153. Consider three isotopes of neon: $^{18}_{10}Ne$, $^{20}_{10}Ne$, and $^{24}_{10}Ne$. Neon-20, which is the most abundant isotope of neon, is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes positron emission. Identify the isotope that makes each of these changes, and explain your choices.

154. Consider three isotopes of chromium: ${}^{48}_{24}Cr$, ${}^{52}_{24}Cr$, and ${}^{56}_{24}Cr$. Chromium-52, the most abundant, is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes electron capture. Identify the isotope that makes each of these changes, and explain your choices.
155. Write the nuclear equation for the alpha emission of bismuth-189.
156. Write the nuclear equation for the alpha emission of radium-226, which is used in radiation therapy.
157. Phosphorus-32, which is used to detect breast cancer, undergoes beta emission. Write the nuclear equation for this reaction.
158. Radioactive xenon-133 is used to measure lung capacity. It shifts toward stability by emitting beta particles. Write the nuclear equation for this reaction.
159. Write the nuclear equation for the positron emission of potassium-40.
160. Liver disease can be diagnosed with the help of radioactive copper-64, which is a positron emitter. Write the nuclear equation for this reaction.
161. Radioactive selenium-75, used to determine the shape of the pancreas, shifts to a more stable nuclide via electron capture. Write the nuclear equation for this change.
162. Intestinal fat absorption can be measured using iodine-125, which undergoes electron capture. Write an equation that describes this change.
163. Germanium-78 atoms undergo two beta emissions before they reach a stable nuclide. What is the final product?
164. Iron-61 atoms undergo two beta emissions before they reach a stable nuclide. What is the final product?
165. Iron-52 atoms undergo one positron emission and one electron capture before they reach a stable nuclide. What is the final product?
166. Titanium-43 atoms undergo two positron emissions before they reach a stable nuclide. What is the final product?
167. Arsenic-69 atoms undergo one positron emission and one electron capture before they reach a stable nuclide. What is the final product?
168. Radon-217 atoms undergo two alpha emissions and a beta emission before they reach a stable nuclide. What is the final product?
169. Astatine-216 atoms undergo an alpha emission, a beta emission, and another alpha emission before they reach a stable nuclide. What is the final product?
170. Complete the following nuclear equations.

    a. ${}^{249}_{98}Cf + {}^{15}_{7}N \rightarrow$ _____ $+ 5{}^{1}_{0}n$

    b. _____ $+ {}^{10}_{5}B \rightarrow {}^{257}_{103}Lr + 2{}^{1}_{0}n$

    c. ${}^{121}_{51}Sb + {}^{1}_{1}H \rightarrow {}^{121}_{52}Te +$ _____

171. Complete the following nuclear equations.

    a. ${}^{10}_{5}B + {}^{1}_{0}n \rightarrow$ _____ $+ {}^{1}_{1}H$

    b. _____ $+ {}^{4}_{2}He \rightarrow {}^{124}_{53}I + {}^{1}_{0}n$

    c. ${}^{239}_{94}Pu + {}^{4}_{2}He \rightarrow$ _____ $+ {}^{1}_{1}H + 2{}^{1}_{0}n$

172. Nitrogen-containing explosives carried by potential terrorists can be detected at airports by bombarding suspicious luggage with low-energy neutrons. The nitrogen-14 atoms absorb the neutrons, forming nitrogen-15 atoms. The nitrogen-15 atoms emit gamma photons of a characteristic wavelength that can be detected outside the luggage. Write a nuclear equation for the reaction that forms nitrogen-15 from nitrogen-14.

173. In September 1982, the element meitnerium-266, $^{266}_{109}Mt$, was made from the bombardment of bismuth-209 atoms with iron-58 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.)

174. In March 1984, the nuclide hassium-265, $^{265}_{108}Hs$, was made from the bombardment of lead-208 atoms with iron-58 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.)

175. In November 1994, the nuclide darmstadtium-269, $^{271}_{110}Ds$, was made from the bombardment of lead-208 atoms with nickel-62 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.)

176. Krypton-79, which is used to assess cardiovascular function, has a half-life of 34.5 hours. How long before a sample decreases to $\frac{1}{8}$ of what was originally there?

177. Strontium-90 has a half-life of 29 years. How long before a sample decreases to $\frac{1}{32}$ of what was originally there?

178. Iron-59, which is used to diagnose anemia, has a half-life of 45 days. What fraction of it is left in 90 days?

179. Fluorine-17 has a half-life of 66 s. What fraction of it is left in 264 s?

Discussion Questions

180. Suggest a way radioactive sulfur-35 could be used to show that the following reversible change takes place in a saturated solution of silver sulfide with excess solid on the bottom.

$$Ag_2S(s) \rightarrow 2Ag^+(aq) + S^{2-}(aq)$$

181. Vitamin B_{12} is water soluble vitamin that can be derived from oysters, salmon, liver, and kidney. At the core of the complex structure of vitamin B_{12} is a cobalt ion. Suggest a way that radioactive cobalt-57 could be used to determine which tissues of the body adsorb the most vitamin B_{12}.