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)

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

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.

$^{59}_{26}\mathbf{Fe}$ **or** $^{59}\mathbf{Fe}$ **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

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

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

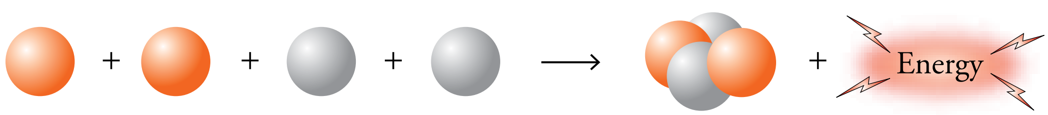
OBJECTIVE 5

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

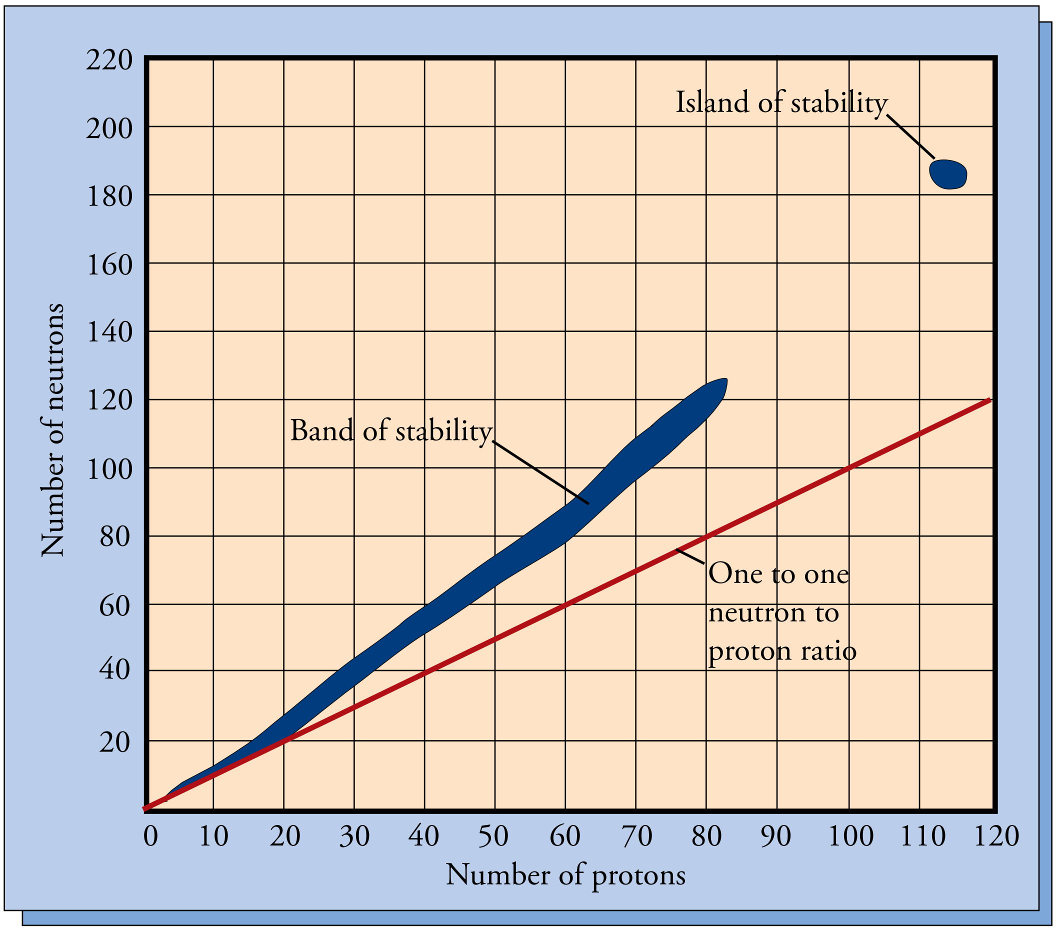
For many of the lighter elements, the possession of an equal number of protons and neutrons leads to stable atoms. For example, carbon-12 atoms, ${}^{12}_{6}\mathrm{C}$, with six protons and six neutrons, and oxygen-16 atoms, ${}^{16}_{8}\mathrm{O}$, with eight protons and eight neutrons, are both very 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



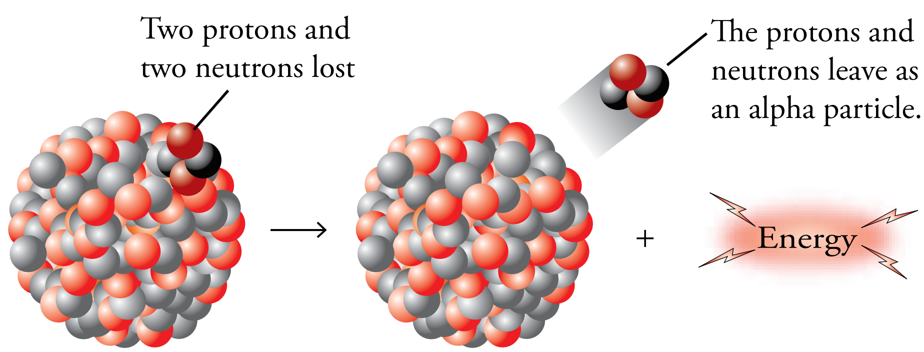
A nuclide containing numbers of protons and neutrons that place it outside this band of stability will be unstable until it undergoes one or more nuclear reactions that take it into the band of stability. We call these unstable atoms **radioactive nuclides**, and the changes they undergo to reach stability 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

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



Objective 7

In nuclear equations for alpha emission, the alpha particle is written as either α or $^{4}_{2}\mathrm{He}$. 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

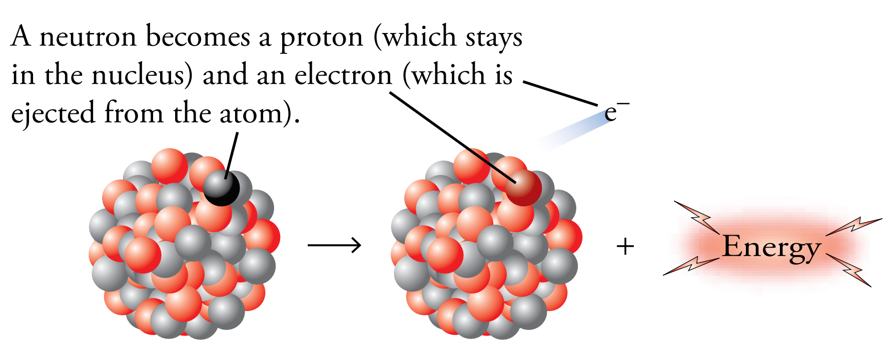
Some radioactive nuclides have a neutron-to-proton ratio that is too high, placing them above the band of stability. To reach a more stable state they undergo **beta emission** (β^-). In this process, a neutron becomes a proton and an electron. The proton stays in the nucleus, and the electron, which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

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

Objective 7

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

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



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

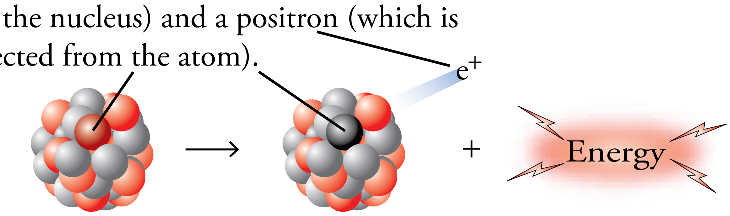
If a radioactive nuclide has a neutron-to-proton ratio that is too low, placing it below the band of stability, it can move toward stability in one of two ways, positron emission or electron capture. **Positron emission** (β^+) is similar to beta emission, but in this case, a proton becomes a neutron 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.

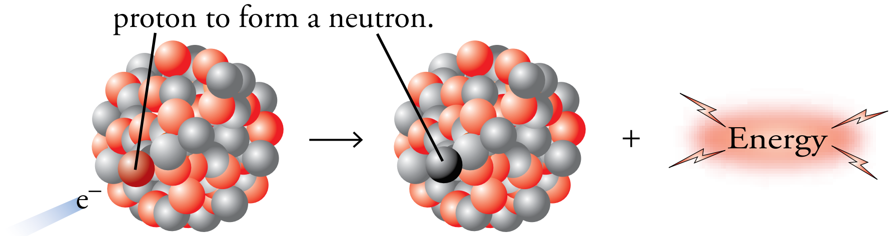
Objective 6
Objective 8

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.

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



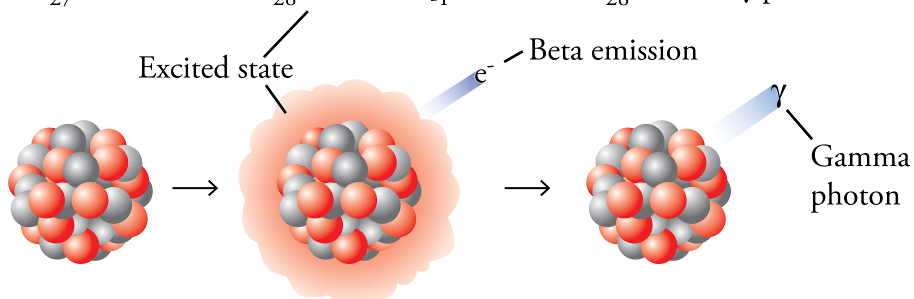
Like positron emission, electron capture causes the radioactive nuclide to change to a new element, with an atomic number that is lower by 1 but with the same mass number.

[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, cobalt-60 is a beta emitter that also releases gamma radiation. The energy released in the beta emission leaves the product element, nickel-60, in an excited state. When the nickel-60 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.)

$$^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni}^{*} + {}^{0}_{-1}\text{e} \longrightarrow {}^{60}_{28}\text{Ni} + \gamma\text{-photon}$$



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.

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

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

mass number	238		234 + 4 = 238
	${}^{238}_{92}U$	$\longrightarrow$	${}^{234}_{90}Th + {}^{4}_{2}He$
atomic number	92		90 + 2 = 92

Beta emission

mass number	131		131 + 0 = 131
	${}^{131}_{53}I$	$\longrightarrow$	${}^{131}_{54}Xe + {}^{0}_{-1}e$
atomic number	53		54 + (–1) = 53

Positron emission

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

Electron capture

mass number	0 + 125 = 125		125
	${}^{0}_{-1}e + {}^{125}_{53}I$	$\longrightarrow$	${}^{125}_{52}Te$
atomic number	–1 + 53 = 52		52

Objective 12

The following general equations describe these nuclear changes:

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

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

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

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

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

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

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

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

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

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

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.

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

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

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

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.

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

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

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

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

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

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

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

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 ($1/2 \times 1/2$). The next day you can only eat one-eighth of the original pie ($1/2 \times 1/4$ or $1/2 \times 1/2 \times 1/2$), and on the next day one-sixteenth ($1/2 \times 1/8$ or $1/2 \times 1/2 \times 1/2 \times 1/2$). On the fifth day (after five half-lives), the piece you eat is only $1/32$ of the original pie ($1/2 \times 1/16$ or $1/2 \times 1/2 \times 1/2 \times 1/2 \times 1/2$). 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 $1/2$, $1/4$, $1/8$, $1/16$, or $1/32$ 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

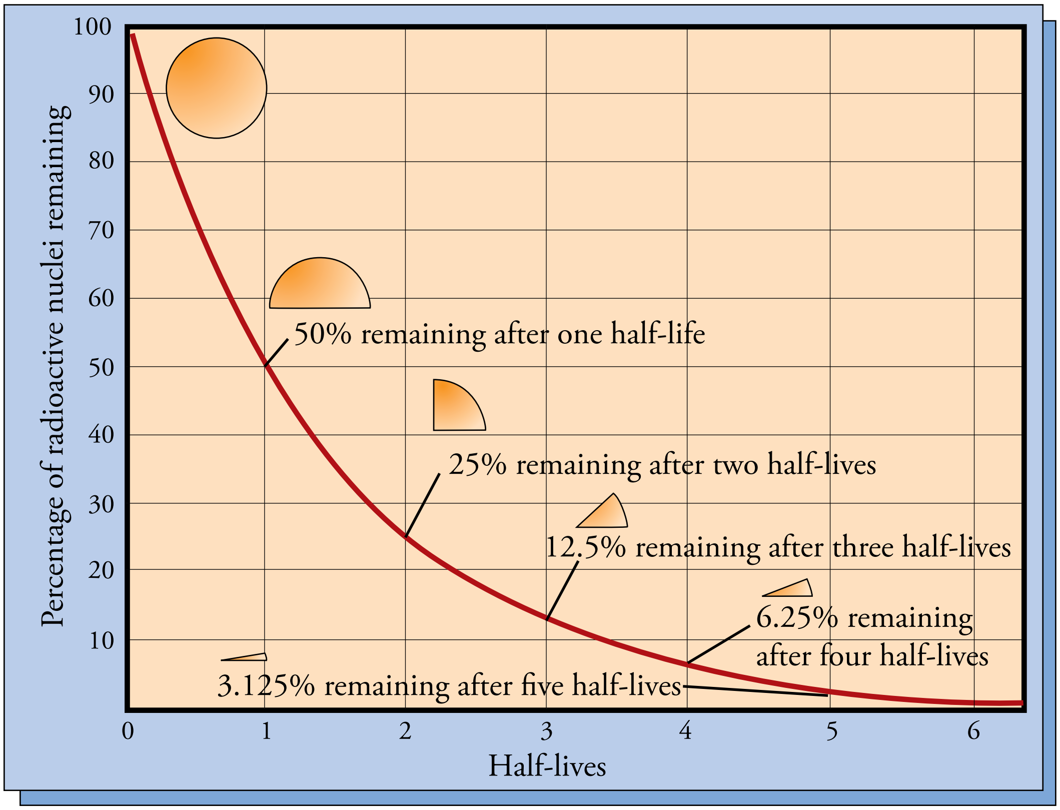


Table 16.3
Half-Lives of Common Radioactive Isotopes

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

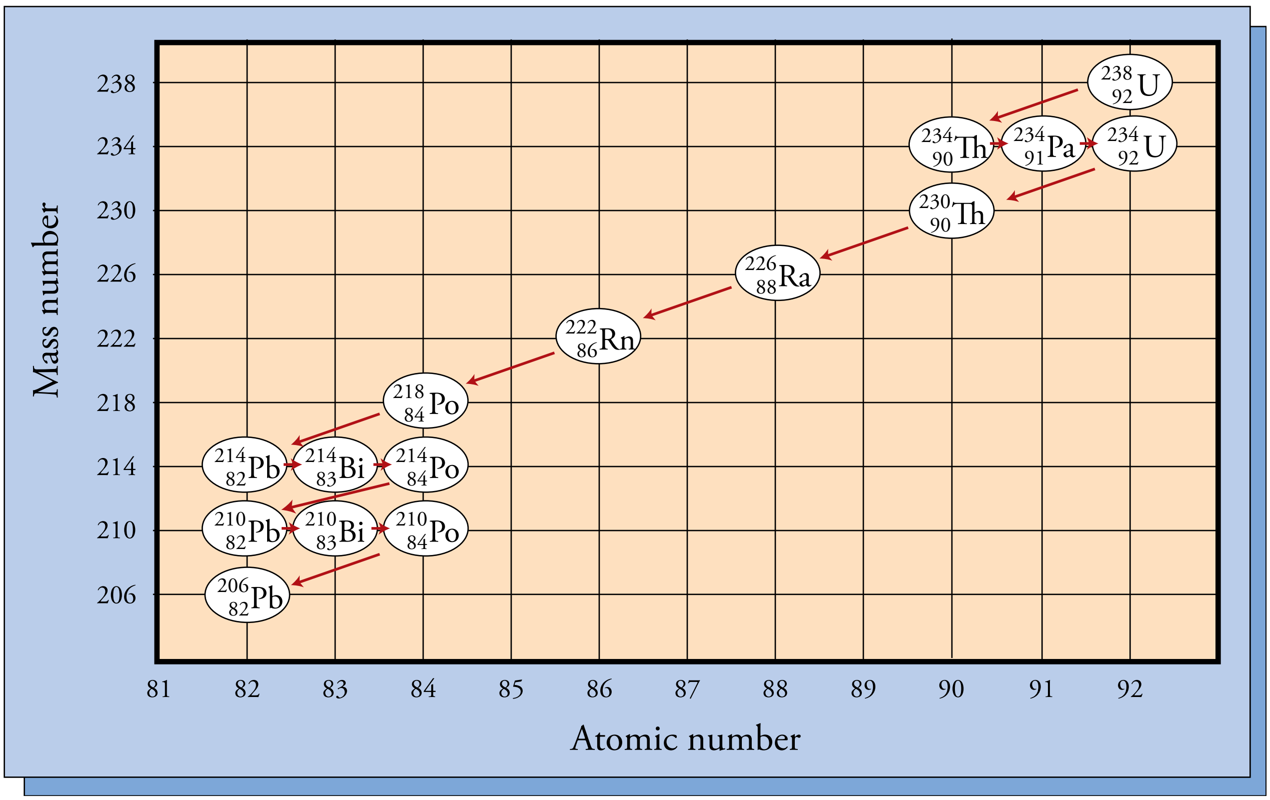
Objective 16

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

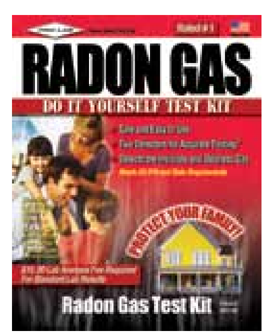
Figure 16.3
Uranium-238 Decay Series



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

$$H_2O^{\bullet +} + H_2O \rightarrow H_3O^+ + {}^{\bullet}OH$$

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

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.

OBJECTIVE 21

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.