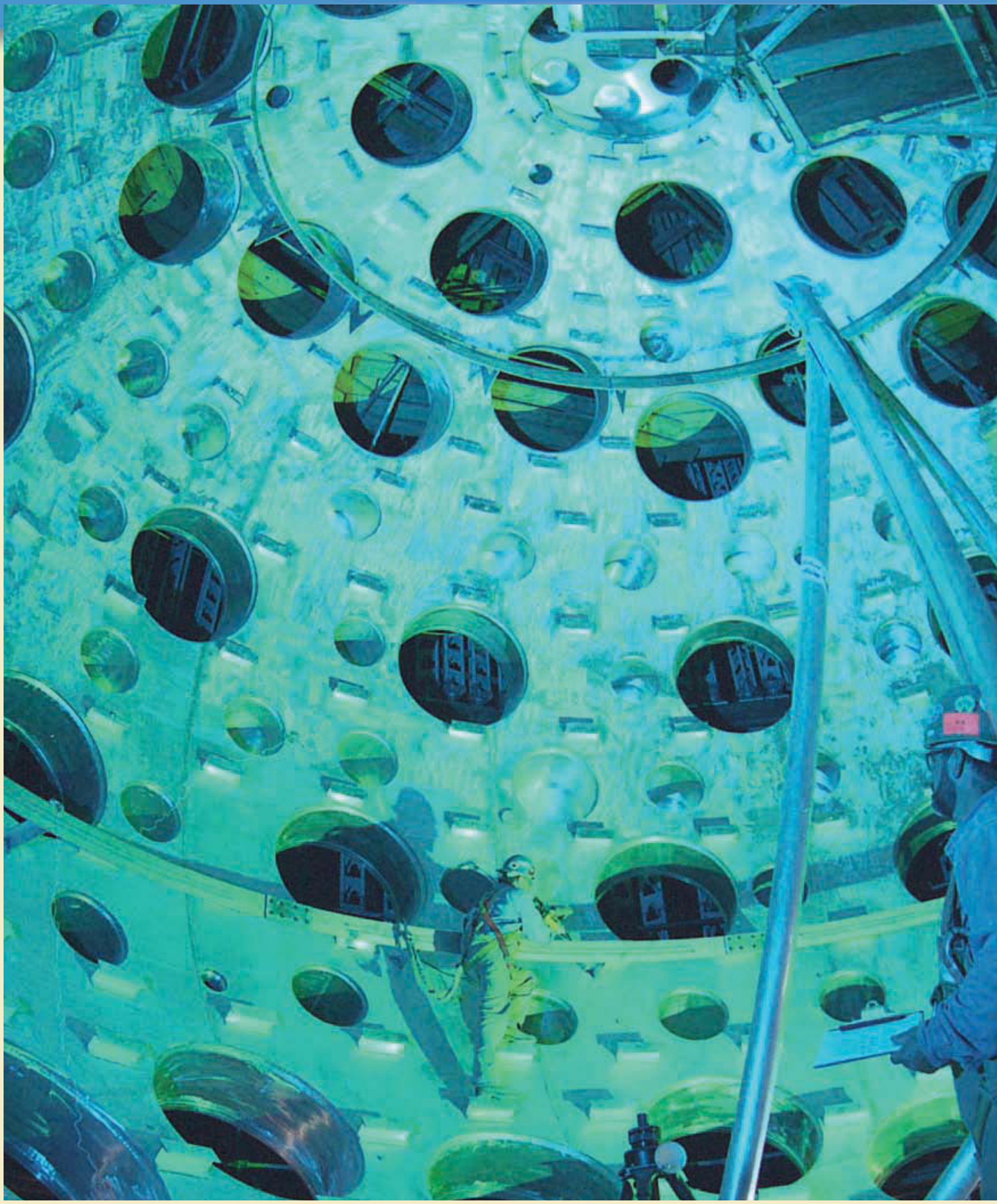
18 The Nucleus: A Chemist's View

Contents



Workers inside a giant chamber at the National Ignition Facility in California. This chamber will be used to induce nuclear fusion by aiming 192 lasers at a pellet of fuel.

Since the chemistry of an atom is determined by the number and arrangement of its electrons, the properties of the nucleus are not of primary importance to chemists. In the simplest view, the nucleus provides the positive charge to bind the electrons in atoms and molecules. However, a quick reading of any daily newspaper will show you that the nucleus and its properties have an important impact on our society. This chapter considers those aspects of the nucleus about which everyone should have some knowledge.

Several aspects of the nucleus are immediately impressive: its very small size, its very large density, and the magnitude of the energy that holds it together. The radius of a typical nucleus appears to be about 10^{-13} cm. This can be compared to the radius of a typical atom, which is on the order of 10^{-8} cm. A visualization will help you appreciate the small size of the nucleus: If the nucleus of the hydrogen atom were the size of a Ping-Pong ball, the electron in the 1*s* orbital would be, on average, 0.5 kilometer (0.3 mile) away. The density of the nucleus is equally impressive—approximately 1.6×10^{14} g/cm^3. A sphere of nuclear material the size of a Ping-Pong ball would have a mass of 2.5 *billion tons!* In addition, the energies involved in nuclear processes are typically millions of times larger than those associated with normal chemical reactions. This fact makes nuclear processes very attractive for feeding the voracious energy appetite of our civilization.

Atomos, the Greek root of the word *atom,* means "indivisible." It was originally believed that the atom was the ultimate indivisible particle of which all matter was composed. However, as we discussed in Chapter 2, Lord Rutherford showed in 1911 that the atom is not homogeneous, but rather has a dense, positively charged center surrounded by electrons. Subsequently, scientists have learned that the nucleus of the atom can be subdivided into particles called **neutrons** and **protons.** In fact, in the past two decades it has become apparent that even the protons and neutrons are composed of smaller particles called *quarks.*

For most purposes, the nucleus can be regarded as a collection of **nucleons** (neutrons and protons), and the internal structures of these particles can be ignored. As we discussed in Chapter 2, the number of protons in a particular nucleus is called the **atomic number** (Z), and the sum of the neutrons and protons is the **mass number** (A). Atoms that have identical atomic numbers but different mass number values are called **isotopes.** However, we usually do not use the singular form *isotope* to refer to a particular member of a group of isotopes. Rather, we use the term *nuclide.* A **nuclide** is a unique atom, represented by the symbol

The atomic number Z is the number of protons in a nucleus; the mass number A is the sum of protons and neutrons in a nucleus.

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

where X represents the symbol for a particular element. For example, the following nuclides constitute the isotopes of carbon: carbon-12 ($^{12}_{6}\mathrm{C}$), carbon-13 ($^{13}_{6}\mathrm{C}$), and carbon-14 ($^{14}_{6}\mathrm{C}$).

The term *isotopes* refers to a group of nuclides with the same atomic number. Each individual atom is properly called a *nuclide,* not an isotope.

18.1 Nuclear Stability and Radioactive Decay

Nuclear stability is the central topic of this chapter and forms the basis for all the important applications related to nuclear processes. Nuclear stability can be considered from both a kinetic and a thermodynamic point of view. **Thermodynamic stability,** as we will use the term here, refers to the potential energy of a particular nucleus as compared with the sum of the potential energies of its component protons and neutrons. We will use the term **kinetic stability** to describe the probability that a nucleus will undergo decomposition to form a different nucleus—a process called **radioactive decay.** We will consider radioactivity in this section.

Many nuclei are radioactive; that is, they decompose, forming another nucleus and producing one or more particles. An example is carbon-14, which decays as follows:

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

where ${}^{0}_{-1}e$ represents an electron, which is called a **beta particle,** or **β particle,** in nuclear terminology. This equation is typical of those representing radioactive decay in that both A and Z must be conserved. That is, the Z values must give the same sum on both sides of the equation $(6 = 7 - 1)$, as must the A values $(14 = 14 + 0)$.

Of the approximately 2000 known nuclides, only 279 are stable with respect to radioactive decay. Tin has the largest number of stable isotopes—10.

It is instructive to examine how the numbers of neutrons and protons in a nucleus are related to its stability with respect to radioactive decay. Figure 18.1 shows a plot of the positions of the stable nuclei as a function of the number of protons (Z) and the number of neutrons ($A - Z$). The stable nuclides are said to reside in the **zone of stability.**

The following are some important observations concerning radioactive decay:

- All nuclides with 84 or more protons are unstable with respect to radioactive decay.
- Light nuclides are stable when Z equals $A - Z$, that is, when the neutron/proton ratio is 1. However, for heavier elements the neutron/proton ratio required for stability is greater than 1 and increases with Z.

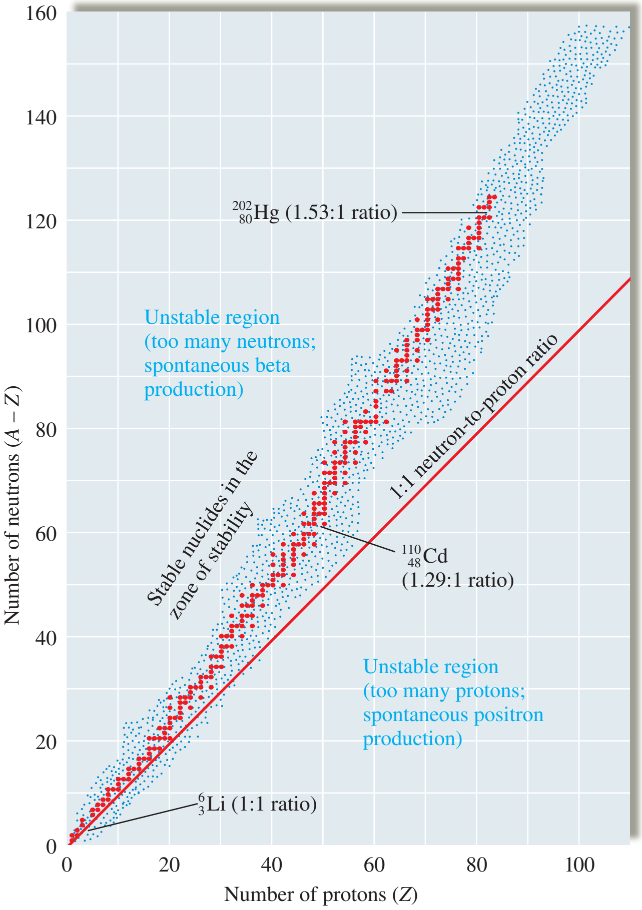


FIGURE 18.1
The zone of stability. The red dots indicate the nuclides that *do not* undergo radioactive decay. Note that as the number of protons in a nuclide increases, the neutron/proton ratio required for stability also increases.

TABLE 18.1 Number of Stable Nuclides Related to Numbers of Protons and Neutrons

Number of Protons	Number of Neutrons	Number of Stable Nuclides	Examples
Even	Even	168	${}^{12}_{6}C$, ${}^{16}_{8}O$
Even	Odd	57	${}^{13}_{6}C$, ${}^{47}_{22}Ti$
Odd	Even	50	${}^{19}_{9}F$, ${}^{23}_{11}Na$
Odd	Odd	4	${}^{2}_{1}H$, ${}^{6}_{3}Li$

Note: Even numbers of protons and neutrons seem to favor stability.

- Certain combinations of protons and neutrons seem to confer special stability. For example, nuclides with even numbers of protons and neutrons are more often stable than those with odd numbers, as shown by the data in Table 18.1.
- There are also certain specific numbers of protons or neutrons that produce especially stable nuclides. These *magic numbers* are 2, 8, 20, 28, 50, 82, and 126. This behavior parallels that for atoms in which certain numbers of electrons (2, 10, 18, 36, 54, and 86) produce special chemical stability (the noble gases).

Types of Radioactive Decay

Radioactive nuclei can undergo decomposition in various ways. These decay processes fall into two categories: those that involve a change in the mass number of the decaying nucleus and those that do not. We will consider the former type of process first.

α-particle production involves a change in A for the decaying nucleus; β-particle production has no effect on A.

An **alpha particle,** or **α particle,** is a helium nucleus (${}^{4}_{2}He$). **Alpha-particle production** is a very common mode of decay for heavy radioactive nuclides. For example, ${}^{238}_{92}U$, the predominant (99.3%) isotope of natural uranium, decays by α-particle production:

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

Visualization: Nuclear Particles

Another α-particle producer is ${}^{230}_{90}Th$:

$${}^{230}_{90}Th \longrightarrow {}^{4}_{2}He + {}^{226}_{88}Ra$$

Another decay process in which the mass number of the decaying nucleus changes is **spontaneous fission,** the splitting of a heavy nuclide into two lighter nuclides with similar mass numbers. Although this process occurs at an extremely slow rate for most nuclides, it is important in some cases, such as for ${}^{254}_{98}Cf$, where spontaneous fission is the predominant mode of decay.

The most common decay process in which the mass number of the decaying nucleus remains constant is **β-particle production.** For example, the thorium-234 nuclide produces a β particle and is converted to protactinium-234:

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

Iodine-131 is also a β-particle producer:

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

The β particle is assigned the mass number 0, since its mass is tiny compared with that of a proton or neutron. Because the value of Z is -1 for the β particle, the atomic number for the new nuclide is greater by 1 than for the original nuclide. Thus *the net effect of β-particle production is to change a neutron to a proton.* We therefore expect nuclides that lie above the zone of stability (those nuclides whose neutron/proton ratios are too high) to be β-particle producers.

It should be pointed out that although the β particle is an electron, the emitting nucleus does not contain electrons. As we shall see later in this chapter, a given quantity of energy (which is best regarded as a form of matter) can become a particle (another form of matter) under certain circumstances. The unstable nuclide creates an electron as it releases energy in the decay process. The electron thus results from the decay process rather than being present before the decay occurs. Think of this as somewhat like talking: Words are not stored inside us but are formed as we speak. Later in this chapter we will discuss in more detail this very interesting phenomenon where matter in the form of particles and matter in the form of energy can interchange.

A **gamma ray,** or **γ ray,** refers to a high-energy photon. Frequently, γ-ray production accompanies nuclear decays and particle reactions, such as in the α-particle decay of ${}^{238}_{92}\text{U}$:

$${}^{238}_{92}\text{U} \longrightarrow {}^{4}_{2}\text{He} + {}^{234}_{90}\text{Th} + 2\,{}^{0}_{0}\gamma$$

where two γ rays of different energies are produced in addition to the α particle. The emission of γ rays is one way a nucleus with excess energy (in an excited nuclear state) can relax to its ground state.

Positron production occurs for nuclides that are below the zone of stability (those nuclides whose neutron/proton ratios are too small). The positron is a particle with the same mass as the electron but opposite charge. An example of a nuclide that decays by positron production is sodium-22:

$${}^{22}_{11}\text{Na} \longrightarrow {}^{0}_{1}\text{e} + {}^{22}_{10}\text{Ne}$$

Note that *the net effect is to change a proton to a neutron,* causing the product nuclide to have a higher neutron/proton ratio than the original nuclide.

Besides being oppositely charged, the positron shows an even more fundamental difference from the electron: It is the *antiparticle* of the electron. When a positron collides with an electron, the particulate matter is changed to electromagnetic radiation in the form of high-energy photons:

$${}^{0}_{-1}\text{e} + {}^{0}_{1}\text{e} \longrightarrow 2\,{}^{0}_{0}\gamma$$

This process, which is characteristic of matter–antimatter collisions, is called *annihilation* and is another example of the interchange of the forms of matter.

Electron capture is a process in which one of the inner-orbital electrons is captured by the nucleus, as illustrated by the process

$$\underbrace{{}^{201}_{80}\text{Hg} + {}^{0}_{-1}\text{e}}_{\text{Inner-orbital electron}} \longrightarrow {}^{201}_{79}\text{Au} + {}^{0}_{0}\gamma$$

This reaction would have been of great interest to the alchemists, but unfortunately it does not occur at a rate that would make it a practical means for changing mercury to gold. Gamma rays are always produced along with electron capture to release excess energy. The various types of radioactive decay are summarized in Table 18.2.

Sample Exercise 18.1 Nuclear Equations I

Write balanced equations for each of the following processes.

a. ${}^{11}_{6}\text{C}$ produces a positron.

b. ${}^{241}_{83}\text{Bi}$ produces a β particle.

c. ${}^{237}_{93}\text{Np}$ produces an α particle.

TABLE 18.2 Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

Process	Change in *A*	Change in *Z*	Change in Neutron/Proton Ratio	Example
β-particle (electron) production	0	+1	Decrease	$^{227}_{89}\text{Ac} \longrightarrow {}^{227}_{90}\text{Th} + {}^{0}_{-1}\text{e}$
Positron production	0	−1	Increase	$^{13}_{7}\text{N} \longrightarrow {}^{13}_{6}\text{C} + {}^{0}_{1}\text{e}$
Electron capture	0	−1	Increase	$^{73}_{33}\text{As} + {}^{0}_{-1}\text{e} \longrightarrow {}^{73}_{32}\text{Ge}$
α-particle production	−4	−2	Increase	$^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He}$
γ-ray production	0	0	—	Excited nucleus $\longrightarrow$ ground-state nucleus + $^{0}_{0}\gamma$
Spontaneous fission	—	—	—	$^{254}_{98}\text{Cf} \longrightarrow$ lighter nuclides + neutrons

Solution

a. We must find the product nuclide represented by $^{A}_{Z}\text{X}$ in the following equation:

$$^{11}_{6}\text{C} \longrightarrow \underset{\substack{\uparrow \\ \text{Positron}}}{{}^{0}_{1}\text{e}} + {}^{A}_{Z}\text{X}$$

We can find the identity of $^{A}_{Z}\text{X}$ by recognizing that the total of the Z and A values must be the same on both sides of the equation. Thus for X, Z must be $6 - 1 = 5$ and A must be $11 - 0 = 11$. Therefore, $^{A}_{Z}\text{X}$ is $^{11}_{5}\text{B}$. (The fact that Z is 5 tells us that the nuclide is boron.) Thus the balanced equation is

$$^{11}_{6}\text{C} \longrightarrow {}^{0}_{1}\text{e} + {}^{11}_{5}\text{B}$$

b. Knowing that a β particle is represented by $^{0}_{-1}\text{e}$ and that Z and A are conserved, we can write

$$^{214}_{83}\text{Bi} \longrightarrow {}^{0}_{-1}\text{e} + {}^{214}_{84}\text{X}$$

so $^{A}_{Z}\text{X}$ must be $^{214}_{84}\text{Po}$.

c. Since an α particle is represented by $^{4}_{2}\text{He}$, the balanced equation must be

$$^{237}_{93}\text{Np} \longrightarrow {}^{4}_{2}\text{He} + {}^{233}_{91}\text{Pa}$$

See Exercises 18.11 and 18.12.

Sample Exercise 18.2

Nuclear Equations II

In each of the following nuclear reactions, supply the missing particle.

a. $^{195}_{79}\text{Au} + ? \rightarrow {}^{195}_{78}\text{Pt}$

b. $^{38}_{19}\text{K} \rightarrow {}^{38}_{18}\text{Ar} + ?$

Solution

a. Since A does not change and Z decreases by 1, the missing particle must be an electron:

$$^{195}_{79}\text{Au} + {}^{0}_{-1}\text{e} \longrightarrow {}^{195}_{78}\text{Pt}$$

This is an example of electron capture.

b. To conserve Z and A, the missing particle must be a positron:

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

Thus potassium-38 decays by positron production.

See Exercises 18.13 and 18.14.

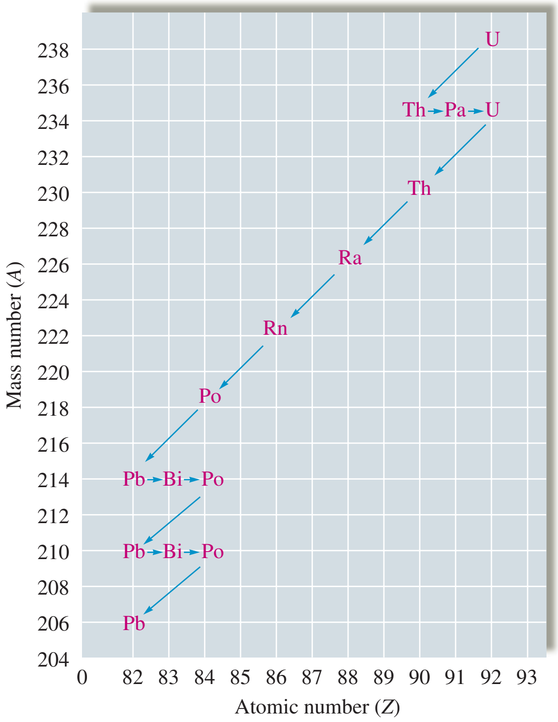


FIGURE 18.2
The decay series from $^{238}_{92}U$ to $^{206}_{82}Pb$. Each nuclide in the series except $^{206}_{82}Pb$. is unstable, and the successive transformations (shown by the arrows) continue until $^{206}_{82}Pb$ is finally formed. Note that horizontal arrows indicate processes where *A* is unchanged, while diagonal arrows signify that both *A* and *Z* change.

Often a radioactive nucleus cannot reach a stable state through a single decay process. In such a case, a **decay series** occurs until a stable nuclide is formed. A well-known example is the decay series that starts with $^{238}_{92}U$ and ends with $^{206}_{82}Pb$, as shown in Fig. 18.2. Similar series exist for $^{235}_{92}U$:

$$^{235}_{92}\mathrm{U} \xrightarrow[\text{decays}]{\text{Series of}} {}^{207}_{82}\mathrm{Pb}$$

and for $^{232}_{90}Th$:

$$^{232}_{90}\mathrm{Th} \xrightarrow[\text{decays}]{\text{Series of}} {}^{208}_{82}\mathrm{Pb}$$

18.2 The Kinetics of Radioactive Decay

Rates of reaction are discussed in Chapter 12.

In a sample containing radioactive nuclides of a given type, each nuclide has a certain probability of undergoing decay. Suppose that a sample of 1000 atoms of a certain nuclide produces 10 decay events per hour. This means that over the span of an hour, 1 out of every 100 nuclides will decay. Given that this probability of decay is characteristic for this type of nuclide, we could predict that a 2000-atom sample would give 20 decay events per hour. Thus, for radioactive nuclides, the **rate of decay,** which is the negative of the change in the number of nuclides per unit time

$$\left(-\frac{\Delta N}{\Delta t}\right)$$

is directly proportional to the number of nuclides *N* in a given sample:

$$\text{Rate} = -\frac{\Delta N}{\Delta t} \propto N$$

The negative sign is included because the number of nuclides is decreasing. We now insert a proportionality constant k to give

$$\text{Rate} = -\frac{\Delta N}{\Delta t} = kN$$

This is the rate law for a first-order process, as we saw in Chapter 12. As shown in Section 12.4, the integrated first-order rate law is

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

where N_0 represents the original number of nuclides (at $t = 0$) and N represents the number *remaining* at time t.

Half-Life

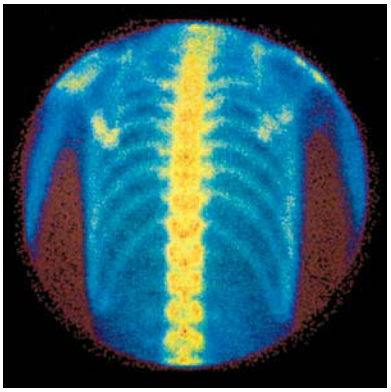
Visualization: Half-Life of Nuclear Decay

The **half-life** ($t_{1/2}$) of a radioactive sample is defined as the time required for the number of nuclides to reach half the original value ($N_0/2$). We can use this definition in connection with the integrated first-order rate law (as we did in Section 12.4) to produce the following expression for $t_{1/2}$:

$$t_{1/2} = \frac{\ln(2)}{k} = \frac{0.693}{k}$$

Thus, if the half-life of a radioactive nuclide is known, the rate constant can be easily calculated, and vice versa.

Sample Exercise 18.3 Kinetics of Nuclear Decay I



The image of a bone scan of a normal chest (posterior view). Radioactive technetium-99m is injected into the patient and is then concentrated in bones, allowing a physician to look for abnormalities such as might be caused by cancer.

Technetium-99m is used to form pictures of internal organs in the body and is often used to assess heart damage. The *m* for this nuclide indicates an excited nuclear state that decays to the ground state by gamma emission. The rate constant for decay of ${}^{99\text{m}}_{43}\text{Tc}$ is known to be 1.16×10^{-1}/h. What is the half-life of this nuclide?

Solution

The half-life can be calculated from the expression

$$t_{1/2} = \frac{0.693}{k} = \frac{0.693}{1.16 \times 10^{-1}/\text{h}}$$
$$= 5.98 \text{ h}$$

Thus it will take 5.98 h for a given sample of technetium-99m to decrease to half the original number of nuclides.

See Exercise 18.21.

As we saw in Section 12.4, the half-life for a first-order process is constant. This is shown for the β-particle decay of strontium-90 in Fig. 18.3; it takes 28.8 years for each halving of the amount of ${}^{90}_{38}\text{Sr}$. Contamination of the environment with ${}^{90}_{38}\text{Sr}$ poses serious health hazards because of the similar chemistry of strontium and calcium (both are in Group 2A). Strontium-90 in grass and hay is incorporated into cow's milk along with calcium and is then passed on to humans, where it lodges in the bones. Because of its relatively long half-life, it persists for years in humans, causing radiation damage that may lead to cancer.

The harmful effects of radiation will be discussed in Section 18.7.

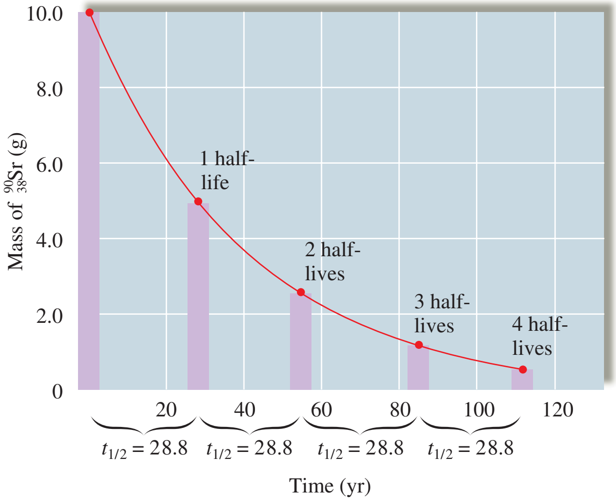


FIGURE 18.3
The decay of a 10.0-g sample of strontium-90 over time. Note that the half-life is a constant 28.8 years.

Sample Exercise 18.4

Kinetics of Nuclear Decay II

The half-life of molybdenum-99 is 67.0 h. How much of a 1.000-mg sample of $^{99}_{42}$Mo is left after 335 h?

Solution

The easiest way to solve this problem is to recognize that 335 h represents five half-lives for $^{99}_{42}$Mo:

$$335 = 5 \times 67.0$$

We can sketch the change that occurs, as is shown in Fig. 18.4. Thus, after 335 h, 0.031 mg $^{99}_{42}$Mo remains.

See Exercise 18.23.

The half-lives of radioactive nuclides vary over a tremendous range. For example, $^{144}_{60}$Nd has a half-life of 5×10^{15} years, while $^{214}_{84}$Po has a half-life of 2×10^{-4} second. To give you some perspective on this, the half-lives of the nuclides in the $^{238}_{92}$U decay series are given in Table 18.3.

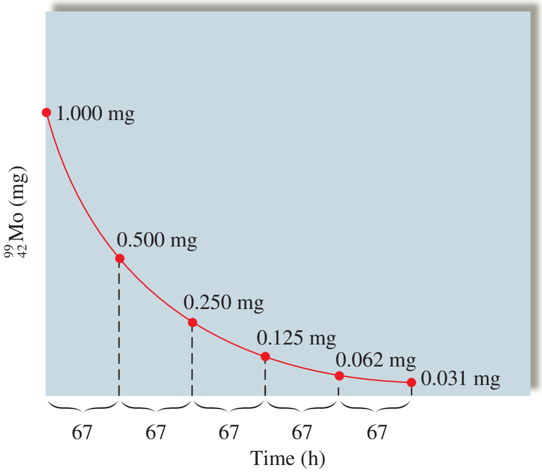


FIGURE 18.4
The change in the amount of $^{99}_{42}$Mo with time ($t_{1/2}$ = 67 h).

TABLE 18.3 The Half-Lives of Nuclides in the $^{238}_{92}\mathrm{U}$ Decay Series

Nuclide	Particle Produced	Half-Life
Uranium-238 ($^{238}_{92}\mathrm{U}$)	α	4.51×10^{9} years
↓		
Thorium-234 ($^{234}_{90}\mathrm{Th}$)	β	24.1 days
↓		
Protactinium-234 ($^{234}_{91}\mathrm{Pa}$)	β	6.75 hours
↓		
Uranium-234 ($^{234}_{92}\mathrm{U}$)	α	2.48×10^{5} years
↓		
Thorium-230 ($^{230}_{90}\mathrm{Th}$)	α	8.0×10^{4} years
↓		
Radium-226 ($^{226}_{88}\mathrm{Ra}$)	α	1.62×10^{3} years
↓		
Radon-222 ($^{222}_{86}\mathrm{Rn}$)	α	3.82 days
↓		
Polonium-218 ($^{218}_{84}\mathrm{Po}$)	α	3.1 minutes
↓		
Lead-214 ($^{214}_{82}\mathrm{Pb}$)	β	26.8 minutes
↓		
Bismuth-214 ($^{214}_{83}\mathrm{Bi}$)	β	19.7 minutes
↓		
Polonium-214 ($^{214}_{84}\mathrm{Po}$)	α	1.6×10^{-4} second
↓		
Lead-210 ($^{210}_{82}\mathrm{Pb}$)	β	20.4 years
↓		
Bismuth-210 ($^{210}_{83}\mathrm{Bi}$)	β	5.0 days
↓		
Polonium-210 ($^{210}_{84}\mathrm{Po}$)	α	138.4 days
↓		
Lead-206 ($^{206}_{82}\mathrm{Pb}$)	—	Stable

18.3 Nuclear Transformations

In 1919 Lord Rutherford observed the first **nuclear transformation,** *the change of one element into another.* He found that by bombarding $^{14}_{7}\mathrm{N}$ with α particles, the nuclide $^{17}_{8}\mathrm{O}$ could be produced:

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

Fourteen years later, Irene Curie and her husband Frederick Joliot observed a similar transformation from aluminum to phosphorus:

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n}$$

where $^{1}_{0}\mathrm{n}$ represents a neutron.

Over the years, many other nuclear transformations have been achieved, mostly using **particle accelerators,** which, as the name reveals, are devices used to give particles very high velocities. Because of the electrostatic repulsion between the target nucleus and a positive ion, accelerators are needed when positive ions are used as bombarding particles. The particle, accelerated to a very high velocity, can overcome the repulsion and penetrate the target nucleus, thus effecting the transformation. A schematic diagram of one type of particle accelerator, the **cyclotron,** is shown in Fig. 18.5. The ion is introduced at the center of the cyclotron and is accelerated in an expanding spiral path by use of alternating electric fields in the presence of a magnetic field. The **linear accelerator**

CHEMICAL IMPACT

Stellar Nucleosynthesis

How did all the matter around us originate? The scientific answer to this question is a theory called *stellar nucleosynthesis*—literally, the formation of nuclei in stars.

Many scientists believe that our universe originated as a cloud of neutrons that became unstable and produced an immense explosion, giving this model its name—*the big bang theory*. The model postulates that, following the initial explosion, neutrons decomposed into protons and electrons,

$$^{1}_{0}\text{n} \longrightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\text{e}$$

which eventually recombined to form clouds of hydrogen. Over the eons, gravitational forces caused many of these hydrogen clouds to contract and heat up sufficiently to reach temperatures where proton fusion was possible, which released large quantities of energy. When the tendency to expand due to the heat from fusion and the tendency to contract due to the forces of gravity are balanced, a stable young star such as our sun can be formed.

Eventually, when the supply of hydrogen is exhausted, the core of the star will again contract with further heating until temperatures are reached where fusion of helium nuclei can occur, leading to the formation of $^{12}_{6}\text{C}$ and $^{16}_{8}\text{O}$ nuclei. In turn, when the supply of helium nuclei runs out, further contraction and heating will occur, until fusion of heavier nuclei takes place. This process occurs repeatedly, forming heavier and heavier nuclei until iron nuclei are formed. Because the iron nucleus is the most stable of all, energy is required to fuse iron nuclei. This endothermic fusion process cannot furnish energy to sustain the star, and therefore it cools to a small, dense *white dwarf*.

illustrated in Fig. 18.6 employs changing electric fields to achieve high velocities on a linear pathway.

In addition to positive ions, neutrons are often employed as bombarding particles to effect nuclear transformations. Because neutrons are uncharged and thus not repelled electrostatically by a target nucleus, they are readily absorbed by many nuclei, leading to new nuclides. The most common source of neutrons for this purpose is a fission reactor (see Section 18.6).

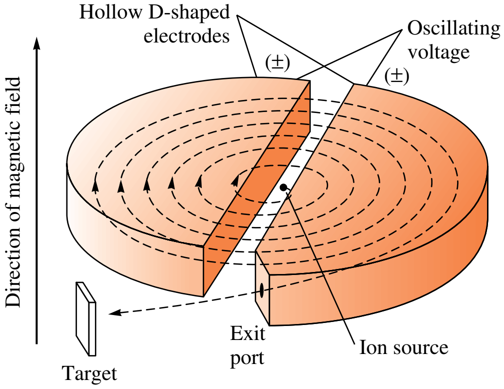


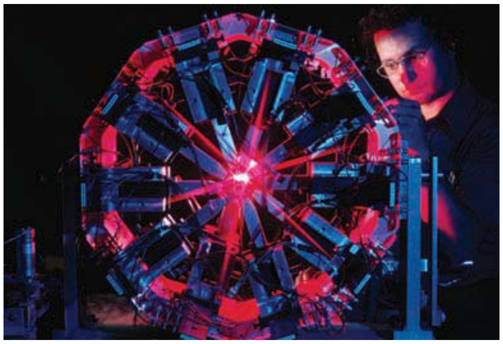
FIGURE 18.5
A schematic diagram of a cyclotron. The ion is introduced in the center and is pulled back and forth between the hollow D-shaped electrodes by constant reversals of the electric field. Magnets above and below these electrodes produce a spiral path that expands as the particle velocity increases. When the particle has sufficient speed, it exits the accelerator and is directed at the target nucleus.

The evolution just described is characteristic of small and medium-sized stars. Much larger stars, however, become unstable at some time during their evolution and undergo a *supernova explosion.* In this explosion, some medium-mass nuclei are fused to form heavy elements. Also, some light nuclei capture neutrons. These neutron-rich nuclei then produce β particles, increasing their atomic number with each event. This eventually leads to heavy nuclei. In fact, almost all nuclei heavier than iron are thought to originate from supernova explosions. The debris of a supernova explosion thus contains a large variety of elements and might eventually form a solar system such as our own.

Although other theories for the origin of matter have been suggested, there is much evidence to support the big bang theory, and it continues to be widely accepted.

Image of a portion of the Cygnus Loop supernova remnant, taken by the Hubble space telescope.

For more information see V. E. Viola, “Formation of the chemical elements and the evolution of our universe,” *J. Chem. Ed.* **67** (1990): 723.



A physicist works with a small cyclotron at the University of California at Berkeley.

By using neutron and positive-ion bombardment, scientists have been able to extend the periodic table. Prior to 1940, the heaviest known element was uranium ($Z = 92$), but in 1940, neptunium ($Z = 93$) was produced by neutron bombardment of ${}^{238}_{92}\text{U}$. The process initially gives ${}^{239}_{92}\text{U}$, which decays to ${}^{239}_{93}\text{Np}$ by β-particle production:

$${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{239}_{92}\text{U} \xrightarrow[t_{1/2}\,=\,23\text{ min}]{} {}^{238}_{92}\text{Np} + {}^{0}_{-1}\text{p}$$

In the years since 1940, the elements with atomic numbers 93 through 112, called the **transuranium elements,*** have been synthesized. Many of these elements have very short half-lives, as shown in Table 18.4. As a result, only a few atoms of some have ever been formed. This, of course, makes the chemical characterization of these elements extremely difficult.

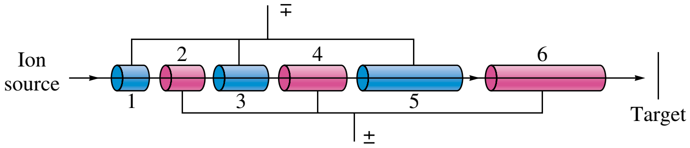


FIGURE 18.6

Schematic diagram of a linear accelerator, which uses a changing electric field to accelerate a positive ion along a linear path. As the ion leaves the source, the odd-numbered tubes are negatively charged, and the even-numbered tubes are positively charged. The positive ion is thus attracted into tube 1. As the ion leaves tube 1, the tube polarities are reversed. Now tube 1 is positive, repelling the positive ion, and tube 2 is negative, attracting the positive ion. This process continues, eventually producing high particle velocity.

---

*For more information see G. B. Kauffman, “Beyond uranium,” *Chem. Eng. News* (Nov. 19, 1990): 18.

TABLE 18.4 Syntheses of Some of the Transuranium Elements

Element	Neutron Bombardment	Half-Life
Neptunium (Z = 93)	$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \longrightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e}$	2.35 days ($^{239}_{93}\text{Np}$)
Plutonium (Z = 94)	$^{239}_{93}\text{Np} \longrightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}$	24,400 years ($^{239}_{94}\text{Pu}$)
Americium (Z = 95)	$^{239}_{94}\text{Pu} + 2\,^{1}_{0}\text{n} \longrightarrow ^{241}_{94}\text{Pu} \longrightarrow ^{241}_{95}\text{Am} + ^{0}_{-1}\text{e}$	458 years ($^{241}_{95}\text{Am}$)
Element	**Positive-Ion Bombardment**	**Half-Life**
Curium (Z = 96)	$^{239}_{94}\text{Pu} + ^{4}_{2}\text{He} \longrightarrow ^{242}_{96}\text{Cm} + ^{1}_{0}\text{n}$	163 days ($^{242}_{96}\text{Cm}$)
Californium (Z = 98)	$^{242}_{96}\text{Cm} + ^{4}_{2}\text{He} \longrightarrow ^{245}_{98}\text{Cf} + ^{1}_{0}\text{n}$ or $^{238}_{92}\text{U} + ^{12}_{6}\text{C} \longrightarrow ^{246}_{98}\text{Cf} + 4\,^{1}_{0}\text{n}$	44 minutes ($^{245}_{98}\text{Cf}$)
Rutherfordium (Z = 104)	$^{249}_{98}\text{Cf} + ^{12}_{6}\text{C} \longrightarrow ^{257}_{104}\text{Rf} + 4\,^{1}_{0}\text{n}$	
Dubnium (Z = 105)	$^{249}_{98}\text{Cf} + ^{15}_{7}\text{N} \longrightarrow ^{260}_{105}\text{Db} + 4\,^{1}_{0}\text{n}$	
Seaborgium (Z = 106)	$^{249}_{98}\text{Cf} + ^{18}_{8}\text{O} \longrightarrow ^{263}_{106}\text{Sg} + 4\,^{1}_{0}\text{n}$	

18.4 Detection and Uses of Radioactivity

Geiger counters are often called *survey meters* in the industry.

Although various instruments measure radioactivity levels, the most familiar of them is the **Geiger–Müller counter,** or **Geiger counter** (see Fig. 18.7). This instrument takes advantage of the fact that the high-energy particles from radioactive decay processes produce ions when they travel through matter. The probe of the Geiger counter is filled with argon gas, which can be ionized by a rapidly moving particle. This reaction is demonstrated by the equation:

$$\text{Ar}(g) \xrightarrow[\text{particle}]{\text{High-energy}} \text{Ar}^{+}(g) + \text{e}^{-}$$

Visualization: Geiger Counter

Normally, a sample of argon gas will not conduct a current when an electrical potential is applied. However, the formation of ions and electrons produced by the passage of the high-energy particle allows a momentary current to flow. Electronic devices detect this current flow, and the number of these events can be counted. Thus the decay rate of the radioactive sample can be determined.

Another instrument often used to detect levels of radioactivity is a **scintillation counter,** which takes advantage of the fact that certain substances, such as zinc sulfide,

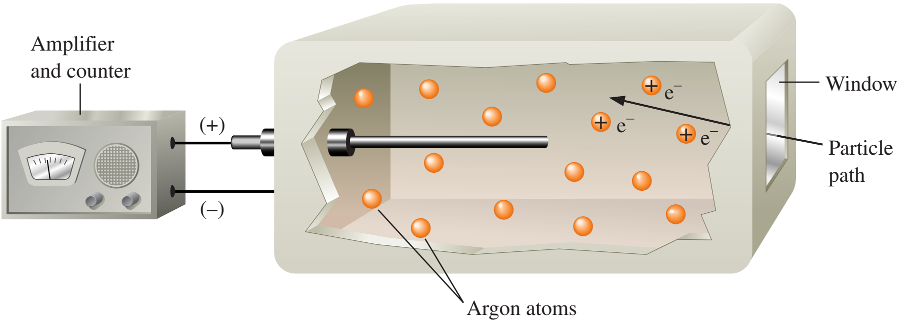


FIGURE 18.7
A schematic representation of a Geiger–Müller counter. The high-energy radioactive particle enters the window and ionizes argon atoms along its path. The resulting ions and electrons produce a momentary current pulse, which is amplified and counted.

give off light when they are struck by high-energy radiation. A photocell senses the flashes of light that occur as the radiation strikes and thus measures the number of decay events per unit of time.

Brigham Young researcher Scott Woodward taking a bone sample for carbon-14 dating at an archeological site in Egypt.

Dating by Radioactivity

Archeologists, geologists, and others involved in reconstructing the ancient history of the earth rely heavily on radioactivity to provide accurate dates for artifacts and rocks. A method that has been very important for dating ancient articles made from wood or cloth is **radiocarbon dating,** or **carbon-14 dating,** a technique originated in the 1940s by Willard Libby, an American chemist who received a Nobel Prize for his efforts in this field.

Radiocarbon dating is based on the radioactivity of the nuclide $^{14}_{6}C$, which decays via β-particle production:

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

Carbon-14 is continuously produced in the atmosphere when high-energy neutrons from space collide with nitrogen-14:

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

Radioactive nuclides are often called *radionuclides.* Carbon dating is based on the radionuclide $^{14}_{6}C$.

The $^{14}_{6}C/^{12}_{6}C$ ratio is the basis for carbon-14 dating.

Thus carbon-14 is continuously produced by this process, and it continuously decomposes through β-particle production. Over the years, the rates for these two processes have become equal, and like a participant in a chemical reaction at equilibrium, the amount of $^{14}_{6}C$ that is present in the atmosphere remains approximately constant.

Carbon-14 can be used to date wood and cloth artifacts because the $^{14}_{6}C$, along with the other carbon isotopes in the atmosphere, reacts with oxygen to form carbon dioxide. A living plant consumes carbon dioxide in the photosynthesis process and incorporates the carbon, including $^{14}_{6}C$, into its molecules. As long as the plant lives, the $^{14}_{6}C/^{12}_{6}C$ ratio in its molecules remains the same as in the atmosphere because of the continuous uptake of carbon. However, as soon as a tree is cut to make a wooden bowl or a flax plant is harvested to make linen, the $^{14}_{6}C/^{12}_{6}C$ ratio begins to decrease because of the radioactive decay of $^{14}_{6}C$ (the $^{12}_{6}C$ nuclide is stable). Since the half-life of $^{14}_{6}C$ is 5730 years, a wooden bowl found in an archeological dig showing a $^{14}_{6}C/^{12}_{6}C$ ratio that is half that found in currently living trees is approximately 5730 years old. This reasoning assumes that the current $^{14}_{6}C/^{12}_{6}C$ ratio is the same as that found in ancient times.

A dendrochronologist cutting a section from a dead tree in South Africa.

Dendrochronologists, scientists who date trees from annual growth rings, have used data collected from long-lived species of trees, such as bristlecone pines and sequoias, to show that the $^{14}_{6}C$ content of the atmosphere has changed significantly over the ages. These data have been used to derive correction factors that allow very accurate dates to be determined from the observed $^{14}_{6}C/^{12}_{6}C$ ratio in an artifact, especially for artifacts 10,000 years old or younger. Recent measurements of uranium/thorium ratios in ancient coral indicate that dates in the 20,000- to 30,000-year range may have errors as large as 3000 years. As a result, efforts are now being made to recalibrate the $^{14}_{6}C$ dates over this period.

Sample Exercise 18.5

^{14}C Dating

The remnants of an ancient fire in a cave in Africa showed a $^{14}_{6}C$ decay rate of 3.1 counts per minute per gram of carbon. Assuming that the decay rate of $^{14}_{6}C$ in freshly cut wood (corrected for changes in the $^{14}_{6}C$ content of the atmosphere) is 13.6 counts per minute per gram of carbon, calculate the age of the remnants. The half-life of $^{14}_{6}C$ is 5730 years.

Solution

The key to solving this problem is to realize that the decay rates given are directly proportional to the number of $^{14}_{6}C$ nuclides present. Radioactive decay follows first-order kinetics:

$$\text{Rate} = kN$$

Thus

↙ Number of nuclides present at time t

$$\frac{3.1 \text{ counts/min} \cdot \text{g}}{13.6 \text{ counts/min} \cdot \text{g}} = \frac{\text{rate at time } t}{\text{rate at time } 0} = \frac{kN}{kN_0}$$

↖ Number of nuclides present at time 0

$$= \frac{N}{N_0} = 0.23$$

We can now use the integrated first-order rate law:

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

where $k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5730 \text{ years}}$

to solve for t, the time elapsed since the campfire:

$$\ln\left(\frac{N}{N_0}\right) = \ln(0.23) = -\left(\frac{0.693}{5730 \text{ years}}\right)t$$

Solving this equation gives $t = 12{,}000$ years; the campfire in the cave occurred about 12,000 years ago.

See Exercises 18.31 and 18.32.

One drawback of radiocarbon dating is that a fairly large piece of the object (from a half to several grams) must be burned to form carbon dioxide, which is then analyzed for radioactivity. Another method for counting ${}^{14}_{6}\text{C}$ nuclides avoids destruction of a significant portion of a valuable artifact. This technique, requiring only about 10^{-3} g, uses a mass spectrometer (see Chapter 3), in which the carbon atoms are ionized and accelerated through a magnetic field that deflects their path. Because of their different masses, the various ions are deflected by different amounts and can be counted separately. This allows a very accurate determination of the ${}^{14}_{6}\text{C}/{}^{12}_{6}\text{C}$ ratio in the sample.

In their attempts to establish the geologic history of the earth, geologists have made extensive use of radioactivity. For example, since ${}^{238}_{92}\text{U}$ decays to the stable ${}^{206}_{82}\text{Pb}$ nuclide, the ratio of ${}^{206}_{82}\text{Pb}$ to ${}^{238}_{92}\text{U}$ in a rock can, under favorable circumstances, be used to estimate the age of the rock. The radioactive nuclide ${}^{176}_{71}\text{Lu}$, which decays to ${}^{176}_{72}\text{Hf}$, has a half-life of 37 billion years (only 186 nuclides out of 10 trillion decay each year!). Thus this nuclide can be used to date very old rocks. With this technique, scientists have estimated that the earth's crust formed 4.3 billion years ago.

Sample Exercise 18.6

Dating by Radioactivity

A rock containing ${}^{238}_{92}\text{U}$ and ${}^{206}_{82}\text{Pb}$ was examined to determine its approximate age. Analysis showed the ratio of ${}^{206}_{82}\text{Pb}$ atoms to ${}^{238}_{92}\text{U}$ atoms to be 0.115. Assuming that no lead was originally present, that all the ${}^{206}_{82}\text{Pb}$ formed over the years has remained in the rock, and that the number of nuclides in intermediate stages of decay between ${}^{238}_{92}\text{U}$ and ${}^{206}_{82}\text{Pb}$ is negligible, calculate the age of the rock. The half-life of ${}^{238}_{92}\text{U}$ is 4.5×10^9 years.

Because the half-life of ${}^{238}_{92}\text{U}$ is very long compared with those of the other members of the decay series (see Table 18.3) to reach ${}^{206}_{82}\text{Pb}$, the number of nuclides present in intermediate stages of decay is negligible. That is, once a ${}^{238}_{92}\text{U}$ nuclide starts to decay, it reaches ${}^{206}_{82}\text{Pb}$ relatively fast.

Solution

This problem can be solved using the integrated first-order rate law:

$$\ln\left(\frac{N}{N_0}\right) = -kt = -\left(\frac{0.693}{4.5 \times 10^9 \text{ years}}\right)t$$

where N/N_0 represents the ratio of ${}^{238}_{92}\text{U}$ atoms now found in the rock to the number present when the rock was formed. We are assuming that each ${}^{206}_{82}\text{Pb}$ nuclide present must have come from decay of a ${}^{238}_{92}\text{U}$ atom:

$$ {}^{238}_{92}\text{U} \longrightarrow {}^{206}_{82}\text{Pb} $$

Thus

$$ \boxed{\begin{array}{c}\text{Number of } {}^{238}_{92}\text{U atoms}\\ \text{originally present}\end{array}} = \boxed{\begin{array}{c}\text{number of } {}^{206}_{82}\text{Pb atoms}\\ \text{now present}\end{array}} + \boxed{\begin{array}{c}\text{number of } {}^{238}_{92}\text{U atoms}\\ \text{now present}\end{array}} $$

$$ \frac{\text{Atoms of } {}^{206}_{82}\text{Pb now present}}{\text{Atoms of } {}^{238}_{92}\text{U now present}} = 0.115 = \frac{0.115}{1.000} = \frac{115}{1000} $$

Think carefully about what this means. For every 1115 ${}^{238}_{92}\text{U}$ atoms originally present in the rock, 115 have been changed to ${}^{206}_{82}\text{Pb}$ and 1000 remain as ${}^{238}_{92}\text{U}$. Thus

$$ \frac{N}{N_0} = \frac{\overset{\text{Now present}}{{}^{238}_{92}\text{U}}}{\underbrace{{}^{206}_{82}\text{Pb} + {}^{238}_{92}\text{U}}_{{}^{238}_{92}\text{U originally present}}} = \frac{1000}{1115} = 0.8969 $$

$$ \ln\left(\frac{N}{N_0}\right) = \ln(0.8969) = -\left(\frac{0.693}{4.5 \times 10^9 \text{ years}}\right)t $$

$$ t = 7.1 \times 10^8 \text{ years} $$

This is the approximate age of the rock. It was formed sometime in the Cambrian period.

See Exercises 18.33 and 18.34.

Medical Applications of Radioactivity

Although the rapid advances of the medical sciences in recent decades are due to many causes, one of the most important has been the discovery and use of **radiotracers,** radioactive nuclides that can be introduced into organisms in food or drugs and whose pathways can be *traced* by monitoring their radioactivity. For example, the incorporation of nuclides such as ${}^{14}_{6}\text{C}$ and ${}^{32}_{15}\text{P}$ into nutrients has produced important information about metabolic pathways.

Iodine-131 has proved very useful in the diagnosis and treatment of illnesses of the thyroid gland. Patients drink a solution containing small amounts of Na^{131}I, and the uptake of the iodine by the thyroid gland is monitored with a scanner (see Fig. 18.8).

A pellet containing radioactive ^{131}I.

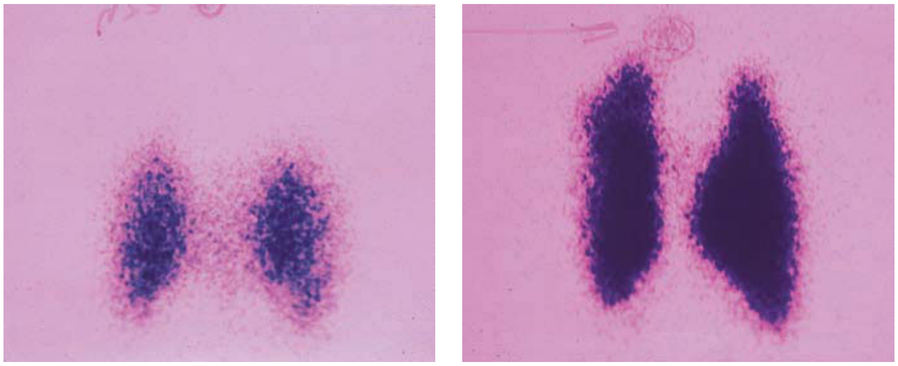


FIGURE 18.8
After consumption of Na^{131}I, the patient's thyroid is scanned for radioactivity levels to determine the efficiency of iodine absorption. (left) A normal thyroid. (right) An enlarged thyroid.

TABLE 18.5 Some Radioactive Nuclides, with Half-Lives and Medical Applications as Radiotracers

Nuclide	Half-Life	Area of the Body Studied
^{131}I	8.1 days	Thyroid
^{59}Fe	45.1 days	Red blood cells
^{99}Mo	67 hours	Metabolism
^{32}P	14.3 days	Eyes, liver, tumors
^{51}Cr	27.8 days	Red blood cells
^{87}Sr	2.8 hours	Bones
^{99m}Tc	6.0 hours	Heart, bones, liver, and lungs
^{133}Xe	5.3 days	Lungs
^{24}Na	14.8 hours	Circulatory system

Thallium-201 can be used to assess the damage to the heart muscle in a person who has suffered a heart attack, because thallium is concentrated in healthy muscle tissue. Technetium-99m is also taken up by normal heart tissue and is used for damage assessment in a similar way.

Radiotracers provide sensitive and noninvasive methods for learning about biologic systems, for detection of disease, for monitoring the action and effectiveness of drugs, and for early detection of pregnancy, and their usefulness should continue to grow. Some useful radiotracers are listed in Table 18.5.

18.5 Thermodynamic Stability of the Nucleus

We can determine the thermodynamic stability of a nucleus by calculating the change in potential energy that would occur if that nucleus were formed from its constituent protons and neutrons. For example, let's consider the hypothetical process of forming a $^{16}_{8}O$ nucleus from eight neutrons and eight protons:

$$8\,^{1}_{0}n + 8\,^{1}_{1}H \longrightarrow {}^{16}_{8}O$$

The energy change associated with this process can be calculated by comparing the sum of the masses of eight protons and eight neutrons with that of the oxygen nucleus:

$$\text{Mass of } (8\,^{1}_{0}n + 8\,^{1}_{1}H) = 8\underbrace{(1.67493 \times 10^{-24}\text{ g})}_{\uparrow\ \text{Mass of } ^{1}_{0}n} + 8\underbrace{(1.67262 \times 10^{-24}\text{ g})}_{\uparrow\ \text{Mass of } ^{1}_{1}H}$$

$$= 2.67804 \times 10^{-23}\text{ g}$$

$$\text{Mass of } ^{16}_{8}O \text{ nucleus} = 2.65535 \times 10^{-23}\text{ g}$$

The difference in mass for one nucleus is

$$\text{Mass of } ^{16}_{8}O - \text{mass of } (8\,^{1}_{0}n + 8\,^{1}_{1}H) = -2.269 \times 10^{-25}\text{ g}$$

The difference in mass for formation of 1 mole of $^{16}_{8}O$ nuclei is therefore

$$(-2.269 \times 10^{-25}\text{ g/nucleus})(6.022 \times 10^{23}\text{ nuclei/mol}) = -0.1366\text{ g/mol}$$

Thus 0.1366 g of mass would be lost if 1 mole of oxygen-16 were formed from protons and neutrons. What is the reason for this difference in mass, and how can this information be used to calculate the energy change that accompanies this process?

Energy is a form of matter.

The answers to these questions can be found in the work of Albert Einstein. As we discussed in Section 7.2, Einstein's theory of relativity showed that energy should be considered a form of matter. His famous equation

$$E = mc^2$$

where c is the speed of light, gives the relationship between a quantity of energy and its mass. When a system gains or loses energy, it also gains or loses a quantity of mass, given by E/c^2. Thus the mass of a nucleus is less than that of its component nucleons because the process is so exothermic.

The energy changes associated with normal chemical reactions are small enough that the corresponding mass changes are not detectable.

Einstein's equation in the form

$$\text{Energy change} = \Delta E = \Delta mc^2$$

where Δm is the change in mass, or the **mass defect,** can be used to calculate ΔE for the hypothetical formation of a nucleus from its component nucleons.

Sample Exercise 18.7 Nuclear Binding Energy I

Calculate the change in energy if 1 mol $^{16}_{8}O$ nuclei was formed from neutrons and protons.

Solution

We have already calculated that 0.1366 g of mass would be lost in the hypothetical process of assembling 1 mol $^{16}_{8}O$ nuclei from the component nucleons. We can calculate the change in energy for this process from

$$\Delta E = \Delta mc^2$$

where

$$c = 3.00 \times 10^8 \text{ m/s} \quad \text{and} \quad \Delta m = -0.1366 \text{ g/mol} = -1.366 \times 10^{-4} \text{ kg/mol}$$

Thus

$$\Delta E = (-1.366 \times 10^{-4} \text{ kg/mol})(3.00 \times 10^8 \text{ m/s})^2 = -1.23 \times 10^{13} \text{ J/mol}$$

The negative sign for the ΔE value indicates that the process is exothermic. Energy, and thus mass, is lost from the system.

See Exercises 18.35 through 18.37.

The energy changes observed for nuclear processes are extremely large compared with those observed for chemical and physical changes. Thus nuclear processes constitute a potentially valuable energy resource.

The thermodynamic stability of a particular nucleus is normally represented as energy released per nucleon. To illustrate how this quantity is obtained, we will continue to consider $^{16}_{8}O$. First, we calculate ΔE per nucleus by dividing the molar value from Sample Exercise 18.7 by Avogadro's number:

$$\Delta E \text{ per } ^{16}_{8}\text{O nucleus} = \frac{-1.23 \times 10^{13} \text{ J/mol}}{6.022 \times 10^{23} \text{ nuclei/mol}} = -2.04 \times 10^{-11} \text{ J/nucleus}$$

In terms of a more convenient energy unit, a million electronvolts (MeV), where

$$1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$$

$$\Delta E \text{ per } ^{16}_{8}\text{O nucleus} = (-2.04 \times 10^{-11} \text{ J/nucleus})\left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}}\right)$$
$$= -1.28 \times 10^{2} \text{ MeV/nucleus}$$

Next, we can calculate the value of ΔE per nucleon by dividing by A, the sum of neutrons and protons:

$$\Delta E \text{ per nucleon for } ^{16}_{8}\text{O} = \frac{-1.28 \times 10^{2} \text{ MeV/nucleus}}{16 \text{ nucleons/nucleus}}$$
$$= -7.98 \text{ MeV/nucleon}$$

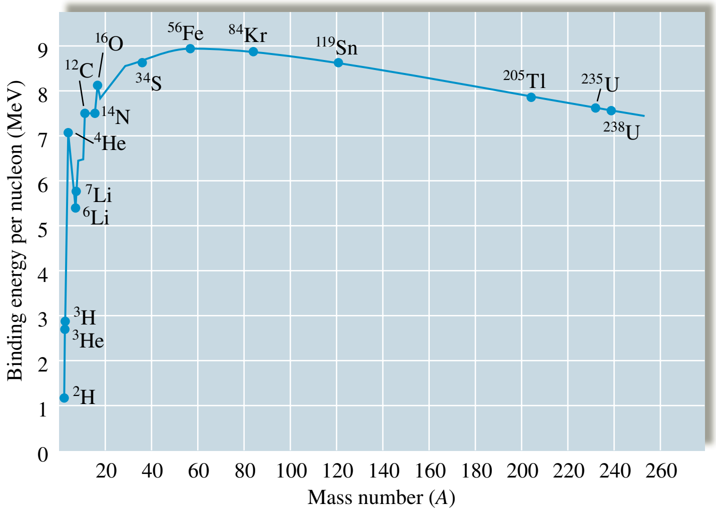


FIGURE 18.9
The binding energy per nucleon as a function of mass number. The most stable nuclei are at the top of the curve. The most stable nucleus is $^{56}_{26}\text{Fe}$.

This means that 7.98 MeV of energy per nucleon would be *released* if $^{16}_{8}\text{O}$ were formed from neutrons and protons. The energy required to *decompose* this nucleus into its components has the same numeric value but a positive sign (since energy is required). This is called the **binding energy** per nucleon for $^{16}_{8}\text{O}$.

The values of the binding energy per nucleon for the various nuclides are shown in Fig. 18.9. Note that the most stable nuclei (those requiring the largest energy per nucleon to decompose the nucleus) occur at the top of the curve. The most stable nucleus known is $^{56}_{26}\text{Fe}$, which has a binding energy per nucleon of 8.79 MeV.

Sample Exercise 18.8 Nuclear Binding Energy II

Calculate the binding energy per nucleon for the $^{4}_{2}\text{He}$ nucleus (atomic masses: $^{4}_{2}\text{He}$ = 4.0026 amu; $^{1}_{1}\text{H}$ = 1.0078 amu).

Solution

First, we must calculate the mass defect (Δm) for $^{4}_{2}\text{He}$. Since atomic masses (which include the electrons) are given, we must decide how to account for the electron mass:

Since atomic masses include the masses of the electrons, to obtain the mass of a given atomic nucleus from its atomic mass, we must subtract the mass of the electrons.

$$4.0026 = \text{mass of } ^{4}_{2}\text{He atom} = \text{mass of } ^{4}_{2}\text{He nucleus} + 2m_e$$

Electron mass

$$1.0078 = \text{mass of } ^{1}_{1}\text{H atom} = \text{mass of } ^{1}_{1}\text{H nucleus} + m_e$$

Thus, since a $^{4}_{2}\text{He}$ nucleus is "synthesized" from two protons and two neutrons, we see that

$$\begin{aligned}\Delta m &= \underbrace{(4.0026 - 2m_e)}_{\text{Mass of } ^{4}_{2}\text{He nucleus}} - [2\underbrace{(1.0078 - m_e)}_{\text{Mass of } ^{1}_{1}\text{H nucleus (proton)}} + 2\underbrace{(1.0087)}_{\text{Mass of neutron}}] \\ &= 4.0026 - 2m_e - 2(1.0078) + 2m_e - 2(1.0087) \\ &= 4.0026 - 2(1.0078) - 2(1.0087) \\ &= -0.0304 \text{ amu}\end{aligned}$$

Note that in this case the electron mass cancels out in taking the difference. This will always happen in this type of calculation if the atomic masses are used both for the nuclide of interest and for $^{1}_{1}\text{H}$. Thus 0.0304 amu of mass is *lost* per $^{4}_{2}\text{He}$ nucleus formed.

The corresponding energy change can be calculated from

$$\Delta E = \Delta mc^2$$

where

$$\Delta m = -0.0304 \frac{\text{amu}}{\text{nucleus}} = \left(-0.0304 \frac{\text{amu}}{\text{nucleus}}\right)\left(1.66 \times 10^{-27} \frac{\text{kg}}{\text{amu}}\right)$$

$$= -5.04 \times 10^{-29} \frac{\text{kg}}{\text{nucleus}}$$

and

$$c = 3.00 \times 10^8 \text{ m/s}$$

Thus

$$\Delta E = \left(-5.04 \times 10^{-29} \frac{\text{kg}}{\text{nucleus}}\right)\left(3.00 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2$$

$$= -4.54 \times 10^{-12} \text{ J/nucleus}$$

This means that 4.54×10^{-12} J of energy is *released* per nucleus formed and that 4.54×10^{-12} J would be required to decompose the nucleus into the constituent neutrons and protons. Thus the binding energy (BE) per nucleon is

$$\text{BE per nucleon} = \frac{4.54 \times 10^{-12} \text{ J/nucleus}}{4 \text{ nucleons/nucleus}}$$

$$= 1.14 \times 10^{-12} \text{ J/nucleon}$$

$$= \left(1.14 \times 10^{-12} \frac{\text{J}}{\text{nucleon}}\right)\left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}}\right)$$

$$= 7.13 \text{ MeV/nucleon}$$

See Exercises 18.38 through 18.40.

18.6 Nuclear Fission and Nuclear Fusion

The graph shown in Fig. 18.9 has very important implications for the use of nuclear processes as sources of energy. Recall that energy is released, that is, ΔE is negative, when a process goes from a less stable to a more stable state. The higher a nuclide is on the curve, the more stable it is. This means that two types of nuclear processes will be exothermic (see Fig. 18.10):

1. Combining two light nuclei to form a heavier, more stable nucleus. This process is called **fusion.**
2. Splitting a heavy nucleus into two nuclei with smaller mass numbers. This process is called **fission.**

Because of the large binding energies involved in holding the nucleus together, both these processes involve energy changes more than a million times larger than those associated with chemical reactions.

Nuclear Fission

Visualization: Nuclear Fission

Nuclear fission was discovered in the late 1930s when $^{235}_{92}\text{U}$ nuclides bombarded with neutrons were observed to split into two lighter elements:

$$^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \longrightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,^{1}_{0}\text{n}$$

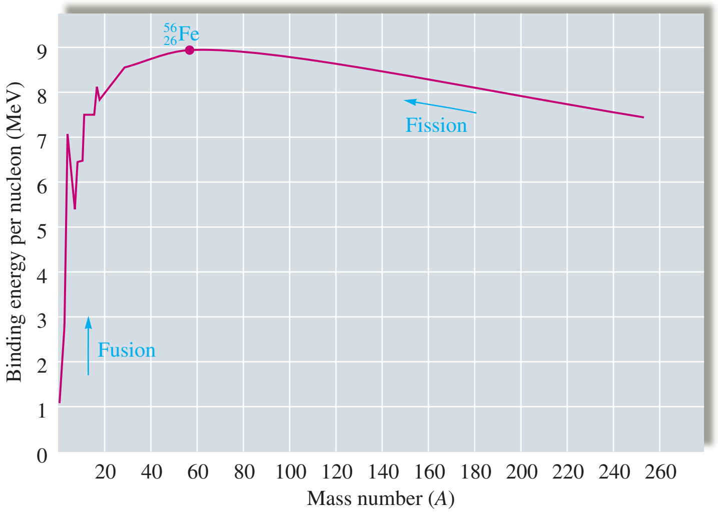


FIGURE 18.10
Both fission and fusion produce more stable nuclides and are thus exothermic.

This process, shown schematically in Fig. 18.11, releases 3.5×10^{-11} J of energy per event, which translates to 2.1×10^{13} J per mole of $^{235}_{92}U$. Compare this figure with that for the combustion of methane, which releases only 8.0×10^{5} J of energy per mole. The fission of $^{235}_{92}U$ produces about 26 million times more energy than the combustion of methane.

The process shown in Fig. 18.11 is only one of the many fission reactions that $^{235}_{92}U$ can undergo. Another is

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{137}_{52}Te + ^{97}_{40}Zr + 2\,^{1}_{0}n$$

In fact, over 200 different isotopes of 35 different elements have been observed among the fission products of $^{235}_{92}U$.

In addition to the product nuclides, neutrons are produced in the fission reactions of $^{235}_{92}U$. This makes it possible to have a self-sustaining fission process—a **chain reaction** (see Fig. 18.12). For the fission process to be self-sustaining, at least one neutron from each fission event must go on to split another nucleus. If, on average, *less than one* neutron causes another fission event, the process dies out and the reaction is said to be **subcritical.** If *exactly one* neutron from each fission event causes another fission event, the process sustains itself at the same level and is said to be **critical.** If *more than one* neutron from each fission event causes another fission event, the process rapidly escalates and the heat buildup causes a violent explosion. This situation is described as **supercritical.**

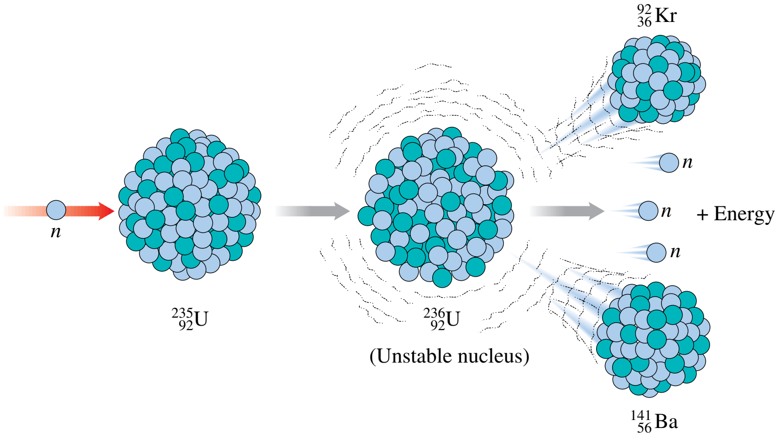


FIGURE 18.11
On capturing a neutron, the $^{235}_{92}U$ nucleus undergoes fission to produce two lighter nuclides, free neutrons (typically three), and a large amount of energy.

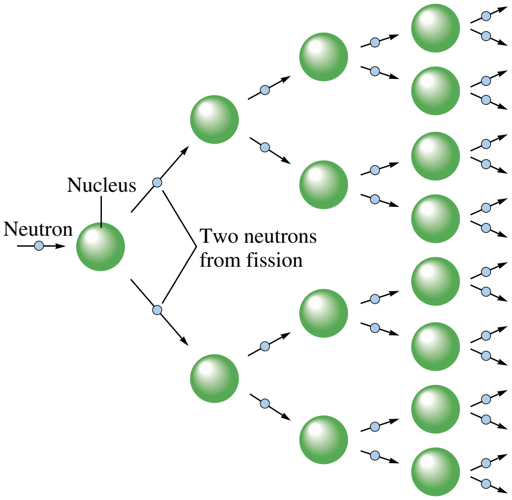


FIGURE 18.12
Representation of a fission process in which each event produces two neutrons, which can go on to split other nuclei, leading to a self-sustaining chain reaction.

To achieve the critical state, a certain mass of fissionable material, called the **critical mass,** is needed. If the sample is too small, too many neutrons escape before they have a chance to cause a fission event, and the process stops. This is illustrated in Fig. 18.13.

During World War II, an intense research effort called the Manhattan Project was carried out by the United States to build a bomb based on the principles of nuclear fission. This program produced the fission bombs that were used with devastating effects on the cities of Hiroshima and Nagasaki in 1945. Basically, a fission bomb operates by suddenly combining subcritical masses of fissionable material to form a supercritical mass, thereby producing an explosion of incredible intensity.

Nuclear Reactors

Because of the tremendous energies involved, it seemed desirable to develop the fission process as an energy source to produce electricity. To accomplish this, reactors were designed in which controlled fission can occur. The resulting energy is used to heat water to produce steam to run turbine generators, in much the same way that a coal-burning power plant generates energy. A schematic diagram of a nuclear power plant is shown in Fig. 18.14.

In the **reactor core,** shown in Fig. 18.15, uranium that has been enriched to approximately 3% $^{235}_{92}\text{U}$ (natural uranium contains only 0.7% $^{235}_{92}\text{U}$) is housed in cylinders. A **moderator** surrounds the cylinders to slow down the neutrons so that the uranium fuel can capture them more efficiently. **Control rods,** composed of substances that absorb

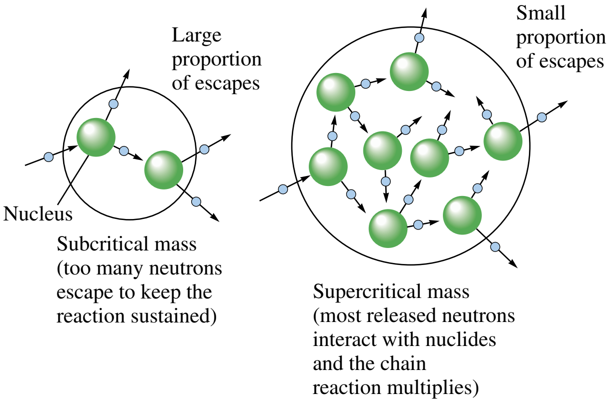


FIGURE 18.13
If the mass of fissionable material is too small, most of the neutrons escape before causing another fission event, and the process dies out.

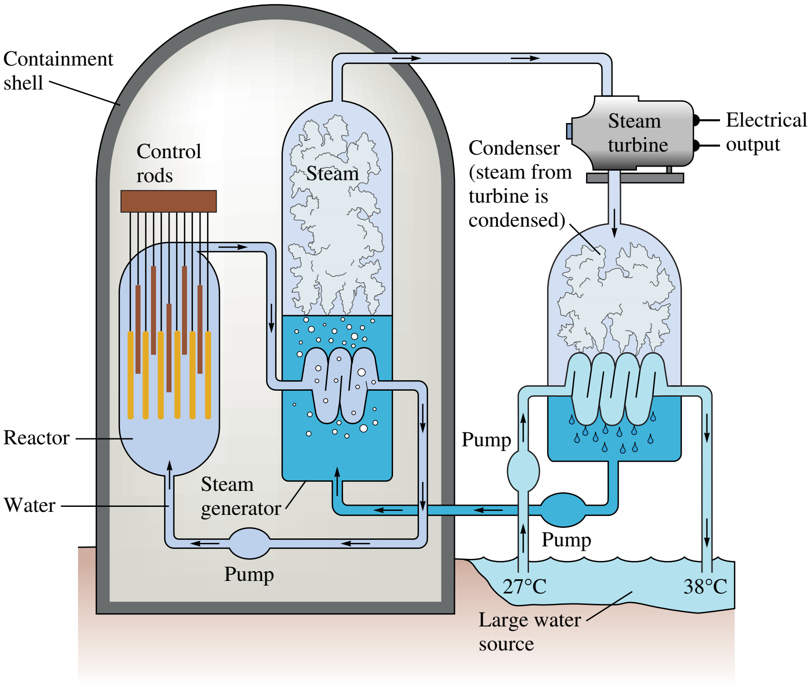


FIGURE 18.14
A schematic diagram of a nuclear power plant.

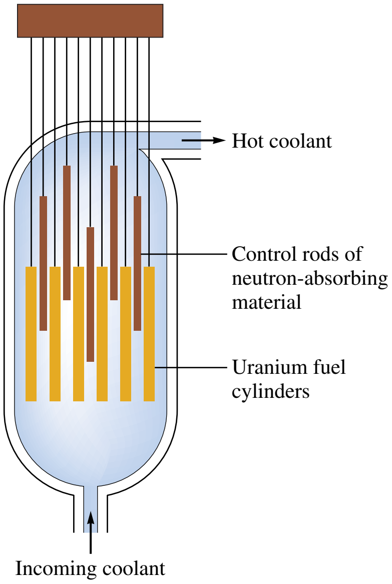


FIGURE 18.15
A schematic of a reactor core. The position of the control rods determines the level of energy production by regulating the amount of fission taking place.

neutrons, are used to regulate the power level of the reactor. The reactor is designed so that should a malfunction occur, the control rods are automatically inserted into the core to stop the reaction. A liquid (usually water) is circulated through the core to extract the heat generated by the energy of fission; the energy can then be passed on via a heat exchanger to water in the turbine system.

Although the concentration of ${}^{235}_{92}\text{U}$ in the fuel elements is not great enough to allow a supercritical mass to develop in the core, a failure of the cooling system can lead to temperatures high enough to melt the core. As a result, the building housing the core must be designed to contain the core even if meltdown occurs. A great deal of controversy now exists about the efficiency of the safety systems in nuclear power plants. Accidents such as the one at the Three Mile Island facility in Pennsylvania in 1979 and in Chernobyl,* Ukraine, in 1986 have led to questions about the wisdom of continuing to build fission-based power plants.

Uranium oxide (refined uranium).

Breeder Reactors

One potential problem facing the nuclear power industry is the supply of ${}^{235}_{92}\text{U}$. Some scientists have suggested that we have nearly depleted those uranium deposits rich enough in ${}^{235}_{92}\text{U}$ to make production of fissionable fuel economically feasible. Because of this possibility, **breeder reactors** have been developed, in which fissionable fuel is actually produced while the reactor runs. In the breeder reactors now being studied, the major component of natural uranium, nonfissionable ${}^{238}_{92}\text{U}$, is changed to fissionable ${}^{239}_{94}\text{Pu}$. The reaction involves absorption of a neutron, followed by production of two β particles:

$$
\begin{aligned}
{}^{1}_{0}\text{n} + {}^{238}_{92}\text{U} &\longrightarrow {}^{239}_{92}\text{U} \\
{}^{239}_{92}\text{U} &\longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e} \\
{}^{239}_{93}\text{Np} &\longrightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}
\end{aligned}
$$

---

*See C. A. Atwood, "Chernobyl—What happened?" *J. Chem. Ed.* 65 (1988): 1037.

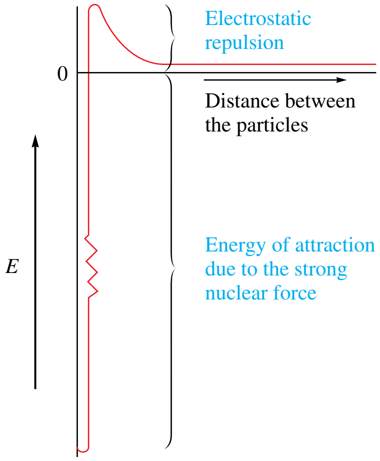


FIGURE 18.16
A plot of energy versus the separation distance for two $^{2}_{1}H$ nuclei. The nuclei must have sufficient velocities to get over the electrostatic repulsion "hill" and get close enough for the nuclear binding forces to become effective, thus "fusing" the particles into a new nucleus and releasing large quantities of energy. The binding force is at least 100 times the electrostatic repulsion.

As the reactor runs and $^{235}_{92}U$ is split, some of the excess neutrons are absorbed by $^{238}_{92}U$ to produce $^{239}_{94}Pu$. The $^{239}_{94}Pu$ is then separated out and used to fuel another reactor. Such a reactor thus "breeds" nuclear fuel as it operates.

Although breeder reactors are now used in France, the United States is proceeding slowly with their development because of their controversial nature. One problem involves the hazards in handling plutonium, which flames on contact with air and is very toxic.

Fusion

Visualization: Nuclear Fusion

Large quantities of energy are also produced by the fusion of two light nuclei. In fact, stars produce their energy through nuclear fusion. Our sun, which presently consists of 73% hydrogen, 26% helium, and 1% other elements, gives off vast quantities of energy from the fusion of protons to form helium:

$$
\begin{aligned}
{}^{1}_{1}H + {}^{1}_{1}H &\longrightarrow {}^{2}_{1}H + {}^{0}_{1}e \\
{}^{1}_{1}H + {}^{2}_{1}H &\longrightarrow {}^{3}_{2}He \\
{}^{3}_{2}He + {}^{3}_{2}He &\longrightarrow {}^{4}_{2}He + 2\,{}^{1}_{1}H \\
{}^{3}_{2}He + {}^{1}_{1}H &\longrightarrow {}^{4}_{2}He + {}^{0}_{1}e
\end{aligned}
$$

Intense research is under way to develop a feasible fusion process because of the ready availability of many light nuclides (deuterium, $^{2}_{1}H$, in seawater, for example) that can serve as fuel in fusion reactors. The major stumbling block is that high temperatures are required to initiate fusion. The forces that bind nucleons together to form a nucleus are effective only at *very small* distances ($\sim 10^{-13}$ cm). Thus, for two protons to bind together and thereby release energy, they must get very close together. But protons, because they are identically charged, repel each other electrostatically. This means that to get two protons (or two deuterons) close enough to bind together (the nuclear binding force is *not* electrostatic), they must be "shot" at each other at speeds high enough to overcome the electrostatic repulsion.

The electrostatic repulsion forces between two $^{2}_{1}H$ nuclei are so great that a temperature of 4×10^{7} K is required to give them velocities large enough to cause them to collide with sufficient energy that the nuclear forces can bind the particles together and thus release the binding energy. This situation is represented in Fig. 18.16.

Currently, scientists are studying two types of systems to produce the extremely high temperatures required: high-powered lasers and heating by electric currents. At present, many technical problems remain to be solved, and it is not clear which method will prove more useful or when fusion might become a practical energy source. However, there is still hope that fusion will be a major energy source sometime in the future.

18.7 Effects of Radiation

Everyone knows that being hit by a train is very serious. The problem is the energy transfer involved. In fact, any source of energy is potentially harmful to organisms. Energy transferred to cells can break chemical bonds and cause malfunctioning of the cell systems. This fact is behind the concern about the ozone layer in the earth's upper atmosphere, which screens out high-energy ultraviolet radiation from the sun. Radioactive elements, which are sources of high-energy particles, are also potentially hazardous, although the effects are usually quite subtle. The reason for the subtlety of radiation damage is that even though high-energy particles are involved, the quantity of energy actually deposited in tissues *per event* is quite small. However, the resulting damage is no less real, although the effects may not be apparent for years.

The ozone layer is discussed in Section 20.5.

CHEMICAL IMPACT

Nuclear Physics: An Introduction

Nuclear physics is concerned with the fundamental nature of matter. The central focuses of this area of study are the relationship between a quantity of energy and its mass, given by $E = mc^2$, and the fact that matter can be converted from one form (energy) to another (particulate) in particle accelerators. Collisions between high-speed particles have produced a dazzling array of new particles—hundreds of them. These events can best be interpreted as conversions of kinetic energy into particles. For example, a collision of sufficient energy between a proton and a neutron can produce four particles: two protons, one antiproton, and a neutron:

$$^{1}_{1}\mathrm{H} + ^{1}_{0}\mathrm{n} \longrightarrow 2\,^{1}_{1}\mathrm{H} + ^{\;\,1}_{-1}\mathrm{H} + ^{1}_{0}\mathrm{n}$$

where $^{\;\,1}_{-1}\mathrm{H}$ is the symbol for an *antiproton,* which has the same mass as a proton but the opposite charge. This process is a little like throwing one baseball at a very high speed into another and having the energy of the collision converted into two additional baseballs.

The results of such accelerator experiments have led scientists to postulate the existence of three types of forces important in the nucleus: the *strong force,* the *weak force,* and the *electromagnetic force.* Along with the *gravitational force,* these forces are thought to account for all types of interactions found in matter. These forces are believed to be generated by the exchange of particles between the interacting pieces of matter. For example, gravitational forces are thought to be carried by particles called *gravitons.* The electromagnetic force (the classical electrostatic force between charged particles) is assumed to be exerted through the exchange of *photons.* The strong force, not charge-related and effective only at very short distances ($\sim 10^{-13}$ cm), is postulated to involve the exchange of particles called *gluons.* The weak force is 100 times weaker than the strong force and seems to be exerted through the exchange of two types of large particles, the W (has a mass 70 times the proton mass) and the Z (has a mass 90 times the proton mass).

The particles discovered have been classified into several categories. Three of the most important classes are as follows:

1. *Hadrons* are particles that respond to the strong force and have internal structure.
2. *Leptons* are particles that do not respond to the strong force and have no internal structure.
3. *Quarks* are particles with no internal structure that are thought to be the fundamental constituents of hadrons. Neutrons and protons are hadrons that are thought to be composed of three quarks each.

The world of particle physics appears mysterious and complicated. For example, particle physicists have discovered new properties of matter they call “color,” “charm,”

Radiation damage to organisms can be classified as somatic or genetic damage. **Somatic damage** is damage to the organism itself, resulting in sickness or death. The effects may appear almost immediately if a massive dose of radiation is received; for smaller doses, damage may appear years later, usually in the form of cancer. **Genetic damage** is damage to the genetic machinery, which produces malfunctions in the offspring of the organism.

The biologic effects of a particular source of radiation depend on several factors:

1. *The energy of the radiation.* The higher the energy content of the radiation, the more damage it can cause. Radiation doses are measured in **rads** (which is short for *r*adiation *a*bsorbed *d*ose), where 1 rad corresponds to 10^{-2} J of energy deposited per kilogram of tissue.
2. *The penetrating ability of the radiation.* The particles and rays produced in radioactive processes vary in their abilities to penetrate human tissue: γ rays are highly penetrating, β particles can penetrate approximately 1 cm, and α particles are stopped by the skin.
3. *The ionizing ability of the radiation.* Extraction of electrons from biomolecules to form ions is particularly detrimental to their functions. The ionizing ability of radiation

and "strangeness" and have postulated conservation laws involving these properties. This area of science is extremely important because it should help us to understand the interactions of matter in a more elegant and unified way. For example, the classification of force into four categories is probably necessary only because we do not understand the true nature of forces. All forces may be special cases of a single, all-pervading force field that governs all of nature. In fact, Einstein spent the last 30 years of his life looking for a way to unify the gravitational and electromagnetic forces—without success. Physicists may now be on the verge of accomplishing what Einstein failed to do.

Although the practical aspects of the work in nuclear physics are not yet totally apparent, a more fundamental understanding of the way nature operates could lead to presently undreamed-of devices for energy production and communication, which could revolutionize our lives.

(left) An aerial view of Fermilab, a high-energy particle accelerator in Batavia, Illinois. (right) The accelerator tunnel at Fermilab.

varies dramatically. For example, γ rays penetrate very deeply but cause only occasional ionization. On the other hand, α particles, although not very penetrating, are very effective at causing ionization and produce a dense trail of damage. Thus ingestion of an α-particle producer, such as plutonium, is particularly damaging.

4. *The chemical properties of the radiation source.* When a radioactive nuclide is ingested into the body, its effectiveness in causing damage depends on its residence time. For example, ${}^{85}_{36}\text{Kr}$ and ${}^{90}_{38}\text{Sr}$ are both β-particle producers. However, since krypton is chemically inert, it passes through the body quickly and does not have much time to do damage. Strontium, being chemically similar to calcium, can collect in bones, where it may cause leukemia and bone cancer.

Because of the differences in the behavior of the particles and rays produced by radioactive decay, both the energy dose of the radiation and its effectiveness in causing biologic damage must be taken into account. The **rem** (which is short for *r*oentgen *e*quivalent for *m*an) is defined as follows:

$$\text{Number of rems} = (\text{number of rads}) \times \text{RBE}$$

where RBE represents the relative effectiveness of the radiation in causing biologic damage.

TABLE 18.6 Effects of Short-Term Exposures to Radiation

Dose (rem)	Clinical Effect
0–25	Nondetectable
25–50	Temporary decrease in white blood cell counts
100–200	Strong decrease in white blood cell counts
500	Death of half the exposed population within 30 days after exposure

TABLE 18.7 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

	Exposure (millirems/year)
Cosmic radiation	50
From the earth	47
From building materials	3
In human tissues	21
Inhalation of air	5
Total from natural sources	126
X-ray diagnosis	50
Radiotherapy	10
Internal diagnosis/therapy	1
Nuclear power industry	0.2
TV tubes, industrial wastes, etc.	2
Radioactive fallout	4
Total from human activities	67
Total	193

Table 18.6 shows the physical effects of short-term exposure to various doses of radiation, and Table 18.7 gives the sources and amounts of radiation exposure for a typical person in the United States. Note that natural sources contribute about twice as much as human activities to the total exposure. However, although the nuclear industry contributes only a small percentage of the total exposure, the major controversy associated with nuclear power plants is the *potential* for radiation hazards. These arise mainly from two sources: accidents allowing the release of radioactive materials and improper disposal of the radioactive products in spent fuel elements. The radioactive products of the fission of $^{235}_{92}U$, although only a small percentage of the total products, have half-lives of several hundred years and remain dangerous for a long time. Various schemes have been advanced for the disposal of these wastes. The one that seems to hold the most promise is the incorporation of the wastes into ceramic blocks and the burial of these blocks in geologically stable formations. At present, however, no disposal method has been accepted, and nuclear wastes continue to accumulate in temporary storage facilities.

Even if a satisfactory method for permanent disposal of nuclear wastes is found, there will continue to be concern about the effects of exposure to low levels of radiation. Exposure is inevitable from natural sources such as cosmic rays and radioactive minerals, and many people are also exposed to low levels of radiation from reactors, radioactive tracers, or diagnostic X rays. Currently, we have little reliable information on the long-term effects of low-level exposure to radiation.

Two models of radiation damage, illustrated in Fig. 18.17, have been proposed: the *linear model* and the *threshold model.* The linear model postulates that damage from radiation is proportional to the dose, even at low levels of exposure. Thus any exposure is dangerous. The threshold model, on the other hand, assumes that no significant damage occurs below a certain exposure, called the *threshold exposure.* Note that if the linear model is correct, radiation exposure should be limited to a bare minimum (ideally at the natural levels). If the threshold model is correct, a certain level of radiation exposure beyond natural levels can be tolerated. Most scientists feel that since there is little evidence available to evaluate these models, it is safest to assume that the linear hypothesis is correct and to minimize radiation exposure.

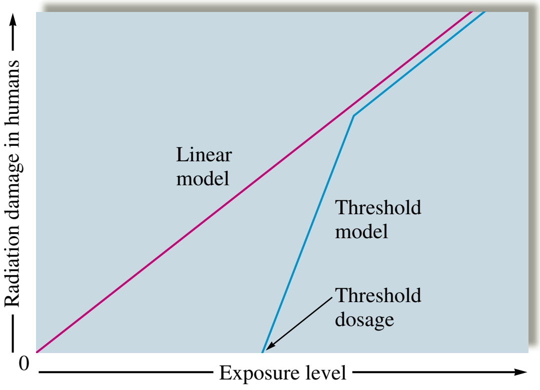


FIGURE 18.17
The two models for radiation damage. In the linear model, even a small dosage causes a proportional risk. In the threshold model, risk begins only after a certain dosage.

Key Terms

neutron
proton
nucleon
atomic number
mass number
isotopes
nuclide

Section 18.1

thermodynamic stability
kinetic stability
radioactive decay
beta (β) particle
zone of stability
alpha (α) particle
α-particle production
spontaneous fission
β-particle production
gamma (γ) ray
positron production
electron capture
decay series

Section 18.2

rate of decay
half-life

Section 18.3

nuclear transformation
particle accelerator
cyclotron
linear accelerator
transuranium elements

Section 18.4

Geiger–Müller counter (Geiger counter)
scintillation counter
radiocarbon dating (carbon-14 dating)
radiotracers

Section 18.5

mass defect
binding energy

Section 18.6

fusion
fission
chain reaction
subcritical reaction
critical reaction
supercritical reaction
critical mass
reactor core
moderator
control rods
breeder reactor

Section 18.7

somatic damage
genetic damage
rad
rem

For Review

Radioactivity

- Certain nuclei decay spontaneously into more stable nuclei
- Types of radioactive decay:
  - α-particle ($^{4}_{2}\text{He}$) production
  - β-particle ($^{0}_{-1}\text{e}$) production
  - Positron ($^{0}_{1}\text{e}$) production
  - γ rays are usually produced in a radioactive decay event
- A decay series involves several radioactive decays to finally reach a stable nuclide
- Radioactive decay follows first-order kinetics
  - Half-life of a radioactive sample: the time required for half of the nuclides to decay
- The transuranium elements (those beyond uranium in the periodic table) can be synthesized by particle bombardment of uranium or heavier elements
- Radiocarbon dating employs the $^{14}_{6}\text{C}/^{12}_{6}\text{C}$ ratio in an object to establish its date of origin

Thermodynamic stability of a nucleus

- Compares the mass of a nucleus to the sum of the masses of its component nucleons
- When a system gains or loses energy, it also gains or loses mass as described by the relationship $E = mc^2$
- The difference between the sum of the masses of the component nucleons and the actual mass of a nucleus (called the mass defect) can be used to calculate the nuclear binding energy

Nuclear energy production

- Fusion: the process of combining two light nuclei to form a heavier, more stable nucleus
- Fission: the process of splitting a heavy nucleus into two lighter, more stable nuclei
  - Current nuclear power reactors employ controlled fission to produce energy

Radiation damage

- Radiation can cause direct (somatic) damage to a living organism or genetic damage to the organism's offspring
- The biologic effects of radiation depend on the energy, the penetrating ability, the ionizing ability of the radiation, and the chemical properties of the nuclide producing the radiation

REVIEW QUESTIONS

1. Define or illustrate the following terms:
   a. thermodynamic stability
   b. kinetic stability
   c. radioactive decay
   d. beta-particle production
   e. alpha-particle production
   f. positron production
   g. electron capture
   h. gamma-ray emissions

   In radioactive decay processes, *A* and *Z* are conserved. What does this mean?
2. Figure 18.1 illustrates the zone of stability. What is the zone of stability? Stable light nuclides have about equal numbers of neutrons and protons. What happens to the neutron-to-proton ratio for stable nuclides as the number of protons

increases? Nuclides that are not already in the zone of stability undergo radioactive processes to get to the zone of stability. If a nuclide has too many neutrons, which process(es) can the nuclide undergo to become more stable? Answer the same question for a nuclide having too many protons.

3. All radioactive decay processes follow first-order kinetics. What does this mean? What happens to the rate of radioactive decay as the number of nuclides is halved? Write the first-order rate law and the integrated first-order rate law. Define the terms in each equation. What is the half-life equation for radioactive decay processes? How does the half-life depend on how many nuclides are present? Are the half-life and rate constant k directly related or inversely related?
4. What is a nuclear transformation? How do you balance nuclear transformation reactions? Particle accelerators are used to perform nuclear transformations. What is a particle accelerator?
5. What is a Geiger counter and how does it work? What is a scintillation counter and how does it work? Radiotracers are used in the medical sciences to learn about metabolic pathways. What are radiotracers? Explain why ^{14}C and ^{32}P radioactive nuclides would be very helpful in learning about metabolic pathways. Why is I-131 useful for diagnosis of diseases of the thyroid? How could you use a radioactive nuclide to demonstrate that chemical equilibrium is a dynamic process?
6. Explain the theory behind carbon-14 dating. What assumptions must be made and what problems arise when using carbon-14 dating?

   The decay of uranium-238 to lead-206 is also used to estimate the age of objects. Specifically, ^{206}Pb-to-^{238}U ratios allow dating of rocks. Why is the ^{238}U decay to ^{206}Pb useful for dating rocks but worthless for dating objects 10,000 years old or younger? Similarly, why is carbon-14 dating useful for dating objects 10,000 years old or younger but worthless for dating rocks?
7. Define *mass defect* and *binding energy.* How do you determine the mass defect for a nuclide? How do you convert the mass defect into the binding energy for a nuclide? Iron-56 has the largest binding energy per nucleon among all known nuclides. Is this good or bad for iron-56? Explain.
8. Define *fission* and *fusion.* How does the energy associated with fission or fusion processes compare to the energy changes associated with chemical reactions? Fusion processes are more likely to occur for lighter elements, whereas fission processes are more likely to occur for heavier elements. Why? (*Hint:* Reference Figure 18.10.) The major stumbling block for turning fusion reactions into a feasible source of power is the high temperature required to initiate a fusion reaction. Why are elevated temperatures necessary to initiate fusion reactions but not fission reactions?
9. The fission of U-235 is used exclusively in nuclear power plants located in the United States. There are many different fission reactions of U-235, but all the fission reactions are self-sustaining chain reactions. Explain. Differentiate between the terms *critical, subcritical,* and *supercritical.* What is the critical mass? How does a nuclear power plant produce electricity? What are the purposes of the moderator and the control rods in a fission reactor? What are some problems associated with nuclear reactors? What are breeder reactors? What are some problems associated with breeder reactors?
10. The biological effects of a particular source of radiation depend on several factors. List some of these factors. Even though ^{85}Kr and ^{90}Sr are both beta-particle emitters, the dangers associated with the decay of ^{90}Sr are much greater than those linked to ^{85}Kr. Why? Although gamma rays are far more penetrating than alpha particles, the latter are more likely to cause damage to an organism. Why? Which type of radiation is more effective at promoting the ionization of biomolecules?

A blue question or exercise number indicates that the answer to that question or exercise appears at the back of this book and a solution appears in the *Solutions Guide.*

Questions

1. When nuclei undergo nuclear transformations, γ rays of characteristic frequencies are observed. How does this fact, along with other information in the chapter on nuclear stability, suggest that a quantum mechanical model may apply to the nucleus?
2. There is a trend in the United States toward using coal-fired power plants to generate electricity rather than building new nuclear fission power plants. Is the use of coal-fired power plants without risk? Make a list of the risks to society from the use of each type of power plant.
3. Which type of radioactive decay has the net effect of changing a neutron into a proton? Which type of decay has the net effect of turning a proton into a neutron?
4. What is annihilation in terms of nuclear processes?
5. What are transuranium elements and how are they synthesized?
6. Scientists have estimated that the earth's crust was formed 4.3 billion years ago. The radioactive nuclide ^{176}Lu, which decays to ^{176}Hf, was used to estimate this age. The half-life of ^{176}Lu is 37 billion years. How are ratios of ^{176}Lu to ^{176}Hf utilized to date very old rocks?
7. Why are the observed energy changes for nuclear processes so much larger than the energy changes for chemical and physical processes?
8. Natural uranium is mostly nonfissionable ^{238}U; it contains only about 0.7% of fissionable ^{235}U. For uranium to be useful as a nuclear fuel, the relative amount of ^{235}U must be increased to about 3%. This is accomplished through a gas diffusion process. In the diffusion process, natural uranium reacts with fluorine to form a mixture of $^{238}UF_6(g)$ and $^{235}UF_6(g)$. The fluoride mixture is then enriched through a multistage diffusion process to produce a 3% ^{235}U nuclear fuel. The diffusion process utilizes Graham's law of effusion (see Chapter 5, Section 5.7). Explain how Graham's law of effusion allows natural uranium to be enriched by the gaseous diffusion process.
9. Strontium-90 and radon-222 both pose serious health risks. ^{90}Sr decays by β-particle production and has a relatively long half-life (28.8 yr). Radon-222 decays by alpha-particle production and has a relatively short half-life (3.82 days). Explain why each decay process poses health risks.
10. A recent study concluded that any amount of radiation exposure can cause biological damage. Explain the differences between the two models of radiation damage, the linear model and the threshold model.

Exercises

In this section similar exercises are paired.

Radioactive Decay and Nuclear Transformations

11. Write balanced equations for each of the processes described below.
    - **a.** Chromium-51, which targets the spleen and is used as a tracer in studies of red blood cells, decays by electron capture.
    - **b.** Iodine-131, used to treat hyperactive thyroid glands, decays by producing a β particle.
12. Write balanced equations for each of the processes described below.
    - **a.** Phosphorus-32, which accumulates in the liver, decays by β-particle production.
    - **b.** Uranium-235, which is used in atomic bombs, decays initially by α-particle production.
13. Write an equation describing the radioactive decay of each of the following nuclides. (The particle produced is shown in parentheses, except for electron capture, where an electron is a reactant.)
    - **a.** ^{68}Ga (electron capture) **c.** ^{212}Fr (α)
    - **b.** ^{62}Cu (positron) **d.** ^{129}Sb (β)
14. In each of the following nuclear reactions, supply the missing particle.
    - **a.** $^{73}\text{Ga} \rightarrow {}^{73}\text{Ge} + ?$ **c.** $^{205}\text{Bi} \rightarrow {}^{205}\text{Pb} + ?$
    - **b.** $^{192}\text{Pt} \rightarrow {}^{188}\text{Os} + ?$ **d.** $^{241}\text{Cm} + ? \rightarrow {}^{241}\text{Am}$
15. The radioactive isotope ^{247}Bk decays by a series of α-particle and β-particle productions, taking ^{247}Bk through many transformations to end up as ^{207}Pb. In the complete decay series, how many α particles and β particles are produced?
16. One type of commercial smoke detector contains a minute amount of radioactive americium-241 (^{241}Am), which decays by α-particle production. The α particles ionize molecules in the air, allowing it to conduct an electric current. When smoke particles enter, the conductivity of the air is changed and the alarm buzzes.
    - **a.** Write the equation for the decay of $^{241}_{95}$Am by α-particle production.
    - **b.** The complete decay of ^{241}Am involves successively α, α, β, α, α, β, α, α, α, β, α, and β production. What is the final stable nucleus produced in this decay series?
    - **c.** Identify the 11 intermediate nuclides.
17. There are four stable isotopes of iron with mass numbers 54, 56, 57, and 58. There are also two radioactive isotopes: iron-53 and iron-59. Predict modes of decay for these two isotopes. (See Table 18.2.)
18. The only stable isotope of fluorine is fluorine-19. Predict possible modes of decay for fluorine-21, fluorine-18, and fluorine-17.
19. In 1994 it was proposed (and eventually accepted) that element 106 be named seaborgium, Sg, in honor of Glenn T. Seaborg, discoverer of the transuranium elements.
    - **a.** ^{263}Sg was produced by the bombardment of ^{249}Cf with a beam of ^{18}O nuclei. Complete and balance an equation for this reaction.
    - **b.** ^{263}Sg decays by α emission. What is the other product resulting from the α decay of ^{263}Sg?
20. Many elements have been synthesized by bombarding relatively heavy atoms with high-energy particles in particle accelerators. Complete the following nuclear reactions, which have been used to synthesize elements.
    - **a.** $\_\_\_\_\_\_\_\_ + {}^{4}_{2}\text{He} \rightarrow {}^{243}_{97}\text{Bk} + {}^{1}_{0}\text{n}$
    - **b.** ${}^{238}_{92}\text{U} + {}^{12}_{6}\text{C} \rightarrow \_\_\_\_\_\_\_\_ + 6\,{}^{1}_{0}\text{n}$
    - **c.** ${}^{249}_{98}\text{Cf} + \_\_\_\_\_\_\_\_ \rightarrow {}^{260}_{105}\text{Db} + 4\,{}^{1}_{0}\text{n}$
    - **d.** ${}^{249}_{98}\text{Cf} + {}^{10}_{5}\text{B} \rightarrow {}^{257}_{103}\text{Lr} + \_\_\_\_\_\_\_\_$

Kinetics of Radioactive Decay

21. The rate constant for a certain radioactive nuclide is $1.0 \times 10^{-3}\ h^{-1}$. What is the half-life of this nuclide?

22. Americium-241 is widely used in smoke detectors. The radiation released by this element ionizes particles that are then detected by a charged-particle collector. The half-life of ^{241}Am is 432.2 years, and it decays by emitting alpha particles. How many alpha particles are emitted each second by a 5.00-g sample of ^{241}Am?

23. Krypton consists of several radioactive isotopes, some of which are listed in the following table.

	Half-life
Kr-73	27 s
Kr-74	11.5 min
Kr-76	14.8 h
Kr-81	2.1×10^5 yr

Which of these isotopes is most stable and which isotope is "hottest"? How long does it take for 87.5% of each isotope to decay?

24. Radioactive copper-64 decays with a half-life of 12.8 days.

a. What is the value of k in s^{-1}?

b. A sample contains 28.0 mg ^{64}Cu. How many decay events will be produced in the first second? Assume the atomic mass of ^{64}Cu is 64.0.

c. A chemist obtains a fresh sample of ^{64}Cu and measures its radioactivity. She then determines that to do an experiment, the radioactivity cannot fall below 25% of the initial measured value. How long does she have to do the experiment?

25. Phosphorus-32 is a commonly used radioactive nuclide in biochemical research, particularly in studies of nucleic acids. The half-life of phosphorus-32 is 14.3 days. What mass of phosphorus-32 is left from an original sample of 175 mg of $Na_3{}^{32}PO_4$ after 35.0 days? Assume the atomic mass of ^{32}P is 32.0.

26. The curie (Ci) is a commonly used unit for measuring nuclear radioactivity: 1 curie of radiation is equal to 3.7×10^{10} decay events per second (the number of decay events from 1 g of radium in 1 s).

a. What mass of $Na_2{}^{38}SO_4$ has an activity of 10.0 mCi? Sulfur-38 has an atomic mass of 38.0 and a half-life of 2.87 h.

b. How long does it take for 99.99% of a sample of sulfur-38 to decay?

27. The first atomic explosion was detonated in the desert north of Alamogordo, New Mexico, on July 16, 1945. What fraction of the strontium-90 ($t_{1/2} = 28.8$ years) originally produced by that explosion still remains as of July 16, 2006?

28. Iodine-131 is used in the diagnosis and treatment of thyroid disease and has a half-life of 8.1 days. If a patient with thyroid disease consumes a sample of $Na^{131}I$ containing 10 μg of ^{131}I, how long will it take for the amount of ^{131}I to decrease to 1/100 of the original amount?

29. The Br-82 nucleus has a half-life of 1.0×10^3 min. If you wanted 1.0 g of Br-82 and the delivery time was 3.0 days, what mass of NaBr should you order (assuming all of the Br in the NaBr was Br-82)?

30. Fresh rainwater or surface water contains enough tritium (^3_1H) to show 5.5 decay events per minute per 100. g of water. Tritium has a half-life of 12.3 years. You are asked to check a vintage wine that is claimed to have been produced in 1946. How many decay events per minute should you expect to observe in 100. g of that wine?

31. A living plant contains approximately the same fraction of carbon-14 as in atmospheric carbon dioxide. Assuming that the observed rate of decay of carbon-14 from a living plant is 13.6 counts per minute per gram of carbon, how many counts per minute per gram of carbon will be measured from a 15,000-year-old sample? Will radiocarbon dating work well for small samples of 10 mg or less? (For ^{14}C, $t_{1/2} = 5730$ years.)

32. Assume a constant $^{14}C/^{12}C$ ratio of 13.6 counts per minute per gram of living matter. A sample of a petrified tree was found to give 1.2 counts per minute per gram. How old is the tree? ($t_{1/2} = {}^{14}C = 5730$ years.)

33. A rock contains 0.688 mg of ^{206}Pb for every 1.000 mg of ^{238}U present. Assuming that no lead was originally present, that all the ^{206}Pb formed over the years has remained in the rock, and that the number of nuclides in intermediate stages of decay between ^{238}U and ^{206}Pb is negligible, calculate the age of the rock. (For ^{238}U, $t_{1/2} = 4.5 \times 10^9$ years.)

34. The mass ratios of ^{40}Ar to ^{40}K also can be used to date geologic materials. Potassium-40 decays by two processes:

$$^{40}_{19}K + {}^{0}_{-1}e \longrightarrow {}^{40}_{18}Ar\ (10.7\%) \qquad t_{1/2} = 1.27 \times 10^9 \text{ years}$$
$$^{40}_{19}K \longrightarrow {}^{40}_{20}Ca + {}^{0}_{-1}e\ (89.3\%)$$

a. Why are $^{40}Ar/^{40}K$ ratios used to date materials rather than $^{40}Ca/^{40}K$ ratios?

b. What assumptions must be made using this technique?

c. A sedimentary rock has an $^{40}Ar/^{40}K$ ratio of 0.95. Calculate the age of the rock.

d. How will the measured age of a rock compare to the actual age if some ^{40}Ar escaped from the sample?

Energy Changes in Nuclear Reactions

35. The sun radiates 3.9×10^{23} J of energy into space every second. What is the rate at which mass is lost from the sun?

36. The earth receives 1.8×10^{14} kJ/s of solar energy. What mass of solar material is converted to energy over a 24-h period to provide the daily amount of solar energy to the earth? What mass of coal would have to be burned to provide the same amount of energy? (Coal releases 32 kJ of energy per gram when burned.)

37. Many transuranium elements, such as plutonium-232, have very short half-lives. (For ^{232}Pu, the half-life is 36 minutes.) However, some, like protactinium-231 (half-life $= 3.34 \times 10^4$ years), have relatively long half-lives. Use the masses given in the following table to calculate the change in energy when 1 mol of ^{232}Pu nuclei and 1 mol of ^{231}Pa nuclei are each formed from their respective number of protons and neutrons.

Atom or Particle	Atomic Mass
Neutron	1.67493×10^{-24} g
Proton	1.67262×10^{-24} g
Electron	9.10939×10^{-28} g
Pu-232	3.85285×10^{-22} g
Pa-231	3.83616×10^{-22} g

(Since the masses of ^{232}Pu and ^{231}Pa are atomic masses, they each include the mass of the electrons present. The mass of the nucleus will be the atomic mass minus the mass of the electrons.)

38. The most stable nucleus in terms of binding energy per nucleon is ^{56}Fe. If the atomic mass of ^{56}Fe is 55.9349 amu, calculate the binding energy per nucleon for ^{56}Fe.

39. Calculate the binding energy in J/nucleon for carbon-12 (atomic mass 12.0000) and uranium-235 (atomic mass 235.0439). The atomic mass of $^{1}_{1}H$ is 1.00782 amu and the mass of a neutron is 1.00866 amu. The most stable nucleus known is ^{56}Fe (see Exercise 38). Would the binding energy per nucleon for ^{56}Fe be larger or smaller than that of ^{12}C or ^{235}U? Explain.

40. Calculate the binding energy per nucleon for $^{2}_{1}H$ and $^{3}_{1}H$. The atomic masses are $^{2}_{1}H$, 2.01410, and $^{3}_{1}H$, 3.01605.

41. The mass defect for a Li-6 nucleus is −0.03434 g/mol. Calculate the atomic mass of Li-6.

42. The binding energy per nucleon for Mg-27 is 1.326×10^{-12} J/nucleon. Calculate the atomic mass of Mg-27.

43. Calculate the amount of energy released per gram of hydrogen nuclei reacted for the following reaction. The atomic masses are $^{1}_{1}H$, 1.00782 amu, $^{2}_{1}H$, 2.01410 amu, and an electron, 5.4858×10^{-4} amu. (*Hint:* Think carefully about how to account for the electron mass.)

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

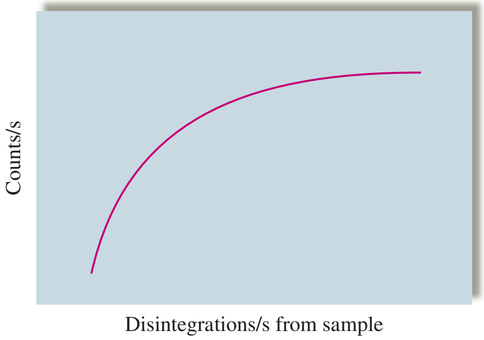
44. The easiest fusion reaction to initiate is

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

Calculate the energy released per $^{4}_{2}He$ nucleus produced and per mole of $^{4}_{2}He$ produced. The atomic masses are $^{2}_{1}H$, 2.01410; $^{3}_{1}H$, 3.01605; and $^{4}_{2}He$, 4.00260. The masses of the electron and neutron are 5.4858×10^{-4} and 1.00866 amu, respectively.

Detection, Uses, and Health Effects of Radiation

45. The typical response of a Geiger–Müller tube is shown below. Explain the shape of this curve.



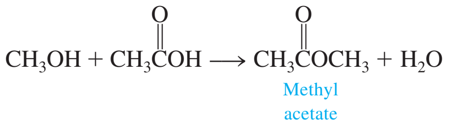
46. When using a Geiger–Müller counter to measure radioactivity, it is necessary to maintain the same geometrical orientation between the sample and the Geiger–Müller tube to compare different measurements. Why?

47. Photosynthesis in plants can be represented by the following overall reaction:

$$6CO_2(g) + 6H_2O(l) \xrightarrow{\text{Light}} C_6H_{12}O_6(s) + 6O_2(g)$$

Algae grown in water containing some ^{18}O (in $H_2{}^{18}O$) evolve oxygen gas with the same isotopic composition as the oxygen in the water. When algae growing in water containing only ^{16}O were furnished carbon dioxide containing ^{18}O, no ^{18}O was found to be evolved from the oxygen gas produced. What conclusions about photosynthesis can be drawn from these experiments?

48. Consider the following reaction to produce methyl acetate:



$$CH_3OH + CH_3\overset{O}{\overset{\|}{C}}OH \longrightarrow \underset{\text{Methyl acetate}}{CH_3\overset{O}{\overset{\|}{C}}OCH_3} + H_2O$$

When this reaction is carried out with CH_3OH containing oxygen-18, the water produced does not contain oxygen-18. Explain.

49. U-235 undergoes many different fission reactions. For one such reaction, when U-235 is struck with a neutron, Ce-144 and Sr-90 are produced along with some neutrons and electrons. How many neutrons and β-particles are produced in this fission reaction?

50. Breeder reactors are used to convert the nonfissionable nuclide $^{238}_{92}U$ to a fissionable product. Neutron capture of the $^{238}_{92}U$ is followed by two successive beta decays. What is the final fissionable product?

51. Which do you think would be the greater health hazard: the release of a radioactive nuclide of Sr or a radioactive nuclide of Xe into the environment? Assume the amount of radioactivity is the same in each case. Explain your answer on the basis of the chemical properties of Sr and Xe. Why are the chemical properties of a radioactive substance important in assessing its potential health hazards?

52. Consider the following information:

i. The layer of dead skin on our bodies is sufficient to protect us from most α-particle radiation.
ii. Plutonium is an α-particle producer.
iii. The chemistry of Pu^{4+} is similar to that of Fe^{3+}.
iv. Pu oxidizes readily to Pu^{4+}.

Why is plutonium one of the most toxic substances known?

Additional Exercises

53. Predict whether each of the following nuclides is stable or unstable (radioactive). If the nuclide is unstable, predict the type of radioactivity you would expect it to exhibit.

a. $^{45}_{19}K$ **b.** $^{56}_{26}Fe$ **c.** $^{20}_{11}Na$ **d.** $^{194}_{81}Tl$

54. At a flea market, you've found a very interesting painting done in the style of Rembrandt's "dark period" (1642–1672). You suspect that you really do not have a genuine Rembrandt, but you take it to the local university for testing. Living wood shows a carbon-14 activity of 15.3 counts per minute per gram. Your painting showed a carbon-14 activity of 15.1 counts per minute per gram. Could it be a genuine Rembrandt?

55. Define "third-life" in a similar way to "half-life" and determine the "third-life" for a nuclide that has a half-life of 31.4 years.

56. A proposed system for storing nuclear wastes involves storing the radioactive material in caves or deep mine shafts. One of the most toxic nuclides that must be disposed of is plutonium-239, which is produced in breeder reactors and has a half-life of 24,100 years. A suitable storage place must be geologically stable long enough for the activity of plutonium-239 to decrease to 0.1% of its original value. How long is this for plutonium-239?

57. During World War II, tritium (^3H) was a component of fluorescent watch dials and hands. Assume you have such a watch that was made in January 1944. If 17% or more of the original tritium was needed to read the dial in dark places, until what year could you read the time at night? (For ^3H, $t_{1/2} = 12.3$ yr.)

58. A positron and an electron can annihilate each other on colliding, producing energy as photons:

$$^{\ \ 0}_{-1}e + ^{\ \ 0}_{+1}e \longrightarrow 2\,^0_0\gamma$$

Assuming that both γ rays have the same energy, calculate the wavelength of the electromagnetic radiation produced.

59. A small atomic bomb releases energy equivalent to the detonation of 20,000 tons of TNT; a ton of TNT releases 4×10^9 J of energy when exploded. Using 2×10^{13} J/mol as the energy released by fission of ^{235}U, approximately what mass of ^{235}U undergoes fission in this atomic bomb?

60. During the research that led to production of the two atomic bombs used against Japan in World War II, different mechanisms for obtaining a supercritical mass of fissionable material were investigated. In one type of bomb, a "gun" shot one piece of fissionable material into a cavity containing another piece of fissionable material. In the second type of bomb, the fissionable material was surrounded with a high explosive that, when detonated, compressed the fissionable material into a smaller volume. Discuss what is meant by critical mass, and explain why the ability to achieve a critical mass is essential to sustaining a nuclear reaction.

61. Using the kinetic molecular theory (Section 5.6), calculate the root mean square velocity and the average kinetic energy of ^2_1H nuclei at a temperature of 4×10^7 K. (See Exercise 44 for the appropriate mass values.)

Challenge Problems

62. A 0.20-mL sample of a solution containing ^3_1H that produces 3.7×10^3 cps is injected into the bloodstream of an animal. After allowing circulatory equilibrium to be established, a 0.20-mL sample of blood is found to have an activity of 20. cps. Calculate the blood volume of the animal.

63. A 0.10-cm^3 sample of a solution containing a radioactive nuclide (5.0×10^3 counts per minute per milliliter) is injected into a rat. Several minutes later 1.0 cm^3 of blood is removed. The blood shows 48 counts per minute of radioactivity. Calculate the volume of blood in the rat. What assumptions must be made in performing this calculation?

64. Zirconium is one of the few metals that retains its structural integrity upon exposure to radiation. The fuel rods in most nuclear reactors therefore are often made of zirconium. Answer the following questions about the redox properties of zirconium based on the half-reaction

$$ZrO_2 \cdot H_2O + H_2O + 4e^- \longrightarrow Zr + 4OH^- \qquad \mathscr{E}° = -2.36\ V$$

a. Is zirconium metal capable of reducing water to form hydrogen gas at standard conditions?

b. Write a balanced equation for the reduction of water by zirconium.

c. Calculate $\mathscr{E}°$, $\Delta G°$, and K for the reduction of water by zirconium metal.

d. The reduction of water by zirconium occurred during the accidents at Three Mile Island in 1979. The hydrogen produced was successfully vented and no chemical explosion occurred. If 1.00×10^3 kg of Zr reacts, what mass of H_2 is produced? What volume of H_2 at 1.0 atm and 1000.°C is produced?

e. At Chernobyl in 1986, hydrogen was produced by the reaction of superheated steam with the graphite reactor core:

$$C(s) + H_2O(g) \longrightarrow CO(g) + H_2(g)$$

It was not possible to prevent a chemical explosion at Chernobyl. In light of this, do you think it was a correct decision to vent the hydrogen and other radioactive gases into the atmosphere at Three Mile Island? Explain.

65. In addition to the process described in the text, a second process called the *carbon–nitrogen cycle* occurs in the sun:

$$\begin{array}{rcl}
^1_1H + ^{12}_{\ 6}C & \longrightarrow & ^{13}_{\ 7}N + ^0_0\gamma \\
^{13}_{\ 7}N & \longrightarrow & ^{13}_{\ 6}C + ^{\ \ 0}_{+1}e \\
^1_1H + ^{13}_{\ 6}C & \longrightarrow & ^{14}_{\ 7}N + ^0_0\gamma \\
^1_1H + ^{14}_{\ 7}N & \longrightarrow & ^{15}_{\ 8}O + ^0_0\gamma \\
^{15}_{\ 8}O & \longrightarrow & ^{15}_{\ 7}N + ^{\ \ 0}_{+1}e \\
^1_1H + ^{15}_{\ 7}N & \longrightarrow & ^{12}_{\ 6}C + ^4_2He + ^0_0\gamma \\
\hline
\text{Overall reaction:}\quad 4\,^1_1H & \longrightarrow & ^4_2He + 2\,^{\ \ 0}_{+1}e
\end{array}$$

a. What is the catalyst in this process?

b. What nucleons are intermediates?

c. How much energy is released per mole of hydrogen nuclei in the overall reaction? (The atomic masses of ^1_1H and ^4_2He are 1.00782 and 4.00260, respectively.)

66. The most significant source of natural radiation is radon-222. ^{222}Rn, a decay product of ^{238}U, is continuously generated in the earth's crust, allowing gaseous Rn to seep into the basements of buildings. Because ^{222}Rn is an α-particle producer with a relatively short half-life of 3.82 days, it can cause biological damage when inhaled.

a. How many α particles and β particles are produced when ^{238}U decays to ^{222}Rn? What nuclei are produced when ^{222}Rn decays?

b. Radon is a noble gas so one would expect it to pass through the body quickly. Why is there a concern over inhaling ^{222}Rn?

c. Another problem associated with ^{222}Rn is that the decay of ^{222}Rn produces a more potent α-particle producer ($t_{1/2} =$ 3.11min) that is a solid. What is the identity of the solid? Give the balanced equation of this species decaying by α-particle production. Why is the solid a more potent α-particle producer?

d. The U.S. Environmental Protection Agency (EPA) recommends that ^{222}Rn levels not exceed 4 pCi per liter of air (1 Ci = 1 curie = 3.7×10^{10} decay events per second; 1 pCi = 1×10^{-12} Ci). Convert 4.0 pCi per liter of air into concentrations units of ^{222}Rn atoms per liter of air and moles of ^{222}Rn per liter of air.

67. To determine the K_{sp} value of Hg_2I_2, a chemist obtained a solid sample of Hg_2I_2 in which some of the iodine is present as radioactive ^{131}I. The count rate of the Hg_2I_2 sample is 5.0×10^{11} counts per minute per mole of I. An excess amount of $Hg_2I_2(s)$ is placed into some water, and the solid is allowed to come to equilibrium with its respective ions. A 150.0-mL sample of the saturated solution is withdrawn and the radioactivity measured at 33 counts per minute. From this information, calculate the K_{sp} value for Hg_2I_2.

$$Hg_2I_2(s) \rightleftharpoons Hg_2^{2+}(aq) + 2I^-(aq) \qquad K_{sp} = [Hg_2^{2+}][I^-]^2$$

68. Estimate the temperature needed to achieve the fusion of deuterium to make an alpha particle. The energy required can be estimated from Coulomb's law [use the form $E = 9.0 \times 10^9 (Q_1Q_2/r)$, using $Q = 1.6 \times 10^{-19}$ C for a proton, and $r = 2 \times 10^{-15}$ m for the helium nucleus; the unit for the proportionality constant in Coloumb's law is $J \cdot m/C^2$.]

Integrative Problems

These problems require the integration of multiple concepts to find the solutions.

69. A recently reported synthesis of the transuranium element bohrium (Bh) involved the bombardment of berkelium-249 with neon-22 to produce bohrium-267. Write a nuclear reaction for this synthesis. The half-life of bohrium-267 is 15.0 seconds. If 199 atoms of bohrium-267 could be synthesized, how much time would elapse before only 11 atoms of bohrium-267 remain? What is the expected electron configuration of elemental bohrium?

70. Radioactive cobalt-60 is used to study defects in vitamin B_{12} absorption because cobalt is the metallic atom at the center of the vitamin B_{12} molecule. The nuclear synthesis of this cobalt isotope involves a three-step process. The overall reaction is iron-58 reacting with two neutrons to produce cobalt-60 along with the emission of another particle. What particle is emitted in this nuclear synthesis? What is the binding energy in J per nucleon for the cobalt-60 nucleus (atomic masses: ^{60}Co = 59.9338 amu; ^{1}H = 1.00782 amu). What is the de Broglie wavelength of the emitted particle if it has a velocity equal to 0.90c where c is the speed of light?

Get help understanding core concepts and visualizing molecular-level interactions, and practice problem solving, by visiting the Online Study Center at **college.hmco.com/PIC/zumdahl7e.**