Nuclear Chemistry

What You'll Learn

- You will trace the history of nuclear chemistry from discovery to application.
- You will identify types of radioactive decay and solve decay rate problems.
- You will describe the reactions involved in nuclear fission and fusion.
- You will learn about applications of nuclear reactions and the effects of radiation exposure.

Why It's Important

From its role in shaping world politics to its applications that produce electrical power and diagnose and treat disease, nuclear chemistry has profound effects upon the world in which we live.

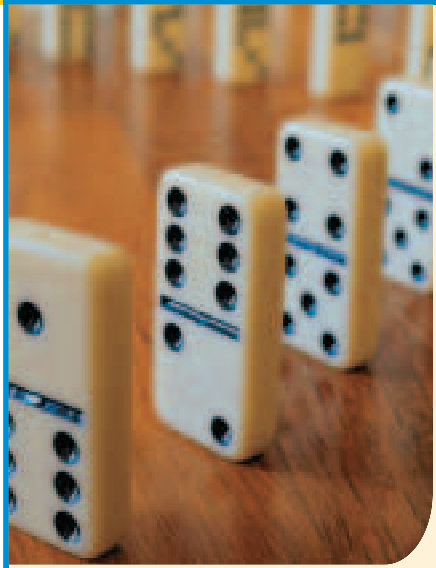
Chemistry Online

Visit the Chemistry Web site at **chemistrymc.com** to find links about nuclear chemistry.

Many medical diagnostic tests and treatments involve the use of radioactive substances. Here, a radioactive substance known as a radiotracer is used to illuminate the carotid artery, which runs through the neck into the skull.

CONTENTS

DISCOVERY LAB



Chain Reactions

When the products of one nuclear reaction cause additional nuclear reactions to occur, the resulting chain reaction can release large amounts of energy in a short period of time. Explore escalating chain reactions by modeling them with dominoes.

Procedure

1. Obtain a set of domino tiles.
2. Stand the individual dominoes on end and arrange them so that when the first domino falls, it causes the other dominoes to fall in series.
3. Practice using different arrangements until you determine how to cause the dominoes to fall in the least amount of time.
4. Time your domino chain reaction. Compare your time with those of your classmates.

Analysis

What arrangement caused the dominoes to fall in the least amount of time? Do the dominoes fall at a steady rate or an escalating rate? What happens to the domino chain reaction if a tile does not contact the next tile in the sequence?

Materials

28 domino tiles (1 set)
stopwatch

Section 25.1 Nuclear Radiation

Objectives

- **List** the founding scientists in the study of radioactivity and **state** their discoveries.
- **Identify** alpha, beta, and gamma radiation in terms of composition and key properties.

Vocabulary

radioisotope
X ray

You may recall from Chapter 4 that the nuclei of some atoms are unstable and undergo nuclear reactions. In this chapter you will study nuclear chemistry, which is concerned with the structure of atomic nuclei and the changes they undergo. An application of a nuclear reaction is shown in the photo of the human neck and skull. **Table 25-1** offers a comparison of chemical and nuclear reactions.

Table 25-1

Characteristics of Chemical and Nuclear Reactions	
Chemical reactions	**Nuclear reactions**
1. Occur when bonds are broken and formed.	**1.** Occur when nuclei emit particles and/or rays.
2. Atoms remain unchanged, though they may be rearranged.	**2.** Atoms are often converted into atoms of another element.
3. Involve only valence electrons.	**3.** May involve protons, neutrons, and electrons.
4. Associated with small energy changes.	**4.** Associated with large energy changes.
5. Reaction rate is influenced by temperature, pressure, concentration, and catalysts.	**5.** Reaction rate is not normally affected by temperature, pressure, or catalysts.

The Discovery of Radioactivity

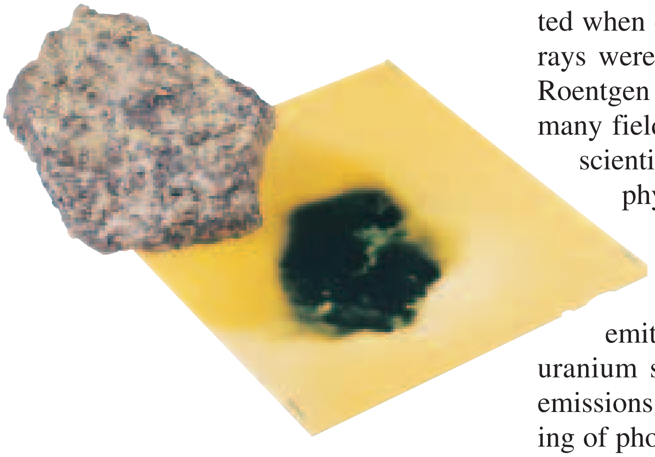


Figure 25-1

A sample of radioactive uranium-containing ore exposes photographic film.

In 1895, Wilhelm Roentgen (1845–1923) found that invisible rays were emitted when electrons bombarded the surface of certain materials. The emitted rays were discovered because they caused photographic plates to darken. Roentgen named these invisible high-energy emissions X rays. As is true in many fields, Roentgen's discovery of X rays created excitement within the scientific community and stimulated further research. At that time, French physicist Henri Becquerel (1852–1908) was studying minerals that emit light after being exposed to sunlight, a phenomenon called phosphorescence. Building on Roentgen's work, Becquerel wanted to determine whether phosphorescent minerals also emitted X rays. Becquerel accidentally discovered that phosphorescent uranium salts—even when not exposed to light—produced spontaneous emissions that darkened photographic plates. **Figure 25-1** shows the darkening of photographic film that is exposed to uranium-containing ore.

Marie Curie (1867–1934) and her husband Pierre (1859–1906) took Becquerel's mineral sample (called pitchblende) and isolated the components emitting the rays. They concluded that the darkening of the photographic plates was due to rays emitted specifically from the uranium atoms present in the mineral sample. Marie Curie named the process by which materials give off such rays radioactivity; the rays and particles emitted by a radioactive source are called radiation.

The work of Marie and Pierre Curie was extremely important in establishing the origin of radioactivity and the field of nuclear chemistry. In 1898, the Curies identified two new elements, polonium and radium, on the basis of their radioactivity. Henri Becquerel and the Curies shared the 1903 Nobel Prize in Physics for their work. Marie Curie also received the 1911 Nobel Prize in Chemistry for her work with polonium and radium. **Figure 25-2** shows the Curies at work in their laboratory.

Types of Radiation

While reading about the discovery of radioactivity, several questions may have occurred to you. Which atomic nuclei are radioactive? What types of radiation do radioactive nuclei emit? It is best to start with the second question first, and explore the types of radiation emitted by radioactive sources.

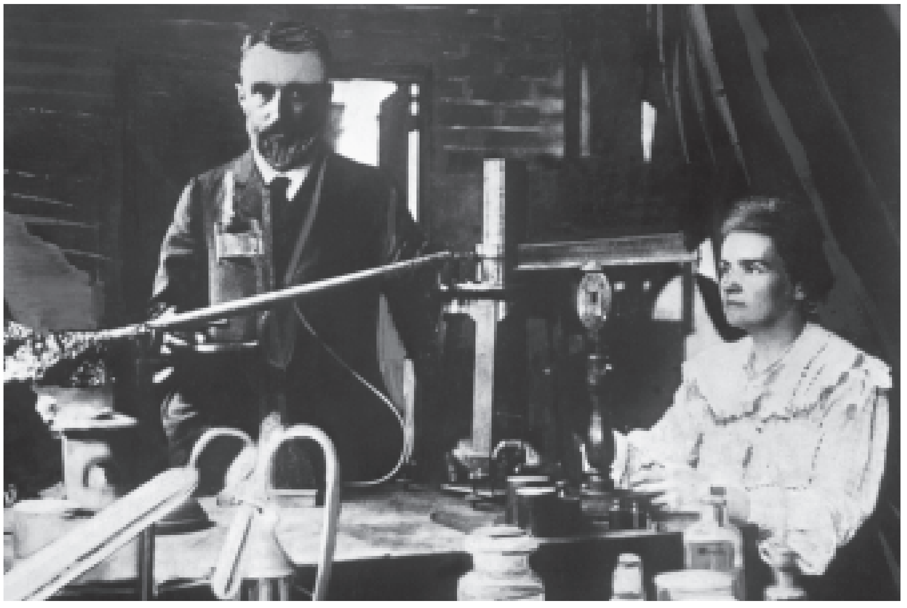


Figure 25-2

Both Pierre and Marie Curie played important roles in founding the field of nuclear chemistry. Marie Curie went on to show that unlike chemical reactions, radioactivity is not affected by changes in physical conditions such as temperature and pressure. She is the only person in history to receive Nobel Prizes in two different sciences—physics in 1903, and chemistry in 1911.

As you may recall, isotopes are atoms of the same element that have different numbers of neutrons. Isotopes of atoms with unstable nuclei are called **radioisotopes**. These unstable nuclei emit radiation to attain more stable atomic configurations in a process called radioactive decay. During radioactive decay, unstable atoms lose energy by emitting one of several types of radiation. The three most common types of radiation are alpha (α), beta (β), and gamma (γ). **Table 25-2** summarizes some of their important properties. Later in this chapter you'll learn about other types of radiation that may be emitted in a nuclear reaction.

Try at Home LAB

See page 964 in Appendix E for **Modeling Radiation Penetration**

Table 25-2

Properties of Alpha, Beta, and Gamma Radiation

Property	Alpha (α)	Beta (β)	Gamma (γ)
Composition	Alpha particles	Beta particles	High-energy electromagnetic radiation
Description of radiation	Helium nuclei $^{4}_{2}He$	Electrons $^{0}_{-1}\beta$	photons $^{0}_{0}\gamma$
Charge	2+	1−	0
Mass	6.64×10^{-24} kg	9.11×10^{-28} kg	0
Approximate energy*	5 MeV	0.05 to 1 MeV	1 MeV
Relative penetrating power	Blocked by paper	Blocked by metal foil	Not completely blocked by lead or concrete

*(1 MeV = 1.60×10^{-13} J)

Ernest Rutherford (1871–1937), whom you know of because of his famous gold foil experiment that helped define modern atomic structure, identified alpha, beta, and gamma radiation when studying the effects of an electric field on the emissions from a radioactive source. As you can see in **Figure 25-3**, alpha particles carry a 2+ charge and are deflected toward the negatively charged plate. Beta particles carry a 1– charge and are deflected toward the positively charged plate. In contrast, gamma rays carry no charge and are not affected by the electric field.

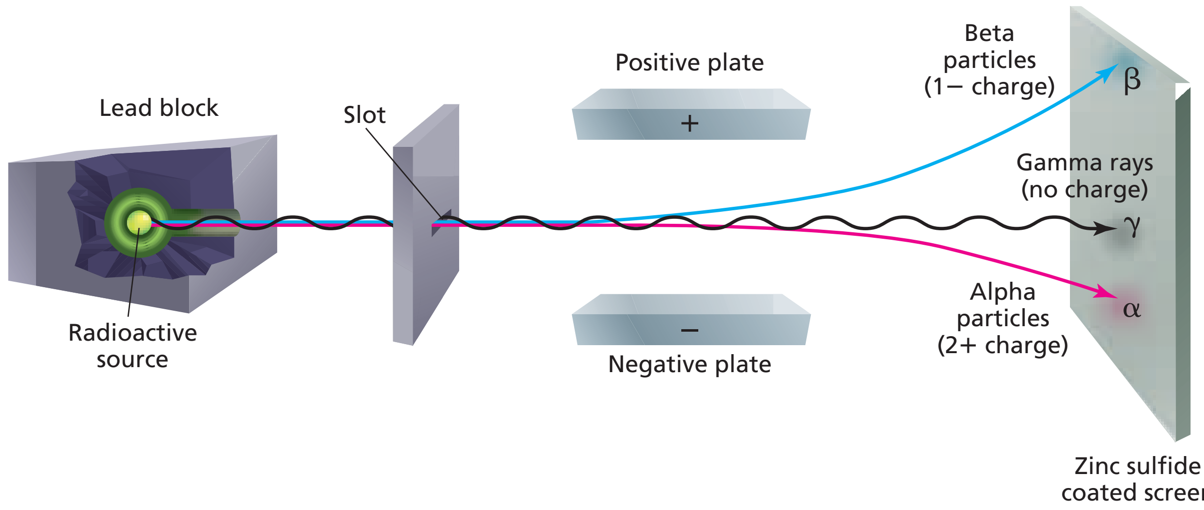
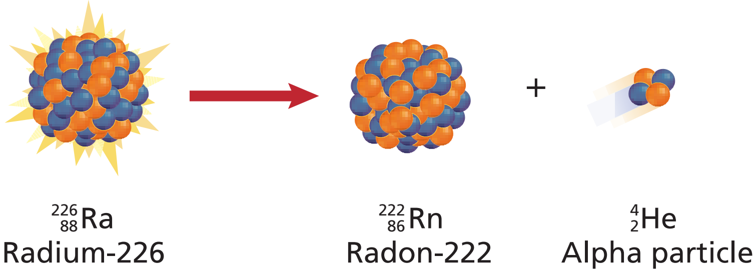


Figure 25-3

The effect of an electric field on three types of radiation is shown here. Positively charged alpha particles are deflected toward the negatively charged plate. Negatively charged beta particles are deflected toward the positively charged plate. Beta particles undergo greater deflection because they have considerably less mass than alpha particles. Gamma rays, which have no electrical charge, are not deflected.

Figure 25-4

A radium-226 nucleus undergoes alpha decay to form radon-222. What is the charge on the alpha particle that is emitted?



An alpha particle (α) has the same composition as a helium nucleus—two protons and two neutrons—and is therefore given the symbol $^{4}_{2}$He. The charge of an alpha particle is 2+ due to the presence of the two protons. Alpha radiation consists of a stream of alpha particles. As you can see in **Figure 25-4**, radium-226, an atom whose nucleus contains 88 protons and 138 neutrons, undergoes alpha decay by emitting an alpha particle. Notice that after the decay, the resulting atom has an atomic number of 86, a mass number of 222, and is no longer radium. The newly formed radiosiotope is radon-222.

In examining **Figure 25-4**, you should note that the particles involved are balanced. That is, the sum of the mass numbers (superscripts) and the sum of the atomic numbers (subscripts) on each side of the arrow are equal. Also note that when a radioactive nucleus emits an alpha particle, the product nucleus has an atomic number that is lower by two and a mass number that is lower by four. What particle is formed when polonium-210 ($^{210}_{84}$Po) undergoes alpha decay?

Because of their mass and charge, alpha particles are relatively slow-moving compared with other types of radiation. Thus, alpha particles are not very penetrating—a single sheet of paper stops alpha particles.

A beta particle is a very-fast moving electron that has been emitted from a neutron of an unstable nucleus. Beta particles are represented by the symbol $^{0}_{-1}\beta$. The zero superscript indicates the insignificant mass of an electron in comparison with the mass of a nucleus. The –1 subscript denotes the negative charge of the particle. Beta radiation consists of a stream of fast-moving electrons. An example of the beta decay process is the decay of iodine-131 into xenon-131 by beta-particle emission, as shown in **Figure 25-5**. Note that the mass number of the product nucleus is the same as that of the original nucleus (they are both 131), but its atomic number has increased by 1 (54 instead of 53). This change in atomic number, and thus, change in identity, occurs because the electron emitted during the beta decay has been removed from a neutron, leaving behind a proton.

$$^{1}_{0}\text{n} \longrightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta$$

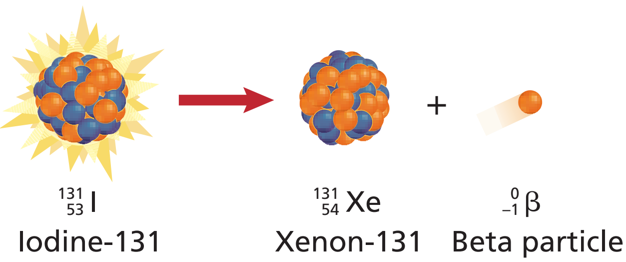
As you may recall, because the number of protons in an atom determines its identity, the formation of an additional proton results in the transformation from iodine to xenon. Because beta particles are both lightweight and fast

Physics CONNECTION

Exposing certain foods such as strawberries to small amounts of gamma radiation allows them to last longer before spoiling. The process, called irradiation, uses decaying cobalt-60 nuclei as a source of gamma radiation. By disrupting their cell metabolism, gamma radiation destroys the microorganisms that cause food to spoil. Irradiation can also be used to slow the ripening process, extend shelf life, and allow foods to be stored for long periods of time without refrigeration. The food does not become radioactive from the process. More than 30 nations around the world have approved irradiation as a means of preserving food.

Figure 25-5

An iodine-131 nucleus undergoes beta decay to form xenon-131. How does beta decay affect the mass number of the decaying nucleus?



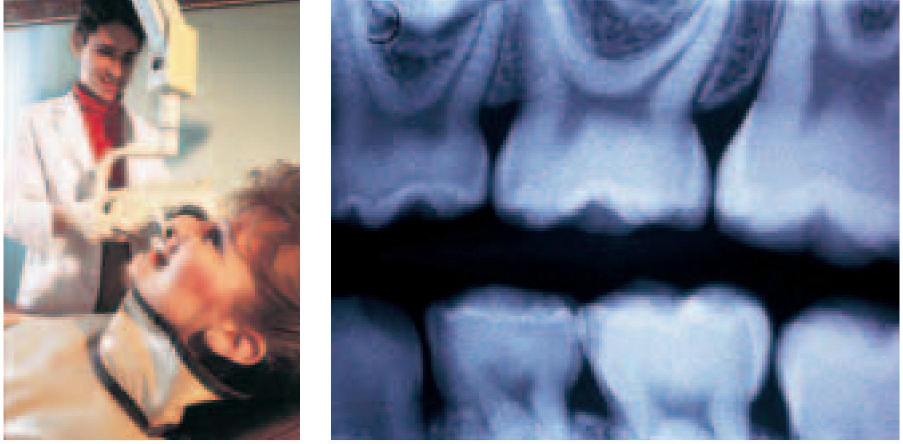


Figure 25-6

A heavy lead-lined vest absorbs errant radiation from a dental X-ray machine, limiting exposure to the rest of the body. Dentists use dental X rays as a diagnostic tool for determining the health of teeth and gums.

moving, they have greater penetrating power than alpha particles. A thin metal foil is required to stop beta particles.

Gamma rays are high-energy (short wavelength) electromagnetic radiation. They are denoted by the symbol ${}^{0}_{0}\gamma$. As you can see from the symbol, both the subscript and superscript are zero. Thus, the emission of gamma rays does not change the atomic number or mass number of a nucleus. Gamma rays almost always accompany alpha and beta radiation, as they account for most of the energy loss that occurs as a nucleus decays. For example, gamma rays accompany the alpha-decay reaction of uranium-238.

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

The 2 in front of the γ symbol indicates that two gamma rays of different frequencies are emitted. Because gamma rays have no effect on mass number or atomic number, it is customary to omit them from nuclear equations.

As you have learned, the discovery of X rays helped set off the events that led to the discovery of radioactivity. **X rays**, like gamma rays, are a form of high-energy electromagnetic radiation. Unlike gamma rays, X rays are not produced by radioactive sources. Instead, X rays are emitted from certain materials that are in an excited electron state. Both X rays and gamma rays are extremely penetrating and can be very damaging to living tissue. X rays and gamma rays are only partially blocked by lead and concrete. If your dentist has recently taken dental X rays of your teeth, you may recall wearing a heavy vest over your chest during the procedure. The vest, which can be seen in **Figure 25-6**, is lined with lead, and its purpose is to limit your body's exposure to the potentially damaging X rays.

Section 25.1 Assessment

1. Describe the contributions of Roentgen, Becquerel, Rutherford, and the Curies to the field of nuclear chemistry.
2. What subatomic particles are involved in nuclear reactions? What subatomic particles are involved in chemical reactions?
3. Using **Table 25-2** as a guide, qualitatively compare and contrast alpha, beta, and gamma radiation in terms of composition, energy, mass, and penetrating power.
4. **Thinking Critically** An atom undergoes a reaction and attains a more stable form. How do you know if the reaction was a chemical reaction or a nuclear reaction?
5. **Converting Units** **Table 25-2** gives Approximate Energy values in units of MeV. Convert each value into joules using the following conversion factor ($1 \text{ MeV} = 1.61 \times 10^{-13}$ J). For more help, refer to *Unit Conversion* in the **Math Handbook** on page 901 of this textbook.

Radioactive Decay

Objectives

- **Explain** why certain nuclei are radioactive.
- **Apply** your knowledge of radioactive decay to write balanced nuclear equations.

Vocabulary

nucleon
strong nuclear force
band of stability
positron emission
positron
electron capture
radioactive decay series

It may surprise you to learn that of all the known isotopes, only about 17% are stable and don't decay spontaneously. In Chapter 4 you learned that the stability of an atom is determined by the neutron-to-proton ratio of its nucleus. You may be wondering if there is a way to know what type of radioactive decay a particular radioisotope will undergo. There is, and as you'll learn in this section, it is the neutron-to-proton ratio of the nucleus that determines the type of radioactive decay that will occur.

Nuclear Stability

Every atom has an extremely dense nucleus that contains most of the atom's mass. The nucleus contains positively charged protons and neutral neutrons, both of which are referred to as **nucleons**. You may have wondered how protons remain in the densely packed nucleus despite the strong electrostatic repulsion forces produced by the positively charged particles. The answer is that the **strong nuclear force**, a force that acts only on subatomic particles that are extremely close together, overcomes the electrostatic repulsion between protons.

The fact that the strong nuclear force acts on both protons and neutrons is important. Because neutrons are neutral, a neutron that is adjacent to a positively charged proton creates no repulsive electrostatic force. Yet these two adjacent particles are subject to the strong nuclear force that works to hold them together. Likewise, two adjacent neutrons create no attractive or repulsive electrostatic force, but they too are subject to the strong nuclear force holding them together. Thus, the presence of neutrons adds an attractive force within the nucleus. The number of neutrons in a nucleus is important because nuclear stability is related to the balance between electrostatic and strong nuclear forces.

To a certain degree, the stability of a nucleus can be correlated with its neutron-to-proton (n/p) ratio. For atoms with low atomic numbers (< 20), the most stable nuclei are those with neutron-to-proton ratios of 1 : 1. For example, helium ($^{4}_{2}He$) has two neutrons and two protons, and a neutron-to-proton ratio of 1 : 1. As atomic number increases, more and more neutrons are needed to produce a strong nuclear force that is sufficient to balance the electrostatic repulsion forces. Thus, the neutron-to-proton ratio for stable atoms gradually increases, reaching a maximum of approximately 1.5 : 1 for the largest atoms. An example of this is lead ($^{206}_{82}Pb$). With 124 neutrons and 82 protons, lead has a neutron-to-proton ratio of 1.51 : 1. You can see the calculation of lead's neutron-to-proton ratio in **Figure 25-7**.

Figure 25-7

The steps in calculating the neutron-to-proton ratio (the n/p ratio) for lead-206 are illustrated here.

Mass number — 206
Atomic number — 82

$$^{206}_{82}Pb$$

$$\text{Atomic number} = \text{Number of protons} = 82$$

$$\text{Mass number} = \text{Number of protons} + \text{Number of neutrons} = 206$$

$$\text{Number of neutrons} = \text{Mass number} - \text{Atomic number}$$

$$\text{Number of neutrons} = 206 - 82 = 124$$

$$\text{Neutron-to-proton ratio} = \frac{\text{Number of neutrons}}{\text{Number of protons}}$$

$$\text{Neutron-to-proton ratio} = \frac{124}{82}$$

$$\text{Neutron-to-proton ratio} = \frac{1.51}{1}$$

Examine the plot of the number of neutrons versus the number of protons for all known stable nuclei shown in **Figure 25-8**. As you can see, the slope of the plot indicates that the number of neutrons required for a stable nucleus increases as the number of protons increases. This correlates with the increase in the neutron-to-proton ratio of stable nuclei with increasing atomic number. The area on the graph within which all stable nuclei are found is known as the **band of stability**. As shown in **Figure 25-8**, ${}^{4}_{2}He$ and ${}^{206}_{82}Pb$, with their very different neutron-to-proton ratios, are both positioned within the band of stability. Radioactive nuclei are found outside the band of stability—either above or below—and undergo decay in order to gain stability. After decay, the new atom is positioned more closely to, if not within, the band of stability. The band of stability ends at bismuth-209; all elements with atomic numbers greater than 83 are radioactive.

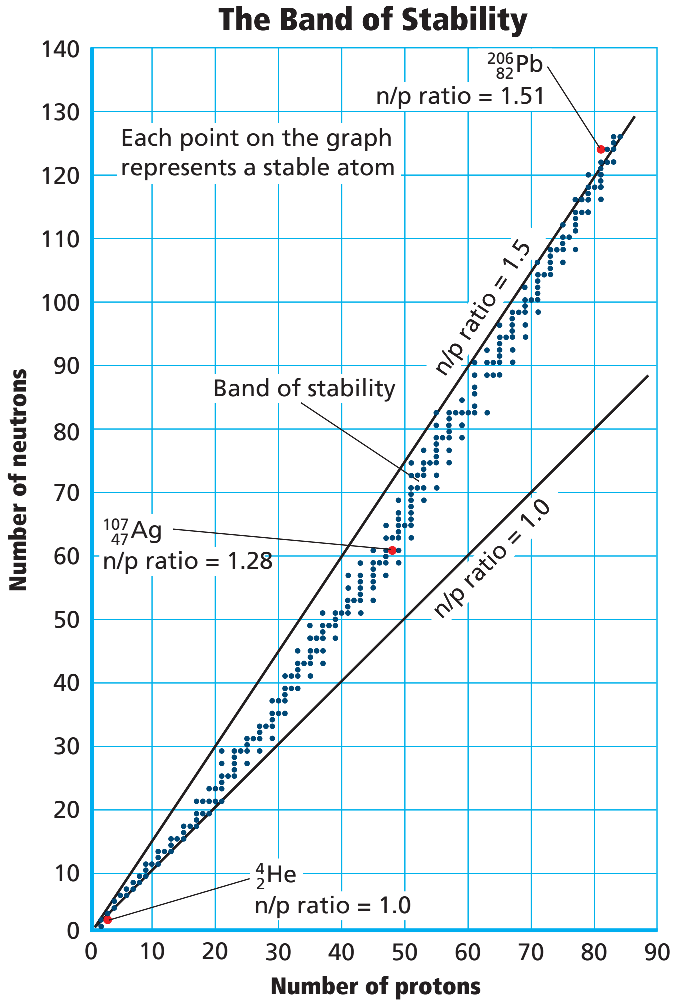


Figure 25-8

Plotting the number of neutrons versus the number of protons for all stable nuclei produces a region called the band of stability. As you move from low atomic number nuclei to high atomic number nuclei, the neutron-to-proton ratio for stable nuclei gradually increases from 1 : 1 to 1.5 : 1.

Types of Radioactive Decay

The type of radioactive decay a particular radioisotope undergoes depends to a large degree on the underlying causes for its instability. Atoms lying above the band of stability generally have too many neutrons to be stable, whereas atoms lying below the band of stability tend to have too many protons to be stable.

Beta decay A radioisotope that lies above the band of stability is unstable because it has too many neutrons relative to its number of protons. For example, unstable ${}^{14}_{6}C$ has a neutron-to-proton ratio of 1.33 : 1, whereas stable elements of similar mass, such as ${}^{12}_{6}C$ and ${}^{14}_{7}N$, have neutron-to-proton ratios of approximately 1 : 1. It is not surprising then that ${}^{14}_{6}C$ undergoes beta decay, as this type of decay decreases the number of neutrons in the nucleus.

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

Note that the atomic number of the product nucleus, ${}^{14}_{7}N$, has increased by one. The nitrogen-14 atom now has a stable neutron-to-proton ratio of 1 : 1. Thus, beta emission has the effect of increasing the stability of a neutron-rich atom by lowering its neutron-to-proton ratio. The resulting atom is closer to, if not within, the band of stability.

Alpha decay All nuclei with more than 83 protons are radioactive and decay spontaneously. Both the number of neutrons and the number of protons must be reduced in order to make these radioisotopes stable. These very heavy nuclei often decay by emitting alpha particles. For example, polonium-210 spontaneously decays by alpha emission.

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

The atomic number of ${}^{210}_{84}Po$ decreases by two and the mass number decreases by four as the nucleus decays into ${}^{206}_{82}Pb$. How does the n/p ratio change?

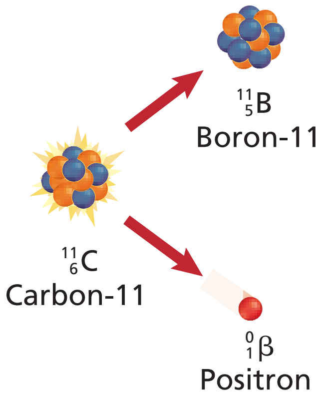


Figure 25-9

Positron emission from carbon-11 decreases the number of protons from six to five, and increases the number of neutrons from five to six.

Positron emission and electron capture For nuclei with low neutron-to-proton ratios lying below the band of stability, there are two common radioactive decay processes that occur, positron emission and electron capture. These two processes tend to increase the neutron-to-proton ratio of the neutron-poor atom. After an unstable atom undergoes electron capture or positron emission, the resulting atom is closer to, if not within, the band of stability.

Positron emission is a radioactive decay process that involves the emission of a positron from a nucleus. A **positron** is a particle with the same mass as an electron but opposite charge, thus it is represented by the symbol $^{0}_{1}\beta$. During positron emission, a proton in the nucleus is converted into a neutron and a positron, and then the positron is emitted.

$$^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{1}\beta$$

Figure 25-9 shows the positron emission of a carbon-11 nucleus. Carbon-11 lies below the band of stability and has a low neutron-to-proton ratio of 0.8 : 1. Carbon-11 undergoes positron emission to form boron-11. Positron emission decreases the number of protons from six to five, and increases the number of neutrons from five to six. The resulting atom, $^{11}_{5}B$, has a neutron-to-proton ratio of 1.2 : 1, which is within the band of stability.

Electron capture is the other common radioactive decay process that decreases the number of protons in unstable nuclei lying below the band of stability. **Electron capture** occurs when the nucleus of an atom draws in a surrounding electron, usually one from the lowest energy level. This captured electron combines with a proton to form a neutron.

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

The atomic number of the nucleus decreases by one as a consequence of electron capture. The formation of the neutron also results in an X-ray photon being emitted. These two characteristics of electron capture can be seen in the electron capture of rubidium-81 shown in **Figure 25-10**. The balanced nuclear equation for the reaction is shown below.

$$^{0}_{-1}e + {}^{81}_{37}Rb \longrightarrow {}^{81}_{36}Kr + \text{X-ray photon}$$

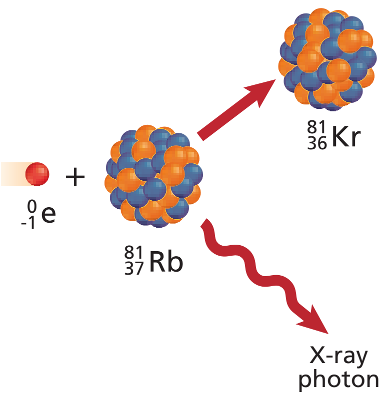


Figure 25-10

The electron capture of rubidium-81 decreases the number of protons in the nucleus while the mass number remains the same. Thus, the neutron-to-proton ratio increases from 1.19 : 1 for $^{81}_{37}Rb$ to 1.25 : 1 for $^{81}_{36}Kr$.

How is the neutron-to-proton ratio of the product, Kr-81, different from that of Rb-81?

The five types of radioactive decay you have read about in this chapter are summarized in **Table 25-3**. Which of the decay processes listed in the table result in an increased neutron-to-proton ratio? In a decrease?

Table 25-3

Summary of Radioactive Decay Processes

Type of radioactive decay	Particle emitted	Change in mass number	Change in atomic number
Alpha decay	$^{4}_{2}He$	Decreases by 4	Decreases by 2
Beta decay	$^{0}_{-1}\beta$	No change	Increases by 1
Positron emission	$^{0}_{1}\beta$	No change	Decreases by 1
Electron capture	X-ray photon	No change	Decreases by 1
Gamma emission	$^{0}_{0}\gamma$	No change	No change

Writing and Balancing Nuclear Equations

The radioactive decay processes you have just read about are all examples of nuclear reactions. As you probably noticed, nuclear reactions are expressed by balanced nuclear equations just as chemical reactions are expressed by balanced chemical equations. However, in balanced chemical equations, numbers and kinds of atoms are conserved; in balanced nuclear equations, mass numbers and atomic numbers are conserved.

EXAMPLE PROBLEM 25-1

Balancing a Nuclear Equation

Using the information provided in **Table 25-3**, write a balanced nuclear equation for the alpha decay of thorium-230 ($^{230}_{90}Th$).

1. Analyze the Problem

You are given that a thorium atom undergoes alpha decay and forms an unknown product. Thorium-230 is the initial reactant, while the alpha particle is one of the products of the reaction. The reaction is summarized below.

$$^{230}_{90}Th \longrightarrow X + ^{4}_{2}He$$

You must determine the unknown product of the reaction, *X*. This can be done through the conservation of atomic number and mass number. The periodic table can then be used to identify *X*.

Known

reactant: thorium-230 ($^{230}_{90}Th$)

decay type: alpha particle emission ($^{4}_{2}He$)

Unknown

reaction product $X = ?$

balanced nuclear equation = ?

2. Solve for the Unknown

Using each particle's mass number, make sure mass number is conserved on each side of the reaction arrow.

mass number: $230 = X + 4$

$$X = 230 - 4 = 226$$

Thus, the mass number of *X* is 226.

Using each particle's atomic number, make sure atomic number is conserved on each side of the reaction arrow.

atomic number: $90 = X + 2$

$$X = 90 - 2 = 88$$

Thus, the atomic number of *X* is 88. The periodic table identifies the element as radium (Ra).

Write the balanced nuclear equation.

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

3. Evaluate the Answer

The correct formula for an alpha particle is used. The sums of the superscripts on each side of the equation are equal. The same is true for the subscripts. Therefore, the atomic number and the mass number are conserved. The nuclear equation is balanced.

Thorium fluoride is used in the manufacture of propane lantern mantles and high-intensity searchlights.

Practice!

For more practice with balancing nuclear equations, go to **Supplemental Practice Problems** in Appendix A.

PRACTICE PROBLEMS

6. Write a balanced nuclear equation for the reaction in which oxygen-15 undergoes positron emission.
7. Determine what type of decay occurs when thorium-231 undergoes radioactive decay to form protactinium-231.
8. Write a balanced nuclear equation for the reaction in which the transition metal zirconium-97 undergoes beta decay.
9. Complete the following nuclear equations.

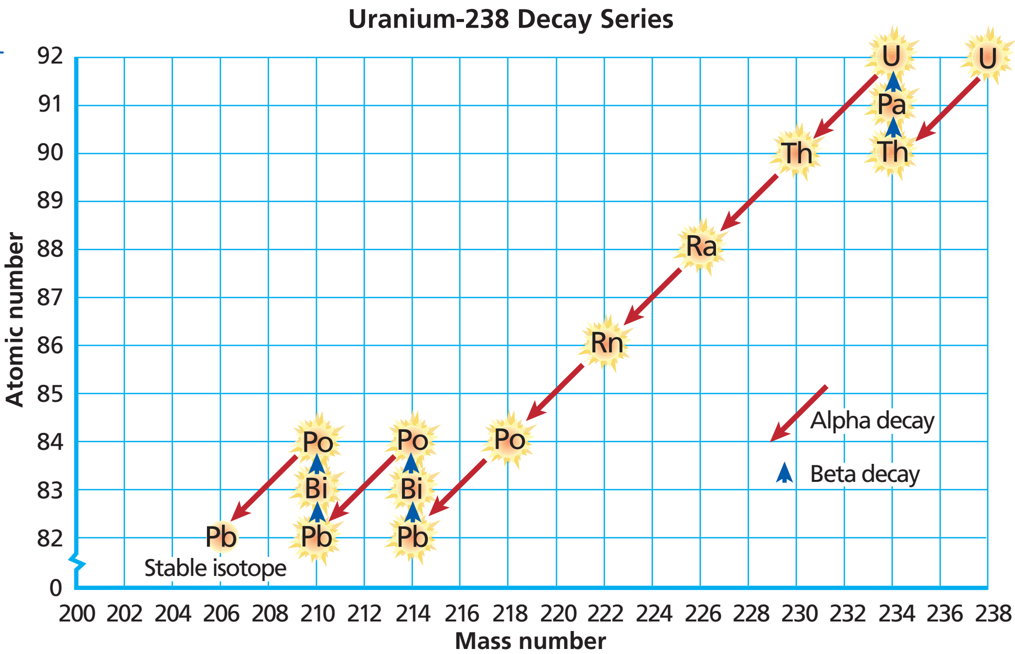
   a. $^{142}_{61}Pm + ? \longrightarrow {}^{142}_{60}Nd$ **b.** $^{218}_{84}Po \longrightarrow {}^{4}_{2}He + ?$ **c.** $? \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$

Radioactive Series

A series of nuclear reactions that begins with an unstable nucleus and results in the formation of a stable nucleus is called a **radioactive decay series**. As you can see in **Figure 25-11**, uranium-238 first decays to thorium-235, which in turn decays to protactinium-234. Decay reactions continue until a stable nucleus, lead-206, is formed.

Figure 25-11

Uranium-238 undergoes 14 different radioactive decay processes before forming stable lead-206.



Section 25.2 Assessment

10. Explain how you can predict whether or not an isotope is likely to be stable if you know the number of neutrons and protons in its nucleus.
11. Write the nuclear equation for the alpha decay of astatine-213.
12. Complete and balance the following.

    a. $^{66}_{29}Cu \longrightarrow {}^{66}_{30}Zn + ?$

    b. $? \longrightarrow {}^{181}_{77}Ir + {}^{4}_{2}He$
13. **Thinking Critically** A new element is synthesized in a laboratory. The element has a neutron-to-proton ratio of 1.6 : 1. Will the element be radioactive? If so, what type of radioactive decay will it most likely undergo?
14. **Communicating** Describe the forces acting on the particles within a nucleus. Explain why neutrons are the "glue" holding the nucleus together.

Section 25.3 Transmutation

All the nuclear reactions that have been described thus far are examples of radioactive decay, where one element is converted into another element by the spontaneous emission of radiation. This conversion of an atom of one element to an atom of another element is called **transmutation**. Except for gamma emission, which does not alter an atom's atomic number, all nuclear reactions are transmutation reactions. Some unstable nuclei, such as the uranium salts used by Henri Becquerel, undergo transmutation naturally. However, transmutation may also be forced, or induced, by bombarding a stable nucleus with high-energy alpha, beta, or gamma radiation.

Objectives

- **Describe** how induced transmutation is used to produce a transuranium element.
- **Solve** problems involving radioactive decay rates.

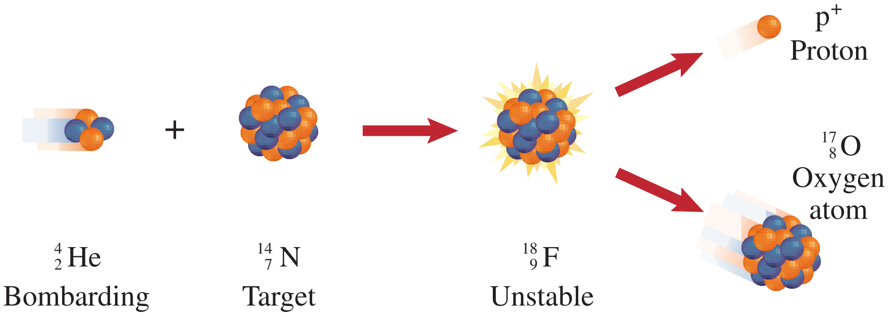
Vocabulary

transmutation
induced transmutation
transuranium element
half-life
radiochemical dating

Induced Transmutation

In 1919, Ernest Rutherford performed the first laboratory conversion of one element into another element. By bombarding nitrogen-14 with high-speed alpha particles, an unstable fluorine-18 occurred, and then oxygen-17 was formed. This transmutation reaction is illustrated below.

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



Rutherford's experiments demonstrated that nuclear reactions can be induced, in other words, produced artificially. The process, which involves striking nuclei with high-velocity charged particles, is called **induced transmutation**. The charged particles, such as alpha particles used by Rutherford, must be moving at extremely high speeds to overcome the electrostatic repulsion between themselves and the target nucleus. Because of this, scientists have developed methods to accelerate charged particles to extreme speeds by using very strong electrostatic and magnetic fields. Particle accelerators, which are commonly called "atom smashers," are built to produce the high-speed particles needed to induce transmutation. The inside of the Fermi National Accelerator Laboratory's Tevatron is shown in **Figure 25-12**. The Tevatron is the world's highest-energy particle accelerator. The purpose of the facility, which opened in 1999, is to research high-energy nuclear reactions and particle physics. Since Rutherford's first experiments involving induced transmutation, scientists have used the technique to synthesize hundreds of new isotopes in the laboratory.

Figure 25-12

The main Tevatron ring has a diameter of more than 0.8 km and a circumference of about 6.4 km. The accelerator uses conventional and superconducting magnets to accelerate particles to high speeds and high energies.

Transuranium elements The elements immediately following uranium in the periodic table—elements with atomic numbers 93 and greater—are known as the **transuranium elements**. All transuranium elements have been produced in the laboratory by induced transmutation and are radioactive.

First discovered in 1940, elements 93 (neptunium) and 94 (plutonium) are prepared by bombarding uranium-238 with neutrons.

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

If you read through the names of the transuranium elements, you'll notice that many of them have been named in honor of their discoverers or the laboratories at which they were created. There are ongoing efforts throughout the world's major scientific research centers to synthesize new transuranium elements and study their properties.

EXAMPLE PROBLEM 25-2

Induced Transmutation Reaction Equations

Write a balanced nuclear equation for the induced transmutation of aluminum-27 into phosphorus-30 by alpha particle bombardment. A neutron is emitted from the aluminum atom in the reaction.

1. Analyze the Problem

You are given all of the particles involved in an induced transmutation reaction, from which you must write the balanced nuclear equation. Because the alpha particle bombards the aluminum atom, they are reactants and must appear on the reactant side of the reaction arrow. Obtain the atomic number of aluminum and phosphorus from the periodic table. Write out the nuclear reaction, being sure to include the alpha particle (reactant) and the neutron (product).

Known

reactants: aluminum-27 and an alpha particle
products: phosphorus-30 and a neutron

Unknown

nuclear equation for the reaction = ?

2. Solve for the Unknown

Write the formula for each participant in the reaction.
Aluminum is atomic number 13; its nuclear formula is $^{27}_{13}\text{Al}$.
Phosphorus is atomic number 15; its nuclear formula is $^{30}_{15}\text{P}$.
The formula for the alpha particle is $^{4}_{2}\text{He}$.
The formula for the neutron is $^{1}_{0}\text{n}$.
Write the balanced nuclear equation.

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

3. Evaluate the Answer

The sums of the superscripts on each side of the equation are equal. The same is true for the subscripts. Therefore, the atomic number and the mass number are conserved. The formula for each participant in the reaction is also correct. The nuclear equation is written correctly.

PRACTICE PROBLEMS

15. Write the balanced nuclear equation for the induced transmutation of aluminum-27 into sodium-24 by neutron bombardment. An alpha particle is released in the reaction.

16. Write the balanced nuclear equation for the alpha particle bombardment of $^{239}_{94}\text{Pu}$. One of the reaction products is a neutron.

Practice!

For more practice with transmutation reactions, go to **Supplemental Practice Problems** in Appendix A.

Radioactive Decay Rates

You may be wondering how it is that there are any naturally occurring radioisotopes found on Earth. After all, if radioisotopes undergo continuous radioactive decay, won't they eventually disappear? And with the exception of synthesized radioisotopes, few new radioisotopes are being formed. Furthermore, radioisotopes have been decaying for about 4.6 billion years (the span of Earth's existence). Yet naturally occurring radioisotopes are not uncommon on Earth. The explanation for this involves the differing decay rates of isotopes.

Radioactive decay rates are measured in half-lives. A **half-life** is the time required for one-half of a radioisotope's nuclei to decay into its products. For example, the half-life of the radioisotope strontium-90 is 29 years. If you had 10.0 g of strontium-90 today, 29 years from now you would have 5.0 g left. **Table 25-4** shows how this decay continues through four half-lives of strontium-90. **Figure 25-13** presents the data from the table in terms of the percent of strontium-90 remaining after each half-life.

Table 25-4

The Decay of Strontium-90		
Number of half-lives	**Elapsed time**	**Amount of strontium-90 present**
0	0	10.0 g
1	29 years	$10.0\text{ g} \times \left(\frac{1}{2}\right) = 5.00\text{ g}$
2	58 years	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 2.50\text{ g}$
3	87 years	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 1.25\text{ g}$
4	116 years	$10.0\text{ g} \times \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 0.625\text{ g}$

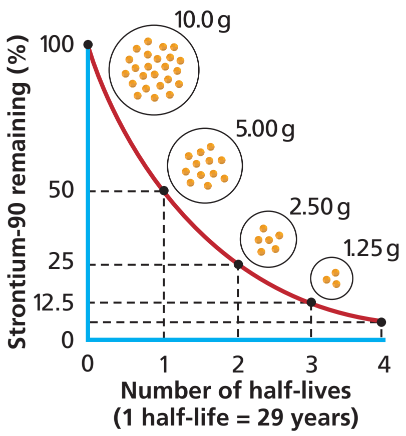


Figure 25-13

The graph shows the percent of a strontium-90 sample remaining over a period of four half-lives. With the passing of each half-life, half of the strontium-90 sample decays. Approximately what percent of strontium-90 remains after 1½ half-lives have passed?

The decay continues until negligible strontium-90 remains.

The data in **Table 25-4** can be summarized in a simple equation representing the decay of any radioactive element.

$$\text{Amount remaining} = (\text{Initial amount})\left(\frac{1}{2}\right)^{n}$$

In the equation, n is equal to the number of half-lives that have passed. Note that the initial amount may be in units of mass or number of particles. A more versatile form of the equation can be written if the exponent n is replaced by the equivalent quantity t/T, where t is the elapsed time and T is the duration of the half-life.

$$\text{Amount remaining} = (\text{Initial amount})\left(\frac{1}{2}\right)^{t/T}$$

Note that both t and T must have the same units of time. This type of expression is known as an exponential decay function. **Figure 25-13** shows the graph of a typical exponential decay function—in this case, the decay curve for strontium-90.

Each radioisotope has its own characteristic half-life. Half-lives for several representative radioisotopes are given in **Table 25-5** on the following page. As the table shows, half-lives have an incredible range of values, from millionths of a second to billions of years! To gain a greater understanding of half-life, do the **miniLAB** on page 819.

Table 25-5

Half-Lives of Several Radioisotopes		
Radioisotope	**Symbol**	**Half-life**
Polonium-214	$^{214}_{84}Po$	163.7 microseconds
Cobalt-60	$^{60}_{27}Co$	5.272 years
Radon-222	$^{222}_{86}Ra$	3.8 days
Phosphorous-32	$^{32}_{15}P$	14.28 days
Tritium	$^{3}_{1}H$	12.32 years
Carbon-14	$^{14}_{6}C$	5730 years
Uranium-238	$^{238}_{92}U$	4.46×10^9 years

EXAMPLE PROBLEM 25-3

Iron-59 is used to produce this image of a patient's circulatory system.

Calculating Amount of Remaining Isotope

Iron-59 is used in medicine to diagnose blood circulation disorders. The half-life of iron-59 is 44.5 days. How much of a 2.000-mg sample will remain after 133.5 days?

1. Analyze the Problem

You are given a known mass of a radioisotope with a known half-life. You must first determine the number of half-lives that passed during the 133.5 day period. Then use the exponential decay equation to calculate the amount of the sample remaining.

Known

Initial amount = 2.000 mg

Elapsed time (t) = 133.5 days

Half-life (T) = 44.5 days

Unknown

Amount remaining = ? mg

2. Solve for the Unknown

Determine the number of half-lives passed during the 133.5 days.

$$\text{Number of half-lives } (n) = \frac{\text{Elapsed time}}{\text{Half-life}}$$

$$n = \frac{(133.5 \cancel{\text{days}})}{(44.5 \cancel{\text{days}}/\text{half-life})} = 3.00 \text{ half-lives}$$

Substitute the values for n and initial mass into the exponential decay equation and solve.

$$\text{Amount remaining} = (\text{Initial amount})\left(\frac{1}{2}\right)^n$$

$$\text{Amount remaining} = (2.000 \text{ mg})\left(\frac{1}{2}\right)^{3.00}$$

$$\text{Amount remaining} = (2.000 \text{ mg})\left(\frac{1}{8}\right)$$

Amount remaining = 0.2500 mg

3. Evaluate the Answer

Three half-lives is equivalent to $\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)$, or $\frac{1}{8}$. The answer (0.2500 mg) is equal to $\frac{1}{8}$ of the original mass of 2.000 mg. The answer has four significant figures because the original mass was given with four significant figures. The values of n and $\frac{1}{2}$ do not affect the number of significant figures in the answer.

PRACTICE PROBLEMS

17. If gallium-68 has a half-life of 68.3 minutes, how much of a 10.0-mg sample is left after one half-life? Two half-lives? Three half-lives?

18. If the passing of five half-lives leaves 25.0 mg of a strontium-90 sample, how much was present in the beginning?

19. Using the half-life given in **Table 25-5**, how much of a 1.0-g polonium-214 sample remains after 818 microseconds?

Practice!

For more practice with half-life problems, go to **Supplemental Practice Problems** in Appendix A.

Radiochemical Dating

Chemical reaction rates are greatly affected by changes in temperature, pressure, and concentration, and by the presence of a catalyst. In contrast, nuclear reaction rates remain constant regardless of such changes. In fact, the half-life of any particular radioisotope is constant. Because of this, radioisotopes can be used to determine the age of an object. The process of determining the age of an object by measuring the amount of a certain radioisotope remaining in that object is called **radiochemical dating**.

miniLAB

Modeling Radioactive Decay

Formulating Models Because of safety concerns, it is usually not possible to directly experiment with radioactive isotopes in the classroom. Thus, in this lab you will use pennies to model the half-life of a typical radioactive isotope. Each penny represents an individual atom of the radioisotope.

Materials 100 pennies, 5-oz. or larger plastic cup, graph paper, graphing calculator (optional)

Procedure

1. Place the pennies in the plastic cup.
2. Place your hand over the top of the cup and shake the cup several times.
3. Pour the pennies onto a table. Remove all the pennies that are "heads-up." These pennies represent atoms of the radioisotope that have undergone radioactive decay.
4. Count the number of pennies that remain ("tails-up" pennies) and record this number in the Decay Results data table as the Number of pennies remaining for trial 1.
5. Place all of the "tails-up" pennies back in the plastic cup.
6. Repeat steps 2 through 5 for as many times as needed until no pennies remain.

Decay Results

Trial number	Number of pennies remaining
0	100
1	
2	
3	
4	
5	
6	
7	
8	

Analysis

1. Make a graph of Trial number versus Number of pennies remaining from the Decay Results data table. Draw a smooth curve through the plotted points.
2. How many trials did it take for 50% of the sample to decay? 75%? 90%?
3. If the time between each trial is one minute, what is the half-life of the radioisotope?
4. Suppose that instead of using pennies to model the radioisotope you use 100 dice. After each toss, any die that comes up a "6" represents a decayed atom and is removed. How would the result using the dice compare with the result obtained from using the pennies?

Figure 25-14

a Radiochemical dating is often used to determine the age of bones discovered at archaeological sites. Using this technique, these human bones frozen in a glacier were estimated to be from about 3000 B.C.
b Could carbon-14 dating be used to determine the age of a stone disk with a leather thong which was found with the skeleton in the glacier?

A type of radiochemical dating known as carbon dating is commonly used to measure the age of artifacts that were once part of a living organism, such as the human skeleton shown in **Figure 25-14**. Carbon dating, as its name implies, makes use of the radioactive decay of carbon-14. The procedure relies on the fact that unstable carbon-14 is formed by cosmic rays in the upper atmosphere at a fairly constant rate.

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

These carbon-14 atoms become evenly spread throughout Earth's biosphere, where they mix with stable carbon-12 and carbon-13 atoms. Plants then use carbon dioxide from the environment, which contains carbon-14, to build more complex molecules through the process of photosynthesis. When animals eat plants, the carbon-14 atoms that were part of the plant become part of the animal. Because organisms are constantly taking in carbon compounds, they contain the same ratio of carbon-14 to carbon-12 and carbon-13 found in the atmosphere. However, this all changes once the organism dies. After death, organisms no longer ingest new carbon compounds, and the carbon-14 they already contain continues to decay. The carbon-14 undergoes beta decay to form nitrogen-14.

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

This beta decay reaction has a half-life of 5730 years. Because the amount of stable carbon in the dead organism remains constant while the carbon-14 continues to decay, the ratio of unstable carbon-14 to stable carbon-12 and carbon-13 decreases. By measuring this ratio and comparing it to the nearly constant ratio present in the atmosphere, the age of an object can be estimated. For example, if an object's C-14 to (C-12 + C-13) ratio is one-quarter the ratio measured in the atmosphere, the object is approximately two half-lives, or 11 460 years, old. Carbon-14 dating is limited to accurately dating objects up to approximately 24 000 years of age.

The decay process of a different radioisotope, uranium-238 to lead-206, is commonly used to date objects such as rocks. Because the half-life of uranium-238 is 4.5×10^9 years, it can be used to estimate the age of objects that are too old to be dated using carbon-14. By radiochemical dating of meteorites, the age of the solar system has been estimated at 4.6×10^9 years of age.

Section 25.3 Assessment

20. Describe the process of induced transmutation. Give two examples of induced transmutation reactions that produce transuranium elements.

21. The initial mass of a radioisotope is 10.0 g. If the radioisotope has a half-life of 2.75 years, how much remains after four half-lives?

22. After 2.00 years, 1.986 g of a radioisotope remains from a sample that had an original mass of 2.000 g.

a. Calculate the half-life of the radioisotope.

b. How much of the radioisotope remains after 10.00 years?

23. Thinking Critically Compare and contrast how the half-life of a radioisotope is similar to a sporting tournament in which the losing team is eliminated.

24. Graphing A sample of polonium-214 originally has a mass of 1.0 g. Express the mass of polonium-214 remaining as a percent of the original sample after a period of one, two, and three half-lives. Graph the percent remaining versus the number of half-lives. Approximately how much time has elapsed when 20% of the original sample remains?

Section 25.4

Fission and Fusion of Atomic Nuclei

As you know, there are major differences between chemical and nuclear reactions. One such difference is the amount of energy the reactions produce. You already know that exothermic chemical reactions can be used to generate electricity. Coal-and oil-burning power plants are common examples. The amount of energy released by chemical reactions, however, is insignificant compared with that of certain nuclear reactions. In this section you will learn about the awesome amounts of energy produced by nuclear reactions. The energy producing capability of nuclear reactions leads naturally to their best-known application—nuclear power plants.

Objectives

- **Compare** and **contrast** nuclear fission and nuclear fusion.
- **Explain** the process by which nuclear reactors generate electricity.

Vocabulary

mass defect
nuclear fission
critical mass
breeder reactor
nuclear fusion
thermonuclear reaction

Nuclear Reactions and Energy

In your study of chemical reactions, you learned that mass is conserved. For most practical situations this is true—but, in the strictest sense, it is not. It has been discovered that energy and mass can be converted into each other. Mass and energy are related by Albert Einstein's most famous equation.

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

In this equation, ΔE stands for change in energy (joules), Δm for change in mass (kg), and c for the speed of light (3.00×10^8 m/s). This equation is of major importance for all chemical and nuclear reactions, as it means a loss or gain in mass accompanies *any* reaction that produces or consumes energy.

The binding together or breaking apart of an atom's nucleons also involves energy changes. Energy is released when an atom's nucleons bind together. The nuclear binding energy is the amount of energy needed to break one mole of nuclei into individual nucleons. The larger the binding energy per nucleon is, the more strongly the nucleons are held together, and the more stable the nucleus is. Less stable atoms have lower binding energies per nucleon. **Figure 25-15** shows the average binding energy per nucleon versus mass number for

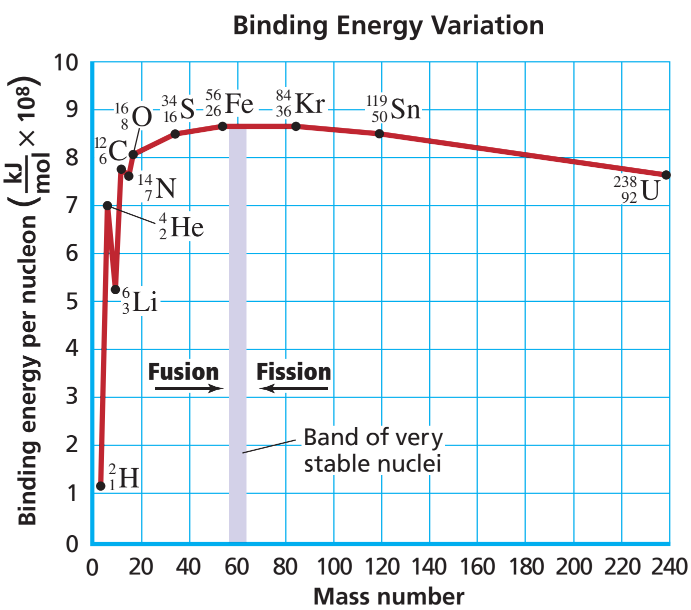


Figure 25-15

The graph shows the relationship between binding energy per nucleon and mass number. The greater the binding energy, the greater the stability of the nucleus. Light nuclei can gain stability by undergoing nuclear fusion, whereas heavy nuclei can gain stability by undergoing nuclear fission.

the elements. Note that the binding energy per nucleon reaches a maximum around a mass number of 60. This means that elements with a mass number near 60 are the most stable. You will see the importance of this relationship in the nuclear fission and fusion processes.

In typical chemical reactions, the energy produced or consumed is so small that the accompanying changes in mass are negligible. In contrast, the mass changes and associated energy changes in nuclear reactions are significant. For example, the energy released from the nuclear reaction of one kilogram of uranium is equivalent to the energy released during the chemical combustion of approximately four billion kilograms of coal!

The tremendous energy released by certain nuclear reactions is a measure of the energy required to bond the subatomic particles in nuclei together. You might be wondering where this energy comes from. The answer involves the $\Delta E = \Delta mc^2$ equation. Scientists have determined that the mass of the nucleus is always less than the sum of the masses of the individual protons and neutrons that comprise it. This difference in mass between a nucleus and its component nucleons is called the **mass defect**. Applying Einstein's $\Delta E = \Delta mc^2$ equation, you can see how the missing mass in the nucleus provides the tremendous energy required to bind the nucleus together.

Nuclear Fission

Binding energies in **Figure 25-15** indicate that heavy nuclei would be more stable if they fragmented into several smaller nuclei. Because atoms with mass numbers around 60 are the most stable, heavy atoms (mass number greater than 60) tend to fragment into smaller atoms in order to increase their stability. The splitting of a nucleus into fragments is known as **nuclear fission**. The fission of a nucleus is accompanied by a very large release of energy.

Nuclear power plants use nuclear fission to generate power. The first nuclear fission reaction discovered involved uranium-235. As you can see in **Figure 25-16**, when a uranium-235 nucleus is struck by a neutron, it undergoes fission. Barium-141 and krypton-92 are just two of the many possible products of this fission reaction. In fact, scientists have identified more than 200 different product isotopes from the fission of a uranium-235 nucleus.

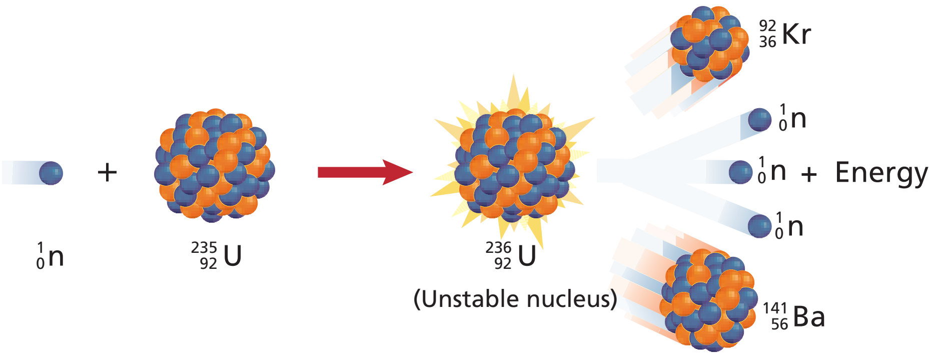


Figure 25-16

The figure shows the nuclear fission of uranium-235. When bombarded with a neutron, uranium-235 forms unstable uranium-236, which then splits into two lighter nuclei and additional neutrons. The splitting (fission) of the nucleus is accompanied by a large release of energy.

Each fission of uranium-235 releases additional neutrons. If one fission reaction produces two neutrons, these two neutrons can cause two additional fissions. If those two fissions release four neutrons, those four neutrons could then produce four more fissions, and so on, as shown in **Figure 25-17.** This self-sustaining process in which one reaction initiates the next is called a chain reaction. As you can imagine, the number of fissions and the amount of energy released can increase extremely rapidly. The explosion from an atomic bomb is an example of an uncontrolled chain reaction.

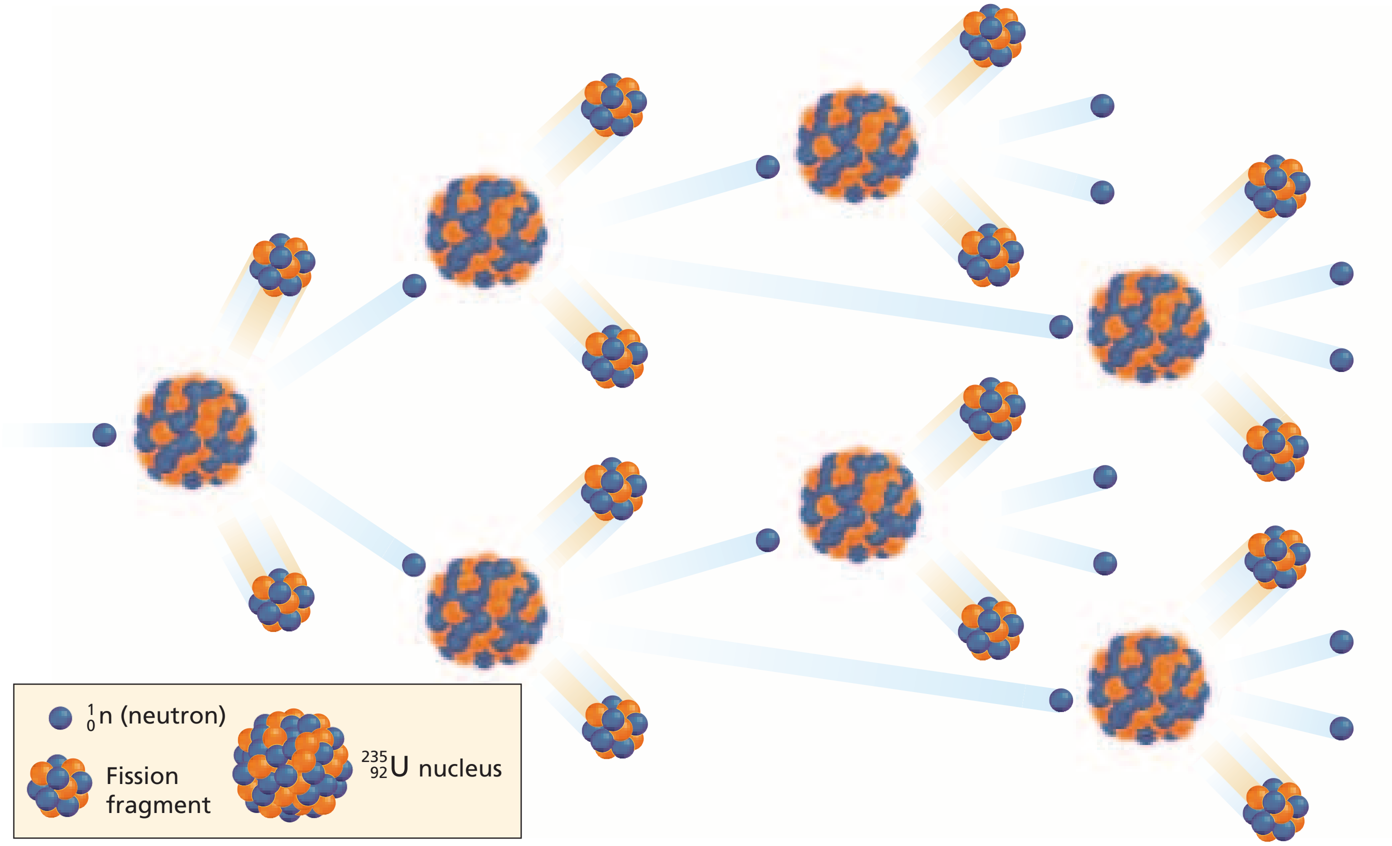


Figure 25-17

This figure illustrates the ongoing reactions characteristic of a nuclear fission chain reaction.

A sample of fissionable material must have sufficient mass in order for a fission chain reaction to occur. If it does not, neutrons escape from the sample before they have the opportunity to strike other nuclei and continue the chain reaction—the chain reaction never begins. A sample that is not massive enough to sustain a chain reaction is said to have subcritical mass. A sample that is massive enough to sustain a chain reaction has **critical mass**. When a critical mass is present, the neutrons released in one fission cause other fissions to occur. If much more mass than the critical mass is present, the chain reaction rapidly escalates. This can lead to a violent nuclear explosion. A sample of fissionable material with a mass greater than the critical mass is said to have supercritical mass. **Figure 25-18** shows the effect of mass on the initiation and progression of a fission reaction.

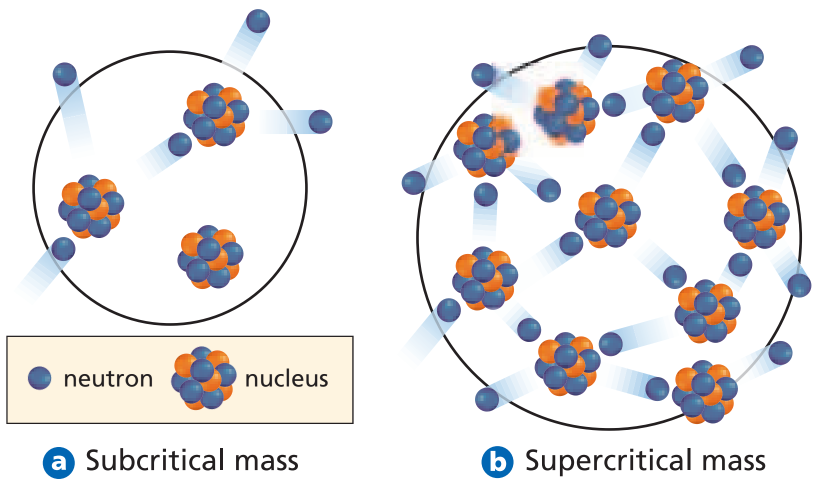


Figure 25-18

The amount of fissionable matter present determines whether a nuclear chain reaction can be sustained. **a** In a subcritical mass, the chain reaction stops because neutrons escape the sample before causing sufficient fissions to sustain the reaction. **b** In a supercritical mass, the chain reaction accelerates as neutrons cause more and more fissions to occur.

Figure 25-19

Worldwide, there are more than 400 operating nuclear power plants such as this one. Currently, 18 countries rely on nuclear power to supply at least 25% of their total electricity needs.

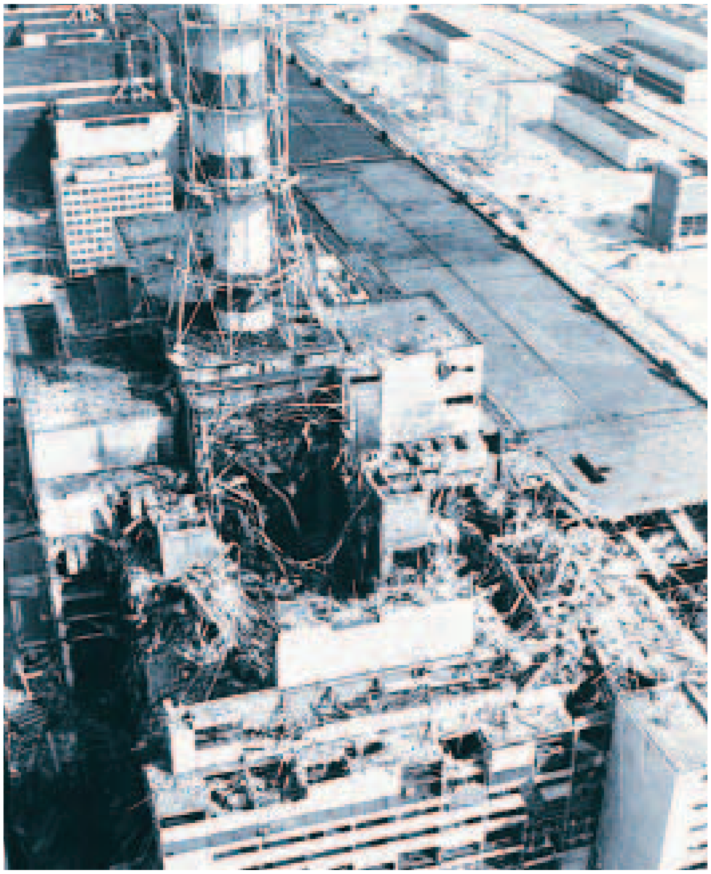
Nuclear Reactors

You may be familiar with the sight of a nuclear power plant, such as the one shown in **Figure 25-19**. Nuclear fission produces the energy generated by nuclear reactors. This energy is primarily used to generate electricity. What fuels the energy production of the reactor? A common fuel is fissionable uranium(IV) oxide (UO_2) encased in corrosion-resistant fuel rods. The fuel is enriched to contain 3% uranium-235, the amount required to sustain a chain reaction. Additional rods composed of cadmium or boron control the fission process inside the reactor by absorbing neutrons released during the reaction.

Keeping the chain reaction going while preventing it from racing out of control requires precise monitoring and continual adjusting of the control rods. Much of the concern about nuclear power plants focuses on the risk of losing control of the nuclear reactor, possibly resulting in the accidental release of harmful levels of radiation. The Three Mile Island nuclear accident in the United States in 1979 and the Chernobyl nuclear accident in Ukraine in 1986, shown in **Figure 25-20**, provide powerful examples of why controlling the reactor is critical.

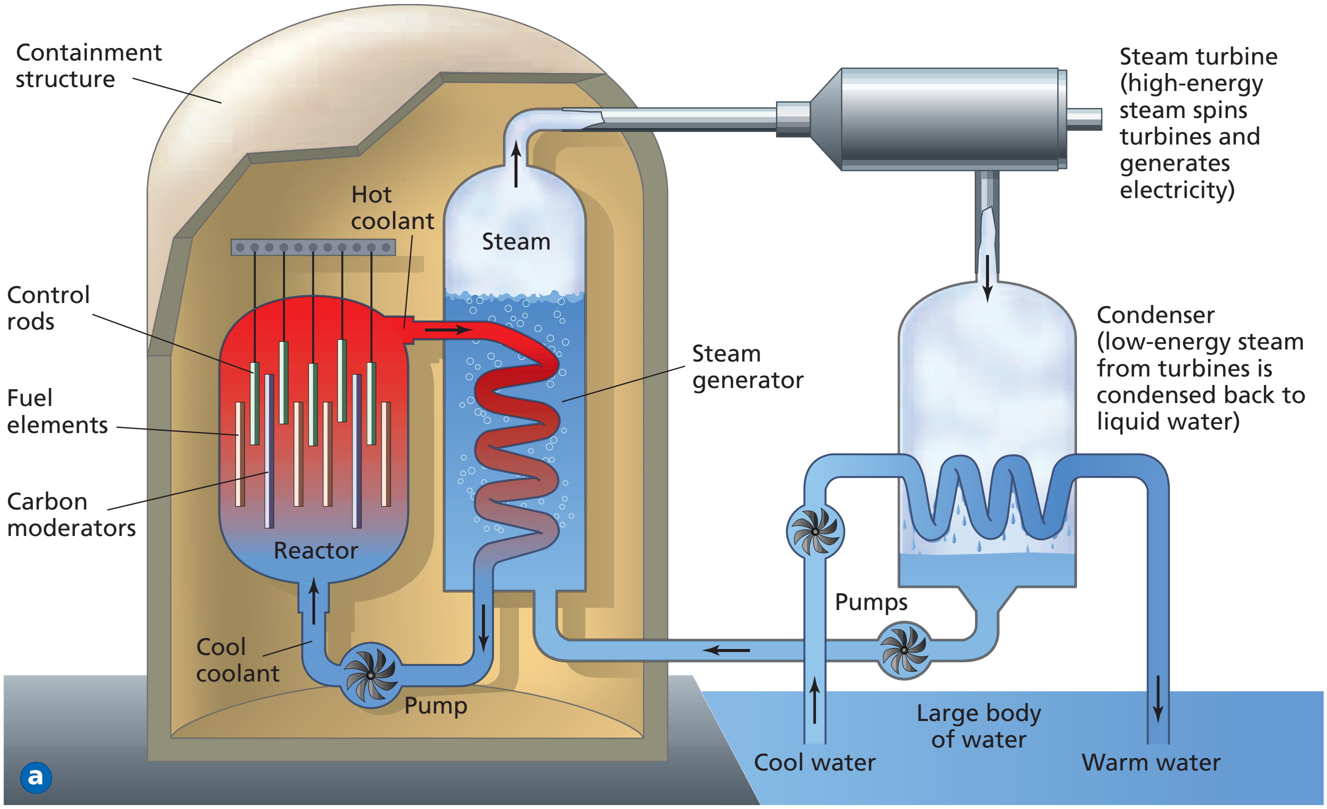
Figure 25-20

The exploded fourth reactor of the Chernobyl nuclear power plant is seen in this aerial view taken in April, 1986. Radiation from the reactor caused great environmental damage to the surrounding areas.

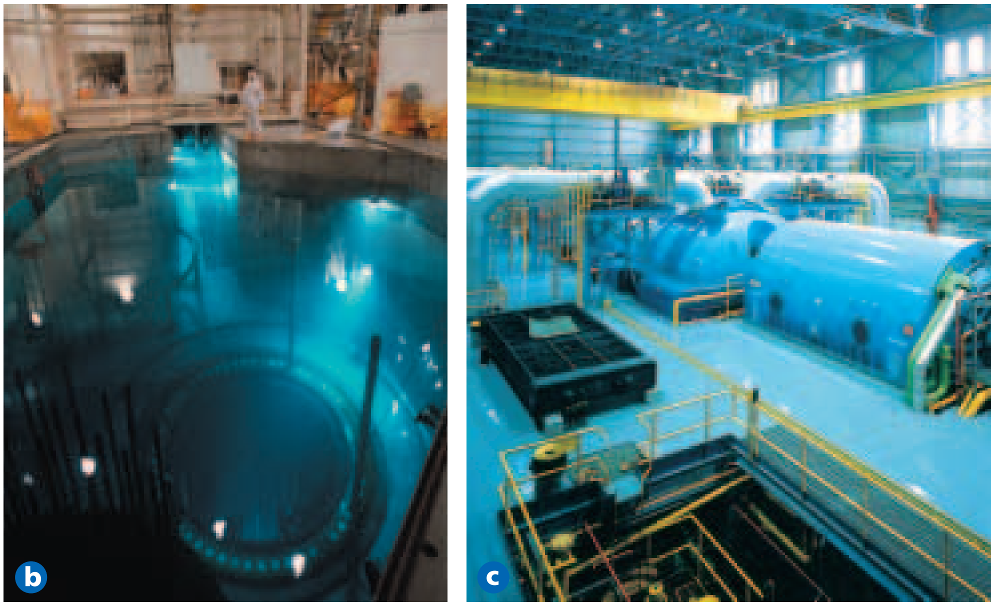


The fission within a nuclear reactor is started by a neutron-emitting source and is stopped by positioning the control rods to absorb virtually all of the neutrons produced in the reaction. The reactor core contains a reflector that acts to reflect neutrons back into the core where they will react with the fuel rods. A coolant, usually water, circulates through the reactor core to carry off the heat generated by the nuclear fission reaction. The hot coolant heats water that is used to power stream-driven turbines which produce electrical power.

In many ways, the design of a nuclear power plant and that of a fossil fuel burning power plant are very similar. In both cases heat from a reaction is used to generate steam. The steam is then used to drive turbines that produce electricity. In a typical fossil fuel power plant, the chemical combustion of coal, oil, or gas generates the heat, whereas in a nuclear power plant, a nuclear fission reaction generates the heat. Because of the hazardous radioactive fuels and fission products present at nuclear power plants, a dense concrete structure is usually built to enclose



the reactor. The main purpose of the containment structure is to shield personnel and nearby residents from harmful radiation. The major components of a nuclear power plant are illustrated in **Figure 25-21**.



As the reactor operates, the fuel rods are gradually depleted and products from the fission reaction accumulate. Because of this, the reactor must be serviced periodically. Spent fuel rods can be reprocessed and repackaged to make new fuel rods. Some fission products, however, are extremely radioactive and cannot be used again. These products must be stored as nuclear waste. The storage of highly radioactive nuclear waste is one of the major issues surrounding the debate over the use of nuclear power. Approximately 20 half-lives are required for the radioactivity of nuclear waste materials to reach levels acceptable for biological exposure. For some types of nuclear fuels, the wastes remain substantially radioactive for thousands of years. A considerable amount of scientific research has been devoted to the disposal of radioactive wastes. How does improper disposal or storage of nuclear wastes affect the environment? Is this a short-term effect? Why?

Another issue is the limited supply of the uranium-235 used in the fuel rods. One option is to build reactors that produce new quantities of fissionable fuels. Reactors able to produce more fuel than they use are called **breeder reactors**. Although the design of breeder reactors poses many difficult technical problems, breeder reactors are in operation in several countries.

Figure 25-21

a The diagram illustrates the major parts of a nuclear power plant. The photos show **b** the submerged reactor and **c** the steam-driven turbines.

How does this containment structure protect the environment? What would be the effect on the environment if this structure leaked radiation?

Nuclear Fusion

Recall from the binding energy diagram in **Figure 25-15** that a mass number of about 60 has the most stable atomic configuration. Thus, it is possible to bind together two or more light (mass number less than 60) and less stable nuclei to form a single more stable nucleus. The combining of atomic nuclei is called **nuclear fusion**. Nuclear fusion reactions are capable of releasing very large amounts of energy. You already have some everyday knowledge of this fact—the Sun is powered by a series of fusion reactions as hydrogen atoms fuse to form helium atoms.

$$4\,{}^{1}_{1}\text{H} \longrightarrow 2\,{}^{0}_{-1}\beta + {}^{4}_{2}\text{He} + \text{energy}$$

Figure 25-22

The characteristic circular-shape of the tokamak reactor is clearly seen here. The reactor uses strong magnetic fields to contain the intensely hot fusion reaction and keep it from direct contact with the interior reactor walls.

Scientists have spent several decades researching nuclear fusion. Why? One reason is that there is a tremendous abundance of lightweight isotopes, such as hydrogen, that can be used to fuel fusion reactions. Also, fusion reaction products are generally not radioactive. Unfortunately, there are major problems that have yet to be overcome on a commercially viable scale. One major problem is that fusion requires extremely high energies to initiate and sustain a reaction. The required energy, which is achieved only at extremely high temperatures, is needed to overcome the electrostatic repulsion between the nuclei in the reaction. Because of the energy requirements, fusion reactions are also known as **thermonuclear reactions**. Just how much energy is needed? The lowest temperature capable of producing a fusion reaction is 40 000 000 K! This temperature—and even higher temperatures—have been achieved using an atomic explosion to initiate the fusion process, but this approach is not practical for controlled electrical power generation.

Obviously there are many problems that must be resolved before fusion becomes a practical energy source. Another significant problem is confinement of the reaction. There are currently no materials capable of withstanding the tremendous temperatures that are required by a fusion reaction. Much of the current research centers around an apparatus called a tokamak reactor. A tokamak reactor, which you can see in **Figure 25-22**, uses strong magnetic fields to contain the fusion reaction. While significant progress has been made in the field of fusion, temperatures high enough for continuous fusion have not been sustained for long periods of time.

Section 25.4 Assessment

25. Compare and contrast nuclear fission and nuclear fusion reactions in terms of the particles involved and the changes they undergo.

26. Describe the process that occurs during a nuclear chain reaction.

27. Explain how nuclear fission can be used to generate electrical power.

28. **Thinking Critically** Present an argument supporting or opposing nuclear power as your state's primary power source. Assume that the primary source of power currently is the burning of fossil fuels.

29. **Calculating** What is the energy change (ΔE) associated with a change in mass (Δm) of 1.00 mg?

Section 25.5

Applications and Effects of Nuclear Reactions

As you learned in the previous section, using nuclear fission reactions to generate electrical power is an important application of nuclear chemistry. Another very important application is in medicine, where the use of radioisotopes has made dramatic changes in the way some diseases are treated. This section explores the detection, uses, and effects of radiation.

Objectives

- **Describe** several methods used to detect and measure radiation.
- **Explain** an application of radiation used in the treatment of disease.
- **Describe** some of the damaging effects of radiation on biological systems.

Vocabulary

ionizing radiation
radiotracer

Detecting Radioactivity

You learned earlier that Becquerel discovered radioactivity because of the effect of radiation on photographic plates. Since this discovery, several other methods have been devised to detect radiation. The effect of radiation on photographic film is the same as the effect of visible light on the film in your camera. With some care, film can be used to provide a quantitative measure of radioactivity. A film badge is a device containing a piece of radiation-sensitive film that is used to monitor radiation exposure. People who work with radioactive substances carry film badges to monitor the extent of their exposure to radiation.

Radiation energetic enough to ionize matter with which it collides is called **ionizing radiation**. The Geiger counter is a radiation detection device that makes use of ionizing radiation in its operation. As you can see in **Figure 25-23**, a Geiger counter consists of a metal tube filled with a gas. In the center of the tube is a wire that is connected to a power supply. When ionizing radiation penetrates the end of the tube, the gas inside the tube absorbs the radiation and becomes ionized. The ionized gas contains ions and free electrons. The free electrons are attracted to the wire, causing a current to flow. A current meter that is built into the Geiger counter measures the current flow through the ionized gas. This current measurement is used to determine the amount of ionizing radiation present.

Another detection device is a scintillation counter, which uses a phosphor-coated surface to detect radiation. Scintillations are bright flashes of light

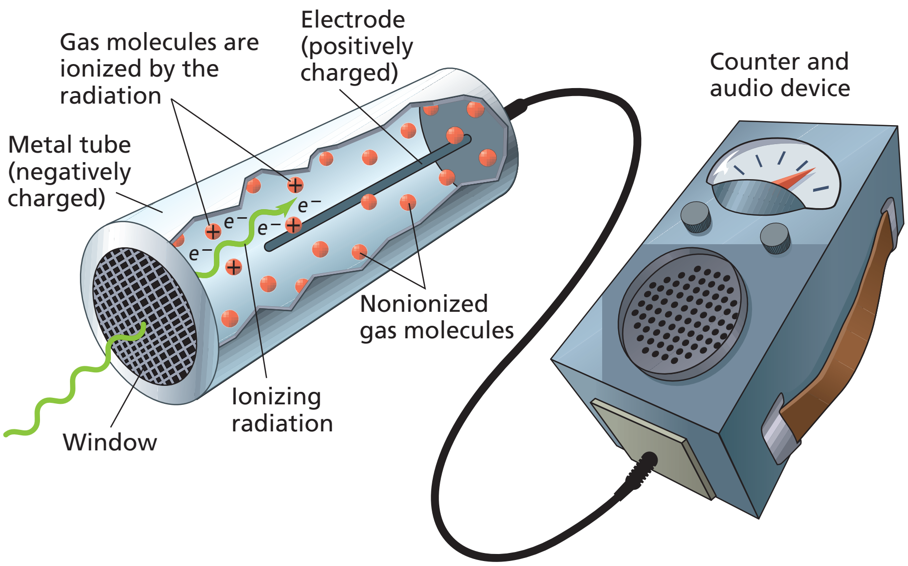


Figure 25-23

The Geiger counter is used to detect and measure radiation levels. The small device is usually hand-held. Ionizing radiation produces an electric current in the Geiger counter. The current is displayed on a scaled meter, while a speaker is used to produce audible sounds.

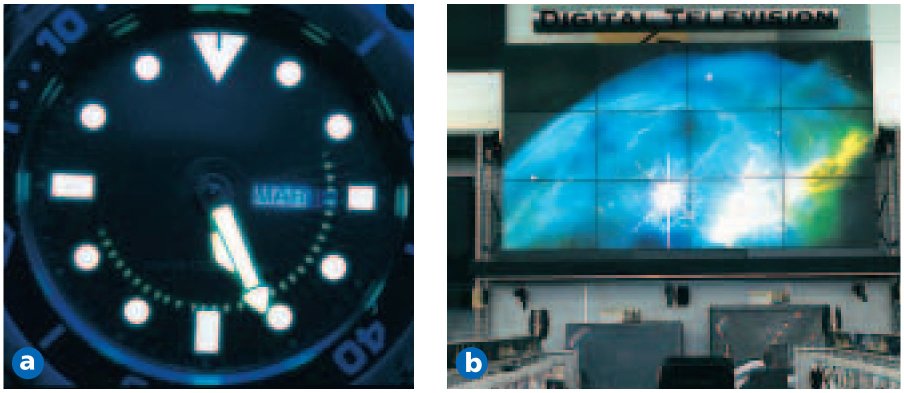


Figure 25-24

a Phosphors are used to aid in the night time readability of watches.
b Television and computer screens are phosphor coated. An electron gun aimed at the back of the screen illuminates the phosphors.

produced when ionizing radiation excites the electrons in certain types of atoms called phosphors. The number and brightness of the scintillations are detected and recorded, giving a measure of the amount of ionizing radiation present. As shown in **Figure 25-24a**, the dials of some watches are painted with a radium-containing phosphor that causes the watch to glow in the dark. Televisions and computer monitors, such as those shown in **Figure 25-24b**, also make use of phosphor screens that produce scintillations when struck by electrons.

Uses of Radiation

With proper safety procedures, radiation can be very useful in many scientific experiments. Neutron activation analysis is used to detect trace amounts of elements present in a sample. Computer chip manufacturers use this technique to analyze the composition of highly purified silicon wafers. In the process, the sample is bombarded with a beam of neutrons from a radioactive source, causing some of the atoms in the sample to become radioactive. The type of radiation emitted by the sample is used to determine the types and quantities of elements present. Neutron activation analysis is a very sensitive measurement technique capable of detecting quantities of less than 1×10^{-9} g.

Radioisotopes can also be used to follow the course of an element through a chemical reaction. For example, CO_2 gas containing radioactive carbon-14 isotopes has been used to study glucose formation in photosynthesis.

$$6CO_2 + 6H_2O + \text{chlorophyll} \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

Because the CO_2 containing carbon-14 is used to trace the progress of carbon through the reaction, it is referred to as a radiotracer. A **radiotracer** is a radioisotope that emits non-ionizing radiation and is used to signal the presence of an element or specific substance. The fact that all of an element's isotopes have the same chemical properties makes the use of radioisotopes possible. Thus, replacing a stable atom of an element in a reaction with one of its isotopes does not alter the reaction. Radiotracers are important in a number of areas of chemical research, particularly in analyzing the reaction mechanisms of complex, multi-step reactions.

Radiotracers also have important uses in medicine. Iodine-131, for example, is commonly used to detect diseases associated with the thyroid gland. One of the important functions of the thyroid gland is to extract iodine from the bloodstream to make the hormone thyroxine. If a thyroid problem is suspected, a doctor will give the patient a drink containing a small amount of iodine-131. The iodine-containing radioisotope is then used to monitor the functioning of the thyroid gland, as shown in **Figure 25-25**. After allowing

Careers Using Chemistry

Radiation Therapist

Would you like to work with a team of medical specialists that help people battle and recover from cancer? If so, consider a career as a radiation therapist.

Radiation therapists, working under the direction of physicians, administer doses of radiation to cancer patients in order to kill invasive cancer cells. Computers are used to help plan the course of treatment. The therapists also prepare the patients for treatment and explain the expected side effects. The administration of the radiation often involves the use of state-of-the-art medical equipment.

time for the iodine to be absorbed, the amount of iodide taken up by the thyroid is measured. This is just one example of the many ways radioisotopes are useful in diagnosing disease.

Another radiation-based medical diagnostic tool is called positron emission transaxial tomography (PET). In this procedure, a radiotracer that decays by positron emission is injected into the patient's bloodstream. Positrons emitted by the radiotracer cause gamma ray emissions that are then detected by an array of sensors surrounding the patient. The type of radiotracer injected depends on what biological function the doctor wants to monitor. For example, as shown in **Figure 25-26**, a fluorine-based radiotracer is commonly used in the PET analysis of the brain's glucose metabolism. Abnormalities in how glucose is metabolized by the brain can help in the diagnosis of brain cancer, schizophrenia, epilepsy, and other brain disorders.

Radiation can pose serious health problems for humans because of the damage it causes to living cells. Healthy cells can be badly damaged or completely destroyed by radiation. However, radiation can also destroy unhealthy cells, including cancer cells. All cancers are characterized by the runaway growth of abnormal cells. This growth can produce masses of abnormal tissue, called malignant tumors. Radiation therapy is used to treat cancer by destroying the fast-growing cancer cells. In fact, cancer cells are more susceptible to destruction by radiation than healthy ones. In the process of destroying unhealthy cells, some healthy cells are also damaged. Despite this major drawback, radiation therapy has become one of the most important treatment options used in the fight against cancer.

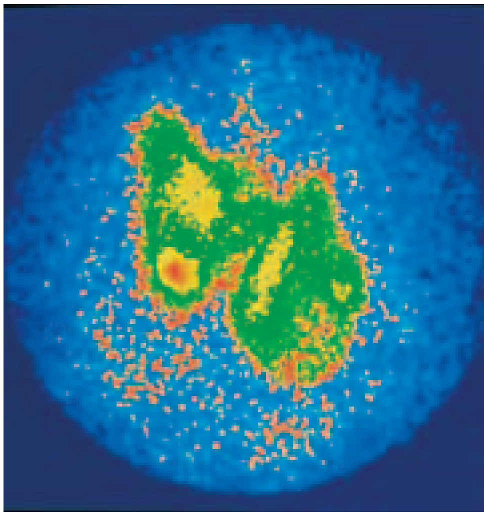


Figure 25-25

Doctors analyze radiotracer produced images such as this to determine whether a patient's thyroid gland is functioning properly.

Biological Effects of Radiation

Although radiation has a number of medical and scientific applications, it can be very harmful. The damage produced from ionizing radiation absorbed by the body depends on several factors, such as the energy of the radiation, the type of tissue absorbing the radiation, and the distance from the source. Do the **problem-solving LAB** on the next page to see how radiation exposure is affected by distance. Gamma rays are particularly dangerous because they easily penetrate human tissue. In contrast, the skin usually stops alpha radiation, and beta radiation generally penetrates only about 1–2 cm beneath the skin.

Figure 25-26

Shown here are images produced from a fluorine-based PET scan of a patient's brain.

Chemistry Online

Topic: Food Irradiation
To learn more about food irradiation, visit the Chemistry Web site at **chemistrymc.com**

Activity: Research the process of food irradiation and scientific responses to consumer concerns. Hold a class debate about its use.

High-energy ionizing radiation is dangerous because it can readily fragment and ionize molecules within biological tissue. When ionizing radiation penetrates a living biological system, the ionized atoms and molecules that are generated are unstable and highly reactive. A free radical is an atom or molecule that contains one or more unpaired electrons and is one example of the highly reactive products of ionizing radiation. In a biological system, free radicals can affect a large number of other molecules and ultimately disrupt the operation of normal cells.

Ionizing radiation damage to living systems can be classified as either somatic or genetic. Somatic damage affects only nonreproductive body tissue and therefore affects the organism only during its own lifetime. Genetic damage, on the other hand, can affect offspring because it damages reproductive tissue, which may affect the genes and chromosomes in the sperm and the eggs of the organism. Somatic damage from radiation includes burns similar to those produced by fire, and cancer caused by damage to the cell's growth mechanism. Genetic damage is more difficult to study because it may not become apparent for several generations. Many scientists presently believe that exposure to any amount of radiation poses some risk to the body.

A dose of radiation refers to the amount of radiation your body absorbs from a radioactive source. Two units, the rad and rem, are commonly used to measure radiation doses. The rad, which stands for Radiation-Absorbed Dose,

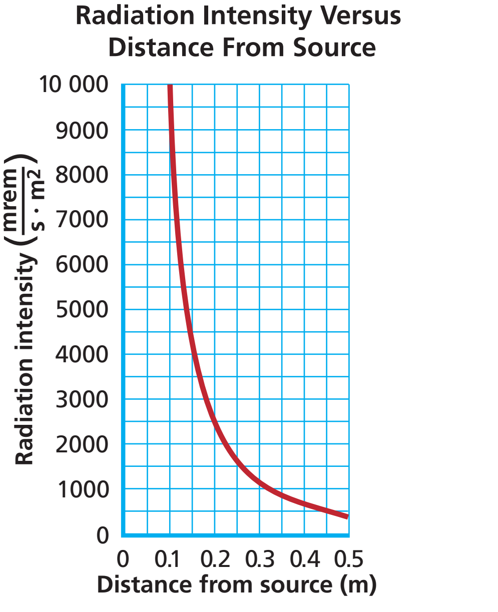
problem-solving LAB

How does distance affect radiation exposure?

Interpreting Graphs Some people, such as X-ray technicians, must work near radioactive sources. They know the importance of keeping a safe distance from the source. The graph shows the intensity of a radioactive source versus the distance from the source.

Analysis

Note how the intensity of the radiation varies with the distance from the source. The unit of radiation intensity is millirem per second per square meter. (This is the amount of radiation striking a square meter of area each second.) Use the graph to answer the Thinking Critically questions that follow.



Thinking Critically

1. How does the radiation exposure change as the distance doubles from 0.1 meter to 0.2 meter? As the distance quadruples from 0.1 meter to 0.4 meter?
2. State in words the mathematical relationship described in your answer to question 1.
3. The maximum radiation exposure intensity that is considered safe is 0.69 mrem/s·m^2. At what distance from the source has the radiation decreased to this level? (*Hint:* Use the equation

$$\frac{I_1}{d_1^2} = \frac{I_2}{d_2^2}$$

where I_1 is the radiation intensity at distance d_1, and I_2 is the radiation intensity at distance d_2.)

Table 25-6

Effects of Short-term Radiation Exposure	
Dose (rem)	**Effects on humans**
0–25	No detectable effects
25–50	Temporary decrease in white blood cell population
100–200	Nausea, substantial decrease in white blood cell population
500	50% chance of death within 30 days of exposure

is a measure of the amount of radiation that results in the absorption of 0.01 J of energy per kilogram of tissue. The dose in rads, however, does not account for the energy of the radiation, the type of living tissue absorbing the radiation, or the time of the exposure. To account for these factors, the dose in rads is multiplied by a numerical factor that is related to the radiation's effect on the tissue involved. The result of this multiplication is a unit called the rem. The rem, which stands for Roentgen Equivalent for Man, is named after Wilhelm Roentgen, who, as you learned in Section 25.1, discovered X rays in 1895.

So how does radiation exposure affect you? You may be surprised to learn that you are exposed to radiation on a regular basis. A variety of sources—some naturally occurring, others not—constantly bombard your body with radiation. Read the **Chemistry and Society** at the end of this chapter to learn about one of the most common sources of exposure. Your exposure to these sources results in an average annual radiation exposure of 100–300 millirems of high-energy radiation. Remembering that the SI prefix *milli-* stands for one-thousandth, this dose of radiation is equivalent to 0.10 to 0.30 rem. To help you put this in perspective, a typical dental X ray exposes you to the virtually harmless dose of 0.0005 rem. However, both short exposures to high doses of radiation and long exposures to lower doses of radiation can be harmful. As you can see from the data in **Table 25-6**, short-term radiation exposures in excess of 500 rem can be fatal. **Table 25-7** shows your annual exposure to common radiation sources. You can perform the **CHEMLAB** at the end of this chapter to examine radiation emitted by a common substance.

Table 25-7

Average Annual Radiation exposure	
Source	**Average exposure (mrem/y)**
Cosmic Radiation	20–50
Radiation from ground	25–170
Radiation from buildings	10–160
Radiation from air	20–260
Human body (internal)	~20
Medical and dental X rays	50–75
Nuclear weapon testing	<1
Air travel	5
Total average	100–300

Section 25.5 Assessment

30. Describe several methods used to detect and measure radiation.

31. Explain one way in which nuclear chemistry is used to diagnose or treat disease.

32. Compare and contrast somatic and genetic biological damage.

33. **Thinking Critically** Using what you know about the biological effects of radiation, explain why it is safe to use radioisotopes for the diagnosis of medical problems.

34. **Hypothesizing** The average person is exposed to 100–300 millirems of radiation per year. Airline crewmembers, however, are exposed to almost twice the average amount of radiation per year. Suggest a possible reason for their increased exposure to radiation.

Measuring Naturally Occurring Radiation

As you may know, some common everyday substances are radioactive. In this lab you will investigate the three naturally occurring potassium isotopes found in a common store-bought salt substitute. Two of potassium's isotopes, potassium-39 (93.1%) and potassium-41 (6.89%) are stable. However, potassium-40 (0.01%) decays by beta emission to form stable calcium-40. You will first measure the background radiation level, and then use that information to determine the radiation due to the beta decay of potassium-40. You will also measure radiation at various locations around your school.

Problem

How can you determine if a substance contains radioactive isotopes?

Objectives

- **Measure** background radiation and radiation emitted by a radioactive isotope.
- **Compare** the level of background radiation to the level of radiation emitted by a radioactive isotope.

Materials

CBL system
RADIATIN software program
graphing calculator
link-to-link cable
Student Radiation Monitor
CBL-P adapter
TI-Graphlink cable
petri dish (with lid)
salt substitute or pure potassium chloride (KCl)
balance

Safety Precautions

- Always wear safety goggles and a lab apron.

Pre-Lab

1. Read the entire **CHEMLAB**.
2. Prepare all written materials that you will take into the laboratory. Include any necessary safety precautions, procedure notes, and a data table.

Radiation Level Data	
Data point	**Counts/minute**

3. What is an isotope? A radioactive isotope?
4. Write the nuclear equation for the radioactive decay of potassium-40 by beta emission. Identify the "parent" and "daughter" nuclides in the decay.
5. Using nuclide-stability rules, form a hypothesis that explains why calcium-40 should be a more stable nuclide than potassium-40.

Procedure

1. Load the program RADIATIN into the graphing calculator.
2. Connect the graphing calculator to the CBL system using the link-to-link cable. Connect the CBL system to the Student Radiation Monitor using the CBL-P adapter. Turn on all devices. Set the Student Radiation Monitor on the audio setting and place it on top of an empty petri dish.

3. Start the RADIATIN program. Go to MAIN MENU. Select 4:SET NO. SAMPLE. Choose 20 for the number of samples in each reading. Press ENTER.
4. Select 1:COLLECT DATA from the MAIN MENU. Select 4:TRIGGER/PROMPT from the COLLECTING MODE menu. Press ENTER to begin collecting data. After a few seconds, the calculator will ask you to enter a PROMPT. Enter 1 (because this is the first data point) and press ENTER. Choose 1:MORE DATA under TRIGGER/PROMPT.
5. Press ENTER to begin the next data point. A graph will appear. When asked to enter the next PROMPT, enter the number that appears at the top right corner of the calculator screen, and then press ENTER. Choose 1:MORE DATA under TRIGGER/PROMPT.
6. Repeat step 5 until you have at least five data points. This set of data is the background level of radiation from natural sources.
7. Use the balance to measure out 10.0 g salt substitute or pure potassium chloride (KCl). Pour the substance into the center of the petri dish so that it forms a small mound. Place the Student Radiation Monitor on top of the petri dish so that the Geiger Tube is positioned over the mound. Repeat step 5 until you have at least five data points.
8. When you are finished collecting data, choose 2:STOP AND GRAPH under TRIGGER/PROMPT. The data points (PROMPTED) are stored in L1, the counts per minute (CTS/MIN) are stored in L2. Press ENTER to view a graph of data.

Cleanup and Disposal

1. Return the salt substitute or potassium chloride (KCl) used in the experiment to the container prepared by your instructor.
2. Disconnect the lab setup and return all equipment to its proper place.

Analyze and Conclude

1. **Collecting Data** Record the data found in L1 and L2 (STAT, EDIT) in the Radiation Level Data table.
2. **Graphing Data** Graph the data from L1 and L2. Use the graph from the graphing calculator as a guide.

3. **Interpreting Data** What is the average background radiation level in counts/minute?
4. **Interpreting Data** What is the average radiation level in counts/minute for the potassium-40 isotope found in the salt substitute?
5. **Observing and Inferring** How can you explain the difference between the background radiation level and the radiation level of the salt substitute?
6. **Thinking Critically** Is the data for the background radiation and the radiation from the potassium-containing sample consistent or random in nature? Propose an explanation for the pattern or lack of pattern seen in the data.
7. **Error Analysis** Describe several ways to improve the experimental procedure so it yields more accurate radiation level data.

Real-World Chemistry

1. Arrange with your teacher to plan and perform a field investigation using the experimental setup from this experiment to measure the background level radiation at various points around school or around town. Propose an explanation for your findings.
2. Using the procedure in this lab, determine if other consumer products contain radioisotopes. Report on your findings.

CHEMISTRY and Society

The Realities of Radon

In the late 1800s, doctors identified lung cancer as a prevalent cause of mine worker deaths throughout the world. It became clear that something in the air of underground mines was related to the deaths. Today scientists believe radon gas was the primary culprit. The heaviest known gas, with a density nine times greater than air, radon is naturally occurring and highly radioactive. Regardless of your location, radon, a gas you cannot see, smell, or taste, is an ever-present part of the air you breathe.

Why be concerned?

Radon is produced when uranium-238, an element present in many rock layers and soil, decays. Because buildings are built on top of soil, and sometimes constructed of stone and brick, radon gas often accumulates inside.

Radon exposure is the second leading cause of lung cancer in the United States, causing about 14 000 deaths annually. Because of the health threat posed by radon, Congress mandated the U.S. Environmental Protection Agency (EPA) make the reduction of indoor radon gas levels a national goal.

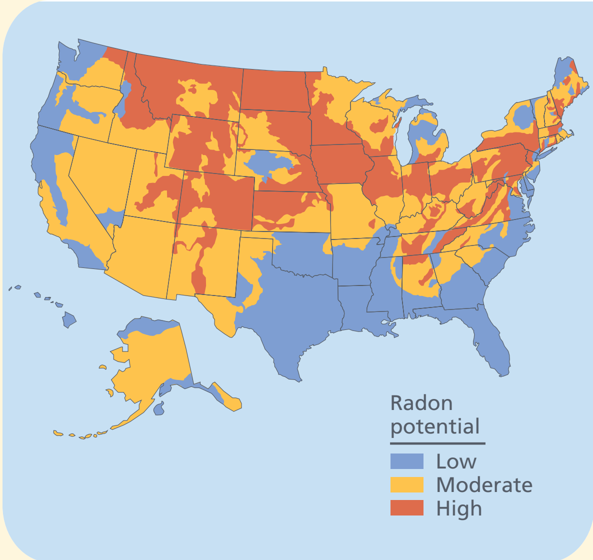
Although radon is an inert gas, its decay produces highly radioactive heavy metals. Polonium is one of the radioactive decay products. Breathing radon-containing air results in the collection of polonium in the tissues of the lungs. Inside the lungs, the polonium decays further, emitting alpha particles and gamma radiation. This radiation damages the cells of the lungs.

How much is too much?

The average outdoor radiation level due to radon is 0.04 pCi/L (picocuries per liter of air). The maximum level considered to be safe is 4.0 pCi/L.

What is your risk factor?

Examine the map showing the risk of radon in your area of the United States. Are you in a high-risk area? Fortunately, only 8% of U.S. homes are believed to have radon levels exceeding 4 pCi/L. Homes at highest risk include those built on uranium-rich rock and thin, dry, permeable soil. However, even buildings in high-risk areas may be safe if there are few pathways into the building, or if the building's air is regularly exchanged with the outside air. People worried about radon levels can test the quality of their air. Do-it-yourself kits are available that test for high levels of radon.



Investigating the Issue

1. **Communicating Ideas** Research radon levels in your state, as well as any radon-related regulations governing real estate transactions. Draw a map of your state. Shade the various levels of radon. Identify your area.

2. **Debating the Issue** Knowing the radon levels in your area, should it be mandated that property inspections include radon testing prior to a sale? If radon levels above 4 pCi/L are discovered at your home or school, how should the problem be addressed?

Chemistry Online

Visit the Chemistry Web site at **chemistrymc.com** to find links to more information about radon exposure.

Summary

25.1 Nuclear Radiation

- Wilhelm Roentgen discovered X rays in 1895. Henri Becquerel, Marie Curie and Pierre Curie pioneered the fields of radioactivity and nuclear chemistry.
- Radioisotopes, isotopes of atoms with unstable nuclei, emit radiation to attain more stable atomic configurations.

25.2 Radioactive Decay

- The strong nuclear force acts on protons and neutrons within a nucleus to hold the nucleus together.
- The neutron-to-proton (n/p) ratio of a nucleus affects its stability. Stable n/p ratios range from 1 : 1 for small atoms to 1.5 : 1 for the largest atoms.
- Atomic number and mass number are conserved in nuclear reactions and equations.
- **Table 25-3** summarizes the characteristics of the five primary types of radioactive decay.

25.3 Transmutation

- The conversion of an atom of one element to an atom of another by radioactive decay processes is called transmutation. Induced transmutation is the process of bombarding nuclei with high-velocity charged particles in order to create new elements.
- A half-life is the time required for half the atoms in a radioactive sample to decay. Every radioisotope has a characteristic half-life.
- Radiochemical dating is a technique for determining the age of an object by measuring the amount of certain radioisotopes remaining in the object.

25.4 Fission and Fusion of Atomic Nuclei

- Nuclear fission is the splitting of large nuclei into smaller more stable fragments. Fission reactions release large amounts of energy.
- In a chain reaction, one reaction induces others to occur. A sufficient mass of a fissionable material must be present for a fission chain reaction to occur.
- Nuclear reactors make use of nuclear fission reactions to generate steam. The steam is used to drive turbines that produce electrical power.
- Nuclear fusion is the process of binding smaller nuclei into a single larger and more stable nucleus. Fusion reactions release large amounts of energy, but require extremely high temperatures.

25.5 Applications and Effects of Nuclear Reactions

- Geiger counters, scintillation counters, and film badges are used to detect and measure radiation.
- Radiotracers, which emit non-ionizing radiation, are used to diagnose disease and to analyze complex chemical reaction mechanisms.
- Both short-term and long-term radiation exposure can cause damage to living cells.

Key Equations and Relationships

- Exponential decay function:
  Amount remaining = (Initial amount)$\left(\frac{1}{2}\right)^n$ or Amount remaining = (Initial amount)$\left(\frac{1}{2}\right)^{t/T}$ (p. 817)

Vocabulary

- band of stability (p. 811)
- breeder reactor (p. 825)
- critical mass (p. 823)
- electron capture (p. 812)
- half-life (p. 817)
- induced transmutation (p. 815)
- ionizing radiation (p. 827)
- mass defect (p. 822)
- nuclear fission (p. 822)
- nuclear fusion (p. 826)
- nucleon (p. 810)
- positron (p. 812)
- positron emission (p. 812)
- radioactive decay series (p. 814)
- radiochemical dating (p. 819)
- radioisotope (p. 807)
- radiotracer (p. 828)
- thermonuclear reaction (p. 826)
- transmutation (p. 815)
- transuranium element (p. 815)
- strong nuclear force (p. 810)
- X ray (p. 809)

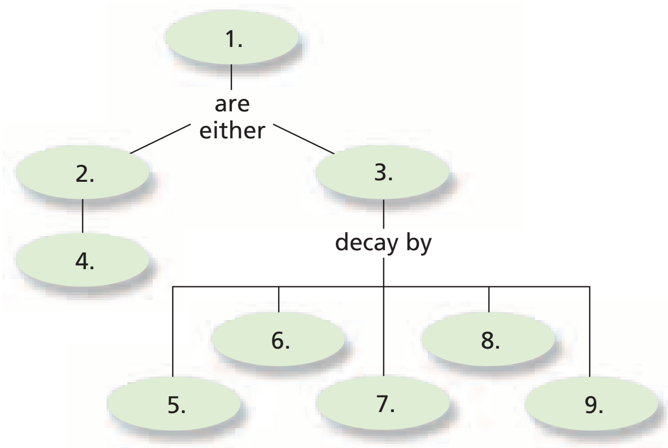
chemistrymc.com/vocabulary_puzzlemaker

CHAPTER 25 ASSESSMENT

Go to the Chemistry Web site at **chemistrymc.com** *for additional Chapter 25 Assessment.*

Concept Mapping

35. Complete the concept map using the following terms: positron emission, alpha decay, atoms, unstable, do not decay, beta decay, stable, gamma emission, and electron capture.



Mastering Concepts

36. What did the Curies contribute to the field of radioactivity and nuclear chemistry? (25.1)

37. Compare and contrast chemical reactions and nuclear reactions in terms of energy changes and the particles involved. (25.1)

38. Match each numbered choice on the right with the correct radiation type on the left. (25.1)

a. alpha	**1.** high speed electrons
b. beta	**2.** 2+ charge
c. gamma	**3.** no charge
	4. helium nucleus
	5. blocked very easily
	6. electromagnetic radiation

39. What is a nucleon? (25. 2)

40. What is the difference between a positron and an electron? (25.2)

41. Describe the differences between a balanced nuclear equation and a balanced chemical equation. (25.2)

42. What is the strong nuclear force? On what particles does it act? (25.2)

43. Explain the difference between positron emission and electron capture. (25.2)

44. Explain the relationship between an atom's neutron-to-proton ratio and its stability. (25.2)

45. What is the significance of the band of stability? (25.2)

46. What is a radioactive decay series? When does the decay series end? (25.2)

47. What scientist performed the first induced transmutation reaction? What element was synthesized in the reaction? (25.3)

48. Define transmutation. Are all nuclear reactions also transmutation reactions? Explain. (25.3)

49. Why are some radioisotopes found in nature, while others are not? (25.3)

50. What are some of the characteristics of transuranium elements? (25.3)

51. Using the band of stability diagram shown in **Figure 25-8** would you expect $^{39}_{20}$Ca to be radioactive? Explain. (25.3)

52. Carbon-14 dating makes use of a specific ratio of two different radioisotopes. Define the ratio used in carbon-14 dating. Why is this ratio constant in living organisms? (25.3)

53. Why is carbon-14 dating limited to objects that are approximately 24 000 years old or less? (25.3)

54. What is a mass defect? (25.4)

55. Describe some of the current limitations of fusion as a power source. (25.4)

56. Describe some of the problems of using fission as a power source. (25.4)

57. What is a chain reaction? Give an example of a nuclear chain reaction. (25.4)

58. How is binding energy per nucleon related to mass number? (25.4)

59. Explain how binding energy per nucleon is related to fission and fusion reactions. (25.4)

60. Discuss how the amount of a fissionable material present affects the likelihood of a chain reaction. (25.4)

61. Explain the purpose of control rods in a nuclear reactor. (25.4)

62. What is a breeder reactor? Why were breeder reactors developed? (25.4)

63. Why does nuclear fusion require so much heat? How is heat contained within a tokamak reactor? (25.4)

64. What is ionizing radiation? (25.5)

65. What is the difference between somatic and genetic damage? (25.5)

66. What property of isotopes allows radiotracers to be useful in studying chemical reactions? (25.5)

67. List several applications that involve phosphors. (25.5)

Mastering Problems

Radioactive Decay (25.2)

68. Calculate the neutron-to-proton ratio for each of the following atoms.

a. tin-134
b. silver-107
c. carbon-12
d. nickel-63
e. carbon-14
f. iron-61

69. Complete the following equations:

a. $^{214}_{83}\text{Bi} \longrightarrow {}^{4}_{2}\text{He} + ?$
b. $^{239}_{93}\text{Np} \longrightarrow {}^{239}_{94}\text{Pu} + ?$

70. Write a balanced nuclear equation for the alpha decay of americium-241.

71. Write a balanced nuclear equation for the beta decay of bromine-84.

72. Write a balanced nuclear equation for the beta decay of selenium-75.

Induced Transmutation (25.3)

73. Write a balanced nuclear equation for the induced conversion of carbon-13 to carbon-14.

74. Write the balanced nuclear equation for the alpha particle bombardment of $^{253}_{99}\text{Es}$. One of the reaction products is a neutron.

75. Write a balanced nuclear equation for the induced transmutation of uranium-238 into californium-246 by bombardment with carbon-12.

76. Write the balanced nuclear equation for the alpha particle bombardment of plutonium-239. The reaction products include a hydrogen atom and two neutrons.

Half-Life (25.3)

77. The half-life of tritium ($^{3}_{1}\text{H}$) is 12.3 years. If 48.0 mg of tritium is released from a nuclear power plant during the course of a mishap, what mass of the nuclide will remain after 49.2 years? After 98.4 years?

78. Technetium-104 has a half-life of 18.0 minutes. How much of a 165.0 g sample remains after 90.0 minutes?

79. Manganese-56 decays by beta emission and has a half-life of 2.6 hours. How many half-lives are there in 24 hours? How many mg of a 20.0 mg sample will remain after five half-lives?

80. A 20.0 g sample of thorium-234 has a half-life of 25 days. How much will remain as a percentage of the original sample after 90 days?

81. The half-life of polonium-218 is 3.0 minutes. If you start with 20.0 g, how long will it be before only 1.0 g remains?

82. A sample of an unknown radioisotope exhibits 8540 decays per second. After 350.0 minutes, the number of decays has decreased to 1250 per second. What is the half-life?

83. Phosphorous-32 has a half-life of 14.32 days. Write and graph an equation for the amount remaining of phosphorous-32 after *t* days if the sample initially contains 150.0 mg of phosphorous-32.

84. Plot the exponential decay curve for a period of five half-lives for the decay of thorium-234 given in Problem 80. How much time has elapsed when 30% of the original sample remains?

85. A rock once contained 1.0 mg of uranium-238, but now contains only 0.257 mg. Given that the half-life for uranium-238 is 4.5×10^{9} y, how old is the rock?

Mixed Review

Sharpen your problem-solving skills by answering the following.

86. A sample initially contains 150.0 mg of radon-222. After 11.4 days, the sample contains 18.7 mg of radon-222. Calculate the half-life.

87. Write a balanced nuclear equation for the positron emission of nitrogen-13.

88. Describe the penetration power of alpha, beta, and gamma radiation.

89. Plot the exponential decay curve for a period of six half-lives using the data given for technetium-104 in Problem 78. How much time has elapsed when 60% of the original sample remains?

90. What information about an atom can you use to predict whether or not it will be radioactive?

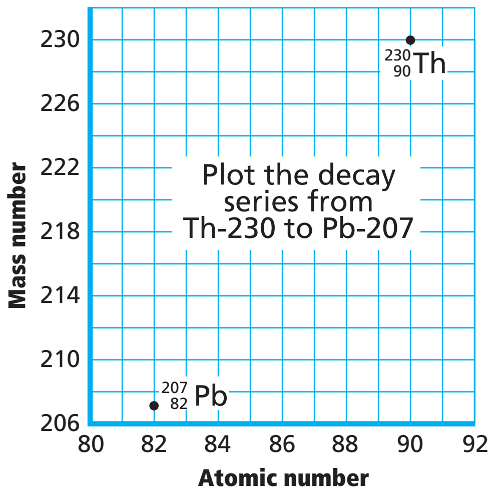
91. A bromine-80 nucleus can decay by gamma emission, positron emission, or electron capture. What is the product nucleus in each case?

92. Explain how a Geiger counter measures levels of ionizing radiation present.

93. The half-life of plutonium-239 is 24 000 years. What fraction of nuclear waste generated today will be present in the year 3000?

Thinking Critically

94. Making and Using Graphs Thorium-231 decays to lead-207 in a stepwise fashion by emitting the following particles in successive steps: β, α, α, β, α, α, α, β, β, α. Plot each step of the decay series on a graph of mass number versus atomic number. Label each plotted point with the symbol of the radioisotope.



95. Analyzing Information Scientists often use heavy ion bombardment to produce new elements. Balance the following nuclear reactions involving heavy ion bombardments.

a. $^{6}_{3}\text{Li} + ^{63}_{28}\text{Ni} \longrightarrow ?$
b. $^{252}_{98}\text{Cf} + ^{10}_{5}\text{B} \longrightarrow ?$

96. Applying Concepts Chemical treatment is often used to destroy harmful chemicals. For example, bases neutralize acids. Why can't chemical treatment be applied to destroy the fission products produced in a nuclear reactor?

97. Applying Concepts A radioactive decay series that begins with $^{237}_{93}$Np ends with the formation of stable $^{209}_{83}$Bi. How many alpha emissions and how many beta emissions are involved in the sequence of radioactive decays?

Writing in Chemistry

98. Research and report on the lives of Marie Curie and her daughter, Irene Curie Joliot. What kind of scientific training did each receive? What was it like to be a female chemist in their time? What other discoveries did each make beyond those made in the field of nuclear chemistry?

99. Research and write a report on the nuclear power plant accidents that occurred at Three Mile Island in Pennsylvania and Chernobyl in the former Soviet Union. What went wrong in each case? How much radiation escaped and entered the surrounding environment? What were the health effects of the released radiation?

100. Evaluate environmental issues associated with nuclear wastes. Research the Yucca Mountain nuclear waste disposal plan, the Hanford nuclear site, or a local nuclear facility. Prepare a poster or multimedia presentation on your findings.

Cumulative Review

Refresh your understanding of previous chapters by answering the following.

101. Identify each of the following as a chemical property or a physical property. (Chapter 3)

a. The element mercury has a high density.
b. Solid carbon dioxide sublimes at room temperature.
c. Zinc oxidizes when exposed to air.
d. Sucrose is a white crystalline solid.

102. Why does the second period of the periodic table contain eight elements? (Chapter 6)

103. Draw the following molecules and show the locations of hydrogen bonds between the molecules. (Chapter 9)

a. two water molecules
b. two ammonia molecules
c. one water molecule and one ammonia molecule

104. Name the process taking place in each situation described below. (Chapter 13)

a. a solid air freshener cube getting smaller and smaller
b. dewdrops forming on leaves in the morning
c. steam rising from a hot spring
d. a crust of ice forming on top of a pond

105. If the volume of a sample of chlorine gas is 4.5 L at 0.65 atm and 321 K, what volume will the gas occupy at STP? (Chapter 14)

106. The temperature of 756 g of water in a calorimeter increases from 23.2°C to 37.6°C. How much heat was given off by the reaction in the calorimeter? (Chapter 16)

107. Explain what a buffer is and why buffers are found in body fluids. (Chapter 19)

108. Explain how the structure of benzene can be used to explain its unusually high stability compared to other unsaturated cyclic hydrocarbons. (Chapter 22)

STANDARDIZED TEST PRACTICE
CHAPTER 25

Use these questions and the test-taking tip to prepare for your standardized test.

1. All of the following are true of alpha particles EXCEPT

a. they have the same composition as helium nuclei.
b. they carry a charge of 2+.
c. they are more penetrating than β particles.
d. they are represented by the symbol $^{4}_{2}He$.

2. In the first steps of its radioactive decay series, thorium-232 decays to radium-228, which then decays to actinium-228. What are the balanced nuclear equations describing these first two decay steps?

a. $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + ^{0}_{-1}\beta$, $^{228}_{88}Ra \rightarrow ^{228}_{89}Ac + ^{0}_{1}\beta$
b. $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + ^{4}_{2}He$, $^{228}_{88}Ra \rightarrow ^{228}_{89}Ac + ^{0}_{-1}\beta$
c. $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + 2\,^{0}_{1}\beta$, $^{228}_{88}Ra \rightarrow ^{228}_{89}Ac + ^{0}_{-1}\beta$
d. $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + ^{4}_{2}He$, $^{228}_{88}Ra + ^{0}_{-1}e \rightarrow ^{228}_{89}Ac$

3. In the early 1930s, van de Graaf generators were used to generate neutrons by bombarding stable beryllium atoms with deuterons ($^{2}_{1}H$), the nuclei of deuterium atoms. A neutron is released in the reaction. Which is the balanced nuclear equation describing this induced transmutation?

a. $^{9}_{4}Be + ^{2}_{1}H \rightarrow ^{10}_{5}B + ^{1}_{0}n$
b. $^{6}_{4}Be + ^{2}_{1}H \rightarrow ^{8}_{5}B + ^{1}_{0}n$
c. $^{9}_{4}Be \rightarrow ^{10}_{5}B + ^{2}_{1}H + ^{1}_{0}n$
d. $^{9}_{4}Be + ^{2}_{1}H \rightarrow ^{11}_{5}B + ^{1}_{0}n$

4. Geologists use the decay of potassium-40 in volcanic rocks to determine their age. Potassium-40 has a half-life of 1.26×10^{9} years, so it can be used to date very old rocks. If a sample of rock 3.15×10^{8} years old contains 2.73×10^{-7} g of potassium-40 today, how much potassium-40 was originally present in the rock?

a. 2.30×10^{-7} g
b. 1.71×10^{-8} g
c. 3.25×10^{-7} g
d. 4.37×10^{-6} g

Interpreting Graphs Use **Figure 25-8** on page 811 to answer questions 5–7.

5. Why will calcium-35 will undergo positron emission?

a. it lies above the line of stability
b. it lies below the line of stability
c. it has a high neutron-to-proton ratio
d. it has an overabundance of neutrons

6. Based on its position relative to the band of stability, ^{80}Zn will undergo which of the following?

a. beta decay
b. positron emission
c. electron capture
d. nuclear fusion

7. Based on its position relative to the band of stability, phosphorous-26 will transmute into which of the following isotopes in the first step of its radioactive decay series?

a. $^{22}_{13}Al$
b. $^{26}_{16}S$
c. $^{26}_{17}Cl$
d. $^{26}_{14}Si$

8. Which of the following is NOT characteristic of a sample of a fissionable element capable of sustaining a chain reaction?

a. The element has a mass number < 60.
b. The sample of the element possesses critical mass.
c. The element's atoms have low binding energy per nucleon.
d. The element's nuclei are more stable if split into smaller nuclei.

9. The immense amount of energy released by the Sun is due to which of the following reactions occuring within its core?

a. nuclear fission
b. gamma decay
c. nuclear fusion
d. alpha decay

10. All of the following are beneficial applications of radioactivity EXCEPT

a. tracing the path of an element through a complex reaction.
b. mutating genetic material using ionizing radiation.
c. diagnosing brain disorders using PET scans.
d. destroying cancer cells with radiation therapy.

TEST-TAKING TIP

Don't Be Afraid To Ask For Help If you're practicing for a test and you find yourself stuck, unable to understand why you got a question wrong, or unable to answer it in the first place, ask someone for help. As long as you ask for help before the test, you'll do fine!