25.2 Nuclear Transformations

Connecting to Your World Weather stripping and insulation help lower heating and cooling bills by conserving energy. They can, however, reduce the exchange of indoor and outdoor air. As a result, radioactive substances such as radon gas can accumulate indoors and pose a health risk. Radon-222 is a radioactive isotope that is present naturally in the soil in some areas. It has a constant rate of decay. In this section, you will learn about decay rates of radioactive substances.

Guide for Reading

Key Concepts

- What determines the type of decay a radioisotope undergoes?
- How much of a sample of a radioisotope remains after each half-life?
- What are two ways that transmutation can occur?

Vocabulary

nuclear force
band of stability
positron
half-life
transmutation
transuranium elements

Reading Strategy

Building Vocabulary Before you read, make a list of the vocabulary terms above. As you read the section, write a definition of each vocabulary term in your own words.

Nuclear Stability and Decay

All nuclei, except those of hydrogen atoms, consist of neutrons and two or more protons. If a force did not hold these subatomic particles together, the like-charged protons would repel one another and fly apart. The **nuclear force** is an attractive force that acts between *all* nuclear particles that are extremely close together, such as protons and neutrons in a nucleus. At these short distances, the nuclear force dominates over electromagnetic repulsions and holds the nucleus together.

More than 1,500 different nuclei are known. Of those, only 264 are stable and do not decay or change with time. The stability of a nucleus depends on the neutron-to-proton ratio. Figure 25.4 shows a graph of number of neutrons vs. number of protons for all known stable nuclei. These nuclei are in a region called the **band of stability.** For elements of low atomic number (below about 20), this ratio is about 1. Above atomic number 20, stable nuclei have more neutrons than protons.

Number of Neutrons vs. Number of Protons for Stable Nuclei

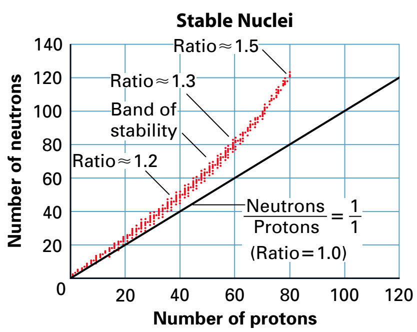


Figure 25.4 A neutron-versus-proton plot of all stable nuclei forms a pattern called the band of stability (shown in red).

INTERPRETING GRAPHS

a. Identify What do the dots on the graph represent?
b. Apply Concepts What is the approximate ratio of neutrons to protons for neodymium, whose atomic number is 60?
c. Describe How does the neutron-to-proton ratio change as the number of protons increases?

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 25.2
- **Core Teaching Resources,** Section 25.2 Review, Interpreting Graphics
- **Transparencies,** T289–T292
- **Small-Scale Chemistry Lab Manual,** Lab 41

Technology

- **Interactive Textbook with ChemASAP,** Simulation 30, Problem-Solving 25.7, Assessment 25.2
- **Go Online,** Section 25.2

25.2

1 FOCUS

Objectives

25.2.1 Describe the type of decay a radioisotope undergoes.
25.2.2 Solve problems that involve half-life.
25.2.3 Identify two ways transmutations can occur.

Guide for Reading

Build Vocabulary L2

Paraphrase Have students look up the definitions of the vocabulary words. Then, have them paraphrase each of these definitions.

Reading Strategy L2

Relate Cause and Effect As students read through the section, have them list examples of cause and effect. For example, nuclei are unstable because their neutron-to-proton ratio is greater than one.

2 INSTRUCT

Connecting to Your World

Have students study the photograph and read the text that opens the section. Ask, **Which type of radiation does radon emit?** *(alpha particles)* **How do scientists express the decay rates of radioactive isotopes?** *(as a half-life—the time it takes for half of the nuclei in the sample to decay)*

Nuclear Stability and Decay

Interpreting Graphs L2

a. The dots represent stable nuclei.
b. 1.3
c. It also increases.

Enrichment L3

Ask, **In terms of stability, what purpose do the neutrons serve in an atom?** *The neutrons separate the positive charges in a nucleus and contribute to the **strong force**, an attractive force between all nucleons.*

Half-Life

Discuss L2

Explain that, for each element, there exists only a small range of neutron-to-proton ratios that produce stable nuclei. If a nucleus does not reflect a stable ratio, it spontaneously decays until a stable ratio of neutrons to protons results.

Relate L2

Explain that the nuclear stability that results from a proper ratio of neutrons to protons in an atom is like the structural stability that results from a proper ratio of mortar to bricks in a building. In the building, gravitational and adhesive forces are balanced; in the nucleus, forces of repulsion (between protons) and attraction (the strong force) are balanced.

Interpreting Graphs L2

a. 50%
b. 25%
c. three half-lives

Enrichment Question L3

Will the curve on the graph ever reach zero? *(Theoretically, it could reach zero if a final atom decays. However, it would not be practical to graph the number of half-lives this event would take, and the amount of radioisotope present would be undectable.)*

Use Visuals L1

Figure 25.5 After students examine the graph, have them consider the role neutrons play in stabilizing the nuclei of atoms. Encourage students to research the strong nuclear force, the force of attraction that holds nucleons together in a stable nucleus.

Table 25.2

Decay Processes
Beta Emission
${}^{66}_{29}\text{Cu} \longrightarrow {}^{66}_{30}\text{Zn} + {}^{0}_{-1}\text{e}$
${}^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e}$
Electron Capture
${}^{59}_{28}\text{Ni} + {}^{0}_{-1}\text{e} \longrightarrow {}^{59}_{27}\text{Co}$
${}^{37}_{18}\text{Ar} + {}^{0}_{-1}\text{e} \longrightarrow {}^{37}_{17}\text{Cl}$
Positron Emission
${}^{8}_{5}\text{B} \longrightarrow {}^{8}_{4}\text{Be} + {}^{0}_{+1}\text{e}$
${}^{15}_{8}\text{O} \longrightarrow {}^{15}_{7}\text{N} + {}^{0}_{+1}\text{e}$
Alpha Emission
${}^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$
${}^{232}_{90}\text{Th} \longrightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$

A nucleus may be unstable and undergo spontaneous radioactive decay for several reasons. **The neutron-to-proton ratio determines the type of decay that occurs.** Some nuclei have too many neutrons relative to the number of protons. These nuclei decay by turning a neutron into a proton to emit a beta particle (an electron) from the nucleus.

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

This process is known as beta emission. It increases the number of protons while decreasing the number of neutrons. Table 25.2 shows examples of beta emission.

Other nuclei are unstable because they have too few neutrons relative to the number of protons. These nuclei increase their stability by converting a proton to a neutron. An electron is captured by a nucleus during this process of electron capture.

A **positron** is a particle with the mass of an electron but a positive charge. During positron emission, a proton changes to a neutron.

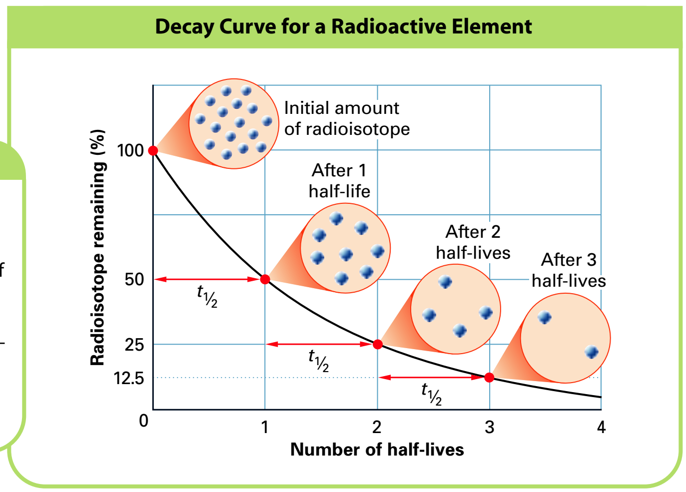
All nuclei that have an atomic number greater than 83 are radioactive. These nuclei have both too many neutrons and too many protons to be stable. Therefore they undergo radioactive decay. Most of them emit alpha particles. Alpha emission increases the neutron-to-proton ratio, which tends to increase the stability of the nucleus. In alpha emission the mass number decreases by four and the atomic number decreases by two.

If all the masses in a nuclear reaction were measured accurately enough, you would find that mass is not conserved. An extremely small quantity of mass is converted into energy released in radioactive decay.

Half-Life

Every radioisotope has a characteristic rate of decay measured by its half-life. A **half-life** ($t_{1/2}$) is the time required for one-half of the nuclei of a radioisotope sample to decay to products, as shown in Figure 25.5. **After each half-life, half of the existing radioactive atoms have decayed into atoms of a new element.**

Figure 25.5 This decay curve shows that during each half-life, half of the radioactive atoms decay exponentially into atoms of another element.



INTERPRETING GRAPHS

a. Identify What percent of the atoms remains after 1 half-life?
b. Describe What percent of the atoms remains after two half-lives?
c. Apply Concepts Approximately how many half-lives does it take for 12.5% of the radioisotope to remain?

Facts and Figures

Unstable Matter

Nearly 85% of all known nuclei are unstable. This fact does not mean that 85% of all matter is unstable. The distribution of stable and unstable isotopes is not even. Because neutrons help bind protons together in the nucleus, the ratio of protons to neutrons is a major factor in determining stability.

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Table 25.3

Half-Lives and Radiation of Some Naturally Occurring Radioisotopes

Isotope	Half-life	Radiation emitted
Carbon-14	5.73×10^3 years	β
Potassium-40	1.25×10^9 years	β, γ
Radon-222	3.8 days	α
Radium-226	1.6×10^3 years	α, γ
Thorium-234	24.1 days	β, γ
Uranium-235	7.0×10^8 years	α, γ
Uranium-238	4.46×10^9 years	α

Half-lives can be as short as a fraction of a second or as long as billions of years. Table 25.3 shows the half-lives of some radioisotopes that occur in nature. Scientists use the half-lives of some radioisotopes found in nature to determine the age of ancient artifacts. Many artificially produced radioisotopes have short half-lives, which is useful in nuclear medicine. The short-lived isotopes are not a long-term radiation hazard to the patient.

One isotope that has a long half-life is uranium-238. Uranium-238 decays through a complex series of radioactive isotopes to the stable isotope lead-206. Figure 25.6 illustrates this process. The age of uranium-containing minerals can be estimated by measuring the ratio of uranium-238 to lead-206. Because the half-life of uranium-238 is 4.5×10^9 years, it is possible to use its half-life to date rocks as old as the solar system.

Checkpoint ***What is the half-life of carbon-14?***

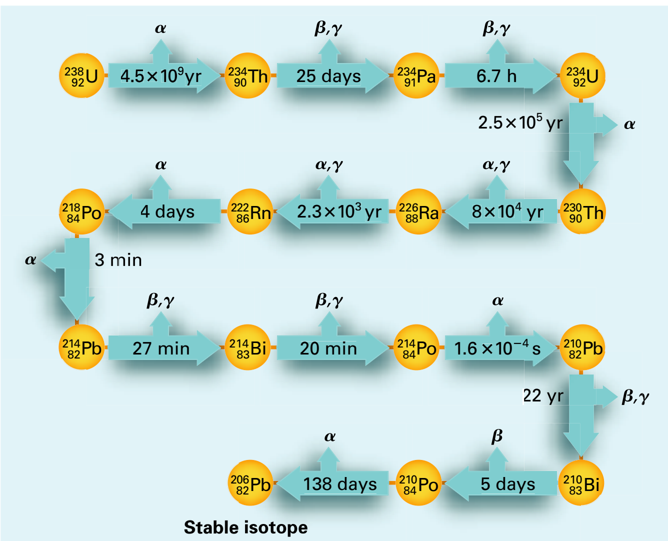

Figure 25.6 Uranium-238 decays through a complex series of radioactive intermediates, including radon (Rn) gas. **Interpreting Diagrams** ***What is the stable end product of this series?***

Go Online NSTA SCILINKS
For: Links on Radioactive Dating
Visit: www.scilinks.org
Web Code: cdn-1252

Interactive Textbook
Simulation 30 Simulate the decay of several isotopes.
with ChemASAP

Use Visuals L1

Table 25.3 Refer students to the table and have them note the range of half-life values. Remind them that these values do not indicate how long a given atom of an isotope will exist, but only how long it takes for half of the atoms in a sample to undergo radioactive decay.

Go Online NSTA SCILINKS

Download a worksheet on **Radioactive Dating** for students to complete, and find additional teacher support from NSTA Sci Links.

Discuss L2

Emphasize that the rate of disintegration of the nuclei of an isotope is unaffected by factors such as heat, pressure, or chemical reactions. Note that the half-life for a particular radioactive isotope is unique to that isotope. No two isotopes have exactly the same half-life.

Use Visuals L1

Figure 25.6 Have students study Figure 25.6, which charts the radioactive decay of uranium-238. Explain that many radioisotopes go through a complex series of nuclear reactions before a stable product is formed.

Differentiated Instruction

Less Proficient Readers L1

Have students who have difficulty reading draw inferences from tables and numbers. For example, have students compare and contrast the change in radioactivity levels over time for samples of the isotopes potassium-40 and thorium-234. Using Table 25.3, they should be able to infer that the radiation emitted by a sample of K-40 would diminish much less rapidly than the radiation from a sample of Th-234 because of the much longer half-life of K-40.

Answers to...

Figure 25.6 lead-206

Checkpoint 5.73×10^3 years

Sample Problem 25.1

Answers

7. 10.4 h/2.6 h/half-life = 4 half-lives
1.0 mg/2^4 = 0.063 mg Mn-56

8. 48.2 da/24.1 da/half-life = 2 half-lives
No, $(^1/_2)^2$, or $^1/_4$, of the sample will remain.

Practice Problems Plus L2

1. How much of a 0.74-mg sample of uranium-235 will remain after 2.8×10^9 years? *(4.6×10^{-2} mg)*

2. A 0.456-mg sample of hydrogen-3 was collected. After 24.52 years, 0.114 mg of the sample remains. **What is the half-life of hydrogen-3?** (*12.26 years*)

3. Strontium-90 is a beta emitter with a half-life of 29 years. **What is the mass of strontium-90 in a 5.0-g sample of the isotope at the end of 87 years?** *(0.63 g)*

Math Handbook

For a math refresher and practice, direct students to dimensional analysis, page R66.

Figure 25.7 This archaeologist is digging for artifacts. The age of an artifact can often be determined from its measured carbon-14 content.

Scientists often find the age of an object that was once part of a living system by measuring the amount of carbon-14 ($^{14}_{6}C$) it contains. Carbon-14 has a half-life of 5730 years. Most of Earth's carbon, however, consists of the more stable isotopes $^{12}_{6}C$ and $^{13}_{6}C$. The ratio of $^{14}_{6}C$ to the other carbon isotopes in the environment is fairly constant because high-energy cosmic rays from space constantly produce $^{14}_{6}C$ in the upper atmosphere. Plants grow by producing sugars, cellulose, and other compounds from carbon dioxide in the atmosphere. Animals grow by eating the plants, and sometimes other animals. This keeps the ratio of carbon-14 to other carbon isotopes constant during any living organism's lifetime. When an organism dies, it stops exchanging carbon with the environment and its radioactive $^{14}_{6}C$ atoms decay without being replaced. Therefore, the ratio of $^{14}_{6}C$ to stable carbon in the remains of an organism changes in a predictable way that enables the archaeologist in Figure 25.7 to obtain an estimate of its age.

SAMPLE PROBLEM 25.1

Using Half-lives in Calculations

Carbon-14 emits beta radiation and decays with a half-life ($t_{1/2}$) of 5730 years. Assume you start with a mass of 2.00×10^{-12} g of carbon-14.

a. How long is three half-lives?

b. How many grams of the isotope remain at the end of three half-lives?

1 Analyze *List the knowns and the unknowns.*

Knowns	Unknowns
• $t_{1/2}$ = 5730 years	• 3 half-lives = ? years
• initial mass 2.00×10^{-12} g	• mass after 3 half-lives = ? g
• number of half-lives = 3	

First, calculate the time for three half-lives by multiplying the length of each half-life by three. Find the mass remaining by multiplying the original mass by $\frac{1}{2}$ three times.

2 Calculate *Solve for the unknowns.*

a. 3 half-lives = 3 × 5730 years = 17,190 years

b. The initial mass of carbon-14 is reduced by one half for each of the three half-lives, so for three half-lives

$$\text{Remaining mass} = 2.00 \times 10^{-12}\text{g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 0.250 \times 10^{-12}\text{g}$$

3 Evaluate *Do the results make sense?*

The mass of carbon-14 after three half-lives should be much lower than the original mass. The final answer has the proper units and the proper number of significant figures.

Practice Problems

7. Manganese-56 is a beta emitter with a half-life of 2.6 h. What is the mass of manganese-56 in a 1.0-mg sample of the isotope at the end of 10.4 h?

8. A sample of thorium-234 has a half-life of 24.1 days. Will all the thorium undergo radioactive decay in 48.2 days? Explain.

Math Handbook

For help with scientific notation, go to page R56 of the Math Handbook.

Interactive Textbook

Problem-Solving 25.7
Solve Problem 7 with the help of an interactive guided tutorial.

with ChemASAP

Differentiated Instruction

Gifted and Talented L3

Review exponential notation and rules of exponents as they apply to logarithms. Review the rules for manipulating logs, such as log xy = log x + log y and log x^a = a log x. Assign practice problems that require students to apply these rules. Challenge students to apply logarithms to solving half-life problems that involve fractions of half-lives.

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Transmutation Reactions

The conversion of an atom of one element to an atom of another element is called **transmutation.** There are at least two ways transmutation occurs. **Transmutation can occur by radioactive decay. Transmutation can also occur when particles bombard the nucleus of an atom.** The bombarding particles may be protons, neutrons, or alpha particles.

Many transmutations occur in nature. The production of carbon-14 from naturally occurring nitrogen-14, for example, takes place in the upper atmosphere. Another naturally occurring isotope, uranium-238, undergoes 14 transmutations before reaching a stable isotope. Many other transmutations are done in laboratories or in nuclear reactors. The earliest artificial transmutation was performed in 1919 by Ernest Rutherford (1871–1937). He bombarded nitrogen gas with alpha particles to produce an unstable isotope of fluorine. The results of this reaction are shown in Figure 25.8. The first step of the reaction forms fluorine-18.

$$\underset{\text{Nitrogen-14}}{{}^{14}_{7}\text{N}} + \underset{\text{Alpha particle}}{{}^{4}_{2}\text{He}} \longrightarrow \underset{\text{Fluorine-18}}{{}^{18}_{9}\text{F}}$$

The fluorine isotope quickly decomposes to a stable isotope of oxygen and a proton.

$$\underset{\text{Fluorine-18}}{{}^{18}_{9}\text{F}} \longrightarrow \underset{\text{Oxygen-17}}{{}^{17}_{8}\text{O}} + \underset{\text{Proton}}{{}^{1}_{1}\text{H}}$$

Rutherford's experiment eventually led to the discovery of the proton. James Chadwick's discovery of the neutron in 1932 also involved a transmutation experiment. Neutrons were produced when beryllium-9 was bombarded with alpha particles.

$$\underset{\text{Beryllium-9}}{{}^{9}_{4}\text{Be}} + \underset{\text{Alpha particle}}{{}^{4}_{2}\text{He}} \longrightarrow \underset{\text{Carbon-12}}{{}^{12}_{6}\text{C}} + \underset{\text{Neutron}}{{}^{1}_{0}\text{n}}$$

Checkpoint ***What is transmutation?***

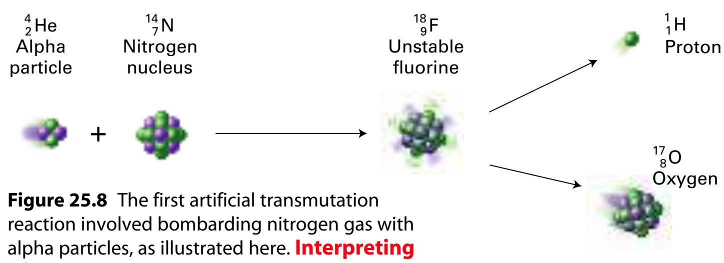

Figure 25.8 The first artificial transmutation reaction involved bombarding nitrogen gas with alpha particles, as illustrated here. **Interpreting Diagrams** ***What particles were formed?***

Differentiated Instruction

Special Needs L1

To reinforce the concept of half-life, have students consider the following problem: Imagine winning a $1000 prize but the conditions of the award require that half of the remainder of the prize is spent each month. Ask, **After how many months would you be left with less than $1? What is the half-life of this prize?** *(10 months; 1 month)* As an extension, have students plot a decay curve, like the one in Figure 25.5, except the *x*-axis should represent time (days or years), for one of the elements in Table 25.3. Tell students that the initial amount of radioisotope is 100 g.

Transmutation Reactions

Discuss L2

Explain that one of the main goals of medieval alchemists was the conversion of common metals to precious metals. No chemical reaction can achieve this goal. However, through transmutations, modern chemists can change one element into another. Point out that transmutation reactions also allow chemists to produce elements that do not occur naturally.

CLASS Activity

Particle Accelerators L2

Purpose Students learn about and model an accelerator.

Materials reference materials and Internet access, materials for making models

Procedure Particle accelerators, such as linear accelerators, cyclotrons, and synchrotrons, are used in transmutation experiments. Divide the class into groups of four to five. Have each group choose one type of accelerator and conduct library research on its design and function. The group should create a model of the accelerator, which students can display and explain.

Expected Outcome Models and explanations should show understanding of how transmutation is accomplished.

Discuss L2

Write equations for a number of transmutation reactions on the board. Point out that the mass numbers and atomic numbers for reactants and products in transmutation reactions are balanced. Write partial equations such as

$${}^{239}_{94}\text{Pu} + ? \longrightarrow {}^{242}_{96}? + {}^{1}_{0}\text{n}$$

$${}^{238}_{92}\text{U} + {}^{?}_{?}\text{C} \longrightarrow {}^{246}_{98}\text{Cf} + 4\,{}^{1}_{0}\text{n}$$

on the board. Then have students supply the missing information.

Answers to...

Figure 25.8 ultimately, oxygen-17 atoms and protons

Checkpoint the conversion of an atom of one element to an atom of another element

3 ASSESS

Evaluate Understanding L2

Ask students how the ratio of neutrons to protons changes in nuclei that undergo beta particle and alpha particle emission. Ask students to explain the concept of half-life using a numerical example. (For example: original state = 256 atoms; one half-life = 128 atoms; two half-lives = 64 atoms, and so on.) Write several balanced and unbalanced nuclear equations on the board and have students identify and correct the unbalanced equations.

Reteach L1

Point out the three natural processes that can result in a nucleus attaining a stable ratio of neutrons to protons. A beta emission increases the number of protons and decreases the number of neutrons. A positron emission decreases the number of protons and increases the number of neutrons. In heavy elements, the nucleus may emit an alpha particle, which decreases the numbers of both neutrons and protons.

Writing Activity

C-14 is used to date once-living artifacts such as bones or coral. Its range is limited to 5.00×10^4 years by its relatively short half-life. The oldest rocks are dated with U-238. Its half-life is about 4.5 billion years. The decay product is Pb-207. K-40 has a half-life of 1.25×10^9 years. It decays to Ar-40. Items made of clay, such as pottery, can be dated using a property called thermoluminescence.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 25.2.

with ChemASAP

Figure 25.9 Fermilab is a major accelerator center located in Batavia, Illinois. The main accelerator is a ring that has a radius of 1.0 km.

The elements in the periodic table with atomic numbers above 92, the atomic number of uranium, are called the **transuranium elements.** All the transuranium elements undergo transmutation. None of them occurs in nature, and all of them are radioactive. These elements have been synthesized in nuclear reactors and nuclear accelerators. Accelerators like the one in Figure 25.9 accelerate bombarding particles to very high speeds, while reactors produce beams of low-energy particles. When uranium-238 is bombarded with relatively slow neutrons from a nuclear reactor, some uranium nuclei capture neutrons to produce uranium-239.

$${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{239}_{92}\text{U}$$

Uranium-239 is radioactive and emits a beta particle. The product is an isotope of the artificial radioactive element neptunium (atomic number 93).

$${}^{239}_{92}\text{U} \longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e}$$

Neptunium is unstable and decays, emitting a beta particle, to produce a second artificial element, plutonium (atomic number 94).

$${}^{239}_{93}\text{Np} \longrightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$$

Plutonium and neptunium are both transuranium elements and do not occur in nature. Scientists in Berkeley, California synthesized these first artificial elements in 1940. Since that time, more than 20 additional transuranium elements have been produced artificially.

25.2 Section Assessment

9. **Key Concept** What determines the type of decay a radioisotope will undergo?
10. **Key Concept** How much of a sample of radioisotope remains after one half-life? After two half-lives?
11. **Key Concept** What are two ways that transmutation can occur?
12. Complete and balance the equations for the following nuclear reactions.
    - **a.** ${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \longrightarrow {}^{30}_{14}\text{Si} + ?$
    - **b.** ${}^{214}_{83}\text{Bi} \longrightarrow {}^{4}_{2}\text{He} + ?$
    - **c.** ${}^{27}_{14}\text{Si} \longrightarrow {}^{0}_{-1}\text{e} + ?$
    - **d.** ${}^{66}_{29}\text{Cu} \longrightarrow {}^{66}_{30}\text{Zn} + ?$
13. A radioisotope has a half-life of 4 days. How much of a 20-gram sample of this radioisotope remains at the end of each time period?
    - **a.** 4 days
    - **b.** 8 days
14. The mass of cobalt-60 in a sample is found to have decreased from 0.800 g to 0.200 g in a period of 10.5 years. From this information, calculate the half-life of cobalt-60.

Writing Activity

Research the methods used to date materials such as pottery, coral, and stone. Prepare a written report that summarizes your findings on the radioisotopes used, their half-lives, and their limitations.

Interactive Textbook

Assessment 25.2 Test yourself on the concepts in Section 25.2.

with ChemASAP

Section 25.2 Assessment

9. the neutron-to-proton ratio
10. 50% of the sample remains after one half-life; 25% remains after two half-lives.
11. radioactive decay and particle bombardment of a nucleus
12. **a.** ${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \longrightarrow {}^{30}_{14}\text{Si} + {}^{1}_{1}\text{H}$
    b. ${}^{214}_{83}\text{Bi} \longrightarrow {}^{4}_{2}\text{He} + {}^{210}_{81}\text{Tl}$
    c. ${}^{27}_{14}\text{Si} \longrightarrow {}^{0}_{-1}\text{e} + {}^{27}_{15}\text{P}$
    d. ${}^{66}_{29}\text{Cu} \longrightarrow {}^{66}_{30}\text{Zn} + {}^{0}_{-1}\text{e}$
13. **a.** 10 g
    b. 5 g
14. 5.25 years

Small-Scale LAB

Radioactivity and Half-Lives

Purpose

To simulate the transformation of a radioactive isotope over time and to graph the data and relate it to radioactive decay and half-lives.

Materials

- pencil
- ruler
- penny
- paper
- graph paper

Procedure

On a sheet of paper, make a data table similar to the one below. For trial number 1, flip a penny 100 times and, in your grid, record the total number of heads that result. Now flip the penny the same number of times as the number of heads that you obtained in the first 100 flips. Record the total number of flips and the number of heads that result. Continue this procedure until you obtain no more heads.

Trial #	Number of flips	Number of heads
1	100	
2		
3		
4		
5		
6		
7		

Analyze

Using your experimental data, record the answers to the following questions below your data table.

1. Use graph paper to plot the number of flips (*y*-axis) versus the trial number (*x*-axis). Draw a smooth line through the points.
2. Examine your graph. Is the rate of the number of heads produced over time linear or nonlinear? Is the rate constant over time or does it change?
3. Why does each trial reduce the number of heads by approximately one-half?
4. A half-life is the time required for one-half of the atoms of a radioisotope to emit radiation and to decay to products. What value represents one half-life for the process of flipping coins?

You're The Chemist

The following small-scale activities allow you to develop your own procedures and analyze the results.

1. **Design It!** Design and carry out an experiment using a single die to model radioactive decay. Plot your data.
2. **Analyze It!** Many radioisotopes undergo alpha decay. They emit an alpha particle (helium nucleus $^{4}_{2}He$). For example,

   $$^{222}_{86}Rn \longrightarrow ^{218}_{84}Po + ^{4}_{2}He$$

   Find the half-life of radon-222 in Table 25.3 and determine how long it takes for only one eighth of a sample of radon-222 to remain.
3. **Analyze It!** Other radioisotopes undergo beta decay, emitting a beta particle (electron $^{0}_{-1}e$). For example,

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

   Find the half-life of carbon-14 in Table 25.3 and determine what fraction of the carbon-14 in a sample has not yet decayed by beta emission after 11,460 years.

Small-Scale LAB

Radioactivity and Half-Lives L2

Objective After completing this activity, students will be able to simulate the transformation of a radioactive isotope and relate simulated data to radioactive decay and half-life.

TIME SAVER **Prep Time** 5 minutes
Class Time 20 minutes

Teaching Tips

- Emphasize that the trials involving flipping a coin to simulate radioactivity. The appearance and removal of a "head" represents the decay of an unstable nucleus. The rate of removal is analogous to the half-life of a radioactive isotope—around 50%. Although the number of heads decreases over time, the percent of heads produced remains relatively steady until the sample becomes too small.
- Point out that in a sample as small as 100, the likelihood of producing a number of heads other than 50 is high. If the sample size were increased, the relative error would decrease. As the sample size approaches zero, the results are no longer statistically reliable.
- Remind students that the probabilities relate to the overall sample, not to any individual coin or atom. Predictions for a mole of atoms, which provides a large sample, can be quite accurate.

Expected Outcome For each trial, the number of heads is approximately half the number of flips.

Analyze

1. Student graphs should resemble the graph in Figure 25.5. **2.** Nonlinear; the rate decreases over time. **3.** For each flip, the probability of a head is 0.50. **4.** one trial

You're the Chemist

1. Count the total number of even numbers that result in 100 rolls of the die. Roll the die again a number of times equal to the number obtained on the first trial. Do trials until the number of events equals zero. Plot number of evens versus trial.
2. After 3.8 days, half the sample remains. After 7.6 days, one-fourth remains, and, after 11.4 days, one-eighth remains.
3. This time period is two half-lives (11,460 years/5730 years = 2) of carbon-14. After two half-lives, one-fourth of the sample remains.

For Enrichment L3

Repeat the procedure four more times, using a new table for each trial. Average the results in each cell of the table for the five trials. Ask, **Which is closer to the expected values, the results from a single trial or the averaged results?** *(The average values should be closer.)* Ask students to discuss the advantages of using multiple trials in an experiment.