Nuclear Stability and Decay

More than 1500 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 its neutron-to-proton ratio. Figure 25.4 is a graph of the number of neutrons vs. number of protons for all known stable nuclei. The stable nuclei are in a region called the band of stability. For elements of low atomic number (below about 20), the ratio of neutrons to protons for stability is about 1. That means the stable nuclei have roughly equal numbers of neutrons and protons. For example, the isotopes $^{12}$C, $^{14}$N, and $^{16}$O are stable. Above atomic number 20, stable nuclei have more neutrons than protons. The neutron-to-proton ratio reaches about 1.5 for heavy elements. The lead isotope $^{206}$Pb, for example, with 124 neutrons and 82 protons, is stable. Its neutron-to-proton ratio is $\frac{124}{82}$, or approximately 1.5.

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
- band of stability
- proton
- 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 key term in your own words.

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 70?

c. Describe How does the neutron-to-proton ratio change as the number of protons increases?

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

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.

Nuclear Stability and Decay

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Half-Life
Discuss
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
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
a. 50%
b. 25%
c. three half-lives

Enrichment Question
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 undetectable.)

Use Visuals
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.

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.
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 $4.5 \times 10^9$ years, it is possible to use its half-life to date rocks as old as the solar system.

**Differentiated Instruction**

**Less Proficient Readers**

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.

**Use Visuals**

**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.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Radiation emitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-14</td>
<td>$5.73 \times 10^3$ years</td>
<td>β, γ</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>$1.25 \times 10^9$ years</td>
<td>β, γ</td>
</tr>
<tr>
<td>Radon-222</td>
<td>3.8 days</td>
<td>α</td>
</tr>
<tr>
<td>Radium-226</td>
<td>$1.6 \times 10^5$ years</td>
<td>α, γ</td>
</tr>
<tr>
<td>Thorium-234</td>
<td>24.1 days</td>
<td>β, γ</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>$7.0 \times 10^4$ years</td>
<td>α, γ</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$4.46 \times 10^3$ years</td>
<td>α</td>
</tr>
</tbody>
</table>

**Use Visuals**

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

**Discuss**

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**

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.

**Checkpoints**

**Figure 25.6 lead-206**

$5.73 \times 10^3$ years
Scientists often find the age of an object that was once part of a living system by measuring the amount of carbon-14 (\( ^{14}C \)) it contains. Carbon-14 has a half-life of 5730 years. Most of Earth’s carbon, however, consists of the more stable isotopes \( ^{12}C \) and \( ^{13}C \). The ratio of \( ^{14}C \) to the other carbon isotopes in the environment is fairly constant because high-energy cosmic rays from space constantly produce \( ^{14}C \) 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 \( ^{14}C \) atoms decay without being replaced. Therefore, the ratio of \( ^{14}C \) to stable carbon in the remains of an organism changes in a predictable way that enables the archaeologists in Figure 25.7 to obtain an estimate of its age.

### 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 \( 2.00 \times 10^{-15} \text{ g} \) of carbon-14.

1. How long is three half-lives?
2. How many grams of the isotope remain at the end of three half-lives?

**Answers**

7. \( 10.4 \text{ h}/2.6 \text{ h}/\text{half-life} = 4 \text{ half-lives} \\
   1.0 \text{ mg}/2^4 = 0.063 \text{ mg Mn-56} \\
8. \( 48.2 \text{ da}/24.1 \text{ da}/\text{half-life} = 2 \text{ half-lives} \\
   \text{No.}(1/2)^2 \text{, or } 1/4, \text{ of the sample will remain.} \\

**Practice Problems Plus**

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

\[
\text{^{14}N} + \text{^{4}He} \rightarrow \text{^{18}F}
\]

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

\[
\text{^{18}F} \rightarrow \text{^{17}O} + \text{^{1}H}
\]

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 bombarded with alpha particles.

\[
\text{^{9}Be} + \text{^{4}He} \rightarrow \text{^{12}C} + \text{^{1}n}
\]

This activity will help students understand how transmutation reactions occur.

**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**

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**

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.

### Particle Accelerators

**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**

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

\[
\text{^{239}Pu} + \ ? \rightarrow \text{^{242}Cf} + \text{^{1}n}
\]

\[
\text{^{238}U} + \text{^{4}He} \rightarrow \text{^{246}Cf} + \text{^{4}He}
\]

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

**Checkpoint**

the conversion of an atom of one element to an atom of another element
What determines the type of decay a radioisotope will undergo?

How much of a sample of radioactive element remains after one half-life? After two half-lives?

What are two ways that transmutation can occur?

Complete and balance the equations for the following nuclear reactions.

C-14 is used to date once-living artifacts such as bones or coral. Its range is limited to 5.00 x 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 x 10^9 years. It decays to Ar-40. Items made of clay, such as pottery, can be dated using a property called thermoluminescence.

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.

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

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

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.

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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 heads and the number of heads that result. Continue this procedure until you obtain no more heads.

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Number of flips</th>
<th>Number of heads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Analysis**
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 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 $^{4}\text{He}$). For example,
   \[ ^{222}\text{Rn} \rightarrow ^{218}\text{Po} + ^{4}\text{He} \]
   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 $^{0}\text{e}$). For example,
   \[ ^{14}\text{C} \rightarrow ^{14}\text{N} + ^{0}\text{e} \]
   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.

**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

**For Enrichment**
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.

**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%.
- 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.

**Prep Time** 5 minutes

**Class Time** 20 minutes

**Radioactivity and Half-Lives**

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.

**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.