Section 10.1

10.1 Radioactivity

Objectives
10.1.1 Describe the process of nuclear decay.
10.1.2 Classify nuclear radiation as alpha particles, beta particles, or gamma rays.
10.1.3 Balance nuclear equations.
10.1.4 Identify sources of nuclear radiation, and describe how nuclear radiation affects matter.
10.1.5 Describe methods of detecting nuclear radiation.

Reading Focus

Key Concepts
- What happens during nuclear decay?
- What are the types of nuclear radiation?
- How does nuclear radiation affect atoms?
- What devices can detect nuclear radiation?

Vocabulary
- radioactivity
- radionuclide
- nuclear radiation
- alpha particle
- beta particle
- gamma ray
- background radiation

 vocabulary terms that contain the word radiation (nuclear radiation, background radiation). Explain that the word comes from a Latin word meaning “to spread out from a point.”

Build Vocabulary

Word-Part Analysis
- Point out the two vocabulary terms that contain the word radiation (nuclear radiation, background radiation).
- Explain that the word comes from a Latin word meaning “to spread out from a point.”

Reading Strategy

Student answers may include:
- a. Nuclear decay is the spontaneous change of one isotope into another.
- b. What are the types of nuclear radiation? c. What are the effects of nuclear radiation? d. One effect of nuclear radiation is the ionization of matter.
- e. How can nuclear radiation be detected? f. Nuclear radiation can be detected by a Geiger counter or film badge.

2 INSTRUCT

Nuclear Decay

Many students think that gamma rays, X-rays, and visible light are unrelated.

Address Misconceptions
- Point out that all three are different parts of the continuous electromagnetic spectrum. Explain that the photographic plate in Becquerel’s experiment detected all three kinds of electromagnetic waves.

- Just as photographic film can detect visible light, it can detect X-rays and gamma rays emitted during nuclear decay. Students will read about the electromagnetic spectrum in Chapter 18.

Logical

In 1896, French physicist Antoine Henri Becquerel (1852–1908) was experimenting with uranium salts. He hypothesized that the salts, which glow after being exposed to light, produced X-rays while they glowed. To test his hypothesis, Becquerel performed an experiment.

- First, he wrapped a photographic plate in paper. Then, he placed some uranium salts on the plate and set it outside in the sunlight, which caused the salts to glow. When Becquerel developed the plate, he got a foggy image. At the time, Becquerel thought that X-rays from the salts had penetrated the paper and fogged the plate.

- Like any good scientist, Becquerel wanted to repeat his experiment, but a spell of bad weather forced him to wait. In the meantime, he left a wrapped photographic plate and uranium salts in a desk drawer. After several days, Becquerel decided to develop the plate without exposing the uranium to sunlight. To his surprise, he got the foggy image shown in Figure 1A.

- Later, Becquerel determined that the uranium salts had emitted rays that had never been observed before.

Nuclear Decay

Becquerel’s experiment marked the discovery of radioactivity. Radioactivity is the process in which an unstable atomic nucleus emits charged particles and energy. Any atom containing an unstable nucleus is called a radioactive isotope, or radioisotope for short.

Radiotopes of uranium—primarily uranium-238—were the source of radioactivity in Becquerel's experiment. (Recall that the name of an isotope includes its mass number.) Another common radiotope is carbon-14, which can be found in fossils like the ones shown in Figure 2.

Unlike stable isotopes such as carbon-12 or oxygen-16, radiotopes spontaneously change into other isotopes over time. When the composition of a radiotope changes, the radiotope is said to undergo nuclear decay. During nuclear decay, atoms of one element can change into atoms of a different element altogether. For example, uranium-238 decays into thorium-234, which is also a radiotope.

**Types of Nuclear Radiation**

Scientists can detect a radioactive substance by measuring the nuclear radiation it gives off. Nuclear radiation is charged particles and energy that are emitted from the nuclei of radiotopes. Common types of nuclear radiation include alpha particles, beta particles, and gamma rays. Figure 3 shows the properties of these three types of radiation.

**Alpha Decay** When a uranium-238 sample decays, it emits alpha particles. An alpha particle is a positively charged particle made up of two protons and two neutrons—the same as a helium nucleus. It has a charge of 2+. The common symbol for an alpha particle is \(^{2}\text{He}\). The subscript is the atomic number (the number of protons). The superscript is the mass number (the sum of the numbers of protons and neutrons). Another symbol for an alpha particle is the Greek letter \(\alpha\).

Alpha decay, which refers to nuclear decay that releases alpha particles, is an example of a nuclear reaction. Like chemical reactions, nuclear reactions can be expressed as equations. The following nuclear equation describes the alpha decay of uranium-238.

\[
^{238}\text{U} \rightarrow ^{234}\text{Th} + ^{4}\text{He}
\]

In alpha decay, the product isotope has two fewer protons and two fewer neutrons than the reactant isotope. In the equation above, the mass number on the left (238) equals the sum of the mass numbers on the right (238 + 4). Also, the atomic number on the left (92) equals the sum of the atomic numbers on the right (90 + 2). In other words, the equation is balanced.

Alpha particles are the least penetrating type of nuclear radiation. Most alpha particles travel no more than a few centimeters in air, and can be stopped by a sheet of paper or by clothing.

**Beta Radiation** A beta particle is a negatively charged particle, which is an electron. It has a charge of 1−. The mass of a beta particle is 0 amu.

**Gamma Radiation** A gamma ray is a photon, which is a form of electromagnetic radiation. It has no mass and no charge.

**Characteristics of Nuclear Radiation**

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Symbol</th>
<th>Charge</th>
<th>Mass (amu)</th>
<th>Common Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particle</td>
<td>(\alpha)(^{4}\text{He})</td>
<td>2+</td>
<td>4</td>
<td>Radium-226</td>
</tr>
<tr>
<td>Beta particle</td>
<td>(\beta)</td>
<td>1−</td>
<td>0</td>
<td>Carbon-14</td>
</tr>
<tr>
<td>Gamma ray</td>
<td>(\gamma)</td>
<td>0</td>
<td>0</td>
<td>Cobalt-60</td>
</tr>
</tbody>
</table>

**Types of Nuclear Radiation**

**Build Science Skills**

**Inferring** Have students look at Figure 3, which shows the particles emitted in nuclear decay. Explain that a nucleus that emits an alpha particle gives up two protons and two neutrons (a helium nucleus). A nucleus that emits a beta particle (an electron) gives up a neutron but gains a proton, because a neutron decomposes into a proton and an electron during beta decay. Ask, Which type of radioactive decay causes the largest change in the atomic number of a nucleus? (Alpha decay, which reduces the atomic number of the nucleus by two)

**Logical, Visual**

**Build Reading Literacy**

**Compare and Contrast** Refer to page 226D in Chapter 8, which provides the guidelines for comparing and contrasting.

Ask students to construct a compare/contrast table. Have them skim the sections on alpha decay, beta decay, and gamma decay. Then, ask students to describe similarities and differences of the decay types in their table.

**Verbal, Visual**

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**Customize for English Language Learners**

**Build a Science Glossary**

Encourage English language learners to make a science glossary as they read the section. Suggest that they start with the vocabulary terms and then add any other new terms they encounter. Encourage students to copy the table in Figure 3 into their glossary, as these particles are key to understanding the chapter. Model how to divide words into parts such as prefix, root word, and suffix. Posting a list of suffixes and prefixes with their meanings in the classroom will help students when they encounter new words.

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**Answer to . . .**

**Figure 3** Alpha particles have a charge of 2+; beta particles have a charge of 1−; gamma rays have no charge. Alpha particles have a mass of 4 amu; beta particles have a mass of 0 amu; and gamma rays have no mass.

Nuclear Chemistry 293
Beta Decay When thorium-234 decays, it releases negatively charged radiation called beta particles. A beta particle is an electron emitted by an unstable nucleus. In nuclear equations, a beta particle is written as $\beta^-$ or $\beta^-$. Because of its single negative charge, a beta particle is assigned an atomic number of $-1$. In Chapter 4, you learned that an electron has very little mass when compared with a proton. For this reason, a beta particle is assigned a mass number of $0$.

How can an atomic nucleus, which has a positive charge, emit a negatively charged particle? During beta decay, a neutron decomposes into a proton and an electron. The proton stays trapped in the nucleus, while the electron is released. The following equation describes the beta decay of thorium-234.

$$^{234}_{90}\text{Th} \rightarrow ^{234}_{91}\text{Pa} + ^0_1\beta^-$$

In beta decay, the product isotope has one proton more and one neutron fewer than the reactant isotope. The mass numbers of the isotopes are equal because the emitted beta particle has essentially no mass.

Due to their smaller mass and faster speed, beta particles are more penetrating than alpha particles. As Figure 4 illustrates, beta particles pass through paper, but can be stopped by a thin sheet of metal.

Gamma Decay Not all nuclear radiation consists of charged particles. A gamma ray is a penetrating ray of energy emitted by an unstable nucleus. The symbol for a gamma ray is $\gamma$. Gamma radiation has no mass and no charge. Like X-rays and visible light, gamma rays are energy waves that travel through space at the speed of light.

Beta Decay

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Figure 4 Alpha particles (shown in red) are the least penetrating type of nuclear radiation. Gamma rays (shown in green) are the most penetrating. A concrete slab can block most but not all of the gamma rays released by a radioactive source.

Interpreting Diagrams What type of radiation can penetrate paper but is blocked by aluminum foil?

Radioactive sample

Lead box

Paper

Aluminum

Concrete

Facts and Figures

Explaining Energy The amount of energy emitted in alpha and gamma decay is equal to the energy difference of the nucleus before and after emission. However, this is not true in beta decay. Physicists had difficulty explaining this discrepancy, because the law of conservation of energy states that the total energy should remain unchanged during the process. In 1930, physicist Wolfgang Pauli proposed that an undetected particle, called the neutrino, was emitted along with the beta particles, accounting for some of the energy change in beta decay. In 1956, the neutrino was directly observed for the first time by American physicists Frederick Reines and Clyde Cowan.
Balancing Nuclear Equations

Write a balanced nuclear equation for the alpha decay of polonium-210.

1. Read and Understand
What information are you given?
- Reactant isotope = polonium-210
- Radiation emitted = \(^{4}\)He (alpha particle)
- Use the periodic table to obtain the atomic number of polonium.
- Reactant isotope = \(^{210}\)Po

2. Plan and Solve
What unknowns are you trying to calculate?
- Atomic number of product isotope, \(Z = ?\)
- Mass number of product isotope, \(A = ?\)
- Chemical symbol of product isotope, \(X = ?\)

What equation contains the given information?
\[ \text{\(^{210}\)Po} \rightarrow \frac{2}{4}\text{X} + \frac{4}{4}\text{He} \]

Write and solve equations for atomic mass and atomic number.

\[ 210 = A + 4 \quad \text{and} \quad 84 = Z + 2 \]
\[ 210 = A + 4 \quad \text{and} \quad 84 = Z + 2 \]
\[ 206 = A \quad \text{and} \quad 82 = Z \]

According to the periodic table, the element with an atomic number of 82 is lead, \(\text{Pb}\). So, \(X\) is \(\text{Pb}\). The balanced nuclear equation is shown below.
\[ \text{\(^{210}\)Po} \rightarrow \frac{2}{82}\text{Pb} + \frac{4}{4}\text{He} \]

3. Look Back and Check
Is your answer reasonable?

The mass number on the left equals the sum of the mass numbers on the right. The atomic number on the left equals the sum of the atomic numbers on the right. The equation is balanced.

Solutions

1. \(\text{\(^{238}\)Th} \rightarrow \frac{2}{24}\text{X} + \frac{4}{4}\text{He} \)
- \(A = 238 - 4 = 234\)
- \(Z = 90 - 0 = 90\)
- \(X = \text{Ra}\)

2. \(\text{\(^{226}\)Ra} \rightarrow \frac{2}{88}\text{Ra} + \frac{4}{4}\text{He} \)
- \(A = 226 - 4 = 222\)
- \(Z = 88 - 0 = 88\)
- \(X = \text{Th}\)

3. \(\text{\(^{14}\)C} \rightarrow \frac{4}{14}\text{He} + \frac{0}{1}\text{e} \)
- \(A = 14 - 0 = 14\)
- \(Z = 6 - 0 = 6\)
- \(X = \text{N}\)

4. \(\text{\(^{95}\)Am} \rightarrow \frac{2}{93}\text{X} + \frac{4}{4}\text{He} \)
- \(A = 241 - 4 = 237\)
- \(Z = 95 - 2 = 93\)
- \(X = \text{Np}\)

For Extra Help

Remind students that when they write and solve the equation for atomic mass and atomic number, they must remember to change the sign of the constant when it is moved to the left side of the equation.

Academic

Direct students to the Math Skills in the Skills and Reference Handbook at the end of the student text for additional help.

Additional Problems

1. Write a balanced nuclear equation for the alpha decay of uranium-238.
\[ \text{\(^{238}\)U} \rightarrow \frac{2}{92}\text{Th} + \frac{4}{4}\text{He} \]

2. Write a balanced nuclear equation for the beta decay of sodium-24.
\[ \text{\(^{23}Na} \rightarrow \frac{12}{11}\text{Mg} + \frac{0}{1}\text{e} \]

Logical, Portfolio

Answer to . . .

A beta particle is an electron emitted by an unstable nucleus.

Figure 4 Gamma rays are the most penetrating type of nuclear radiation shown in the diagram.
Radon is a naturally occurring radioactive element that is formed in the decay chain of uranium-238. Uranium can be found in almost all rocks and soil. Fortunately, in most areas the amount of uranium in rocks and soil is very small. Higher concentrations of uranium and its minerals are commonly found in light colored igneous rocks, granite, dark shale, phosphate-containing sedimentary rocks, and metamorphic rocks derived from these rocks. Soils derived from these rocks also have high uranium concentrations. Encourage students to work in small groups to research the concentrations of uranium in their community. They may use library resources, such as the Internet, to assist them in their research.

**Group, Portfolio**

**Use Community Resources**

Arrange to have someone from your state or local health department come to your class to talk about the hazards of radon. Have students prepare questions for the speaker in advance. The speaker can inform students about the possible dangers of radon in their homes and what kinds of tests are available. The speaker may also provide information on what the EPA considers to be safe radon levels. Have pairs or groups of students write thank-you notes to the speaker, incorporating a few of the facts that students learned from the presentation.

**Interpersonal, Group**

**Integrate Earth Science**

Radon is a colorless, odorless, tasteless gas. The most stable isotope, radon-222, is produced by the alpha decay of radium-226. The fact that radon may be a serious health hazard was not recognized until the late 1980s. Today, radon is considered by some to be the second leading cause of lung cancer in the United States, after smoking. Cigarette smokers who become exposed to radon are at particularly high risk of lung cancer.

During gamma decay, the atomic number and mass number of the atom remain the same, but the energy of the nucleus decreases. Gamma decay often accompanies alpha or beta decay. For example, thorium-234 emits both beta particles and gamma rays (abbreviated as \( \gamma \)) as it decays.

\[
\frac{^{234}_{90}Th}{^{234}_{90}Th} \rightarrow \frac{^{234}_{90}Pa}{^{234}_{90}Pa} + \bar{\nu} + \gamma
\]

Gamma rays are much more penetrating than either alpha particles or beta particles. It can take several centimeters of lead or several meters of concrete to stop gamma radiation.

**Effects of Nuclear Radiation**

You may not realize it, but you are exposed to nuclear radiation every day. Most of this is background radiation, or nuclear radiation that occurs naturally in the environment. Radioisotopes in air, water, rocks, plants, and animals all contribute to background radiation. Most rocks, such as the one in Figure 5, contain at least trace amounts of radioactive elements. Another source of background radiation is cosmic rays. Cosmic rays are streams of charged particles (mainly protons and alpha particles) from outer space. Collisions between cosmic rays and Earth’s atmosphere shower the surface below with nuclear radiation. All this radioactivity may sound dangerous. However, background radiation levels are generally low enough to be safe.

When nuclear radiation exceeds background levels, it can damage the cells and tissues of your body. Nuclear radiation can ionize atoms. When cells are exposed to nuclear radiation, the bonds holding together proteins and DNA molecules may break. As these molecules change, the cells may no longer function properly.

Alpha particles, beta particles, and gamma rays are all forms of ionizing radiation. Alpha particles can cause skin damage similar to a burn, but they are not a serious health hazard unless an alpha-emitting substance is inhaled or eaten. For example, radon gas is a potentially dangerous natural source of alpha particles because it can be inhaled. Radon-222 is formed through a series of nuclear decays that begins with uranium-238 in rocks deep underground. As radon-222 is produced, it seeps upward toward the surface. It sometimes collects in the basements of buildings that lack proper ventilation, as shown in Figure 6. Prolonged exposure to radon-222 can lead to lung cancer.

[Figure 5: The mineral autunite is an important source of uranium.]

[Figure 6: Radon enters buildings from underground. Therefore, ventilating the basement of the house in Figure 6 would help reduce overall radon levels.]
When exposure to nuclear radiation is external, the amount of tissue damage depends on the penetrating power of the radiation. For example, beta particles can damage tissues in the body more than alpha particles, but less than gamma rays. Gamma rays can penetrate deeply into the human body, potentially exposing all organs to ionization damage.

**Detecting Nuclear Radiation**

Although you can’t see, hear, or feel the radioactivity around you, scientific instruments can measure nuclear radiation. Devices that are used to detect nuclear radiation include Geiger counters and film badges. A Geiger counter, shown in Figure 7, uses a gas-filled tube to measure ionizing radiation. When nuclear radiation enters the tube, it ionizes the atoms of the gas. The ions produce an electric current, which can be measured. The greater the amount of nuclear radiation, the greater the electric current produced in the tube is.

Recall that in Becquerel’s experiment, nuclear radiation left an image on a photographic plate. Today, many people who work with or near radioactive materials wear film badges to monitor their exposure to nuclear radiation. A film badge contains a piece of photographic film wrapped in paper. The film is developed and replaced with a new piece periodically. The exposure on the film indicates the amount of radiation exposure for the person wearing the badge.

**Section 10.1 Assessment**

**Reviewing Concepts**

1. How does an element change during nuclear decay?
2. What are the three types of nuclear radiation?
3. How are atoms affected by nuclear radiation?
4. What devices can be used to detect nuclear radiation?
5. How do types of nuclear radiation differ in charge?
6. Describe the penetrating power of each type of radiation.
7. What is background radiation? List some of its sources.

**Critical Thinking**

8. Predicting What is the effect of beta decay on the composition of a nucleus?
9. Inferring Why do you think airplane pilots wear film badges?

**Math Practice**

10. Write a balanced nuclear equation for the alpha decay of radium-226.
11. Write a nuclear equation that describes the beta decay of hydrogen-3.

**Detecting Nuclear Radiation**

**Use Visuals**

**Figure 7** Have students carefully examine the photograph. Ask, Why is it important to wear protective clothing around radioactive materials? (Protective clothing keeps radioactive materials away from skin.) Tell students that the EPA recommends heavy clothing as protection from beta radiation. Ask, Does a Geiger counter protect against the effects of nuclear radiation? (No. The Geiger counter serves only as a monitoring device, not a shielding device.) Visual, Logical

**ASSESS**

**Evaluate Understanding**

Randomly ask students to name the symbol or charge for each type of nuclear decay.

**Reteach**

Use Figure 4 to summarize the three different types of nuclear decay and how each type affects matter.

**Solutions**

10. $^{226}\text{Ra} \rightarrow ^{3}X + ^{2}\text{He}$
   $A = 226 - 4 = 222; Z = 88 - 2 = 86;
   X = \text{Rn}$
   $^{222}\text{Rn} \rightarrow ^{222}\text{Rn} + ^{2}\text{He}$

11. $^1\text{H} \rightarrow ^{2}X + ^0\text{e}$
   $A = 3 - 0 = 3; Z = 1 - (-1) = 2;
   X = \text{He}$
   $^1\text{H} \rightarrow ^{2}\text{He} + ^0\text{e}$

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 10.1.
A well-known theory is that early Americans were people from Siberia who crossed the Bering Strait into Alaska about 13,000 years ago. However, this theory has been challenged by recent scientific discoveries. In the 1990s, archaeologists working at a site in Cactus Hill, Virginia, found stone tools, charcoal, and animal bones that were at least 15,000 years old. Some of the artifacts were as much as 17,000 years old. The age of these artifacts suggests that the first Americans reached the continent much earlier than formerly thought. Some archaeologists have since revised their theories on the origin of America’s earliest ancestors. One possible explanation is that the first Americans were people from Europe who crossed the Atlantic Ocean by using boats.

Figure 8 shows some of the artifacts from the Cactus Hill site. They certainly look very old, but the archaeologists needed to find out how old. One clue that can reveal the age of an object is how many radioactive nuclei it contains. Because most materials contain at least trace amounts of radioisotopes, scientists can estimate how old they are based on rates of nuclear decay. A useful technique is radiocarbon dating, which uses the radioisotope carbon-14.
Half-life

A nuclear decay rate describes how fast nuclear changes take place in a radioactive substance. Every radioisotope decays at a specific rate that can be expressed as a half-life. A half-life is the time required for one half of a sample of a radioisotope to decay. After one half-life, half of the atoms in a radioactive sample have decayed, while the other half remain unchanged. After two half-lives, half of the remaining half-decays, leaving one quarter of the original sample unchanged. Figure 9 illustrates the nuclear decay rate of iodine-131. Iodine-131 has a half-life of 8.07 days. After two half-lives, or 16.14 days, the fraction of iodine-131 remaining is one quarter. After three half-lives, or 24.21 days, the fraction of iodine-131 remaining is one quarter of one quarter, or one eighth.

Half-lives can vary from fractions of a second to billions of years. Figure 10 lists the half-lives of some common radioisotopes. Uranium-238, for instance, has a half-life of 4.5 billion years. This means that in 4.5 billion years, there will be half as much uranium-238 on Earth as there is today. Unlike chemical reaction rates, which vary with the conditions of a reaction, nuclear decay rates are constant. Regardless of the temperature, pressure, or surface area of a uranium-238 sample, its half-life is still 4.5 billion years.

What is a half-life?

Half-Life

Use Visuals

Figure 9 The half-life for the beta decay of iodine-131 is 8.07 days. After one half-life (4.035 days), half of a sample of iodine-131 will have decayed into xenon-131. After two half-lives (16.14 days), three quarters of the sample will have decayed.

Predicting Decay

Purpose Students learn that it is not possible to predict which atom decays in a radioactive sample.

Materials hot plate, 250-mL or 500-mL beaker, glass plate, popcorn, cooking oil

Procedure Place the beaker on the hot plate. Pour a small amount of cooking oil into the beaker and add popcorn to form a single layer 1 kernel thick. Put the glass plate on top of the beaker. Tell students that each kernel represents an atom that will decay. Explain to students that it is not possible to accurately predict which kernel will pop first. Tell students that when radioisotopes decay, they decay throughout the sample rather than in one particular area.

Safety Caution students to stand at a safe distance when you heat the cooking oil and pop the corn. Remind students never to eat anything in a laboratory.

Expected Outcome There will be no observable pattern to the order in which the kernels pop.

Visual, Logical

Customize for for Inclusion Students

Visually Impaired

Give students 75 metal washers. Have the students count out 40 washers and line them up in a single row. Explain that after the first half-life of a radioisotope, half of the atoms decay. Next, have them count out 20 washers and put them in a single row next to the first row of washers. Have them repeat this again for the second half-life with 10 washers, and then count out 5 washers for the third half-life.

With all the rows even at the left, the students should be able to determine the shape of the “graph” by touching the right edge of each row. Inform students that in reality, exactly half of the particles do not decay each half-life, but that this process averages out to the half-life rate over a long period of time. However, reinforce that the general shape of the “graph” is accurate.

Answer to . . .

Figure 10 Polonium-218. The equation is:

\[ _{86}^{218}\text{Po} \rightarrow _{84}^{218}\text{Po} + _{2}^{4}\text{He} \]

A half-life is the time required for one half of a sample of a radioisotope to decay.
Modeling Half-Life

**Objective**
After completing this activity, students will be able to
- analyze data to calculate the "half-life" of a model radioactive element.

**Address Misconceptions**
Students may think that a half-life is half the time it takes for a radioactive substance to decay completely. This lab can help dispel this misconception.

**Skills Focus**
- Analyzing Data, Calculating, Using Graphs
- Prep Time 20 minutes

**Materials**
- 100 1-cm squares of wallpaper, large plastic bag, graph paper
- Advance Prep Use a paper cutter to cut up the wallpaper quickly.

**Class Time**
- 20 minutes

**Teaching Tips**
- Students can cut up the paper squares themselves.
- Explain to students that, on average, half the remaining squares will be removed each time Step 4 is repeated.
- Ask students: How does this lab model radioactive decay? (Like the wallpaper squares, half the radioactive element decays during each half-life.)

**Expected Outcome**
- Students will need to spill and remove paper squares six to nine times to remove all of the squares.

**Analyze and Conclude**
1. On average, half the squares will be removed in one spill and three-fourths of the squares will be removed in two spills.
2. Students’ graphs should reflect the information in their data tables.
3. One year
   - Visual, Logical

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**Facts and Figures**

**Radioactive Dating**
An American chemist, Dr. Willard F. Libby, developed this technique in the late 1940s. Radiocarbon dating is used to date once-living materials. The date when the organism died is the date when it stopped absorbing carbon-14.

Radiocarbon dating cannot be used to date the remains of organisms that died after the 1940s. Starting in the 1940s, the testing of nuclear bombs and use of nuclear reactors has dramatically increased the amount of carbon-14 and other radioisotopes in the environment.
Carbon reacts with oxygen in the atmosphere and forms carbon dioxide. As plants absorb carbon dioxide during photosynthesis, they maintain the same ratio of carbon-14 to carbon-12 as in the atmosphere. Likewise, animals have the same ratio of carbon isotopes as the plants they eat. When a plant or animal dies, however, it can no longer absorb carbon. From this point on, the organism’s carbon-14 levels decrease as the radioactive carbon decays. In radiocarbon dating, the age of an object is determined by comparing the object’s carbon-14 levels with carbon-14 levels in the atmosphere. For example, if the ratio of carbon-14 to carbon-12 in a fossil is half the ratio in the atmosphere, then the organism lived about 5730 years ago.

Because atmospheric carbon-14 levels can change over time, the calculated age of the fossil is not totally accurate. To get a more accurate radiocarbon date, scientists compare the carbon-14 levels in a sample to carbon-14 levels in objects of known age. Such objects might include trees (which can be dated by counting tree rings) or artifacts from a specific historical period.

Radiocarbon dating can be used to date any carbon-containing object less than 50,000 years old, such as the artifact in Figure 11. Objects older than 50,000 years contain too little carbon-14 to be measurable. To date objects thought to be older than 50,000 years, scientists measure the amounts of radioisotopes with longer half-lives than carbon-14. Geologists, for instance, use the half-lives of potassium-40, uranium-235, and uranium-238 to date rock formations. The older the rock, the lower the are the levels of the radioisotope present.

**Section 10.2 Assessment**

### Reviewing Concepts
1. How are nuclear decay rates different from chemical reaction rates?
2. How can scientists determine the age of an object that contains carbon-14?
3. If a radioactive sample has decayed until only one-eighth of the original sample remains unchanged, how many half-lives have elapsed?
4. What type of nuclear radiation is emitted when carbon-14 decays?

### Critical Thinking
5. **Predicting** Can radiocarbon dating be used to determine the age of dinosaur fossils? Explain. (Hint: Dinosaurs roamed Earth more than 65 million years ago.)

### Writing in Science

**Explanatory Paragraph** Archaeology is the study of past cultures. Explain how a concept in chemistry led to advances in archaeology.

**Radioactive Dating**

**Build Science Skills**

**Measuring** Ask students to choose a radioactive isotope for dating a hypothetical fossil. Tell students that archaeologists hypothesize that the fossil is about 20,000 years old. Have students look at the half-lives of radioisotopes in this section. Ask, Which isotope would you recommend that the scientists first try? (Carbon-14) Why would that isotope be a good choice? (It is a good choice because the half-life of carbon-14 is 5370 years. The half-life of radium-226, at 1620 years, is too short. The half-life of thorium-230 is 75,200 years, which is too long. Using either of these could result in a less accurate measurement.)

**Logical, Verbal**

### Assess

**Evaluate Understanding**

Randomly ask students to determine the number of particles present after one, two, or three half-lives have passed from a specified initial number of particles.

**Reteach**

Use Figure 10 to review how different radioisotopes may be used to date objects of different ages. Emphasize that some radioisotopes with shorter half-lives are useful for dating young objects while radioisotopes with long half-lives are useful for dating old objects.

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 10.2.

Half-life is a concept in nuclear chemistry that has led to profound advances in archaeology, the study of past cultures. A half-life is the time required for one half of a sample of a radioisotope to decay. Using radioisotopes such as carbon-14, scientists have been able to accurately date fossils and archaeological sites up to 50,000 years old.
**Should Radon Testing in Schools Be Mandatory?**

**Background**

Prior to 1984, radon gas was considered a health risk only for workers in uranium mines. Then, in 1984, a nuclear engineer set off an alarm while passing through a radiation monitor at the Limerick Nuclear Power Plant. The engineer, Stan Watras, was leaving work at the time. Since there was no nuclear fuel on site, there was no major source of radiation contamination at the plant. The Health Physics staff at the plant determined that the source of the radiation was Mr. Watras’s house in Boyertown, Pennsylvania. The staff took remedial actions to fix Mr. Watras’ home. Mr. Watras and his family still live in the house today.

The Watras case put radon testing in the national spotlight. In October of 1988, Congress passed legislation that established a national goal that indoor radon levels not exceed ambient outdoor radon levels (0.2–0.7 pCi/L). A picocurie (Ci) is a unit of radioactivity equal to 0.037 disintegrations per second. The law set aside funds for states to initiate radon testing in schools and workplaces.

**Answers**

1. The issue that needs to be resolved is whether indoor radon poses a health risk serious enough in schools to warrant mandatory testing.
2. Two reasons why radon testing should be mandatory in all schools is that radon is the second leading cause of lung cancer in the United States and that many classrooms are above the EPA’s action level of 4 pCi/L.
3. Answers will vary based on which arguments students choose.

**Go Online**

Have students further research issues related to this topic.

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**The Viewpoints**

**Radon Testing in Schools Should Be Mandatory**

The EPA estimates that indoor radon exposure contributes to 21,000 lung cancer deaths in the United States each year. After smoking, radon is the second-leading cause of lung cancer.

Students and teachers spend extended periods of time indoors at school. A nationwide survey of radon levels in schools found that nearly one in five schools has at least one classroom with radon exceeding the EPA’s action level of 4 pCi/L.

Indoor radon can be easily tested. If elevated radon levels are found, they can be reduced using proven techniques. But without mandatory testing, school administrators may not be aware of the potential risk of radon exposure in their schools.

**Radon Testing in Schools Should Not Be Mandatory**

The EPA’s radon guidelines are based mainly on studies of workers in uranium mines. Radon levels in these mines were far greater than those found in homes or schools. In addition, the miners engaged in tiring labor, resulting in heavy breathing of the surrounding air. Lastly, most of the miners were smokers. The data from these studies are appropriate for predicting the risk of radon exposure for uranium miners—but not for the general public.

The EPA’s action level of 4 pCi/L is not universally accepted. In Canada and Europe, for example, radon guidelines are much less strict. Until scientists gather more data about the risk of residential radon exposures, radon testing in schools should not be mandatory.

**Research and Decide**

1. **Defining the Issue** In your own words, explain the issue that needs to be resolved about indoor radon.
2. **Analyzing the Viewpoints** List two arguments of those who think that radon testing should be mandatory in schools. List two arguments of those who think that radon testing should not be mandatory in schools.
3. **Forming Your Opinion** Should there be mandatory radon testing in schools? Which argument did you find more convincing?

**Go Online**

For: More on this issue
Visit: PHSchool.com
Web Code: cch-1100
During the Middle Ages, a number of people, like the ones shown in Figure 12, were obsessed with the idea of changing lead into gold. For centuries, these early scientists, known as alchemists, tried to use chemical reactions to make gold. But no matter how many recipes they tried, the alchemists only succeeded in making compounds that contained lead. What were they doing wrong?

**Nuclear Reactions in the Laboratory**

The alchemists were trying to achieve transmutation. Transmutation is the conversion of atoms of one element to atoms of another. It involves a nuclear change, not a chemical change.

Nuclear decay is an example of a transmutation that occurs naturally. Transmutations can also be artificial. Scientists can perform artificial transmutations by bombarding atomic nuclei with high-energy particles such as protons, neutrons, or alpha particles.

Early experiments involving artificial transmutation led to important clues about atomic structure. In 1919, a decade after he discovered the atomic nucleus, Ernest Rutherford performed the first artificial transmutation. Rutherford had been studying the effects of nuclear radiation on various gases. When Rutherford exposed nitrogen gas to alpha particles, he found that some of the alpha particles were absorbed by the nitrogen nuclei. Each newly formed nucleus then ejected a proton, leaving behind the isotope oxygen-17.

${}_1^1\text{N} + {}_2^4\text{He} \rightarrow {}_8^{17}\text{O} + {}_1^1\text{H}$

Note that $H$ represents a proton. Rutherford’s experiment provided evidence that the nucleus contains protons.

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**Section Resources**

- **Print**
  - Reading and Study Workbook With Math Support, Section 10.3
  - Transparencies, Section 10.3

- **Technology**
  - Interactive Textbook, Section 10.3
  - Presentation Pro CD-ROM, Section 10.3
Transuranium Elements

Modeling Transmutation

Objective
After completing this activity, students will be able to:
• balance equations that describe simple nuclear reactions.

Skills Focus Calculating, Using Models

Quick Lab

Materials
periodic table, 2 sheets of unlined white paper, 32 green beads, 32 purple beads

Procedure
1. Use the periodic table to complete the following nuclear reaction. Then, write it on one of the sheets of paper.

\[ ^{13}N + ^{4}He \rightarrow ^{17}X + ^{1}H \]

2. Count the number of protons and neutrons present in each reactant and product.

3. Using the green beads to represent protons and the purple beads to represent neutrons, make a model of each reactant and product below its symbol on the sheet of paper.

Analyze and Conclude
1. Applying Concepts What was the missing product in each of the equations? How did you know what the missing product was?
2. Using Models Make a model of the nuclear reaction between an alpha particle and an atom of aluminum-27. (Hint: One of the two products is a proton.)

Transuranium Elements

Elements with atomic numbers greater than 92 (uranium) are called transuranium elements. All transuranium elements are radioactive, and they are generally not found in nature. Scientists can synthesize a transuranium element by the artificial transmutation of a lighter element.

Neptunium was the first transuranium element synthesized. In 1940, scientists at the University of California, Berkeley, bombarded uranium-238 with neutrons, producing uranium-239. The uranium-239 underwent beta decay to form neptunium-239.

Although most transuranium elements have only been produced for research, some are synthesized for industrial or consumer use. For example, americium-241 is a transuranium element used in smoke detectors. As americium-241 decays, it emits alpha radiation. This radiation ionizes the air inside a smoke detector to allow an electric current to flow. When smoke enters the smoke detector, it disrupts the current and the alarm goes off. Another useful transuranium element is plutonium-238. Figure 13 shows a space probe that runs on electrical energy generated by the decay of plutonium-238.

What is a transuranium element?

Customize for Inclusion Students

Gifted
Challenge students to find the names of different types of subatomic particles besides protons, neutrons, and electrons. For example, have them research the six types of quarks. (The six quarks are often called up, down, charmed, strange, top, and bottom.) Then, have students find out when they were discovered and what properties are known about them. Have students create a presentation that explains the characteristics and discovery of several subatomic particles. (Other subatomic particle types or categories include leptons, muons, tau particles, neutrinos, bosons, fermions, gluons, mesons, and baryons.)
Particle Accelerators

In Rutherford’s transmutation experiment, the radioactive element radium was used as a source of alpha particles. However, sometimes transmutations will not occur unless the bombarding particles are moving at extremely high speeds. In order to perform such transmutations, scientists use devices called particle accelerators. In a particle accelerator, charged particles can be accelerated to speeds very close to the speed of light. The fast-moving particles are guided toward a target, where they collide with atomic nuclei. With the help of particle accelerators, scientists have produced more than 3000 different isotopes.

Scientists also conduct collision experiments in order to study nuclear structure. Since the discoveries of the proton, neutron, and electron, more than 200 different subatomic particles have been detected. According to the current model of the atom, protons and neutrons are made up of even smaller particles called quarks. A quark is a subatomic particle theorized to be among the basic units of matter. Both protons and neutrons belong to a class of particles that are made up of three quarks. Six types of quarks are currently thought to exist. Two of these types were discovered at Fermi National Accelerator Laboratory, also known as Fermilab. Figure 14 shows one of the devices used at Fermilab to detect subatomic particles.

Figure 14 This particle detector records subatomic particles produced in the Tevatron, the most powerful particle accelerator in the world. The Tevatron is located at Fermilab in Batavia, Illinois.

Section 10.3 Assessment

Reviewing Concepts

1. How do scientists perform artificial transmutations?
2. How are transuranium elements produced?
3. How does artificial transmutation differ from nuclear decay?
4. Write the equation for the transmutation that occurs when an alpha particle combines with an oxygen-16 atom, emitting a proton.

Critical Thinking

6. Bombarding a lithium-6 atom with a neutron produces helium-4 and another particle. What is that particle?

7. Curium was first synthesized by bombarding a target isotope with alpha particles, which produced curium-242 and a neutron. What was the target isotope? (Hint: Use the symbol \( n \) to represent a neutron.)

8. Why can’t the transuranium elements be made by exposing other elements to naturally occurring alpha radiation?

Writing in Science

Write a brief summary of the first artificial transmutation, performed by Ernest Rutherford. (Hint: Your summary should describe an example of a nuclear reaction.)

Summary

Evaluate Understanding

Assess

Ask students to write three completed equations for transmutations. Have students take turns giving the reactants for the equation while another student determines the product with the correct number of protons and neutrons for each transmutation.

Rutherford performed the first artificial transmutation while studying the effects of nuclear radiation on gases. After he exposed nitrogen gas to alpha radiation, he observed that some of the alpha particles were temporarily absorbed by the nitrogen nuclei. Each newly formed nucleus then ejected a proton, leaving behind oxygen-17. In this transmutation, nitrogen-14 was converted into oxygen-17.

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 10.3.

Answer to . . .

Figure 13 Uranium-234. The equation is:

\[ _{92}^{238}U + _{2}^{4}He \rightarrow _{92}^{234}U + _{1}^{1}H \]

An element with an atomic number greater than 92.
Nuclear Medicine

Background

PET (positron emission tomography) scanning can detect subtle changes in the body’s metabolism and chemical reactions. The PET scanner detects radiation produced by a positron-emitting radioisotope injected into the body. Chemical compounds containing radioisotopes of carbon, nitrogen, or oxygen are commonly used as tracers.

Once the tracer enters the body, it travels through the bloodstream to the target organ. When the tracer reaches the target organ, the chemical that it is attached to begins taking part in the chemical reactions. Positrons, the antimatter equivalent of electrons, are released from the tracer and collide with electrons. Each collision annihilates a positron and an electron and releases two gamma rays. The PET scanner detects these gamma rays. The data is fed into a computer and a three-dimensional image is produced of the processes occurring in the target organ.

PET scans are used to evaluate a number of different medical conditions. They can be used to detect cancers, determine the extent to which cancer has spread, and determine the effectiveness of cancer treatment. PET scans can help diagnose brain conditions such as epilepsy and Alzheimer’s disease. They can also evaluate cardiac conditions such as heart muscle function and coronary artery disease.

Radioisotopes are detectable by their radiation, they can be used as tracers that map out specific locations in the body. For example, the radioisotope iodine-131 is absorbed by the thyroid gland in the same way that iodine-127 is. If iodine-131 is injected into the body, the radiation it emits will show how well the thyroid gland is functioning.

Radioactive tracers can also be used to pinpoint the location of cancer cells. Cancer cells multiply rapidly and absorb glucose much faster than normal cells. If the glucose molecules are “tagged” with a radioactive tracer, such as fluorine-18, the location of the cancer cells can be found by tracking areas of high glucose concentration.

Radioisotopes with short half-lives are chosen for medical uses. These isotopes decay so rapidly that after only a day or two, practically none of the isotope remains.

Tagged glucose is absorbed slowly in the blue areas, indicating normal tissue.

Red color shows greater glucose absorption in possibly cancerous areas.

PET scanner

PET (positron emission tomography) scans use radioactive tracers to examine parts of the body, such as the brain. The patient receives an injection of radioactive tracer. The tracer produces gamma rays that are detected by the scanner.

PET scan of brain

This scan shows the level of activity in different areas of the brain. Glucose tagged with fluorine-18 is absorbed more rapidly in areas of high brain activity and by cancer cells. Here, red shows the greatest activity and blue the least.

Exposure to nuclear radiation is often harmful to the human body. However, scientists have also found nuclear radiation to be a powerful tool in the field of medicine.

Because radioisotopes are detectable by their radiation, they can be used as tracers that map out specific locations in the body. For example, the radioisotope iodine-131 is absorbed by the thyroid gland in the same way that iodine-127 is. If iodine-131 is injected into the body, the radiation it emits will show how well the thyroid gland is functioning.

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PET scan of brain

This scan shows the level of activity in different areas of the brain. Glucose tagged with fluorine-18 is absorbed more rapidly in areas of high brain activity and by cancer cells. Here, red shows the greatest activity and blue the least.
Build Science Skills

Using Models

Purpose Students model the radiation detected by a PET scanner.

Materials 500-mL beaker; sponges; shallow pans; food coloring; 1-cm strips of thin and thick cardboard, newspaper, and waxed paper; paper towels

Class Time 20 minutes

Advance Prep Fill the beaker with water and add several drops of food coloring. For each group, prepare a solution-soaked sponge placed flat in a pan.

Procedure Distribute several different strips to students and have them make a pattern on top of the sponge. Tell students to leave some areas of the sponge uncovered. Then, have students gently press the paper towel on top of the sponge for three seconds and remove it, placing the paper towel faceup next to the sponge. Ask, How does the pattern on the paper towel compare to the pattern of squares on the sponge? (They are similar, but not identical. The waxed paper and heavy cardboard completely blocked the absorption of the solution. The newspaper did not block the absorption at all, and the light cardboard partially blocked the solution.) If the paper towel were a PET scan, which areas would show the most activity? (The areas that absorbed the most colored water.) Which areas would show the least? (The areas that absorbed the least.)

Expected Outcome Students will gain a better understanding of how PET images are formed. Logical, Kinesthetic

Going Further
- Write a paragraph describing how radioactive tracers are used in medicine. Indicate what qualities make a particular radioisotope useful as a radioactive tracer in the human body.
- Take a Discovery Channel Video Field Trip by watching “Nuclear Medicine.”

Nuclear Chemistry 307

Video Field Trip

Nuclear Medicine

After students have viewed the Video Field Trip, ask them the following questions: What is nuclear medicine? (The use of small amounts of radioactive materials that enable a physician to look inside the body and to treat diseases such as some forms of cancer.) What did Marie and Pierre Curie discover? (Student answers may include: They discovered radium and polonium.) What did Irene Curie discover? (She discovered artificial radioactivity by determining that aluminum remained radioactive after being bombarded with radioactive particles.) If radioactive substances are used today to treat certain types of cancer, how was it possible for Marie Curie and Irene Curie to develop a form of cancer by working with radioactive substances? (When treating certain types of cancer, only small dosages of radioactivity are used. However, when Marie and Irene Curie did their research, they were in contact with large amounts of radioactive substances for prolonged periods of time.)
10.4 Fission and Fusion

Reading Focus

**Key Concepts**
- Under what conditions does the strong nuclear force overcome electric forces in the nucleus?
- What property of fission makes it so useful?

**Vocabulary**
- strong nuclear force
- fission
- chain reaction
- critical mass
- fusion
- plasma

**Reading Strategy**
Comparing and Contrasting
Copy the Venn diagram below. As you read, contrast fission and fusion by listing the ways they differ.

A

Alternative energy sources may someday replace fossil fuels such as coal and oil. One alternative energy source that is widely used today is nuclear energy. Nuclear energy is the energy released by nuclear reactions.

Shortly after the discovery of radioactivity, scientists realized that atomic nuclei contained vast amounts of energy. By the late 1930s, scientists discovered that transmutations involved more than just the conversion of one element into another—they also involved the conversion of mass into energy.

**Nuclear Forces**

What holds the nucleus together? Remember that the protons in the nucleus are all positively charged, so they tend to repel one another. Clearly, there must be an attractive force that binds the particles of the nucleus. Otherwise, the protons would simply push one another away.

The **strong nuclear force** is the attractive force that binds protons and neutrons together in the nucleus. Because the strong nuclear force does not depend on charge, it acts on protons and neutrons alike. Electric forces in the nucleus are repulsive, and act only among protons.

Using Models: What atomic nucleus is represented above?

Figure 15 Two kinds of forces act upon particles in the nucleus. Strong nuclear forces, which are attractive, act on protons and neutrons alike. Electric forces in the nucleus are repulsive, and act only among protons.

Using Models: What atomic nucleus is represented above?

308 Chapter 10

Section Resources

**Print**
- Reading and Study Workbook With Math Support, Section 10.4
- Transparencies, Section 10.4

**Technology**
- Interactive Textbook, Section 10.4
- Presentation Pro CD-ROM, Section 10.4
- Go Online, NSTA SciLinks, Fission
**The Effect of Size on Nuclear Forces** Electric forces in atomic nuclei depend on the number of protons. The greater the number of protons in a nucleus, the greater is the electric force that repels those protons. So in larger nuclei, the repulsive electric force is stronger than in smaller nuclei.

The effect of size on the strong nuclear force is more complicated. On one hand, the more protons and neutrons there are in a nucleus, the more possibilities there are for strong nuclear force attractions. However, as the size of the nucleus increases, the average distance between protons and neutrons increases. Because the strong nuclear force only acts over short ranges, the possibility of many attractions is never realized in a large nucleus. As a result, the strong nuclear force felt by one proton or neutron in a large nucleus is about the same as in a small nucleus, as shown in Figure 16.

**Unstable Nuclei** A nucleus becomes unstable, or radioactive, when the strong nuclear force can no longer overcome the repulsive electric forces among protons. While the strong nuclear force does not increase with the size of the nucleus, the electric forces do. There is, therefore, a point beyond which all elements are radioactive. All nuclei with more than 83 protons are radioactive.

**Fission**

In 1938, two German chemists, Otto Hahn and Fritz Strassman, performed a series of important transmutation experiments. By bombarding uranium-235 with high-energy neutrons, Hahn and Strassman hoped to produce more massive elements. Instead, their experiments produced isotopes of a smaller element, barium. Unable to explain their data, Hahn and Strassman turned to a colleague for help. In 1939, Lise Meitner, shown in Figure 17, and Otto Frisch, another physicist, offered a groundbreaking explanation for the experiments. The uranium-235 nuclei had been broken into smaller fragments. Hahn and Strassman had demonstrated nuclear fission. Fission is the splitting of an atomic nucleus into two smaller parts.

---

**Fission Reading Literacy**

**Sequence** Refer to page 290D in this chapter, which provides guidelines for using a sequence.

Have students read the text on nuclear fission on pp. 309 and 310. Then, have students do the following:
1. Ask students to make a sketch similar to Figure 18. Tell students that they can use circles to represent the nuclei. Students should use larger circles to represent the uranium nuclei.
2. Have students label and describe what happens as a neutron strikes the uranium-235 nucleus and the steps that follow. Start with the neutron as Step 1. Each following step should be numbered in sequence.
3. Students’ sketches should include as much detail as they find from the text, Figure 18, and the caption.

**Integrate Language Arts**

Tell students that scientists in several countries were instrumental to the understanding of nuclear fission. The English scientist James Chadwick discovered the neutron in 1932. In 1934, Italian scientists led by Enrico Fermi conducted experiments involving the slow-neutron bombardment of uranium. Fermi’s results prompted German chemists Otto Hahn and Fritz Strassman, and Austrian physicist Lise Meitner, to further investigate the products formed when uranium is bombarded with neutrons. Meitner and Otto Frisch built on the results of this research and in 1939 described the fission process. Have students write a brief biography of one of the scientists who contributed to the understanding of nuclear fission.

**Verbal**
Chapter 10

The fission of ccn-1104 is rep
represents the speed of light (3.0 \times 10^8 \text{ m/s}). The conversion of mass into energy, the total amount of mass and energy remains constant.

Figure 18 illustrates the fission of a uranium-235 nucleus. Notice that one of the products of the reaction is energy. In nuclear fission, tremendous amounts of energy can be produced from very small amounts of mass. For example, the nuclear energy released by the fission of 1 kilogram of uranium-235 is equivalent to the chemical energy produced by burning more than 17,000 kilograms of coal.

**Converting Mass Into Energy** In the nuclear equation shown in Figure 18, the mass numbers on the left equal the mass numbers on the right. Yet when the fission of uranium-235 is carried out, about 0.1 percent of the mass of the reactants is lost during the reaction. This "lost" mass is converted into energy.

In 1905, more than 30 years before the discovery of fission, physicist Albert Einstein had introduced the mass-energy equation. It describes how mass and energy are related.

**Mass–Energy Equation**

\[ E = mc^2 \]

In the mass-energy equation, \( E \) represents energy, \( m \) represents mass, and \( c \) represents the speed of light \( (3.0 \times 10^8 \text{ m/s}) \). The conversion of a small amount of mass releases an enormous amount of energy. Likewise, a large amount of energy can be converted into a small amount of mass. The explosion of the first atomic bomb in 1945 offered a powerful demonstration of the mass-energy equation. The bomb contained 5 kilograms of plutonium-239. Fission of the plutonium produced an explosion that was equivalent to 18,600 tons of TNT.

Recall how the law of conservation of mass applied to chemical reactions. In nuclear reactions, however, the energies involved are much larger. To account for the conversion of mass into energy, a modified conservation law is used. According to the law of conservation of mass and energy, the total amount of mass and energy remains constant.
Facts and Figures

Natural Nuclear Reactor In 1972 when Francis Perrin uncovered evidence of a “natural nuclear reactor” in mines in Gabon, Africa, other scientists questioned his findings. They wanted to know how a natural nuclear reactor could exist when it required precise engineering work to construct one.

Further study showed that the expected proportions of uranium-238 (99.3%) and uranium-235 (0.7%), were not present in the Gabon mines. There was much less uranium-235. Scientists used this data and calculated that 1.7 billion years ago, the proportion of uranium-235 was 3%, enough for nuclear fission. Underground water helped create the right conditions for a chain reaction. Scientists think the natural nuclear reaction continued intermittently for at least a million years until the uranium-235 was mostly used up.

Nuclear Processes

Purpose Students observe a model of nuclear fission and fuel.

Materials bubble solution, 2 bubble wands

Procedure Dip the end of each wand into the solution and remove. Gently blow into the ring of each wand to make a bubble with a diameter a little larger than the ring, and catch the bubble on the wand. Bring the wands together to form a large bubble, illustrating fusion. Pull the two frames farther apart to separate the bubble into two bubbles, one in each frame, simulating fission. When this is done a little faster small bubbles may be released, representing the released neutrons. Discuss with students the strengths and weaknesses of this model.

Expected Outcome Students observe how to use bubbles to model nuclear fusion and nuclear fission. Students may point out that this demonstration does not model the neutron required to initiate fission.

Visual, Group

Answer to . . .

Figure 18 Unlike nuclear decay, fission is generally not spontaneous. A neutron must be introduced in order for the fission of uranium-235 to occur. During the nuclear decay of uranium-235, however, no other reactants are necessary in order for the radioisotope to decay into thorium-231 and emit alpha radiation.

Figure 19 No, fission of uranium-235 can produce a number of different combinations of product isotopes. Although fission results in the fragmentation of the nucleus into two parts, the composition of those two parts (and hence the number of neutrons released) can vary widely.

A chain reaction is a nuclear reaction sequence in which neutrons released during the splitting of an initial nucleus trigger a series of nuclear fissions.
Nuclear Energy from Fission Today, nuclear power plants generate about 20 percent of the electricity in the United States. In a nuclear power plant, controlled fission of uranium-235 occurs in a vessel called a fission reactor.

Unlike power plants that burn fossil fuels, nuclear power plants do not emit air pollutants such as oxides of sulfur and nitrogen. However, nuclear power plants have their own safety and environmental issues. For example, workers in nuclear power plants need to wear protective clothing to reduce their exposure to nuclear radiation. In addition, the fission of uranium-235 produces many radioactive isotopes with half-lives of hundreds or thousands of years. This radioactive waste must be
isolated and stored so that it cannot harm people or contaminate the environment while it decays.

Another concern about nuclear power is that the operators of the plant could lose control of the reactor. For instance, if the reactor’s cooling system failed, then a meltdown might occur. During a meltdown, the core of the reactor melts and radioactive material may be released. If the structure that houses the reactor is not secure, then the environment can become contaminated. In 1986, one of the reactors at the nuclear power station in Chernobyl, Ukraine, overheated during an experiment. A partial meltdown resulted, and large amounts of radioactive material were released into the atmosphere.

1942 The first controlled, self-sustaining nuclear chain reaction is achieved by Enrico Fermi’s research group in Chicago.

1945 United States explodes first atom bomb in a test near Alamagordo, New Mexico.

1951 Electricity from nuclear fission produced at National Reactor Testing Station, Idaho.

1960 Willard Libby wins the Nobel Prize for developing carbon-14 dating. The technique became widely used in archaeology and geology.

1986 Partial meltdown occurs at Chernobyl power plant.

Use Community Resources

Ask students to find out what percentage of the power in their state comes from nuclear power plants. Encourage them to use library resources, such as the Internet, to find statistics. If your state does not receive power from nuclear power plants, instruct students to find that information for another state. Ask students to make a diagram and write a brief summary of their findings.

Interpersonal, Portfolio
Nuclear Power Station

Background

Uranium-235, the fissile material used in nuclear power plants, makes up only about 0.7% of all uranium found in nature. In order for a nuclear reactor to operate, about 3% of the uranium in the fuel rods must be uranium-235. Samples of uranium must be enriched so that they contain this higher percentage of uranium-235.

A bundle of fuel rods contains slightly more than the critical mass of uranium-235. Control rods are placed in the bundle in order to control when and how quickly the process of fission occurs.

Interpreting Diagrams

In a nuclear power station, water is used to transfer the energy generated in the reactor core. Heat released in the core is absorbed by water in the steam generator. The steam produced is used to drive a turbine, the kinetic energy of the turbine is then converted into electrical energy. Water is also used as a coolant to condense the steam exiting the turbine. The steam condenses into liquid water and is piped back to the steam generator.

Visual

For Enrichment

The U.S. Navy uses nuclear reactors to power many different types of ships, ranging from submarines to aircraft carriers. Nuclear power is useful on ships that are at sea for long periods of time because the ships do not have to carry large quantities of fuel or fuel while they are on a mission. Ask students to research how nuclear reactors in ships differ from those in nuclear power stations.

Verbal
**Fusion**

Another type of nuclear reaction that can release huge amounts of energy is fusion. Fusion is a process in which the nuclei of two atoms combine to form a larger nucleus. As in fission, during fusion a small fraction of the reactant mass is converted into energy.

On any day or night, you can detect the energy released by fusion reactions occurring far away from Earth. The sun and other stars are powered by the fusion of hydrogen into helium. Inside the sun, an estimated 600 million tons of hydrogen undergo fusion each second. About 4 million tons of this matter is converted into energy.

Fusion requires extremely high temperatures. Within the sun, temperatures can reach 10,000,000°C. At temperatures this high, matter exists as plasma. Plasma is a state of matter in which atoms have been stripped of their electrons. You can think of plasma as a gas containing two kinds of particles—nuclei and electrons.

Fusion may someday provide an efficient and clean source of electricity. Scientists envision fusion reactors fueled by two hydrogen isotopes, deuterium (hydrogen-2) and tritium (hydrogen-3). The fusion of deuterium and tritium produces helium, neutrons, and energy:

\[
\text{D} + \text{T} \rightarrow \text{He} + \text{n} + \text{energy}
\]

Scientists face two main problems in designing a fusion reactor. They need to achieve the high temperatures required to start the reaction, and they must contain the plasma.

---

**Section 10.4 Assessment**

### Reviewing Concepts

1. Under what conditions does the strong nuclear force overcome the repulsive effect of electric forces in the nucleus?
2. What property of fission makes it a useful reaction?
3. What particles are affected by strong nuclear forces?
4. What must happen in order for a nuclear chain reaction to occur?
5. Why is a cooling system necessary in a nuclear reactor?
6. How do the products of a fusion reaction differ from the products of a fission reaction?

### Critical Thinking

7. **Inferring** How does the strong nuclear force affect an atom's electrons? (Hint: Think about where the electrons are located in the atom.)
8. **Inferring** Why do fission chain reactions of uranium-235 not occur in underground uranium deposits?

### Connecting Concepts

- **Fossil Fuels** Reread the description of fossil fuels in Section 9.1. Then compare fossil fuel combustion with nuclear fission.

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### Fusion

**Address Misconceptions**

Students may think that the sun is actually burning because it gives off light and heat. Explain that the light and heat given off by the sun result from nuclear fusion, not combustion.

**Build Science Skills**

**Observing** Tell students that the sun produces energy by nuclear fusion. Explain that fusion releases very large amounts of energy. Ask, How do you know that the sun produces large amounts of energy? (Students may come up with examples such as heat, bright sunlight, sunburn, and so on.)

**Logical**

**Evaluate Understanding**

Have students write down three characteristics of nuclear fission and fusion. Have students take turns giving a characteristic while the other students identify whether it is typical of fission or fusion.

**Reteach**

Use Figures 18 and 19 to summarize controlled and uncontrolled fission reactions.

Possible answer: Both fossil fuel combustion and nuclear fission produce heat, which can be used to generate electricity. Fossil fuel combustion is a chemical reaction, the products of which include carbon dioxide, water, carbon monoxide, nitrogen oxides, and soot. Air pollution is one of the main drawbacks of fossil fuel combustion as an energy source. Fission is a nuclear reaction whose products include lighter nuclei and neutrons. Radioactive waste is one of the main drawbacks of fission as an energy source.

---

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 10.4.
Chapter 10 Nuclear Chemistry

ASSESS PRIOR KNOWLEDGE

Use the Chapter Pretest below to assess students’ prior knowledge. As needed, review these Science Concepts and Math Skills with students.

Review Science Concepts

Section 10.1 Encourage students to recall what they have learned about balancing chemical equations. Review how chemical equations show conservation of mass.

Section 10.2 Encourage students to remember what they have learned about the rates of chemical reactions. To prepare students for a discussion of half-life, ask students to recall basic probability calculations.

Section 10.3 Review the different parts of the periodic table. Encourage students to recall the location of uranium and the elements heavier than uranium in the periodic table.

Section 10.4 Ask students to recall what they have learned about modern models of the atom.

Review Math Skills

Equations and Formulas Students will need to manipulate variables and constants to solve for unknowns in equations representing nuclear decay.

Direct students to the Math Skills in the Skills and Reference Handbook at the end of the student text.

Chapter Pretest

1. According to the law of conservation of mass, if element X has a molar mass of 3 g/mol, and element Y has a molar mass of 5 g/mol, what must be the total mass of products formed when one mole of the compound X₂Y decomposes? (11 g)
2. True or False: A reaction rate is the rate at which reactants change into products over time. (True)
3. If you tossed 128 coins in the air, about how many could you expect to land heads up? (b) a. About 178 b. About 64 c. About 32 d. Almost none
4. Suppose you were to remove any coins that landed heads up, and then toss the remaining coins in the air. How many times could you expect to repeat this process until you had removed all of the coins? (About 7 times)
6. Which subatomic particles are found in the nucleus? (Protons and neutrons)
What Happens When an Atom Decays? L2

Purpose
In this activity, students begin to describe one mechanism of atomic decay that causes atoms to change from one element to another.

Address Misconceptions
Students may think that elements are unchangeable, and they may doubt that an atom of one element can change to another. Challenge this misconception by asking students to discuss the outcome of this activity. This activity demonstrates how elements can change, though it does not prove that such changes actually occur.

Skills Focus Using Models

Prep Time 5 minutes
Materials green and purple beads
Class Time 10 minutes
Expected Outcome The model will demonstrate the decay of $^{8}_{4}$Be to $^{4}_{2}$He by loss of an alpha particle (two protons and two neutrons).

Think About It
1. Two protons and two neutrons are left in the model.
2. The model represents helium.

Kinesthetic, Logical

Encourage students to view the Video Field Trip “Nuclear Medicine.”
Chapter 10

Modeling a Chain Reaction

Objective
After completing this activity, students will be able to
• describe how a nuclear chain reaction occurs
• list some of the factors that affect the rate of nuclear chain reactions.

Skills Focus: Observing, Using Models

Prep Time: 5 minutes
Class Time: 45 minutes

Teaching Tips
• If students have difficulty arranging the dominoes correctly, perform this lab as a demonstration or provide diagrams of the positions of the bases of the dominoes. Students can then place the dominoes directly on the diagram.

Expected Outcome: Rearranging the dominoes from a single line to a fan shape in Steps 3 and 4 increased the speed with which they fell. Inserting a metric ruler in Step 5 and adding supporting dominoes in Step 6 prevented some of the dominoes from falling.

Materials
• 20 dominoes
• watch with a second hand, or stopwatch
• metric ruler

Problem: How can you make a model of a nuclear fission chain reaction?

Materials
• 20 dominoes
• watch with a second hand, or stopwatch
• metric ruler

Skills: Observing, Using Models

Procedure
1. Stand 15 dominoes in a single straight row in such a way that the distance between them is about one half of their height. Knock over the first domino. Measure and record the time it takes for all the dominoes to fall.
2. Repeat Step 1 two more times. Then, average the three time measurements to get a more accurate time.
3. Arrange 15 dominoes as shown below so that each domino will knock over two others. Observe what happens when you knock over the first domino. Measure and record how long it takes for the whole set of dominoes to fall over.
4. Repeat Step 3 two more times. Average the three time measurements to get a more accurate time.
5. Set up 15 dominoes again as you did in Step 3. This time, however, hold a metric ruler on end, in the middle of the arrangement of dominoes, as shown in the photograph on the next page. Knock over the first domino. Observe what happens.
6. Set up 15 dominoes as you did in Step 3, but this time, place 5 additional dominoes behind and at right angles to 5 randomly chosen dominoes for support, as shown below. The 5 supported dominoes represent atoms of a different isotope that must be struck with more energy to undergo fission.
7. Knock over the first domino. Measure and record the time it takes for the dominoes to fall and how many dominoes fall.
8. Repeat Steps 6 and 7 two more times. Then, average the three time measurements to get a more accurate time.
9. Repeat Steps 6 through 8, but this time, place supporting dominoes behind only 3 dominoes.
10. Repeat Steps 6 through 8, but this time, place a supporting domino behind only 1 domino.
Analyze and Conclude

6. Applying Concepts

Steps 6 through 10, explain why this element. On the basis of your observations in removing less fissionable isotopes of the same fissionable isotope is used, it is refined by representing the fission of the nucleus and the release of neutrons.

5. Using Models

In your falling-dominoes model of nuclear fission chain reactions, what did the striking of one domino by another represent? What did the fall of a domino represent?

4. Applying Concepts

In your falling-dominoes model of nuclear fission chain reactions, what did the striking of one domino by another represent? What did the metric ruler represent?

3. Analyzing Data

Before a sample of an easily fissionable isotope is used, it is refined by removing less fissionable isotopes of the same element. On the basis of your observations in Steps 6 through 10, explain why this refinement is necessary.

6. Inferring

What factors do you think would affect the rate of a nuclear fission chain reaction?

7. Drawing Conclusions

What do you think would happen to a nuclear fission chain reaction if control rods were not present?

8. Evaluating and Revising

What are some of the limitations of using falling dominos to model a nuclear fission chain reaction? Suggest how you might revise this model to make it more representative of a chain reaction.

Go Further

Visit the library and find out about the Manhattan Project and how it made history. Use what you have learned from the falling-dominos model to help you understand the scientific discoveries related to controlled and uncontrolled nuclear chain reactions.

Analyse and Conclude

1. Calculating

What was the average fall time for the arrangement of dominos in Steps 1 and 2? In Steps 3 and 4?

2. Applying Concepts

What type of reaction was modeled in Steps 3 and 4?

3. Using Models

In your falling-dominos model of nuclear fission chain reactions, what did a standing domino represent? What did the fall of a domino represent?

4. Using Models

In your falling-dominos model of nuclear fission chain reactions, what did the striking of one domino by another represent? What did the metric ruler represent?

5. Analyzing Data

Before a sample of an easily fissionable isotope is used, it is refined by removing less fissionable isotopes of the same element. On the basis of your observations in Steps 6 through 10, explain why this refinement is necessary.

6. Inferring

What factors do you think would affect the rate of a nuclear fission chain reaction?

7. Drawing Conclusions

What do you think would happen to a nuclear fission chain reaction if control rods were not present?

8. Evaluating and Revising

What are some of the limitations of using falling dominoes to model a nuclear fission chain reaction? Suggest how you might revise this model to make it more representative of a chain reaction.

Go Further

Visit the library and find out about the Manhattan Project and how it made history. Use what you have learned from the falling-dominos model to help you understand the scientific discoveries related to controlled and uncontrolled nuclear chain reactions.

Analyze and Conclude

1. The time should be shorter in Steps 3 and 4.

2. A nuclear chain reaction was modeled in Steps 3 and 4.

3. A standing domino represented the nucleus of an atom. The fall of a domino represented the fission of the nucleus and the release of neutrons.

4. The striking of one domino by another represented the striking of a nucleus of a nearby atom by a neutron. The ruler represented a control rod.

5. Atoms of the less-easily fissionable isotopes can interfere with the development of a chain reaction.

6. The number of neutrons released during fission and the number of other atoms that are nearby and available for the released neutrons to strike affect the rate of the reaction.

7. The reaction would go out of control, perhaps leading to a meltdown or explosion.

8. One limitation of the domino model is that it treats each fission reaction as the same; according to the model, each fission reaction (represented by a single falling domino) leads to exactly two more fissions. In reality, the fission of one nucleus can produce more than two neutrons, each of which may trigger another fission reaction. One way that the model could be revised is to use dominos of varying sizes and/or colors. The arrangement of dominos could be modified so that the falling of a larger-sized domino caused more than two smaller-sized dominos to fall. Alternatively, different colored dominos could be used to represent the differing numbers of neutrons released by each fission reaction (as well as the different product isotopes formed).

Visual, Logical

Go Further

Initiated by the U.S. government during World War II, the Manhattan Project was a large-scale research project that succeeded in developing the first atomic bomb. In their research, students may relate their knowledge of fission chain reactions to Enrico Fermi’s experiments with the first nuclear reactor at the University of Chicago in 1942, as well as earlier breakthroughs in nuclear chemistry made by Lise Meitner and Fritz Strassman.

Verbal

Nuclear Chemistry 317
### Section Objectives

<table>
<thead>
<tr>
<th>Section</th>
<th>Objectives</th>
<th>Standards</th>
<th>Activities and Labs</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2 Rates of Nuclear Decay, pp. 298–301</td>
<td><em>10.2.1 Define half-life, and relate half-life to the age of a radioactive sample.</em>&lt;br&gt;<em>10.2.2 Compare and contrast nuclear reaction rates with chemical reaction rates.</em>&lt;br&gt;<em>10.2.3 Describe how radioisotopes are used to estimate the age of materials.</em></td>
<td>A-1, A-2, B-1, B-3</td>
<td>SE Quick Lab: Modeling Half-Life, p. 300&lt;br&gt;TE Teacher Demo: Predicting Decay, p. 299&lt;br&gt;LM Investigation 10A: Modeling Radioactive Decay</td>
</tr>
<tr>
<td>10.3 Artificial Transmutation, pp. 303–305</td>
<td><em>10.3.1 Describe and identify examples of transmutation.</em>&lt;br&gt;<em>10.3.2 Describe how transuranium elements are synthesized.</em>&lt;br&gt;<em>10.3.3 Explain how particle accelerators have been used in scientific research.</em></td>
<td>A-1, A-2, B-1, B-6, E-2, F-1, F-5, G-1, G-2, G-3</td>
<td>SE Quick Lab: Modeling Transmutation, p. 304</td>
</tr>
<tr>
<td>10.4 Fission and Fusion, pp. 308–315</td>
<td><em>10.4.1 Compare and contrast nuclear forces.</em>&lt;br&gt;<em>10.4.2 Describe the process of nuclear fission.</em>&lt;br&gt;<em>10.4.3 Explain how nuclear reactors are used to produce energy.</em>&lt;br&gt;<em>10.4.4 Describe the process of nuclear fusion.</em></td>
<td>A-1, A-2, B-1, E-2, F-1, F-2, F-4, F-5, G-1, G-2, G-3</td>
<td>SE Exploration Lab: Modeling a Chain Reaction, pp. 316–317&lt;br&gt;TE Teacher Demo: Nuclear Processes, p. 311</td>
</tr>
</tbody>
</table>
### RESOURCES

<table>
<thead>
<tr>
<th>Ability Levels</th>
<th>PRINT and TECHNOLOGY</th>
<th>SECTION ASSESSMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>SE Section 10.1</td>
<td>L1 SE Section 10.1 Assessment, p. 297</td>
</tr>
<tr>
<td>L2</td>
<td>RSW Section 10.1</td>
<td>L1 RSW Section 10.1 Assessment, p. 301</td>
</tr>
<tr>
<td>L3</td>
<td>RSW Section 10.2</td>
<td>L1 RSW Section 10.2 Assessment, p. 305</td>
</tr>
<tr>
<td>L1</td>
<td>RSW Section 10.3</td>
<td>L1 RSW Section 10.3 Assessment, p. 315</td>
</tr>
<tr>
<td>L2</td>
<td>RSW Section 10.4</td>
<td>L1 RSW Section 10.4 Assessment, p. 319</td>
</tr>
</tbody>
</table>

### Materials for Activities and Labs

#### Quantities for each group

**STUDENT EDITION**

- **Inquiry Activity**, p. 291
  - green and purple beads

- **Quick Lab**, p. 300
  - 100 1-cm squares of wallpaper, large plastic bag, graph paper

- **Quick Lab**, p. 304
  - periodic table, 2 sheets of unlined white paper, 32 green beads, 32 purple beads

- **Exploration Lab**, pp. 316–317
  - 20 dominoes, watch with a second hand (or stopwatch), metric ruler

#### TEACHER'S EDITION

**Teacher Demo**, p. 294
- medical X-ray image or photograph of a medical X-ray image

**Teacher Demo**, p. 299
- hot plate, 250-mL or 500-mL beaker, glass plate, popcorn, cooking oil

**Build Science Skills**, p. 307
- 500-mL beaker; sponges; shallow pans; food coloring; 1-cm strips of thin and thick cardboard, newspaper, and waxed paper; paper towels

**Teacher Demo**, p. 311
- bubble solution, 2 bubble wands

### Chapter Assessment

**CHAPTER ASSESSMENT**

- SE Chapter Assessment, pp. 319–320
- CUT Chapter 10 Test A, B
- CTB Chapter 10
- TP Chapter 10
- IT Chapter 10

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- Web Code: cca-1100
- Interactive Textbook with assessment at PHSchool.com

**STANDARDIZED TEST PREP**

- SE Chapter 10, p. 321
- IT Diagnose and Prescribe

- Transparencies
- Interactive Textbook
- Presentation Pro CD-ROM
- Internet Resources
Radioactivity is the process in which an unstable atomic nucleus emits radiation in the form of particles and energy. The release of charged particles from a nucleus results in the formation of a different isotope with a different atomic number and/or atomic mass. Unlike stable isotopes, radioisotopes spontaneously decay into other isotopes. Three common types of nuclear radiation are alpha particles, beta particles, and gamma rays. Nuclear radiation can ionize atoms. When cells of living tissue are exposed to nuclear radiation, they may no longer function properly. Nuclear radiation can be monitored using devices such as Geiger counters and film badges.

Half-Life and Radiocarbon Dating

The rate at which radioisotopes undergo nuclear decay is constant for each isotope under all conditions and depends on the number (fraction) of nuclei present. The amount of time required for half the atoms of a sample of a radioisotope to decay is called the half-life of the radioisotope. Carbon-14 is a radioisotope commonly used for this purpose, through a method called radiocarbon dating. The small fraction of carbon atoms in the atmosphere that are carbon-14 has remained roughly constant for thousands of years. The carbon-14 is produced by the interaction of cosmic rays from outer space with Earth’s atmosphere. All living organisms take in carbon, a certain percentage of which is carbon-14. When an organism dies, it no longer takes in carbon-14. The amount of carbon-14 in the dead organism decreases over time as the radioactive carbon undergoes beta decay to form nitrogen-14. Scientists can measure the ratio of carbon-14 to carbon-12 in the remains of the organism, and use this ratio to estimate how long ago the organism died.
Artificial Transmutation  10.3

During nuclear decay, atoms of one element change into atoms of another element. This change is called transmutation. Scientists carry out artificial transmutations by bombarding atomic nuclei with high-energy particles. This process can be used to synthesize transuranium elements (elements with atomic numbers greater than 92), which are not usually found in nature.

Nuclear Forces and Reactions  10.4

The subatomic particles in the nucleus are held together by strong nuclear forces. Repulsive electric forces between protons exist. In small nuclei, the strong nuclear forces are generally much greater than the electric forces. In very large nuclei, however, the opposing nuclear forces become similar in strength, resulting in an unstable nucleus.

A large, unstable nucleus may undergo nuclear fission, in which it splits into two smaller nuclei. Fission releases neutrons and a considerable amount of energy. In the presence of many unstable nuclei, fission can lead to a chain reaction, which can be either uncontrolled or controlled. An atomic bomb explosion is an example of an uncontrolled chain reaction. A controlled chain reaction occurs in the reactor of a nuclear power plant.

Another type of nuclear reaction is called fusion, in which two nuclei combine to form one larger nucleus. Fusion reactions release a tremendous amount of energy. The sun is powered by a fusion reaction in which hydrogen nuclei are fused together to form helium nuclei.

Build Reading Literacy

Sequence

Ordering Events

Strategy  Help students understand and visualize the steps in a process, or the order in which events occur. Sequences frequently involve cause-effect relationships. Readers can construct graphic organizers to help themselves visualize and comprehend a sequence. For most sequences, flowcharts are the graphic of choice. However, cycle diagrams are more appropriate for cycles. Before students begin, locate a description in the text of a several-step process or a chain of causes and effects, such as those in Section 10.4 related to a fission chain reaction (p. 311) or nuclear power generation (p. 314).

Example

1. Have students read the passage, thinking about what takes place first, second, third, and so on. Point out that the text will not always use order words such as first, next, then, and finally.
2. Review the passage, listing the steps or events in order.
3. If the passage describes a chain of steps or events, draw a flowchart on the board, having students tell the sequence of events, steps, or causes and effects, and writing each part of the process in a separate box.

```
[Diagram]
```

4. If the passage describes a cycle, use a cycle diagram to show the sequence.

```
[Diagram]
```

5. Have students locate additional examples of sequential relationships in the text or visuals of the chapter. Students can depict the steps or events using graphic organizers.

See p. 309 for a script on how to use the sequence strategy with students. For additional Build Reading Literacy strategies, see pp. 293 and 304.
10.1 Radioactivity

**Key Concepts**
- During nuclear decay, atoms of one element can change into atoms of a different element altogether.
- Common types of nuclear radiation include alpha particles, beta particles, and gamma rays.
- Nuclear radiation can ionize atoms.
- Devices that are used to detect nuclear radiation include Geiger counters and film badges.

**Vocabulary**
- Alpha particle, p. 292
- Beta particle, p. 294
- Gamma ray, p. 294
- Background radiation, p. 296

10.2 Rates of Nuclear Decay

**Key Concepts**
- Unlike chemical reaction rates, which vary with the conditions of a reaction, nuclear decay rates are constant.
- In radiocarbon dating, the age of an object is determined by comparing the object’s carbon-14 levels with carbon-14 levels in the atmosphere.

**Vocabulary**
- Half-life, p. 299

10.3 Artificial Transmutation

**Key Concepts**
- Scientists can perform artificial transmutations by bombarding atomic nuclei with high-energy particles such as protons, neutrons, or alpha particles.
- Scientists can synthesize a transuranium element by the artificial transmutation of a lighter element.

**Vocabulary**
- Transmutation, p. 303
- Transuranium elements, p. 304
- Quark, p. 305

10.4 Fission and Fusion

**Key Concepts**
- Over very short distances, the strong nuclear force is much greater than the electric forces among protons.
- In nuclear fission, tremendous amounts of energy can be produced from very small amounts of mass.

**Vocabulary**
- Strong nuclear force, p. 308
- Fission, p. 309
- Chain reaction, p. 311
- Critical mass, p. 311
- Fusion, p. 315
- Plasma, p. 315

**Thinking Visually**

**Concept Map** Use information from the chapter to complete the concept map below.
CHAPTER 10

Assessment

Reviewing Content

Choose the letter that best answers the questions or completes the statement.

1. An alpha particle is identical to  
   a. a neutron.  
   b. a helium nucleus.  
   c. an electron.  
   d. a hydrogen nucleus.

2. When a beta particle is emitted, the mass number of a nucleus  
   a. increases by one.  
   b. decreases by one.  
   c. increases by four.  
   d. remains the same.

3. The most penetrating form of nuclear radiation is  
   a. an alpha particle.  
   b. a beta particle.  
   c. a gamma ray.  
   d. an electron.

4. The half-life of cobalt-60 is 5.3 years. What fraction of a sample remains after 21.2 years?  
   a. one half  
   b. one quarter  
   c. one eighth  
   d. one sixteenth

5. Which of the following is a radioisotope commonly used in dating archeological artifacts?  
   a. nitrogen-14  
   b. carbon-12  
   c. uranium-235  
   d. carbon-14

6. Transmutation does not occur in which of these nuclear processes?  
   a. nuclear fission  
   b. nuclear fusion  
   c. alpha decay  
   d. gamma decay

7. Based on its location on the periodic table, an element that is not naturally occurring is  
   a. terbium (Tb).  
   b. curium (Cm).  
   c. holmium (Ho).  
   d. lutetium (Lu).

8. Nuclear particles are held together by  
   a. the strong nuclear force.  
   b. electrical attraction.  
   c. quarks.  
   d. electrical repulsion.

9. Nuclear power plants generate electricity from  
   a. nuclear fusion.  
   b. nuclear fission.  
   c. combustion.  
   d. radioactivity.

10. The primary reaction inside stars changes  
    a. hydrogen to helium.  
    b. helium to hydrogen.  
    c. uranium to plutonium.  
    d. nitrogen to carbon.

Understanding Concepts

11. How do radioisotopes of an element differ from other isotopes?  
12. What is the effect on the mass number and charge of a nucleus when it loses an alpha particle?  
13. How do the mass number and charge of a nucleus change when it emits a gamma ray?  
14. Which type of radiation—alpha, beta, or gamma—is most dangerous to living things? Explain.

Understanding Concepts (continued)

Understanding Concepts

11. Unlike stable isotopes, radioisotopes decay spontaneously by emitting nuclear radiation.  
12. The mass number decreases by four; the charge decreases by two.  
13. The mass number and charge are unchanged.  
14. Gamma rays are more dangerous than alpha particles or beta particles because they can penetrate deep inside the body. However, if alpha particles are inhaled or ingested, they can also be dangerous.  
15. The Geiger counter is detecting background radiation.  
16. Temperature has no effect on rates of nuclear decay.  
17. The amount of carbon-14 remaining after 50,000 years is too low to be easily measured.  
18. $^{15}$N + $^{4}$He $\rightarrow$ $^{17}$O + $^{1}$H  
19. Fission and fusion are both nuclear reactions that convert small amounts of matter into large amounts of energy. In fission, a large nucleus is split into two smaller fragments. In fusion, two light nuclei are fused into a larger nucleus. Unlike nuclear fission, which is used widely as a source of electrical energy, nuclear fusion has yet to be developed into a reliable alternate energy source.  
20. In order to sustain a nuclear chain reaction, each fission reaction must on average produce a neutron that subsequently causes another fission.  
21. During nuclear reactions, a small amount of matter is converted into a large amount of energy. During chemical reactions, matter is not converted into energy.  
22. Control rods regulate the nuclear chain reaction by absorbing neutrons produced by fission reactions that take place in the reactor.

Homework Guide

<table>
<thead>
<tr>
<th>Section</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>1-3, 11-17, 24-26, 31, 33</td>
</tr>
<tr>
<td>10.2</td>
<td>4-5, 27-30</td>
</tr>
<tr>
<td>10.3</td>
<td>6-7, 18, 23</td>
</tr>
<tr>
<td>10.4</td>
<td>8-10, 19-22, 32</td>
</tr>
</tbody>
</table>

Nuclear Chemistry 319
23. U-238 to Th-234, alpha; Th-234 to Pa-234, beta and gamma; Pa-234 to U-234, beta and gamma; U-234 to Th-230, alpha; Th-230 to Ra-226, alpha and gamma; Ra-226 to Rn-222, alpha and gamma.
24. Polonium undergoes alpha decay. Bismuth and lead undergo either beta decay or beta decay and gamma decay.
25. Beta radiation or gamma radiation. The plastic or paper wrapped around the film blocks exposure to alpha radiation.
26. Curium-242

Math Skills
27. 12.3 years
28. 22.1 grams
29. 11,460 years (equivalent to two half-lives of carbon-14)

Concepts in Action
30. Radioisotopes used as radioactive tracers have short enough half-lives so as to limit the patient’s exposure to nuclear radiation, but long enough half-lives to permit the diagnostic test.
31. Because radon-222 is a gas, it can be ingested by breathing and cause internal radiation exposure. Americium-241 is a solid that cannot be ingested by breathing.
32. Fusion releases more energy than fission, uses a more available fuel source (hydrogen), and does not produce radioactive wastes.
33. Radon is a naturally occurring radioactive gas produced by the nuclear decay of uranium found in rocks and soil. Because it is a gas, radon can seep into a building through cracks and pinholes in the building’s foundation. If the basement of the building is not ventilated properly, the radon can continue to accumulate, increasing the risk of radiation exposure.

Critical Thinking
Use the figure below to answer Questions 23 and 24.

23. Classifying In the illustrated uranium-238 decay sequence, classify the type of radiation released in each of the transmutations from uranium-238 to radon-222.
24. Making Generalizations Study the sequence of decay from radon-222 to lead-206. Make a generalization as to what type of decay lead, polonium, and bismuth undergo until stable lead-206 is formed.

25. Inferring A film badge consists of a piece of film wrapped in a piece of dark plastic or paper. Doses of what kinds of radiation can be measured with this simple piece of equipment? Explain.
26. Calculating The first sample of californium was made by bombarding a target isotope with alpha particles. In addition to californium-243, the reaction produced a neutron. What was the target isotope?

Math Skills
27. Calculating After 36.9 years, a sample of hydrogen-3 contains one eighth of the amount it contained originally. What is the half-life of the isotope?

28. Calculating The half-life of iron-59 is 44.5 days. After 133.5 days, 2.76 g of iron-59 remains. What was the mass of the original sample?
29. Inferring The beta emissions from a bone that was found buried in a cave indicate that there are 4.6 carbon-14 decays per gram of carbon per minute. A chicken bone from a fast-food restaurant shows 18.4 emissions per gram of carbon per minute. How old is the bone from the cave?

Performance-Based Assessment

30. Inferring Radioisotopes are commonly used in medical tests to diagnose diseases. Do the radioisotopes used for this purpose have long half-lives or short half-lives? Explain.
31. Applying Concepts Americium-241 and radon-222 both emit alpha particles. Americium is found in almost every home as a component of smoke detectors. But radon is considered a health hazard. Why is radon more hazardous?
32. Making Judgments If a fusion power plant could be constructed, why might it be a better source of energy than a fission plant?
33. Writing in Science Write a paragraph explaining how radon gas can collect in buildings. (Hint: The first sentence in your paragraph should state the paragraph’s main idea.)

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Choose the letter that best answers the question or completes the statement.

1. Which equation correctly shows beta decay?
   (A) \( ^{207}\text{Pb} \rightarrow ^{207}\text{Tl} + e^- + \gamma \)
   (B) \( ^{207}\text{Pb} \rightarrow ^{207}\text{Bi} + e^- + \gamma \)
   (C) \( ^{207}\text{Pb} \rightarrow ^{207}\text{Bi} + e^- + \gamma \)
   (D) \( ^{207}\text{Pb} \rightarrow ^{207}\text{Bi} + e^- + \gamma \)

2. The half-life of radon-222 is 3.8 days. If a sample currently has 3.1 grams of radon-222, how much radon-222 did this sample have 15.2 days ago?
   (A) 12.4 grams  
   (B) 47.1 grams  
   (C) 49.6 grams  
   (D) 57.8 grams  
   (E) 92.7 grams

3. Radioactive decay of nuclei often involves several decays before a stable nucleus is formed. This is called a decay chain. What stable isotope is formed when radon-222 undergoes a decay chain of four alpha decays followed by four beta decays?
   (A) tungsten-206  
   (B) platinum-206  
   (C) lead-206  
   (D) tungsten-214  
   (E) lead-214

4. Which nucleus balances the following nuclear equation for the fission of uranium-235?
   \( ^{235}\text{U} + ^{1}\text{n} \rightarrow ^{135}\text{Sr} + ^{94}\text{Kr} + 2\gamma \)
   (A) \( ^{90}\text{Xe} \)  
   (B) \( ^{110}\text{Te} \)  
   (C) \( ^{136}\text{Te} \)  
   (D) \( ^{136}\text{Xe} \)  
   (E) \( ^{136}\text{Sn} \)

5. Uranium-238 is less stable than oxygen-16. What accounts for this difference?
   (A) Uranium is a solid, while oxygen is a gas.  
   (B) Unlike oxygen-16, uranium-238 has a nucleus in which repulsive electric forces surpass the strong nuclear forces.  
   (C) Oxygen-16 has fewer electrons than uranium-238.  
   (D) Uranium-238 has fewer neutrons than oxygen-16.  
   (E) Unlike uranium-238, oxygen-16 has a nucleus in which the strong nuclear forces are overcome by repulsive electric forces.

6. The primary source of energy in stars is the fusion of hydrogen into helium. However, another reaction is believed to occur simultaneously. It is called the carbon-nitrogen-oxygen (CNO) cycle. In the diagram below, the symbol \( e^+ \) represents a positron. A positron is a particle that has the same mass as an electron but a charge of 1+.

Which equation describes the CNO cycle?
   (A) \( ^{1}\text{H} \rightarrow ^{1}\text{He} + e^+ \)  
   (B) \( ^{4}\text{He} \rightarrow ^{1}\text{He} + 2e^+ \)  
   (C) \( ^{1}\text{H} + ^{1}\text{H} \rightarrow ^{1}\text{He} + e^+ \)  
   (D) \( ^{12}\text{C} \rightarrow ^{13}\text{C} + e^+ \)  
   (E) \( ^{13}\text{N} + ^{1}\text{H} \rightarrow ^{14}\text{C} + ^{1}\text{He} \)