Chapter 7

The atomic theory explains radioactivity.

Radioactive elements release energy as a result of changes in their nuclei. In the photograph shown here, radioactive iron-59 is used to make an image of the circulatory system in a hand. The iron-59 releases a tiny amount of energy. Sensitive equipment detects the energy and makes the image. In modern medicine, radioactive substances are also used to treat cancer cells. Medical imaging and cancer treatments are two of the many uses we have for radioactivity.

What You Will Learn

In this chapter, you will
- **define** isotopes in terms of atomic number and mass number
- **relate** radioactive decay to changes in the nucleus
- **explain** half-life using rates of radioactive decay
- **compare** fission and fusion
- **illustrate** radioactive decay, fission, and fusion using nuclear equations

Why It Is Important

Our understanding of the uses and effects of nuclear reactions continues to grow. Issues related to the production and use of nuclear energy are frequent topics in news, international politics, industry, and the diagnosis and treatment of disease.

Skills You Will Use

In this chapter, you will
- **model** changes in isotopes during radioactive decay, fission, and fusion
- **write** nuclear equations
- **model** and **graph** a half-life curve for a radioisotope
- **interpret** information related to absolute dating using isotopes, such as carbon-14

FOLDABLES™
Reading & Study Skills

Shutter Fold

STEP 1 Begin as if you were going to make a hamburger but instead of creasing the paper, pinch it to show the midpoint.

STEP 2 **Fold** the outer edges of the paper to meet at the pinch, or mid-point, forming a shutter fold.

Vocabulary Book

STEP 1 **Fold** a sheet of notebook paper in half like a hotdog.

STEP 2 On one side, **cut** every third line. This results in ten tabs on wide ruled notebook paper and twelve tabs on college ruled.

STEP 3 **Label** the tabs and **record** information beneath.

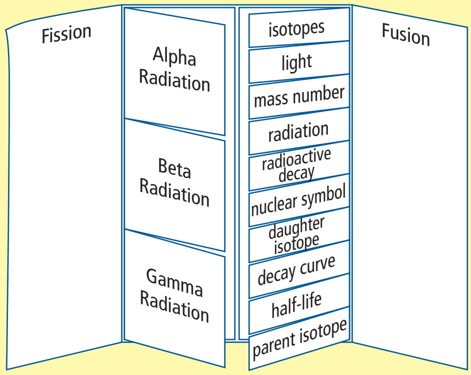
Three-tab Book

STEP 1 **Fold** a sheet of paper like a hot dog.

STEP 2 With the paper horizontal, and the fold of the hot dog up, **fold** the right side toward the center, trying to cover one half of the paper.

STEP 3 **Fold** the left side over the right side to make a book with three folds.

STEP 4 **Open** the folded book. Place your hands between the two thicknesses of paper and **cut** up the two valleys on one side only. This will form three tabs.



7.1 Atomic Theory, Isotopes, and Radioactive Decay

Radiation refers to high-energy rays and particles emitted by radioactive sources. Isotopes are atoms of the same element that differ in the number of neutrons in the nucleus. Radioisotopes are natural or human-made isotopes that decay into other isotopes, releasing radiation. The three major types of radiation are alpha particles, beta particles, and gamma rays. A nuclear reaction occurs when the number of neutrons or protons in a nucleus changes, or when radiation is released from the nucleus. Radioactivity results when the nucleus of an atom decays. If the atom emits one or more protons as it decays, the atom changes into an atom of another element.

Words to Know

alpha particle
beta particle
gamma radiation
isotopes
light
mass number
radiation
radioactive decay

Did You Know?

Trace amounts of radiation from the following sources can be found in food and water that we consume.

- radioactive substances in Earth's crust
- radioactive gas released from Earth's crust
- cosmic rays from outer space that bombard Earth

Imagine you discover that a certain type of rock emits invisible high-energy rays. Then, on further investigation, you find that several other types of rocks also emit high-energy rays. Suppose that with more investigation you discover that high-energy rays are emitted by the ground, by buildings, by humans, and even by the air around you. What explanation could you offer for the source of this energy?

Radioactivity is the release of high-energy particles and rays of energy from a substance as a result of changes in the nuclei of its atoms. We can use radioactivity to improve our lives, such as through medical diagnoses and treatments and by generating electricity.

The stream of high-energy, fast-moving particles or waves that is found in our environment is called **natural background radiation**. Background radiation has the potential to interact with an atom and turn it into an ion.

Radiation refers to high-energy rays and particles emitted by radioactive sources. Radiation includes radio waves, microwaves, infrared rays, visible light, and ultraviolet rays (Figure 7.1). Although most forms of radiation are invisible to the human eye, they are present all around us all the time. **Light** is one form of radiation that is visible to humans.

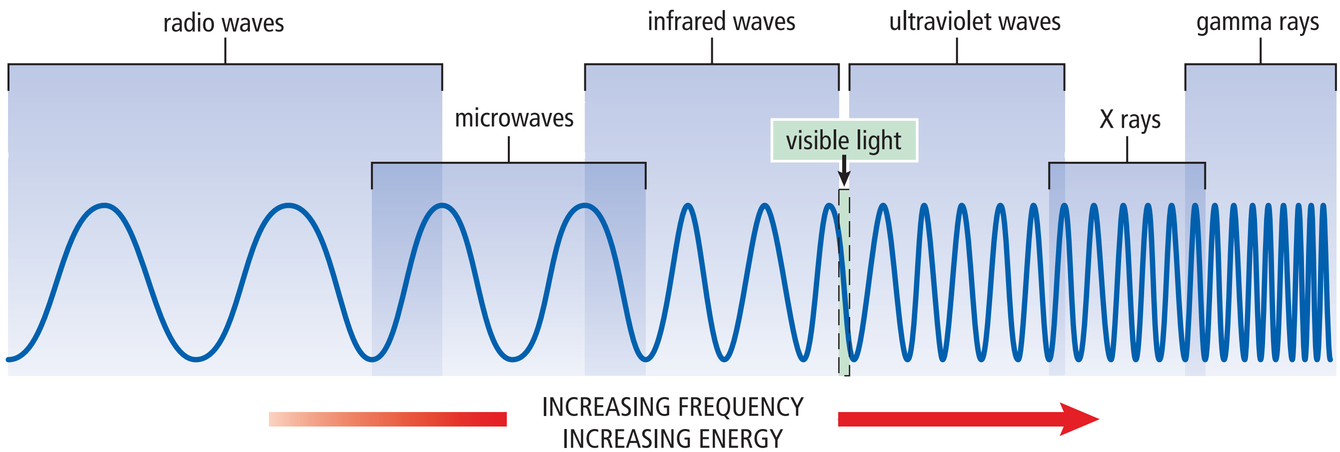


Figure 7.1 The electromagnetic spectrum

7-1A Detecting Radiation

Find Out ACTIVITY

Teacher Demonstration

Many common materials have a small degree of radioactivity. How is radiation measured? In this activity, your teacher will use an instrument known as a Geiger-Müller counter (GM counter) to detect the radiation in several samples and in your classroom.

Materials

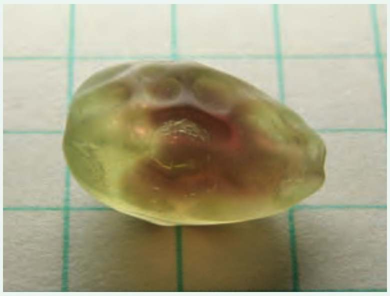
- Geiger-Müller counter
- slightly radioactive materials, which may include Vaseline glass bead, salt substitute (contains potassium), old radium-style watch (1950s era)
- sheets of paper, aluminum foil, lead

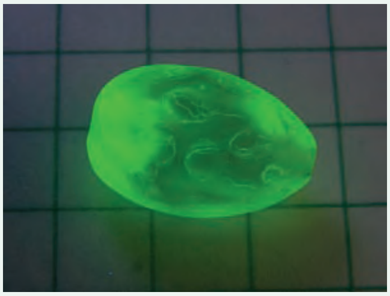
What to Do

1. Design a two-column table that you can use to record your observations. Give your table a title.
2. Your teacher will use the GM counter to measure a selection of radioactive materials and materials that may shield the radiation. Record your observations of each material tested.

What Did You Find Out?

1. How could you demonstrate that a natural level of background radiation exists in your home?
2. Which kinds of materials are effective in shielding radiation from the samples you examined?





Vaseline glass contains a small amount of uranium oxide, making it slightly radioactive.

Searching for Invisible Rays

In 1895, German physicist Wilhelm Roentgen (1845–1923) discovered that an unknown kind of energy was emitted from certain materials when he bombarded them with electrons. These invisible rays could darken photographic film, just like visible light rays could. He called the newly discovered energy X rays, where X stood for "unknown."

Roentgen's work led to the discovery of radioactivity by a French physicist who found himself in the right place at the right time, with a prepared mind. The scientist's name was Henri Becquerel (1852–1908). Becquerel discovered by chance that uranium salts emitted rays that darkened photographic plates (Figure 7.2). This surprised Becquerel because, up to this point, scientists had found evidence of the high-energy rays only when they first directed some sort of radiation onto the material.

Word Connect

The word "radiation" comes from the word radiate, which means to spread out in all directions from a central point. The combining form "radio-" is related to radiant energy.

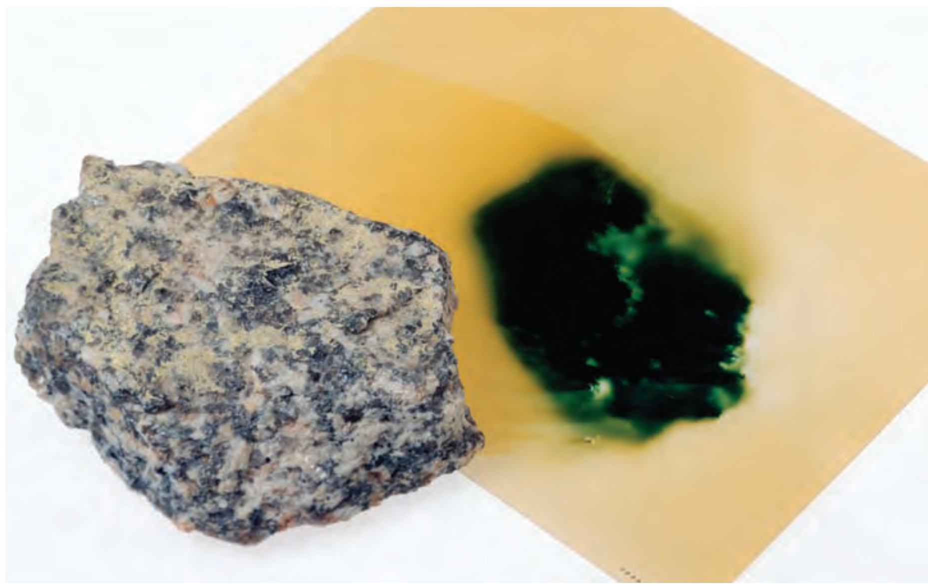


Figure 7.2 A rock containing uranium salts causes photographic film to be exposed. This is evidence that the rock is radioactive. In this example, the radioactivity is coming from the uranium atoms in the rock.

Figure 7.3 Marie Curie is considered one of the greatest scientists in history.

Chemist Marie Curie (1867–1934) (Figure 7.3) and her husband Pierre Curie (1859–1906) used Becquerel's mineral sample and isolated the components emitting the rays. They concluded that the darkening of the photographic plates was due to rays emitted from the uranium atoms present in the mineral sample. Marie Curie called this process radioactivity. Figure 7.4 on the next page shows the darkening of photographic film that is exposed to radiation emitted by radium salts.

The work of Marie and Pierre Curie was extremely important in explaining radioactivity and developing the field of nuclear chemistry. In 1898, the Curies identified two new elements, polonium and radium. Henri Becquerel and the Curies shared the 1903 Noble Prize in physics for their work. Marie Curie also received the 1911 Nobel Prize in chemistry for her work with polonium and radium. She is one of only four people to have won two Nobel prizes.

Did You Know?

Marie Curie named polonium after her home country, Poland.

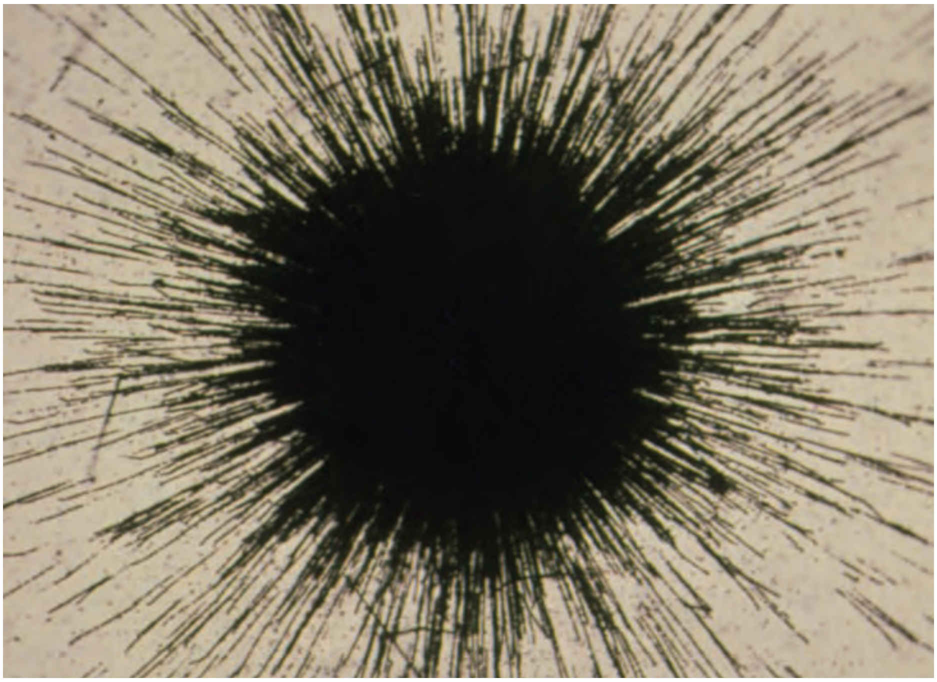


Figure 7.4 Radium salts are placed on a photographic plate. After the plate is developed, the photograph shows the dark traces left by radiation emitted by the radium salts.

Isotopes and Mass Number

Which elements are radioactive? Why are different types of radiation emitted by radioactive nuclei? To answer these questions, you need to first know about isotopes.

Isotopes are different atoms of a particular element that have the same number of protons but different numbers of neutrons. All isotopes of an element have the same atomic number (number of protons). However, since the number of neutrons differs, the mass number and atomic mass differ from one isotope to the next. The **mass number** is an integer (whole number) that represents the sum of an atom's protons and neutrons. The mass number of an isotope is found by adding the atomic number to the number of neutrons.

Mass number = atomic number + number of neutrons

Word Connect

"Isotope" comes from the Greek words *isos*, meaning equal, and *topos*, meaning place. All the isotopes for a particular element are represented by the same box or place on the periodic table. For example, chlorine-35 and chlorine-37 are both represented by the same place (atomic number 17) on the periodic table.

Number of protons and neutrons

You may remember from Chapter 4 that the atomic number is found by counting the number of protons. To find the number of neutrons of an isotope, subtract the atomic number from the mass number.

Number of neutrons = mass number − atomic number

Different isotopes of the same element have the same element symbol. For example, all isotopes of potassium have the symbol K, indicating the same number of protons, even though different numbers of neutrons can be found in the nucleus of different potassium isotopes. You can use the mass number to tell different isotopes apart.

Representing Isotopes

Chemists represent isotopes using standard atomic notation, which is a shortened form involving the chemical symbol, atomic number, and mass number. The mass number is written as a superscript (above) on the left of the symbol. The atomic number is written as a subscript (below) on the left (Figure 7.5). For example, potassium has three naturally occurring isotopes: potassium-39, potassium-40, and potassium-41 (Table 7.1). The standard atomic symbols for these three isotopes of potassium are ${}^{39}_{19}K$, ${}^{40}_{19}K$, and ${}^{41}_{19}K$. Another name for the standard atomic symbol is the **nuclear symbol**.

$${}^{39}_{19}\mathrm{K}$$

Figure 7.5 In standard atomic notation, the mass number (39) is written above the atomic number (19).

Table 7.1 Isotopes of Potassium

	Potassium-39	Potassium-40	Potassium-41
Protons (nucleus)	19	19	19
Neutrons (nucleus)	20	21	22
Electrons (in shells)	19	19	19

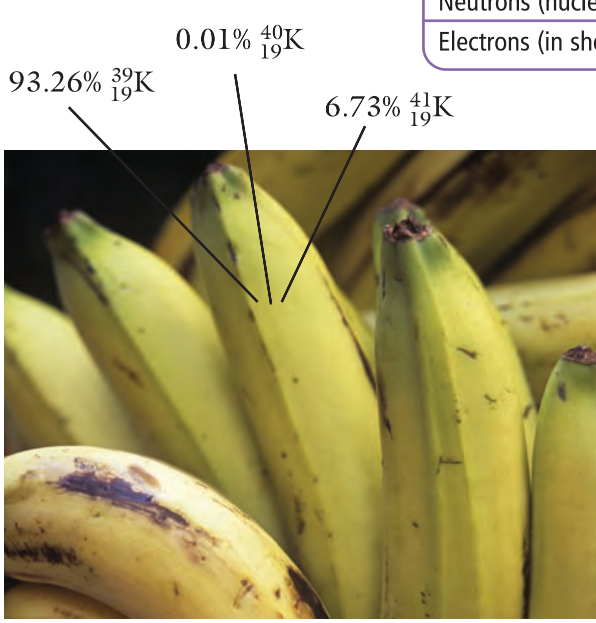


Figure 7.6 Each banana has the same relative abundance of potassium isotopes.

In nature, most elements are found as a mixture of isotopes. Usually, no matter where a sample of an element is taken from, the percentage of each isotope is constant. For example, in a banana, which is a rich source of potassium, approximately 93.26 percent of the potassium atoms will have 20 neutrons, 0.01 percent will have 21 neutrons, and 6.73 percent will have 22 neutrons (Figure 7.6). In another banana or in a totally different source of potassium, the percentage composition of the potassium isotopes will still be about the same.

Reading Check

1. Why was the discovery that uranium salts emitted radiation a surprise to scientists?
2. What did Marie Curie call the process by which some materials give off radiation such as X rays?
3. What is meant by the term "isotope"?
4. (a) What do all isotopes of the same element have in common?
   (b) How do isotopes of the same element differ?
5. What information about the nucleus of an isotope is given by its mass number?

Did You Know?

The atomic mass of an element shown in the periodic table is a decimal number. Atomic mass is an average of the masses of all the isotopes of that element.

Practice Problems

1. Copy and complete the following chart in your notebook.

Isotope	Atomic number (number of protons)	Number of Neutrons	Mass Number
neon-21			
silicon-30			
lithium-7			
	13	14	
	3	3	
	6	8	
		13	25
		10	19

2. A laboratory analyzes the composition of the two naturally occurring isotopes of bromine. One of the isotopes has an atomic number of 35 and a mass number of 81. State the following for the isotope.
   (a) number of protons
   (b) number of neutrons
   (c) name of the isotope
   (d) standard atomic notation
3. An element is analyzed and found to have a mass number of 37. An atom contains 20 neutrons in its nucleus. State the following.
   (a) number of protons
   (b) name of the isotope
   (c) standard atomic notation
4. For an isotope containing 16 protons and 17 neutrons, state the following.
   (a) atomic number
   (b) mass number
   (c) name of the isotope
   (d) standard atomic notation

Answers provided on page 592

7-1B Building Bohr Model Atoms and Ions

Think About It

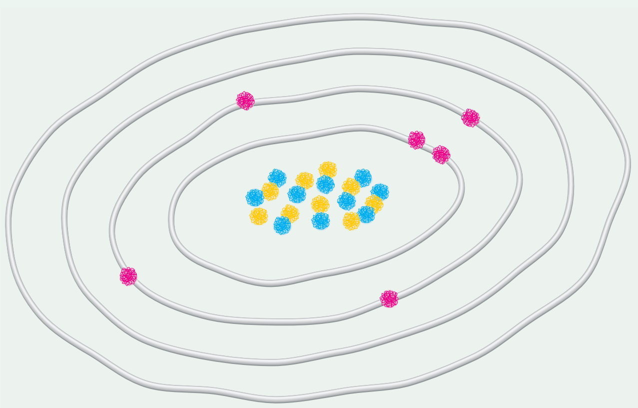
In this activity, you will construct Bohr models of atoms and ions for various isotopes. The centre of your models will represent the nucleus and the strings will represent energy shells. The fur balls are not accurate models of mass or size of subatomic particles. An electron is tiny and has approximately 0.0005 the mass of a proton.

Materials

- 20 of each of three different colours of fur balls
- 4 string loops of increasing length
- periodic table

What to Do

1. Arrange the four string loops one around the other. Decide which colours of fur balls will represent protons, neutrons, and electrons.



Arrange the loops of string around each other on a common centre.

2. Place 9 protons and 10 neutrons in the centre to represent the nucleus. You have just constructed the only stable isotope of fluorine. Complete your model by adding electrons one at a time. Place two on the inner string, paired together. Then put seven electrons on the next string, first placing an electron at each compass point and then pairing electrons. Examine your model. Record the position and number of each type of particle.
3. Build a Bohr model of neon-20 by adding to the Bohr model for fluorine-19. You will have to decide what particle(s) to add in order to make this change. Fluorine-19 and neon-20 are isotopes of different elements. Observe and record their similarities and differences.
4. Add to the Bohr model of neon-20 to create the other two stable isotopes of neon, which are neon-21 and neon-22. The models built in this step are isotopes of the same element. Observe and record their similarities and differences.
5. Build an atom of aluminum-27, showing the correct arrangement of all the subatomic particles. Then, alter the model to show an aluminum ion. The models built in this step are of the same isotope, but one is an atom and the other is an ion. Observe and record their similarities and differences.
6. Build an atom with seven protons, eight neutrons, and the correct number of electrons, arranged correctly. Use a periodic table to help you identify the element that is represented by this model. Record the element.
7. Imagine that all the protons in step 6 became neutrons and the neutrons became protons. Keep the number of electrons unchanged.
   (a) Identify the new element you have made.
   (b) Is the new element an atom or an ion? Why?
8. Construct a Bohr model for a classmate to try to identify. Do not use more than 20 of any subatomic particle. Remember that realistic nuclei with an atomic number lower than 30 have the same or nearly the same number of neutrons and protons.

What Did You Find Out?

1. Describe how to draw a Bohr model of an atom of calcium-42.
2. Explain how to modify a Bohr model of an atom of calcium-42 in order to produce a Ca^{2+} ion involving this isotope.
3. Explain how to modify a Bohr model of an atom of calcium-42 in order to produce an atom of calcium-40.
4. Explain the differences between changing an atom into an ion and changing an atom into a different isotope of the same element.
5. Explain the differences between changing an atom into a different isotope of the same element and changing an atom into an atom of a different element.

Radioactive Decay

Scientists studying radioactivity made an important discovery—that by emitting radiation, atoms of one kind of element can change into atoms of another element. This discovery was a major breakthrough, as no chemical reaction had ever resulted in the formation of new kinds of atoms.

Radioactive atoms emit radiation because their nuclei are unstable (likely to decay). Unstable atoms gain stability by losing energy, and they lose energy by emitting radiation. **Radioactive decay** is the process in which unstable nuclei lose energy by emitting radiation. Unstable radioactive atoms undergo radioactive decay until they form stable non-radioactive atoms, usually of a different element (Figure 7.7). Isotopes that are capable of radioactive decay are called **radioisotopes**.

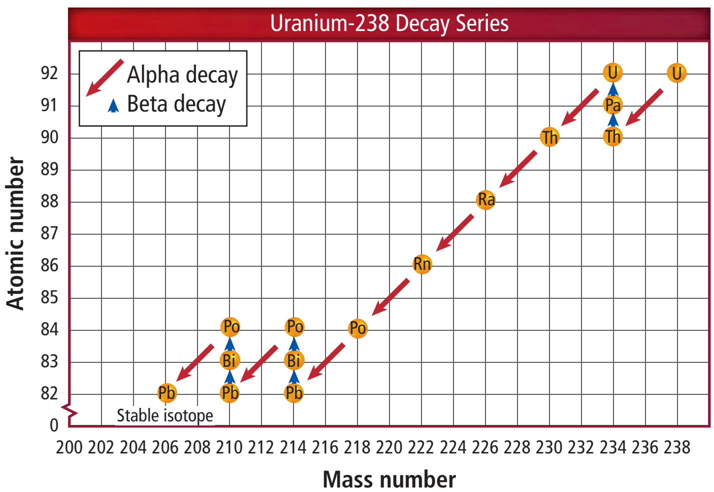


Figure 7.7 Uranium-238 undergoes 14 different radioactive decay steps before forming stable lead-206.

It is not easy to judge by looking at a nuclear symbol for an isotope whether is stable (not likely to decay) or unstable (eventually will decay and therefore is a radioisotope). For example, carbon-12 and carbon-13 are stable, while carbon-14 is not (Table 7.2). You have all three forms of carbon atoms in your body, most of which are carbon-12. Even though only 1 carbon atom in 1 trillion in your body is unstable and can therefore release radiation, this still represents a huge number of carbon-14 atoms.

Table 7.2 Isotopes of Carbon

Isotope Name	Nuclear Symbol	Mass Number (protons + neutrons)	Atomic Number (protons)	Neutrons	Percentage of a Typical Sample of Carbon Atoms
carbon-12 (stable)	${}^{12}_{6}C$	12	6	6	98.9%
carbon-13 (stable)	${}^{13}_{6}C$	13	6	7	1.1%
carbon-14 (unstable)	${}^{14}_{6}C$	14	6	8	1 atom in 1 trillion atoms

Figure 7.8 Ernest Rutherford (1871–1937)

Three Types of Radiation

The three most common types of radiation emitted during radioactive decay were first identified by Ernest Rutherford (Figure 7.8). Rutherford later discovered the nucleus and created a model of the atom. He and his colleagues placed a radioactive source inside a lead block that allowed the radiation to pass out only through a tiny hole. From the hole, the radiation travelled through a slot between electrically charged plates that deflected any electrically charged particles (Figure 7.9). The positively charged particles were deflected toward the negative plate. Rutherford called these positively charged particles alpha particles. The negatively charged particles, called beta particles, were deflected towards the positive plate. A third type of radiation, gamma radiation, has no electric charge, and so passed right through the electric field unaffected.

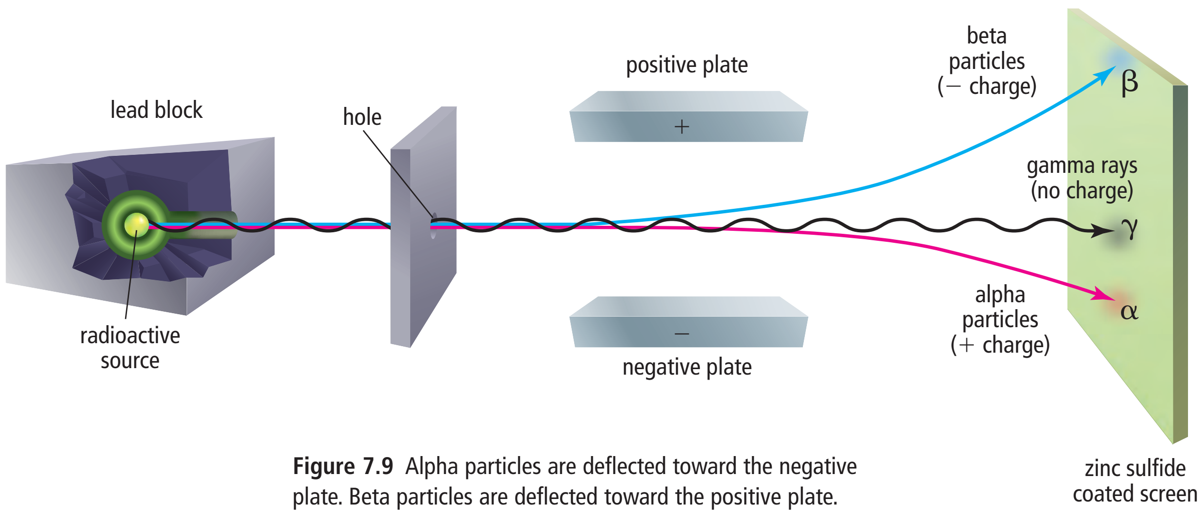


Figure 7.9 Alpha particles are deflected toward the negative plate. Beta particles are deflected toward the positive plate. Gamma radiation is not deflected by the electric field.

Did You Know?

Ernest Rutherford received a Nobel Prize for his investigations into the disintegration of the elements and the chemistry of radioactive substances. He performed many of the experiments that led to the prize while working at McGill University in Montreal. A Canadian stamp honours his work on radioactivity conducted in Canada.

Alpha Radiation

Since Rutherford's discovery, scientists have continued to study radiation. We now understand more about how radiation is emitted.

Alpha radiation is a stream of alpha particles. **Alpha particles** are positively charged atomic particles that are much more massive than either beta particles or gamma radiation. An alpha particle has the same combination of particles as the nucleus of a helium atom. We use the symbols $^{4}_{2}\alpha$ or $^{4}_{2}He$ to represent an alpha particle. The symbols show an alpha particle has a mass number of 4 and an atomic number of 2, which means an alpha particle is composed of two protons and two neutrons. Because it has two protons, an alpha particle has an electric charge of 2+. Because of their mass and charge, alpha particles are relatively slow-moving compared with other types of radiation. Alpha particles are not very penetrating—a single sheet of paper stops alpha particles.

The emission of an alpha particle from a nucleus is a process called **alpha decay** (Figure 7.10).

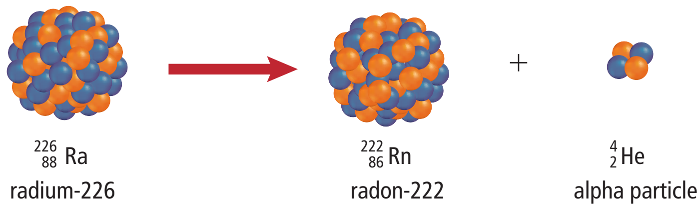


Figure 7.10 The nucleus of an atom of radium-226 contains 88 protons and 138 neutrons. A radium-226 nucleus undergoes alpha decay to form a different element, radon-222, and an alpha particle.

Word Connect

Alpha, beta, and gamma are the first three letters of the Greek alphabet. Rutherford derived the name "proton" from the Greek word *protos*, meaning first. He speculated that there might be more than one particle in the nucleus. The neutron was not discovered until 1932.

Note that the nuclear reaction in Figure 7.10 is balanced. The sum of the atomic numbers (subscripts) and the sum of the mass numbers (superscripts) on each side of the arrow are equal. Also note that, when a radioactive nucleus emits an alpha particle, the product nucleus has an atomic number that is lower by two and a mass number that is lower by four.

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$$

The equation in the example shown above can also be written as:

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

Although a helium nucleus has a 2+ charge (making it $^{4}_{2}\mathrm{He}^{2+}$), it is common practice to omit the charge symbol when representing an alpha particle.

Practice Problems

1. Try the following alpha decay problems yourself. You can refer to the periodic table in Figure 4.3 on page 172.

   (a) $^{208}_{84}\mathrm{Po} \rightarrow$ ____ $+ {}^{4}_{2}\alpha$

   (b) $^{231}_{91}\mathrm{Pa} \rightarrow$ ____ $+ {}^{4}_{2}\mathrm{He}$

   (c) ____ $\rightarrow {}^{221}_{87}\mathrm{Fr} + {}^{4}_{2}\alpha$

   (d) ____ $\rightarrow {}^{192}_{77}\mathrm{Ir} + {}^{4}_{2}\alpha$

   (e) ____ $\rightarrow {}^{207}_{85}\mathrm{At} + {}^{4}_{2}\mathrm{He}$

Answers provided on page 592

Beta Radiation

A **beta particle** is an electron. We can use the symbol ${}^{0}_{-1}\beta$, or ${}^{0}_{-1}e$, to represent a beta particle. The mass of an electron is about 0.0005 the mass of a proton or a neutron, so the beta particle is assigned a mass number of zero. A beta particle has an electric charge of 1−. Because beta particles are both lightweight and fast-moving, they have a greater penetrating power than alpha particles. A thin sheet of aluminum foil can block beta particles.

Some atoms undergo beta decay. In **beta decay**, a neutron changes into a proton and an electron. During beta decay, the proton remains in the nucleus while the electron shoots out from the nucleus with a lot of energy. Since the proton remains in the nucleus, the atomic number of the element increases by one—it has become an atom of the next higher element on the periodic table. The mass number of the resulting isotope does not change because the neutron has been replaced by a proton of almost equal mass.

Example: ${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\beta$

Since a beta particle is an electron that has just been ejected from a nucleus, the equation in the example shown above can also be written in the following form, which means the same thing.

Example: ${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}e$

Did You Know?

Iodine-131 therapy is not used only for humans. Cats with thyroid cancer may receive the treatment as well.

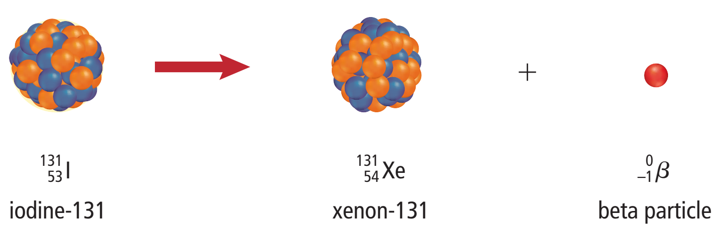


Figure 7.11 The beta particle that is emitted during beta decay has high energy and can penetrate human skin and damage cells.

Figure 7.11 shows the decay of an iodine-131 nucleus, emitting a beta particle. The mass number stays the same, but the atomic number increases by one, producing the element xenon. The iodine-131 isotope is used in the treatment of cancer of the thyroid gland, a small gland in your neck that helps control how your body uses energy (Figure 7.12).

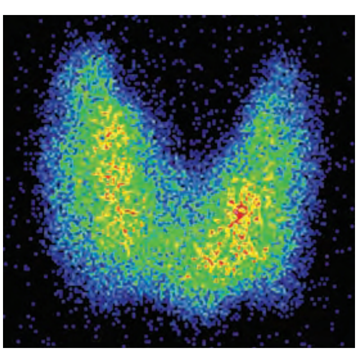


Figure 7.12 Iodine is taken up quickly by the thyroid.

Practice Problems

1. Try the following beta decay problems yourself. You can refer to the periodic table in Figure 4.3 on page 172.

(a) ${}^{14}_{6}\text{C} \rightarrow$ ____ $+ {}^{0}_{-1}\beta$

(b) ${}^{6}_{2}\text{He} \rightarrow$ ____ $+ {}^{0}_{-1}\beta$

(c) ${}^{24}_{11}\text{Na} \rightarrow$ ____ $+ {}^{0}_{-1}e$

(d) ____ $\rightarrow {}^{201}_{80}\text{Hg} + {}^{0}_{-1}\beta$

(e) ____ $\rightarrow {}^{52}_{27}\text{Co} + {}^{0}_{-1}\beta$

(f) ____ $\rightarrow {}^{42}_{20}\text{Ca} + {}^{0}_{-1}e$

Answers provided on page 592

Gamma Radiation

Gamma radiation consists of rays of high-energy, short-wavelength radiation (Figure 7.13). Gamma radiation is represented by the symbol ${}^{0}_{0}\gamma$. Because gamma radiation has almost no mass and no charge, the release of gamma radiation does not change the atomic number or the mass number of a nucleus.

If you turn back to Figure 7.1 on page 287, you will notice that gamma rays are the highest energy form of electromagnetic radiation. Gamma rays have much more energy than ultraviolet rays or X rays and are more dangerous than other forms of electromagnetic radiation. Gamma radiation has the greatest penetrating power of the three types of radiation. Thick blocks of dense materials, such as lead and concrete, are needed to stop gamma rays.

Gamma decay results from a redistribution of energy within the nucleus. A high-energy gamma ray is given off as the isotope falls from a high-energy state to a lower energy state. For example, high-energy nickel-60 can decay to nickel-60 by gamma decay:

$${}^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{0}\gamma$$

The "*" means that the nickel nucleus has extra energy. This extra energy is released as a gamma ray. Many kinds of radioactive decay can release gamma rays. For example, gamma rays accompany the alpha decay of uranium-238.

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

The 2 in front of the γ symbol indicates that two gamma rays are emitted.

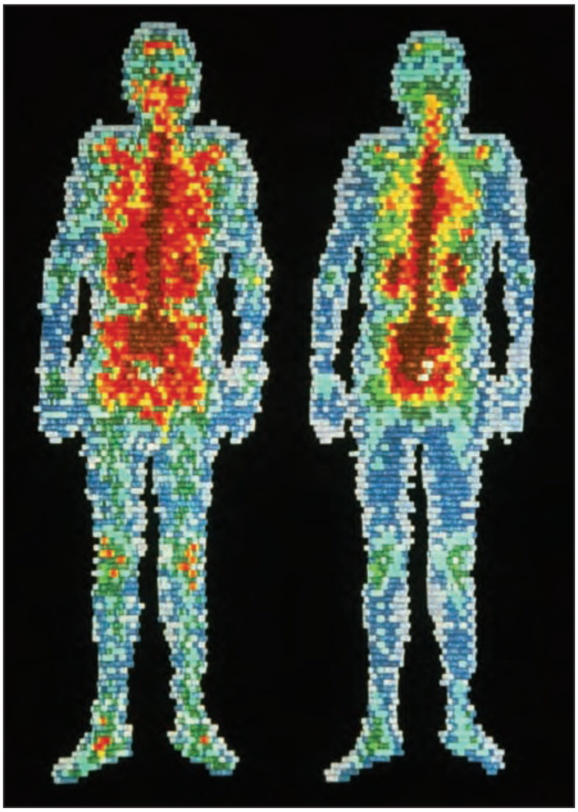


Figure 7.13 Front (right) and back views of a man injected with a radioisotope that concentrates in the bones. The scans are coloured according to the strength of the gamma radiation, ranging from blue for the lowest emission through to brown for the highest emission.

Reading Check

1. What is radioactive decay?
2. What is a radioisotope?
3. What are the names of the three main types of radiation?
4. What is the electric charge of each of the three kinds of radioactive decay?
5. List the symbols used for:
   (a) alpha radiation (two symbols)
   (b) beta radiation (two symbols)
   (c) gamma radiation

Suggested Activity

Think About It 7-1C on page 299

Radiation and Radioactive Decay Summaries

Some isotopes release alpha, beta, and gamma radiation all at once. The properties of alpha, beta, and gamma radiation are summarized below in Table 7.3. A summary of radioactive decay processes is shown below in Table 7.4.

Table 7.3 Properties of Alpha, Beta, and Gamma Radiation

Property	Alpha Radiation	Beta Radiation	Gamma Radiation
Symbol	${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e$	${}^{0}_{0}\gamma$
Composition	Alpha particles	Beta particles	High-energy electromagnetic radiation
Description of radiation	Helium nuclei, ${}^{4}_{2}He$	Electrons	High energy rays
Charge	2+	1−	0
Relative penetrating power	Blocked by paper	Blocked by metal foil or concrete	Partly or completely blocked by lead

Table 7.4 Summary of Radioactive Decay Processes

	Alpha Decay	Beta Decay	Gamma Decay
Particle emitted	${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e$	${}^{0}_{0}\gamma$
Change in mass number of starting nucleus	Decreases by 4	No change	No change
Change in atomic number of starting nucleus	Decreases by 2	Increases by 1	No change

Nuclear equations for radioactive decay

A **nuclear equation** is a set of symbols that indicates changes in the nuclei of atoms during a nuclear reaction. The symbols used in a nuclear equation include element symbols (including atomic number and mass number) and symbols representing neutrons and electrons. Like a chemical equation, a nuclear equation shows reactants on the left and products on the right. The reactants and products are separated by an arrow, which means produces or changes into.

You can use a nuclear equation to show changes in the nucleus due to radioactivity. When you write a nuclear equation, you need to include the mass number and the atomic number of every particle and every nucleus participating in the change. Remember the following rules when you write a nuclear equation.

1. **The sum of the mass numbers does not change.** Even when a neutron changes into a proton and an electron or when a large nucleus splits into smaller ones releasing protons ($^{1}_{1}p$) or neutrons ($^{1}_{0}n$) or gamma rays, the total number of protons plus neutrons remains the same.
2. **The sum of the charges in the nucleus does not change.** The atomic number of an element represents the total (positive) charge in a nucleus. Each nuclear symbol, including electrons and neutrons, has a number in the bottom left. The charge number does not change across a nuclear reaction.

Explore More

Some of the natural background radiation on Earth is caused by exposure to radon, a radioactive gas that seeps from Earth's crust and is present in the air we breathe. This is a problem in some British Columbia communities. Find out more about radon and its presence in our environment. Start your search at **www.bcscience10.ca**.

7-1C Modelling Radioactive Decay

Think About It

In this activity, you will compare radioactive decay to changes in the nucleus. You will build models to represent the isotopes of different elements and then model alpha, beta, and gamma decay. You do not need to show the electrons that exist in energy shells surrounding the nucleus as they do not take part in radioactive decay.

Materials

- small objects, such as foam balls, paper clips, and cloth balls to represent subatomic particles

What to Do

1. Work with a partner or in a small group to build the nuclei of three of the isotopes of carbon. They are carbon-12, carbon-13, and carbon-14. If you are not sure how many of each particle is in each nucleus, refer to Table 7.2, on page 293. Compare the three isotopes. What do they have in common? What makes them different from each other?
2. Build a model of an alpha particle. An alpha particle is made of two protons and two neutrons.
3. Select a particle to represent an electron. An electron is not composed of parts, so it should be represented by a single foam ball or other object. Represent a gamma ray with a long piece of paper with a wave drawn on it labelled "gamma ray."
4. Draw sketches to represent the following nuclear decay reactions. Discuss your sketches with other members of the class or your teacher. Make sure you can explain each part of the sketch.
   Alpha decay: $^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$
   Beta decay: $^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$
   Gamma decay: $^{60}_{28}\text{Ni}^{*} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{0}\gamma$
5. Clean up and put away all your materials.

What Did You Find Out?

1. How is the mass number of an element determined?
2. How did you represent a large nucleus such as radium-226?
3. Why does an alpha particle have a positive charge?
4. How does beta decay result in the production of an element with one more proton than the nucleus started out with?
5. Since gamma rays are not made of matter, how can they be detected?

Wild, Weird, Wonderful

www Science

Fake Money, Real Isotopes

In law enforcement, tracking down counterfeiters, and tracing the origins of illegal substances, there is a new tool in the toolkit: isotope analysis.

Isotopes are atoms of the same element that are chemically identical but which have slightly different weights because they have different numbers of neutrons in the nucleus. For example, carbon-13 is heavier than carbon-12 but lighter than carbon-14. A device called a mass spectrometer can sort out isotopes of the same element. Investigators use a mass spectrometer to compare the amount of carbon-13 isotope to the amount of carbon-12 isotope in a sample. This ratio changes depending on the water content of the soil and the metabolism of the plant. In other words, different plants can have ratios that reflect the growth environment. The differences show up in chemicals that come from plants, such as in illicit drugs like cocaine and heroin.

Cocaine is a chemical derived from the coca plant. The coca plant gets its nutrients from the soil it is planted in. Different soil types have slightly different amounts of isotopes of elements such as carbon and nitrogen. This difference acts like a fingerprint. Investigators can analyze isotopes to determine whether the coca plant grew in Bolivia, Colombia, or Peru.

The powerful drug morphine is refined from opium, which comes from the poppy plant. Heroin is made from morphine. Analyzing the ratio of carbon-12 to carbon-13 and then comparing to data bases can determine whether the poppies grew in Asia, South America, or Mexico, for example. The rate at which plants take up isotopes changes depending on environmental conditions in different parts of the world.

Drug law enforcement officers use isotope analysis to understand where illicit drugs come from and to focus their resources appropriately. Isotope analysis is also used in other areas of law enforcement. Since explosives are made from chemicals that also contain carbon, isotope analysis can help with determining the source of materials used in explosives.

The same techniques can help trace the country of origin of counterfeit paper money, such as $100 bills. Currency paper contains cotton to give it extra strength and durability. Cotton requires water for growth; water contains oxygen. Oxygen isotopes vary in rainwater around the world. Differences in rainwater show up as differences in the cellulose molecules in the cotton. Mass spectrometer analysis can determine the part of the world the cotton used in the fake bills has come from.

Isotope analysis can be used to help identify the source of cotton (top) used in counterfeit currency or where coca plants (bottom) were grown.

Check Your Understanding

Checking Concepts

1. What did Henri Becquerel discover about radiation emitted from uranium salts?
2. Distinguish between the terms "mass number" and "atomic number."
3. How do various isotopes of an element differ?
4. How many protons and neutrons are in the nuclei of each of the following isotopes?

(a) $^{11}_{5}B$	(e) magnesium-26
(b) $^{20}_{10}Ne$	(f) nitrogen-15
(c) $^{31}_{15}P$	(g) silicon-28
(d) $^{7}_{3}Li$	(h) chlorine-37

5. What two rules relate to mass numbers and atomic numbers in a nuclear equation?
6. Explain the changes that occur in the nucleus during each of the following.
   (a) alpha decay
   (b) beta decay
   (c) gamma decay

Understanding Key Ideas

7. Give the name and nuclear symbol for each of the following.
   (a) an element with 9 protons and 10 neutrons
   (b) an element with 8 protons and 10 neutrons
   (c) an element with 26 protons and 30 neutrons
8. Explain the composition of alpha and beta particles in terms of subatomic particles.
9. How is gamma radiation different from alpha and beta radiation?
10. Draw a Bohr model showing the number of protons and neutrons and the electron arrangement (including pairs and single electrons) for these atoms.
    (a) hydrogen-1
    (b) hydrogen-2
    (c) beryllium-9
    (d) magnesium-26
    (e) sulfur-36
11. Classify each of the following as alpha, beta, or gamma decay:
    (a) $^{201}_{80}Hg \rightarrow {}^{201}_{81}Tl + {}^{0}_{-1}\beta$
    (b) $^{231}_{91}Pa \rightarrow {}^{227}_{89}Ac + {}^{4}_{2}He$
    (c) $^{225}_{89}Ac \rightarrow {}^{221}_{87}Fr + {}^{4}_{2}\alpha$
    (d) $^{60}_{28}Ni^{*} \rightarrow {}^{60}_{28}Ni + {}^{0}_{0}\gamma$
    (e) $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
    (f) $^{24}_{11}Na \rightarrow {}^{24}_{12}Mg + {}^{0}_{-1}e$
12. Provide the symbol for the particle or nucleus that correctly completes the equation. For alpha decay, use either $^{4}_{2}\alpha$ or $^{4}_{2}He$. For beta decay, use $^{0}_{-1}\beta$ as needed.
    (a) $^{212}_{84}Po \rightarrow {}^{208}_{82}Pb +$ ____
    (b) $^{90}_{38}Sr \rightarrow {}^{90}_{39}Y +$ ____
    (c) $^{239}_{93}Np \rightarrow$ ____ $+ {}^{0}_{-1}\beta$
    (d) $^{144}_{60}Nd \rightarrow$ ____ $+ {}^{4}_{2}\alpha$
    (e) $^{42}_{19}K^{*} \rightarrow$ ____ $+ {}^{0}_{0}\gamma$
    (f) $^{146}_{62}Sm \rightarrow {}^{142}_{60}Nd +$ ____
13. Complete the following radioactive decay equations.
    (a) $^{257}_{104}Rf^{*} \rightarrow$ (gamma decay)
    (b) $^{8}_{3}Li \rightarrow$ (beta decay)
    (c) $^{255}_{103}Lr \rightarrow$ (alpha decay)
    (d) $^{254}_{98}Cf^{*} \rightarrow$ (gamma decay)
    (e) $^{13}_{5}B \rightarrow$ (beta decay)
    (f) $^{233}_{91}Pa \rightarrow$ (alpha decay)

Pause and Reflect

Both radioactivity and chemical reactions involve changes in matter. What do you think are the main differences between these two kinds of changes?

7.2 Half-Life

A half-life can be used to compare the rate of radioactive decay for an isotope. The shorter the half-life, the faster the decay rate. All radioactive decay rates follow a similar pattern called a decay curve. The difference between different isotopes is the length of their half-lives. The Common Isotope Pairs Chart identifies the parent isotope (which decays) and the daughter isotope (one of the decay products). The chart also shows the half-life of the parent and the dating range the isotope can be used for in radioisotope dating. A decay curve can be used to estimate the amount of parent isotope remaining or the amount of daughter isotope produced at any time after the radioactive sample first formed or, in the case of carbon dating, after the organism died.

Words to Know

daughter isotope
decay curve
half-life
parent isotope
radiocarbon dating

The oldest living organism on Earth is a bristlecone pine tree growing in the California White Mountains (Figure 7.14A). This tree is more than 4780 years old. How can you determine the age of a tree? One method is to extract a sample of wood and count the thin bands (annual rings)—one ring for each year of life (Figure 7.14B). Suppose you wanted to determine the age of something that was no longer alive, such as a bone or an ancient wooden tool. How would you establish its age?

Figure 7.14 An ancient bristlecone pine (A). Annual rings (B)

Did You Know?

The ages of the oldest rocks on Earth were established by American chemist Clair Patterson (1922–1995) in 1953. The rock meteorites Patterson analyzed contain uranium that is slowly turning into lead through radioactive decay. He was able to infer from the amount of each element present that the rocks were 4.55 billion years old.

Anchor Activity

7-2A Modelling Rates of Radioactive Decay

Find Out ACTIVITY

Radioactive elements contain at least one unstable isotope. Each radioisotope decays at a unique rate. However, graphs showing the rate at which isotopes decay show striking similarities. The rate at which a sample of a radioisotope decays can be modelled by tossing pennies and letting them land randomly. In this activity, you will use coin tosses to generate data for a graph.

Safety

- Wash your hands after completing this activity.

Materials

- 100 pennies or other two-sided objects
- container for shaking the pennies
- graph paper

What to Do

1. Create a data table like the following. Give your data table a title.

Number of Tosses Completed	Number of Pennies Remaining	Total Number of Pennies Removed Since the Start
0	100	0
1		
2		
etc.		
Last toss (record the number)	0	100

2. Working in pairs or small groups, count out 100 pennies.
3. Shake the pennies in the container and let them fall on a surface where they can be examined. Count all pennies that landed "heads" up and put them back into the shaker. You will shake them again because they represent atoms that did not yet decay. Record this number of pennies in the column "Number of Pennies Remaining."
4. Count the number of pennies that landed "tails" up. These represent atoms that decayed, so you will not shake them again. Add this number of pennies to the previous total number of pennies removed so you have a running total of all the pennies removed. Record this number of pennies in the third column.
5. Repeat steps 3 and 4 until there are no pennies left.
6. You will plot two smooth curves on the same piece of graph paper.
   - The first curve will show the number of pennies remaining after each toss. This will represent the number of nuclei of the parent isotope remaining in the sample after each decay.
   - The second curve will show the number of pennies removed since the start. This will represent the number of daughter isotopes produced during the decay.

   Your graph should have the following features.
   - Give your graph a title.
   - The *x*-axis (horizontal) will be the number of tosses. The *x*-axis should increase left to right from 0 tosses to how many you needed in the activity.
   - The *y*-axis will plot the number of pennies. The *y*-axis should extend from 0 to 100.
   - Join the dots on each curve with a smooth line.
   - Label the falling curve as parent isotopes and the rising curve as daughter isotopes.

What Did You Find Out?

1. (a) Could you use your graph to estimate how many pennies would be present after four tosses if you had already done three tosses but not the fourth? Explain.
   (b) Does your data suggest you could predict exactly how many pennies would be present after four tosses if you had already done three tosses but not the fourth? Explain why or why not.
   (c) Does your data permit you to predict which particular pennies will land heads up? Explain.
   (d) Obviously there is no such thing as "half a toss" of the pennies. However, does your data suggest that you could estimate the number of pennies remaining after $2\frac{1}{2}$ tosses? Explain.

Carbon Dating

We can measure how the radioactivity in plant or animal remains has changed over time and calculate the age of the remains. All organisms on Earth contain carbon. Plants use carbon dioxide to make their food. Animals take in the carbon when they eat plants. Carbon's isotopes include carbon-12 and carbon-14. When an organism is alive, the ratio of the number of carbon-14 atoms to the number of carbon-12 atoms in the organism remains nearly constant. But when an organism dies, its carbon-14 atoms decay without being replaced. The ratio of carbon-14 to carbon-12 then decreases with time. By measuring this ratio, the age of an organism's remains can be estimated. **Radiocarbon dating** is the process of determining the age of an object by measuring the amount of carbon-14 remaining in that object. Only material from plants and animals that lived within the past 50 000 years contains enough carbon-14 to be measured using radiocarbon dating.

Connection

Section 2.2 has information about the carbon cycle.

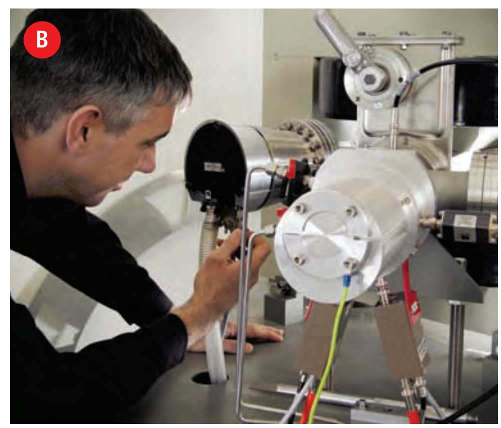


Figure 7.15A A sample is removed from bone for carbon dating. The bone is a human femur that is more than 500 years old.

Figure 7.15B A machine called an accelerator mass spectrometer is used for carbon dating. The machine converts atoms from a sample into a beam of ions. The mass of the ions is then measured using electric and magnetic filters.

The Rate of Radioactive Decay

The rate of radioactive decay can be compared using a quantity called half-life. A **half-life** is a constant for any radioactive isotope and is equal to the time required for half the nuclei in a sample to decay. For example, the half-life of the radioisotope strontium-90 is 29 years (Table 7.5). If you have 10.0 g of strontium-90 today, 29 years from now you will have 5.0 g left.

Table 7.5 Half-Life of Strontium-90

Number of Half-Lives	Elapsed Time (y)	Percentage of Strontium-90 Present	Amount of Strontium-90
0	0	100%	10.0 g
1	29	50%	$10.0\text{ g} \times \frac{1}{2} = 5.00\text{ g}$
2	58	25%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} = 2.50\text{ g}$
3	87	12.5%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 1.25\text{ g}$
4	116	6.25%	$10.0\text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 0.625\text{ g}$

Using a Decay Curve

When the information in Table 7.5 is graphed, a type of line called a decay curve is produced. A **decay curve** is a curved line on a graph that shows the rate at which radioisotopes decay. If you graph the rate of decay of any radioisotope, it will look the same as the decay graph in Figure 7.16. The only difference will be the length of the half-life. Each type of radioisotope decays at a different rate. For example, radon-222 has a fairly short half-life of 3.8 days. Carbon-14 has a longer half-life of 5730 years. Uranium-238 has an extremely long half-life of 4.5 billion years.

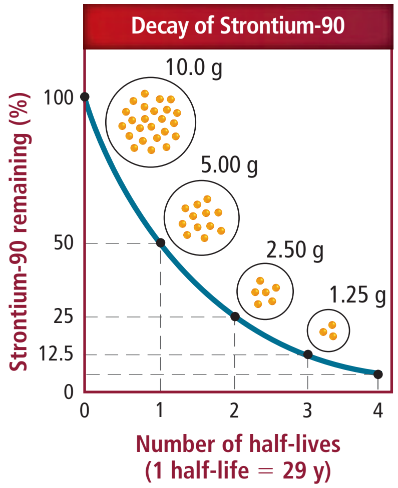


Figure 7.16 The graph shows how the amount of strontium-90 in a sample changes over time.

You can use the information represented in a decay curve to infer additional data.

Example 1: Iodine-131 is an isotope used in the treatment of thyroid cancer. Iodine-131 has a half-life of eight days. This length of half-life is very useful. It is long enough to allow the radiation treatment to work but short enough that the radiation from it drops to very low levels after a few weeks. Fresh iodine-131 must be prepared near or in the hospital before each use, because it decays quickly.

If a sample of iodine-131 weighs 20 g, what mass of iodine would remain after 16 days?

16 days is twice as long as 8 days, so it represents 2 half-lives.

$$\text{mass remaining} = 20 \text{ g} \times \frac{1}{2} \times \frac{1}{2} = 5 \text{ g}$$

Example 2: A sample of rock contains 64 g of a radioisotope. How much of the radioisotope will remain after three half-lives?

Three half-lives mean that the original mass of isotope will be reduced by half three times.

$$\text{mass remaining} = 64 \text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 8 \text{ g}$$

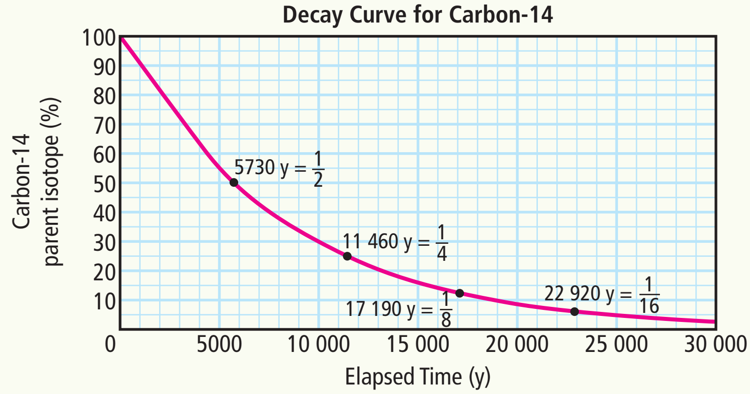
Did You Know?

To a very small extent, even you are radioactive, due to the carbon-14 and other radioisotopes found naturally in the molecules of your body.

Practice Problems

Try the following half-life problems yourself. Use the decay curve shown below for carbon-14.

Decay Curve for Carbon-14



The Decay of Carbon-14

Number of Half-Lives	Elapsed Time (y)	Percentage of Carbon-14 Present
0	0	100%
1	5730	$50\% = 100 \times \frac{1}{2}$
2	11 460	$25\% = 100 \times \frac{1}{2} \times \frac{1}{2}$
3	17 190	$12.5\% = 100 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$
4	22 920	$6.25\% = 100 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$

1. What is the length of one half-life of carbon-14?
2. How many half-lives have passed when there is $\frac{1}{4}$ of the original amount of carbon-14 remaining?
3. Estimate the percentage of carbon-14 remaining after:
   (a) 5000 years
   (b) 10 000 years
   (c) 20 000 years
4. Estimate the time elapsed when the amount of carbon-14 remaining is:
   (a) 70 percent
   (b) 40 percent
   (c) 5 percent

Answers provided on page 592

Common Isotope Pairs

There are many different isotopes that can be used for dating fossils, including those shown in Table 7.6. The isotope that undergoes radioactive decay is called the **parent isotope**. The stable product of radioactive decay is called the **daughter isotope**. The production of a daughter isotope can be a direct reaction or the result of a series of decays. Notice in Table 7.6 that each parent isotope is paired with a daughter isotope. Each isotope can be used for radioisotope dating, but the dating range is different for each depending on the half-life of the parent isotope. The longest half-life shown is 47 billion years.

Table 7.6 Common Isotope Pairs Chart

Isotope		Half-Life of Parent (y)	Effective Dating Range (y)
Parent	Daughter		
carbon-14	nitrogen-14	5730	up to 50 000
uranium-235	lead-207	710 million	> 10 million
potassium-40	argon-40	1.3 billion	10 000 to 3 billion
uranium-238	lead-206	4.5 billion	> 10 million
thorium-235	lead-208	14 billion	> 10 million
rubidium-87	strontium-87	47 billion	> 10 million

The Potassium-40 Clock

A clock does not have to look like a digital display or a dial with two hands on it. Any method for determining the passing of time or the age of something can be considered a kind of clock. Ernest Rutherford created a practical application for half-life of radioisotopes when he used the constant rate of decay as a clock to help determine the age of Earth. His technique has been applied many times since its discovery.

How can we use radioisotopes, such as potassium-40 and argon-40, as a clock? Potassium-40 has a half-life of 1.3 billion years. Its daughter isotope is argon-40. When rock is produced from lava, all the gases in the molten rock, including argon-40, have been driven out. This process sets the potassium radioisotope clock to zero, because there is potassium-40 (the parent) present in the molten rock but no argon-40 (the daughter) present.

Suppose that a very long time goes by. As the molten rock cools, it traps any gases that form inside it as a result of nuclear decay of atoms within the rock. A geologist finds this rock and takes it back to the laboratory for analysis. The analysis shows that both potassium-40 and argon-40 are now present in the rock. The argon gas is present in microscopic gas pockets, trapped inside the rock.

Connection

Chapter 12 has more information about the age of rocks.

Did You Know?

Radioisotopes are atoms whose nuclei are unstable and will eventually disintegrate, even if it takes billions of years. Stable isotopes exist indefinitely and have no known half-life.

Using data from a potassium-40 clock

Table 7.7 shows that, as the mass of the parent isotope drops, the mass of the daughter isotope increases. This should make sense because the potassium-40 is turning into argon-40. If analysis showed that there were equal masses of potassium-40 and argon-40 in a rock, how old is the rock? If you said 1.3 billion years old, you are correct. After one half-life, the parent isotope has decayed by half and is now present in an amount equal to the daughter isotope.

Table 7.7 The Decay of Potassium-40

Number of Half-Lives	Elapsed Time (billion y)	Amount of Potassium-40 Present	Amount of Argon-40 Present	Ratio of Argon-40 to Potassium-40
0	0	1000 g	0	0:1
1	1.3	500 g	500 g	1:1
2	2.6	250 g	750 g	3:1
3	3.9	125 g	875 g	7:1
4	5.2	62.5 g	937.5 g	15:1

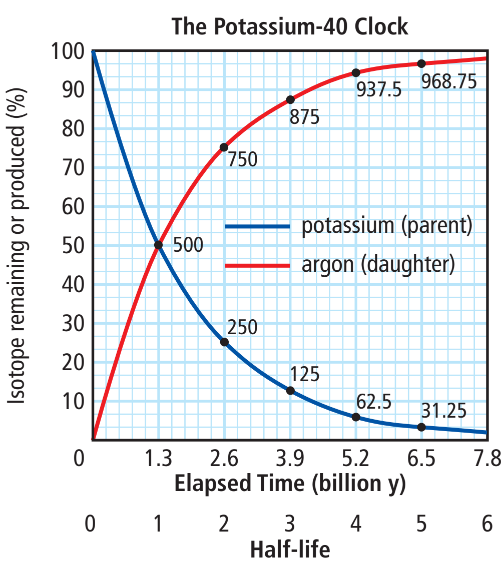


Figure 7.17 The blue line shows that the parent isotope is decaying. The red line shows that the daughter isotope is being produced.

When the trends shown in Table 7.7 are plotted on the same graph (Figure 7.17), a remarkable pattern becomes apparent. Notice in Figure 7.17 that at every age of the rock a different amount of parent is present with the daughter. For example, after one half-life, there are equal amounts of parent isotopes and daughter isotopes. This is shown on the graph at the place where the lines intersect. The red and blue lines intersect at one half-life, which for potassium-40 and argon-40 is 1.3 billion years.

What if there is more of the argon-40 daughter isotope present than there is of the potassium-40 parent isotope? It means that the rock is older than one half-life, or in this case, older than 1.3 billion years. Wherever the red (daughter) curve is above the blue (parent) curve, the age of the rock is greater than one half-life.

Why is this helpful for radioisotope dating of the rock? Because it means that all you have to do to date a rock is compare the amount of daughter isotope to the amount of parent isotope. Then, you can use this chart to find the age.

Suggested Activity

Think About It 7-2B on page 309

Practice Problems

Try the following radioisotope dating problems yourself. You may wish to use Table 7.7 and Figure 7.17 on page 308.

1. What is the ratio of argon-40 to potassium-40 two half-lives after the rock has formed?
2. What ratio of argon-40 to potassium-40 remains 3.9 billion years after the rock formed?
3. (a) When there is more parent isotope present in a sample than there is daughter isotope, what does this tell you about the age of the sample in terms of half-lives?
   (b) For how many years after the start of the potassium-40 clock is there more parent material than daughter material?

Answers provided on page 592

Explore More

The Bluefish Caves in the Yukon contain what may be the oldest evidence of human presence in Canada. Radiocarbon dating of this site indicates that the tools there were used by hunting parties between 12 000 and 25 000 years ago. To find out more about this important site and what tools were found there, visit **www.bcscience10.ca**.

7-2B Uses for Radioisotopes

Think About It

There are many different radioisotopes and many uses for them. In this activity, you will research one particular radioisotope or parent/daughter pair and report on what it is as well as some applications for it.

What to Do

1. Select a radioisotope from a list that your teacher will provide or select your own radioisotope. You may wish to explore an application, such as one of the following, and then find out what radioisotope is used for that application.
   - research, diagnose, and treat disease
   - sterilize medical equipment
   - trace processes in living organisms
   - preserve food
   - detect smoke
   - analyze pollutants
   - detect weakness in metal structures
   - analyze minerals and fuels
   - study the movement of water
   - measure ages of rocks and remains of plants and animals
2. Consult with your teacher about your selection to make sure it is appropriate.
3. Find the name and nuclear symbol for your radioisotope or radioisotope pair, its sources, method of decay (alpha, beta, gamma, or other), half-life, and application.
4. In consultation with your teacher, choose a format for reporting on your investigation. Here are some suggestions.
   - Design an information poster including your own drawing or photographs with captions.
   - Design an informational brochure.
   - Write a 250-word summary in your own words.
   - Give a short oral presentation to the class, explaining what you have found.
   - Create a five-segment slide show presentation.

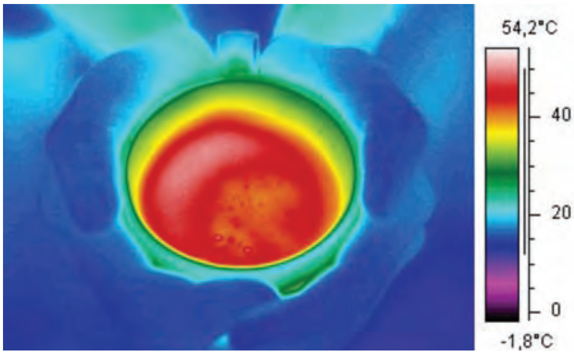
What Did You Find Out?

1. Post or present your information to the class.

Science

Math connect

Exponential Decay



A thermogram shows the various temperatures of hands holding a hot drink. The heat radiation is detected electronically and displayed with different colors representing different temperatures.

How fast will a warm cup of tea cool down? How long will a medicine remain active in your body? How quickly does the air pressure drop as you travel up through the atmosphere? As different as all of these questions may seem, there is a mathematical relationship called the exponential decay equation that can help connect them all. This is the same equation that governs how fast a radioisotope will decay and the concept of a half-life. The equation for the remaining amount of a radioactive element is:

$$N = N_0\left(\frac{1}{2}\right)^{t/T}$$

N is the amount remaining. N_0 is the initial amount. t is the elapsed time. T is the length of the half-life. The $\left(\frac{1}{2}\right)$ that appears in the formula is the mathematical expression of the concept of half-life. For example, the half-life of carbon-14 is 5730 years. What mass of a 50 g sample of carbon-14 remains after 1000 years?

$$N_0 = 50 \text{ g}$$
$$t = 1000 \text{ y}$$
$$T = 5730 \text{ y}$$
$$N = N_0\left(\frac{1}{2}\right)^{t/T} = 50\left(\frac{1}{2}\right)^{\frac{1000}{5730}} = 50\left(\frac{1}{2}\right)^{0.1745}$$
$$= 50 \times 0.8861 = 44 \text{ g}$$

After 1000 y, a 50 g sample of carbon-14 will have 44 g remaining.

How can this mathematical relationship be applied to the cooling of a cup of tea, the rate of removal of a medicine from the body, or a drop in pressure? Consider the following question: Suppose two cups of tea are made and that they are identical in every way, except that one starts out at 80°C while the other starts out at 100°C. Which will be the first to cool by 10 degrees? The answer is the one beginning at 100°C. This is because the total temperature drop is dependent on the starting temperature of the tea. The higher the temperature, the faster the rate at which the temperature drops. The exponential decay equation can even be used to calculate the temperature at any time after cooling has started.

The pressure of the air in our atmosphere decreases the higher you get above sea level. In fact, the higher you get, the faster it decreases. The rate at which the atmospheric pressure decreases is given by the exponential decay equation. The rate at which medicines are removed from our blood by our kidneys can also be given by a form of the exponential decay equation. Part of the beauty of mathematics is discovering that a relationship like this is so deeply connected with our world that it shows up again and again in different places.

Questions

Use the exponential equation to answer the following questions.

1. What mass of a 200 g sample of carbon-14 remains after 25 000 y?
2. What was the original amount of carbon-14 if 10 g of it remains after a period of 2500 y?
3. Suppose that a cup of freshly steeped tea at 100°C is allowed to cool in a room whose air temperature is 0°C. Suppose that every 5 min the temperature of the tea drops half way from its current temperature to 0°C. What is its temperature after 13 min?

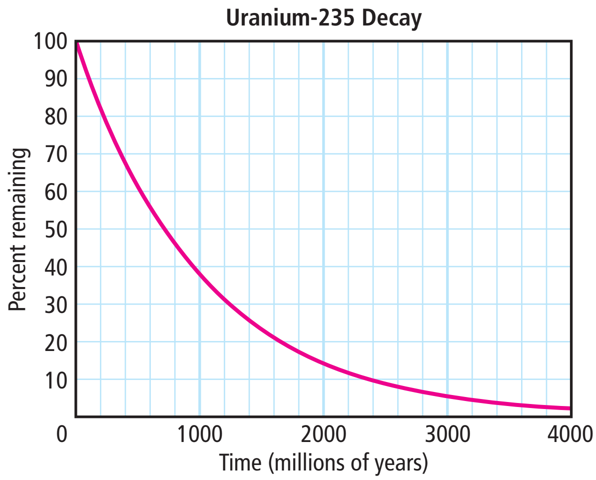
Check Your Understanding

Checking Concepts

1. Define half-life.
2. Distinguish between a parent isotope and a daughter isotope.
3. All isotopes decay in a similar pattern. What is the main difference between the rates of decay of different isotopes?
4. Explain the meaning of this statement: "A radioisotope can be used as a clock."
5. How does the lava cooling to form rock set the potassium-40/argon-40 clock to zero?
6. Iodine-131 has a half-life of eight days. If a sample contained 512 g of iodine-131, what mass of iodine would remain after 32 days?
7. A sample of rock contains 800 g of a radioisotope. How much of the radioisotope will remain after three half-lives?
8. How are decay curves different for different isotopes?

Understanding Key Ideas

9. Consider the following graph showing the decay curve for uranium-235.



(a) What is the half-life of uranium-235?
(b) What percentage of uranium-235 remains after 1420 million years?
(c) The daughter product in this decay is lead-207. What percentage of the total possible amount of lead-207 has been produced after 1420 million years?
(d) What percentage of uranium-235 remains after three half-lives?
(e) If 80 g of uranium-235 decays for 355 million years, estimate the mass of uranium-235 that remains.
(f) How many years does it take for 60 percent of the original amount of uranium-235 to decay?

Use the following chart to answer questions 10 to 13.

Isotope		Half-Life of Parent (y)	Effective Dating Range (y)
Parent	Daughter		
uranium-235	lead-207	710 million	> 10 million
potassium-40	argon-40	1.3 billion	10 000 to 3 billion
carbon-14	nitrogen-14	5730	up to 50 000

10. Which parent isotope has the slowest rate of radioactive decay?
11. State which isotopes would be useful for dating a material that is:
(a) 3000 years old
(b) 30 000 years old
(c) 60 000 years old
(d) 60 million years old
12. If an original 10 g sample of carbon-14 decayed for 11 460 years, what mass of nitrogen-14 would have been produced?
13. Which of the three parent isotopes decays through beta decay?

Pause and Reflect

Why do you think it is important to date the age of the remains of living organisms? Why is it important to date the age of rocks and Earth? How might this information be useful to you in your life?

7.3 Nuclear Reactions

Fission is a nuclear reaction in which a large nucleus breaks apart, producing two or more smaller nuclei, subatomic particles, and energy. Fission is the source of energy for all nuclear power generation used today. The daughter products are often radioactive and are a significant waste disposal problem. Fusion is a nuclear reaction in which small nuclei combine to produce a larger nucleus. Other subatomic particles as well as energy are released in this process. Fusion is the source of energy in the Sun.

Words to Know

chain reaction
fission
fusion
nuclear equation
nuclear reaction

Figure 7.18 If you visit a nuclear energy facility, you might find yourself standing in one of the devices shown above. This full-body scan detects whether the radiation levels of the workers exceed safety standards.

7-3A Nuclear Energy: Fact or Opinion?

Think About It

Is nuclear energy a "green" energy source? How is nuclear energy used to produced electricity? What are safety concerns related to generating nuclear energy? In this activity, you will identify what you know about nuclear energy.

What to Do

1. By yourself or with a partner, prepare a list of information you know about nuclear energy. Try to record your source of information for each point you contribute.
2. After you are finished making your list, classify each point you have made as fact or opinion.
3. Compare your list with other students or the rest of the class.

What Did You Find Out?

1. Which points were difficult to classify as being fact or opinion?
2. What are three questions about nuclear energy for which you would like to know the answers?

Nuclear Fission

All nuclear energy used for power generation anywhere in the world is accomplished through nuclear fission. **Nuclear fission** is the splitting of a more massive nucleus into two less massive nuclei, subatomic particles, and energy. Heavy nuclei tend to be unstable due to the repulsive forces between the many protons. In order to increase their stability, atoms with heavy nuclei may split into atoms with lighter nuclei.

The fission of a nucleus is accompanied by a very large release of energy. We can use this huge amount of energy to generate power to support our present lifestyle.

Although nuclear reactors reduce the need for burning fuels such as coal and natural gas, nuclear reactors produce wastes that need to be stored safely for hundreds of thousands of years. The physical deterioration of nuclear power plants is a significant problem, especially in Ontario. There is an added concern that nuclear material could be used for making nuclear weapons.

Did You Know?

In Canada, all nuclear power generation occurs in just three provinces: Ontario, Quebec, and New Brunswick. No new commercial nuclear reactors have been built since 1993, in part because the production of energy by nuclear reactions remains controversial.

A Review of Chemical Reactions

Earlier in this unit, you learned that mass is conserved in chemical reactions. In typical chemical reactions, the energy produced or used is so small that there is very little change in mass. In chemical reactions, we say that mass is conserved. For example:

$$\text{Mass A (wood + air)} = \text{Mass B (carbon} + CO_2 + H_2O).$$

You have learned that the number of protons in the nucleus of an atom determines the identity of an element. In a chemical reaction, there are no changes in the nuclei of the reactants, so the identities of the atoms do not change. Chemical reactions involve electrons and rearrangements in the way atoms (and ions) are connected to each other.

Nuclear Reactions

Reactions that involve a change in an atom's nucleus are called nuclear reactions. A **nuclear reaction** is a process in which an atom's nucleus changes by gaining or releasing particles or energy. A nuclear reaction can release one, two, or all three types of subatomic particles (protons, neutrons, and electrons), as well as gamma rays. However, in nuclear reactions, a small change in mass results in a large change in energy. For example, the nuclear fission of 1 g of pure uranium-235 releases the same amount of energy as obtained from burning about 2 tonnes of coal!

Comparing chemical reactions with nuclear reactions

Table 7.8 compares chemical reactions with nuclear reactions.

Table 7.8 Comparison of Chemical Reactions and Nuclear Reactions

Chemical Reactions	Nuclear Reactions
Atoms are rearranged by breaking chemical bonds and forming new bonds.	Atoms are changed from one isotope into another, producing different elements.
Only electrons are involved in bond formation and breaking.	Electrons, protons, neutrons, and other subatomic particles may be involved. Electrons may be produced in the nucleus.
Chemical reactions are accompanied by the release or absorption of relatively *small* amounts of energy.	Nuclear reactions are accompanied by absorption or release of *huge* amounts of energy.

Nuclear Equations for Induced Nuclear Reactions

Are there other kinds of nuclear reactions besides the natural radioactive decay (alpha, beta, and gamma) reactions that we have seen so far? Yes. Scientists can even make a nucleus unstable and undergo a nuclear reaction immediately. This process is called an *induced*, or forced, nuclear reaction. A nuclear reaction is induced by bombarding a nucleus with alpha particles, beta particles, or gamma rays.

The nuclear reaction in Figure 7.19 has some similarities to the decay reactions studied in Section 7.1. The difference is that an alpha particle in this nuclear reaction is a reactant, not a product. This nuclear reaction can be induced by exposing nitrogen-14 to alpha radiation.

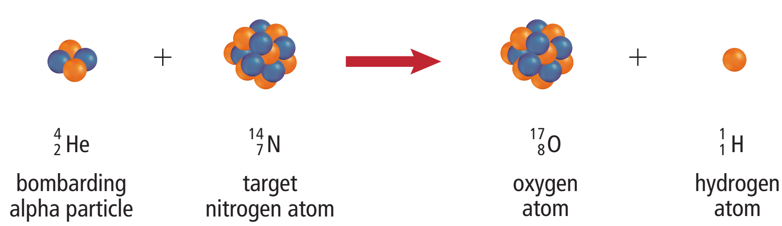


Figure 7.19 When a nitrogen-14 nucleus is bombarded by an alpha particle, a fluorine-18 nucleus is produced, which decays into oxygen-17 and a proton.

Figure 7.19 can be written as a nuclear equation. There are several possible ways to write the same equation. For example:

$$^{4}_{2}\alpha + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

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

Subatomic Particle Symbols

A hydrogen-1 nucleus can be represented either as ${}^{1}_{1}\mathrm{H}$ or as a proton, ${}^{1}_{1}p$, because a proton and a hydrogen-1 nucleus are the same thing. The proton notation shows that a proton has an atomic number of 1 (1 proton) and a mass number of 1 (1 proton + 0 neutrons). A neutron is symbolized ${}^{1}_{0}n$, meaning that it has an atomic number (charge) of 0 (0 protons) and a mass number of 1 (0 protons + 1 neutron). Subatomic symbols are summarized in Table 7.9.

Table 7.9 Subatomic Particles in Nuclear Reactions

Particle (Symbol)	Also Known As
proton (${}^{1}_{1}p$)	hydrogen-1 nucleus (${}^{1}_{1}\mathrm{H}$)
neutron (${}^{1}_{0}n$)	—
helium nucleus (${}^{4}_{2}\mathrm{He}$)	alpha particle (${}^{4}_{2}\alpha$)
electron (${}^{0}_{-1}e$)	beta particle (${}^{0}_{-1}\beta$)

Rules for Writing Nuclear Equations

The rules for writing nuclear equations for induced nuclear reactions are the same as for radioactive decay.

- The sum of the mass numbers on each side of the equation stays the same.
- The sum of the charges (represented by atomic numbers) on each side of the equation stays the same.

Reading Check

1. Explain what is meant by the term:
   (a) nuclear reaction
   (b) induced nuclear reaction
2. List several ways to induce a nucleus to undergo a nuclear reaction.
3. What are two ways to symbolize a electron?
4. What are two ways to symbolize a helium nucleus?
5. State the charge of:
   (a) a proton
   (b) an electron
   (c) a neutron

Did You Know?

The famous equation $E = mc^2$ was formulated by German physicist Albert Einstein (1879–1955). This equation relates the amount of mass in a sample (m) to the energy contained in it (E). The equation says to multiply the mass of an object by the speed of light (3×10^8 m/s) squared to find out how much energy it possesses. There is a tremendous amount of energy stored in even a tiny amount of matter.

Did You Know?

In 1939, Austrian physicist Lise Meitner (1878–1968) was the first to explain how nuclear fission occurs. She realized that the total mass of the particles produced when the uranium nucleus split was less than that of the original nucleus. Although Meitner was passed over for a Nobel Prize (her colleague Otto Hahn received it), element 109, meitnerium, was named in her honour.

Nuclear Fission of Uranium-235

It takes a tremendous amount of energy for an alpha particle (with a charge of 2+) to collide with a nitrogen-14 nucleus (with a charge of 7+), shown in Figure 7.19 on page 314. The repulsion between the positive charges is very great.

Another kind of collision that can happen at much lower energies involves a neutron colliding with a nucleus. The nuclear fission of uranium-235 is the main nuclear reaction in both fission-style nuclear weapons and in Canadian nuclear power plants. The equation for the nuclear fission of uranium-235 is:

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

Figure 7.20 shows that when a nucleus of uranium-235 is struck by or bombarded with a neutron, the nucleus absorbs the neutron. As a result, the mass number of the nucleus increases by one. Because the number of protons has not changed, this is still an atom of uranium—it is just a different isotope.

However, what the equation does not show is that the newly formed and very high-energy uranium-236 is unstable and immediately splits apart into two smaller nuclei, releasing several neutrons and a lot of energy. Table 7.10 on the next page describes some important features of this equation.

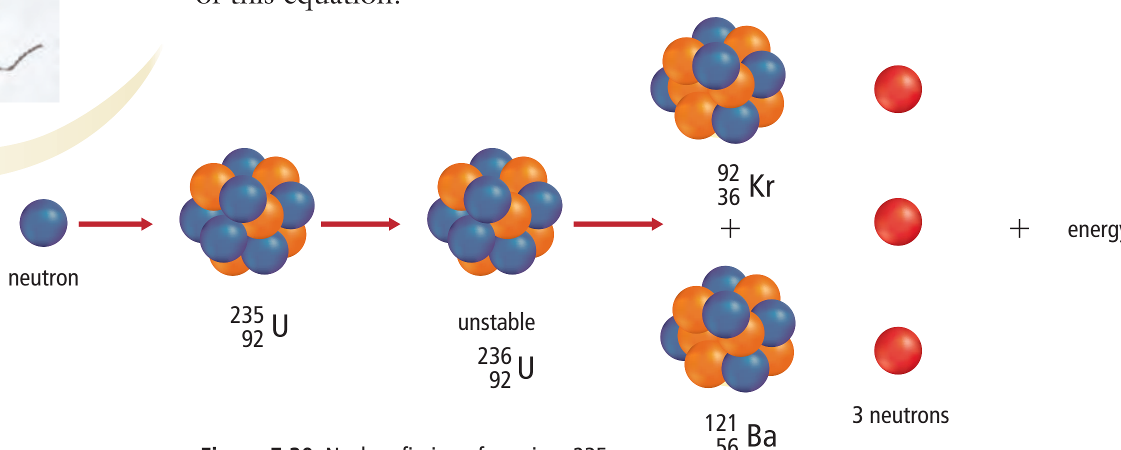


Figure 7.20 Nuclear fission of uranium-235

When uranium nuclei undergo fission, they release neutrons, which trigger more fission reactions. Each fission of uranium-235 releases additional neutrons as shown in Figure 7.20. If one fission reaction produces three neutrons, these three neutrons can cause three additional fissions. If those three fissions release nine neutrons, those nine neutrons could then produce nine more fissions, and so on.

Table 7.10 Important Features of the Fission Reaction for Uranium-235

What Happens in the Reaction	Comments
In neutron bombardment, a nucleus of uranium is struck by a neutron.	The process begins when a neutron strikes a nucleus of uranium-235.
Two smaller nuclei are produced, in this case $^{92}_{36}Kr$ and $^{141}_{56}Ba$.	Different nuclei can be produced in this reaction. There are several hundred ways for the uranium nucleus to split into two.
Fission produces up to five neutrons. Three neutrons is the most common number.	In a large sample of uranium-235, each of the neutrons released from the nucleus strikes other uranium-235 atoms, making them split apart.
A large amount of energy is released.	Though it cannot be seen in the equation, the masses of all the products are slightly less than the masses of both reactants. This represents a tiny amount of matter turning into a huge amount of energy.
The products are radioactive.	It is *not* possible to tell from the equation that these products are unstable. Both $^{92}_{36}Kr$ and $^{141}_{56}Ba$ are unstable and will decay into other isotopes. These further reactions can release useful energy, but they also lead to the problem of nuclear waste.

Did You Know?

In 2006, the *Cassini* spacecraft began a four-year mission exploring the Saturn system, powered by technology that converts energy from the radioactive decay of plutonium into electricity.

Practice Problems

The fission of uranium-235 through bombardment with a neutron can cause the uranium nucleus to split in two in many different ways. In answering the questions below, remember to use these rules:

- The sum of the mass numbers does not change. In these reactions, it is 236.
- The sum of the atomic numbers does not change. In these reactions, it is 92.
- Verify that the mass numbers and the atomic numbers in the reactants do add up to 236 and 92 respectively.

1. Find the indicated daughter nucleus for each of the following.

(a) $^{1}_{0}n + ^{235}_{92}U \rightarrow \_\_\_\_ + ^{143}_{55}Cs + 3\ ^{1}_{0}n + \text{energy}$

(b) $^{1}_{0}n + ^{235}_{92}U \rightarrow \_\_\_\_ + ^{94}_{42}Mo + 3\ ^{1}_{0}n + \text{energy}$

(c) $^{1}_{0}n + ^{235}_{92}U \rightarrow \_\_\_\_ + ^{140}_{60}Nd + 3\ ^{1}_{0}n + \text{energy}$

Answers provided on page 592

Chain Reactions

The ongoing process in which one reaction initiates the next reaction is called a **chain reaction** (Figure 7.21). The number of fissions and the amount of energy released can increase rapidly and lead to a violent nuclear explosion.

Suggested Activity

Find Out Activity 7-3B on page 322

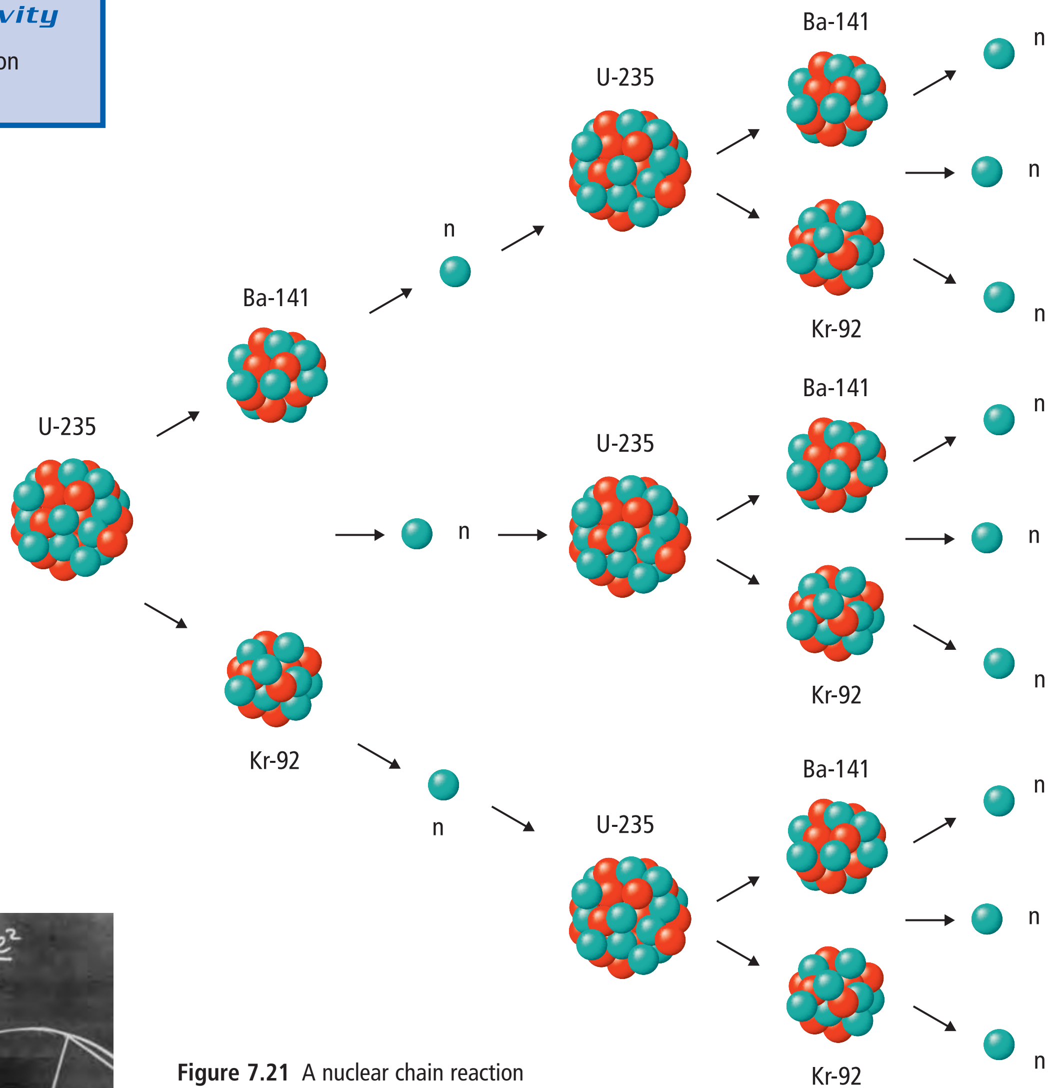


Figure 7.21 A nuclear chain reaction

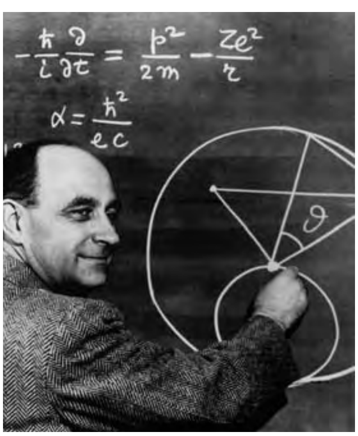


Figure 7.22 Enrico Fermi (1901–1954) received the Nobel Prize in physics in 1938 for his work on induced radioactivity.

How can the energy of a chain reaction be controlled? Italian physicist Enrico Fermi (Figure 7.22), working with colleagues in the United States, realized that materials that absorb neutrons could be used to control the chain reaction. In 1942, Fermi and his colleagues built the first nuclear reactor by using cadmium rods to absorb neutrons.

Keeping the chain reaction going in a nuclear power plant, while preventing it from racing out of control, requires precise monitoring and continual adjusting. Much of the concern about nuclear power plants focusses on the risk of losing control of the nuclear reactor, which could result in the accidental release of harmful levels of radiation or even an explosion.

CANDU Reactors

Canada is a leader in the peaceful use of nuclear technology for both medical uses and for power generation. Canadian nuclear reactors are called CANDU reactors. CANDU stands for "**Can**adian **d**euterium **u**ranium" reactor. Deuterium is an isotope of hydrogen-1 that is twice as heavy as it has both a proton and a neutron in its nucleus.

The design of the CANDU reactor is among the safest in the world, and the reactor can be shut down quickly if a problem arises. Canada provides nuclear power technology and expertise to other countries to help them establish nuclear power generation stations.

Figure 7.23 shows eight CANDU reactors at the Pickering Nuclear Generating Stations. A diagram of the inside of each reactor is shown in Figure 7.24. The reactor core produces heat as a result of reactions like the following:

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

Nuclear power plants and fossil-fuel burning power plants are similar in that both produce a lot of heat. This heat is used to boil water and generate steam, which then drives the turbines that produce electricity. A turbine is a large rotating device that can be forced to turn when steam is applied to it. You may recall from earlier science studies that a turbine drives a generator that produces electricity.

Did You Know?

CANDU reactors use heavy water—water in which the hydrogen atoms are deuterium—as both moderator and coolant.

Figure 7.23 The Pickering Nuclear Generating Stations in Pickering, Ontario, include eight separate reactors. All are visible in the photo.

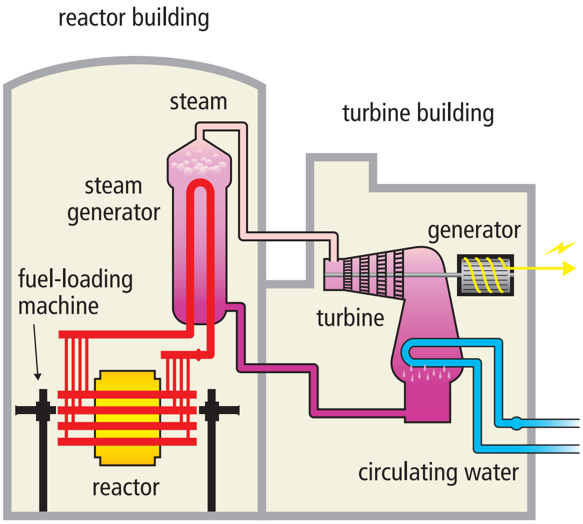


Figure 7.24 The nuclear fuel produces heat, which is used to make steam. The stream drives turbines that are connected to electrical generators.

Hazardous Wastes

The fuel used to produce heat in a CANDU reactor is in the form of bundles of rods containing uranium pellets (Figure 7.25). Each nuclear fuel bundle stays in a CANDU reactor for about 15 months. Used fuel bundles are highly radioactive when they are removed from the reactor. The used bundles are stored in water pools at the reactor for about 10 years before they can be transferred to shielded, above-ground dry storage containers (Figure 7.26).

While the radioactivity of used fuel bundles decreases significantly with time, the bundles remain hazardous for many thousands of years and must be isolated from the natural living environment. Most countries with nuclear power programs, including Canada, are planning to put used nuclear fuel in metal containers that would be placed deep underground in stable rock formations. Some countries reprocess used nuclear fuel to recover material to use in new reactor fuel.

Suggested Activity

Conduct an Investigation 7-3C on page 323

Figure 7.25 Each CANDU fuel bundle is about 50 cm in length and 10 cm in diameter and generates about 1 million kW•h of electricity during its time in the reactor.

Figure 7.26 Each of these 450 containers holds nuclear waste from the Pickering, Ontario, nuclear power plant. About 40 new containers are added each year. Each container is designed to last for about 50 years while a long-term storage solution is sought.

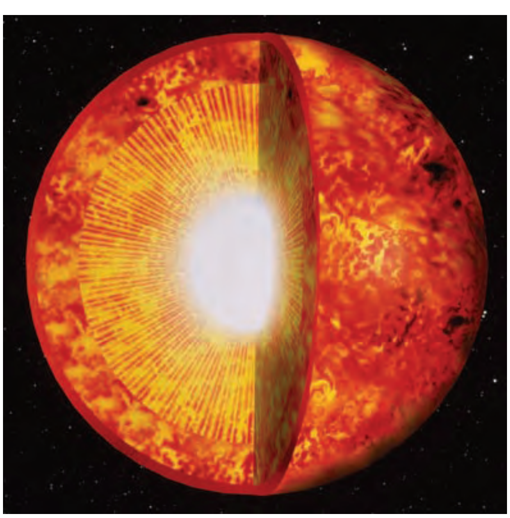


Figure 7.27 A model showing nuclear fusion occurring at the core of the Sun.

Nuclear Fusion

Fusion is the process in which two low mass nuclei join together to make a more massive nucleus. This process occurs at the core of the Sun and other stars (Figure 7.27), where there is sufficient pressure and high enough temperature to force isotopes of hydrogen to collide with great force. This forces two nuclei of hydrogen to merge into a single nucleus.

Although the most common isotope of hydrogen is hydrogen-1, $^{1}_{1}H$, heavier isotopes of hydrogen also exist. In the Sun, a fusion reaction occurs between hydrogen-2 and hydrogen-3. When these combine, a huge amount of energy is released. It is this energy that eventually passes from the Sun as radiation and brings light and heat to our world.

Fusion nuclear equation

The nuclear equation for fusion in the Sun and in fusion reaction experiments is:

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}n + \text{energy}$$

Researchers have worked for over half a century to find a technology that will allow us to extract energy from fusion reactions. One of the difficulties is achieving the high temperatures and pressures needed. Another is simply finding a way to contain a reaction that is so hot that no vessel can hold it without being destroyed. Fission and fusion reactions are compared in Table 7.11.

Table 7.11 Comparison of Fission and Fusion Reactions

Fission Reaction	Fusion Reaction
Heavy unstable nuclei split apart into two smaller nuclei.	Two lightweight nuclei join together to form a heavier nucleus.
Unstable nuclei release a huge amount of energy when they split.	Lightweight nuclei release a huge amount of energy when they join.
Heavy nuclei will not release excess energy by splitting if they are as light as the element iron or lighter.	Lightweight nuclei will not release excess energy if the nucleus generated by fusing is heavier than iron.
Fission reactions often produce daughter products that are radioactive. This causes a radioactive waste problem for nuclear energy production.	Fusion reactions often do not produce products that are radioactive. This makes nuclear fusion reactors an attractive possibility for nuclear energy production.
Many countries, including Canada, generate some electrical power through fission reactions.	No commercial fusion reactors are in use or under construction.
Research continues to try to produce environmentally friendly nuclear power generation.	Research continues to try to produce a fusion nuclear reactor.
A fission reaction is used in modern nuclear weapons by itself or to produce an explosion that will generate sufficient heat and pressure to trigger a fusion reaction.	A fusion reaction is used in modern nuclear weapons to generate most of the energy released in the blast. A fusion reaction needs the heat and pressure from a fission nuclear explosion to get it started.
Equation of a typical reaction: $^{1}_{0}n + ^{235}_{92}\text{U} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3\,^{1}_{0}n + \text{energy}$	Equation of a typical reaction: $^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}n + \text{energy}$

Did You Know?

Due to its constant output of energy, the Sun loses almost 4 million tonnes of mass each second as the mass is converted to energy.

Explore More

A large facility is being built in California to produce fusion in a drop of liquid hydrogen. Powerful lasers are to be directed into a bubble of hydrogen, causing the outside of the bubble to explode and the inside to implode. The shock of the explosion should cause heat and pressures similar to what is found in the centres of stars. This process is called inertial confinement fusion. Find out more at **www.bcscience10.ca**.

7-3B Modelling Chain Reactions

Find Out ACTIVITY

An induced nuclear reaction spreads when a neutron shoots from one nucleus to another. When a large nucleus decays into two smaller nuclei, it can also release one or more fast-moving neutrons. These neutrons can cause other nuclei to become unstable and decay, releasing even more neutrons. In this activity, you will model nuclear chain reactions using dominoes.

Materials

- domino tiles

What to Do

1. Obtain a set of domino tiles and work in pairs or small groups.
2. Set up and try out the simplest possible of chain reactions. It will start with a single domino and have a single path. The dominoes will fall in series all the way to the end if you have set them up correctly. Notice that the rate at which dominoes fall is always the same. This represents a controlled nuclear chain reaction.
3. Try using different patterns, in which a single path splits into two paths. Notice that at the end of the pattern the dominoes fall twice as fast as at the beginning.
4. Set up the dominoes again, but have each path split into two paths over and over again. Make a note of how many dominoes are falling at the end compared to the one domino that falls to start it all off.
5. The next pattern is a model for the process that occurs when uranium-235 decays in nuclear power generation in a CANDU nuclear reactor. Set up one domino so that it will knock down three dominoes all at once. Each of the three dominoes set to fall in the second step needs to knock down three more dominoes. Good luck setting it up. Note how many dominoes fall in the last step of your model compared to the one domino that started it off.
6. Put your materials away.

What Did You Find Out?

1. Which arrangement of tiles caused the most dominoes to fall the fastest?
2. (a) Why is it necessary to control chain reactions in a nuclear power station?

   (b) Are chain reactions controlled in a nuclear weapon? Explain.

You can use dominoes to model a chain reaction.

7-3C Evaluating Nuclear Waste Storage

Conduct an INVESTIGATION

Decision-Making Focus

SkillCheck

- Communicating
- Modelling
- Evaluating information
- Identifying ethical issues

Some wastes from nuclear fuels remain radioactive for thousands of years.

Science Skill

Go to Science Skill 4 for help developing decision-making skills.

Issue

Burning fossil fuels, such as coal, is contributing to global climate change, including dramatic changes in the Canadian Arctic. Should we consider using nuclear power as a "green" energy source for Canada?

Background Information

There are many considerations regarding the production of nuclear energy. One of them is how to manage and store nuclear waste over thousands of years. Nuclear energy production is based on fission technology that uses uranium isotopes for the production of electrical energy. As these isotopes decay through use in the nuclear reactors, other products are made. Some of these isotopes have very long half-lives. They will remain radioactive for thousands of years, producing dangerously high levels of radiation should they ever be released to the environment. CANDU nuclear power stations have been built in Ontario, Quebec, and New Brunswick. These provinces have decades of experience in generating nuclear power but are still awaiting a solution to the problem of waste storage.

Identify and Analyze Alternatives

Consider these two viewpoints on this issue. The pro-nuclear energy group believes that nuclear power is a green technology that should be promoted in order to supply electrical energy needs in British Columbia because the technology does not contribute to carbon emissions. The question of nuclear waste storage is a technological one and will eventually be solved.

The anti-nuclear power group believes it is dangerous to keep producing nuclear waste that will last more than 10 times longer than recorded human history. Other solutions need to be found to provide environmentally friendly energy sources.

Your task is to choose one side of the argument and research the issue. You will present your findings as either a debate or a class presentation. Your teacher will provide more details about how to present your information.

Begin your research using the following resources:

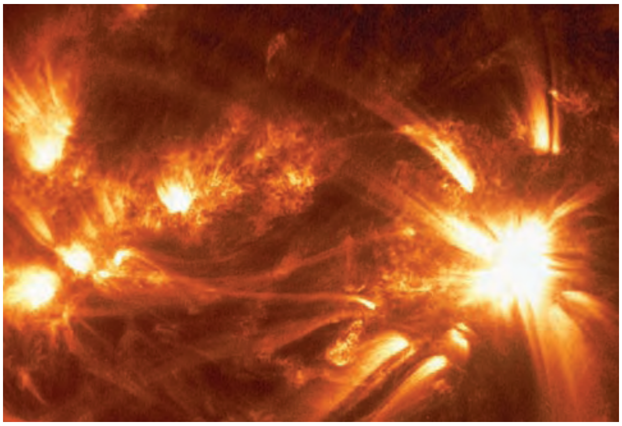
1. Go to **www.bcscience10.ca** to begin your search for information. Also use search engines. Try keywords such as "nuclear power," "CANDU," and "Canadian Nuclear Safety Commission." You may also wish to use print materials such as magazines, newspapers, and books.
2. Summarize the information you find in a short report for presentation to your class or for use in a debate. Be sure to include only information that supports your viewpoint or refutes the opposite view.

Evaluate

Present your findings and conclusions to your classmates either in a presentation or as a debate.

Science Watch

Pursuing the Dream of Fusion Power



Plasma rises from active areas on the Sun's surface and follows the path of powerful magnetic fields.

Nuclear fusion reactions that occur in our Sun produce huge amounts of energy. Is there any way to harness nuclear fusion reactions here on Earth to produce electricity? No commercial nuclear fusion power plants currently exist, but some researchers hope that technologies can be invented to bring fusion power into production in an environmentally friendly way. Many governments have the same hope and have invested billions of dollars in pursuit of this dream.

The centre of our Sun is very hot—about 15 million degrees Celsius. For many decades, researchers have looked for a practical way to recreate the conditions at the centre of our Sun. They have produced extremely hot temperatures during nuclear explosions, but this is not a practical way of producing electricity. An added challenge is that no container made of matter can contain gases that are as hot as the centre of our Sun. Any type of container would melt long before reaching those temperatures. However, there is another way to contain hot gases—with a strong magnetic field.

How can you use a magnetic field to hold gases? Hot gases lose electrons, turning all the atoms into ions. An ionized gas is called plasma.

In a fusion power reactor, a magnetic field traps hydrogen plasma. One reactor design uses an electromagnet positioned in the shape of a doughnut. The hot plasma stays inside the doughnut and away from the magnets used to generate the magnetic field. Currently, a number of existing experimental facilities are using this technology.

A technician performs maintenance on the doughnut-shaped device that confines hot plasma.

Given these tremendous challenges as well as huge development costs, why even bother to try to build a fusion power facility? If it could be made to work, fusion power is expected to have a number of advantages. The materials needed for fusion—isotopes of hydrogen—are as plentiful as the oceans themselves. Also, the products of nuclear fusion are expected to be stable isotopes, meaning that there might be no radioactive wastes to worry about. Finally, a small amount of fusion produces a tremendous amount of energy.

Questions

1. What conditions are necessary before isotopes of hydrogen can combine in a fusion reaction?
2. How is the hot plasma trapped so that it can be millions of degrees yet not melt its container?
3. List three possible advantages of a successful fusion power reactor.

Check Your Understanding

Checking Concepts

1. What is nuclear fission?
2. What is nuclear fusion?
3. Write a nuclear equation representing a fission reaction that occurs in CANDU reactors.
4. Write a nuclear equation representing a fusion reaction that occurs at the centre of our Sun.
5. What is a chain reaction?
6. Write all the symbols that represent each of the following.
   (a) alpha particle
   (b) beta particle
   (c) proton
   (d) electron
   (e) neutron
   (f) hydrogen-1 nucleus
   (g) helium-4 nucleus
7. Consider these particles taken together:
   $^{1}_{0}n + ^{235}_{92}\mathrm{U}$
   (a) What is the total mass number?
   (b) What is the total atomic number?
8. Consider these particles taken together:
   $^{92}_{36}\mathrm{Kr} + ^{141}_{56}\mathrm{Ba} + 3\,^{1}_{0}n$
   (a) What is the total mass number?
   (b) What is the total atomic number?

Understanding Key Ideas

9. Consider the following nuclear equation.

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

   (a) How was the uranium-235 induced to undergo a nuclear reaction?
   (b) How many neutrons were produced by this process?
   (c) Is this reaction a fusion reaction or a fission reaction?
   (d) How could this reaction lead to a chain reaction that could result in a nuclear explosion?
   (e) Does this reaction consume energy or release energy overall? Explain.

10. What is the indicated daughter nucleus?
    (a) $^{1}_{0}n + ^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ ^{127}_{53}\mathrm{I} + 3\,^{1}_{0}n +$ energy
    (b) $^{1}_{0}n + ^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ ^{119}_{50}\mathrm{Sn} + 3\,^{1}_{0}n +$ energy
    (c) $^{1}_{0}n + ^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ ^{115}_{49}\mathrm{In} + 3\,^{1}_{0}n +$ energy

11. Copy and complete the following chart in your notebook.

		Fission	Fusion
(a)	Does this reaction obey the law of conservation of mass?		
(b)	Is this reaction used for the production of electrical energy?		
(c)	Does this reaction produce radioactive by-products?		
(d)	Does this reaction involve the release of energy?		
(e)	Is this reaction used in nuclear weapons?		

Pause and Reflect

Suppose a House of Commons committee for the government of Canada has asked you to advise it on nuclear energy research. Although the committee members would be prepared to wait up to 20 years for energy production to come on line, they would like to pursue research in either fission technology or fusion technology, but not both. What advice would you give the committee to help them make a decision? What alternative would you suggest if you felt neither technology was a good choice?

Chapter Review

Prepare Your Own Summary

In this chapter, you learned to define and categorize isotopes in terms of atomic number and mass number and to explain the decay of radioactive isotopes in terms of changes to the nucleus. You also investigated half-life with reference to rates of radioactive decay. You compared fission and fusion. Create your own summary of the key ideas from this chapter. You may include graphic organizers or illustrations with your notes. (See Science Skill 11 for help with graphic organizers.) Use the following headings to organize your notes:

1. Isotopes and Radioactivity
2. Three Types of Radioactive Decay
3. Half-Life
4. Comparing Fission and Fusion

Checking Concepts

1. What is radiation?
2. What is a radioisotope?
3. (a) List three kinds of radioactive decay.
   (b) State what kind of particle or ray is produced by each type.
   (c) State the electric charge of each of the three kinds of radioactive decay.
4. Write two different symbols used to represent alpha particles.
5. (a) How are the atoms in magnesium-24 and magnesium-26 similar?
   (b) How are they different?
6. Which subatomic particle determines the identity of an element?
7. What subatomic particles are present in an alpha particle?
8. Why does a beta particle have a negative charge?
9. How does the release of an alpha particle by an atom change that atom into a different element?
10. Draw a Bohr model showing the number of protons, neutrons, and the electron arrangement (including pairs and single electrons) for the following atoms.
    (a) carbon-14
    (b) carbon-15
    (c) carbon-16
    (d) sodium-22
    (e) sodium 23
11. Copy and complete the following table in your notebook.

Isotope	Mass Number	Atomic Number	Number of Neutrons
lithium-7			
neon-22			
		14	15
		8	8
	24		12
	26		14

12. A sample of rock contains 128 g of a radioisotope. State how much of the radioisotope will remain after:
    (a) two half-lives
    (b) four half-lives
13. Rock containing potassium-40 and argon-40 is melted and then solidified. Explain why this process sets the potassium-40 clock to zero.
14. What is a nuclear reaction?
15. How does a nuclear reaction differ from a chemical reaction?
16. What is a nuclear equation?
17. What two quantities do not change during a nuclear reaction?
18. How is it possible to induce a nuclear reaction?

Understanding Key Ideas

19. Explain how gamma radiation and visible light are:
(a) similar to each other
(b) different from each other

20. What are two medical applications of radioactivity?

21. What is meant by the phrase "natural background radiation"?

22. How can you use atomic number and mass number to determine the number of protons and neutrons in an atom?

23. Provide the nuclear symbol for each daughter nucleus in the following list. You can refer to the periodic table in Figure 4.3 on page 172.

(a) ${}^{201}_{80}\mathrm{Hg} \rightarrow$ ____ $+ {}^{0}_{-1}\beta$

(b) ${}^{231}_{91}\mathrm{Pa} \rightarrow$ ____ $+ {}^{4}_{2}\mathrm{He}$

(c) ${}^{225}_{89}\mathrm{Ac} \rightarrow$ ____ $+ {}^{4}_{2}\alpha$

(d) ${}^{60}_{28}\mathrm{Ni}^{*} \rightarrow$ ____ $+ {}^{0}_{0}\gamma$

(e) ${}^{238}_{92}\mathrm{U} \rightarrow$ ____ $+ {}^{4}_{2}\mathrm{He}$

(f) ${}^{24}_{11}\mathrm{Na} \rightarrow$ ____ $+ {}^{0}_{-1}e$

24. Complete the following radioactive decay equations.

(a) ____ $\rightarrow {}^{46}_{21}\mathrm{Sc}$ (alpha decay)

(b) ____ $\rightarrow {}^{40}_{19}\mathrm{K}$ (beta decay)

(c) ____ $\rightarrow {}^{3}_{2}\mathrm{He}$ (gamma decay)

(d) ____ $\rightarrow {}^{28}_{12}\mathrm{Mg}$ (alpha decay)

(e) ${}^{26}_{13}\mathrm{Al}^{*} \rightarrow$ ____ (gamma decay)

(f) ${}^{36}_{17}\mathrm{Cl} \rightarrow$ ____ (beta decay)

(g) ${}^{33}_{15}\mathrm{P} \rightarrow$ ____ (alpha decay)

Refer to Table 7.6, Common Isotope Pairs Chart, on page 307, to answer questions 25 to 27.

25. What is the daughter isotope that forms when carbon-14 undergoes radioactive decay?

26. How many years would it take for half of a sample of carbon-14 to decay?

27. If 100 micrograms (or 100 millionths of a gram) of carbon-14 were present in a sample of bone, state how many grams would be left after:
(a) 5730 years
(b) 11 460 years
(c) 17 190 years

28. Find the indicated daughter nucleus.

(a) ${}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ {}^{77}_{34}\mathrm{Se} + 3\,{}^{1}_{0}n +$ energy

(b) ${}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ {}^{93}_{40}\mathrm{Zr} + 3\,{}^{1}_{0}n +$ energy

(c) ${}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow$ ____ $+ {}^{105}_{46}\mathrm{Pd} + 3\,{}^{1}_{0}n +$ energy

29. For each item, decide whether it applies mainly to fusion, fission, or both.
(a) used to produce electrical energy
(b) used in atomic weapons
(c) reactions produce radioactive daughter products
(d) heavy nuclei split to release energy
(e) involves the combining of two light-weight atoms into a heavier one
(f) happens at the core of our Sun

Applying Your Understanding

30. It is not possible to predict which specific nuclei in a given sample of nuclei will decay over the course of one half-life, even if the chance of it decaying in one half-life is 50 percent. How does this compare with a coin toss, in which the likelihood of it landing heads up is very difficult to predict, even though the probability of it landing heads up is 50 percent?

Pause and Reflect

Reflect on what you have learned about radioactivity and fission. How are radioactivity and fission similar to each other? How are they different from each other?