NUCLEAR RADIATION

***M**arie Curie was a Polish scientist whose research led to many discoveries about radiation and radioactive elements. In 1903 she and her husband Pierre won the Nobel Prize for physics. She was also awarded the Nobel Prize for chemistry in 1911 for her research on radioactive elements. Marie Curie's research was invaluable to the understanding and use of newly discovered radioactive elements. In 1934 she died from leukemia caused by her long-term exposure to radiation.* **What types of radiation are there, and how harmful are they?**

objectives

- Discuss the processes of radioactivity and radioactive decay
- Characterize alpha, beta, and gamma radiation in terms of composition and penetrating power

key terms

- radioisotopes
- radioactivity
- radiation
- radioactive decay
- alpha radiation
- alpha particles
- beta radiation
- beta particles
- gamma radiation

Radioactivity

In the preceding chapters, you read about chemical reactions. In such reactions, atoms tend to attain stable electron configurations. This chapter deals with nuclear reactions, reactions in which the nuclei of unstable isotopes, called **radioisotopes,** gain stability by undergoing changes. These changes are always accompanied by the emission of large amounts of energy. Unlike chemical reactions, nuclear reactions are not affected by changes in temperature, pressure, or the presence of catalysts. They are also unaffected by the compounds in which the unstable isotopes are present, and they cannot be slowed down, speeded up, or turned off.

In 1896, the French chemist Antoine Henri Becquerel (1852–1908) made an interesting accidental discovery. He was studying the ability of uranium salts that had been exposed to sunlight to fog photographic film plates. During a period of bad weather in Paris, Becquerel realized that even uranium salts not exposed to the sun caused the same result in the film, as shown in **Figure 28.1.** At that time, two of Becquerel's associates were Marie Curie (1867–1934) and Pierre Curie (1859–1906). The Curies were able to show that the fogging of the plates was caused by rays emitted by the uranium atoms in the ore. Marie Curie named the process by which materials give off such rays **radioactivity.** The penetrating rays and particles emitted by a radioactive source are called **radiation.** Pierre Curie assisted his wife in the isolation of several radioactive elements. Together with Becquerel, they won the Nobel Prize in physics in 1903 for their work.

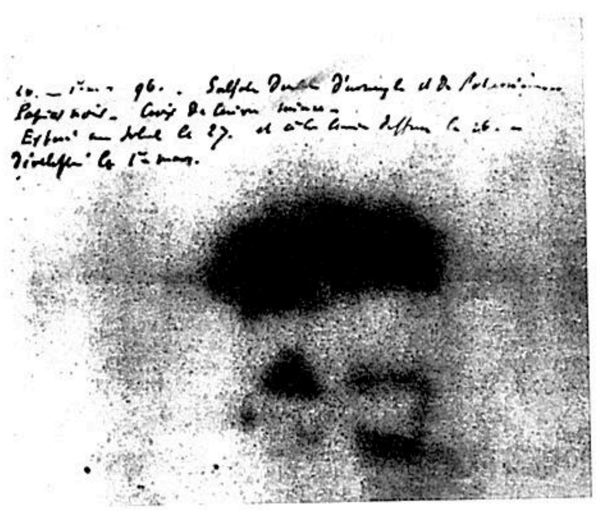


Figure 28.1
Uranium salts, which are radioactive, can fog a photographic plate like this one. This effect was discovered by the French chemist Antoine Henri Becquerel.

Table 28.1

Characteristics of Some Ionizing Radiations			
Property	**Alpha radiation**	**Beta radiation**	**Gamma radiation**
Composition	Alpha particle (helium nucleus)	Beta particle (electron)	High-energy electromagnetic radiation
Symbol	α, ${}^{4}_{2}He$	β, ${}^{0}_{-1}e$	γ
Charge	2+	1−	0
Mass (amu)	4	1/1837	0
Common source	Radium-226	Carbon-14	Cobalt-60
Approximate energy	5 MeV*	0.05 to 1 MeV	1 MeV
Penetrating power	Low (0.05 mm body tissue)	Moderate (4 mm body tissue)	Very high (penetrates body easily)
Shielding	Paper, clothing	Metal foil	Lead, concrete (incompletely shields)

*(1 MeV = 1.60×10^{-13} J)

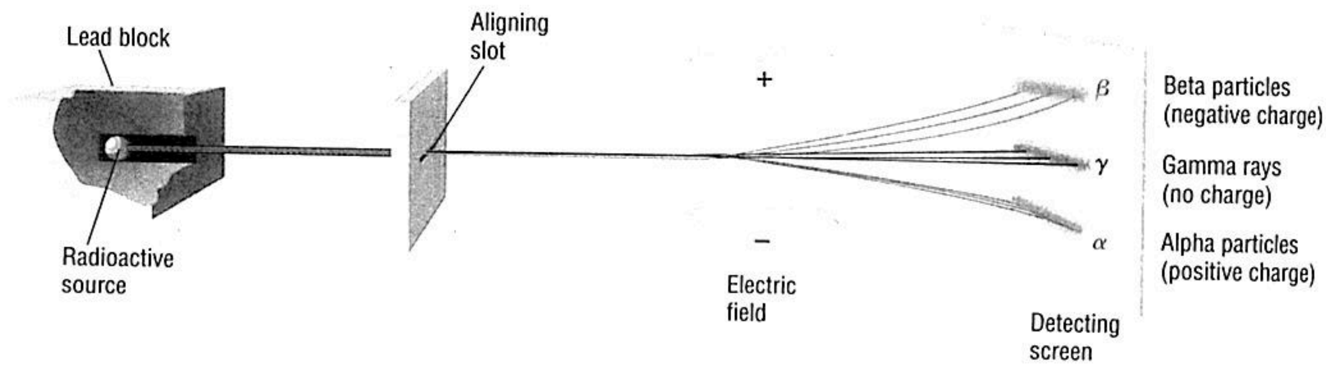
The discovery of radioactivity dealt a deathblow to Dalton's theory of indivisible atoms. A radioactive atom, or radioisotope, undergoes drastic changes as it emits radiation. Such radioisotopes have unstable nuclei. The stability of a nucleus depends on the relative proportion of neutrons to protons in the nucleus as well as on the overall size of the nucleus. The presence of too many or too few neutrons, relative to the number of protons, leads to an unstable nucleus. An unstable nucleus loses energy by emitting radiation during the process of **radioactive decay.** Eventually, unstable radioisotopes of one element are transformed into stable (nonradioactive) isotopes of a different element. Radioactive decay is spontaneous and does not require any input of energy.

Types of Radiation

Several types of radiation can be emitted during radioactive decay. **Table 28.1** summarizes the characteristics of three of these types of radiation. The different types of radiation from a radioactive source can be separated by an electric or magnetic field, as shown in **Figure 28.2.**

Figure 28.2

An electric field has different effects on these three types of radiation. Alpha particles and beta particles are deflected in opposite directions—alpha particles toward the negative plate and beta particles toward the positive plate. Gamma rays are undeflected.



A type of radiation called **alpha radiation** consists of helium nuclei that have been emitted from a radioactive source. These emitted particles, called **alpha particles,** contain two protons and two neutrons and have a double positive charge. In nuclear equations, an alpha particle is written ${}^{4}_{2}He$ or α. The electric charge is generally omitted.

The radioisotope uranium-238 releases alpha radiation and is transformed into another radioisotope, thorium-234. **Figure 28.3** illustrates this transformation.

$$\underset{\text{Uranium-238}}{{}^{238}_{92}U} \xrightarrow[\text{decay}]{\text{Radioactive}} \underset{\text{Thorium-234}}{{}^{234}_{90}Th} + \underset{\text{Alpha particle}}{{}^{4}_{2}He} \ (\alpha \text{ emission})$$

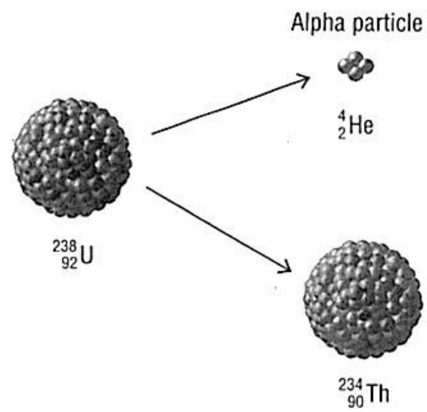


Figure 28.3
Uranium-238 is shown undergoing alpha decay to form thorium-234. What particle is emitted during this decay process?

Note that this nuclear equation is balanced. The sum of the mass numbers (superscripts) on the right equals the sum on the left. How does the sum of the atomic numbers (subscripts) on the right compare with the sum on the left?

When an atom loses an alpha particle, the atomic number of the product atom is lower by two and its mass number is lower by four. Because of their large mass and charge, alpha particles do not tend to travel very far and are not very penetrating. They are easily stopped by a sheet of paper or by the surface of your skin. However, radioisotopes that emit alpha particles are dangerous when ingested. The particles do not have to travel far to penetrate soft tissue and cause damage.

Beta radiation consists of fast-moving electrons formed by the decomposition of a neutron in an atom. The neutron decomposes into a proton, which remains in the nucleus, and an electron, which is released.

$$\underset{\text{Neutron}}{{}^{1}_{0}n} \longrightarrow \underset{\text{Proton}}{{}^{1}_{1}H} + \underset{\text{Electron (beta particle)}}{{}^{0}_{-1}e}$$

The fast-moving electrons released by a nucleus are called **beta particles.** The fact that they are negatively charged is reflected in the subscript -1 where atomic number is generally written. Their virtual lack of mass is represented by the superscript 0, corresponding to mass number.

Carbon-14 emits a beta particle as it undergoes radioactive decay to form nitrogen-14. **Figure 28.4** shows this beta emission.

$$\underset{\text{Carbon-14 (radioactive)}}{{}^{14}_{6}C} \longrightarrow \underset{\text{Nitrogen-14 (stable)}}{{}^{14}_{7}N} + \underset{\text{Beta particle}}{{}^{0}_{-1}e} \ (\beta \text{ emission})$$

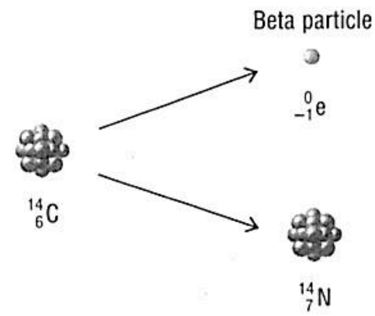


Figure 28.4
Carbon-14 is shown undergoing beta decay to form nitrogen-14. What particle is emitted during this decay process?

The mass number of the nitrogen-14 atom produced is the same as that of carbon-14. Its atomic number has increased by 1. The nucleus now contains an additional proton and one fewer neutron. Note that the nuclear equation is balanced. The sum of the atomic numbers on the right $(7 + (-1))$ equals the sum of the atomic numbers on the left (6). The mass numbers are also balanced (14 on each side). Beta particles have less charge and much less mass than alpha particles. Consequently, they are more penetrating. Beta particles are stopped by aluminum foil or thin pieces of wood.

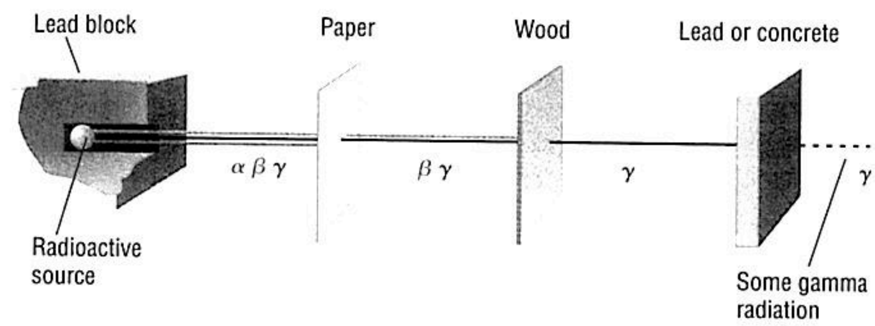


Figure 28.5

Because of their large mass and charge, alpha particles (red) have the least penetrating power of the three main types of radiation. Gamma rays (black) have no mass or charge and are the most penetrating.

Link TO PHYSICS

Particle Accelerators

Since the 1930s, physicists have used particle accelerators to probe the mysteries of the atom. In a particle accelerator, a beam of subatomic particles traveling near the speed of light collides with a nucleus, smashing it into fragments. Using a detection device called a bubble chamber, the path that these fragments take may be traced. Researchers have discovered evidence that suggests that protons and neutrons consist of even smaller particles called quarks. Quarks are thought to be held together by other particles, called gluons.

Gamma radiation is high-energy electromagnetic radiation given off by a radioisotope. Visible light, or the light you see, is also electromagnetic radiation, but of much lower energy. Gamma rays are often emitted along with alpha or beta radiation by the nuclei of disintegrating radioactive atoms. The following examples demonstrate this process.

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

Thorium-230 → Radon-226 + Alpha particle + Gamma ray

$$^{234}_{90}\text{Th} \longrightarrow \, ^{234}_{91}\text{Pa} + \, ^{0}_{-1}\text{e} + \gamma$$

Thorium-234 → Protactinium-234 + Beta particle + Gamma ray

Gamma rays have no mass and no electrical charge. Thus the emission of gamma radiation in itself does not alter the atomic number or mass number of an atom.

X-radiation, or x-rays, behave essentially the same as gamma rays, but their origin is different. X-rays are not emitted during radioactive decay. They are produced as excited electrons in certain metals lose their energy. X-rays are extremely penetrating and potentially very dangerous. Both gamma rays and x-rays pass easily through paper, wood, and the human body. They can be stopped, although not completely, by several meters of concrete or several centimeters of lead, as shown in **Figure 28.5.** Why does your dentist place a heavy apron over your torso before taking an x-ray?

section review 28.1

1. Explain what is meant by radioactivity and radioactive decay.
2. Distinguish among alpha, beta, and gamma radiation on the basis of the following.

   a. mass b. charge c. penetrating power
3. What part of an atom undergoes change during radioactive decay?

Chem ASAP! **Assessment 28.1** Check your understanding of the important ideas and concepts in Section 28.1.

NUCLEAR TRANSFORMATIONS

Although weather stripping and insulation help conserve energy, thus lowering heating and cooling bills, such efforts can prevent an ample exchange of fresh air. As a result, radioactive substances such as radon gas can accumulate and pose a health risk. Radon-222 is a radioactive isotope that is present naturally in the soil in some areas. It has a constant rate of decay. **How is the decay rate of a radioactive substance expressed?**

objectives

- Use half-life information to determine the amount of a radioisotope remaining at a given time
- Give examples of equations for the synthesis of transuranium elements by transmutation

key terms

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

Nuclear Stability and Decay

About 1500 different nuclei are known. Of those, only 264 are stable and do not decay or change with time. As mentioned earlier, the stability of a nucleus depends on its neutron-to-proton ratio. For elements of low atomic number (below about 20), the ratio for stability is about 1. That means the stable nuclei have roughly equal numbers of neutrons and protons. For example, the isotopes $^{12}_{6}C$, $^{14}_{7}N$, and $^{16}_{8}O$ are stable. Above atomic number 20, stable nuclei have more neutrons than protons. The neutron-to-proton ratio reaches about 1.5 for heavy elements. The lead isotope $^{206}_{82}Pb$, for example, with 124 neutrons and 82 protons, is stable. Its ratio is $\frac{124}{82} \approx 1.5$.

Figure 28.6 shows a plot of the number of neutrons versus the number of protons for all the known stable nuclei. The stable nuclei on a neutron-versus-proton plot are located in a region called the **band of stability.** Unstable nuclei undergo spontaneous radioactive decay. The type of decay that occurs depends on the neutron-to-proton ratio of the unstable nucleus.

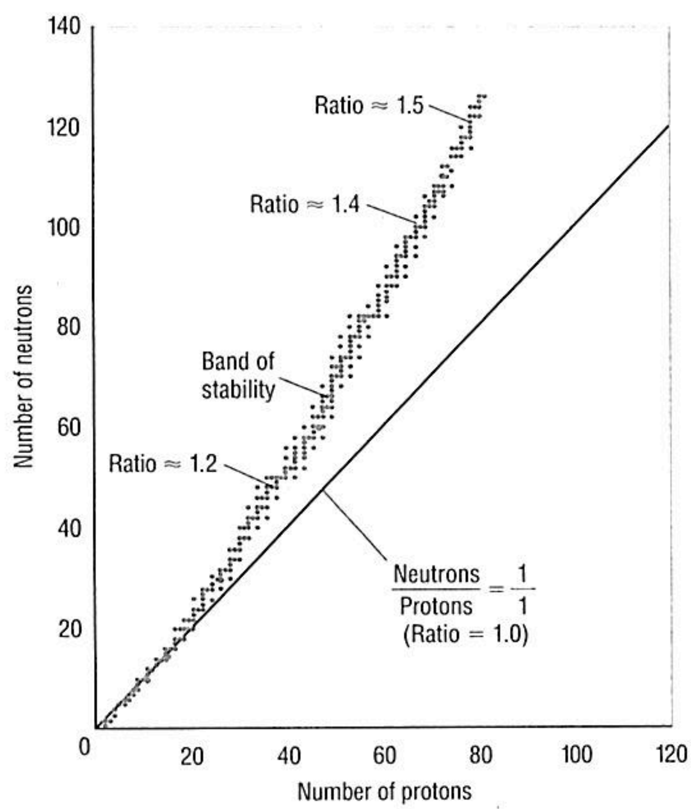


Figure 28.6
A neutron-versus-proton plot of all the known stable nuclei forms a pattern called the band of stability (shown in red). For isotopes of low atomic number, the stability ratio is about 1:1; for the heavier isotopes, the ratio increases to about 1.5:1.

A nucleus may be unstable for several reasons. Some nuclei have too many neutrons relative to the number of protons. These nuclei decay by turning a neutron into a proton and by emitting a beta particle (an electron) from the nucleus.

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

This process is known as beta decay or beta emission. It produces a simultaneous increase in the number of protons and a decrease in the number of neutrons. Here are the nuclear equations for several isotopes that undergo beta emission.

$$^{66}_{29}Cu \longrightarrow {}^{66}_{30}Zn + {}^{0}_{-1}e$$

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

Other nuclei are unstable because they have too few neutrons relative to the number of protons. These nuclei increase their stability by converting a proton to a neutron. As seen in the following examples, an electron is captured by a nucleus during this process.

$$^{59}_{28}Ni + {}^{0}_{-1}e \longrightarrow {}^{59}_{27}Co$$

$$^{37}_{18}Ar + {}^{0}_{-1}e \longrightarrow {}^{37}_{17}Cl$$

A **positron** is a particle with the mass of an electron but a positive charge. Its symbol is ${}^{0}_{+1}e$. A positron may be emitted as a proton changes to a neutron, as in the following cases.

$$^{8}_{5}B \longrightarrow {}^{8}_{4}Be + {}^{0}_{+1}e$$

$$^{15}_{8}O \longrightarrow {}^{15}_{7}N + {}^{0}_{+1}e$$

When a proton is converted to a neutron, the atomic number decreases by 1 and the number of neutrons increases by 1. How does this change affect the mass number?

All nuclei with atomic number greater than 83 are radioactive. These nuclei lie in the upper end of the band of stability, and are especially heavy. They have both too many neutrons and too many protons to be stable. Therefore they undergo decay. Most of them emit alpha particles. Alpha emission results in an increase in the neutron-to-proton ratio, which tends to increase the stability of the nucleus.

$$^{204}_{82}Pb \longrightarrow {}^{200}_{80}Hg + {}^{4}_{2}He$$

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

$$^{232}_{90}Th \longrightarrow {}^{228}_{88}Ra + {}^{4}_{2}He$$

In alpha emission, the mass number decreases by four and the atomic number decreases by two. If the masses of the reactants and products of a nuclear reaction could be determined with a sufficiently sensitive balance, you would find that mass is not conserved! In fact, an infinitesimally small quantity of mass is lost. The lost mass is converted to energy associated with radiation.

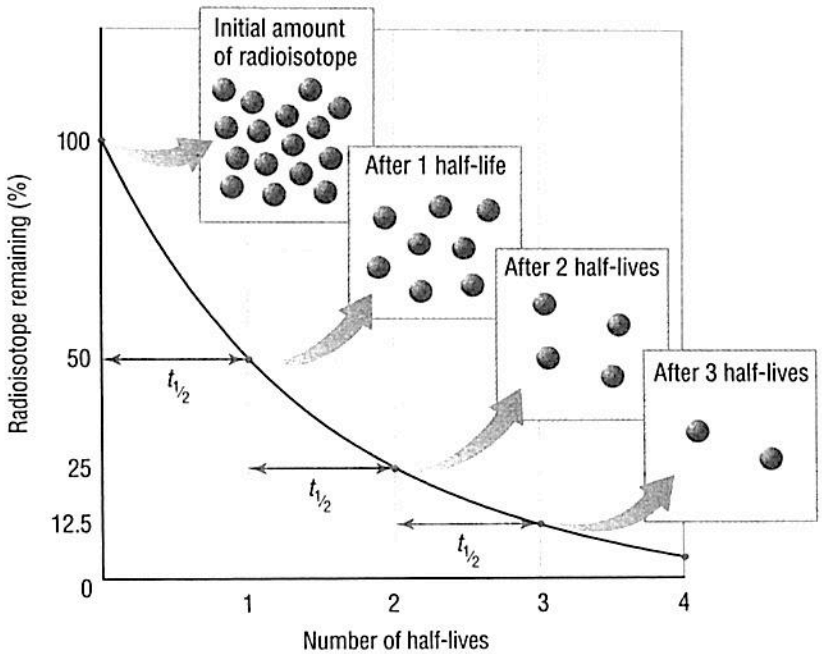


Figure 28.7

This decay curve for a radioactive element shows that by the end of each half-life, half of the remaining original radioactive atoms have decayed into atoms of another element.

Half-Life

Every radioisotope has a characteristic rate of decay measured by its half-life. A **half-life** ($t_{1/2}$) is the time required for one-half of the nuclei of a radioisotope sample to decay to products. After one half-life, half of the original radioactive atoms have decayed into atoms of a new element. The other half are still unchanged at that point, as demonstrated in **Figure 28.7.** After a second half-life, only one-quarter of the original radioactive atoms remain.

Half-lives may be as short as a fraction of a second or as long as billions of years. **Table 28.2** shows the half-lives of some naturally occurring radioisotopes. Scientists use the half-lives of some naturally occurring radioisotopes to determine the age of ancient artifacts. Many artificially produced radioisotopes have very short half-lives, a feature that is a great advantage in nuclear medicine. The rapidly decaying isotopes do not pose long-term biological radiation hazards to the patient.

Table 28.2

Half-Lives and Radiation of Some Naturally Occurring Radioisotopes

Isotope	Half-life	Radiation emitted
Carbon-14	5.73×10^3 years	β
Potassium-40	1.25×10^9 years	β, γ
Radon-222	3.8 days	α
Radium-226	1.6×10^3 years	α, γ
Thorium-230	7.54×10^4 years	α, γ
Thorium-234	24.1 days	β, γ
Uranium-235	7.0×10^8 years	α, γ
Uranium-238	4.46×10^9 years	α

LINK TO ARCHAEOLOGY

Carbon Dating

Carbon-14, which has a half-life of 5730 years, is used extensively to date artifacts that are made of organic material. All living organisms contain carbon-12

and carbon-14 in a fixed ratio. After an organism dies, however, the ratio of carbon-12 to carbon-14 changes as the carbon-14 decays to nitrogen-14. An object that was made of plant fibers might now have a carbon-14 concentration of one-half its original value. This object must therefore be about 5730 years old (one half-life). Carbon-14 dating can be used to determine the ages of objects between 200 and 50 000 years old. The Dead Sea Scrolls, for example, were determined to be 1940 ± 70 years old.

CHEMath

CALCULATING HALF-LIFE

This CHEMath feature provides more detailed information about half-life. With this information, you will have the skills needed to write the exponential decay function for a radioactive element. The table shows the amount of radioactive isotope remaining after 0, 1, and 2 half-lives if the initial amount is A_0.

Do you see the pattern? After n half-lives, the amount remaining is $A = A_0 \times \left(\frac{1}{2}\right)^n$. Since n is the time elapsed divided by the half-life, this equation can be written as $A = A_0 \times \left(\frac{1}{2}\right)^{t/T}$, where t is time and T is the half-life (using the same units). This type of equation is known as an exponential decay function.

Number of Half-Lives	Amount Remaining	Exponential Form
0	A_0	$A_0 \times \left(\frac{1}{2}\right)^0$
1	$A_0 \times \frac{1}{2}$	$A_0 \times \left(\frac{1}{2}\right)^1$
2	$A_0 \times \frac{1}{2} \times \frac{1}{2}$	$A_0 \times \left(\frac{1}{2}\right)^2$

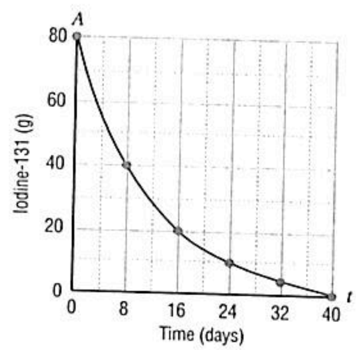
Logarithms can be used to algebraically calculate half-lives. You will use the formula $\log (a^b) = b \times \log a$, and you will want to use a calculator. See Example 2.

Example 1

Iodine-131 has a half-life of 8 days. Write and graph an equation for the amount (A) of iodine-131 after t days if the sample initially contains 80 g iodine-131.
Using $A = A_0 \times \left(\frac{1}{2}\right)^{t/T}$, the equation is $A = 80 \times \left(\frac{1}{2}\right)^{t/8}$.

The graph includes the points listed below.

t (days)	0	8	16	24	32
A (grams)	80	40	20	10	5



Example 2

A sample initially contains 100.0 g of thorium-234. After 16.0 days, the sample contains 63.1 g of thorium-234. Calculate the half-life.

Use the formula $A = A_0 \times \left(\frac{1}{2}\right)^{t/T}$.

$$63.1\ \text{g} = (100\ \text{g}) \times \left(\frac{1}{2}\right)^{(16.0\ \text{days})/T}$$

$$\frac{63.1}{100} = \left(\frac{1}{2}\right)^{(16.0\ \text{days})/T}$$

$$0.631 = 0.5^{(16.0\ \text{days})/T}$$

$$\log 0.631 = \log \left(0.5^{(16.0\ \text{days})/T}\right)$$

$$\log 0.631 = \frac{(16.0\ \text{days})}{T} \times \log 0.5$$

$$T = (16.0\ \text{days}) \times \frac{\log 0.5}{\log 0.631} = 24.1\ \text{days}$$

The half-life of thorium-234 is 24.1 days.

Practice Problems

Practice writing and using exponential decay functions by solving each of the following.

A. Technetium-104 has a half-life of 18 minutes. Write and graph an equation for the amount A of technetium-104 after t minutes if the sample initially contains 64 g of technetium-104.

B. A sample initially contains 248 g of strontium-90, which has a half-life of 29 years. Write an equation for the amount A of strontium-90 after t years. What is the amount of strontium-90 at $t = 52$ years?

C. A sample initially contains 50.0 g of cobalt-60. After 2.00 years, the sample contains 38.4 g of cobalt-60. Calculate the half-life of cobalt-60. What is the amount of cobalt-60 at $t = 8.00$ years?

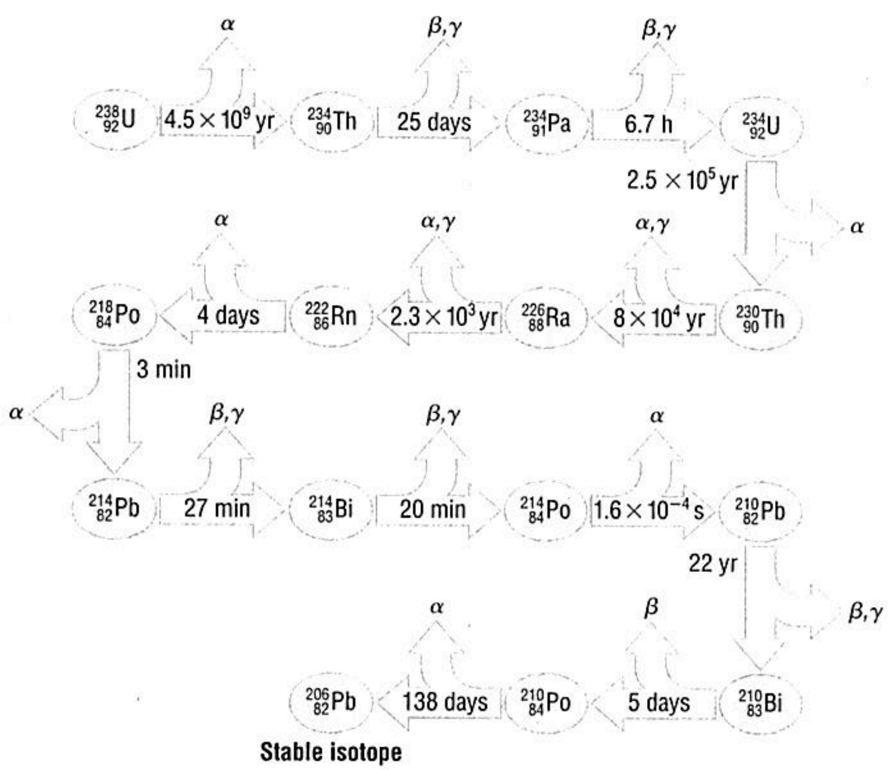


Figure 28.8
Uranium-238 decays through a complex series of radioactive intermediates, including radon gas (Rn). What is the stable end-product of this series?

Chem ASAP!
Simulation 30
Simulate the decay of several radioisotopes.

One isotope that has a long half-life is uranium-238, which decays through a complex series of radioactive intermediates to the stable isotope lead-206. **Figure 28.8** illustrates this process. The age of uranium-containing minerals can be estimated by measuring the ratio of uranium-238 to lead-206. Because the half-life of uranium-238 is 4.5×10^9 years, it is possible to use this method to date rocks nearly as old as the solar system.

Sample Problem 28-1

Nitrogen-13 emits beta radiation and decays to carbon-13 with a half-life ($t_{1/2}$) of 10 min. Assume a starting mass of 2.00 g of nitrogen-13.

a. How long is three half-lives?
b. How many grams of the isotope will still be present at the end of three half-lives?

1. *ANALYZE* ***List the knowns and the unknowns.***

Knowns:
- (t) = 10 min
- initial mass = 2.00 g
- number of half-lives = 3

Unknowns:
- 3 half-lives = ? min
- mass after 3 half-lives = ? g

Calculate the time required for three half-lives by multiplying the length of each half-life by the number of half-lives (3). Determine the mass remaining by multiplying the original mass by $\frac{1}{2}$ for each half-life.

Practice Problems

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

Practice Problems (cont.)

5. A sample of thorium-234 has a half-life of 25 days. Will all the thorium undergo radioactive decay in 50 days? Explain.

Chem ASAP!

Problem-Solving 4
Solve Problem 4 with the help of an interactive guided tutorial.

Sample Problem 28-1 (cont.)

2. ***CALCULATE*** *Solve for the unknowns.*
   a. 3×10 min $= 30$ min
   b. The initial mass of nitrogen-13, 2.00 g, is cut by one-half for each half-life, so for three half-lives

$$2.00 \text{ g} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 0.250 \text{ g}$$

3. ***EVALUATE*** *Do the results make sense?*
   The mass of nitrogen-13 after three half-lives is expected to be much lower than the original mass. The final answer has the proper units and the proper number of significant figures.

Transmutation Reactions

The conversion of an atom of one element to an atom of another element is called **transmutation.** As you have learned, radioactive decay is one way in which transmutation occurs. A transmutation can also occur when high-energy particles bombard the nucleus of an atom. The high-energy particles may be protons, neutrons, or alpha particles.

Many transmutations occur in nature. The production of carbon-14 from naturally occurring nitrogen-14, for example, takes place in the upper atmosphere. Another naturally occurring isotope, uranium-238, undergoes 14 transmutations before reaching a stable isotope, as was shown in **Figure 28.8.** Many other transmutations are done in laboratories or in nuclear reactors. The earliest artificial transmutation was performed in 1919 by Ernest Rutherford (1871–1937). He bombarded nitrogen gas with alpha particles to produce an unstable isotope of fluorine. The results of this reaction are shown in **Figure 28.9.** The reaction is

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

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

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

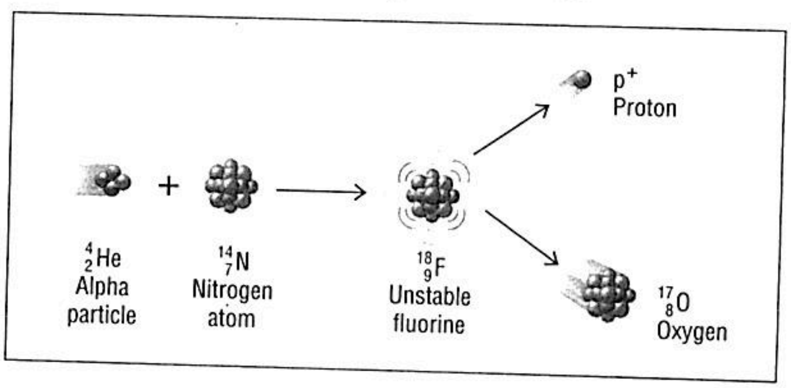


Figure 28.9
In 1919, Ernest Rutherford carried out the first artificial transmutation when he bombarded nitrogen gas with alpha particles. What particles were formed?

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

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

The elements in the periodic table with atomic numbers above 92, called the **transuranium elements,** all undergo transmutation. None of them occurs in nature, and all of them are radioactive. These elements have been synthesized in nuclear reactors and nuclear accelerators, one of which is shown in **Figure 28.10.** Such devices accelerate bombarding particles to very high speeds. When uranium-238 is bombarded with relatively slow neutrons from a nuclear reactor, some uranium nuclei capture neutrons to produce uranium-239.

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

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

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

Neptunium is unstable and decays to produce a second artificial element, plutonium (atomic number 94). What particle is emitted in this reaction?

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

Plutonium and neptunium are both transuranium elements and do not occur naturally. These first artificial elements were synthesized in 1940 by scientists in Berkeley, California. Since that time, more than 20 additional transuranium elements have been synthesized.

Figure 28.10
The Stanford Linear Accelerator Center is operated by Stanford University in California. This research facility houses a linear accelerator that is two miles long.

section review 28.2

6. How is half-life used to determine the amount of a radioisotope remaining at a given time?

7. Give two examples of equations for the synthesis of transuranium elements by transmutation.

8. Complete and balance the equations for the following nuclear reactions.

a. ${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \longrightarrow {}^{30}_{14}\text{Si} + ?$

b. ${}^{214}_{83}\text{Bi} \longrightarrow {}^{4}_{2}\text{He} + ?$

c. ${}^{27}_{14}\text{Si} \longrightarrow {}^{0}_{-1}\text{e} + ?$

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

9. Explain the process of transmutation. Write at least three nuclear equations to illustrate your answer.

10. The mass of cobalt-60 in a sample is found to have decreased from 0.800 g to 0.200 g in a period of 10.5 years. From this information, calculate the half-life of cobalt-60.

Chem ASAP! Assessment 28.2 Check your understanding of the important ideas and concepts in Section 28.2.

portfolio project

Research the methods used by archeologists to date materials such as pottery, coral, and stone. Prepare a poster display on the radioisotopes used, their half-lives, and their limitations.

SMALL-SCALE LAB

RADIOACTIVITY AND HALF-LIVES

SAFETY

Use safe and proper laboratory procedures.

PURPOSE

To simulate the chemical conversion of a reactant over time and to graph the data and relate it to radioactive decay and half-lives.

MATERIALS

- pencil
- paper
- ruler
- graph paper
- penny

PROCEDURE

On a sheet of paper, draw a grid similar to Figure A. Flip a penny 100 times and, in your grid, record the total number of heads that result. Now flip the penny the same number of times as the number of heads that you obtained in the first 100 flips. Record the total number of flips and the number of heads that result. Continue this procedure until you obtain no more heads. Record all your data in Figure A.

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

Figure A

ANALYSIS

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

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

YOU'RE THE CHEMIST

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

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

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

Write similar balanced nuclear equations for the alpha decay of each of the following.

a. Pa-231 **c.** Ra-226

b. Am-241 **d.** Es-252

3. **Analyze It!** Other radioisotopes undergo beta decay, emitting a beta particle (electron $^{0}_{-1}e$). For example,

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

Write similar balanced nuclear equations for the beta decay of each of the following.

a. H-3 **c.** I-131

b. Mg-28 **d.** Se-75

FISSION AND FUSION OF ATOMIC NUCLEI

The sun appears as a fiery ball in the sky—so bright it should never be looked at with unprotected eyes. Although its surface temperature is about 5800 K, the sun is not actually burning. If the energy given off by the sun were the product of a combustion reaction, the sun would have burned out approximately 2000 years after it was formed, long before today. **How is the energy given off by the sun produced?**

objectives

- Compare nuclear fission and nuclear fusion, and comment on their potential as sources of energy
- Describe the methods used in nuclear power plants to produce and control fission reactions
- Explain the issues involved in storage, containment, and disposal of nuclear waste.

key terms

- fission
- neutron moderation
- neutron absorption
- fusion

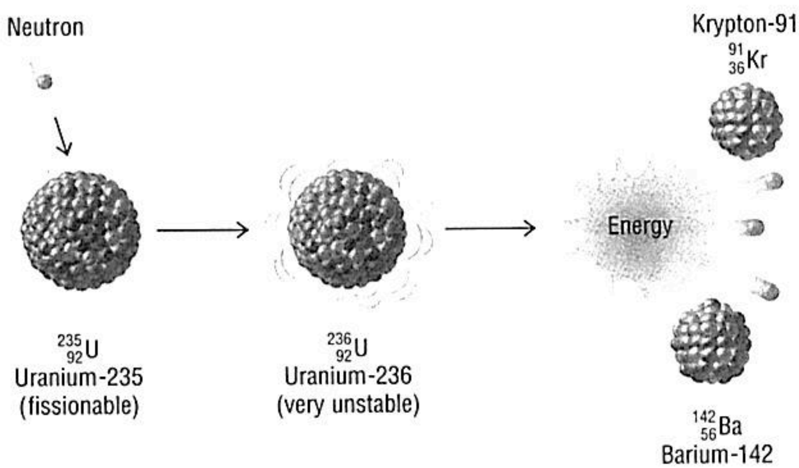
Nuclear Fission

When the nuclei of certain isotopes are bombarded with neutrons, they undergo **fission,** the splitting of a nucleus into smaller fragments. Uranium-235 and plutonium-239 are fissionable materials. As shown in **Figure 28.11,** a fissionable atom, such as uranium-235, breaks into two fragments of roughly the same size when struck by a slow-moving neutron. At the same time, more neutrons are released by the fission. These neutrons strike the nuclei of other uranium-235 atoms, continuing the fission by a chain reaction. In a chain reaction, some of the neutrons produced react with other fissionable atoms, producing more neutrons, which react with still more fissionable atoms. This process is similar to the toppling of dominoes shown in **Figure 28.11.**

Nuclear fission can unleash enormous amounts of energy. The fission of 1 kg of uranium-235, for example, releases an amount of energy equal to that generated in the explosion of 20 000 tons of dynamite. In an uncontrolled nuclear chain reaction, the total energy release is nearly instantaneous. The entire reaction takes only fractions of a second. Atomic bombs are devices that start uncontrolled nuclear chain reactions.

Chem ASAP!

Animation 30
Take a close look at a nuclear fission chain reaction.



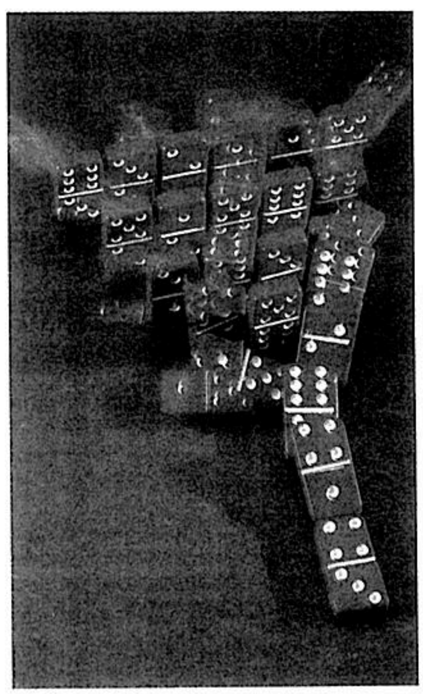


Figure 28.11
In nuclear fission, uranium-235 breaks into two fragments. What is produced? The released neutrons can split other uranium-235 atoms, creating a chain reaction. The toppling dominoes shown in the photograph illustrate the idea of a chain reaction.

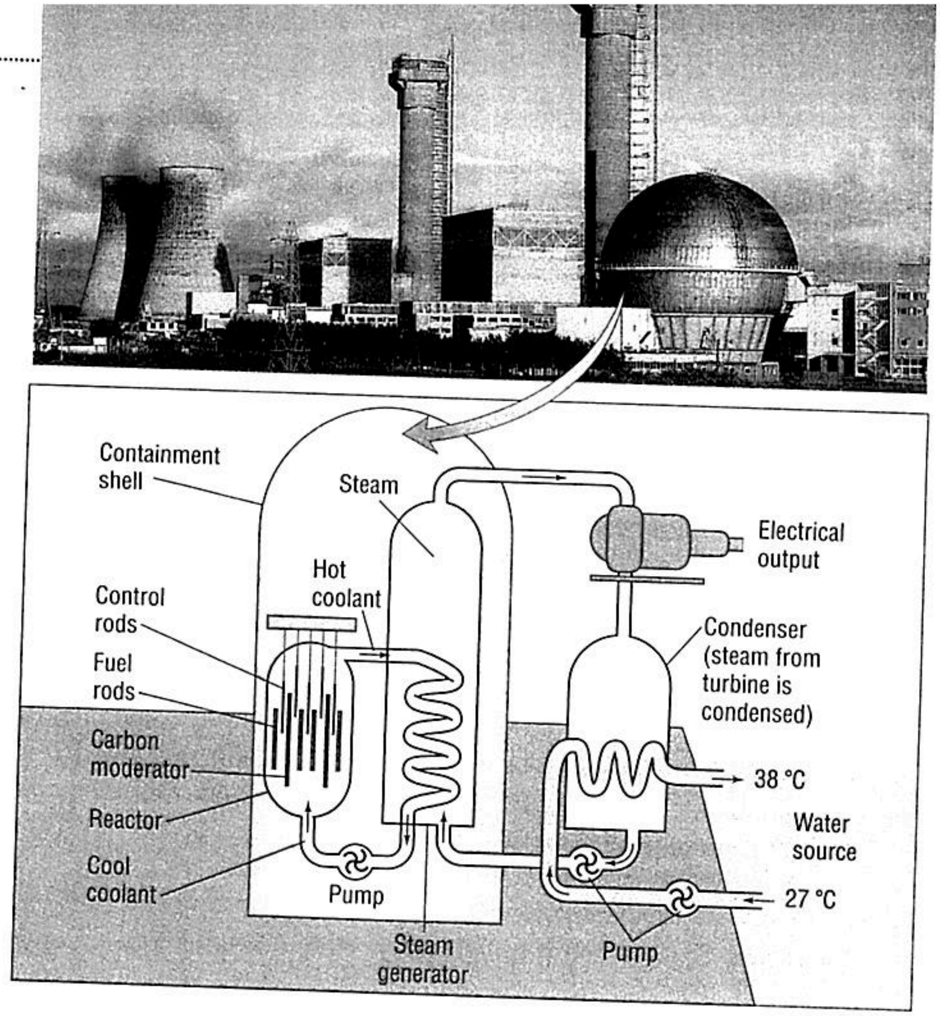


Figure 28.12
The illustration shows the basic components of a nuclear reactor. Heat produced in the reactor by the fission process is removed by circulating coolant. The removed heat is used to power a steam-driven turbine, which generates electricity.

Fission can be controlled so energy is released more slowly. Nuclear reactors, such as the one diagrammed in **Figure 28.12,** use controlled fission to produce useful energy. In the controlled fission reaction within a nuclear reactor, much of the energy generated is in the form of heat. A suitable coolant fluid, usually liquid sodium or water, removes the heat from the reactor core. The heat is used to generate steam, which drives a turbine that in turn generates electricity. The control of fission in a nuclear reactor involves two steps.

1. **Neutron moderation** is a process that reduces the speed of neutrons so they can be captured by the reactor fuel (usually uranium-235 or plutonium-239) in order to continue the chain reaction. Moderation is necessary because most of the neutrons produced move so fast that they will pass right through a nucleus without being absorbed. Water and carbon are good moderators because they slow the neutrons so the chain reaction can be sustained.
2. **Neutron absorption** is a process that decreases the number of slow moving neutrons. To prevent the chain reaction from going too fast, some of the slowed neutrons must be trapped before they hit fissionable atoms. Neutron absorption is carried out by control rods made of a material, such as cadmium, that absorbs neutrons. When the control rods extend almost all the way into the reactor core, they absorb many neutrons, and fission occurs slowly. As the rods are pulled out, they absorb fewer neutrons and the fission process speeds up. If the chain reaction were to go too fast, heat might be produced faster than

it could be removed by the coolant. In this case, the reactor core would overheat, which could lead to mechanical failure and release of radioactive materials into the atmosphere. Ultimately, a meltdown of the reactor core might occur.

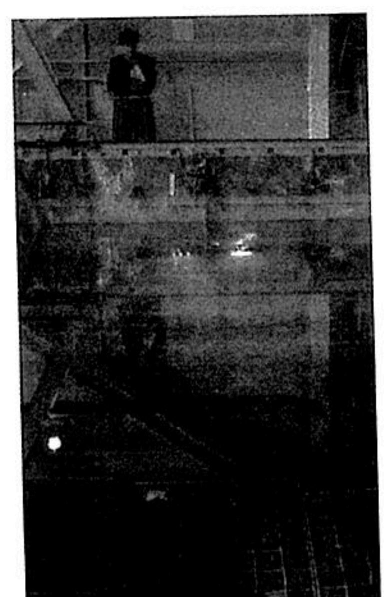
Despite other dangers, a nuclear reactor cannot produce a nuclear explosion. The fuel elements are widely separated and cannot physically connect to produce the critical mass required. Once a nuclear reactor is started, however, it remains highly radioactive for many generations. Shields protect the reactor structure from radiation damage. Walls of high-density concrete are also designed to protect the operating personnel.

Nuclear Waste

Fuel rods from nuclear power plants are one major source of nuclear waste. The fuel rods are made from a fissionable isotope, either uranium-235 or plutonium-239. The fuel rods are long and narrow—typically 3 meters long with a 0.5-cm diameter. Three hundred fuel rods are bundled together to form an assembly and one hundred assemblies are arranged to form the reactor core. During fission, the amount of fissionable isotope in each fuel rod decreases. There comes a time when there is no longer enough fuel in the rods to ensure that the output of the power station remains constant. The isotope-depleted, or spent, fuel rods must be removed and replaced with new fuel rods.

Spent fuel rods are classified as high-level nuclear waste. They contain the remainder of the fissionable isotope along with the fission products, a complex mixture of highly radioactive isotopes. Some of these fission products have very short half-lives, on the order of fractions of seconds. Others have half-lives of hundreds or thousands of years. All nuclear power plants have holding tanks, or swimming pools, for spent fuel rods. These pools, which are typically 12 meters deep, are filled with water as shown in **Figure 28.13.** Storage racks at the bottom of these pools are designed to hold the spent fuel assemblies. There are two reasons fuel assemblies are stored in water. Water cools the rods, which continue to produce heat for years after their removal from the core. Water also acts as a radiation shield to reduce the radiation levels from the spent fuel rods.

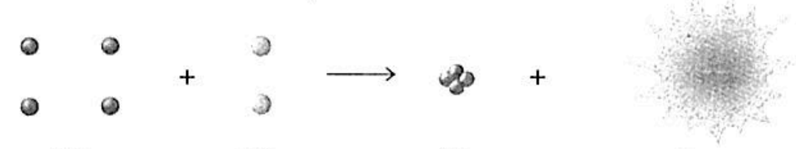
Figure 28.13
The racks at the bottom of this pool contain spent fuel rods.



The assemblies of spent fuel rods may spend a decade or more in a holding pool. Plant operators expected used fuel rods to be reprocessed to recover the remaining fissionable isotope, which would be recycled in the manufacture of new fuel rods. However, with large deposits of uranium ore available—many in the United States—it is less expensive to mine new fuel than to reprocess depleted fuel. At some nuclear plants, there is no space left in the storage pool. In order to keep these plants open, their fuel rods must be moved to off-site storage facilities.

The number of years a nuclear plant can operate is limited. Eventually the plant must be decommissioned and dismantled. Because the plant is usually contaminated with radioactive materials, dismantling produces thousands of tons of low-level nuclear waste. Low-level waste is taken to licensed burial sites that are monitored and controlled by the Department of Transportation (DOT) and the Nuclear Regulatory Commission (NRC). For more information on nuclear waste, see the feature on page 862.

Figure 28.14
Thermonuclear fusion reactions occurring in the sun have provided Earth with energy for billions of years.



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

hydrogen nuclei | beta particles | helium nucleus

Nuclear Fusion

The sun is an extraordinary energy source. The energy released by the sun results from a thermonuclear reaction, or nuclear fusion. **Fusion** occurs when nuclei combine to produce a nucleus of greater mass. In solar fusion, hydrogen nuclei (protons) fuse to make helium nuclei. **Figure 28.14** shows that the reaction also requires two beta particles. Fusion reactions tend to release more energy than do fusion reactions. However, fusion reactions occur only at very high temperatures—in excess of 40 000 000 °C.

The use of controlled nuclear fusion as an energy source on Earth is appealing. The potential fuels are inexpensive and readily available, and the fusion products are usually not radioactive. One reaction that scientists are studying is the combination of a deuterium (hydrogen-2) nucleus and a tritium (hydrogen-3) nucleus to form a helium nucleus.

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

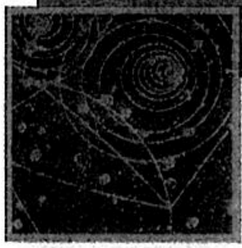
The problems with fusion lie in achieving the high temperatures necessary to start the reaction, and in containing the reaction once it has started. The high temperatures required to initiate fusion reactions have been achieved by using a fission bomb. Such a bomb is the triggering device used for setting off a hydrogen bomb, which is an uncontrolled-fusion device. Such a process is clearly of no use, however, as a controlled generator of power.

At the very high temperatures involved in fusion, matter exists as a plasma, a high-energy state in which ions exist in a gaslike form. To contain a plasma is a formidable task. No known structural material can withstand the hot, corrosive plasma. Scientists are experimenting with magnetic fields to contain plasma.

section review 28.3

11. Compare nuclear fission and fusion. Evaluate the reliability of each as a source of energy.
12. Describe how a nuclear fission power plant operates.
13. Explain what happens in a nuclear chain reaction.
14. Identify two types of nuclear waste produced by nuclear power plants.
15. Assuming technical problems could be overcome, what are some advantages to producing electricity in a fusion reactor?

Chem ASAP! **Assessment 28.3** Check your understanding of the important ideas and concepts in Section 28.3.



RADIATION IN YOUR LIFE

The Scottish physicist C.T.R Wilson wanted to study the formation of clouds, so he built a chamber in which he could duplicate cloud formation. In the chamber, water in the air condensed on dust particles, forming clouds. When Wilson used dust-free air, clouds continued to condense, provided the air was saturated enough. He hypothesized that clouds condensed on ions in the air. To test his hypothesis, Wilson exposed his chamber to ionizing radiation. The radiation left trails of condensed water droplets. When Wilson finished his work in 1912, his chamber had become a radiation detector used by many scientists of the day. **What are some other devices used to detect radiation, and how do they function?**

objectives

- Describe three methods of detecting radiation
- List some applications of radioisotopes in research and medicine

key terms

- ionizing radiation
- Geiger counter
- scintillation counter
- film badge

Detecting Radiation

X-rays and the radiation emitted by radioisotopes are called ionizing radiation. **Ionizing radiation** is radiation with enough energy to knock electrons off some atoms of the bombarded substance to produce ions. You cannot detect ionizing radiation with any of your senses. Instead, various instruments and monitoring devices are used for this purpose. One such device, called a **Geiger counter,** uses a gas-filled metal tube to detect radiation. **Figure 28.15** shows the construction of a Geiger counter. The tube has a central wire electrode that is connected to a power supply. When ionizing radiation penetrates a thin window at one end of tube, the gas inside the tube becomes ionized. Because of the ions and free electrons produced, the gas becomes an electrical conductor. Each time a Geiger tube is exposed to radiation, current flows. The bursts of current drive electronic counters or cause audible clicks from a built-in speaker. Geiger counters are used primarily to detect beta radiation. Alpha particles cannot pass through the end window. Most gamma rays and x-rays pass directly through the gas, causing few ionizations.

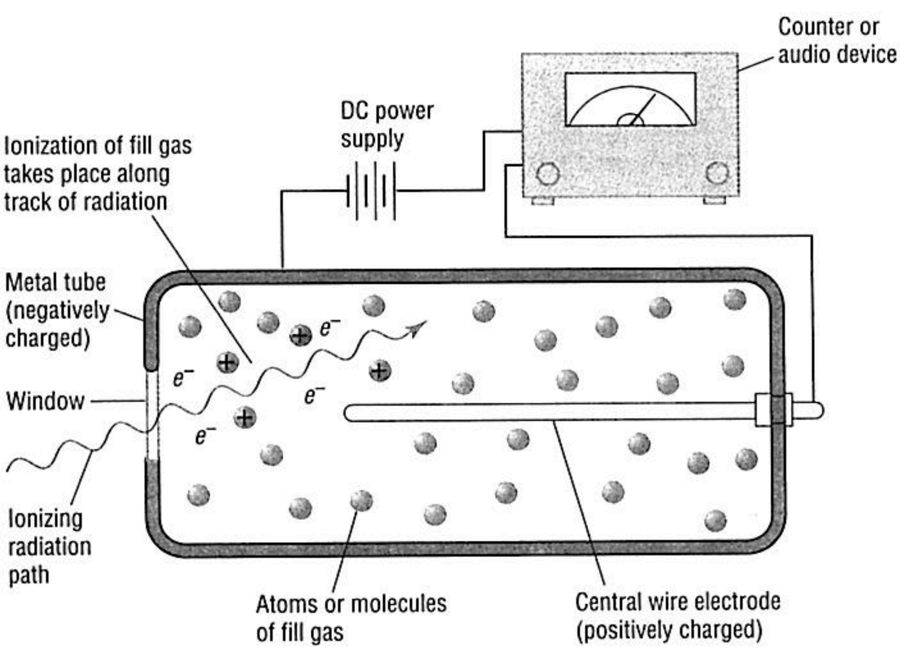


Figure 28.15
Radiation cannot be seen, heard, felt, or smelled. Thus warning signs and radiation-detection instruments must be used to alert people to the presence of radiation and to monitor its level. The Geiger counter is one such instrument that is widely used. What type of radiation does a Geiger counter primarily detect?

MINI LAB

Studying Inverse-Square Relationships

PURPOSE

To demonstrate the relationship between radiation intensity and the distance from the radiation source.

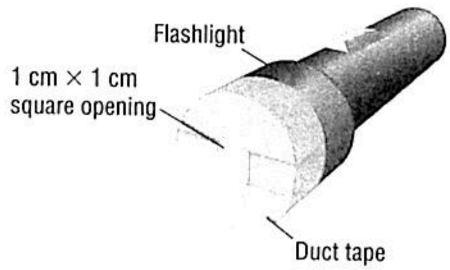
MATERIALS

- flashlight
- strips of duct tape
- scissors
- poster board, white (50 cm × 50 cm)
- meter ruler or tape measure
- flat surface, long enough to hold the meter ruler
- loose-leaf paper
- graph paper
- pen or pencil
- light sensor (optional)

PROCEDURE

Sensor version available in the Probeware Lab Manual.

1. Measure and record the distance (A) from the bulb filament to the front surface of the flashlight.
2. Cover the end of a flashlight with tape. Leave a 1-cm × 1-cm square hole in the center for light to pass through.
3. Place the flashlight on its side on a flat, horizontal surface. Turn on the flashlight. Darken the room.
4. Mount a large piece of white poster board directly in front of the flashlight, perpendicular to the horizontal surface.
5. Move the flashlight backward from the vertical board in short increments. At each position you select, record the distance (B) from the flashlight to the vertical board and the length (L) of one side of the square image projected on the board.



6. On a sheet of graph paper, plot L on the y-axis versus $A + B$ on the x-axis. On another sheet, plot L^2 on the y-axis versus $A + B$ on the x-axis.

ANALYSIS AND CONCLUSIONS

1. As the flashlight is moved away from the vertical board, what do you notice about the intensity of the light in the illuminated square? Use your graphs to demonstrate the relationship between intensity and distance.
2. When the distance of the flashlight from the board is doubled and tripled, what can you say about the areas and intensities of the illuminated squares?

A **scintillation counter** is a device that uses a specially coated phosphor surface to detect radiation. Ionizing radiation striking the phosphor surface produces bright flashes of light, or scintillations. The number of flashes and their respective energies are detected electronically. The information is then converted into electronic pulses, which are measured and recorded. Scintillation counters have been designed to detect all types of ionizing radiation. Such devices are similar to television screens coated with zinc sulfide (ZnS) as the phosphor. Inside a television, electrons are shot at a phosphor screen, producing scintillations. The pattern of these scintillations produces the television picture.

Film badges are important radiation detectors for persons who work near radiation sources. A **film badge,** shown in **Figure 28.16,** consists of several layers of photographic film covered with black lightproof paper, all encased in a plastic or metal holder. The badge is worn the entire time the person is at work. At specific intervals, with the frequency depending on the type of work involved, the film is removed and developed. The strength and type of radiation exposure are determined from the darkening of the film.

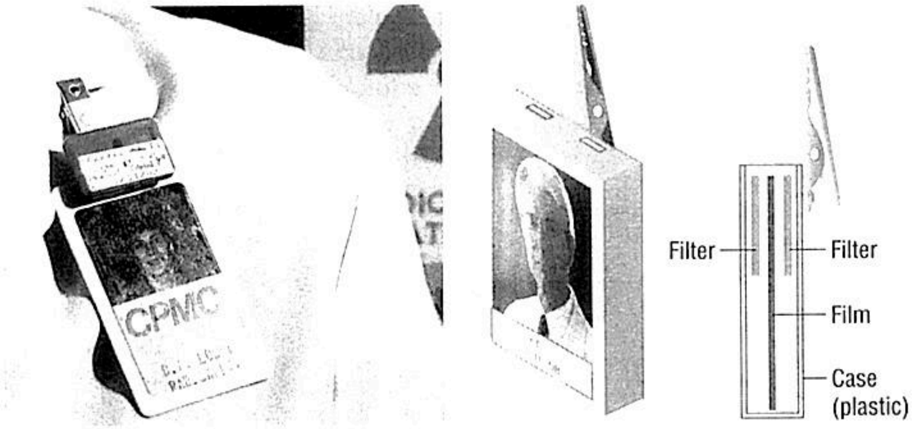


Figure 28.16
People who work with ionizing radiation wear film badge detectors. The film inside such a badge is exposed in proportion to the amount and type of radiation it receives.

Records are kept of the results. Film badges do not protect a person from radiation exposure. They merely serve as precautionary monitoring devices. Protection against radiation is achieved by keeping a safe distance from the source and by using adequate shielding.

Using Radiation

Although radiation can be harmful and should always be handled with care, it can be used safely and is important in many scientific procedures. Neutron activation analysis is a procedure used to detect trace amounts of elements in samples. In this procedure, a sample of interest is bombarded with neutrons from a radioactive source, which causes some atoms in the sample to become radioactive. The half-life and type of radiation emitted by the radioisotopes are detected, and this information is processed by a computer. Because this information is characteristic for each element, scientists can determine what radioisotopes were produced and what elements were originally present in the sample. This is a sensitive technique used to detect trace amounts of elements. It is capable of measuring 10^{-9} g of an element in a sample. Neutron activation analysis is used by museums to detect art forgeries, and by crime laboratories to analyze gunpowder residues.

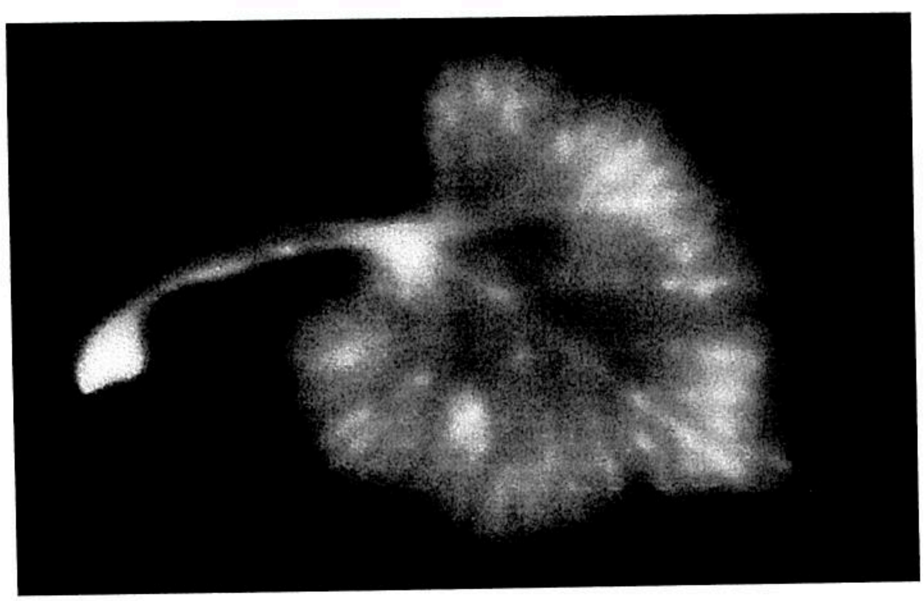


Figure 28.17
A radioactive tracer is used to determine where an absorbed pesticide or fertilizer is taken up by a plant.

Radioisotopes called tracers are used to study chemical reactions and molecular structures. During this procedure, one of the reactants is labeled with a radioisotope and added to the reaction mixture. After the reaction is complete, the radiation of the product is measured to determine the uptake of the tracer. By comparing this amount with the amount originally added, much can be learned about the reaction mechanism. Reactions with many steps can be studied using this method.

Radioisotope tracers are also used in agricultural research to test the effects of herbicides, pesticides, and fertilizers. During this procedure, the tracer is first introduced into the substance being tested to make the substance radioactive. Next, plants are treated with the radioactively labeled substance. Then, the radioactivity of the plants is measured to determine the location of the substance, as shown in **Figure 28.17** on the previous page. Often, the tracer is also monitored in animals that consume the plants, in water, and in soil. This information helps scientists determine the effects of using the substance.

Radioisotopes can even be used to diagnose some diseases. Iodine-131, for example, is used to detect thyroid problems. The thyroid gland extracts iodide ions from the bloodstream and uses them to make the hormone thyroxine. To diagnose thyroid disease, the patient is given a drink containing a small amount of the radioisotope iodine-131. After about two hours, the amount of iodide uptake is measured by scanning the patient's throat with a radiation detector. **Figure 28.18** shows the results of such a scan. In a similar way, the radioisotope technetium-99m is used to detect brain tumors and liver disorders. Phosphorus-32 is used to detect skin cancer.

Radiation has become a routine part of the treatment of some cancers. Cancer is a disease in which abnormal cells in the body are produced at a rate far beyond the rate for normal cells. The mass of cancerous tissue resulting from this runaway growth is called a tumor. Radiation therapy is often used to treat cancer because the fast-growing cancer cells are more susceptible to damage by high-energy radiation such as gamma rays than are the healthy cells. The cancerous area can be treated with radiation to kill the cancer cells. Some normal cells are also killed, however, and cancer cells at the center of the tumor may be resistant to the radiation. Therefore, the benefits of the treatment and the risks to the patient must be carefully evaluated before radiation treatment begins.

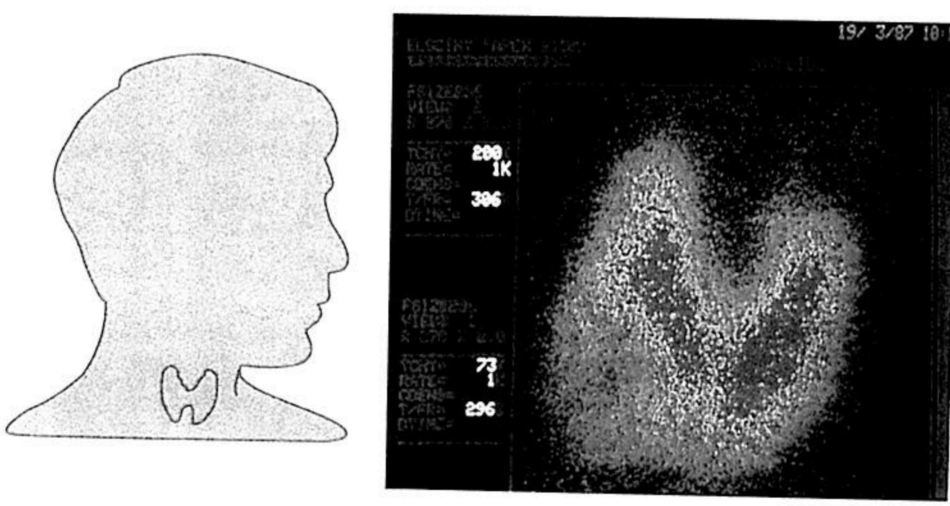


Figure 28.18

This scanned image of a thyroid gland shows where radioactive iodine-131 has been absorbed. Doctors use these images to identify thyroid disorders.

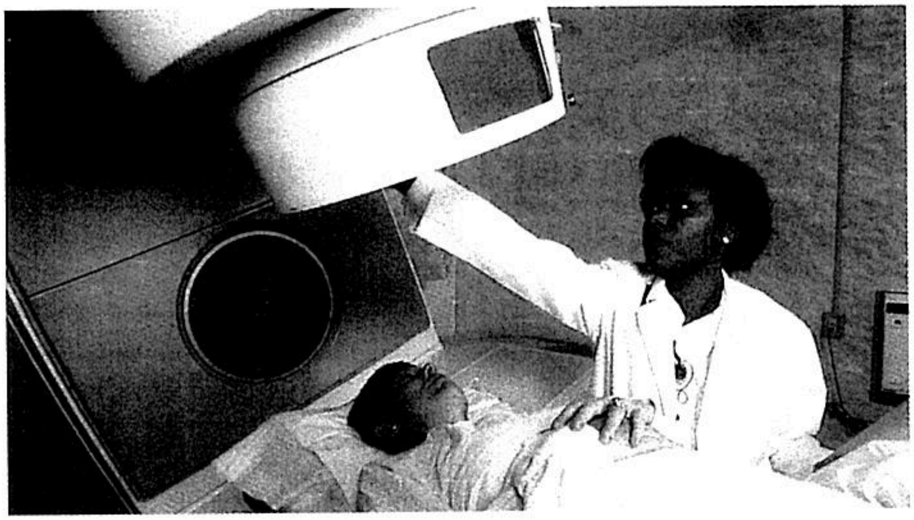


Figure 28.19

Radiation therapy is commonly used to treat cancer. The unit shown here emits a narrow, intense beam of radiation that destroys the ability of cells to reproduce. Cells are most vulnerable to the radiation when they are dividing. Why are cancer cells generally more sensitive to radiation than are normal cells?

In a technique called teletherapy, a narrow beam of high-intensity gamma radiation is directed at cancerous tissue. A radiation therapy unit used for teletherapy is shown in **Figure 28.19.** Cobalt-60 and cesium-137 are commonly used as the radiation sources. To minimize damage to healthy tissue, the patient is positioned so that only the cancerous region is within the radiation beam at all times. The unit rotates so that the radiation dose to the skin and surrounding normal tissue is minimized and distributed in a belt that extends all the way around the patient.

Salts of radioisotopes can also be sealed in gold tubes and directly implanted in tumors. These seeds emit beta and gamma rays that kill the surrounding cancer cells. Because the radioisotope is in a sealed container, it is prevented from traveling throughout the body.

Pharmaceuticals containing radioisotopes of gold, iodine, or phosphorus are sometimes given in radiation therapy. For example, a dose of iodine-131 larger than that used simply to detect thyroid diseases can be given to treat the diseased thyroid. The radioactive iodine accumulates in the thyroid and emits beta and gamma rays to provide therapy.

section review 28.4

16. Describe several methods of detecting radiation.

17. Describe several applications of radioisotopes in scientific research and in medicine.

18. Name an advantage of a scintillation counter over a Geiger counter.

19. Suppose that a radioactive solution containing an alpha emitter accidentally gets on your hands. You wash your hands with soap and water and then check them with a Geiger counter for residual radioactive contamination. The Geiger counter does not register any radioactivity. Are your hands definitely free from radioactive contamination? Explain.

20. What are some uses of radioactive tracers?

21. What is an advantage of using a radioactive seed to treat a cancerous tumor?

Chem ASAP! **Assessment 28.4** Check your understanding of the important ideas and concepts in Section 28.4.

portfolio project

Research and report on the use of technetium-99m to diagnose diseases and disorders of the liver or gallbladder. Explain how doctors use this technique to pinpoint the source of a problem without surgery.