Nuclear Reactions

Unstable nuclei undergo spontaneous changes that change their number of protons and neutrons. In this process, they give off large amounts of energy and increase their stability. These changes are a type of nuclear reaction. *A* **nuclear reaction** *is a reaction that affects the nucleus of an atom.* In equations representing nuclear reactions, the total of the atomic numbers and the total of the mass numbers must be equal on both sides of the equation. An example is shown below.

$$^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \longrightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}n$$

Notice that when the atomic number changes, the identity of the element changes. *A* **transmutation** *is a change in the identity of a nucleus as a result of a change in the number of its protons.*

SAMPLE PROBLEM A

Identify the product that balances the following nuclear reaction: $^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + \underline{\ ?\ }$

SOLUTION

1. The total mass number and atomic number must be equal on both sides of the equation.

$$^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + \underline{\ ?\ }$$

mass number: $212 - 4 = 208$ atomic number: $84 - 2 = 82$

2. The nuclide has a mass number of 208 and an atomic number of 82, $^{208}_{82}\mathrm{Pb}$.
3. The balanced nuclear equation is $^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + ^{208}_{82}\mathrm{Pb}$

PRACTICE

Answers in Appendix E

Using $^{1}_{0}n$ to represent a neutron and $^{0}_{-1}e$ to represent an electron, complete the following nuclear equations:

1. $^{253}_{99}\mathrm{Es} + ^{4}_{2}\mathrm{He} \longrightarrow ^{1}_{0}n + \underline{\ ?\ }$
2. $^{142}_{61}\mathrm{Pm} + \underline{\ ?\ } \longrightarrow ^{142}_{60}\mathrm{Nd}$

extension

Go to **go.hrw.com** for more practice problems that ask you to complete nuclear equations.

Keyword: HC6NUCX

SECTION REVIEW

1. Define mass defect.
2. How is nuclear stability related to the neutron-proton ratio?
3. Complete and balance the following nuclear equations:
   - **a.** $^{187}_{75}\mathrm{Re} + \underline{\ ?\ } \longrightarrow ^{188}_{75}\mathrm{Re} + ^{1}_{1}\mathrm{H}$
   - **b.** $^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \longrightarrow \underline{\ ?\ } + ^{1}_{0}n$
   - **c.** $^{22}_{11}\mathrm{Na} + \underline{\ ?\ } \longrightarrow ^{22}_{10}\mathrm{Ne}$

Critical Thinking

4. **INTERPRETING GRAPHICS** Examine **Figure 2,** and predict if $^{9}_{3}\mathrm{Li}$ is a stable isotope of lithium. Explain your answer.

Radioactive Decay

SECTION 2

OBJECTIVES

- Define and relate the terms *radioactive decay* and *nuclear radiation.*
- Describe the different types of radioactive decay and their effects on the nucleus.
- Define the term *half-life*, and explain how it relates to the stability of a nucleus.
- Define and relate the terms *decay series, parent nuclide,* and *daughter nuclide.*
- Explain how artificial radioactive nuclides are made, and discuss their significance.

In 1896, Henri Becquerel was studying the possible connection between light emission of some uranium compounds after exposure to sunlight and X-ray emission. He wrapped a photographic plate in a lightproof covering and placed a uranium compound on top of it. He then placed them in sunlight. The photographic plate was exposed even though it was protected from visible light, suggesting exposure by X rays. When he tried to repeat his experiment, cloudy weather prevented him from placing the experiment in sunlight. To his surprise, the plate was still exposed. This meant that sunlight was not needed to produce the rays that exposed the plate. The rays were produced by radioactive decay. **Radioactive decay** *is the spontaneous disintegration of a nucleus into a slightly lighter nucleus, accompanied by emission of particles, electromagnetic radiation, or both.* The radiation that exposed the plate was **nuclear radiation,** *particles or electromagnetic radiation emitted from the nucleus during radioactive decay.*

Uranium is a **radioactive nuclide,** *an unstable nucleus that undergoes radioactive decay*. Studies by Marie Curie and Pierre Curie found that of the elements known in 1896, only uranium and thorium were radioactive. In 1898, the Curies discovered two new radioactive metallic elements, polonium and radium. Since that time, many other radioactive nuclides have been identified. In fact, all of the nuclides beyond atomic number 83 are unstable and thus radioactive.

Types of Radioactive Decay

A nuclide's type and rate of decay depend on the nucleon content and energy level of the nucleus. Some common types of radioactive nuclide emissions are summarized in **Table 1.**

TABLE 1 ***Radioactive Nuclide Emissions***

Type	Symbol	Charge	Mass (amu)
Alpha particle	$^{4}_{2}$He	2+	4.001 5062
Beta particle	$^{0}_{-1}\beta$	1−	0.000 5486
Positron	$^{0}_{+1}\beta$	1+	0.000 5486
Gamma ray	γ	0	0

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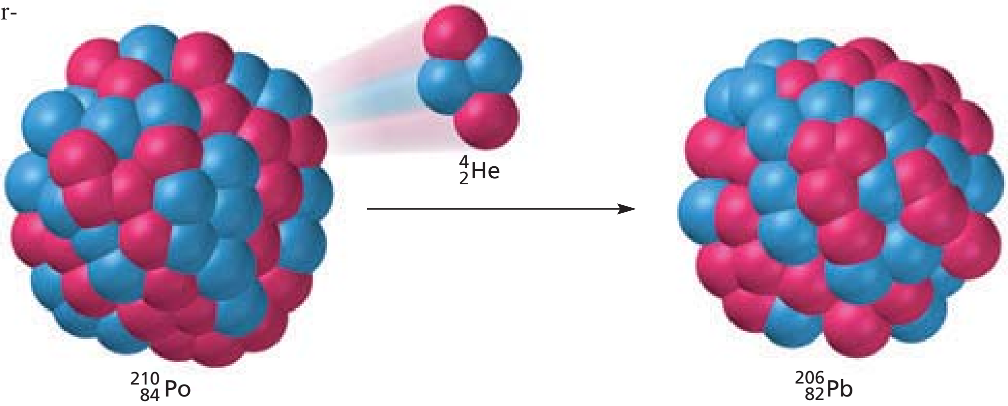
For a variety of links related to this chapter, go to www.scilinks.org

Topic: Radioactive Decay
SciLinks code: HC61254

FIGURE 4 An alpha particle, identical to a helium nucleus, is emitted during the radioactive decay of some very heavy nuclei.



Alpha Emission

An **alpha particle** *(α) is two protons and two neutrons bound together and is emitted from the nucleus during some kinds of radioactive decay.* Alpha particles are helium nuclei and have a charge of 2+. They are often represented with the symbol $^{4}_{2}He$. Alpha emission is restricted almost entirely to very heavy nuclei. In these nuclei, both the number of neutrons and the number of protons need to be reduced in order to increase the stability of the nucleus. An example of alpha emission is the decay of $^{210}_{84}Po$ into $^{206}_{82}Pb$, shown in **Figure 4.** The atomic number decreases by two, and the mass number decreases by four.

$$^{210}_{84}Po \longrightarrow\ ^{206}_{82}Pb +\ ^{4}_{2}He$$

Beta Emission

Nuclides above the band of stability are unstable because their neutron/proton ratio is too large. To decrease the number of neutrons, a neutron can be converted into a proton and an electron. The electron is emitted from the nucleus as a beta particle. *A* **beta particle** *(β) is an electron emitted from the nucleus during some kinds of radioactive decay.*

$$^{1}_{0}n \longrightarrow\ ^{1}_{1}p +\ ^{0}_{-1}\beta$$

An example of beta emission, shown in **Figure 5,** is the decay of $^{14}_{6}C$ into $^{14}_{7}N$. Notice that the atomic number increases by one and the mass number stays the same.

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

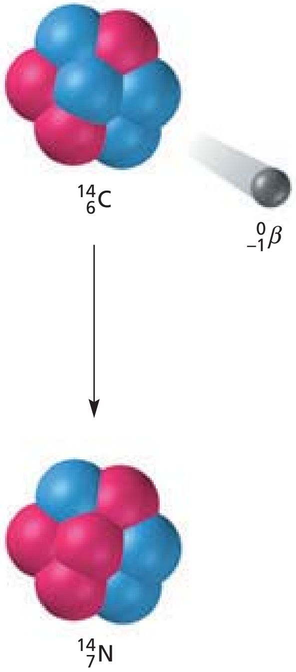


FIGURE 5 Beta emission causes the transmutation of $^{14}_{6}C$ into $^{14}_{7}N$. Beta emission is a type of radioactive decay in which a neutron is converted to a proton with the emission of a beta particle.

Positron Emission

Nuclides below the band of stability are unstable because their neutron/proton ratio is too small. To decrease the number of protons, a proton can be converted into a neutron by emitting a positron. *A* **positron** *is a particle that has the same mass as an electron, but has a positive charge, and is emitted from the nucleus during some kinds of radioactive decay.*

$$ {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta $$

An example of positron emission is the decay of ${}^{38}_{19}\text{K}$ into ${}^{38}_{18}\text{Ar}$. Notice that the atomic number decreases by one but the mass number stays the same.

$$ {}^{38}_{19}\text{K} \longrightarrow {}^{38}_{18}\text{Ar} + {}^{0}_{+1}\beta $$

Electron Capture

Another type of decay for nuclides that have a neutron/proton ratio that is too small is electron capture. *In* **electron capture,** *an inner orbital electron is captured by the nucleus of its own atom.* The inner orbital electron combines with a proton, and a neutron is formed.

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

An example of electron capture is the radioactive decay of ${}^{106}_{47}\text{Ag}$ into ${}^{106}_{46}\text{Pd}$. Just as in positron emission, the atomic number decreases by one but the mass number stays the same.

$$ {}^{106}_{47}\text{Ag} + {}^{0}_{-1}e \longrightarrow {}^{106}_{46}\text{Pd} $$

Gamma Emission

Gamma rays (γ) *are high-energy electromagnetic waves emitted from a nucleus as it changes from an excited state to a ground energy state.* The position of gamma rays in the electromagnetic spectrum is shown in **Figure 6.** The emission of gamma rays is another piece of evidence supporting the nuclear shell model. According to the nuclear shell model, gamma rays are produced when nuclear particles undergo transitions in nuclear-energy levels. This is similar to the emission of photons (light or X rays) when an electron drops to a lower energy level, which was covered in Chapter 4. Gamma emission usually occurs immediately following other types of decay, when other types of decay leave the nucleus in an excited state.

FIGURE 6 Gamma rays, like visible light, are a form of electromagnetic radiation, but they have a much shorter wavelength and are much higher in energy than visible light.

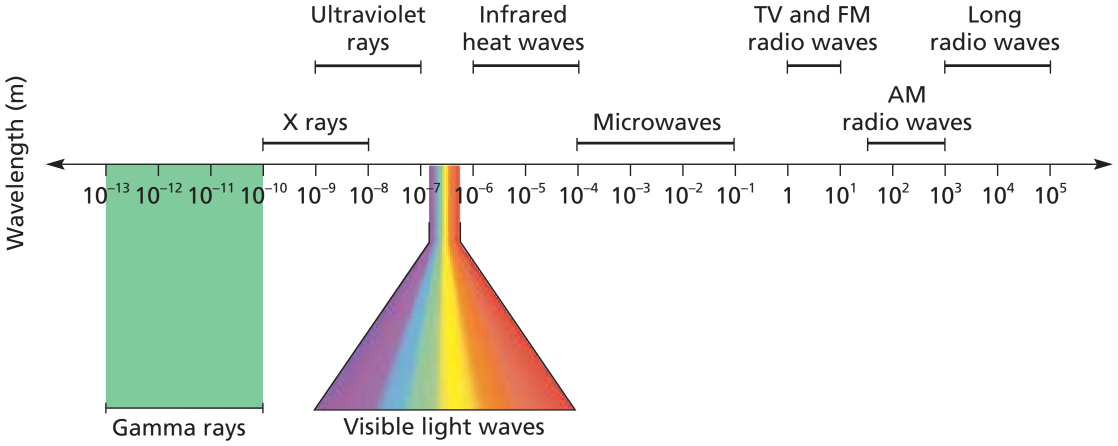
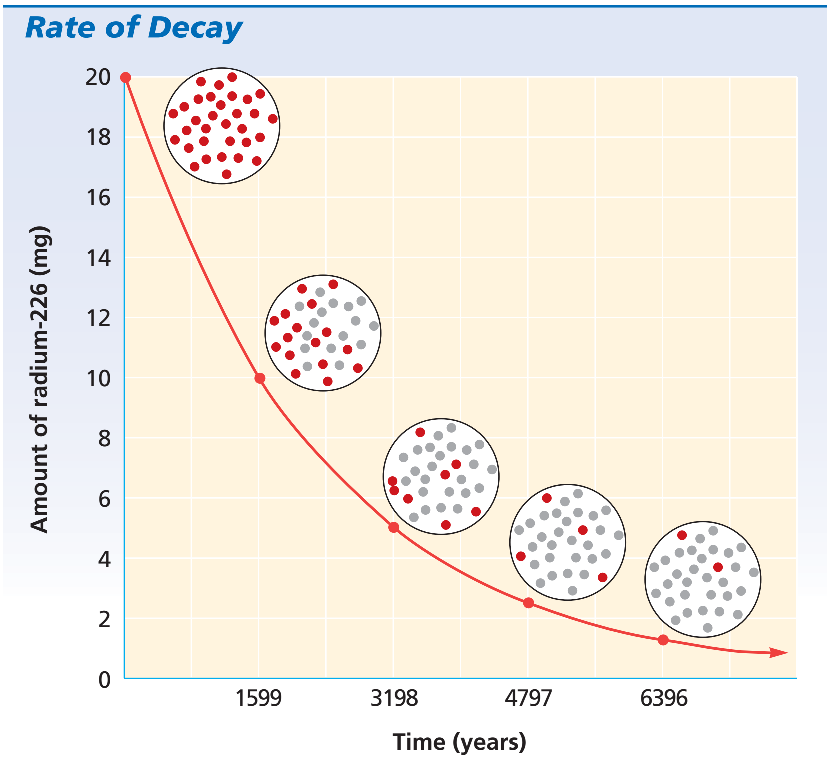


FIGURE 7 The half-life of radium-226 is 1599 years. Half of the remaining radium-226 decays by the end of each additional half-life.



Half-Life

No two radioactive isotopes decay at the same rate. **Half-life,** $t_{1/2}$, *is the time required for half the atoms of a radioactive nuclide to decay.* Look at the graph of the decay of radium-226 in **Figure 7.** Radium-226 has a half-life of 1599 years. Half of a given amount of radium-226 decays in 1599 years. In another 1599 years, half of the remaining radium-226 decays. This process continues until there is a negligible amount of radium-226. Each radioactive nuclide has its own half-life. More-stable nuclides decay slowly and have longer half-lives. Less-stable nuclides decay very quickly and have shorter half-lives, sometimes just a fraction of a second. Some representative radioactive nuclides, along with their half-lives, are given in **Table 2.**

TABLE 2 ***Representative Radioactive Nuclides and Their Half-Lives***

Nuclide	Half-life	Nuclide	Half-life
$^{3}_{1}\text{H}$	12.32 years	$^{214}_{84}\text{Po}$	163.7 μs
$^{14}_{6}\text{C}$	5715 years	$^{218}_{84}\text{Po}$	3.0 min
$^{32}_{15}\text{P}$	14.28 days	$^{218}_{85}\text{At}$	1.6 s
$^{40}_{19}\text{K}$	1.3×10^{9} years	$^{238}_{92}\text{U}$	4.46×10^{9} years
$^{60}_{27}\text{Co}$	5.27 years	$^{239}_{94}\text{Pu}$	2.41×10^{4} years

SAMPLE PROBLEM B

For more help, go to the Math Tutor at the end of the chapter.

Phosphorus-32 has a half-life of 14.3 days. How many milligrams of phosphorus-32 remain after 57.2 days if you start with 4.0 mg of the isotope?

SOLUTION

1 ANALYZE

Given: original mass of phosphorus-32 = 4.0 mg
half-life of phosphorus-32 = 14.3 days
time elapsed = 57.2 days

Unknown: mass of phosphorus-32 remaining after 57.2 days

2 PLAN

To determine the number of milligrams of phosphorus-32 remaining, we must first find the number of half-lives that have passed in the time elapsed. Then the amount of phosphorus-32 is determined by reducing the original amount by half for every half-life that has passed.

$$\text{number of half-lives} = \text{time elapsed (days)} \times \frac{\text{1 half-life}}{\text{14.3 days}}$$

$$\text{amount of phosphorus-32 remaining} = \text{original amount of phosphorus-32} \times \tfrac{1}{2} \text{ for each half-life}$$

3 COMPUTE

$$\text{number of half-lives} = 57.2\ \cancel{\text{days}} \times \frac{\text{1 half-life}}{14.3\ \cancel{\text{days}}} = \text{4 half-lives}$$

$$\text{amount of phosphorus-32 remaining} = 4.0\text{ mg} \times \tfrac{1}{2} \times \tfrac{1}{2} \times \tfrac{1}{2} \times \tfrac{1}{2} = 0.25\text{ mg}$$

4 EVALUATE

A period of 57.2 days is four half-lives for phosphorus-32. At the end of one half-life, 2.0 mg of phosphorus-32 remains; 1.0 mg remains at the end of two half-lives; 0.50 mg remains at the end of three half-lives; and 0.25 mg remains at the end of four half-lives.

PRACTICE

Answers in Appendix E

1. The half-life of polonium-210 is 138.4 days. How many milligrams of polonium-210 remain after 415.2 days if you start with 2.0 mg of the isotope?
2. Assuming a half-life of 1599 years, how many years will be needed for the decay of $\frac{15}{16}$ of a given amount of radium-226?
3. The half-life of radon-222 is 3.824 days. After what time will one-fourth of a given amount of radon remain?
4. The half-life of cobalt-60 is 5.27 years. How many milligrams of cobalt-60 remain after 52.7 years if you start with 10.0 mg?
5. A sample contains 4.0 mg of uranium-238. After 4.46×10^9 years, the sample will contain 2.0 mg of uranium-238. What is the half-life of uranium-238?

extension

Go to **go.hrw.com** for more practice problems that ask you to calculate the half-life or amount of sample remaining.

Keyword: HC6NUCX

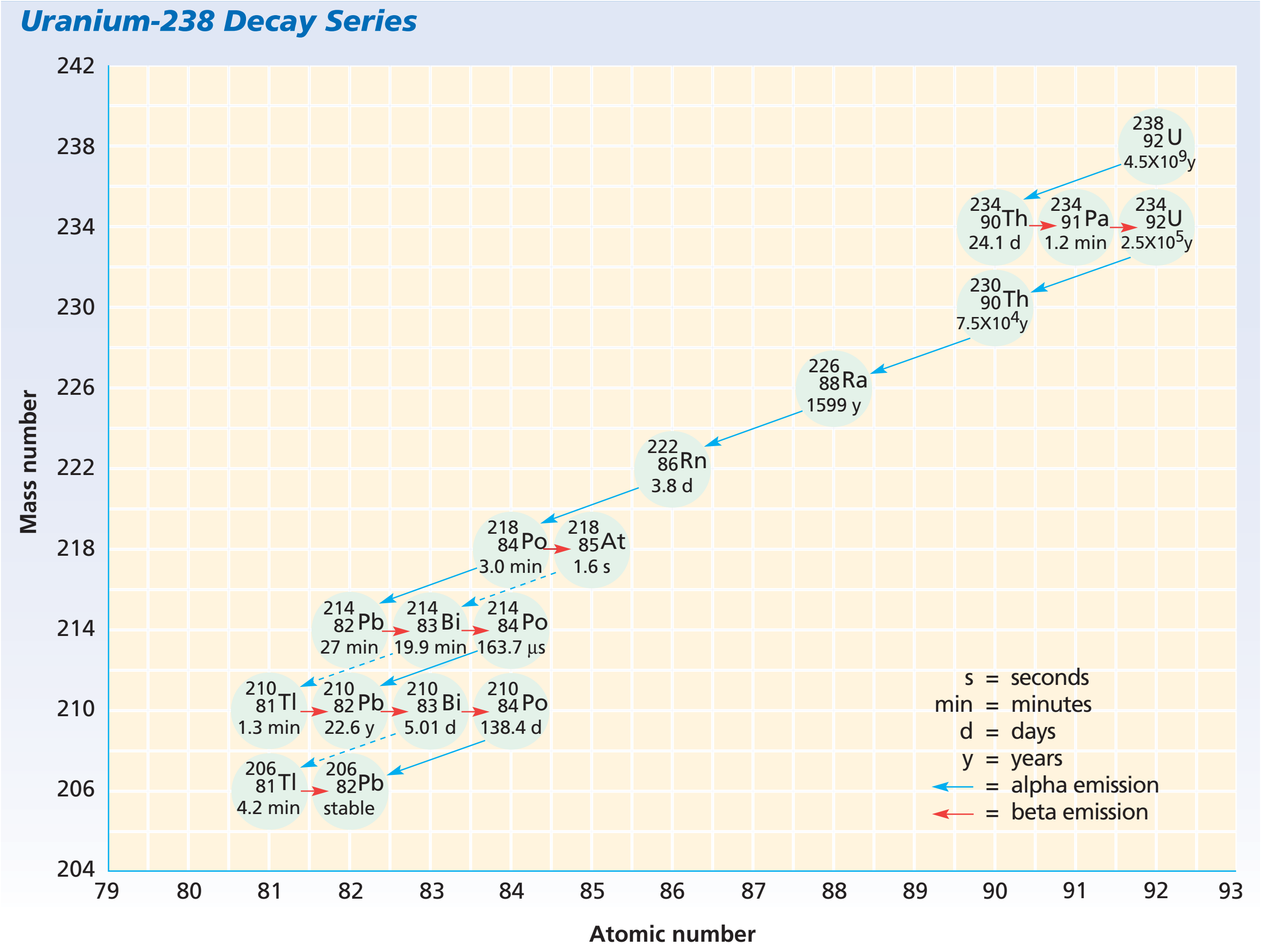
Decay Series

One nuclear reaction is not always enough to produce a stable nuclide. *A* **decay series** *is a series of radioactive nuclides produced by successive radioactive decay until a stable nuclide is reached. The heaviest nuclide of each decay series is called the* **parent nuclide.** *The nuclides produced by the decay of the parent nuclides are called* **daughter nuclides.** All naturally occurring nuclides with atomic numbers greater than 83 are radioactive and belong to one of three natural decay series. The parent nuclides are uranium-238, uranium-235, and thorium-232. The transmutations of the uranium-238 decay series are charted in **Figure 8.**

Locate the parent nuclide, uranium-238, on the chart. As the nucleus of uranium-238 decays, it emits an alpha particle. The mass number of the nuclide, and thus the vertical position on the graph, decreases by four. The atomic number, and thus the horizontal position, decreases by two. The daughter nuclide is an isotope of thorium.

$$^{238}_{92}\text{U} \longrightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

FIGURE 8 This chart shows the transmutations that occur as $^{238}_{92}$U decays to the final, stable nuclide, $^{206}_{82}$Pb. Decay usually follows the solid arrows. The dotted arrows represent alternative routes of decay.



Uranium-238 Decay Series

The half-life of $^{234}_{90}\text{Th}$, about 24 days, is indicated on the chart. It decays by giving off beta particles. This increases its atomic number, and thus its horizontal position, by one. The mass number, and thus its vertical position, remains the same.

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

The remaining atomic number and mass number changes shown on the decay chart are also explained in terms of the particles given off. In the final step, $^{210}_{84}\text{Po}$ loses an alpha particle to form $^{206}_{82}\text{Pb}$. This is a stable, nonradioactive isotope of lead. Notice that $^{206}_{82}\text{Pb}$ contains 82 protons, a magic number. It contains the extra-stable nuclear configuration of a completed nuclear shell.

extension

Historical Chemistry

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Keyword: HC6NUCX

Artificial Transmutations

Artificial radioactive nuclides are radioactive nuclides not found naturally on Earth. They are made by **artificial transmutations,** *bombardment of nuclei with charged and uncharged particles.* Because neutrons have no charge, they can easily penetrate the nucleus of an atom. However, positively charged alpha particles, protons, and other ions are repelled by the nucleus. Because of this repulsion, great quantities of energy are required to bombard nuclei with these particles. The necessary energy may be supplied by accelerating these particles in the magnetic or electrical field of a particle accelerator. An example of an accelerator is shown in **Figure 9.**

FIGURE 9 This is an aerial view of the Fermi International Accelerator Laboratory (Fermilab), in Illinois. The particle accelerators are underground. The Tevatron ring, the larger particle accelerator, has a circumference of 4 mi. The smaller ring (top left) is a new accelerator, the Main Injector.

TABLE 3 *Reactions for the First Preparation of Several Transuranium Elements*

Atomic number	Name	Symbol	Nuclear reaction
93	neptunium	Np	${}^{238}_{92}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{92}\mathrm{U}$ ${}^{239}_{92}\mathrm{U} \longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\beta$
94	plutonium	Pu	${}^{238}_{93}\mathrm{Np} \longrightarrow {}^{238}_{94}\mathrm{Pu} + {}^{0}_{-1}\beta$
95	americium	Am	${}^{239}_{94}\mathrm{Pu} + 2{}^{1}_{0}n \longrightarrow {}^{241}_{95}\mathrm{Am} + {}^{0}_{-1}\beta$
96	curium	Cm	${}^{239}_{94}\mathrm{Pu} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{242}_{96}\mathrm{Cm} + {}^{1}_{0}n$
97	berkelium	Bk	${}^{241}_{95}\mathrm{Am} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{243}_{97}\mathrm{Bk} + 2{}^{1}_{0}n$
98	californium	Cf	${}^{242}_{96}\mathrm{Cm} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{245}_{98}\mathrm{Cf} + {}^{1}_{0}n$
99	einsteinium	Es	${}^{238}_{92}\mathrm{U} + 15{}^{1}_{0}n \longrightarrow {}^{253}_{99}\mathrm{Es} + 7{}^{0}_{-1}\beta$
100	fermium	Fm	${}^{238}_{92}\mathrm{U} + 17{}^{1}_{0}n \longrightarrow {}^{255}_{100}\mathrm{Fm} + 8{}^{0}_{-1}\beta$
101	mendelevium	Md	${}^{253}_{99}\mathrm{Es} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{256}_{101}\mathrm{Md} + {}^{1}_{0}n$
102	nobelium	No	${}^{246}_{96}\mathrm{Cm} + {}^{12}_{6}\mathrm{C} \longrightarrow {}^{254}_{102}\mathrm{No} + 4{}^{1}_{0}n$
103	lawrencium	Lr	${}^{252}_{98}\mathrm{Cf} + {}^{10}_{5}\mathrm{B} \longrightarrow {}^{258}_{103}\mathrm{Lr} + 4{}^{1}_{0}n$

Artificial Radioactive Nuclides

Radioactive isotopes of all the natural elements have been produced by artificial transmutation. In addition, production of technetium and promethium by artificial transmutation has filled gaps in the periodic table. Their positions are shown in **Figure 10.**

Artificial transmutations are also used to produce the transuranium elements. **Transuranium elements** *are elements with more than 92 protons in their nuclei.* All of these elements are radioactive. The nuclear reactions for the synthesis of several transuranium elements are shown in **Table 3.** Currently, 17 artificially prepared transuranium elements have been named. Six more have been reported, but not confirmed. The positions of the transuranium elements in the periodic table are shown in **Figure 10.**

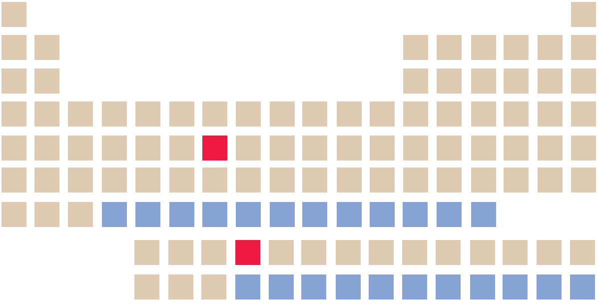


FIGURE 10 Artificial transmutations filled the gaps in the periodic table, shown in red, and extended the periodic table with the transuranium elements, shown in blue.

SECTION REVIEW

1. Define *radioactive decay.*
2. **a.** What are the different types of common radioactive decay?

   b. List the types of radioactive decay that convert one nuclide into another.
3. What fraction of a given sample of a radioactive nuclide remains after four half-lives?
4. When does a decay series end?

Critical Thinking

5. **INTERPRETING CONCEPTS** Distinguish between natural and artificial radioactive nuclides.

Nuclear Radiation

SECTION 3

OBJECTIVES

- Compare the penetrating ability and shielding requirements of alpha particles, beta particles, and gamma rays.
- Define the terms *roentgen* and *rem,* and distinguish between them.
- Describe three devices used in radiation detection.
- Discuss applications of radioactive nuclides.

In Becquerel's experiment, nuclear radiation from the uranium compound penetrated the lightproof covering and exposed the film. Different types of nuclear radiation have different penetrating abilities. Nuclear radiation includes alpha particles, beta particles, and gamma rays.

Alpha particles can travel only a few centimeters in air and have a low penetrating ability due to their large mass and charge. They cannot penetrate skin. However, they can cause damage if ingested or inhaled. Beta particles, which are emitted electrons, travel at speeds close to the speed of light and have a penetrating ability about 100 times greater than that of alpha particles. Beta particles can travel a few meters in air. Gamma rays have the greatest penetrating ability. The penetrating abilities and shielding requirements of different types of nuclear radiation are shown in **Figure 11.**

Radiation Exposure

Nuclear radiation can transfer the energy from nuclear decay to the electrons of atoms or molecules and cause ionization. *The* **roentgen (R)** *is a unit used to measure nuclear radiation exposure; it is equal to the amount of gamma and X ray radiation that produces* 2×10^9 *ion pairs when it passes through 1* cm^3 *of dry air.* Ionization can damage living tissue. Radiation damage to human tissue is measured in rems (roentgen equivalent, man). *A* **rem** *is a unit used to measure the dose of any type of ionizing radiation that factors in the effect that the radiation has on human tissue.* Long-term exposure to radiation can cause DNA mutations that result in cancer and

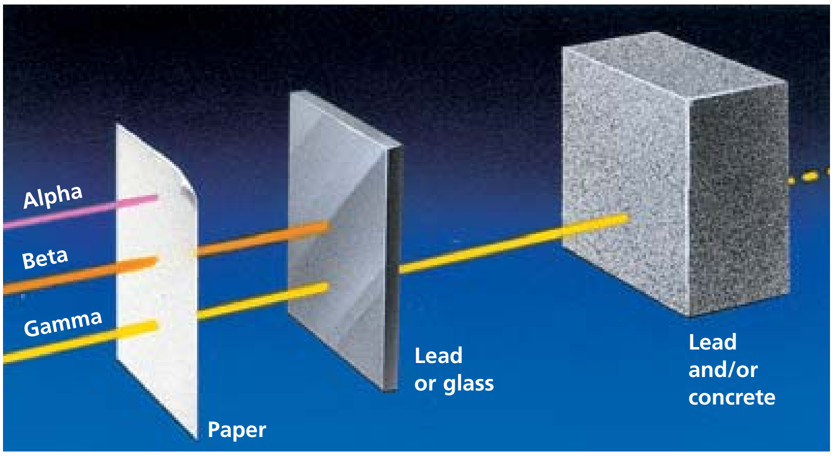


FIGURE 11 The different penetrating abilities of alpha particles, beta particles, and gamma rays require different levels of shielding. Alpha particles can be shielded with just a sheet of paper. Lead or glass is often used to shield beta particles. Gamma rays are the most penetrating and require shielding with thick layers of lead or concrete, or both.

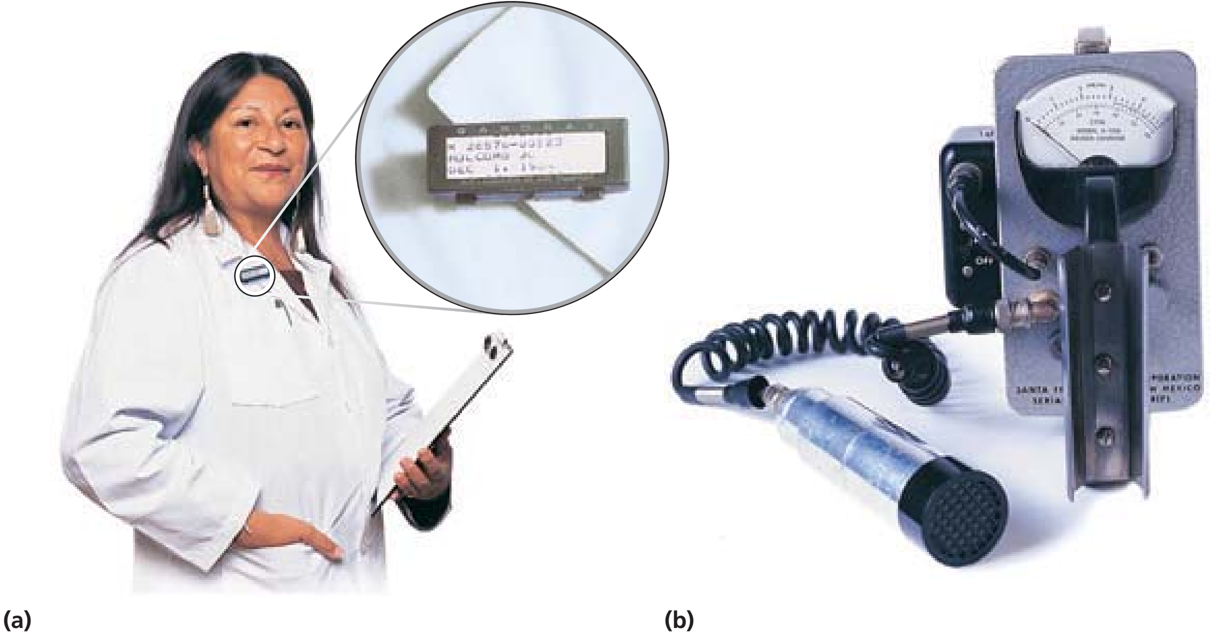
other genetic defects. DNA can be mutated directly by interaction with radiation or indirectly by interaction with previously ionized molecules.

Everyone is exposed to environmental background radiation. Average exposure for people living in the United States is estimated to be about 0.1 rem per year. However, actual exposure varies. The maximum permissible dose of radiation exposure for a person in the general population is 0.5 rem per year. Airline crews and people who live at high altitudes have increased exposure levels because of increased cosmic ray levels at high altitudes. Radon-222 trapped inside homes also causes increased exposure. Because it is a gas, radon released from certain rocks can move up through the soil into homes through holes in the foundation. Radon trapped in homes increases the risk of lung cancer, especially among smokers.

Radiation Detection

Film badges, Geiger-Müller counters, and scintillation counters are three devices commonly used to detect and measure nuclear radiation. A film badge and a Geiger-Müller counter are shown in **Figure 12.** As previously mentioned, nuclear radiation exposes film just as visible light does. This property is used in film badges. **Film badges** *use exposure of film to measure the approximate radiation exposure of people working with radiation*. **Geiger-Müller counters** *are instruments that detect radiation by counting electric pulses carried by gas ionized by radiation.* Geiger-Müller counters are typically used to detect beta-particles, X rays, and gamma radiation. Radiation can also be detected when it transfers its energy to substances that *scintillate,* or absorb ionizing radiation and emit visible light. **Scintillation counters** *are instruments that convert scintillating light to an electric signal for detecting radiation.*

FIGURE 12 Film badges (a) and Geiger-Müller counters (b) are both used to detect nuclear radiation.



Applications of Nuclear Radiation

Many applications are based on the fact that the physical and chemical properties of stable isotopes are essentially the same as those of radioactive isotopes of the same element. A few uses of radioactive nuclides are discussed below.

Radioactive Dating

Radioactive dating *is the process by which the approximate age of an object is determined based on the amount of certain radioactive nuclides present.* Such an estimate is based on the fact that radioactive substances decay with known half-lives. Age is estimated by measuring either the accumulation of a daughter nuclide or the disappearance of the parent nuclide.

Carbon-14 is radioactive and has a half-life of approximately 5715 years. It can be used to estimate the age of organic material up to about 50 000 years old. Nuclides with longer half-lives are used to estimate the age of older objects; methods using nuclides with long half-lives have been used to date minerals and lunar rocks more than 4 billion years old.

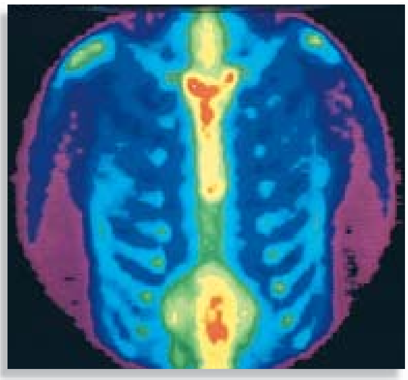


FIGURE 13 Radioactive nuclides, such as technetium-99, can be used to detect bone cancer. In this procedure, technetium-99 accumulates in areas of abnormal bone metabolism. Detection of the nuclear radiation then shows the location of bone cancer.

Radioactive Nuclides in Medicine

In medicine, radioactive nuclides, such as the artificial radioactive nuclide cobalt-60, are used to destroy certain types of cancer cells. Many radioactive nuclides are also used as **radioactive tracers,** *which are radioactive atoms that are incorporated into substances so that movement of the substances can be followed by radiation detectors.* Detection of radiation from radioactive tracers can be used to diagnose cancer and other diseases. See **Figure 13.**

Radioactive Nuclides in Agriculture

In agriculture, radioactive tracers in fertilizers are used to determine the effectiveness of the fertilizer. The amount of radioactive tracer absorbed by a plant indicates the amount of fertilizer absorbed. Nuclear radiation is also used to prolong the shelf life of food. For example, gamma rays from cobalt-60 can be used to kill bacteria and insects that spoil and infest food.

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Topic: Radioisotopes
SciLinks code: HC61256

Nuclear Waste

Nuclear Fission and Nuclear Fusion

In nuclear fission, the nucleus of a very heavy atom, such as uranium, is split into two or more lighter nuclei. The products of the fission include the nuclei as well as the nucleons formed from the fragments' radioactive decay. Fission is the primary process powering nuclear reactors, which include those on nuclear-powered submarines and aircraft carriers. Fusion is the opposite process of fission. In fusion, very high temperatures and pressures are used to combine light atoms, such as hydrogen, to make heavier atoms, such as helium. Fusion is the primary process that fuels our sun and the stars. Creating and maintaining a fusion reaction is more complex and expensive than performing fission. Both fission and fusion release enormous amounts of energy that can be converted into energy as heat and electrical energy, and both produce **nuclear waste.** Fission produces more waste than fusion. As new processes are developed to use energy from fission and fusion, a more vexing question arises: how to contain, store, and dispose of nuclear waste.

Containment of Nuclear Waste

Every radioactive substance has a half-life, which is the amount of time needed for half of a given material to decay. Radioactive waste from medical research, for example, usually has a half-life that is a few months or less. Some of the waste that is produced in a nuclear reactor will take hundreds of thousands of years to decay, and it needs to be contained so that living organisms can be shielded from radioactivity. There are two main types of containment: on-site storage and off-site disposal.

Storage of Nuclear Waste

The most common form of nuclear waste is spent fuel rods from nuclear power plants. These fuel rods can be contained above the ground by placing them in water pools or in dry casks. Each nuclear reactor in the United States has large pools of water where spent rods can be stored, and some of the radioactive materials will decay. When these pools are full, the rods are moved to dry casks, which are usually made of concrete and steel. Both storage pools and casks are meant for only temporary storage before the waste is moved to permanent underground storage facilities.

Disposal of Nuclear Waste

Disposal of nuclear waste is done with the intention of never retrieving the materials. Because of this, building disposal sites takes careful planning. Currently, there are 77 disposal sites around the United States. The U. S. Department of Energy is developing a new site near Las Vegas, Nevada, called Yucca Mountain, for the permanent disposal of much of this waste. Nuclear waste could be transported there by truck and train beginning in 2010. This plan is controversial—some organizations oppose the idea of the disposal site, and others have proposed alternate plans.

SECTION REVIEW

1. What is required to shield alpha particles? Why are these materials effective?
2. **a.** What is the average exposure of people living in the United States to environmental background radiation?

   b. How does this relate to the maximum permissible dose?
3. What device is used to measure the radiation exposure of people working with radiation?
4. Explain why nuclear radiation can be used to preserve food.

Critical Thinking

5. **INFERRING CONCLUSIONS** Explain how nuclear waste is contained, stored, and disposed of, and how each method affects the environment.

Nuclear Fission and Nuclear Fusion

SECTION 4

OBJECTIVES

- Define *nuclear fission, chain reaction,* and *nuclear fusion,* and distinguish between them.
- Explain how a fission reaction is used to generate power.
- Discuss the possible benefits and the current difficulty of controlling fusion reactions.

Nuclear Fission

Review **Figure 1,** which shows that nuclei of intermediate mass are the most stable. *In* **nuclear fission,** *a very heavy nucleus splits into more-stable nuclei of intermediate mass.* This process releases enormous amounts of energy. Nuclear fission can occur spontaneously or when nuclei are bombarded by particles. When uranium-235 is bombarded with slow neutrons, a uranium nucleus may capture one of the neutrons, making it very unstable. The nucleus splits into medium-mass nuclei with the emission of more neutrons. The mass of the products is less than the mass of the reactants. The missing mass is converted to energy.

Nuclear Chain Reaction

When fission of an atom bombarded by neutrons produces more neutrons, a chain reaction can occur. *A* **chain reaction** *is a reaction in which the material that starts the reaction is also one of the products and can start another reaction.* As shown in **Figure 14,** two or three neutrons can be given off when uranium-235 fission occurs. These neutrons can cause the fission of other uranium-235 nuclei. Again neutrons are emitted, which

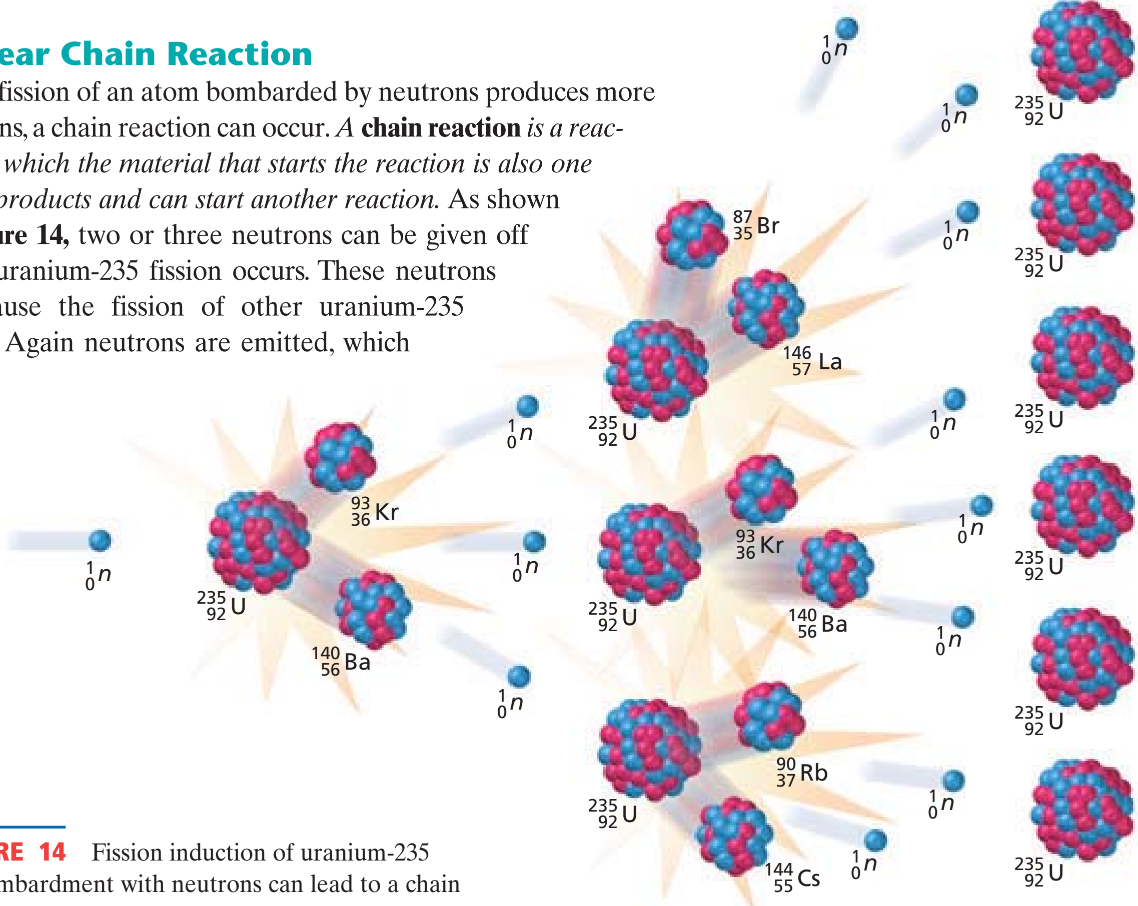

FIGURE 14 Fission induction of uranium-235 by bombardment with neutrons can lead to a chain reaction when a critical mass of uranium-235 is present.

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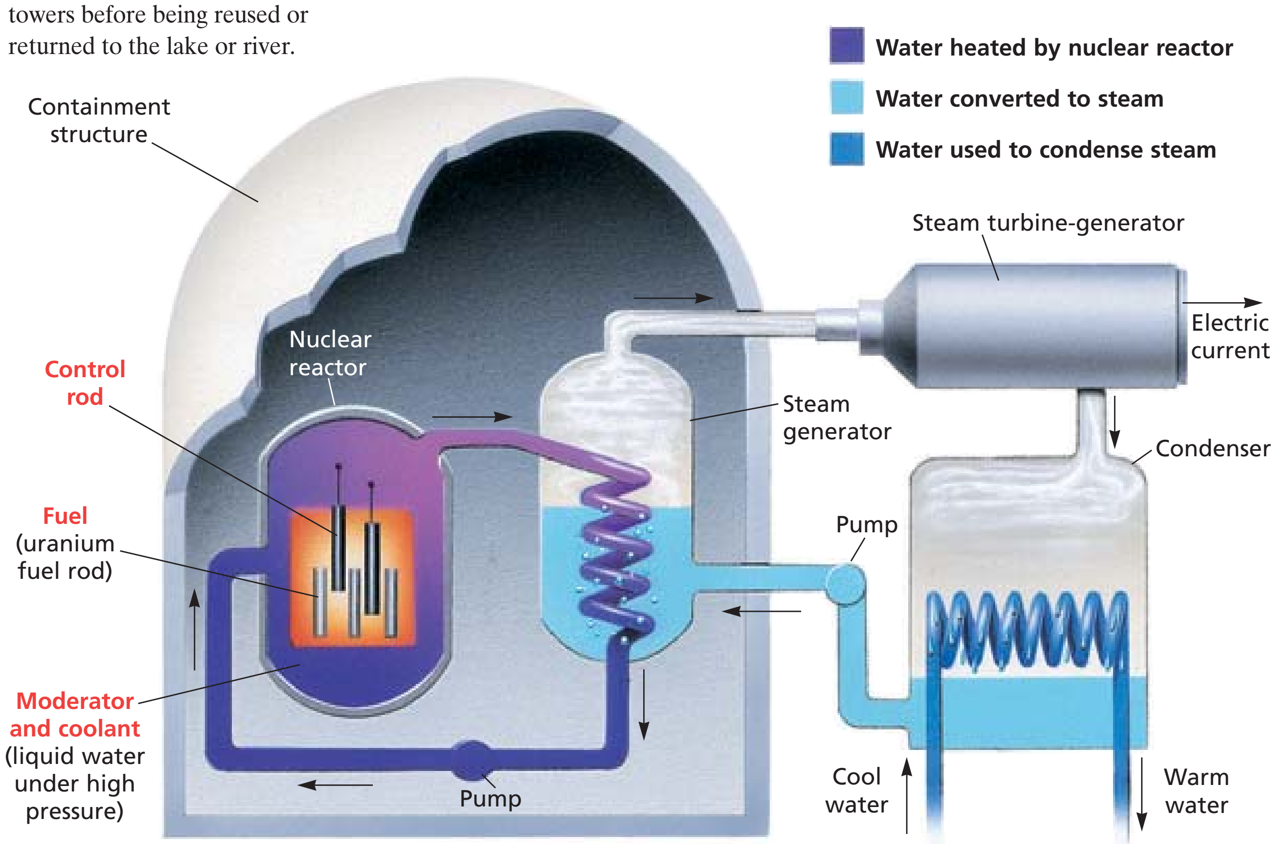
can cause the fission of still other uranium-235 nuclei. This chain reaction continues until all of the uranium-235 atoms have split or until the neutrons fail to strike uranium-235 nuclei. If the mass of the uranium-235 sample is below a certain minimum, too many neutrons will escape without striking other nuclei, and the chain reaction will stop. *The minimum amount of nuclide that provides the number of neutrons needed to sustain a chain reaction is called the* **critical mass.** Uncontrolled chain reactions provide the explosive energy of atomic bombs. **Nuclear reactors** *use controlled-fission chain reactions to produce energy and radioactive nuclides*.

Nuclear Power Plants

Nuclear power plants *use energy as heat from nuclear reactors to produce electrical energy*. They have five main components: shielding, fuel, control rods, moderator, and coolant. The components, shown in **Figure 15,** are surrounded by shielding. **Shielding** *is radiation-absorbing material that is used to decrease exposure to radiation, especially gamma rays, from nuclear reactors*. Uranium-235 is typically used as the fissile fuel to produce energy as heat, which is absorbed by the coolant. **Control rods** *are neutron-absorbing rods that help control the reaction by limiting the number of free neutrons.* Because fission of uranium-235 is more efficiently induced by slow neutrons, a **moderator** *is used to slow down the fast neutrons produced by fission*. Nuclear power plants can provide competitively priced electricity without emitting greenhouse gases or particulates. Concerns about nuclear power include storage and disposal of spent radioactive fuel, as well as public perception.

FIGURE 15 In this model of a nuclear power plant, pressurized water is heated by fission of uranium-235. This water is circulated to a steam generator. The steam drives a turbine to produce electricity. Cool water from a lake or river is then used to condense the steam into water. The warm water from the condenser may be cooled in cooling towers before being reused or returned to the lake or river.



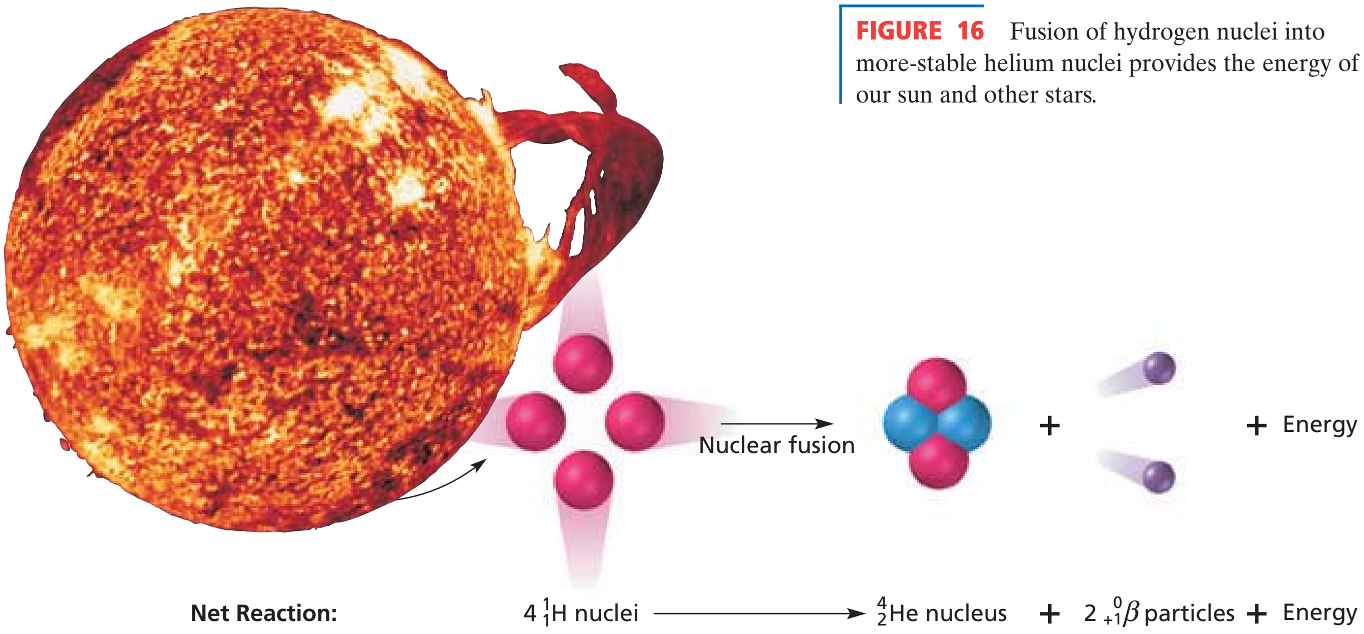


FIGURE 16 Fusion of hydrogen nuclei into more-stable helium nuclei provides the energy of our sun and other stars.

Nuclear Fusion

The high stability of nuclei with intermediate masses can also be used to explain nuclear fusion. *In* **nuclear fusion,** *low-mass nuclei combine to form a heavier, more stable nucleus.* Nuclear fusion releases even more energy per gram of fuel than nuclear fission. In our sun and stars that are similar to the sun, hydrogen nuclei combine at extremely high temperature and pressure to form a helium nucleus with a loss of mass and release of energy. The net reaction is illustrated in **Figure 16.**

If fusion reactions can be controlled, they could be used for energy generation. Researchers are currently studying ways to contain the reacting plasma that is required for fusion. A plasma is an extremely hot mixture of positive nuclei and electrons. There is no known material that can withstand the initial temperatures, about 10^8 K, required to induce fusion. Scientists use strong magnetic fields to suspend the charged plasma inside a container but away from the walls. Additionally, a large amount of energy is needed to initiate fusion reactions. For fusion to be a practical energy source, more energy needs to be generated by the reaction than is put into the reaction.

SECTION REVIEW

1. Distinguish between nuclear fission and nuclear fusion.
2. Define *chain reaction.*
3. List the five main components of a nuclear power plant.

Critical Thinking

4. **RELATING IDEAS** Explain how fusion is one of our sources of energy.