SECTION 1

What Is Radioactivity?

Key Ideas

- What happens when an element undergoes radioactive decay?
- How does radiation affect the nucleus of an unstable isotope?
- How do scientists predict when an atom will undergo radioactive decay?

Key Terms

radioactive decay
nuclear radiation
alpha particle
beta particle
gamma ray
half-life

Why It Matters

Nuclear radiation surrounds us on Earth, but scientists did not identify nuclear radiation until a little more than 100 years ago.

Our lives are affected by radioactivity in many ways. Technology using radioactivity has helped humans detect disease, kill cancer cells, generate electricity, and design smoke detectors. However, there are also risks associated with too much nuclear radiation, so we must know where it may exist and how we can counteract it. But first, what exactly is radioactivity?

Nuclear Radiation

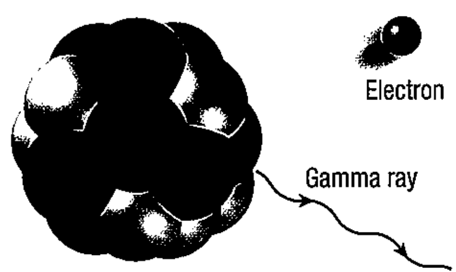
Certain isotopes of many elements undergo a process called radioactive decay. During **radioactive decay,** the unstable nuclei of these isotopes emit particles, or release energy, to become stable isotopes, as **Figure 1** shows. **After radioactive decay, the element changes into a different isotope of the same element or into an entirely different element.** Recall that isotopes of an element are atoms that have the same number of protons but different numbers of neutrons in their nuclei. Different elements are distinguished by having different numbers of protons.

The released energy and matter are collectively called **nuclear radiation.** Just as materials that undergo radioactive decay are changed, materials that are bombarded with nuclear radiation are also affected. These effects depend on the type of radiation and on the properties of the materials that nuclear radiation encounters. (Note that the term *radiation* can refer to light or to energy transfer. To avoid confusion, the term *nuclear radiation* will be used to describe radiation associated with nuclear changes.)

radioactive decay (RAY dee oh AK tiv dee KAY) the disintegration of an unstable atomic nucleus into one or more different nuclides

nuclear radiation (NOO klee uhr RAY dee AY shuhn) the particles that are released from the nucleus during radioactive decay

Figure 1 During radioactive decay, an unstable nucleus emits one or more particles of high-energy electromagnetic radiation.



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Topic: Types of Radiation
Code: **HK81569**

Figure 2 Types of Nuclear Radiation

Radiation type	Symbol	Mass (kg)	Charge	Graphic
Alpha particle	${}^{4}_{2}He$	6.646×10^{-27}	+2	
Beta particle	${}^{0}_{-1}e$	9.109×10^{-31}	−1, (+1)	
Gamma ray	γ	none	0	
Neutron	${}^{1}_{0}n$	1.675×10^{-27}	0	

There are different types of nuclear radiation.

Essentially, there are four types of nuclear radiation. Nuclear radiation can contain alpha particles, beta particles, gamma rays, or neutrons. Some of the properties of these types are listed in **Figure 2.** When a radioactive nucleus decays, the nuclear radiation leaves the nucleus. This nuclear radiation interacts with nearby matter. This interaction depends in part on the properties of nuclear radiation, such as charge, mass, and energy.

Alpha particles consist of protons and neutrons.

Uranium is a radioactive element that naturally occurs as three isotopes. One of its isotopes, uranium-238, undergoes nuclear decay by emitting positively charged particles. Ernest Rutherford, noted for discovering the nucleus, named this radiation *alpha (α) rays* after the first letter of the Greek alphabet. Later, he discovered that alpha rays were actually particles, each made of two protons and two neutrons—the same as helium nuclei. **Alpha particles** are positively charged and more massive than any other type of nuclear radiation.

Alpha particles do not travel far through materials. In fact, they barely pass through a sheet of paper. One factor that limits an alpha particle's ability to pass through matter is that it is massive compared to other subatomic particles. Because alpha particles are charged, they remove electrons from—or ionize—matter as they pass through it. This ionization causes the alpha particle to lose energy and slow further.

Reading Check **To which element is an alpha particle related?** (See Appendix E for answers to Reading Checks.)

alpha particle (AL fuh PAHRT i kuhl) a positively charged particle that consists of two protons and two neutrons and that is emitted from a nucleus during radioactive decay

beta particle (BAYT uh PAHRT i kuhl) an electron or positron that is emitted from a nucleus during radioactive decay

gamma ray (GAM uh RAY) the high-energy photon emitted by a nucleus during fission and radioactive decay

Beta particles are produced from neutron decay.

Some nuclei emit a type of nuclear radiation that travels farther through matter than alpha particles do. This nuclear radiation is composed of beta particles, named after the second Greek letter, *beta* (β). **Beta particles** are often fast-moving electrons but may also be positively charged particles called *positrons*. Positrons have the same mass as electrons.

Negative particles coming from the positively charged nucleus puzzled scientists for years. However, in the 1930s, another discovery helped clear up the mystery. Neutrons, which are not charged, decay to form a proton and an electron. The electron, which has a very small mass, is then ejected at a high speed from the nucleus as a beta particle.

As **Figure 3** shows, beta particles pass through a piece of paper, but most are stopped by 3 mm of aluminum or 10 mm of wood. This greater penetration occurs because beta particles are not as massive as alpha particles. But like alpha particles, beta particles can easily ionize other atoms. As they ionize atoms, beta particles lose energy. This property prevents them from penetrating matter very deeply.

Gamma rays are high-energy electromagnetic radiation.

Unlike alpha or beta particles, gamma rays are not made of matter and do not have an electric charge. Instead, **gamma rays,** named for the third Greek letter, *gamma* (γ), are a form of electromagnetic energy. Like visible light and X rays, gamma rays consist of energy packets called *photons*. Gamma rays, however, have more energy than light or X rays do.

Although gamma rays have no electric charge, they can easily ionize matter. High-energy gamma rays can cause damage in matter. They can penetrate up to 60 cm of aluminum or 7 cm of lead. They are not easily stopped by clothing or most building materials and therefore pose a greater danger to health than either alpha or beta particles do.

Neutron radioactivity occurs in an unstable nucleus.

Like alpha and beta radiation, *neutron emission* consists of matter that is emitted from an unstable nucleus. In fact, scientists first discovered the neutron as a result of this emission.

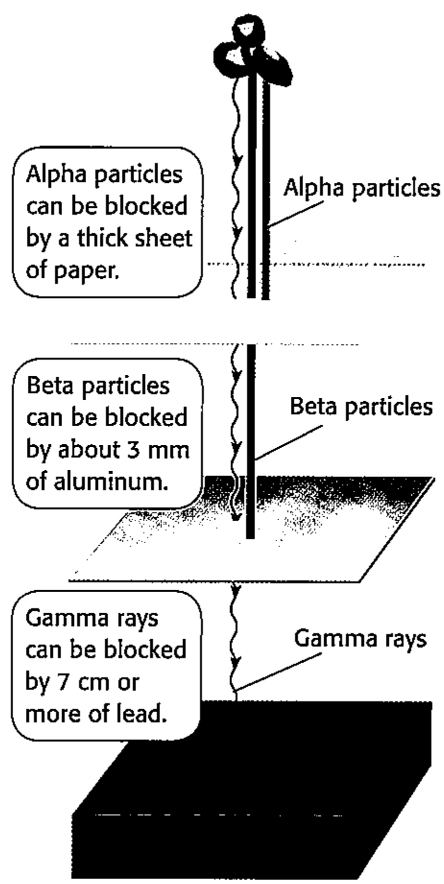
Neutrons have no charge, and therefore they do not ionize matter as alpha and beta particles do. Because neutrons do not use their energy to ionize matter, they are able to travel farther through matter than either alpha or beta particles do. A block of lead about 15 cm thick is required to stop most fast neutrons emitted during radioactive decay.

READING TOOLBOX

Analyzing Comparisons

As you read about the different kinds of nuclear radiation, look for comparisons among them. Create a table of their similarities and differences.

Figure 3 Different kinds of nuclear radiation penetrate different materials. **Why must both the thickness and material be specified?**



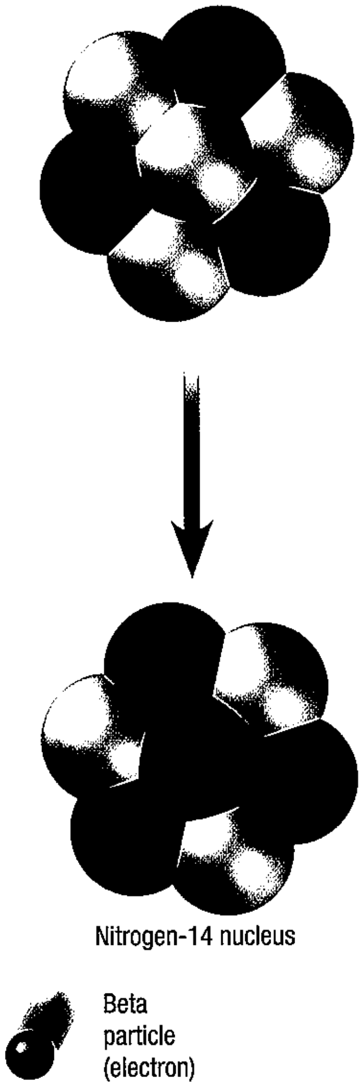


Figure 4 A nucleus that undergoes beta decay has nearly the same atomic mass afterward, but it has one more proton and one less neutron.

Nuclear Decay

Nuclear decay causes changes in the nucleus of an atom. **› Anytime that an unstable nucleus emits alpha or beta particles, the number of protons and neutrons changes.** An example is radium-226 (an isotope of radium with the mass number 226), which changes to radon-222 by emitting an alpha particle.

Nuclear-decay equations are similar to those used for chemical reactions. The nucleus before decay is like a reactant and is placed on the left side of the equation. The products are placed on the right side.

Gamma decay changes the energy of the nucleus.

When an atom undergoes nuclear decay and emits gamma rays, there is no change in the atomic number or the atomic mass of the element. The reason is that the number of protons and neutrons does not change. After gamma decay, the energy content of the nucleus is lower because some of its energy was taken away by the energy in the gamma ray.

The atomic number changes during beta decay.

A beta particle is not an atom and does not have an atomic number, which is the number of positive charges in a nucleus. For the sake of convenience, because an electron has a single negative charge, an electron is given an atomic number of -1 in a nuclear-decay equation. Similarly, the electron's mass is so much less than the mass of a proton or a neutron that the electron can be regarded as having a mass number of 0. The beta particle symbol, with the right mass and atomic numbers, is ${}^{0}_{-1}e$.

A beta-decay process occurs when carbon-14 decays to nitrogen-14 by emitting a beta particle, as **Figure 4** shows. This process can be written as follows.

$${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e \qquad \begin{aligned} 14 &= 14 + 0 \\ 6 &= 7 + (-1) \end{aligned}$$

In all cases of beta decay, the mass number before and after the decay does not change. The atomic number of the product nucleus, however, increases by 1, so the atom changes to a different element. During carbon-14 beta decay, a neutron changes into a proton. As a result, the positive charge of the nucleus increases by 1, and an atom of nitrogen forms.

Reading Check **How do the mass number and the atomic number change during beta decay?**

Both atomic mass and number change in alpha decay.

In alpha decay, the form of the decay equation is the same except that the symbol for an alpha particle is used. The alpha decay of radium-226 is written as follows.

$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He} \qquad \begin{aligned} 226 &= 222 + 4 \\ 88 &= 86 + 2 \end{aligned}$$

The mass number of the atom before decay is 226. The mass number equals the sum of the mass numbers of the products, 222 and 4. The atomic numbers follow the same principle. The 88 protons in radium before the nuclear decay equal the 86 protons in the radon-222 nucleus and 2 protons in the alpha particle.

Academic Vocabulary

principle (PRIN suh puhl) basic law, rule, or belief

Math *Skills* Nuclear Decay

Actinium-217 decays by releasing an alpha particle. Write the equation for this decay process, and determine which element is formed.

Identify Write the equation with the original element on the left side and the products on the right side.	$^{217}_{89}\text{Ac} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\text{He}$ X = unknown product A = unknown mass Z = unknown atomic number
Plan Write math equations for the atomic and mass numbers. Rearrange the equations.	$217 = A + 4 \qquad 89 = Z + 2$ $A = 217 - 4 \qquad Z = 89 - 2$
Solve Solve for the unknown values, and rewrite the equation with all nuclei represented.	$A = 213 \qquad Z = 87$ According to the periodic table, francium has an atomic number of 87. The unknown element is therefore $^{213}_{87}\text{Fr}$. $^{217}_{89}\text{Ac} \rightarrow {}^{213}_{87}\text{Fr} + {}^{4}_{2}\text{He}$

Practice

Complete the following radioactive-decay equations. Identify the isotope *X*. Indicate whether alpha or beta decay takes place.

1. $^{12}_{5}\text{B} \rightarrow {}^{12}_{6}\text{C} + {}^{A}_{Z}X$
2. $^{225}_{89}\text{Ac} \rightarrow {}^{221}_{87}\text{Fr} + {}^{A}_{Z}X$
3. $^{63}_{28}\text{Ni} \rightarrow {}^{A}_{Z}X + {}^{0}_{-1}e$
4. $^{212}_{83}\text{Bi} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\text{He}$

For more practice, visit **go.hrw.com** and enter keyword **HK8MP.**

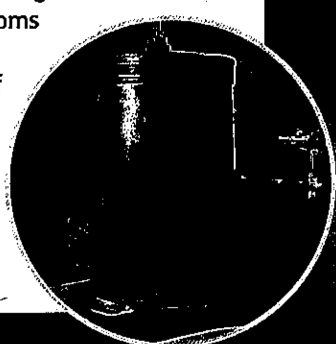
Practice Hint

- In all nuclear-decay problems, the atomic number of the new atom is the key to identifying the new atom.
- After determining the new atomic number, use the periodic table to find out the name of the new element.

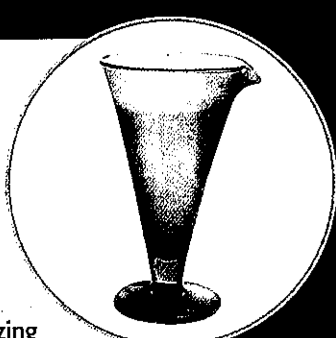
Why It **Matters**

Discovering Nuclear Radiation

In 1898, Marie Curie and her husband, Pierre, discovered two previously unknown elements, both of which were radioactive. They named one element *polonium,* after Marie's homeland of Poland. They named the second element *radium,* from the Latin word for "ray." In 1903, Marie Curie completed her doctoral thesis and was the first woman in France to receive a doctorate. Later that year, Marie and Pierre Curie were awarded the Nobel Prize in physics for their studies of radioactive substances. In 1911, Marie also won the Nobel Prize in chemistry for the discovery of these new elements.



Marie Curie used this *ionization chamber* in her studies of radioactivity. It consists of a tube from which some of the air has been removed. When ionizing radiation—alpha particles, beta particles, or gamma rays—passes through the chamber, some of the remaining atoms are ionized. Applying a voltage across the ends of the chamber creates a current in the chamber. The Curies used that current to detect the presence of radioactive substances.



Marie and Pierre Curie used this glass flask to hold solutions of radioactive elements. Radiation clouded and changed the color of the glass. Like most scientists of her day, Marie did not realize the danger of ionizing radiation and often walked around with uranium ore in her pockets.

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YOUR TURN

WRITING IN SCIENCE

1. Research and write about how the Curies isolated radium.

ONLINE RESEARCH

2. What other scientists have won Nobel Prizes in physics or chemistry? Have any other scientists won both prizes?

Radioactive Decay Rates

If you were asked to determine the age of a rock, you would probably not be able to do so. After all, old rocks do not look much different from new rocks. How, then, would you go about finding the rock's age? Likewise, how would a scientist find out the age of a piece of cloth found at the site of an ancient village?

One way to find the age involves radioactive decay. **❯ It is impossible to predict the moment when any particular nucleus will decay, but it is possible to predict the time required for half of the nuclei in a given radioactive sample to decay.** The time in which half of a radioactive substance decays is called the substance's **half-life.**

Half-life is a measure of how quickly a substance decays.

Different radioactive isotopes have different half-lives, as indicated in the table in **Figure 5.** Half-lives can last from nanoseconds to billions of years, depending on the stability of the isotope's nucleus.

Doctors use isotopes with short half-lives, such as iodine-131, to help diagnose medical problems. A detector follows the element as it moves through the patient's body.

Scientists can also use half-life to predict how old an object is. Geologists calculate the age of rocks by using the half-lives of long-lasting isotopes, such as potassium-40. Potassium-40 decays to argon-40, so the ratio of potassium-40 to argon-40 is smaller for older rocks than it is for younger rocks.

Figure 5 Half-Lives of Selected Isotopes

Isotope	Half-life	Nuclear radiation emitted
Thorium-219	1.05×10^{-6} s	α
Hafnium-156	2.5×10^{-2} s	α
Radon-222	3.82 days	α, γ
Iodine-131	8.1 days	β, γ
Radium-226	1,599 years	α, γ
Carbon-14	5,715 years	β
Plutonium-239	2.412×10^{4} years	α, γ
Uranium-235	7.04×10^{8} years	α, γ
Potassium-40	1.28×10^{9} years	β, γ
Uranium-238	4.47×10^{9} years	α, γ

Integrating **Earth Science**

Internal Furnace Earth's interior is extremely hot. One reason is that uranium and the radioactive elements produced by its decay are present in amounts of about 3 parts per million beneath the surface of Earth and their nuclear decay produces energy that escapes into the surroundings.

The long half-lives of uranium isotopes allow the radioactive decay to heat Earth for billions of years. The very large distance that this energy must travel to reach Earth's surface keeps the interior of Earth much hotter than its surface.

half-life (HAF LIEF) the time required for half of a sample of a radioactive isotope to break down by radioactive decay to form a daughter isotope

Math Skills Half-Life

Radium-226 has a half-life of 1,599 years. How long will seven-eighths of a sample of radium-226 take to decay?

Identify

List the given and unknown values.

Given:

half-life = 1,599 years

fraction of sample decayed = $\frac{7}{8}$

Unknown:

fraction of sample remaining = ?

total time of decay = ?

Plan

Subtract the fraction decayed from 1 to find how much of the sample is remaining.

fraction of sample remaining =

1 – fraction decayed =

$1 - \frac{7}{8} = \frac{1}{8}$

Determine how much of the sample is remaining after each half-life.

amount of sample remaining after one half-life = $\frac{1}{2}$

amount of sample remaining after two half-lives = $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$

amount of sample remaining after three half-lives = $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$

Solve

Multiply the number of half-lives by the time for each half-life to calculate the total time required for the radioactive decay.

Each half-life lasts 1,599 years.

total time of decay =

$3 \text{ ~~half-lives~~} \times \frac{1{,}599 \text{ y}}{\text{~~half-life~~}} = 4{,}797 \text{ y}$

Practice Hint

- Make a diagram that shows how much of the original sample is left:

  1 → 1/2 → 1/4 → 1/8 → 1/16 → . . .

  Each arrow represents one half-life.
- Problems 4 and 5: You will need to work backward from the final answer to get to the time when one-half of the original sample remains.

Practice

1. The half-life of iodine-131 is 8.1 days. How long will three-fourths of a sample of iodine-131 take to decay?
2. Radon-222 is a radioactive gas with a half-life of 3.82 days. How long will fifteen-sixteenths of a sample of radon-222 take to decay?
3. Uranium-238 decays very slowly. Its half-life is 4.47 billion years. What percentage of a sample of uranium-238 will remain after 13.4 billion years?
4. A sample of strontium-90 is found to have decayed to one-eighth of its original amount after 87.3 years. What is the half-life of strontium-90?

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QuickLab Modeling Decay and Half-Life

80 min

Procedure

1. Place **128 pennies** in a **jar**, and place the **lid** on the jar. Shake the jar, and then pour the pennies onto a **flat work surface.**
2. Separate pennies that are heads up from those that are tails up. Count and record the number of heads-up pennies, and set these pennies aside. Place the tails-up pennies back in the jar.
3. Repeat the process until all of the pennies have been set aside.

Analysis

1. For each trial, divide the number of heads-up pennies set aside by the total number of pennies used in the trial. Are these ratios nearly equal to each other? What fraction are they closest to?
2. How well does this experiment model radioactive half-life?

Radioactive decay is exponential decay.

The definition of *half-life* tells us that after the first half-life of a radioactive sample has passed, half of the sample remains unchanged. After the next half-life, half of the remaining half decays, so only a quarter of the original element remains. Of that quarter, half will decay in the next half-life. Only one-eighth will then remain unchanged. This relationship is called an *exponential decay.*

A *decay curve* is a graph of the number of radioactive parent nuclei remaining in a sample as a function of time. The relationship between the fraction of carbon-14 versus time is graphed in **Figure 6.** Notice that the total number of nuclei remains constant and the number of carbon atoms continually decreases over time. As the number of carbon-14 atoms decreases, the number of nitrogen-14 atoms increases.

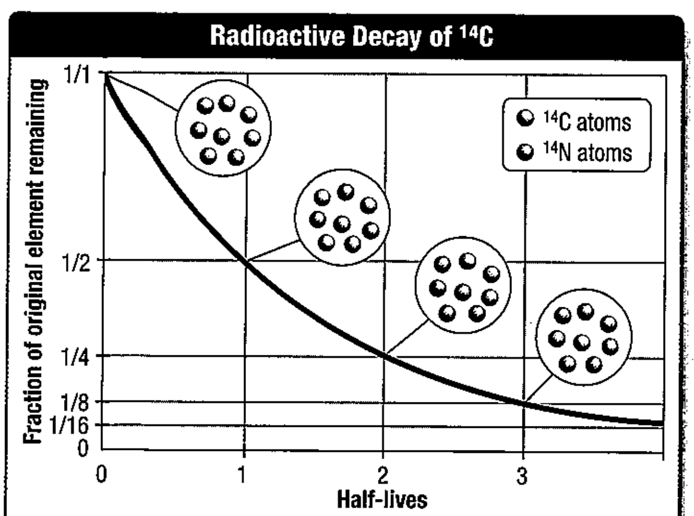

Figure 6 With each successive half-life, half of the remaining sample decays to form another element. **How much of the original element will remain after four half-lives?**

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Figure 7 Carbon-14 dating is used to date the remains of living things, such as this mummy of Petamenophis.

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Carbon-14 is used to date materials.

Archaeologists use the half-life of radioactive carbon-14 to date more-recent materials, such as fibers from ancient clothing, and animal or human remains, such as the mummy shown in **Figure 7.** All of these materials came from organisms that were once alive. When plants absorb carbon dioxide during photosynthesis, a tiny fraction of the CO_2 molecules contains carbon-14 rather than the more common carbon-12. While the plant, or an animal that eats plants, is alive, the ratio of the carbon isotopes remains constant.

When a plant or animal dies, it no longer takes in carbon. The amount of carbon-14 decreases through beta decay, while the amount of carbon-12 remains constant. Thus, the ratio of carbon-14 to carbon-12 decreases with time. By measuring this ratio and comparing it with the ratio in a living plant or animal, scientists can estimate how long ago the once-living organism died.

Section 1 Review

KEY IDEAS

1. **Identify** which of the four common types of nuclear radiation correspond to the following descriptions.
   a. an electron
   b. uncharged particle
   c. particle that can be stopped by a piece of paper
   d. high-energy electromagnetic radiation
2. **Describe** what happens when beta decay occurs.
3. **Explain** why charged particles do not penetrate matter deeply.

CRITICAL THINKING

4. **Analyzing Methods** An archaeologist finds an old piece of wood whose carbon-14 to carbon-12 ratio is one-sixteenth the ratio measured in a newly fallen tree. How old does the wood seem to be?

Math *Skills*

5. Determine the product denoted by *X* in the following alpha decay.
$$^{212}_{86}\text{Rn} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\text{He}$$
6. Determine the isotope produced in the beta decay of iodine-131, an isotope used to check thyroid-gland function.
$$^{131}_{53}\text{I} \rightarrow {}^{A}_{Z}X + {}^{0}_{-1}e$$
7. Calculate the time required for three-fourths of a sample of cesium-138 to decay, given that its half-life is 32.2 min.
8. Calculate the half-life of cesium-135 if seven-eighths of a sample decays in 6×10^6 years.

SECTION 2 Nuclear Fission and Fusion

Key Ideas

- What holds the nuclei of atoms together?
- What is released when the nucleus of a heavy atom is split?
- What happens when the nuclei of small atoms are joined?

Key Terms

fission
nuclear chain reaction
critical mass
fusion

Why It Matters

Nuclear fission can be controlled and used to generate electricity.

In 1939, German scientists Otto Hahn and Fritz Strassman conducted experiments in the hope of forming heavy nuclei. Hahn and Strassman bombarded uranium samples with neutrons and expected that a few nuclei would capture one or more neutrons. The new elements that formed had chemical properties that the scientists could not explain.

An explanation for these results came only after the scientists' former colleague Lise Meitner and her nephew Otto Frisch read the results of the experiments. Meitner and Frisch believed that instead of making heavier elements, the uranium nuclei had split into smaller elements.

In the early 1940s, Enrico Fermi and other scientists at the University of Chicago built stacks of graphite and uranium blocks, similar to the one shown in **Figure 1.** This *nuclear pile* was used to create the first controlled nuclear fission chain reaction and to launch the Manhattan Project, which led to the creation of nuclear weapons.

Figure 1 This nuclear pile was used in the late 1940s and early 1950s to better understand controlled nuclear fission.

Nuclear Forces

Protons and neutrons are tightly packed in the tiny nucleus of an atom. As explained in Section 1, certain nuclei are unstable and undergo decay by emitting nuclear radiation. Also, an element can have both stable and unstable isotopes. For example, carbon-12 is a stable isotope, but carbon-14 is unstable and radioactive. **The stability of a nucleus depends on the nuclear forces that hold the nucleus together. These forces act between the protons and the neutrons.**

Like charges repel, so how can so many positively charged protons fit into an atomic nucleus without flying apart?

Nuclei are held together by a special force.

The neutrons and protons are able to exist together in the nuclei of atoms because of the *strong nuclear force*. This force causes protons and neutrons in the nucleus to attract one another. The attraction is much stronger than the electric repulsion between protons. However, the attraction due to the strong nuclear force occurs over a very short distance, less than 3×10^{-15} m, or about the width of three protons.

Neutrons contribute to nuclear stability.

Because of the strong nuclear force, neutrons and protons in a nucleus attract other protons and neutrons. Because neutrons have no charge, they do not repel one another or the protons. However, the protons in a nucleus both repel and attract one another, as **Figure 2** shows. In stable nuclei, the attractive forces are stronger than the repulsive forces, and the element does not undergo nuclear decay.

READING TOOLBOX

Word Origins
Research how the strong nuclear force was discovered. What is the origin of its name? Is there another nuclear force that is "not strong"?

Too many neutrons or protons can cause a nucleus to become unstable and decay.

Although a greater number of neutrons can help hold a nucleus together, there is a limit to how many neutrons that a nucleus can have. Nuclei with too many or too few neutrons are unstable and undergo decay.

Nuclei with more than 83 protons are always unstable, no matter how many neutrons that the nuclei have. These nuclei will always decay and, in the process, release large amounts of energy and nuclear radiation. Some of this released energy is transferred to the various particles ejected from the nucleus. As a result, the least massive of these particles move very fast. The rest of the energy is emitted in the form of gamma rays. The radioactive decay that takes place results in a more stable nucleus.

Reading Check **What is the maximum number of protons that can be found in a stable nucleus?**

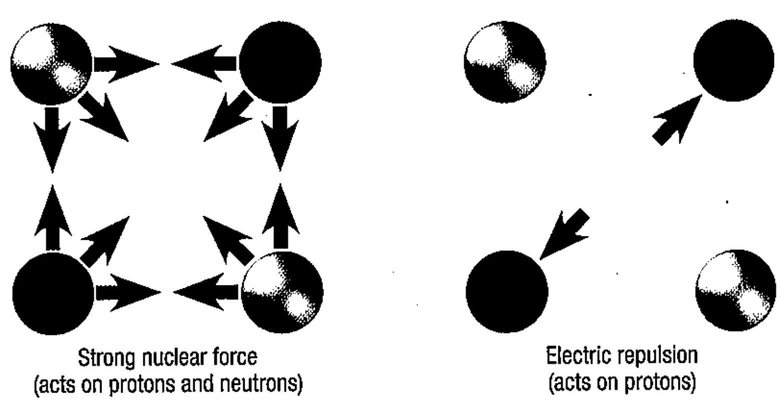

Figure 2 The nucleus is held together by the attractions among protons and neutrons. These forces are greater than the electric repulsion among the protons alone.

Nuclear Fission

The process of splitting heavier nuclei into lighter nuclei, which Hahn and Strassman observed, is called **fission.** In their experiment, uranium-235 was bombarded by neutrons. One set of products for this type of fission reaction includes two lighter nuclei, barium-140 and krypton-93, together with neutrons and energy.

fission (FISH uhn) the process by which a nucleus splits into two or more fragments and releases neutrons and energy

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{56}Ba + ^{93}_{36}Kr + 3^{1}_{0}n + \text{energy}$$

Notice that the products include three neutrons plus energy. Uranium-235 can also undergo fission by producing different pairs of lighter nuclei. An alternative fission of the isotope uranium-235, for example, produces strontium-90, xenon-143, and three neutrons. **❯ In the fission process, when the nucleus splits, both neutrons and energy are released.**

Energy is released during nuclear fission.

During fission, as **Figure 3** shows, the nucleus breaks into smaller nuclei. The reaction also releases large amounts of energy. Each dividing nucleus releases about 3.2×10^{-11} J of energy. In comparison, the chemical reaction of one molecule of the explosive trinitrotoluene (TNT) releases 4.8×10^{-18} J.

In their experiment, Hahn and Strassman determined the masses of all of the nuclei and particles before and after the reaction. They found that the overall mass had decreased after the reaction. The missing mass must have been changed into energy.

The equivalence of mass and energy observed in nature is explained by the special theory of relativity, which Albert Einstein presented in 1905. This equivalence means that matter can be converted into energy, and energy into matter, and is given by the following equation.

Mass-energy equation	*energy = mass × (speed of light)*^{2} $E = mc^2$

The constant, *c*, is equal to 3.0×10^{8} m/s. So, the energy associated with even a small mass is very large. The mass-equivalent energy of 1 kg of matter is 9×10^{16} J, which is more than the chemical energy of 22 million tons of TNT.

Obviously, if objects around us changed into their equivalent energies, the results would be devastating. Under ordinary conditions of pressure and temperature, matter is very stable. Objects, such as chairs and tables, never spontaneously change into energy.

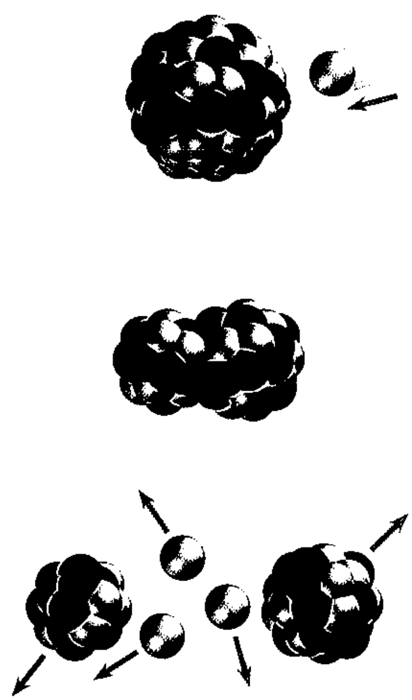

Figure 3 When the uranium-235 nucleus is bombarded by a neutron, the nucleus breaks apart. It forms smaller nuclei, such as xenon-143 and strontium-90, and releases energy through fast neutrons.

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Energy is released when nuclei form.

When the total mass of any nucleus is measured, the mass is less than the individual masses of the neutrons and protons that make up the nucleus. This missing mass is referred to as the *mass defect.* What happens to the missing mass? Einstein's equation provides an explanation—the mass changes into energy. However, the mass defect of a nucleus is very small.

Another way to think about mass defect is to imagine constructing a nucleus by bringing individual protons and neutrons together. During this process, a small amount of mass changes into energy, as described by $E = mc^2$.

Neutrons released by fission can start a chain reaction.

Have you ever played marbles with a lot of marbles in the ring? When one marble is shot into the ring, the resulting collisions cause some of the marbles to scatter. Some nuclear reactions are similar—one reaction triggers another.

Academic Vocabulary

trigger (TRIG uhr) to begin or cause something to start

A nucleus that splits when it is struck by a neutron forms smaller product nuclei. These smaller nuclei need fewer neutrons to be held together. Therefore, excess neutrons are emitted. One of these neutrons can collide with another large nucleus, triggering another nuclear reaction that releases more neutrons. This process starts a **nuclear chain reaction,** which is a continuous series of nuclear fission reactions.

When Hahn and Strassman continued experimenting, they discovered that each dividing uranium nucleus, on average, produced between two and three additional neutrons. Therefore, two or three new fission reactions could be started from the neutrons that were ejected from one reaction.

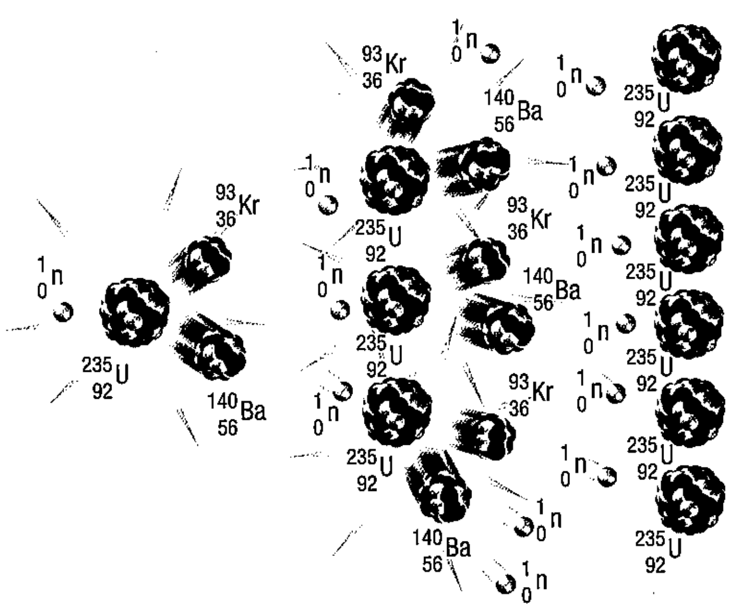


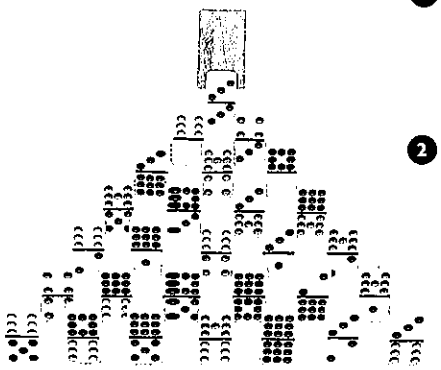
Figure 4 A nuclear chain reaction may be triggered by a single neutron.

If each of these 3 new reactions produces 3 additional neutrons, a total of 9 neutrons become available to trigger 9 additional fission reactions. From these 9 reactions, a total of 27 neutrons are produced, which set off 27 new reactions, and so on. You can probably see from **Figure 4** how the reaction of uranium-235 nuclei would very quickly result in an uncontrolled nuclear chain reaction. Therefore, the ability to create a chain reaction partly depends on the number of neutrons released during each fission reaction.

Reading Check **What causes a nuclear chain reaction?**

QuickLab Modeling Chain Reactions

10 min



Procedure

1. To model a fission chain reaction, you will need a **small wooden building block** and a **set of dominoes.**
2. Place the building block on a **table or counter.** Stand one domino upright in front of the block and parallel to one of its sides. Stand two more dominoes vertically, parallel, and symmetrical to the first domino.
3. Continue this process until you have used all of the dominoes and have created a triangular shape, as shown here.
4. Gently push the first domino away from the block so that it falls and hits the second group. Note that more dominoes fall with each step.

Analysis

1. Use Newton's first law of motion to explain your results.

Chain reactions can be controlled.

Energy produced in a controlled chain reaction can be used to generate electricity. Particles released by the splitting of the atom strike other uranium atoms and split them. The particles that are given off split still other atoms. A chain reaction is begun, which gives off energy that is used to heat water. The superheated water then transfers energy into a heat exchanger filled with water that is used to make steam. The steam then rotates a turbine to generate electricity. Energy released by the chain reaction changes the atomic energy into thermal energy, which ends up as electrical energy.

The chain-reaction principle is also used in making a nuclear bomb. Two or more masses of uranium-235 are contained in the bomb. These masses are surrounded by a powerful chemical explosive. When the explosive is detonated, all of the uranium is pushed together to create a *critical mass.* The **critical mass** refers to the minimum amount of a substance that can undergo a fission reaction and can also sustain a chain reaction. If the amount of fissionable substance is less than the critical mass, a chain reaction will not continue. Fortunately, the concentration of uranium-235 in nature is too low to start a chain reaction naturally. Almost all of the escaping neutrons are absorbed by the more common and more stable isotope uranium-238.

In nuclear power plants, control rods are used to regulate fission by slowing the chain reaction. In nuclear bombs, reactions are not controlled, and almost pure pieces of the element uranium-235 or plutonium of a precise mass and shape must be brought together and held together with great force. These conditions are not present in a nuclear reactor.

nuclear chain reaction (NOO klee uhr CHAYN ree AK shuhn) a continuous series of nuclear fission reactions

critical mass (KRIT i kuhl MAS) the minimum mass of a fissionable isotope that provides the number of neutrons needed to sustain a chain reaction

Nuclear Fusion

Obtaining energy from the fission of heavy nuclei is not the only nuclear process that produces energy. ❯ **Energy can be obtained when very light nuclei are combined to form heavier nuclei.** This type of nuclear process is called **fusion.**

fusion (FYOO zhuhn) the process in which light nuclei combine at extremely high temperatures, forming heavier nuclei and releasing energy

In stars, including the sun, energy is produced primarily when hydrogen nuclei combine, or fuse together, and release tremendous amounts of energy. However, a large amount of energy is needed to start a fusion reaction. The reason is that all nuclei are positively charged and repel one another with the electric force. Energy is required to bring the hydrogen nuclei close enough to one another that the repulsive electric force is overcome by the attractive strong nuclear force. In stars, the extreme temperatures provide the energy needed to bring hydrogen nuclei together.

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Topic: Fusion
Code: **HK80629**

Four hydrogen atoms combine in the sun to make a helium atom and high-energy gamma rays. This nuclear fusion of hydrogen happens in a three step process that involves two isotopes of hydrogen: ordinary hydrogen, ${}^{1}_{1}H$, and deuterium, ${}^{2}_{1}H$, as **Figure 5** shows.

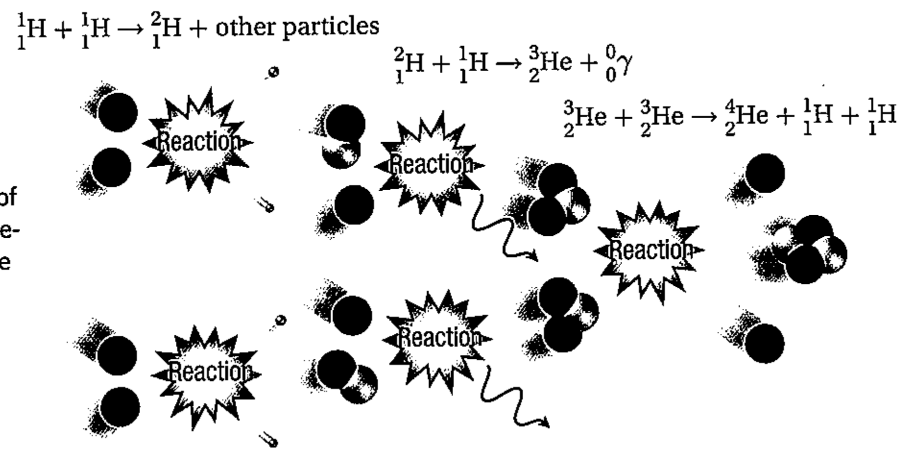


Figure 5 The nuclear fusion of hydrogen takes place in a three-step process that releases large amounts of energy.

Section 2 Review

KEY IDEAS

1. **Explain** why most isotopes of elements that have a high atomic number are radioactive.
2. **Indicate** whether the following are fission or fusion reactions.
   - **a.** ${}^{1}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + \gamma$
   - **b.** ${}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 3{}^{1}_{0}n$
   - **c.** ${}^{21}_{10}Ne + {}^{4}_{2}He \longrightarrow {}^{24}_{12}Mg + {}^{1}_{0}n$
   - **d.** ${}^{208}_{82}Pb + {}^{58}_{26}Fe \longrightarrow {}^{265}_{108}Hs + {}^{1}_{0}n$
3. **Predict** whether the total mass of a nucleus of an atom of ${}^{56}_{26}Fe$ is greater than, less than, or equal to the combined mass of the 26 protons and 30 neutrons that make up the nucleus. If the masses are not equal, explain why.

CRITICAL THINKING

4. **Predicting Outcomes** Suppose that a nucleus captures two neutrons and decays to produce one neutron. Is this process likely to produce a chain reaction? Explain your reasoning.

Why It **Matters**

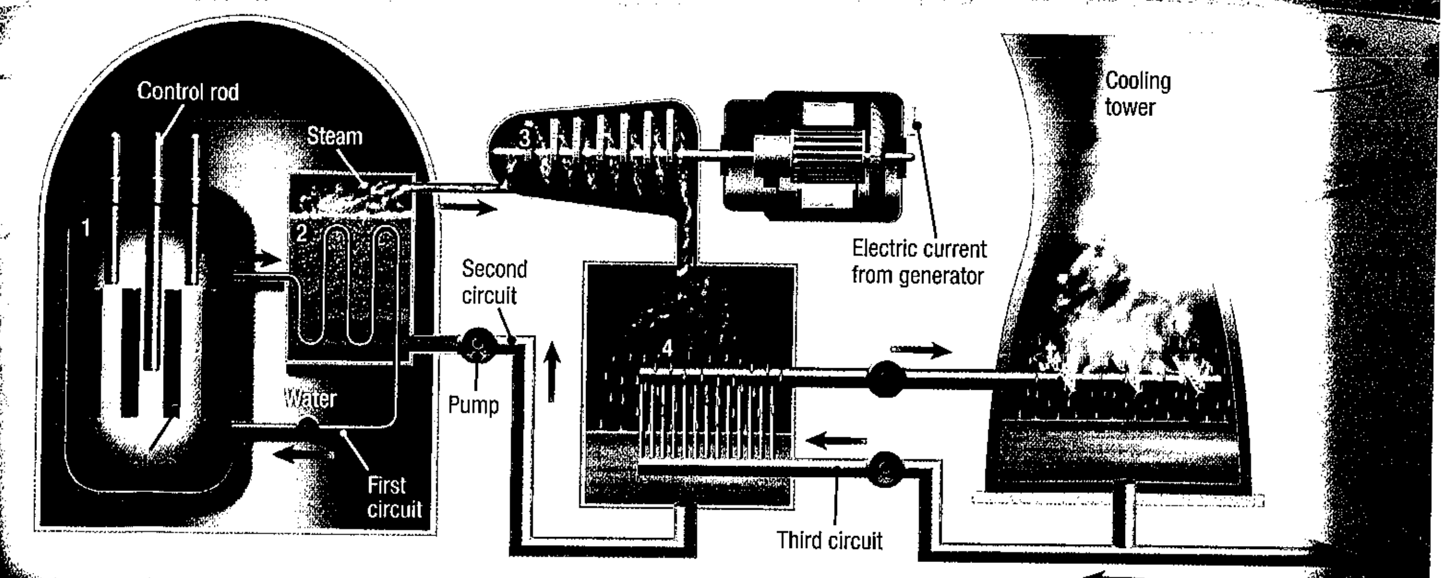
The Power of Fission

SCIENCE & SOCIETY

The United States receives about 20% of its electric power from power plants that use nuclear fission as an energy source. Today, there are more than 1,100 nuclear reactors in use around the world. This number includes 440 large reactors that generate electricity, more than 400 reactors that power ships and submarines, and about 280 small reactors that are used for research and for the creation of isotopes for medicine and energy. The country that currently receives the greatest percentage of its electric power from fission is France. France receives more than 75% of its electricity from nuclear power.

1. Energy released by the nuclear reaction heats water in the high-pressure first circuit to a very high temperature.

3. Steam is directed against a turbine and sets it in motion. The turbine sets the generator in motion to generate electricity.



2. The superheated water is pumped into a heat exchanger, which transfers the heat of the first circuit to the second circuit. Water in the second circuit flashes into high-pressure steam.

4. A third circuit cools the steam from the turbine. The waste heat is released from the cooling tower in the form of steam.

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Topic: Nuclear Energy
Code: **HK81047**

YOUR TURN

UNDERSTANDING CONCEPTS

1. What do nuclear power plants and other electric power plants have in common?

CRITICAL THINKING

2. How would using three circuits help the environment?

SECTION 3

Nuclear Radiation Today

Key Ideas

- › Where are we exposed to radiation?
- › What are some beneficial uses of nuclear radiation?
- › What factors determine the risks of nuclear radiation?
- › How is the energy produced by nuclear fission used?

Key Terms

background radiation
rem
radioactive tracer

Why It Matters

Radioactive tracer elements are used in medical diagnostic procedures such as positron emission tomography.

You may be surprised to learn that you are exposed to some form of nuclear radiation every day. Some forms of nuclear radiation are beneficial. Others present some risks. This section will discuss both the benefits and the possible risks of nuclear radiation.

Where Is Radiation?

Nuclear radiation is all around you. The form of nuclear radiation that arises naturally is called **background radiation.** **› We are continually exposed to radiation from natural sources, such as the sun, soil, rocks, and plants.** More than 80% of the radiation that we are exposed to comes from natural sources, such as those shown in **Figure 1.** The living tissues of most organisms are adapted to survive these low levels of natural nuclear radiation. Human-made sources, such as computer monitors, smoke detectors, and X rays, account for at least 20% of our everyday exposure.

background radiation (BAK GROWND RAY dee AY shuhn) the nuclear radiation that arises naturally from cosmic rays and from radioactive isotopes in the soil and air

rem (REM) the quantity of ionizing radiation that does as much damage to human tissue as 1 roentgen of high-voltage X rays does

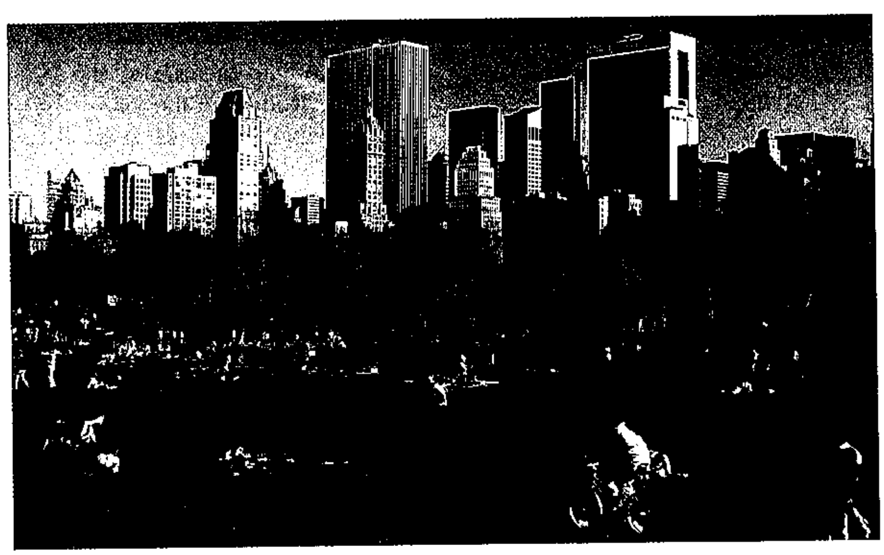


Figure 1 Sources of background radiation, both natural and artificial, are all around us.

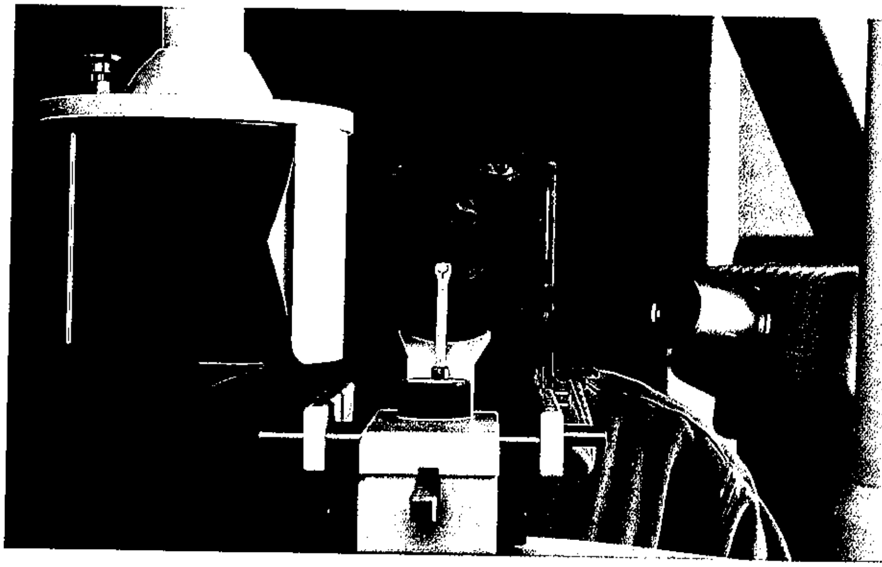


Figure 2 Dental X rays expose a patient to about 1 millirem of radiation.

Radiation is measured in units of rems.

Levels of radiation absorbed by the human body are measured in **rems** or millirems (1 rem = 1,000 millirems). Typical exposure for an X ray at the dentist's office, shown in **Figure 2,** is about 1 millirem.

In the United States, many people work in occupations that involve nuclear radiation. Nuclear engineering, health physics, radiology, radiochemistry, X-ray technology, and other nuclear medical technology all involve nuclear radiation. A safe limit for these workers has been set at 5,000 millirems per year, in addition to natural background exposures.

Exposure varies from one location to another.

People in the United States receive varying amounts of natural radiation. Those at higher elevations receive more exposure to nuclear radiation from space than people do at lower elevations. People in areas with many rocks have higher nuclear radiation exposure than people do in areas without many rocks. Because of large differences both in elevation and background radiation sources, exposure varies greatly from one location to another, as **Figure 3** illustrates.

Some activities add to the amount of nuclear radiation exposure.

Another factor that affects levels of exposure is participation in certain activities. **Figure 4** shows actual exposure to nuclear radiation for just a few activities. Other activities besides those listed in this table also add to the amount of nuclear radiation exposure. All activities that add nuclear radiation to the air will affect everyone in the area around these activities.

Figure 3 Radiation Exposure per Location

Location	Radiation exposure (millirems/year)
Tampa, FL	63.7
Richmond, VA	64.1
Las Vegas, NV	69.5
Los Angeles, CA	73.6
Portland, OR	86.7
Rochester, NY	88.1
Wheeling, WV	111.9
Denver, CO	164.6

Figure 4 Radiation Exposure per Activity

Activity	Radiation exposure (millirems/year)
Smoking 1 1/2 packs of cigarettes per day	8,000
Flying for 720 hours (airline crew)	267
Inhaling radon from the environment	360
Giving or receiving medical X rays	100

Beneficial Uses of Nuclear Radiation

Radioactive substances have a wide range of applications. In these applications, nuclear radiation is used in a controlled way to take advantage of its effects on other materials. ❯ **Some common applications of nuclear radiation include medical diagnosis and treatment, smoke detectors, manufacturing, and agriculture.**

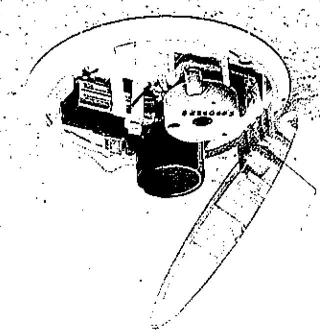


Figure 5 In a smoke alarm, a small amount of alpha-emitting isotope detects smoke particles in the air.

Smoke detectors help save lives.

Small radioactive sources are present in smoke alarms, such as the one shown in **Figure 5.** These sources release alpha particles, which are charged, to produce an electric current. Smoke particles in the air reduce the flow of the current. The drop in current sets off the alarm when even small levels of smoke are present.

Nuclear radiation is used to detect diseases.

The digital computer, ultrasound scanning, CT scanning, PET, and magnetic resonance imaging (MRI) have combined to create a variety of diagnostic imaging techniques. Using these procedures, doctors can view images of parts of the organs and can detect dysfunction or disease.

radioactive tracer (RAY dee oh AK tiv TRAYS uhr) a radioactive material that is added to a substance so that its distribution can be detected later

Radioactive tracers are short-lived isotopes that tend to concentrate in affected cells and are used to locate tumors. Tracers are widely used in medicine.

Nuclear radiation therapy is used to treat cancer.

Radiotherapy is treatment that uses controlled doses of nuclear radiation for treating diseases such as cancer. For example, certain brain tumors can be targeted with small beams of gamma rays.

Radiotherapy treats thyroid cancer by using an iodine isotope. Treatment of leukemia also uses radiotherapy. The defective bone marrow is first killed with a massive dose of nuclear radiation and then replaced with healthy bone marrow from a donor.

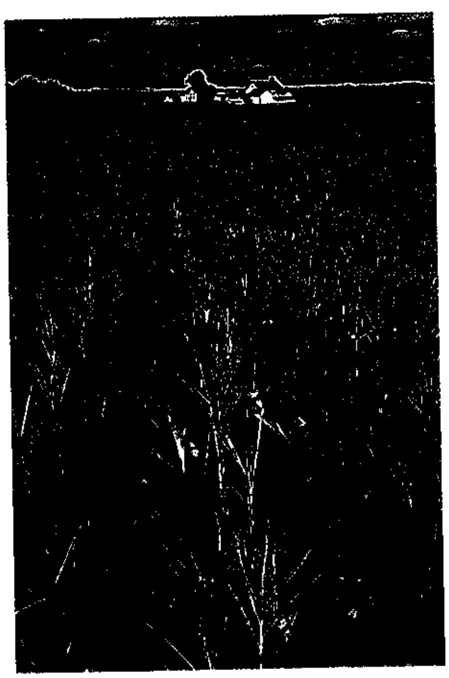


Figure 6 Research farms use radioactive tracers to reveal water movement and other biochemical processes.

Agriculture uses radioactive tracers and radioisotopes.

On research farms, such as the one shown in **Figure 6,** radioactive tracers in flowing water can show how fast water moves through the soil or through stems and leaves of crops. Tracers help us understand biochemical processes in plants. Radioisotopes are chemically identical with other isotopes of the same element. Because of that similarity, they can be substituted in chemical reactions. Radioactive forms of the element are then easily located with sensors.

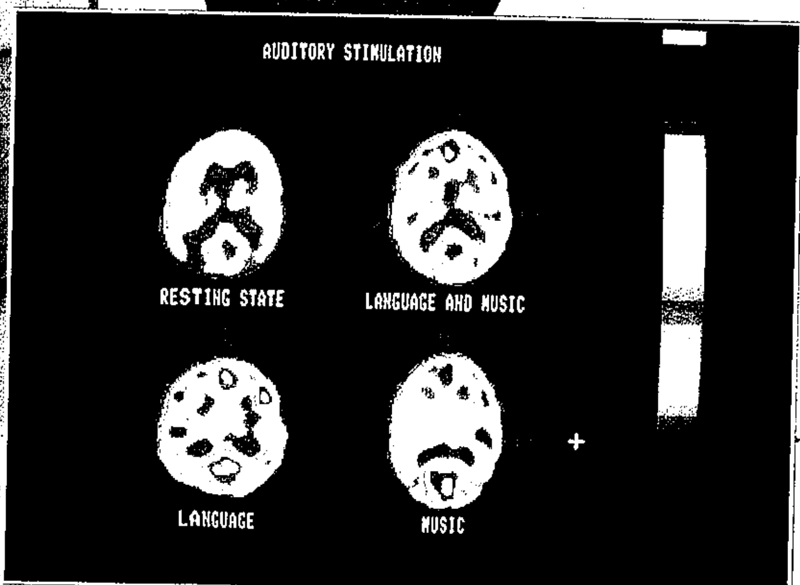
Why It Matters

How Do PET Scans Work?

Positron emission tomography (PET) is a medical procedure that can be used to study how a patient's body is functioning. PET scans can help doctors detect medical problems, such as cancer and heart disease. These scans can show changes in biological processes earlier than changes in anatomy are visible by using other procedures, such as CAT scans and MRIs.

1. Patients receiving a PET scan are injected with a radioactive tracer that is attached to a natural body compound, such as glucose.
2. After 30 to 45 minutes, patients are taken to the PET scanner. They must lie very still while the detectors record the emission of energy from the injected radioactive materials.
3. Because living tissues use glucose for energy, different colors on the computer screen correspond to the different levels of function in the body.

REAL WORLD



Researchers use PET imaging to understand brain function, both for disease detection and for research. In these scans, a research subject's brain was scanned with different sets of stimuli. Scientists can use this information to learn which areas of the brain are used to process different sensations.

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Topic: Radioactive Tracers
Code: HK81257

YOUR TURN

CRITICAL THINKING

1. Name some advantages and disadvantages of PET scans for medical diagnosis.

WRITING IN SCIENCE

2. Research other medical diagnostic techniques. How do they compare to PET scans?

Risks from Nuclear Radiation

Although nuclear radiation has many benefits, there are also risks, because nuclear radiation interacts with living tissue. Alpha and beta particles, as well as gamma rays and X rays, can change the number of electrons in the molecules of living materials. This process is known as *ionization.* Ionized molecules may form substances that are harmful to life.

› The risk of damage from nuclear radiation depends on both the type and the amount of radiation exposure. The effects of low levels of nuclear radiation on living cells are so small that they may not be detected. However, studies have shown a relationship between exposure to high levels of nuclear radiation and cancer. Cancers associated with high-dose exposure include leukemia and breast, lung, and stomach cancers.

The ability to penetrate matter differs among different types of nuclear radiation. A layer of clothing or an inch of air can stop alpha particles. Beta particles are lighter and faster than alpha particles. Beta particles can penetrate a fraction of an inch in solids and liquids and can travel several feet in air. Several feet of material may be required to protect you from high-energy gamma rays.

READING TOOLBOX

Word Origins
What are the origins of the words *ionization* and *dosimeter*? Do these words have root words from other languages? If so, what are the meanings of those root words?

High levels of nuclear radiation can cause radiation sickness.

Radiation sickness is an illness that results from excessive exposure to nuclear radiation. This sickness may occur from a single massive exposure, such as a nuclear explosion, or repeated exposures to very high nuclear radiation levels. Individuals who work with nuclear radiation must protect themselves with shields and special clothing. People who work in radioactive areas wear *dosimeters*, devices for measuring the amount of nuclear radiation exposure. **Figure 7** shows one example of a dosimeter.

Figure 7 A dosimeter contains a piece of film that detects radiation in the environment. Dosimeters help indicate exposure to ionizing radiation.

High concentrations of radon gas can be hazardous.

Colorless and inert, *radon gas* is produced by the radioactive decay of the uranium-238 present in soil and rock. Radon gas emits alpha and beta particles and gamma rays. Tests have shown a correlation between lung cancer and high levels of exposure to radon gas, especially for smokers. Some areas have higher radon levels than others do. Tests for radon gas in buildings are widely available.

High concentrations of radon-222 in homes or offices can be eliminated by sealing cracks in foundations or by installing vents that draw air out of the building.

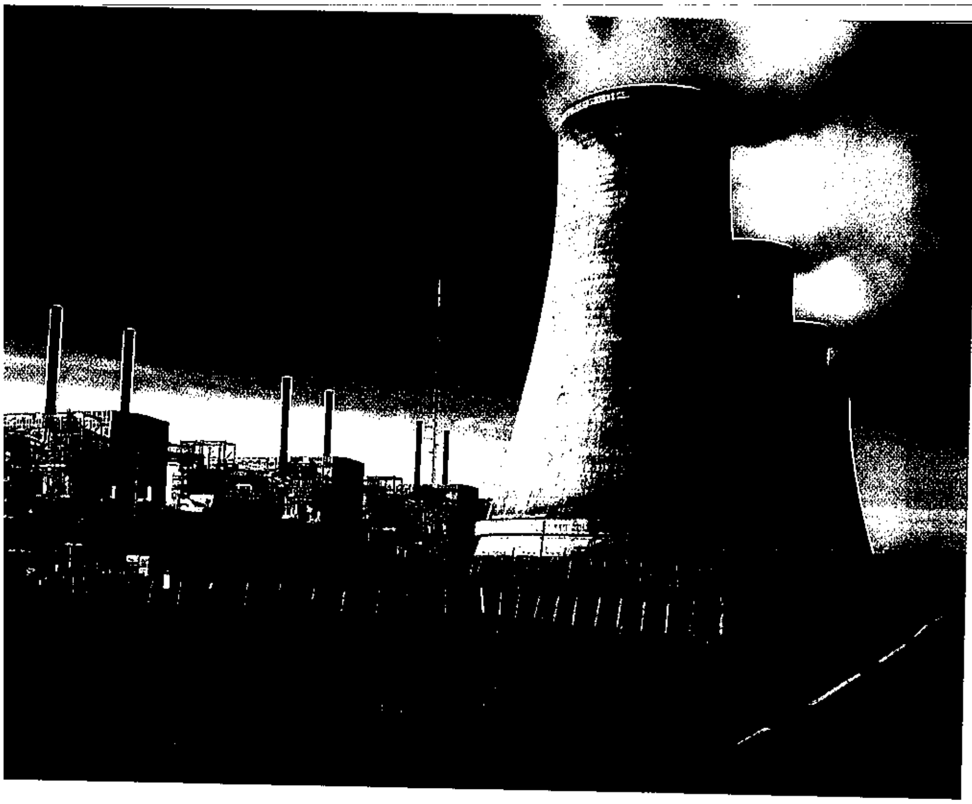

Figure 8 Nuclear reactors such as this one are used over much of the world to generate electricity. **What are some advantages to nuclear power?**

Nuclear Power

Nuclear reactors, such as the one shown in **Figure 8**, are used in dozens of countries to generate electricity. **› Energy produced from fission is used to provide electrical energy to millions of homes and businesses.** There are many advantages to this source of energy. There are also disadvantages.

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www.scilinks.org
Topic: Nuclear Power
Code: HK81052

Nuclear fission has both advantages and disadvantages.

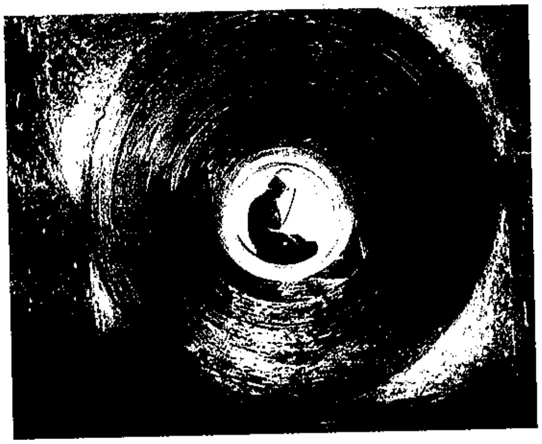
One advantage of nuclear fission is that it does not produce gaseous pollutants. Also, there is much more energy in the known uranium reserves than in the known reserves of coal and oil.

In nuclear fission reactors, energy is produced when a controlled fission reaction is triggered in uranium-235. However, the products of fission reactions are often radioactive isotopes. Therefore, serious safety concerns must be addressed. Radioactive products of fission must be handled carefully so that they do not escape into the environment and release nuclear radiation.

Another safety issue involves the safe operation of the nuclear reactors in which the controlled fission reaction is carried out. A nuclear reactor must be equipped with many safety features. The reactor requires considerable shielding and must meet very strict safety requirements. Thus, nuclear power plants are expensive to build.

Academic Vocabulary
issue (ISH oo) a point of debate

Reading Check **How do energy reserves for uranium compare to those of coal and oil?**



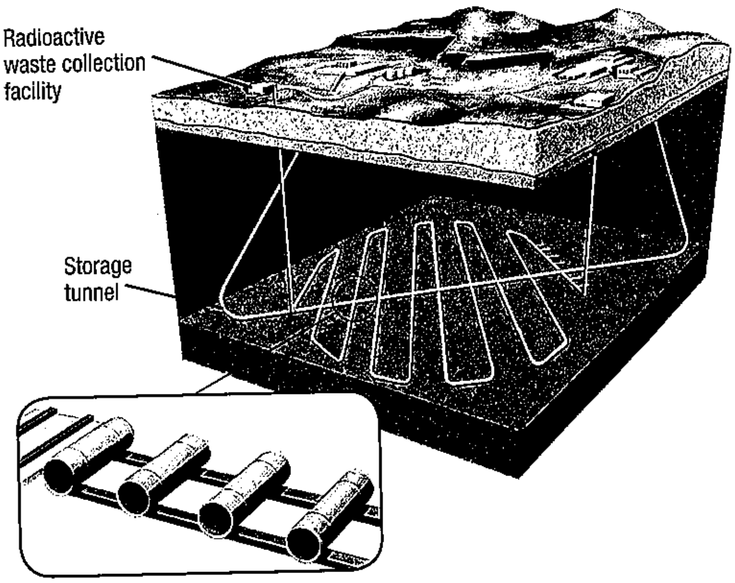


Figure 9 Storage facilities for nuclear waste must be designed to contain radioactive materials safely for thousands of years.

Nuclear waste must be safely stored.

Besides the expense that occurs during the life of a nuclear power plant is the expense of storing radioactive materials, such as the fuel rods used in the reactors. After their use, they must be placed in safe facilities that are well shielded, as **Figure 9** shows. These precautions are necessary to keep nuclear radiation from leaking out and harming living things. The facilities must also keep nuclear radiation from contacting groundwater.

Ideal places for such facilities are sparsely populated areas that have little water on the surface or underground. These areas must also be free from earthquakes.

Nuclear fusion releases large quantities of energy.

The sun uses the nuclear fusion of hydrogen atoms; this fusion results in larger helium atoms. Solar energy can be captured by solar panels or other means to provide energy for homes and businesses. Another option that holds some promise as an energy source is controlled nuclear fusion.

Some scientists estimate that 1 kg of hydrogen in a fusion reactor could release as much energy as 16 million kg of burning coal. The fusion reaction itself releases very little waste or pollution.

Because fusion requires that the electric repulsion between protons be overcome, these reactions are difficult to produce in the laboratory. However, scientists are conducting many experiments in the United States, Japan, and Europe to learn how people can exploit fusion to create a clean source of power that uses fuels extracted from ordinary water.

Integrating **Space Science**

Element Factory All heavy elements, from cobalt to uranium, are made when massive stars explode. The pressure that is produced in the explosion causes nearby nuclei to fuse, in some cases, more than once.

The explosion carries the newly created elements into space. These elements later become parts of new stars and planets. The elements of Earth are believed to have formed in the outer layers of an exploding star.

Nuclear fusion also has advantages and disadvantages.

The most attractive feature of fusion is that the fuel for fusion is abundant. Hydrogen is the most common element in the universe, and it is plentiful in many compounds on Earth, such as water. Earth's oceans could provide enough hydrogen to meet current world energy demands for millions of years.

Practical fusion-based power, illustrated by the concept drawing in **Figure 10,** is far from being a reality. Fusion reactions have some drawbacks. They can produce fast neutrons, a highly energetic and potentially dangerous form of nuclear radiation. Because shielding material in the reactor would have to be replaced periodically, the expense of operating a fusion power plant would still be high. Lithium can be used to slow down these neutrons, but lithium is chemically reactive and rare, so its use is impractical.

Research on nuclear fusion is still in its infancy. Successful experiments are just beginning. Who can say what the future may hold? Perhaps future scientists will find the answers to the nagging questions that plague the government today concerning the perfect fuel for U.S. citizens.

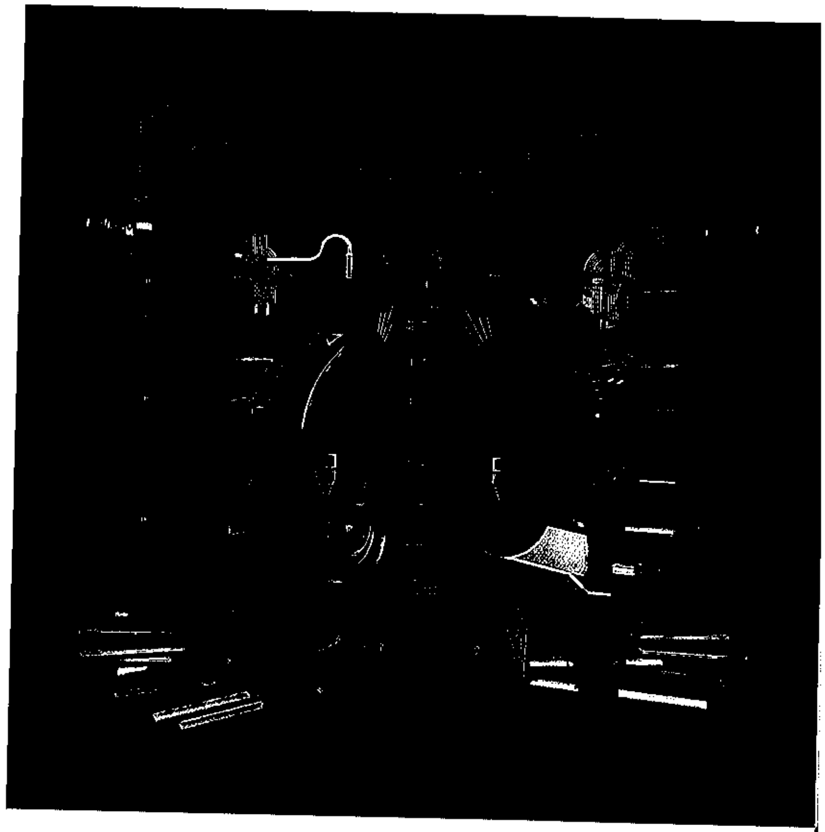


Figure 10 The ITER experimental nuclear fusion research reactor will be built in France.

Section 3 Review

KEY IDEAS

1. **List** three sources of background radiation.
2. **Identify** three activities that add to background radiation under normal circumstances.
3. **Describe** how smoke detectors use alpha particles and what sets off the alarm.
4. **Explain** how radioactive tracers help locate tumors.
5. **Describe** three factors that contribute to how much damage is done to living tissue by radiation.
6. **Identify** some of the advantages and disadvantages of using nuclear energy.

CRITICAL THINKING

7. **Compare and Contrast** What are the benefits and risks of radiation therapy?
8. **Inferring Conclusions** Explain why it is important to use low levels of nuclear radiation for detection and treatment of disease.
9. **Drawing Conclusions** Why is the testing of buildings for radon gas levels important?
10. **Making Predictions** Suppose that uranium-238 could undergo fission as easily as uranium-235 does. Predict how that situation would change the advantages and disadvantages of fission reactors.

Skills Practice Lab

50 min

Simulating Nuclear Decay Reactions

In this lab, you will simulate the decay of lead-210 into its isotope lead-206. This decay of lead-210 into lead-206 occurs in a multistep process. Lead-210, $^{210}_{82}Pb$, first decays into bismuth-210, $^{210}_{83}Bi$, which then decays into polonium-210, $^{210}_{84}Po$, which finally decays into the isotope lead-206, $^{206}_{82}Pb$.

What You'll Do

- **Simulate** the decay of radioactive isotopes by throwing a set of dice, and observe the results.
- **Graph** the results to identify patterns in the amounts of isotopes present.

What You'll Need

cup, paper, large, with plastic lid
dice (10)
pencil
tape, masking

Procedure

Modeling Isotope Decay

1. On a sheet of paper, prepare a data table as shown below. Leave room to add extra rows at the bottom, if necessary.

Sample Data Table: Dice Rolls Modeling Isotope Decay

Throw #	Number of dice representing each isotope			
	$^{210}_{82}Pb$	$^{210}_{83}Bi$	$^{210}_{84}Po$	$^{206}_{82}Pb$
0 (start)	10	0	0	0
1				
2				
3				
4				

DO NOT WRITE IN BOOK

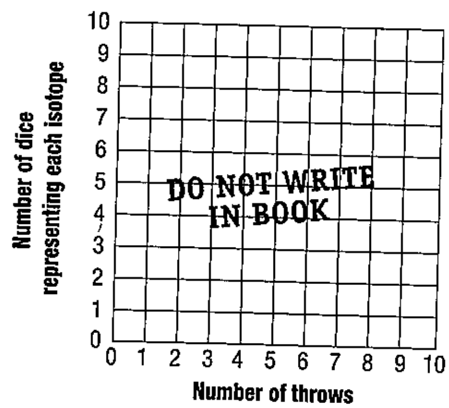
2. Place all 10 dice in the cup. Each die represents an atom of $^{210}_{82}Pb$, a radioactive isotope.
3. Put the lid on the cup, and shake the cup a few times. Then, remove the lid, and spill the dice. In this simulation, each throw represents a *half-life*.
4. All of the dice that land with *1*, *2*, or *3* up represent atoms of $^{210}_{82}Pb$ that have decayed into $^{210}_{83}Bi$. The remaining dice still represent $^{210}_{82}Pb$ atoms. Separate the two sets of dice. Count the dice, and record the results in your data table.
5. To keep track of the dice representing the decayed atoms, you will make a small mark on them. On a die, the faces with *1*, *2*, and *3* share a corner. With a pencil, draw a small circle or loop around this shared corner. This die represents the $^{210}_{83}Bi$ atoms.
6. Put all the dice back in the cup, shake them, and roll them again. In a decay process, there are two possibilities: some atoms decay, and some do not. See the table "Guide to Isotope Decay" to help track your results.

Guide to Isotope Decay

Isotope type	Decays into	Signs of decay	Identifying the atoms in column 2
$^{210}_{82}Pb$	$^{210}_{83}Bi$	Unmarked dice land on *1*, *2*, or *3*.	Mark $^{210}_{83}Bi$ by drawing a circle around the corner where faces *1*, *2*, and *3* meet.
$^{210}_{83}Bi$	$^{210}_{84}Po$	Dice with one loop land on *1*, *2*, or *3*.	Draw a circle around the corner where faces *4*, *5*, and *6* meet.
$^{210}_{84}Po$	$^{206}_{82}Pb$	Dice with two loops land on *1*, *2*, or *3*.	Put a small piece of masking tape over the two circles.
$^{206}_{82}Pb$	Decay ends		

Sorting the Isotopes That Decayed

7. After the second throw, you have three types of atoms. Sort the dice into three sets.
   - **a.** The first set consists of dice with a circle drawn on them that landed with *1*, *2*, or *3* facing up. These dice represent $^{210}_{83}Bi$ atoms that have decayed into $^{210}_{84}Po$.
   - **b.** The second set consists of two types of dice: the dice with one circle that did not land on *1*, *2*, or *3* (undecayed $^{210}_{83}Bi$) and the unmarked dice that landed with *1*, *2*, or *3* facing up (representing the decay of original $^{210}_{82}Pb$ into $^{210}_{83}Bi$).
   - **c.** The third set includes unmarked dice that did not land with *1*, *2*, or *3* facing up. These dice represent the undecayed $^{210}_{82}Pb$ atoms.
8. For your third throw, put all of the dice back into the cup. After the third throw, some of the $^{210}_{84}Po$ will decay into the stable isotope $^{206}_{82}Pb$. After this and each additional throw, do the following: separate the different types of atoms in groups, count the atoms in each group, record your data in your table, and mark the dice to identify each isotope. Use the table above as a guide.
9. Continue throwing the dice until all of the dice have indicated decay into $^{206}_{82}Pb$, which is a stable isotope.



Analysis

1. **Describing Events** Write nuclear-decay equations for the nuclear reactions modeled in this lab.
2. **Graphing Data** In your lab report, prepare a graph like the one shown here. Using a different color or symbol for each atom, plot the data for all four atoms on the same graph.

Communicating Your Results

3. **Drawing Conclusions** What do your results suggest about how the amounts of $^{210}_{82}Pb$ and $^{206}_{82}Pb$ on Earth are changing over time?

Extension

$^{210}_{82}Pb$ is continually produced through a series of nuclear decays that begin with $^{238}_{92}U$. Does this information cause you to modify your answer to item 3? Explain.

Counting Nuclear Decay

Science Skills

Technology

Math

Scientific Methods

Graphing

Problem

In a sample of francium-223, 93.75% of the sample has undergone radioactive decay. Francium-223 has a half-life of 22 min.

a. What fraction of francium-223 remains in the sample?

b. How many half-lives did it take for the sample to decay?

c. How long did the sample take to decay?

Solution

Identify

List all given and unknown values.

Given:

percentage of sample decayed = 93.75%

half-life = 22 min

Unknown:

a. *fraction of sample remaining*

b. n = *number of half-lives*

c. *time of decay*

Plan

a. Subtract the fraction decayed from 1 to find the amount of sample remaining.

b. Determine how many multiples of 1/2 are in the fraction of sample remaining.

c. Multiply the number of half-lives by the half-life to find the time of decay.

a. *fraction of sample remaining* =

$1 - \textit{fraction of sample decayed} =$

$$1 - \frac{\textit{percentage of sample decayed}}{100}$$

b. $\left(\frac{1}{2}\right)^n = \textit{fraction of sample remaining}$

c. $\textit{time of decay} = n \times \textit{half-life}$

Solve

Substitute the given values into the equation, calculate the unknown quantities, and solve.

a. *fraction of sample remaining* =

$$1 - \frac{93.75}{100} = 1 - 0.9375 = 0.0625 = \frac{1}{16}$$

b. $\frac{1}{16} = \left(\frac{1}{2}\right) \times \left(\frac{1}{2}\right) \times \left(\frac{1}{2}\right) \times \left(\frac{1}{2}\right) = \left(\frac{1}{2}\right)^4$

$\textit{number of half-lives} = n = 4$

c. $\textit{time of decay} = 4 \times 22 \text{ min} = 88 \text{ min}$

Practice

1. What fraction of iodine-132 remains if 87.5% has undergone radioactive decay?
2. How many half-lives are required for the sample to decay?
3. Iodine-132 has a half-life of 2.3 h. How long does the sample take to decay completely?

CHAPTER 10 Summary

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SUPER SUMMARY
KEYWORD: HK8NUCS

Key Ideas

Section 1 What Is Radioactivity?

- **Nuclear Radiation** After radioactive decay, elements change into different isotopes of the same element or into entirely different elements. (p. 327)
- **Nuclear Decay** Anytime an unstable nucleus emits alpha or beta particles, the number of protons and neutrons changes. (p. 330)
- **Radioactive Decay Rates** The time required for half of a sample of radioactive material to decay is its half-life. (p. 333)

Key Terms

- **radioactive decay,** p. 327
- **nuclear radiation,** p. 327
- **alpha particle,** p. 328
- **beta particle,** p. 329
- **gamma ray,** p. 329
- **half-life,** p. 333

Section 2 Nuclear Fission and Fusion

- **Nuclear Forces** The stability of a nucleus depends on the nuclear forces that hold the nucleus together. These forces act between the protons and the neutrons. (p. 337)
- **Nuclear Fission** Nuclear fission takes place when a large nucleus divides into smaller nuclei. Energy is released in the process. (p. 339)
- **Nuclear Fusion** Energy is released when light nuclei are combined to form heavier nuclei. (p. 342)

Key Terms

- **fission,** p. 339
- **nuclear chain reaction,** p. 340
- **critical mass,** p. 341
- **fusion,** p. 342

Section 3 Nuclear Radiation Today

- **Where Is Radiation?** We are continually exposed to radiation from natural sources, such as the sun, soil, rocks, and plants. (p. 344)
- **Beneficial Uses of Nuclear Radiation** Applications of nuclear radiation include medical diagnosis and treatment, smoke detectors, and agriculture. (p. 346)
- **Risks from Nuclear Radiation** The risk of damage from nuclear radiation depends on both the type and the amount of radiation exposure. (p. 348)
- **Nuclear Power** Energy produced from fission is used to provide electrical energy to millions of homes and businesses. (p. 349)

Key Terms

- **background radiation,** p. 344
- **rem,** p. 345
- **radioactive tracer,** p. 346

CHAPTER 10 Review

READING TOOLBOX

1. **Four-Corner Fold** Create a four-corner fold as described in Appendix A. Under two of the flaps, describe (1) nuclear fission and (2) nuclear fusion. Under the other two flaps, describe (3) some beneficial uses of nuclear radiation and (4) some risks of nuclear radiation.

USING KEY TERMS

2. Describe the main differences between the four principal types of nuclear radiation: *alpha particles, beta particles, gamma rays,* and *neutron emission*.
3. Where do *beta particles* come from?
4. Why do *gamma rays* have no mass at all?
5. Would a substance with a one-second *half-life* be effective as a *radioactive tracer*?
6. For the nuclear *fission* process, how is *critical mass* important in a *nuclear chain reaction*?
7. What is *background radiation*, and what are its sources?
8. How does nuclear *fusion* account for the energy produced in stars?

UNDERSTANDING KEY IDEAS

9. When a heavy nucleus decays, it may emit any of the following except
   a. alpha particles. **c.** gamma rays.
   b. beta particles. **d.** X rays.
10. A neutron decays to form a proton and a(n)
    a. alpha particle. **c.** gamma ray.
    b. beta particle. **d.** emitted neutron.
11. After three half-lives, _____ of a radioactive sample remains.
    a. all **c.** one-third
    b. one-half **d.** one-eighth
12. Carbon dating can be used to measure the age of each of the following except
    a. a 7,000-year-old human body.
    b. a 1,200-year-old wooden statue.
    c. a 2,600-year-old iron sword.
    d. a 3,500-year-old piece of fabric.
13. The strong nuclear force
    a. attracts protons to electrons.
    b. holds molecules together.
    c. holds the atomic nucleus together.
    d. attracts electrons to neutrons.
14. The process in which a heavy nucleus splits into two lighter nuclei is called
    a. fission. **c.** alpha decay.
    b. fusion. **d.** a chain reaction.
15. The amount of energy produced during nuclear fission is related to
    a. the temperature in the atmosphere during nuclear fission.
    b. the masses of the original nuclei and the particles released.
    c. the volume of the nuclear reactor.
    d. the square of the speed of sound.
16. Which condition is *not* necessary for a chain reaction to occur?
    a. The radioactive sample must have a short half-life.
    b. The neutrons from one split nucleus must cause other nuclei to divide.
    c. The radioactive sample must be at critical mass.
    d. Not too many neutrons must be allowed to leave the radioactive sample.
17. Which of the following is *not* a use for radioactive isotopes?
    a. as tracers for diagnosing disease
    b. as an additive to paints to increase durability
    c. as a way to treat forms of cancer
    d. as a way to study biochemical processes in plants

EXPLAINING KEY IDEAS

18. How does nuclear decay affect the atomic number and mass number of a nucleus that changes after undergoing decay?

19. What are two factors that cause alpha particles to lose energy and travel less distance than neutrons travel?

20. The nuclei of atoms are made of protons and neutrons. Every atomic nucleus larger than that of hydrogen has as least two positively charged protons. Why do the nuclei remain intact instead of being broken apart by the repulsion of their electric charges?

21. The amount of nuclear radiation exposure absorbed by the human body is measured in rems. How does the amount of exposure in rems per year in Denver, Colorado, compare with the amount that has been set as a safe limit for workers in occupations with relatively high radiation exposure? Explain your answer.

22. How can a radioactive tracer be used to locate tumors?

CRITICAL THINKING

23. Compare and Contrast Describe the similarities and differences between atomic electrons and beta particles.

24. Identifying Functions Why do people working around radioactive waste in a radioactive storage facility wear badges that contain strips of photographic film?

25. Drawing Conclusions Why would carbon-14 not be a good choice to use in household smoke detectors?

26. Predicting Outcomes Would an emitter of alpha particles be useful in measuring the thickness of a brick? Explain your answer.

Graphing Skills

27. Graphing Data The first 20 elements on the periodic table have stable nuclei composed of equal numbers of protons and neutrons. Create a graph on which you plot these elements based on the number of protons (*x*-axis) and neutrons (*y*-axis) they contain.

28. Graphing Data Extend your graph of the first 20 elements to include the other elements on the periodic table. What happens to the graph? What does this indicate about the stability of a nucleus?

29. Interpreting Graphics Using a graphing calculator or computer graphing program, create a graph for the decay of iodine-131, which has a half-life of 8.1 days. Use the graph to answer the following questions.

a. Approximately what percentage of the iodine-131 has decayed after 4 days?

b. Approximately what percentage of the iodine-131 has decayed after 12.1 days?

c. What fraction of iodine-131 has decayed after 2.5 half-lives have elapsed?

Math Skills

30. Nuclear Decay Bismuth-212 undergoes a combination of alpha and beta decays to form lead-208. Depending on which decay process occurs first, different isotopes are temporarily formed during the process. Identify these isotopes by completing the equations given below.

a. $^{212}_{83}\text{Bi} \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\text{He}$

$^{A}_{Z}X \rightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}\text{e}$

b. $^{212}_{83}\text{Bi} \rightarrow {}^{A}_{Z}X + {}^{0}_{-1}\text{e}$

$^{A}_{Z}X \rightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\text{He}$

31. Half-Life Health officials are concerned about radon levels in homes. The half-life of radon-222 is 3.82 days. If a sample of gas contains 4.38 μg of radon-222, how much will remain in the sample after 15.2 days?

Standardized Test Prep

Understanding Concepts

Directions (1–3): **For each question, write on a sheet of paper the letter of the correct answer.**

1. The beta-decay equation for the decay of cesium-137 into an isotope of barium is

$$^{137}_{55}Cs \rightarrow ^{X}_{Y}Ba + ^{Z}_{-1}e$$

What are the correct values for *X*, *Y* and *Z*?

A. 136, 55, 1
B. 137, 56, 0
C. 68, 56, 69
D. 69, 54, 68

2. The half-life of a particular radioactive isotope is 10 years. If you begin with 100 g of the substance, how much will be left after 40 years?

F. 6.25 g
G. 12.5 g
H. 25 g
I. 60 g

3. What happens to an atom's mass number and atomic number after the atom emits a beta particle?

A. Both the mass number and the atomic number increase by 1.
B. The atomic number does not change, but the mass number decreases by 1.
C. The mass number does not change, but the atomic number increases by 1.
D. Both the mass number and the atomic number decrease by 1.

Directions (4–5): **For each question, write a short response.**

4. In a particular case of alpha decay, an isotope of uranium, U, with a mass number of 238 and an atomic number of 92 emits an alpha particle and transforms into thorium, Th, which has an atomic number of 90. Write the equation for this decay process.

5. Why doesn't a nucleus full of protons fly apart because of electric repulsion?

Reading Skills

Directions (6–7): **Read the passage below. Then, answer the questions that follow.**

POSITRON

Like an electron, a positron has very little mass; however, an electron has an electric charge of −1, and a positron has an electric charge of +1. Scientists theorize that for every kind of particle, there is an antiparticle, which has the same mass but an opposite electric charge.

There are at least two ways in which positrons can be generated. One way is beta decay. In the most common form of beta decay, a neutron in the nucleus of an isotope is converted to a proton, and a beta particle is emitted in the form of an electron. This form of beta decay is properly called *beta minus decay*. In certain isotopes, however, the mirror image of this process, called *beta plus decay*, takes place: a proton is converted to a neutron, and a beta particle with a positive charge is emitted. This beta particle is a positron.

Another way that positrons can be created is for a photon to collide with a charged particle (such as an alpha particle) with a great amount of energy. The collision can result in the simultaneous creation of an electron and a positron from the energy of the photon, in a process called *pair production*.

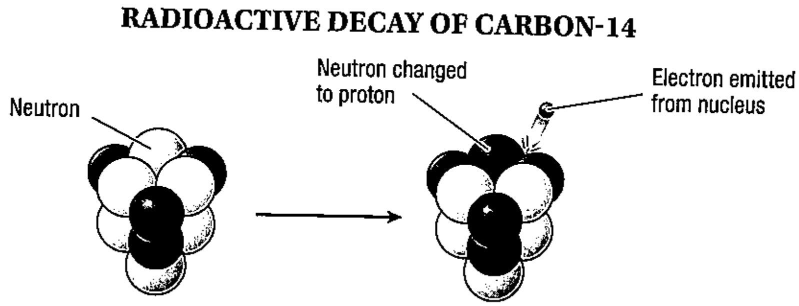
6. What are the two types of beta particles?

F. protons and electrons
G. positrons and photons
H. electrons and photons
I. positrons and electrons

7. Which has greater mass, a positron or a photon? Explain.

Interpreting Graphics

The graphic below shows the radioactive decay of carbon-14. Use this graphic to answer questions 8–10.



8. What type of nuclear reaction is depicted in the diagram?

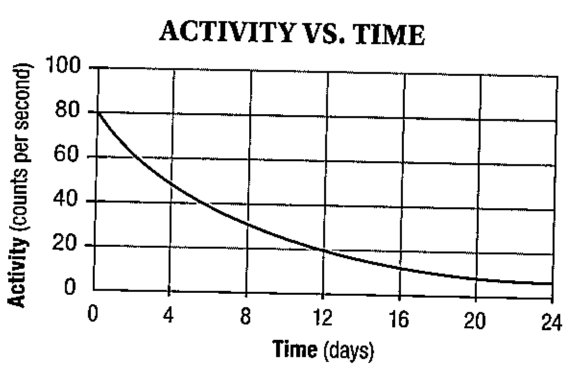
- **A.** alpha decay
- **B.** beta decay
- **C.** fission
- **D.** fusion

9. What isotope is created by this process?

- **F.** carbon-14
- **G.** carbon-12
- **H.** nitrogen-14
- **I.** nitrogen-13

10. Write the equation that describes this process.

One way to measure how much of a radioactive isotope is present is to make a count of how many times per second a particle of radiation is emitted. This count is called an *activity count*. The graphic below shows the change in the activity count for a particular isotope over a period of 24 days. Use this graphic to answer questions 11–12.



11. What is the half-life of the isotope?

- **A.** 40 days
- **B.** 24 days
- **C.** 12 days
- **D.** 6 days

12. Assuming that this quantity of isotope had been decaying at the same rate that is shown in the graph for weeks before the measuring began, what would the activity count have been 12 days before day 0?

Test Tip

Try to figure out the answer to a question before you look at the choices. Then, compare your answer with each answer choice. Choose the answer that most closely matches your own.