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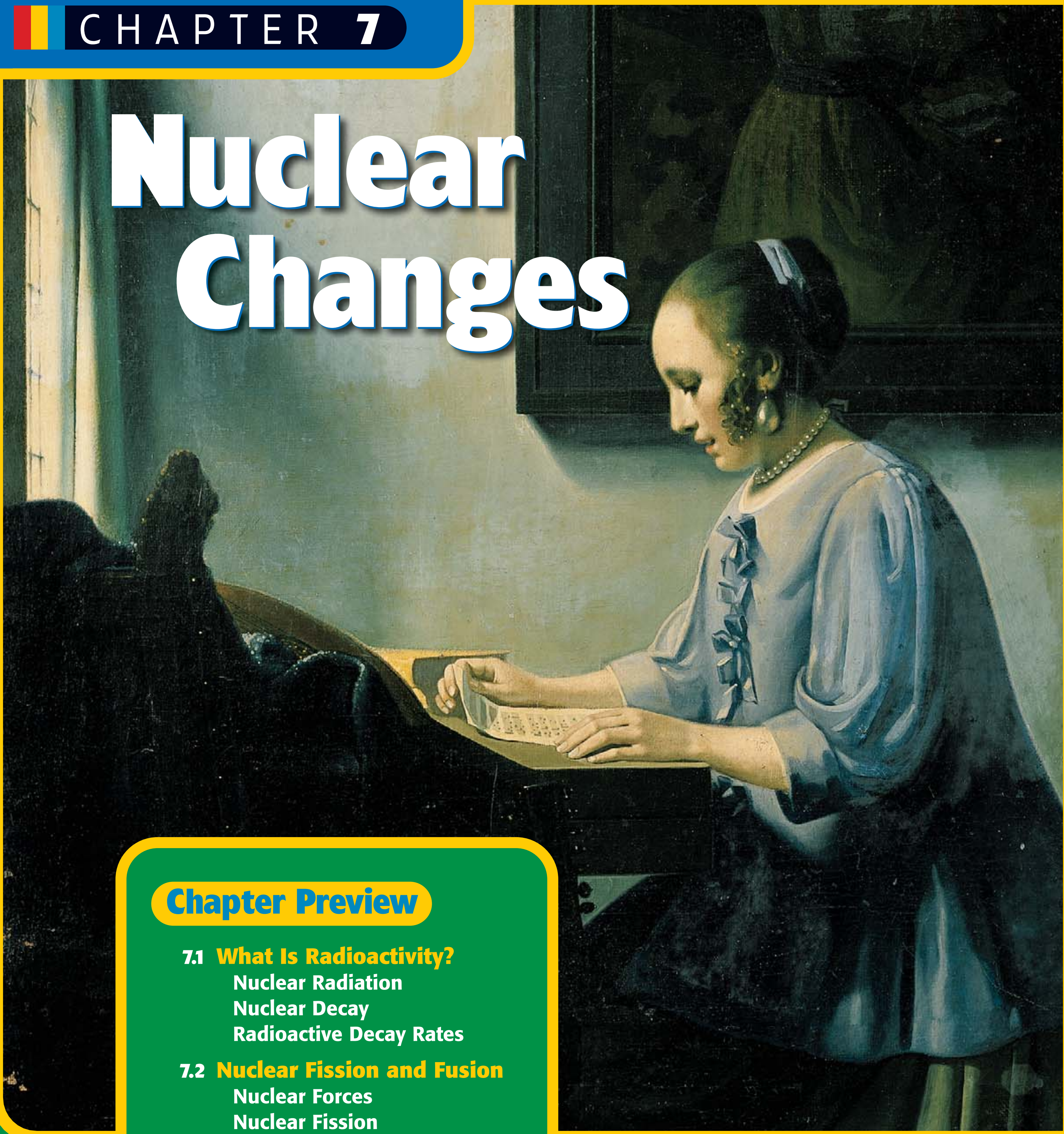
CHAPTER 7

Nuclear Changes



Chapter Preview

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Radioactive substances in the paints and canvases used in painting decay over time. These radioactive substances emit nuclear radiation. The amount of radiation emitted can be used to determine how old the painting is and whether the painting is a forgery or not.

Focus ACTIVITY

Background The painting "Woman Reading Music" was considered one of a series of great finds discovered by Dutch painter and art dealer Han van Meegeren in the 1930s. The previously unknown paintings were believed to be by the great seventeenth century Dutch artist Jan Vermeer. But after World War II, another painting said to be by Vermeer was found in a Nazi art collection, and its sale was traced to van Meegeren. Arrested for collaborating with the Nazis, van Meegeren confessed that both paintings were forgeries. He claimed that he had used one of the fake Vermeers to lure Nazi Germany into returning many genuine paintings to the Dutch.

Was van Meegeren lying to avoid a long prison sentence, or had he really swindled the Nazis? Although X-ray photographs of the painting suggested that it was a forgery, conclusive evidence did not come about until 20 years later. A fraction of the lead in certain pigments used in the painting proved to be radioactive. By measuring the number of radioactive lead nuclei that decayed each minute, experts were able to determine the age of the painting. The fairly rapid decay rate indicated that the paint—and thus the painting—was less than 40 years old.

Activity 1 Radiation exposes photographic film. To test this observation, obtain a small sheet of unexposed photographic film and a new household smoke detector, which contains a radioactive sample. Remove the casing from the detector. In a dark room, place the film next to the smoke detector in a cardboard box and close the box. Be sure that no light can enter the box. After a day, open the box in a dark room and place the film in a thick envelope. Take the film to be processed. Is there an image on the film? How does the image differ from the rest of the film? How can you tell that the image is related to the radioactive source?

Activity 2 Use library resources to research famous art forgeries. How were the forgeries detected? What techniques use radioactive substances to identify the elements in paintings?

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7.1

What Is Radioactivity?

KEY TERMS

radioactivity
nuclear radiation
alpha particle
beta particle
gamma ray
neutron emission
half-life

OBJECTIVES

- Identify four types of nuclear radiation and their properties.
- Balance equations for nuclear decay.
- Calculate the half-life of a radioactive isotope.

In recent years there has been concern about radon gas in buildings and its impact on health. Detectors are used to check the level of radon in a house or a building. Many elements and compounds are dangerous because of the way they react with substances in our bodies. Radon, however, is a gas that, like helium and neon, does not chemically react with substances in the body. Why, then, is it considered a health hazard?

Nuclear Radiation

radioactivity process by which an unstable nucleus emits one or more particles or energy in the form of electromagnetic radiation

Radon is one of many elements that change through **radioactivity.** Radioactive materials, which were mentioned in Chapter 3, have unstable nuclei. These nuclei go through changes by emitting particles or releasing energy, as shown in **Figure 7-1.** After the changes in the nucleus, the element can transform into a different isotope of the same element or change into an entirely different element. This nuclear process is referred to as *nuclear decay.* (Recall from Chapter 3 that isotopes of an element are atoms with the same number of protons but a different number of neutrons in their nuclei.)

nuclear radiation charged particles or energy emitted by an unstable nucleus

The released energy and matter is called **nuclear radiation,** and it can cause damage to living tissue. Nuclear radiation from radon that seeps into houses and buildings is the reason for the health concerns. (Note that the term *radiation* also refers to light or to an energy transfer method between objects at different temperatures. *To avoid confusion, the term* nuclear radiation *will be used to describe radiation associated with nuclear changes.)*

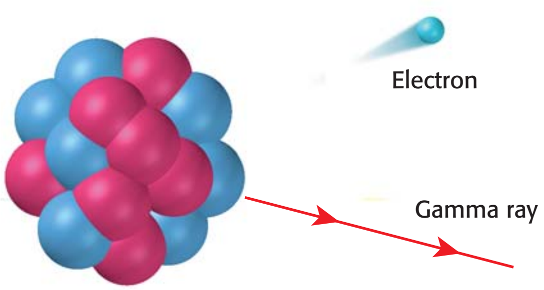

Figure 7-1
During radioactivity an unstable nucleus emits one or more particles or high-energy electromagnetic radiation.

Table 7-1 Types of Nuclear Radiation

Radiation type	Symbol	Mass (kg)	Charge
Alpha particle	$^{4}_{2}\mathrm{He}$	6.646×10^{-27}	+2
Beta particle	$^{0}_{-1}e$	9.109×10^{-31}	–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: alpha particles, beta particles, gamma rays, and neutron emission. Some of their properties are listed in **Table 7-1.** When a radioactive atom decays, the nuclear radiation leaves the nucleus. This nuclear radiation then interacts with nearby matter. The interaction with matter depends in part on the properties of nuclear radiation, like charge, mass, and energy, which are discussed below.

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Alpha particles consist of protons and neutrons

Uranium is a radioactive element that naturally occurs in three isotope forms. One of its isotopes, uranium-238, undergoes nuclear decay by emitting positively charged particles. Ernest Rutherford, noted for discovering the nucleus, named them *alpha* (α) *rays*. 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 particle a positively charged particle, emitted by some radioactive nuclei, that consists of two protons and two neutrons

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 the fact that it is massive. 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 down further.

Beta particles are electrons produced from neutron decay

Some nuclei emit another type of nuclear radiation consisting of negatively charged particles. Compared to alpha particles, this type of nuclear radiation travels farther through matter. This nuclear radiation is named the **beta particle,** after the second Greek letter, *beta* (β). Beta particles are fast-moving electrons.

beta particle an electron emitted during the radioactive decay of a neutron in an unstable nucleus

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Having negative particles come from a positively-charged nucleus puzzled scientists for years. However, in the 1930s, another discovery helped to clear up the mystery: neutrons, which are not charged, decay to form a proton and an electron. The electron, having very little mass, is then ejected from the nucleus at a high speed as a beta particle.

Beta particles easily go 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 aren't as massive as alpha particles and therefore move faster. 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.

Figure 7-2
The element radium, which Marie Curie discovered in 1898, was later found to emit gamma rays.

Gamma rays are very high energy light

In 1898, Marie Curie, shown in **Figure 7-2,** and her husband, Pierre, isolated the radioactive element radium. In 1900, studies of radium by Paul Villard revealed that the element emitted a new form of nuclear radiation. This radiation was much more penetrating than even beta particles. Following the pattern established by Rutherford, this new kind of nuclear radiation was named the **gamma ray,** after the third Greek alphabet letter, *gamma* (γ).

gamma ray high-energy electromagnetic radiation emitted by a nucleus during radioactive decay

Unlike alpha or beta particles, gamma rays are not made of matter and do not have an electric charge. Instead, gamma rays are a form of electromagnetic energy, like visible light or X rays. Gamma rays, however, have more energy than light or X rays.

Because gamma rays have no electrical charge, they do not easily ionize matter. But gamma rays still cause damage because of their high energy. They can go through up to 60 cm of aluminum or 7 cm of lead. Because gamma rays penetrate matter deeply, 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.

Neutron radioactivity may occur in a neutron-rich 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 by detecting its emission from a nucleus.

neutron emission the release of a high-energy neutron by some neutron-rich nuclei during radioactive decay

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

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Nuclear Decay

When an unstable nucleus emits alpha or beta particles, the number of protons or neutrons changes. For instance, radium-226 (an isotope of radium with the mass number 226) changes to radon-222 by emitting an alpha particle.

A nucleus gives up two protons and two neutrons during alpha decay

Nuclear decay processes can be written as equations similar to those 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. In the case of the alpha decay of radium-226, the decay process is written as follows.

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

Notice that the mass numbers and the atomic numbers add up. The mass number of the atom before decay is 226 and 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 equals the 86 protons in the radon-222 nucleus and 2 protons in the alpha particle.

A nucleus gains a proton and loses a neutron during beta decay

With beta decay, the form of the equation is the same except the symbol for a beta particle is used. This symbol, with the appropriate mass and atomic numbers, is $^{0}_{-1}e$.

Of course, an electron is not an atom and should not have an atomic number, which is the number of positive charges in a nucleus. But for the sake of convenience, since an electron has a single negative charge, an electron is given an atomic number of –1 when you write a nuclear decay equation. Similarly, the beta particle's mass is so much less than that of a proton or neutron that it can be regarded as having a mass number of 0.

A beta decay process occurs when carbon-14 decays to nitrogen-14 by emitting a beta particle.

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

In all cases of beta decay, the mass number before and after the decay does not change. Note that the atomic number of the product nucleus increases by 1. This occurs because a neutron

Did You Know?

Ernest Rutherford showed that alpha particles are helium nuclei by trapping alpha particles from radon-222 decay in a glass tube. He then passed a high electric voltage across the gas, causing it to glow. The glow was identical to the glow produced by helium atoms, indicating that the two substances are the same.

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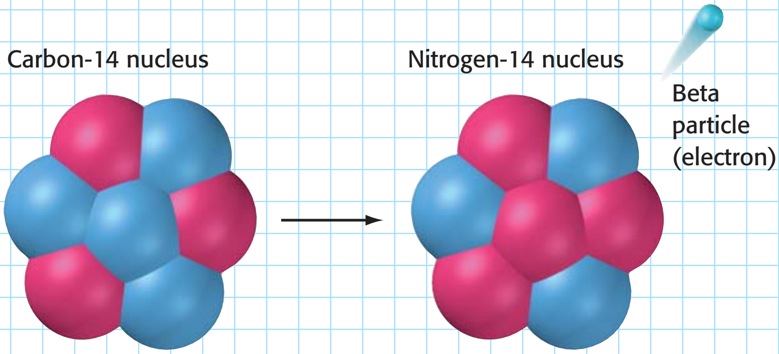
Figure 7-3

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



decays into a proton, causing the positive charge of the nucleus to increase by 1, as illustrated in **Figure 7-3.**

When the nucleus undergoes nuclear decay by gamma rays, there is no change in the atomic number of the element. The only change is in the energy content of the nucleus. The results of neutron emission will be discussed in greater detail in the next section.

Math Skills

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

1 Write down the equation with the original element on the left side and the products on the right side.

Use the letter *X* to denote the unknown product. Note that the mass and atomic numbers of the unknown isotope are represented by the letters *A* and *Z*.

$$^{217}_{89}\text{Ac} \longrightarrow {}^{A}_{Z}\text{X} + {}^{4}_{2}\text{He}$$

2 Write math equations for the atomic and mass numbers.

$217 = A + 4 \qquad 89 = Z + 2$

3 Rearrange the equations.

$A = 217 - 4 \qquad Z = 89 - 2$

4 Solve for the unknown values, and rewrite the equation with all nuclei represented.

$A = 213 \qquad Z = 87$

The unknown decay product has an atomic number of 87, which is francium, according to the periodic table. The element is therefore $^{213}_{87}\text{Fr}$.

$$^{217}_{89}\text{Ac} \longrightarrow {}^{213}_{87}\text{Fr} + {}^{4}_{2}\text{He}$$

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Practice

Nuclear Decay

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

1. $^{12}_{5}\mathrm{B} \longrightarrow {}^{12}_{6}\mathrm{C} + {}^{A}_{Z}X$

2. $^{225}_{89}\mathrm{Ac} \longrightarrow {}^{221}_{87}\mathrm{Fr} + {}^{A}_{Z}X$

3. $^{63}_{28}\mathrm{Ni} \longrightarrow {}^{A}_{Z}X + {}^{0}_{-1}e$

4. $^{212}_{83}\mathrm{Bi} \longrightarrow {}^{A}_{Z}X + {}^{4}_{2}\mathrm{He}$

Radioactive Decay Rates

If you were asked to pick up a rock and determine its age, 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 cloth found at the site of an ancient village?

One way to do it involves radioactive decay. Although it is impossible to predict the moment when any particular nucleus will decay, it is possible to predict the time it takes for half the nuclei in a given radioactive sample to decay. The time in which half a radioactive substance decays is called the substance's **half-life.**

half-life the time required for half a sample of radioactive nuclei to decay

After the first half-life of a radioactive sample has passed, half the sample remains unchanged, as indicated in **Figure 7-4** for carbon-14. After the next half-life, half the remaining half decays, leaving only a quarter of the sample undecayed. Of that quarter, half will decay in the next half-life. Only one-eighth will remain undecayed then. Eventually, the entire sample will decay.

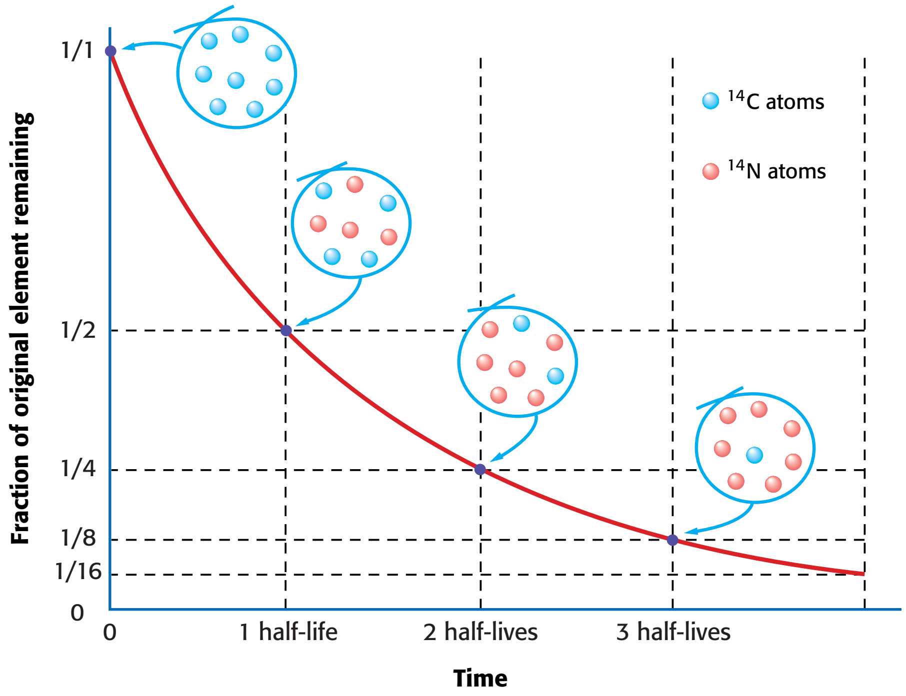

Figure 7-4
With each successive half-life, half the remaining sample decays to form another element.

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Table 7-2
Half-lives of Selected Isotopes

Isotope	Half-life	Nuclear radiation emitted
Thorium-219	1.05×10^{-6} s	${}^{4}_{2}He$
Hafnium-156	2.5×10^{-2} s	${}^{4}_{2}He$
Radon-222	3.82 days	${}^{4}_{2}He$, γ
Iodine-131	8.1 days	${}^{0}_{-1}e$, γ
Radium-226	1599 years	${}^{4}_{2}He$, γ
Carbon-14	5730 years	${}^{0}_{-1}e$
Plutonium-239	2.412×10^{4} years	${}^{4}_{2}He$, γ
Uranium-235	7.04×10^{8} years	${}^{4}_{2}He$, γ
Potassium-40	1.28×10^{9} years	${}^{0}_{-1}e$, γ
Uranium-238	4.47×10^{9} years	${}^{4}_{2}He$, γ

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

Different radioactive isotopes have different half-lives, as indicated in **Table 7-2.** Half-lives can last from nanoseconds to billions of years, depending on the stability of the nucleus.

If you know how much of a particular radioactive isotope was present in an object at the beginning, you can predict how old the object is. Geologists, people who study the Earth, use the half-lives of long-lasting isotopes, such as potassium-40, to calculate the age of rocks. Potassium-40 decays to argon-40, so the ratio of potassium-40 to argon-40 is smaller for older rocks.

Quick ACTIVITY

Modeling Decay and Half-life

For this exercise, you will need a jar with a lid, 128 pennies, pencil and paper, and a flat work surface.

1. Place the pennies in the jar, and place the lid on the jar. Shake the jar, and then pour the pennies onto the 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 pennies have been set aside.
4. 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?

Archaeologists use the half-life of radioactive carbon-14 to date more recent materials, such as the remains of an animal or fibers from ancient clothing. 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 is alive, the ratio of the carbon isotopes remains constant. This is also true for animals that eat plants.

When a plant or animal dies, it no longer takes in carbon-14. 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, the age of the once-living organism can be estimated.

Math Skills

Half-life Radium-226 has a half-life of 1599 years. How long would it take seven-eighths of a radium-226 sample to decay?

1 List the given and unknown values.

Given: half-life = 1599 years

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

Unknown: fraction of sample remaining = ?

total time of decay = ?

2 Calculate the fraction of radioactive sample remaining.

To find the fraction of sample remaining, subtract the fraction that has decayed from 1.

fraction of sample remaining = 1 – fraction decayed

fraction of sample remaining $= 1 - \frac{7}{8} = \frac{1}{8}$

3 Calculate the number of half-lives needed to equal that fraction.

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

$= \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$

Three half-lives are needed for one-eighth of the sample to remain undecayed.

4 Calculate the total time required for the radioactive decay.

Each half-life lasts 1599 years.

$$\text{total time of decay} = 3 \text{ half-lives} \times \frac{1599 \text{ y}}{\text{half-life}} = 4797 \text{ years}$$

INTEGRATING EARTH SCIENCE

The Earth's interior is extremely hot. One reason is because radioactive elements are present in trace amounts beneath the surface of the Earth and their nuclear decay produces energy that raises the temperature of their surroundings.

Many radioactive isotopes, like uranium-238, are very dense, which causes them to sink deep into Earth's interior. This is similar to what happens when dense liquids sink below less dense liquids, like syrup does in water.

The long half-lives of these radioactive isotopes can cause some of the surrounding matter to remain hot for billions of years.

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Practice

Half-life

1. The half-life of iodine-131 is 8.1 days. How long will it take for three-fourths of a sample of iodine-131 to decay?
2. Radon-222 is a radioactive gas with a half-life of 3.82 days. How long would it take for fifteen-sixteenths of a sample of radon-222 to decay?
3. Uranium-238 decays very slowly, with a half-life of 4.47 billion years. What percentage of a sample of uranium-238 would 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?
5. A sample of francium-212 will decay to one-sixteenth its original amount after 80 minutes. What is the half-life of francium-212?

SECTION 7.1 REVIEW

SUMMARY

- Nuclear radiation includes alpha particles, beta particles, gamma rays, and neutron emissions.
- Alpha particles are helium-4 nuclei.
- Beta particles are electrons emitted by neutrons decaying in the nucleus.
- Gamma radiation is an electromagnetic wave like visible light but with much greater energy.
- In nuclear decay, the sums of the mass numbers and the atomic numbers of the decay products equal the mass number and atomic number of the decaying nucleus.
- The time required for half a sample of radioactive material to decay is called its half-life.

CHECK YOUR UNDERSTANDING

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

Math Skills

4. **Determine** the product denoted by *X* in the following alpha decay.

$$^{212}_{86}\text{Rn} \longrightarrow {}^{A}_{Z}\text{X} + {}^{4}_{2}\text{He}$$

5. **Determine** the isotope produced in the beta decay of iodine-131, an isotope used to check thyroid-gland function.

$$^{131}_{53}\text{I} \longrightarrow {}^{A}_{Z}\text{X} + {}^{0}_{-1}e$$

6. **Calculate** the time required for three-fourths of a sample of cesium-138 to decay given that its half-life is 32.2 minutes.
7. **Calculate** the half-life of cesium-135 if seven-eighths of a sample decays in 6×10^6 years.
8. **Critical Thinking** An archaeologist discovers a wooden mask whose carbon-14 to carbon-12 ratio is one-sixteenth the ratio measured in a newly fallen tree. How old does the wooden mask seem to be, given this evidence?

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7.2

Nuclear Fission and Fusion

OBJECTIVES

- Describe how the strong nuclear force affects the composition of a nucleus.
- Distinguish between fission and fusion, and provide examples of each.
- Recognize the equivalence of mass and energy, and why small losses in mass release large amounts of energy.
- Explain what a chain reaction is, how one is initiated, and how it can be controlled.

KEY TERMS

strong nuclear force
fission
nuclear chain reaction
critical mass
fusion

In 1939, two German scientists, Otto Hahn and Fritz Strassman, conducted experiments in the hope of forming heavy nuclei. Using the apparatus shown in **Figure 7-5,** they bombarded uranium samples with neutrons, expecting a few nuclei to capture one or more neutrons. They were surprised to discover that the result was less-massive nuclei instead of more-massive nuclei.

It wasn't until their colleague Lise Meitner and her nephew Otto Frisch read the results of Hahn and Strassman's work that an explanation was offered. Meitner and Frisch believed that instead of making heavier elements, the uranium nuclei had split into smaller elements.

Nuclear Forces

Protons and neutrons are tightly packed in the tiny nucleus of an atom. As we saw in the previous section, certain nuclei are unstable and undergo decay by emitting nuclear radiation. Also, an element can have both stable and unstable isotopes. For instance, carbon-12 is a stable isotope, while carbon-14 is unstable and radioactive. The stability of a nucleus depends on the nuclear forces that hold the nucleus together. This force acts between the protons and the neutrons.

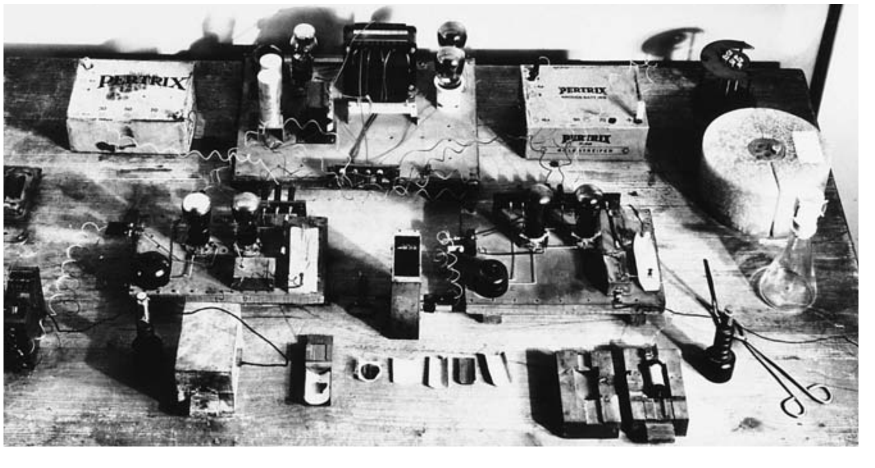

Figure 7-5
Using this equipment, Otto Hahn and Fritz Strassman first discovered nuclear fission.

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Nuclei are held together by a special force

You may know that like charges repel. But how is it that so many positively charged protons fit into an atomic nucleus without flying apart?

strong nuclear force the interaction that binds protons and neutrons together in a nucleus

The answer lies in the existence of the **strong nuclear force.** This force causes protons and neutrons in the nucleus to attract each other. The attraction is much stronger than the electric repulsion between protons. However, this 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

Due to the strong nuclear force, neutrons and protons in a nucleus attract other protons and neutrons. Because neutrons have no charge, they do not repel each other or the protons. On the other hand, the protons in a nucleus both repel and attract each other, as shown in **Figure 7-6.** In stable nuclei, the attractive forces are stronger than the repulsive forces.

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

While more neutrons can help hold a nucleus together, there is a limit to how many neutrons 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 they have. These nuclei will always decay, releasing large amounts of energy and nuclear radiation. Some of this released energy is transferred to the various particles ejected from the nucleus, the least massive of which move very fast as a result. The rest of the energy is emitted in the form of gamma rays.

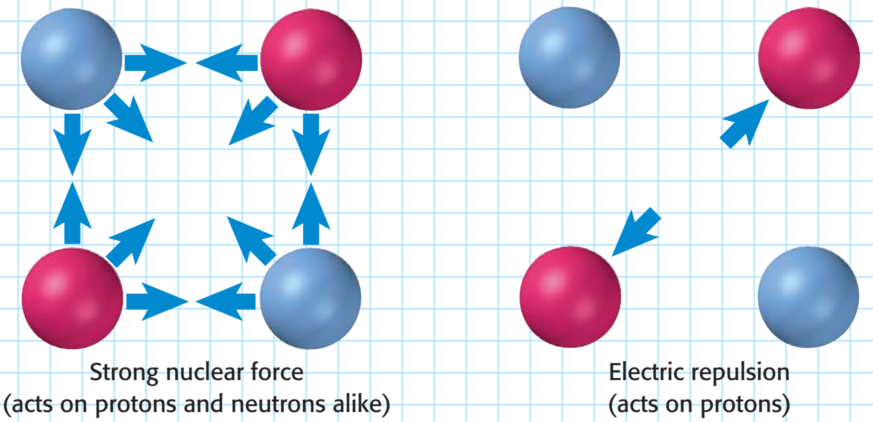

Figure 7-6 The nucleus is held together by the attractions among protons and neutrons. These forces are greater than the electric repulsion among the protons alone.

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Nuclear Fission

The process of the production of lighter nuclei from heavier nuclei, which Hahn and Strassman observed, is called **fission.** In their experiment, uranium-235 was bombarded by neutrons. The products of this fission reaction included two lighter nuclei barium-137 and krypton-84, together with neutrons and energy.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{137}_{56}Ba + ^{84}_{36}Kr + 15^{1}_{0}n + \text{energy}$$

Notice that the products include 15 neutrons. Uranium-235 can also undergo fission by producing different pairs of lighter nuclei with a different number of neutrons. For example, a different fission of uranium-235 produces strontium-90, xenon-143, and three neutrons. On average, two or three neutrons are released when uranium-235 undergoes fission.

fission the process by which a nucleus splits into two or more smaller fragments, releasing neutrons and energy

Energy is released during nuclear fission

During fission, as shown in **Figure 7-7,** 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. By comparison, the chemical reaction of one molecule of the explosive trinitrotoluene (TNT) releases only 4.8×10^{-18} J.

In their experiment, Hahn and Strassman determined the masses of all the nuclei and particles before and after the reaction. They found that the overall mass had decreased after the reaction. The missing mass had 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. This equivalence is expressed by the following equation.

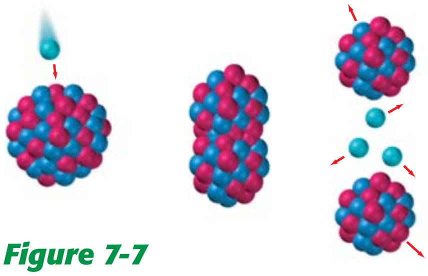

Figure 7-7
When the uranium-235 nucleus is bombarded by a neutron the nucleus breaks apart. It forms smaller nuclei, such as barium-137 and krypton-84, and releases energy through fast neutrons.

Mass-Energy Equation

$$\textit{Energy} = \textit{mass} \times (\textit{speed of light})^2$$
$$E = mc^2$$

Because c, which is constant, has such a large value, 3.0×10^8 m/s, the energy associated with even a small mass is immense. The mass-equivalent energy of 1 kg of matter is 9×10^{16} J. This is more than the chemical energy of 8 million tons of TNT.

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

Did You Know?

Enrico Fermi and his associates achieved the first controlled nuclear reaction in December 1942. The reactor was built on squash courts under the unused football stadium at the University of Chicago. The reactor consisted of blocks of uranium-235 for fuel and graphite to slow the neutrons so that they could be captured by the uranium nuclei and cause fission.

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When the total mass of any nucleus is measured, it turns out to be 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.* But what happens to the missing mass? Einstein's equation provides an explanation—it 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 lots 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 like this, where one reaction triggers another.

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. This reaction releases more neutrons, and so it is possible to start a chain reaction.

nuclear chain reaction a series of fission processes in which the neutrons emitted by a dividing nucleus cause the division of other nuclei

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

If each of these three new reactions produce three additonal neutrons, a total of nine neutrons become available to trigger nine additional fission reactions. From these nine reactions, a total of 27 neutrons are produced, setting off 27 new reactions, and so on. You can probably see from **Figure 7-8** how the reaction of uranium-235 nuclei would quickly result in an uncontrolled **nuclear chain reaction.** Therefore, the ability to create a chain reaction partly depends on the number of neutrons released.

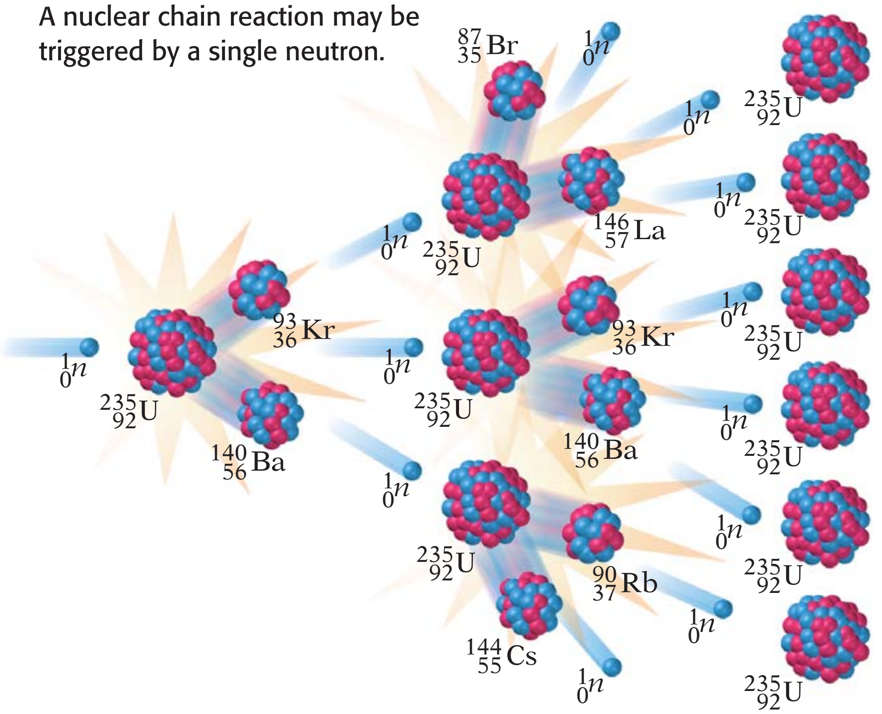

Figure 7-8
A nuclear chain reaction may be triggered by a single neutron.

Back

The chain-reaction principle is used in the 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 not only undergo a fission reaction but also sustain a chain reaction. If the amount of fissionable substance is less than the critical mass, a chain reaction will not continue.

critical mass the minimum mass of a fissionable isotope in which a nuclear chain reaction can occur

In a nuclear bomb, a chain reaction is started and proceeds very quickly. The result is the release of a large amount of energy in a very short time, causing devastation to the environment and to the life-forms within it for many miles.

The ease with which uranium-235 can make an uncontrolled chain reaction makes it extremely dangerous. Fortunately, the concentration of uranium-235 in nature is too low to start a chain reaction. Almost all of the escaping neutrons are absorbed by the more common and more stable isotope uranium-238.

Chain reactions can be controlled

Not all neutrons released in a fission reaction succeed in triggering a fission reaction. For this reason, the more neutrons that are produced per reaction, the better the chances are of a chain reaction sustaining itself. It is also possible to use materials that will slow a fission chain reaction by absorbing some of the neutrons. In this way, the reaction is controlled, unlike in a nuclear bomb. The energy produced in a controlled reaction can be used to generate electricity.

Quick ACTIVITY

Modeling Chain Reactions

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, as shown at right.
3. Stand two more dominoes vertically, parallel, and symmetrical to the first domino. Continue this process until you have used all the dominoes and a triangular shape is created, as shown at right.
4. Gently push the first domino away from the block so that it falls and hits the second group. Note how more dominoes fall with each step.

Back

Nuclear Fusion

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

Just as energy is obtained when heavy nuclei break apart, energy can also be obtained when very light nuclei are combined to form heavier nuclei. This type of nuclear process is called **fusion.**

In stars, including the sun, energy is primarily produced 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. This is because all nuclei are positively charged, and they repel each other with an electrical force. Energy is required to bring the hydrogen nuclei close together until the electrical forces are overcome by the attractive nuclear forces between two protons. In stars, the extreme temperatures provide the energy needed to bring hydrogen nuclei together.

Four hydrogen atoms fuse together in the sun to produce a helium atom and enormous energy in the form of gamma rays. This occurs in a multistep process that involves two isotopes of hydrogen: ordinary hydrogen ($^{1}_{1}H$), and deuterium ($^{2}_{1}H$).

$$^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{2}_{1}H + \text{two particles}$$
$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He + ^{0}_{0}\gamma$$
$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

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SECTION 7.2 REVIEW

SUMMARY

- Neutrons and protons in the nucleus are held together by the strong nuclear force.
- Nuclear fission takes place when a large nucleus divides into smaller nuclei.
- Nuclear fusion occurs when two light nuclei combine.
- Mass is converted into energy during both fusion and fission reactions.

CHECK YOUR UNDERSTANDING

1. **Explain** why most isotopes of elements with a high atomic number are radioactive.
2. **Indicate** if 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 the 26 protons and 30 neutrons that make up the iron nucleus will be more, less, or equal to 55.847 amu, the mass of an iron atom, $^{56}_{26}Fe$. If it is not equal, explain why.
4. **Critical Thinking** Suppose a nucleus captures two neutrons and decays to produce one neutron, is this process likely to produce a chain reaction? Explain your reasoning.

Back

7.3

Dangers and Benefits of Nuclear Radiation

INTEGRATING TECHNOLOGY and Society

OBJECTIVES

- Describe the dangers and possible health effects of exposure to nuclear radiation.
- Identify several beneficial uses of nuclear radiation.
- Explain the benefits and drawbacks of nuclear power.

KEY TERMS
background radiation
radioactive tracer

When you think about nuclear radiation, do you have a negative reaction? Do you immediately think about danger? The plots of many science-fiction movies and television shows have revolved around the dangers of nuclear radiation, showing it causing mutations or death and destruction.

Dangers of Nuclear Radiation

In many cases, especially when it is used carelessly, nuclear radiation can be extremely dangerous. However, it may surprise you to know that we are exposed to nuclear radiation of some sort every day. This kind of radiation is called **background radiation.** Most of it comes from natural sources, such as the sun, soil, water, and plants, as shown in **Figure 7-9.** The living tissues of most organisms are adapted to survive these low levels of natural nuclear radiation. Only when these background levels are exceeded do problems arise.

background radiation nuclear radiation that arises naturally from cosmic rays and from radioactive isotopes in the soil and air

Figure 7-9
Sources of background radiation are all around us.

Figure 7-10
Radon-222 levels in the air of basements and cellars can become dangerously high. Radon detectors are used to monitor radon-222 levels.

Nuclear radiation can ionize atoms in living tissue

When hemoglobin—the molecule in blood that carries oxygen throughout the body—is exposed to excessive amounts of nuclear radiation, its structure is changed. This changed hemoglobin can no longer draw oxygen into the blood, so the body cannot get oxygen as easily.

Most of your body's tissues are made of large molecules. Among these are proteins, carbohydrates, and fats. The chemical properties of these molecules change when the molecules lose or gain electrons through ionization caused by nuclear radiation. If enough molecules in a cell are ionized, the cell no longer functions properly. This can affect the overall health of the body.

Fortunately, the outer skin keeps most radiation outside the body. But if a source of alpha and beta particles is introduced into the body through air, water, or food, the nuclear radiation can severely damage the delicate linings of the body's organs.

Energetic gamma rays and fast neutrons can damage tissues regardless of whether the source of these types of nuclear radiation is inside or outside the body. Nuclear radiation can cause burns in the skin, and it also destroys bone marrow cells, which form red and white blood cells.

High concentrations of radon gas can be dangerous

The potential for internal damage by alpha particles explains the public concern over radon gas. Radon-222 is produced through a series of nuclear reactions of uranium-238 in the Earth's crust. The gas drifts up through the rock and enters the air we breathe.

Outdoors, the radon concentration is low and the gas is less harmful. However, radon can accumulate in the basements of buildings, as shown in **Figure 7-10**, until it reaches dangerous concentrations. The alpha particles emitted by inhaled radon-222 can destroy lung tissue. Prolonged exposure to radon-222 can lead to lung cancer, especially among smokers.

Radiation sickness results from exposure to high levels of nuclear radiation

Not all nuclear radiation causes intense damage to the body's cells. A person exposed for long periods or to high intensities of nuclear radiation will have more damage in his or her cells than a person who is exposed for short periods or to low intensities.

Observable effects from nuclear radiation exposure often do not appear for days or even years. Some common symptoms after serious exposure include a decrease in the number of white blood cells (leucopenia), hair loss, sterility, destruction and death of bones (bone necrosis), and cancer.

Did You Know?

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

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Nuclear radiation can cause genetic mutations

Long-term effects of nuclear radiation appear when DNA molecules in the body are damaged. As described in Chapter 4, DNA directs the synthesis of proteins by the body, so it contains all the information cells need to function. DNA also carries all the genetic information of an organism. If DNA molecules are extensively damaged by nuclear radiation, the cell may repair them incorrectly, as shown in **Figure 7-11.** When the DNA in reproductive cells is damaged, there is a strong chance of birth defects.

Biologists have observed birth defects in animals that have been exposed to large amounts of nuclear radiation in water or soil. An example of this occurred near the Shiprock Uranium Mine, which operated from 1954 to 1968 in northwestern New Mexico. Radioactive waste from the mine contaminated water that the nearby Navajo used for their sheep and cattle. Although the animals that drank the water remained healthy, the nuclear radiation from the water damaged the DNA in their reproductive cells. This caused their offspring to be born with birth defects.

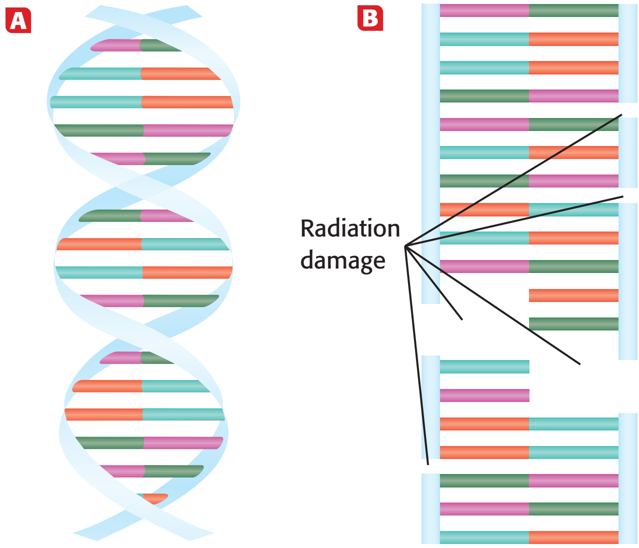

Figure 7-11
After extensive radiation damage, a normal DNA molecule (A) is likely to be rebuilt with its nitrogen bases out of sequence (B).

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Beneficial Uses of Nuclear Radiation

In spite of their dangers, radioactive substances are highly useful. They have a wide range of applications from medicine to archeological dating.

Small radioactive sources are present in smoke alarms, as shown in **Figure 7-12.** They release alpha particles, which are charged and produce an electric current. If smoke is present in the air, the smoke particles reduce the flow of this current. The drop in current sets off the alarm before dangerous levels of smoke build up.

Figure 7-12
In a smoke alarm, a small alpha-emitting isotope detects smoke particles in the air.

Nuclear radiation therapy is used to treat cancer

Controlled doses of nuclear radiation are used for treating diseases such as cancer. For example, certain brain tumors can be targeted with small beams of gamma rays. These beams are focused to kill only the tumor cells. The surrounding healthy tissue is harmed only minimally. Different kinds of tumors throughout the body can be treated in a similar way.

radioactive tracer a radioactive material added to a substance so that the substance's location can be detected later

Radioactive tracers are used in agriculture, medicine, and scientific research

Radioactive tracers are short-lived isotopes, like magnesium-28, that can be observed with sensitive detectors. On research farms, tracers in flowing water can show how fast water moves through the soil or through the stems and leaves of crops. Geologists use tracers to follow underground water flow.

Tracers are widely used in medicine as well. Tracers that tend to concentrate in affected cells are used to locate tumors. Other tracers can follow the path of drugs in the body to help doctors be sure they are delivered to the desired area.

Nuclear Power

Today, nuclear reactors are used in dozens of countries to generate electricity. Energy produced from fission is used to light the homes of millions of families. There are numerous benefits to this source of energy. Nuclear fission does not produce gaseous pollutants, and there is much more energy in the known uranium reserves than in the known reserves of coal and oil.

REAL WORLD APPLICATIONS

Medical Radiation Exposure

Graves's disease is an illness in which the thyroid gland produces excess hormones. This excess causes an increase in metabolism, weight loss (despite a healthy appetite), and an irregular heartbeat.

Graves's disease and similar illnesses can be treated in several ways. Parts of the thyroid gland can be surgically removed, or patients can be treated with radioactive iodine-131. The thyroid cells need iodine to make hormones. When they take in the radioactive iodine-131, the overactive cells are destroyed, and hormone levels drop.

There is some concern that low-level nuclear radiation might cause cancers, such as leukemia. Examine the table below, which shows radiation exposures for different situations and the resulting increased risks in leukemia rates. Note that a *rem* is a unit for measuring doses of nuclear radiation.

Applying Information

1. Given that the typical exposure for radioisotope therapy is about 10 rems, mostly delivered at once, do you think leukemia rates are likely to go up for this group? If so, estimate what risk you would expect.
2. Low-level nuclear radiations and its link to cancers such as leukemia is still in question. Describe what other information would help you evaluate the risks. **WRITING SKILL**

Person tested	Radiation exposure	Measured increased leukemia risk
Hiroshima atomic bomb survivor	27 rem at once	6%
U.S. WW II radiology technician	50 rem over 2 years	0%
Austrian citizen after the nuclear accident at Chernobyl	0.025 rem	0%

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Nuclear fission has disadvantages

In nuclear fission reactors, energy is produced by triggering a controlled fission reaction 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 they do not escape in the environment releasing 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 in case of a reactor failure. The reactor requires considerable shielding and must meet stricter safety requirements than those required for fossil-fuel-burning power plants. Thus, nuclear power plants are expensive to build.

According to regulations, nuclear power plants can be operated for only about 40 years. After that time, they must be shut down. To avoid accidental contamination, this process is very slow and expensive. Equipment used to take the reactor apart can become contaminated and must also be disposed of as radioactive waste. Because of political opposition, few nuclear power plants have operated for 40 years. This is one of the many factors that limit how effective nuclear power can be.

INTEGRATING

SPACE SCIENCE Unmanned space probes have greatly increased our knowledge of the solar system. Nuclear-powered probes can venture far from the sun without losing power, as solar-powered probes do. *Cassini,* which has been sent to explore Saturn, has been powered by the heat generated by the radioactive decay of plutonium.

Nuclear waste must be safely stored

Besides the expenses that occur during the life of a nuclear power plant, there 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 shown in **Figure 7-13.** These precautions are necessary to keep nuclear radiation from leaking out which harms living things and taints ground water.

Ideal places for such facilities are sparsely populated areas with little water on the surface or underground. These areas must be free from earthquakes. Even with these considerations, one cannot be sure about long-term safety. Little nuclear waste is stored this way because of debates about where to put facilities.

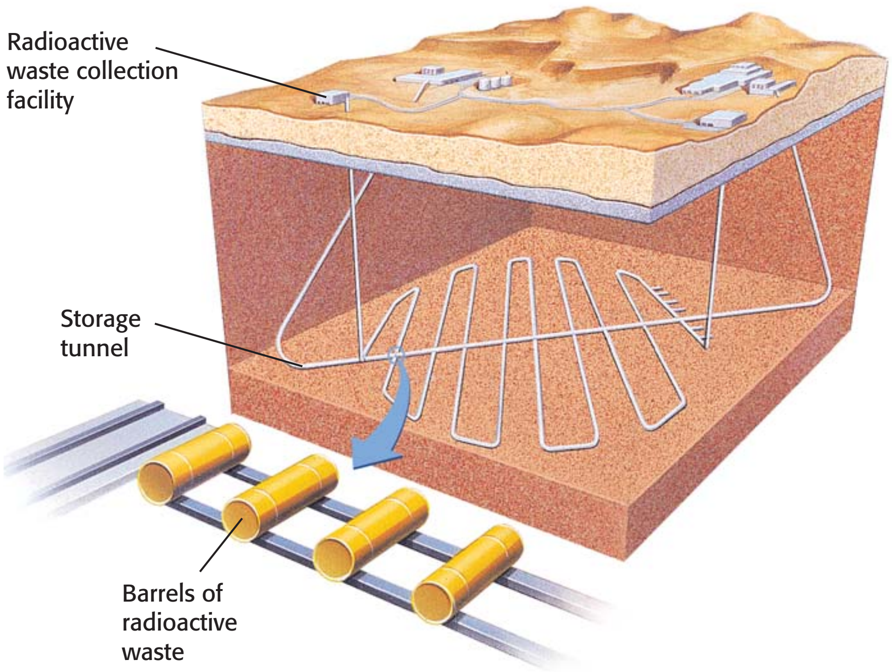

Figure 7-13
Storage facilities for nuclear waste must be designed to contain radioactive materials safely for thousands of years.

The main problem with some radioactive wastes is that they have long half-lives, from hundreds of thousands to millions of years. The oldest human-made structures that are still standing, such as the pyramids of Egypt, are only about 5000 years old. It is hard to imagine whether people could ever build structures that could last 20 to 200 times as long.

Nuclear-fusion reactors are being tested

Another option that holds some promise as an energy source is nuclear fusion. Recall from the last section that fusion takes place when light nuclei, such as hydrogen, are forced together to produce heavier nuclei, such as helium, and energy. Because fusion requires that the electrical repulsion between protons be overcome, these reactions are difficult to produce in the laboratory and have never been produced in a power plant.

The most attractive feature of fusion is that the fuel for it is abundant. Hydrogen is the most common element in the universe and 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.

Unfortunately, practical fusion-based power is far from being a reality. Fusion reactions have some drawbacks. They can produce fast neutrons, a highly energetic and dangerous form of nuclear radiation. Shielding material in the reactor would have to be replaced periodically, increasing the expense of operating a fusion power plant. Lithium can be used to slow down these neutrons, but it is chemically reactive and rare, making its use impractical.

INTEGRATING

SPACE SCIENCE

All heavy elements, from cobalt to uranium, are made when massive stars explode. The pressure produced in the explosion causes nearby nuclei to fuse together, 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.

SECTION 7.3 REVIEW

SUMMARY

- Nuclear radiation can damage living cells, causing radiation sickness and birth defects, even death.
- Nuclear radiation is used in medicine to diagnose and treat diseases.
- Nuclear fission is an alternative to fossil fuels as a source of energy.

CHECK YOUR UNDERSTANDING

1. **Describe** the ways in which nuclear radiation can cause damage to living tissues.
2. **Explain** how gamma rays are used in cancer therapy without harming the patient.
3. **List** several uses for low-level radioactive tracers.
4. **Describe** how sea water could be a source of hydrogen for nuclear fusion.
5. **Critical Thinking** Suppose uranium-238 could undergo fission as easily as uranium-235. Predict how that would change the advantages and drawbacks of fission reactors.

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CHAPTER 7 REVIEW

Chapter Highlights

Before you begin, review the summaries of the key ideas of each section, found on pages 228, 234, and 240. The key vocabulary terms are listed on pages 220, 229, and 235.

UNDERSTANDING CONCEPTS

1. When a heavy nucleus decays, it may emit ________.
   a. alpha particles
   b. neutrons
   c. gamma rays
   d. All of the above
2. A neutron decays to form a proton and a(n) ________.
   a. alpha particle
   b. beta particle
   c. gamma ray
   d. emitted neutron
3. After three half-lives, ________ of a radioactive sample remains.
   a. all
   b. one-half
   c. one-third
   d. one-eighth
4. Carbon dating can be used to measure the age of each of the following except ________.
   a. a 7000-year-old human body
   b. a 1200-year-old wooden statue
   c. a 2600-year-old iron sword
   d. a 3500-year-old piece of fabric
5. Of the following elements, only the isotopes of ________ are all radioactive.
   a. nitrogen
   b. gold
   c. sulfur
   d. uranium
6. The strong nuclear force ________.
   a. attracts protons to electrons
   b. holds molecules together
   c. holds the atomic nucleus together
   d. attracts electrons to neutrons
7. The process in which a heavy nucleus splits into two lighter nuclei is called ________.
   a. fission
   b. fusion
   c. alpha decay
   d. a chain reaction
8. 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.
9. Alpha emitters can be dangerous when they are ________.
   a. inhaled into the lungs
   b. consumed in drinking water
   c. eaten in food
   d. All of the above
10. 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 their durability
    c. as a way of treating forms of cancer
    d. as a way to check the thickness of newly made metal sheets

Using Vocabulary

11. How can *radioactivity* affect the atomic number and mass number of a nucleus that changes after undergoing decay?
12. Describe the main differences between the four main types of nuclear *radiation: alpha particles, beta particles, gamma rays,* and *neutron emission.*
13. Would a substance with an extremely short *half-life* be effective as a *radioactive tracer*?
14. For the nuclear *fission* process, how is *critical mass* important in a *chain reaction*?
15. How does nuclear *fusion* account for the energy produced in stars?
16. What is *background radiation,* and what are its sources?

CHAPTER 7 REVIEW

BUILDING MATH SKILLS

17. Graphing 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:

COMPUTER SKILL

- **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?
- **d.** What percentage of the original iodine-131 remains after 3.5 half-lives?

18. 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. $^{212}_{83}\text{Bi} \longrightarrow {}^{\square}_{\square}\text{X} + {}^{4}_{2}\text{He}$

$^{\square}_{\square}\text{X} \longrightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}e$

b. $^{212}_{83}\text{Bi} \longrightarrow {}^{\square}_{\square}\text{Y} + {}^{0}_{-1}e$

$^{\square}_{\square}\text{Y} \longrightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\text{He}$

19. Nuclear Decay The longest-lived radioactive isotope yet discovered is the beta-emitter tellurium-130. It has been determined that it would take 2.5×10^{21} years for 99.9% of this isotope to decay. Write the equation for this reaction, and identify the isotope into which tellurium-130 decays.

20. Nuclear Decay It takes about 10^{16} years for just half the samarium-149 in nature to decay by alpha-particle emission. Write the decay equation, and find the isotope that is produced by the reaction.

21. Half-life The ratio of carbon-14 to carbon-12 in a prehistoric wooden artifact is measured to be one-eighth of the ratio measured in a fresh sample of wood from the same region. The half-life of carbon-14 is 5730 years. Determine its age.

22. 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 taken from a basement contains 4.38 μg of radon-222, how much will remain in the sample after 15.2 days?

THINKING CRITICALLY

23. Applying Knowledge Explain how the equivalence of mass and energy accounts for the small difference between the mass of a uranium-235 nucleus and the masses of the nuclei of its fission fragments.

24. Applying Knowledge Describe the similarities and differences between atomic electrons and beta particles.

25. Creative Thinking Why do people working around radioactive waste in a radioactive storage facility wear badges containing strips of photographic film?

26. Creative Thinking Many radioactive isotopes have half-lives of several billion years. Other radioactive isotopes have half-lives of billionths of a second. Suggest a way in which the half-lives of such isotopes are measured.

27. Problem Solving A radioactive tracer can be used to measure water movement through soil. In order to avoid contamination of ground water, 99.9% of the tracer must decay between the time it is introduced into the soil and the time it reaches the ground-water supply. Estimate this time and calculate the half-life of an ideal tracer that could be used in this application.

DEVELOPING LIFE/WORK SKILLS

28. Allocating Resources An archeologist has collected seven samples from a site: two scraps of fabric, two strips of leather, and three bone fragments. The age of each item must be determined, but the budget for carbon-14 dating is only $4500. Carbon-14 mass spectrometry is an accurate way to find a sample's age, but it costs $820 per sample. Carbon-14 dating by liquid scintillation costs only $400 a sample, but is less reliable. How would you apply either or both of these techniques to the samples to obtain the most reliable information and still stay within your budget?

29. Making Decisions Suppose you are an energy consultant who has been asked to evaluate a proposal to build a power plant in a remote area of the desert. Investigate the requirements for and possible hazards of nuclear-fission power plants, coal-burning power plants, and solar-energy farms. Study research about their environmental impacts. Using this information and what you have learned from this chapter, write a paragraph supporting your decision about which of these power plants would be best for its surroundings.

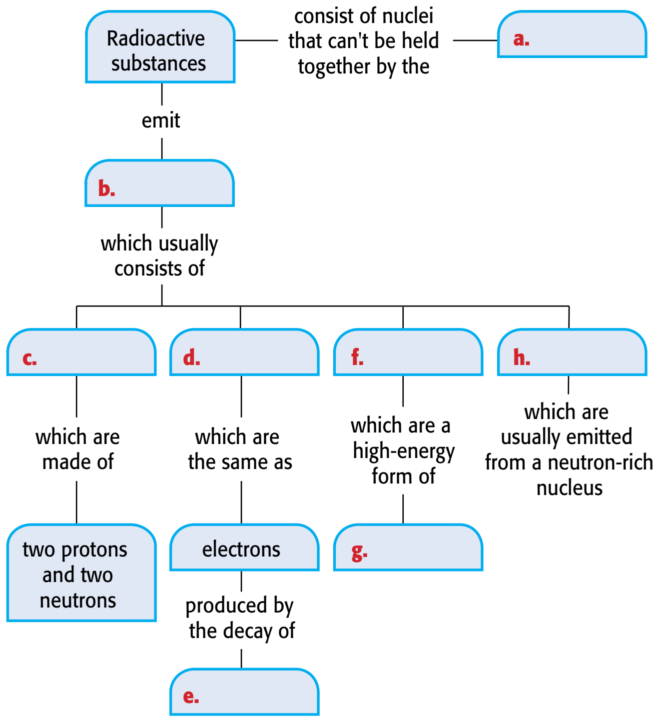
WRITING SKILL

30. Working Cooperatively Read the following, and discuss with a group of classmates a possible solution to the problem that makes use of radioactivity.

A person believed to be suffering from cancer has been admitted to a hospital. What are some possible methods of diagnosing the patient's conditions? Assuming that cancer is found, how might the disease be treated? Suppose you suspect that another patient is suffering from radiation poisoning. How would you be able to tell?

INTEGRATING CONCEPTS

31. Concept Mapping Copy the unfinished concept map below onto a sheet of paper. Complete the map by writing the correct word or phrase in the lettered boxes.



32. Connection to Social Studies Research the philosophical debate surrounding the discovery of radioactive decay. Examine the arguments against the transmutation of elements as presented by scientists such as Lord Kelvin. What ideas were these arguments based on? What experiments convinced most scientists that radioactive elements changed into other elements?

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Skill Builder Lab

Introduction

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

Objectives

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

Materials

10 dice
large paper cup with plastic lid
roll of masking tape
scissors

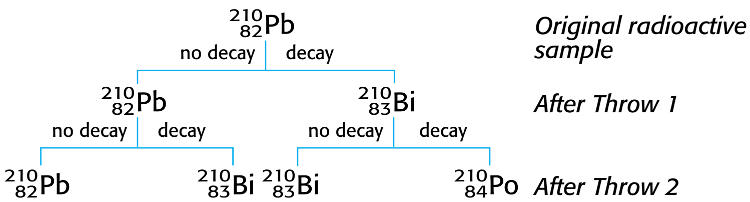
Simulating Nuclear Decay Reactions

Preparing for Your Experiment

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

Throw #	# 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				

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 it a few times. Then remove the lid, and spill the dice. In this simulation, each throw represents a *half-life.*
4. All 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 around this shared corner, and 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 diagram below to track your results.



Back

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

7. After the second throw, we 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 represent $^{210}_{83}\text{Bi}$ atoms that have decayed into $^{210}_{84}\text{Po}$.

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 $^{210}_{83}\text{Bi}$) and the unmarked dice that landed with *1, 2,* or *3* facing up (representing the decay of original $^{210}_{82}\text{Pb}$ into $^{210}_{83}\text{Bi}$).

c. The third set includes unmarked dice that did not land with *1, 2,* or *3* facing up. These represent the original undecayed $^{210}_{82}\text{Pb}$ atoms.

8. After each 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. For your third throw, put all the dice back into the cup. After the third throw, some of the $^{210}_{84}\text{Po}$ will decay into the stable isotope $^{206}_{82}\text{Pb}$. Use the table above and step 8 to figure out what else happens after the third throw.

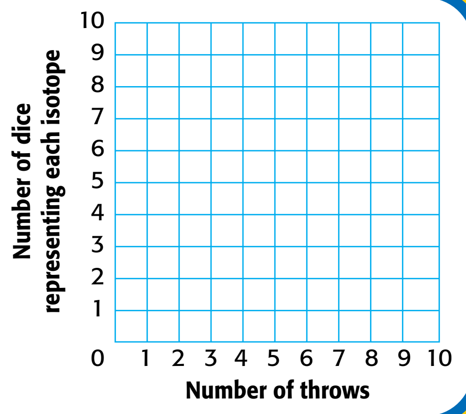
10. Continue throwing the dice until all the dice have decayed into $^{206}_{82}\text{Pb}$, which is a stable isotope. Hence, these dice will remain unchanged in all future throws.

▶ Analyzing Your Results

1. Write nuclear decay equations for the nuclear reactions modeled in this lab.

2. In your lab report, prepare a graph like the one shown at right. Using a different color or symbol for each atom, plot the data for all four atoms on the same graph.

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



▶ Defending Your Conclusions

4. $^{210}_{82}\text{Pb}$ is continually produced through a series of nuclear decays that begin with $^{238}_{92}\text{U}$. Does this information cause you to modify your answer to item 3? Explain why.

Back

CareerLink

Science Reporter

Science reporters are usually among the first people to hear about scientific discoveries. News organizations hire science reporters to explain these discoveries to the general public in a clear, understandable, and entertaining way. To learn more about science reporting as a career, read the interview with science reporter Corinna Wu, who writes for* Science News *magazine, in Washington, D.C.

Corinna Wu describes scientific research and discovery in the articles she writes.

"I think writing is something you can learn—it's a craft. Lots of people talk about talents, but I think it's something you can do if you work at it."

What does a science reporter do?

I write and report news and feature articles for a weekly science news magazine. That entails finding news stories—generally about research. I have to call the researchers and ask them questions about how they did their work and the significance of the work. Then I write a short article explaining the research to ordinary people.

What is your favorite part of your work?

I like learning about a new subject every week. I get to ask all the stupid questions I was afraid to ask in school.

How did you become interested in science reporting as a career?

After college, I had a summer internship at NASA, at the Johnson Space Center in Houston, Texas, doing materials research there. I had lots of time to read space news magazines. It was at that time that I realized, "Hey, people write this stuff."

What kinds of skills are important for a science reporter?

One thing that is really important is to really love writing. If you don't like to write already, it's pretty hard to make yourself do it every day. It helps to have a creative bent, too. It also helps to enjoy explaining things. Science writing by nature is explanatory, more so than other kinds of journalism.

You have a science background. How does that help you do your job?

I majored in chemistry as an undergraduate and got a master's degree in materials science. I find that I draw on that academic background a lot, in terms of understanding the research.

Do you think a science reporter needs a science background?

Ideally, you should be studying science while writing on the side. But if you have to do one or the other, I'd do science first. It's harder to pick up the science later. Science builds on itself. It takes years to really get a grasp of it.

Why do you think science reporting is important?

Science and technology are becoming part of our everyday lives. It's important for people to keep up on research in these areas. There is an element of education in everything you write.

What advice do you have for students who are interested in science reporting?

Read as much as you can—newspapers, magazines, books. Nothing beats getting real experience writing. If you have a newspaper or magazine at school, get involved in that. You draw on academic experiences—you don't know when they will become useful.

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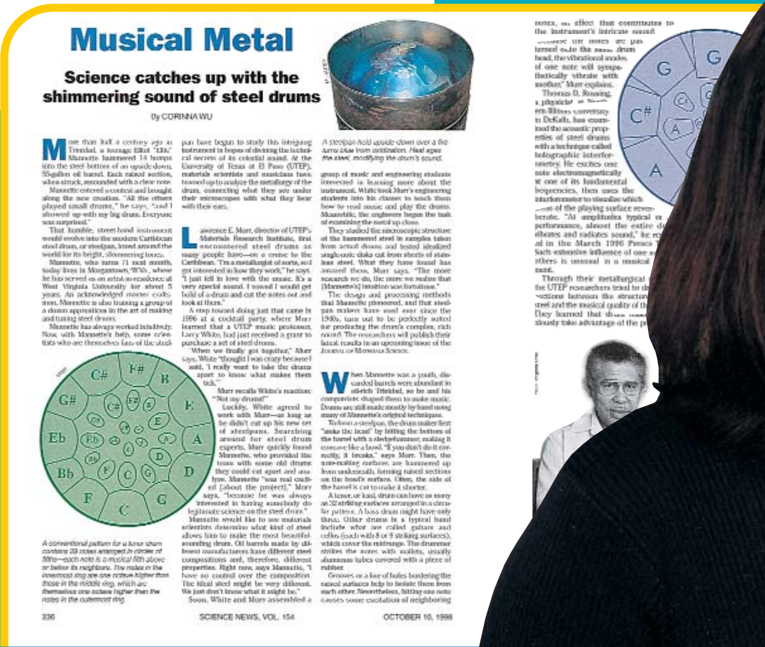

Musical Metal

Science catches up with the shimmering sound of steel drums

By CORINNA WU

236 SCIENCE NEWS, VOL. 154 OCTOBER 10, 1998

"Science is a strong tool, a strong way of looking at the world. I feel that trying to introduce people to that way of looking at the world is very important."

—Corinna Wu