Nuclear Changes

CHAPTER 9

Chapter Preview

1 What Is Radioactivity?
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   - Nuclear Decay
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2 Nuclear Fission and Fusion
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3 Nuclear Radiation Today
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Radioactive substances in the paints and canvases used in painting decay over time. These radioactive substances emit nuclear radiation. The nuclear radiation emitted can be used to determine how old the painting is and whether the painting is a forgery or not.

**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, 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 some 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 was less than 40 years old.

**Activity 1** Radiation exposes photographic film. To test this, obtain a sheet of unexposed photographic film and a new household smoke detector, which contains a radioactive sample. Remove the detector’s casing. In a dark room, place the film next to the smoke detector in a cardboard box. Close the box. After a day, open the box in a dark room. Place the film in a thick envelope. Have the film processed. How does the image differ from the rest of the film? How can you tell that the image is related to the radioactive source?

**Pre-Reading Questions**
1. What are some applications of nuclear radiation?
2. How does nuclear power compare to other sources of power?
What Is Radioactivity?

**KEY TERMS**
- radioactivity
- nuclear radiation
- alpha particle
- beta particle
- gamma ray
- 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.

Our lives are affected by radioactivity in many ways. Technology using radioactivity has helped to detect disease and dysfunction, kill cancer cells, generate electricity, and design smoke detectors. On the other hand, there are also risks associated with too much nuclear radiation, so it is important to know where it may exist and how to counteract it. What exactly is radioactivity?

**Nuclear Radiation**

Many elements change through radioactivity. Radioactive materials have unstable nuclei, which go through changes by emitting particles or releasing energy to become stable, as shown in Figure 1. This nuclear process is called nuclear decay. After the changes in the nucleus, the element can transform 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 in their nuclei.

The released energy and matter are called nuclear radiation. Just as radioactivity changes the materials that undergo nuclear decay, nuclear radiation has effects on other materials. 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.)

**Figure 1**

During radioactivity an unstable nucleus emits one or more particles or high-energy electromagnetic radiation.
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 1. 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, which are discussed below.

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 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 that travels farther through matter than alpha particles do. This nuclear radiation is named the beta particle, after the second Greek letter, beta (β). Beta particles are often fast-moving electrons.

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Symbol</th>
<th>Mass (kg)</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha particle</td>
<td>(^{4}_{2}\text{He})</td>
<td>(6.646 \times 10^{-27})</td>
<td>+2</td>
</tr>
<tr>
<td>Beta particle</td>
<td>(^{0}_{-1}\text{e})</td>
<td>(9.109 \times 10^{-31})</td>
<td>−1</td>
</tr>
<tr>
<td>Gamma ray</td>
<td>(\gamma)</td>
<td>none</td>
<td>0</td>
</tr>
<tr>
<td>Neutron</td>
<td>(^{1}_{0}\text{n})</td>
<td>(1.675 \times 10^{-27})</td>
<td>0</td>
</tr>
</tbody>
</table>
Negative particles coming 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 at a high speed from the nucleus 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.

Gamma rays are very high energy

In 1898, Marie Curie, shown in Figure 2, and her husband, Pierre, isolated the radioactive element radium. In 1900, studies of radium by Paul Villard revealed that the element emitted a previously undetected 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).

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

Although gamma rays have no electrical 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.

Neutron radioactivity may occur 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 by detecting its emission from a nucleus.

Because neutrons have no charge, they do not ionize matter as alpha and 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.
Nuclear Decay

Anytime an unstable nucleus emits alpha or beta particles, the number of protons or neutrons changes. An example would be radium-226 (an isotope of radium with the mass number 226), which changes to radon-222 by emitting an alpha particle.

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

Nuclear decay equations are similar to those for chemical reactions. The nucleus before decay is like a reactant and is placed on the left side of the equation. Products are placed on the right side. The process of the alpha decay of radium-226 is written as follows.

\[
\text{Ra}^{226}_{88} \rightarrow \text{Rn}^{222}_{86} + \text{He}^4_2 \quad 226 = 222 + 4
\]

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.

\[
\text{C}^{14}_{6} \rightarrow \text{N}^{14}_{7} + \text{e}^{0}_{-1} \quad 14 = 14 + 0
\]

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 decays into a proton, causing the positive charge of the nucleus to increase by 1.
**Figure 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.

**Figure 3** shows how the positive charge of the nucleus increases by 1 when a neutron decays into a proton. When the nucleus undergoes nuclear decay by gamma rays, there is no change in the atomic number of the element. This is because the number of protons does not change. The atomic number is the number of protons in the nucleus of the atom. The only change is in the energy content of the nucleus.

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**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 $Z$.
   
   $$^{217}_{89}\text{Ac} \rightarrow \frac{A}{2}X + \frac{4}{2}\text{He}$$

2. **Write math equations for the atomic and mass numbers.**
   
   $$217 = A + 4$$
   $$89 = Z + 2$$

3. **Rearrange the equations.**
   
   $$A = 217 - 4$$
   $$Z = 89 - 2$$

4. **Solve for the unknown values, and rewrite the equation with all nuclei represented.**
   
   $$A = 213$$
   $$Z = 87$$
   
   The unknown decay product has an atomic number of 87, which is francium, according to the periodic table. The element is therefore $^{213}_{87}\text{Fr}$.
   
   $$^{217}_{89}\text{Ac} \rightarrow ^{213}_{87}\text{Fr} + ^{4}_{2}\text{He}$$

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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.

After the first half-life of a radioactive sample has passed, half the sample remains unchanged, as indicated in Figure 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.

\[ \text{Fraction of original element remaining} = \left(\frac{1}{2}\right)^n \]

where \( n \) is the number of half-lives.

\[ 0 \quad 1/16 \quad 1/8 \quad 1/4 \quad 1/2 \]

\[ 0 \quad 1 \text{ half-life} \quad 2 \text{ half-lives} \quad 3 \text{ half-lives} \]

Figure 4

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

Practice

Nuclear Decay

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

1. \( ^{12}_{5}\text{B} \to ^{12}_{6}\text{C} + \nu^X \)
2. \( ^{225}_{89}\text{Ac} \to ^{221}_{87}\text{Fr} + \nu^X \)
3. \( ^{63}_{28}\text{Ni} \to ^{\nu^X}_{2} + 0^e \)
4. \( ^{212}_{83}\text{Bi} \to ^{\nu^X}_{2} + 4^e \)

half-life: the time required for half of a sample of a radioactive substance to disintegrate by radioactive decay or by natural processes.
**Half-life is a measure of how quickly a substance decays**

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

Using half-lives, scientists can predict how old an object is. Using the half-lives of long-lasting isotopes, such as potassium-40, geologists 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 than it is for younger rocks.

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**Table 2** Half-lives of Selected Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Nuclear radiation emitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorium-219</td>
<td>$1.05 \times 10^{-6}$ s</td>
<td>$\frac{4}{2}$He</td>
</tr>
<tr>
<td>Hafnium-156</td>
<td>$2.5 \times 10^{-2}$ s</td>
<td>$\frac{4}{2}$He</td>
</tr>
<tr>
<td>Radon-222</td>
<td>3.82 days</td>
<td>$\frac{4}{2}$He, $\gamma$</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>8.1 days</td>
<td>$\frac{0}{7}$e, $\gamma$</td>
</tr>
<tr>
<td>Radium-226</td>
<td>1599 years</td>
<td>$\frac{4}{2}$He, $\gamma$</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>5715 years</td>
<td>$\frac{0}{7}$e</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>$2.412 \times 10^4$ years</td>
<td>$\frac{4}{2}$He, $\gamma$</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>$7.04 \times 10^8$ years</td>
<td>$\frac{4}{2}$He, $\gamma$</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>$1.28 \times 10^9$ years</td>
<td>$\frac{0}{7}$e, $\gamma$</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$4.47 \times 10^9$ years</td>
<td>$\frac{4}{2}$He, $\gamma$</td>
</tr>
</tbody>
</table>

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**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?
Carbon-14 is used to date materials

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 CO₂ 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, scientists can estimate the age of the once-living organism.

**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.**
   - 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.
   - total time of decay = 3 half-lives \( \times \frac{1599 \text{ y}}{\text{half-life}} \) = 4797 years
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 1 REVIEW

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.

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

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

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

   $$^{131}_{53}\text{I} \longrightarrow \frac{4}{2}X + _0^1\text{e}$$

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 $6 \times 10^6$ years.

8. Critical Thinking An archaeologist discovers charred 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, given this evidence?
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.

In 1939, German scientists Otto Hahn and Fritz Strassman conducted experiments in the hope of forming heavy nuclei. Using the apparatus shown in Figure 5, they bombarded uranium samples with neutrons, expecting a few nuclei to capture one or more neutrons. The new elements they made had chemical properties they could not explain.

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. These forces act between the protons and the neutrons.
Nuclei are held together by a special force
Like charges repel, so how can so many positively charged protons fit into an atomic nucleus without flying apart?

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 $3 \times 10^{-15}$ 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 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. The radioactive decay that takes place results in a more stable nucleus.

**Figure 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.
**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. The products of this fission reaction included two lighter nuclei barium-137 and krypton-84, together with neutrons and energy.

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

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. So, in either fission process when the nucleus splits, both neutrons and energy are released.

**Energy is released during nuclear fission**

During fission, as shown in **Figure 7**, the nucleus breaks into smaller nuclei. The reaction also releases large amounts of energy. Each dividing nucleus releases about $3.2 \times 10^{-11}$ J of energy. By comparison, the chemical reaction of one molecule of the explosive trinitrotoluene (TNT) releases only $4.8 \times 10^{-18}$ 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.

$$E = mc^2$$

Because $c$, which is constant, has such a large value, $3.0 \times 10^8$ m/s, the energy associated with even a small mass is immense. The mass-equivalent energy of 1 kg of matter is $9 \times 10^{16}$ J. This is more than the chemical energy of 22 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.
When the total mass of any nucleus is measured, it 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. 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.

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 ejected from one reaction.

If each of these three new reactions produce three additional 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 8** 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.
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, splitting them. The particles that are given off split still other atoms. A chain reaction is begun, which gives off heat energy that is used to boil water. The boiling water heats another set of pipes filled with water to make steam. The steam then rotates a turbine to generate electricity. So, energy released by the chain reaction changes the atomic energy into heat energy.

The chain-reaction principle is also 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 undergo a fission reaction and can also sustain a chain reaction. If the amount of fissile 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 splitting, 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 Fusion

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 ($^{1}\text{H}$), and deuterium ($^{2}\text{H}$).

\[
\begin{align*}
^{1}\text{H} + ^{1}\text{H} & \rightarrow ^{2}\text{H} + \text{two particles} \\
^{2}\text{H} + ^{1}\text{H} & \rightarrow ^{3}\text{He} + ^{0}\gamma \\
^{3}\text{He} + ^{3}\text{He} & \rightarrow ^{4}\text{He} + ^{1}\text{H} + ^{1}\text{H}
\end{align*}
\]

SECTION 2 REVIEW

1. Explain why most isotopes of elements with a high atomic number are radioactive.

2. Indicate whether the following are fission or fusion reactions.
   a. $^{1}\text{H} + ^{1}\text{H} \rightarrow ^{2}\text{He} + \gamma$
   b. $^{0}\text{n} + ^{235}\text{U} \rightarrow ^{146}\text{Ba} + ^{87}\text{Br} + ^{3}\text{He}$
   c. $^{21}\text{Ne} + ^{4}\text{He} \rightarrow ^{24}\text{Mg} + ^{0}\text{n}$
   d. $^{208}\text{Pb} + ^{58}\text{Fe} \rightarrow ^{265}\text{Hs} + ^{1}\text{n}$

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, $^{56}\text{Fe}$. 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.
It may surprise you 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. This form of nuclear radiation is called **background radiation**. Most of it comes from natural sources, such as the sun, heat, soil, rocks, and plants, as shown in Figure 9. The living tissues of most organisms are adapted to survive these low levels of natural nuclear radiation.
Radiation is measured in units of rems.

Levels of radiation absorbed by the human body are measured in rems or millirems (1 rem = 1000 millirems).

In the United States, many people work in occupations involving nuclear radiation. Nuclear engineering, health physics, radiology, radiochemistry, X-ray technology, magnetic resonance imaging (MRI), and other nuclear medical technology all involve nuclear radiation. A safe limit for these workers has been set at 5000 millirems annually, 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 in higher altitudes receive more exposure to nuclear radiation from space than those in lower altitudes do. People in areas with many rocks have higher nuclear radiation exposure than people in areas without many rocks do. Because of large differences both in altitude and background radiation sources, exposure varies greatly from one location to another, as illustrated in Table 3.

Some activities add to the amount of nuclear radiation exposure.

Another factor that affects levels of exposure is participation in certain activities. Table 4 shows actual exposure to nuclear radiation for just a few activities. There are more activities that add to the amount of nuclear radiation exposure than those in this table, but these listed are at least a few of the activities that will add nuclear radiation to the air, affecting all those in the area around these activities.

Table 3 Radiation Exposure Per Location

<table>
<thead>
<tr>
<th>Location</th>
<th>Radiation Exposure (millirems/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tampa, FL</td>
<td>63.7</td>
</tr>
<tr>
<td>Richmond, VA</td>
<td>64.1</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>69.5</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td>73.6</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>86.7</td>
</tr>
<tr>
<td>Rochester, NY</td>
<td>88.1</td>
</tr>
<tr>
<td>Wheeling, WV</td>
<td>111.9</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>164.6</td>
</tr>
</tbody>
</table>

Source: United States Department of Energy, Nevada Operations Office

Table 4 Radiation Exposure Per Activity

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

Source: United States Department of Energy, Nevada Operations Office
**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.

**Smoke detectors help to save lives**

Small radioactive sources are present in smoke alarms, as shown in Figure 10. They release alpha particles, which are charged and produce an electric current. Smoke particles in the air reduce the flow of the current. The drop in current sets off the alarm before levels of smoke increase.

**Nuclear radiation is used to detect diseases**

Several types of nuclear radiation procedures have been very helpful to medical science. The digital computer, ultrasound scanning, CT scanning, PET, and magnetic resonance imaging (MRI) have combined to create a large variety of diagnostic imaging techniques. Using these procedures, doctors can view images of parts of the organs and can detect dysfunction or disease.

An X ray once was the primary imaging technique used in medicine. An image was created by focusing X rays for 11 minutes through a part of the body and onto a single piece of film. Today, X-ray imaging is done in milliseconds.

The MRI, an imaging process, as in Figure 11, uses radio frequency pulses to provide images of even small bodily structures. **Radioactive tracers** are widely used in medicine. Tracers are short-lived isotopes that tend to concentrate in affected cells and are used to locate tumors.

---

**Figure 10**

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

**Figure 11**

A This is an image of a healthy brain obtained with magnetic resonance imaging (MRI).

B Magnetic resonance imaging reveals that this brain has Alzheimer’s disease.
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 is also used for treating thyroid cancer, 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.

Agriculture uses radioactive tracers and radioisotopes

On research farms, as in Figure 12, radioactive tracers in flowing water can show how fast water moves through the soil or through stems and leaves of crops. They help us to understand biochemical processes in plants. Radioisotopes are chemically identical with other isotopes of the same element. Because of that similarity, they are substituted in chemical reactions. Radioactive forms of the element can then be easily located with sensors.

Possible Risks of Nuclear Radiation

While nuclear radiation has many benefits, there are also risks. It is important to know what they are so that you can make informed decisions and exercise caution.

Nuclear radiation can ionize atoms

Nuclear radiation interacts with living tissue. This radiation includes charged particles (alpha and beta) as well as gamma rays and X rays. Alpha and beta particles, as well as gamma and X rays, can change the number of electrons in atoms in living materials. This is known as ionization. Molecules containing ionized atoms may form substances that are harmful to life.

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, which are heavy and slow moving. 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. The ability of gamma rays to penetrate a material depends upon their energy. Several feet of material may protect you from high-energy gamma rays.
The risk depends upon amounts of radiation

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 as well as breast, lung, and stomach cancers.

Radiation sickness results from high levels of nuclear radiation

Radiation sickness is an illness resulting 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 working with nuclear radiation must protect themselves with shields and special clothing. A person working in radioactive areas should wear a dosimeter, a device for measuring the amount of nuclear radiation exposure.

Medical Radiation Exposure

Graves’ disease causes the thyroid gland to produce excess hormones. This excess induces increase in metabolism, weight loss (despite a healthy appetite), and irregular heartbeat.

Graves’ 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.

Examine the table below, which shows radiation exposures for different situations and the resulting increased risks in leukemia rates.

<table>
<thead>
<tr>
<th>Person tested</th>
<th>Radiation exposure</th>
<th>Measured increased leukemia risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiroshima atomic bomb survivor</td>
<td>27 rem at once</td>
<td>6%</td>
</tr>
<tr>
<td>U.S. WW II radiology technician</td>
<td>50 rem over 2 years</td>
<td>0%</td>
</tr>
<tr>
<td>Austrian citizen after the nuclear accident at Chernobyl</td>
<td>0.025 rem</td>
<td>0%</td>
</tr>
</tbody>
</table>
High concentrations of radon gas can be hazardous

Colorless and inert, radon gas is produced by the radioactive decay of 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.

Nuclear Power

Today, nuclear reactors, as shown in Figure 13, 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 advantages to this source of energy. There are also disadvantages.

Nuclear fission has both advantages and disadvantages

One advantage of nuclear fission is that it 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.

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 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.

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.

Figure 13

Nuclear reactors like this are used over much of the world to generate electricity.
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 14. These precautions are necessary to keep nuclear radiation from leaking out and harming living things. The facilities must also keep nuclear radiation from contacting 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.

Nuclear fusion reactors are being tested

Another option that holds some promise as an energy source is nuclear fusion. Fusion means joining (fusing) smaller nuclei to make a larger nucleus. The sun uses the nuclear fusion of hydrogen atoms; this fusion results in larger helium atoms. This process of fusion gives off heat, light, and other radiation, otherwise known as solar energy. Solar energy can be captured by solar panels or other means to provide energy for homes and other types of buildings.

Recall from the last section that the process of fusion takes place when light nuclei, such as hydrogen, are forced together to produce heavier nuclei, such as helium, producing large amounts of energy. Some scientists estimate that 1 pound of hydrogen in a fusion reactor could release as much energy as 16 million pounds of burning coal. Nuclear fusion releases very little waste or pollution.

Because fusion requires that the electrical repulsion between protons be overcome, these reactions are difficult to produce in the laboratory. However, successful experiments have been conducted in the United States when researchers took a major step toward exploiting a safe, clean source of power that uses fuels extracted from ordinary water. Other experiments for power generated in a nuclear fusion reactor have also been carried out near Oxford, England.
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.

Nuclear fusion also has advantages and disadvantages

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 potentially 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.

Nuclear fusion is still in its infancy. Successful experiments are just beginning. Who can say what the future may hold? Perhaps scientists yet to come will find the answers to the nagging questions that plague the government today concerning the perfect fuel for United States citizens.

SUMMARY

- Background radiation comes from natural sources and is everywhere. Living tissue adapts to background radiation in most cases.
- Beneficial uses of nuclear radiation include smoke detectors, X rays, CT, MRI, radioactive tracers, PET, radiotherapy, radioactive tracers, and radioisotopes.
- Risks of high levels of nuclear radiation include cancers and radiation sickness. High levels of radon gas can be harmful. Tests for radon gas are widely available.
- Nuclear fission is an alternative to fossil fuels as a source of energy.

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. Name three nuclear radiation diagnostic imaging techniques that help detect diseases.
5. Explain how radioactive tracers help locate tumors.
6. Describe how gamma rays are used in cancer therapy.
7. Compare and contrast the benefits and risks of radiation therapy in general.
8. Explain why it is important to use low levels of nuclear radiation for detection and treatment of disease.
9. Summarize why the testing of buildings for radon gas levels may be important, especially for smokers.
10. 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.
Calculating Times of Decay

A sample of francium-223 has a half-life of 22 minutes.

a. What fraction of francium-223 remains if 93.75 percent of it has undergone radioactive decay?

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

c. How long does it take for the sample to decay?

**List all given and unknown values.**

**Given:** fraction of sample decayed, 93.75 percent
half-life, 22 min

**Unknown:** fraction of sample remaining
number of half-lives (n)
time of decay

**Write down the equation relating the fraction of the sample remaining to the percentage of sample decayed, and the equation relating the time of decay to the number of half-lives.**

\[
\text{fraction of sample remaining} = 1 - \text{fraction of sample decayed} \\
= 1 - \frac{\text{percentage of sample decayed}}{100} \\
= \left(\frac{1}{2}\right)^n \\
\text{time of decay} = n \times \text{half-life}
\]

**Calculate the unknown quantities.**

a. fraction of sample remaining
\[
= 1 - \frac{93.75}{100} = 1 - 0.9375 = 0.0625
\]

To express this as a fraction, divide the answer into 1 to find the denominator of the fraction. \(1/0.0625 = 16\), so the fraction of sample remaining is \(1/16\).

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

number of half-lives = \(n = 4\)

c. time of decay = \(4 \times 22\) min = 88 min

**Practice**

Following the example above, calculate the following:

1. What fraction of iodine-132 remains if 87.5% has undergone radioactive decay?
2. How many half-lives does it take for the sample to decay?
3. Iodine-132 has a half-life of 2.3 hours. How long does it take for the sample to decay?
### Chapter 9 Review

#### Chapter Highlights

Before you begin, review the summaries of the key ideas of each section, found at the end of each section. The key vocabulary terms are listed on the first page of each section.

#### Understanding Concepts

1. When a heavy nucleus decays, it may emit
   - a. alpha particles.
   - b. beta particles.
   - 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. Alpha particles
   - a. are negatively charged rays emitted from uranium-238.
   - b. are equivalent to lithium nuclei.
   - c. are too massive to pass through paper.
   - d. gain energy as they ionize matter.
4. Beta particles
   - a. are actually electrons emitted from a decayed neutron.
   - b. are neutral in charge because they came from a neutron.
   - c. are negatively charged but cannot ionize other atoms.
   - d. gain energy as they ionize and then deeply penetrate matter.
5. Gamma rays
   - a. have a positive charge and can therefore ionize matter.
   - b. have a negative charge and can therefore ionize matter.
   - c. have no electrical charge and cannot therefore ionize matter.
   - d. have no electrical charge but can ionize matter.
6. Neutrons
   - a. cannot travel as far through matter as alpha and beta particles can.
   - b. can travel farther through matter than either alpha or beta particles.
   - c. can ionize matter, although they have no charge.
   - d. cannot ionize matter, although they do have a charge.
7. After three half-lives, __________ of a radioactive sample remains.
   - a. all
   - b. one-half
   - c. one-third
   - d. one-eighth
8. 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.
9. Of the following elements, only the isotopes of __________ are all radioactive.
   - a. nitrogen
   - b. gold
   - c. sulfur
   - d. uranium
10. The strong nuclear force
    - a. attracts protons to electrons.
    - b. holds molecules together.
    - c. holds the atomic nucleus together.
    - d. attracts electrons to neutrons.
11. 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.
12. 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 missing nuclei and particles released.
    - c. the volume of the nuclear reactor.
    - d. the square of the speed of sound.
13. 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.

14. Exposure to nuclear radiation varies from location to location because
   a. the altitude varies from location to location.
   b. the activities in certain areas vary from those in other locations.
   c. the amount of rock varies with location.
   d. All of the above

15. 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 study biochemical processes in plants

16. How can nuclear radioactivity affect the atomic number and mass number of a nucleus that changes after undergoing decay?

17. Describe the main differences between the four main types of nuclear radiation: alpha particles, beta particles, gamma rays, and neutron emission.

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

19. Where do beta particles come from?

20. Why do gamma rays have no mass at all?

21. Would a substance with a one-second half-life be effective as a radioactive tracer?

22. For the nuclear fission process, how is critical mass important in a chain reaction?

23. How does nuclear fusion account for the energy produced in stars?

24. What is background radiation, and what are its sources?

25. The amount of nuclear radiation exposure that is received into a 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?

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

27. 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. $^{212}_{83}\text{Bi} \rightarrow X + ^{4}_{2}\text{He}$
      $X \rightarrow ^{208}_{82}\text{Pb} + ^{0}_{-1}\text{e}$
   b. $^{212}_{83}\text{Bi} \rightarrow Y + ^{0}_{-1}\text{e}$
      $Y \rightarrow ^{208}_{82}\text{Pb} + ^{4}_{2}\text{He}$

28. Nuclear Decay The longest-lived radioactive isotope yet discovered is the beta-emitter tellurium-130. It has been determined that it would take $2.5 \times 10^{21}$ years for 99.9% of this isotope to decay. Write the equation for this reaction, and identify the isotope into which tellurium-130 decays.
29. **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.

30. **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.

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

32. **Graphing** Draw a graph representing stable nuclei. Entitle it “Number of protons versus number of neutrons for stable nuclei.” Let the $x$-axis (horizontal axis) represent number of protons. Let the $y$-axis (vertical axis) represent number of neutrons. Remember that in a stable nucleus, there are equal numbers of protons and neutrons.

33. **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:
   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?

34. **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.

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

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

37. **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.

38. **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 that it is introduced into the soil and the time that it reaches the ground water supply. Estimate this time and calculate the half-life of an ideal tracer that could be used in this particular application.

39. **Critical Thinking** Explain the concept of why carbon-14 is used to determine the age of an object.

40. **Critical Thinking** Why would carbon-14 not be a good choice to use in household smoke detectors?

41. **Critical Thinking** Would an emitter of alpha particles be useful in measuring the thickness of a brick? Explain your answer.
42. **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?

43. **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.

44. **Working Cooperatively** Read the following, and research with a group of classmates possible solutions that make use of radioactivity. Report your findings.

> 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?

---

45. **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.

---

**Radioactive substances**

- emit which usually consist of __________
- which are made of __________
- which are the same as __________
- which are a high-energy form of __________
- are usually emitted from a neutron-rich nucleus __________
- produced by the decay of __________
- consist of nuclei that can’t be held together by the __________

---

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Simulating Nuclear Decay Reactions

**Procedure**

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

<table>
<thead>
<tr>
<th>Throw #</th>
<th># of dice representing each Isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (start)</td>
<td>2¹⁰Pb</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

2. Place all 10 dice in the cup. Each die represents an atom of 2¹⁰Pb, 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 2¹⁰Pb that have decayed into 2¹⁰Bi. The remaining dice still represent 2¹⁰Pb 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 2¹⁰Bi 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.

---

**Introduction**

In this lab you 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, 2¹⁰Pb, first decays into bismuth-210, 2¹⁰Bi, which decays into polonium-210, 2¹⁰Po, which finally decays into the isotope lead-206, 2⁰⁶Pb.

**Objectives**

- **Using Scientific Methods** 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.

**Materials**

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

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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 $^{210}\text{Bi}$ atoms that have decayed into $^{210}\text{Po}$.
   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 $^{210}\text{Bi}$) and the unmarked dice that landed with 1, 2, or 3 facing up (representing the decay of original $^{210}\text{Pb}$ into $^{210}\text{Bi}$).
   c. The third set includes unmarked dice that did not land with 1, 2, or 3 facing up. These represent the original undecayed $^{210}\text{Pb}$ 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 $^{210}\text{Po}$ will decay into the stable isotope $^{206}\text{Pb}$. 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 $^{206}\text{Pb}$, which is a stable isotope. Hence, these dice will remain unchanged in all future throws.

► **Analysis**

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 $^{210}\text{Pb}$ and $^{206}\text{Pb}$ on Earth are changing over time?

► **Conclusions**

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

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.

“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.”

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

“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