Chapter 4

Nuclear Chemistry

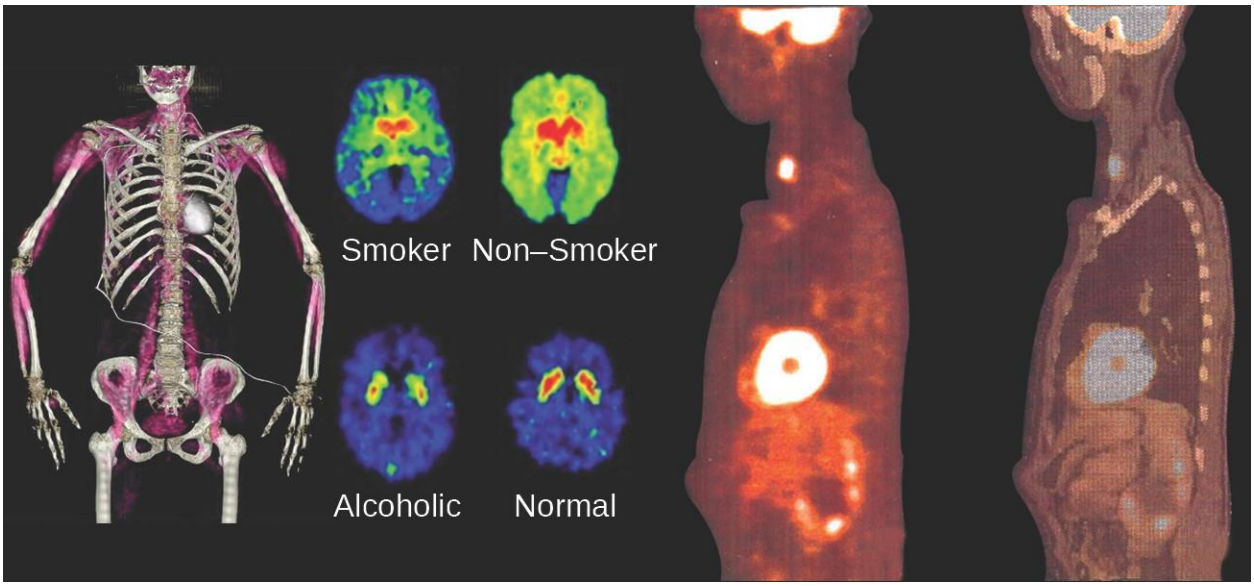


Figure 4.1 Nuclear chemistry provides the basis for many useful diagnostic and therapeutic methods in medicine, such as these positron emission tomography (PET) scans. The PET/computed tomography scan on the left shows muscle activity. The brain scans in the center show chemical differences in dopamine signaling in the brains of addicts and nonaddicts. The images on the right show an oncological application of PET scans to identify lymph node metastasis.

Chapter Outline

4.1 Nuclear Structure and Stability
4.2 Nuclear Equations
4.3 Radioactive Decay
4.4 Transmutation and Nuclear Energy
4.5 Uses of Radioisotopes
4.6 Biological Effects of Radiation

Introduction

This chapter will introduce the topic of nuclear chemistry, which began with the discovery of radioactivity in 1896 by French physicist Antoine Becquerel and has become increasingly important during the twentieth and twenty-first centuries, providing the basis for various technologies related to energy, medicine, geology, and many other areas.

Nuclear structure, the numbers of protons and neutrons within the nuclei of the atoms involved, remains unchanged during chemical reactions.

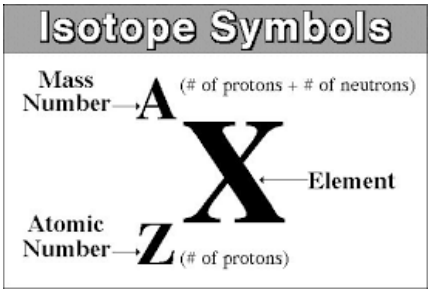
4.1 Nuclear Structure and Stability

By the end of this section, you will be able to:

- Describe nuclear structure in terms of protons, neutrons, and electrons

Not all elements and isotopes are stable. A nuclear reaction is a change in the composition of the nucleus of an atom. This is not normally considered a chemical reaction, and does not depend on what molecule the atom might be in.

Nuclear chemistry is the study of reactions that involve changes in nuclear structure. The nucleus of an atom is composed of protons and, with the exception of Hydrogen, neutrons. The number of protons in the nucleus is called the **atomic number (Z)** of the element, and the sum of the number of protons and the number of neutrons is the mass **number (A)**. Atoms with the same atomic number but different mass numbers are **isotopes** of the same element. When referring to a single type of nucleus, we often use the term **nuclide** and identify it by the notation $^{A}_{Z}X$, where X is the symbol for the element, A is the mass number, and Z is the atomic number. Often a nuclide is referenced by the name of the element followed by a hyphen and the mass number. For example, ^{14}C is called "carbon-14."



Nuclear Stability

A nucleus is stable if it cannot be transformed into another configuration without adding energy from the outside. Of the thousands of nuclides that exist, about 250 are stable. Unstable nuclides exhibit **radioactivity**. They change spontaneously (decay) into other nuclei. These nuclear decay reactions convert one unstable isotope (or **radioisotope**) into another, more stable, isotope.

Example 4.1

Writing Atomic Symbols for Isotopes: Using the periodic table, state the atomic number, element symbol, number of protons for each of the following elements: Calcium, Zinc, and Oxygen.

Solution:

Calcium: Atomic number = 20; symbol Ca; protons = 20

Zinc: Atomic number = 30; symbol Zn; protons = 30

Oxygen: Atomic number = 8; symbol O; protons = 8

Check Your Learning

Naturally occurring iodine has 74 neutrons write the atomic symbol

Answer: ${}^{127}_{53}I$

Self-assessment 4.1

The nuclide symbols for three isotopes of carbon are below.

${}^{12}_{6}C$	${}^{13}_{6}C$	${}^{14}_{6}C$
carbon-12	carbon-13	carbon-14

a) How many protons and neutrons does each have?

b) What is the same and what is different among the isotopes?

c) What does the subscript 6 represent?

Answer:

a) carbon-12 = 6 protons and 6 neutrons; carbon-13 = 6 protons and 7 neutrons; carbon-14 = 6 protons and 8 neutrons

b) The number of protons are the same but the number of neutrons differ.

c) The number of protons

4.2 Nuclear Equations

By the end of this section, you will be able to:

- Describe alpha, beta, positron and gamma radiation
- Write and balance nuclear equations

A **nuclear reaction** is a change in the composition of the nucleus of an atom. The nuclei of radioactive isotopes break down (decay) and result in changes in their atomic numbers, mass numbers, or energy states. To describe a nuclear reaction, we use an equation that identifies the nuclides involved in the reaction, their mass numbers and atomic numbers, and the other particles involved in the reaction.

Types of Particles in Nuclear Reactions

Many entities can be involved in nuclear reactions. The most common are protons, neutrons, alpha particles, beta particles, positrons, and gamma rays, as shown in Figure 4.4. Protons and neutrons, as we saw earlier, are the constituents of atomic nuclei. Alpha particles, α, are high-energy helium nuclei. Beta particles, β, are high-energy electrons, and gamma rays are photons of very high-energy electromagnetic radiation. Positrons are positively charged electrons (“anti-electrons”).

Name	Symbol(s)	Representation	Description
Alpha particle	${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$		(High-energy) helium nuclei consisting of two protons and two neutrons
Beta particle	${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$		(High-energy) electrons
Positron	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta$		Particles with the same mass as an electron but with 1 unit of positive charge
Proton	${}^{1}_{1}H$ or ${}^{1}_{1}p$		Nuclei of hydrogen atoms
Neutron	${}^{1}_{0}n$		Particles with a mass approximately equal to that of a proton but with no charge
Gamma ray	γ	γ	Very high-energy electromagnetic radiation

Figure 4.2 Although many species are encountered in nuclear reactions, this table summarizes the names, symbols, representations, and descriptions of the most common of these.

The subscripts and superscripts are necessary for balancing nuclear equations, but are usually optional in other circumstances. For example, an alpha particle is a helium nucleus (He) with 2 protons and a mass number of 4, so it is symbolized as ${}^{4}_{2}He$. Note that positrons are exactly like electrons, except they have the opposite charge. Gamma rays compose short wavelength, high-energy electromagnetic radiation and are more energetic than better-known X-rays. Gamma rays are a type of high-energy electromagnetic radiation produced when a nucleus undergoes a transition from a higher to a lower energy state, similar to how a photon is produced by an electronic transition from a higher to a lower energy level.

Balancing Nuclear Reactions

A balanced chemical reaction equation reflects the fact that during a chemical reaction, bonds break and form, and atoms are rearranged, but the total numbers of atoms of each element are conserved and do not change. A balanced nuclear reaction equation indicates that there is a rearrangement during a nuclear reaction, but of nucleons (subatomic particles within the atoms' nuclei) rather than atoms. Nuclear reactions also follow conservation laws, and they are balanced in two ways:

1. The sum of the mass numbers of the reactants equals the sum of the mass numbers of the products.
2. The sum of the atomic numbers of the reactants equals the sum of the atomic numbers of the products.

Example 4.2

Balancing Equations for Nuclear Reactions: The reaction of an α particle with magnesium-25 $\left({}^{25}_{12}\boldsymbol{Mg}\right)$ produces a proton and a nuclide of another element. Identify the new nuclide produced.

Solution:

The nuclear reaction can be written as:

$$^{25}_{12}Mg + ^{4}_{2}He \rightarrow \ ^{1}_{1}H + \ ^{A}_{Z}X$$

where A is the mass number and Z is the atomic number of the new nuclide, X. Because the sum of the mass numbers of the reactants must equal the sum of the mass numbers of the products:

$25 + 4 = \mathrm{A} + 1$, or $\mathrm{A} = 28$

Similarly, the atomic number must balance, so:

$12 + 2 = \mathrm{Z} + 1$, and $\mathrm{Z} = 13$

Check the periodic table: The element with atomic number = 13 is aluminum. Thus, the product is $^{28}_{13}Al$

Check Your Learning

The nuclide $\mathbf{^{125}_{53}I}$ combines with an electron and produces a new nucleus and no other massive particles. What is the equation for this reaction?

Answer: $\mathbf{^{125}_{53}I + {}_{-1}^{0}e \rightarrow \ ^{125}_{52}Te}$

Self-assessment 4.2

Complete the following nuclear equations.

a) $^{42}_{19}K \rightarrow \mathbf{_{-1}^{0}e} + _____$

b) $^{6}_{3}Li \rightarrow \mathbf{^{4}_{2}He} + _____$

c) $^{9}_{4}Be \rightarrow \mathbf{^{9}_{4}Be} + _____$

d) $^{240}_{95}Am + _____ \rightarrow \mathbf{^{243}_{97}Bk + {}_{0}^{1}n}$

e) $^{232}_{91}Pa \rightarrow _____ + \mathbf{_{-1}^{0}e}$

Answer:

a) $^{42}_{20}Ca$

b) $^{2}_{1}H$

c) γ

d) $\mathbf{^{4}_{2}He}$

e) $\mathbf{^{232}_{92}U}$

4.3 Radioactive Decay

By the end of this section, you will be able to:

- Recognize common modes of radioactive decay
- Identify common particles and energies involved in nuclear decay reactions
- Write and balance nuclear decay equations
- Calculate half-life

Following the somewhat serendipitous discovery of radioactivity by Becquerel, many prominent scientists began to investigate this new, intriguing phenomenon. Among them were Marie Curie (the first woman to win a Nobel Prize, and the only person to win two Nobel Prizes in different sciences—chemistry and physics), who was the first to coin

the term "radioactivity," and Ernest Rutherford (of gold foil experiment fame), who investigated and named three of the most common types of radiation. During the beginning of the twentieth century, many radioactive substances were discovered, the properties of radiation were investigated and quantified, and a solid understanding of radiation and nuclear decay was developed.

The spontaneous change of an unstable nuclide into another is **radioactive decay**. The unstable nuclide is called the **parent nuclide**; the nuclide that results from the decay is known as the **daughter nuclide**. The daughter nuclide may be stable, or it may decay itself. The radiation produced during radioactive decay is such that the daughter nuclide is more stable than the parent nuclide (**Figure 4.3**).

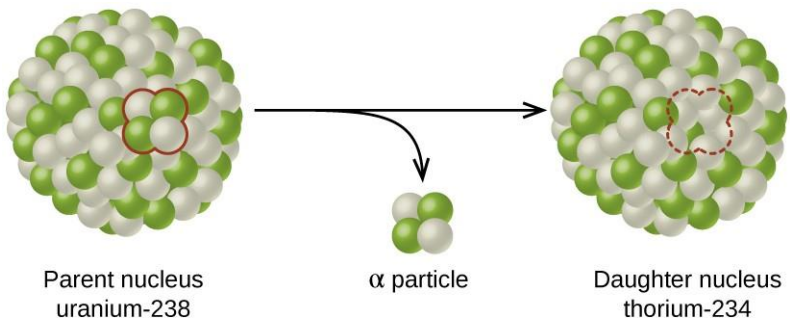


Figure 4.3 A nucleus of uranium-238 (the parent nuclide) undergoes α decay to form thorium-234 (the daughter nuclide). The alpha particle removes two protons (green) and two neutrons (gray) from the uranium-238 nucleus.

Link to Learning

Although the radioactive decay of a nucleus is too small to see with the naked eye, we can indirectly view radioactive decay in an environment called a cloud chamber. Click **here (http://openstaxcollege.org/l/16cloudchamb)** to learn about cloud chambers and to view an interesting Cloud Chamber Demonstration from the Jefferson Lab.

Types of Radioactive Decay

Ernest Rutherford's experiments involving the interaction of radiation with a magnetic or electric field (**Figure 4.4**) helped him determine that one type of radiation consisted of positively charged and relatively massive α particles; a second type was made up of negatively charged and much less massive β particles; and a third was uncharged electromagnetic waves, γ rays. We now know that α particles are high-energy helium nuclei, β particles are high-energy electrons, and γ radiation compose high-energy electromagnetic radiation. We classify different types of radioactive decay by the radiation produced.

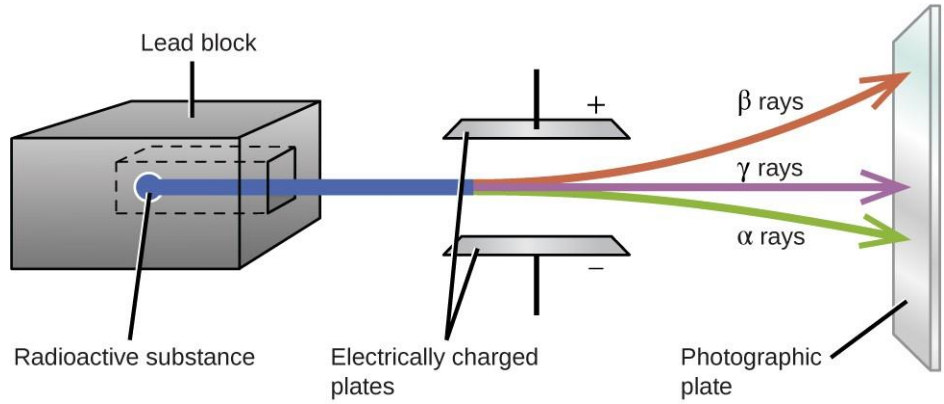


Figure 4.4 Alpha particles, which are attracted to the negative plate and deflected by a relatively small amount, must be positively charged and relatively massive. Beta particles, which are attracted to the positive plate and deflected a relatively large amount, must be negatively charged and relatively light. Gamma rays, which are unaffected by the electric field, must be uncharged.

Alpha (α) decay is the emission of an α particle from the nucleus. For example, polonium-210 undergoes α decay:

$$^{210}_{84}Po \rightarrow {}^{4}_{2}He + {}^{206}_{82}Pb \qquad or \quad {}^{210}_{84}Po \rightarrow {}^{4}_{2}\alpha + {}^{206}_{82}Pb$$

Alpha decay occurs primarily in heavy nuclei (A > 200, Z > 83). Because the loss of an α particle gives a daughter nuclide with a mass number four units smaller and an atomic number two units smaller than those of the parent nuclide.

Check Your Learning

a. Bismuth-213, used to treat leukemia, emits alpha particles that destroy cancer cells. Write the balanced nuclear equation for the alpha decay of Bi-213.

b. Radium-226 are naturally present in many types of rocks and soils. Radium-226 emits an alpha particle and is converted into radon gas. Radon gas can enter a building through cracks in the foundation or other openings. In the lungs, radon -222 emits alpha particles to form polonium-218, which is known to cause lung cancer. Write balanced nuclear equations for both of these processes.

Answer: a. $\boldsymbol{^{213}_{83}Bi \rightarrow {}^{4}_{2}He + {}^{209}_{81}Tl}$ $\boldsymbol{b.}$ $\boldsymbol{^{226}_{88}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{86}Rn}$ $\boldsymbol{^{222}_{86}Rn \rightarrow {}^{4}_{2}He + {}^{218}_{84}Po}$

Beta (β) decay is the emission of an electron from a nucleus. Iodine-131 is an example of a nuclide that undergoes β decay:

$$^{131}_{53}I \rightarrow {}^{0}_{-1}e + {}^{131}_{54}Xe \quad or \quad {}^{131}_{53}I \rightarrow {}^{0}_{-1}\beta + {}^{131}_{54}Xe$$

Beta decay, which can be thought of as the conversion of a neutron into a proton and a β particle. The beta particle (electron) emitted is from the atomic nucleus and is not one of the electrons surrounding the nucleus. Emission of an electron does not change the mass number of the nuclide but does increase the number of its protons and decrease the number of its neutrons.

Gamma emission (γ emission) is observed when a nuclide is formed in an excited state and then decays to its ground

state with the emission of a γ ray, a quantum of high-energy electromagnetic radiation. The presence of a nucleus in an excited state is often indicated by an asterisk (*). Cobalt-60 emits γ radiation and is used in many applications including cancer treatment:

$$^{60}_{27}Co* \rightarrow {}^{0}_{0}\gamma + {}^{60}_{27}Co$$

There is no change in mass number or atomic number during the emission of a γ ray unless the γ emission accompanies one of the other modes of decay.

Check Your Learning

a. Cobalt-60 is a beta-emitting radioactive isotope. In cobalt-60 therapy, cobalt-60-generated gamma radiation is used to destroy tumors. Write the balanced nuclear equation for the decay of Co-60.

b. Thorium-234 is radioactive and emits a □-particle. Write a balance equation for this process.

Answer: a. $^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + 2\gamma$ **b.** $^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$

The mass number is the same, the atomic number has increased by 1 by the conversion of a neutron into a proton and an electron.

Positron emission (β^+ decay) is the emission of a positron from the nucleus. Oxygen-15 is an example of a nuclide that undergoes positron emission:

$$^{15}_{8}O \rightarrow {}^{0}_{+1}e + {}^{15}_{7}N \qquad or \qquad {}^{15}_{8}O \rightarrow {}^{0}_{+1}\beta + {}^{15}_{7}N$$

Positron decay is the conversion of a proton into a neutron with the emission of a positron.

Electron capture occurs when one of the inner electrons in an atom is captured by the atom's nucleus. For example, potassium-40 undergoes electron capture:

$$^{40}_{19}K + {}^{0}_{-1}e \rightarrow {}^{40}_{18}Ar$$

Electron capture occurs when an inner shell electron combines with a proton and is converted into a neutron. The loss of an inner shell electron leaves a vacancy that will be filled by one of the outer electrons. As the outer electron drops into the vacancy, it will emit energy. In most cases, the energy emitted will be in the form of an X-ray. Electron capture has the same effect on the nucleus as does positron emission: The atomic number is decreased by one and the mass number does not change. **Figure 4.5** summarizes these types of decay, along with their equations and changes in atomic and mass numbers.

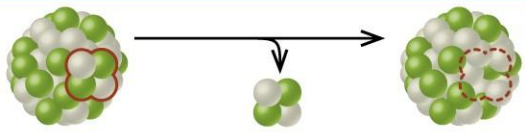
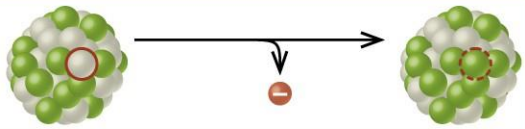
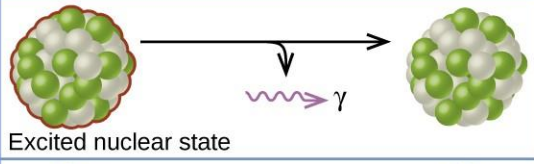
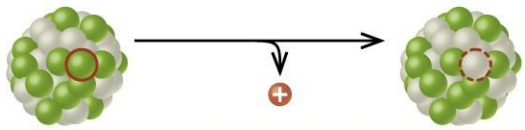
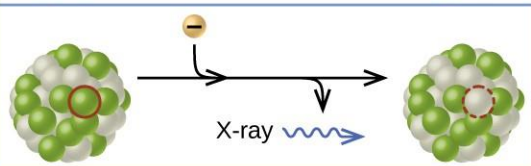
Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}X \quad {}^{4}_{2}He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}X \quad {}^{0}_{0}\gamma + {}^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	${}^{A}_{Z}X \quad {}^{0}_{+1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Figure 4.5 This table summarizes the type, nuclear equation, representation, and any changes in the mass or atomic numbers for various types of decay.

Self-assessment 4.3

a) Technetium-99m is used in many diagnostic scans done in hospitals. It is made on-site from Mo-99. Write a balanced nuclear equation for its formation.

b) Colbolt-60 is used in cancer treatment it produces a beta particle and a gamma ray. Draw a balance equation.

Answer: a. $\boldsymbol{{}^{99}_{42}Mo \rightarrow {}^{0}_{-1}e + {}^{99}_{43}Tc}$ **b.** $\boldsymbol{{}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + \gamma}$

Chemistry in everyday life

PET Scan

Positron emission tomography (PET) scans use radiation to diagnose and track health conditions and monitor medical treatments by revealing how parts of a patient's body function (**Figure 4.6**). To perform a PET scan, a positron-emitting radioisotope is produced in a cyclotron and then attached to a substance that is used by the part of the body being investigated. This "tagged" compound, or radiotracer, is then put into the patient (injected via IV or breathed in as a gas), and how it is used by the tissue reveals how that organ or other area of the body functions.

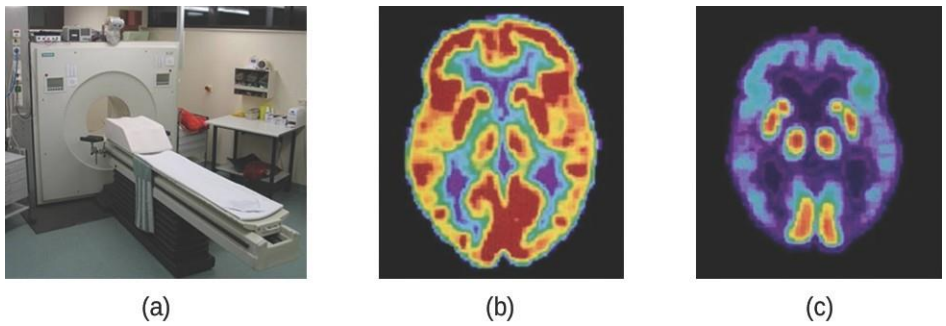


Figure 4.6 A PET scanner (a) uses radiation to provide an image of how part of a patient's body functions. The scans it produces can be used to image a healthy brain (b) or can be used for diagnosing medical conditions such as Alzheimer's disease (c). (credit a: modification of work by Jens Maus)

For example, F-18 is produced by proton bombardment of ^{18}O (${}^{18}_{8}O + {}^{1}_{1}P \rightarrow {}^{18}_{9}F + {}^{1}_{0}n$) and incorporated into a glucose analog called fludeoxyglucose (FDG). How FDG is used by the body provides critical diagnostic information; for example, since cancers use glucose differently than normal tissues, FDG can reveal cancers. The ^{18}F emits positrons that interact with nearby electrons, producing a burst of gamma radiation. This energy is detected by the scanner and converted into a detailed, three-dimensional, color image that shows how that part of the patient's body functions. Different levels of gamma radiation produce different amounts of brightness and colors in the image, which can then be interpreted by a radiologist to reveal what is going on. PET scans can detect heart damage and heart disease, help diagnose Alzheimer's disease, indicate the part of a brain that is affected by epilepsy, reveal cancer, show what stage it is, and how much it has spread, and whether treatments are effective. Unlike magnetic resonance imaging and X-rays, which only show how something looks, the big advantage of PET scans is that they show how something functions. PET scans are now usually performed in conjunction with a computed tomography scan.

Self-assessment 4.4

Positron emission tomography (PET) is a

a) Cancer treatment using positrons

b) Diagnostic technique for monitoring glucose metabolism in the body

c) Transmutation reaction in the body

Answer: b. Diagnostic technique for monitoring glucose metabolism in the body

Radioactive Half-Lives

Each radioactive nuclide has a characteristic, constant **half-life** ($t_{1/2}$), the time required for half of the atoms in a sample to decay. An isotope's half- life allows us to determine how long a sample of a useful isotope will be available, and how long a sample of an undesirable or dangerous isotope must be stored before it decays to a low-enough radiation level that is no longer a problem.

For example, cobalt-60, an isotope that emits gamma rays used to treat cancer, has a half-life of 5.27 years (**Figure 4.7**). In a given cobalt-60 source, since half of the $^{60}_{27}Co$ nuclei decay every 5.27 years, both the amount of material and the intensity of the radiation emitted is cut in half every 5.27 years. (Note that for a given substance, the intensity of radiation that it produces is directly proportional to the rate of decay of the substance and the amount of the substance.) Thus, a cobalt-60 source that is used for cancer treatment must be replaced regularly to continue to be effective.

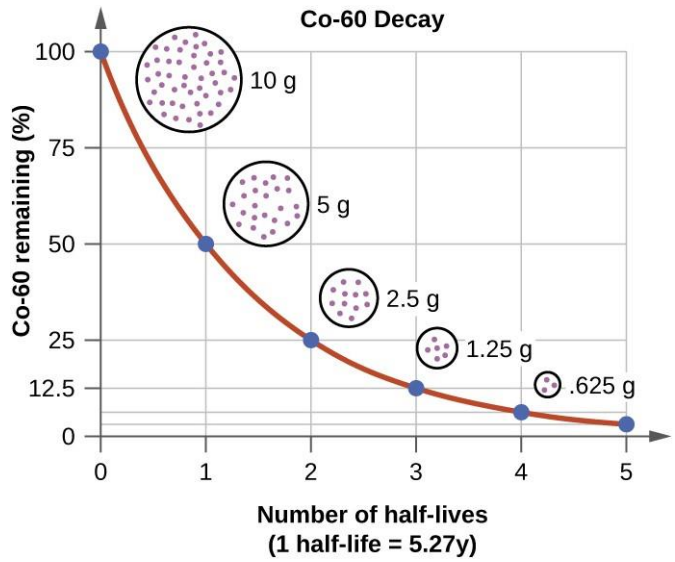


Figure 4.7 For cobalt-60, which has a half-life of 5.27 years, 50% remains after 5.27 years (one half-life), 25% remains after 10.54 years (two half-lives), 12.5% remains after 15.81 years (three half-lives), and so on. A can represent a mass or a number of nuclei of the isotope. **Example 4.2** applies these calculations to find the rates of radioactive decay for specific nuclides.

Example 4.2

Rates of Radioactive Decay: $^{59}_{26}Fe$ decays with a half-life of 44 days to produce $^{59}_{27}Co$

(a) Write a balance nuclear equation for the decay of iron-59? What type of decay does iron-59 undergo?

(b) If a lab receives a 10.0 □g sample of iron-59, how many micrograms of iron-59 are remaining after 132 days?

(c) How long does it take for a sample of $^{59}_{26}Fe$ to disintegrate to the extent that only 25% of the original amount remains?

Solution:

(a) The balance nuclear equation is:

$$^{59}_{26}Fe \rightarrow {}^{0}_{-1}e + {}^{59}_{27}co \qquad Beta\ decay$$

(b) 1 half-life = 44 days

Number of half-lives =132 days x $\frac{1\ \text{half-life}}{44\ days}$ = 3 half-lives

1st half-life 2nd half-life 3rd half-life

10.0 µg of $^{59}_{26}Fe$ → 5.0 µg of $^{59}_{26}Fe$ → 2.5 µg of $^{59}_{26}Fe$ → 1.25 µg of $^{59}_{26}Fe$

The amount of iron- 59 that will remain after 132 days is 1.25µg

1 half-life 2nd half-life

(c) 100% → 50% → 25%

Days = 2 half-lives x $\frac{44 \text{ days}}{1 \text{ half-life}}$ = 88 days

It would take 88 days for there to be only 25% of the radioactive Fe-59 remaining

Check your learning

Iodine-123, which is used to test the uptake of iodine by the thyroid, has a half-life of 13 hours. If 100 mg of I-123 were prepared at 8:00 AM on Monday, how many mg remain at 10:00 AM the following day?

Answer: 25.0 mg

Tritium (H-3) is a radioactive isotope of hydrogen with a half-life of 12.3 years. How long would it take for a 40.0 g sample to decay to 1.25g?

Answer: 61.5 years

The half-lives of a few radioactive isotopes important to medicine are shown in **Table 4.1**.

Half-lives of Radioactive Isotopes Important to Medicine

Type[1]	Decay Mode	Half-Life	Uses
F-18	β^+ decay	110. minutes	PET scans
Co-60	β decay, γ decay	5.27 years	cancer treatment
Tc-99m	γ decay	6.0 hours	scans of brain, lung, heart, bone
I-131	β decay	8.0 days	thyroid scans and treatment
Tl-201	electron capture	3 days	heart and arteries scans; cardiac stress tests

Table 4.1 Note: The "m" in Tc-99m stands for "metastable," indicating that this is an unstable, high-energy state of Tc-99. Metastable isotopes emit γ radiation to rid themselves of excess energy and become (more) stable.

Self-assessment 4.4

Iron-50 used to study iron metabolism in the spleen, has a half-life of 44 days. How many grams remain from an initial 100 g sample after 132 days?

Answer: First determine the number of half-lives $132\ day\ x\ \frac{1\ half-life}{44\ days} = 3\ half-lives$

Next, multiple the mass by ½ three times

100g → 50g→ 25g→ 12.5

thus, 12.5 g of Iron-50 remains after 132 day.

Self-assessment 4.5

Technetium-99m is the most widely used radioisotope in medicine. Tc-99m has a half-life of 6 hours. How many

hours would it take an 8 mg sample of Tc-99m to decay to 0.25 mg?

Answer: 8 mg → 4 mg→ 2 mg→ 1 mg→ 0.5 mg→ 0.25 mg

5 half-lives x 6 hours = 30 hours

Radiometric Dating

Several radioisotopes have half-lives and other properties that make them useful for purposes of "dating" the origin of objects such as archaeological artifacts, formerly living organisms, or geological formations. This process is **radiometric dating** and has been responsible for many breakthrough scientific discoveries about the geological history of the earth, the evolution of life, and the history of human civilization. We will explore some of the most common types of radioactive dating and how the particular isotopes work for each type.

Radioactive Dating Using Carbon-14

The radioactivity of carbon-14 provides a method for dating objects that were a part of a living organism. This method of radiometric dating, which is also called **radiocarbon dating** or carbon-14 dating, is accurate for dating carbon-containing substances that are up to about 30,000 years old and can provide reasonably accurate dates up to a maximum of about 50,000 years old.

Naturally occurring carbon consists of three isotopes: ${}^{12}_{6}c$, which constitutes about 99% of the carbon on earth; ${}^{13}_{6}C$, about 1% of the total; and trace amount of ${}^{14}_{6}C$. Carbon-14 forms in the upper atmosphere by the reaction of nitrogen atoms with neutrons from cosmic rays in space:

$$ {}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H $$

All isotopes of carbon react with oxygen to produce CO_2 molecules. When carbon-16 reacts with oxygen it forms radioactive carbon dioxide ${}^{14}_{6}CO_2$. Living plants continuously absorb carbon dioxide which incorporates carbon-14 into the plant material. The uptake of carbon-14 stops when the plant. After dying, the amount of radioactive carbon-14 in plant material steadily decreases as the carbon-14 undergoes beta decay with a half-life of 5730 years:

$$ {}^{14}_{6}C \rightarrow {}^{12}_{7}N + {}^{0}_{-1}e $$

Thus, the ${}^{14}_{6}C : {}^{12}_{6}C$ ratio gradually decreases after the plant dies. The decrease in the ratio with time provides a measure of the time that has elapsed since the death of the plant (or other organism that ate the plant). **Figure 4.11** visually depicts this process.

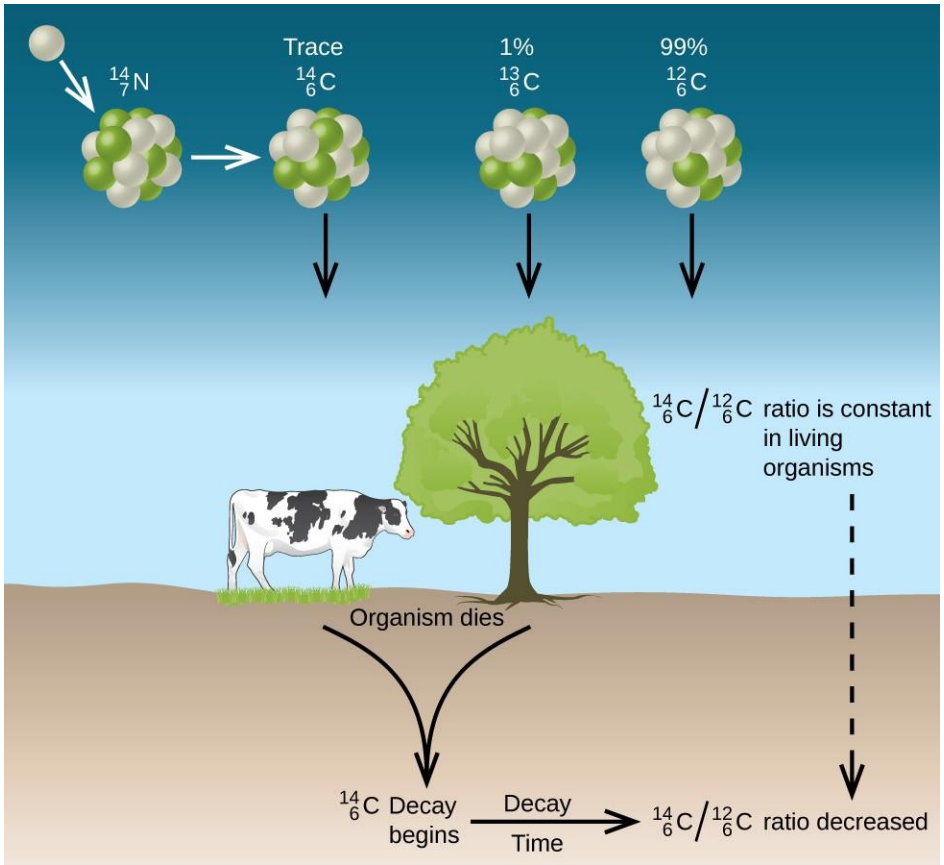


Figure 4.11 Along with stable carbon-12, radioactive carbon-14 is taken in by plants and animals, and remains at a constant level within them while they are alive. After death, the C-14 decays and the C-14:C-12 ratio in the remains decreases. Comparing this ratio to the C-14:C-12 ratio in living organisms allows us to determine how long ago the organism lived (and died).

For example, with the half-life of Carbon-14 being 5730 years, if the 14 C: 12 C ratio in a wooden object found in an archaeological dig is half what it is in a living tree, this indicates that the wooden object is 5730 years old. In general, radioactive dating only works for about 10 half-lives; therefore, the limit for carbon-14 dating is about 57,000 years.

4.4 Medical Uses of Radioisotopes

By the end of this section, you will be able to:

4.2.1 List common applications of radioactive isotopes

Radioactive isotopes have the same chemical properties as stable isotopes of the same element, but they emit radiation, which can be detected. If we replace one (or more) atom(s) with radioisotope(s) in a compound, we can track them by monitoring their radioactive emissions. This type of compound is called a **radioactive tracer** (or **radioactive label**). Radioisotopes are used to follow the paths of biochemical reactions or to determine how a substance is distributed within an organism. Radioactive tracers are also used in many medical applications, including both diagnosis and treatment.

Radioisotopes have revolutionized medical practice (see Appendix M), where they are used extensively. Over 10 million nuclear medicine procedures and more than 100 million nuclear medicine tests are performed annually in the United States. Four typical examples of radioactive tracers used in medicine are technetium-99.$({}^{99}_{43}Tc)$ (thallium-201$({}^{201}_{81}Tl)$iodine-131 $({}^{131}_{53}I)$,and sodium-24$({}^{24}_{11}Na)$ .Damaged tissues in the heart, liver, and lungs absorb certain compounds of technetium-99 preferentially. After it is injected, the location of the technetium compound, and hence the damaged tissue, can be determined by detecting the γ rays emitted by the Tc-99 isotope. Thallium-201 (**Figure 4.24**) becomes concentrated in healthy heart tissue, so the two isotopes, Tc-99 and Tl-201, are used together to study heart tissue. Iodine-131 concentrates in the thyroid gland, the liver, and some parts of the brain. It can therefore be used to monitor goiter and treat thyroid conditions, such as Grave's disease, as well as liver and brain tumors. Salt solutions containing compounds of sodium-24 are injected into the bloodstream to help locate obstructions to the flow of blood.

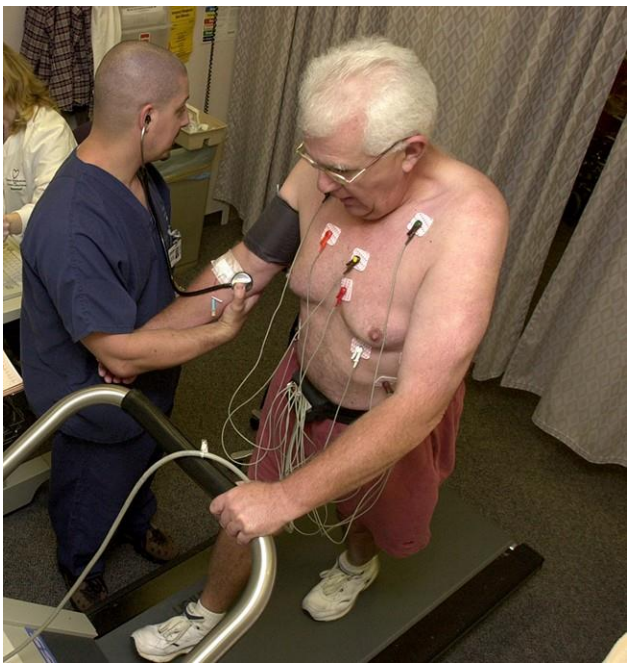


Figure 4.24 Administering thallium-201 to a patient and subsequently performing a stress test offer medical professionals an opportunity to visually analyze heart function and blood flow. (credit: modification of work by "Blue0ctane"/Wikimedia Commons)

Radioisotopes used in medicine typically have short half-lives—for example, the ubiquitous Tc-99m has a half-life of 6.01 hours. This makes Tc-99m essentially impossible to store and prohibitively expensive to transport, so it is made on-site instead. Hospitals and other medical facilities use Mo-99 (which is primarily extracted from U-235 fission products) to generate Tc-99. Mo-99 undergoes β decay with a half-life of 66 hours, and the Tc-99 is then chemically extracted.

Radioisotopes can also be used, typically in higher doses than as a tracer, as treatment. **Radiation therapy** is the use of high-energy radiation to damage the DNA of cancer cells, which kills them or keeps them from dividing (**Figure 4.26**). A cancer patient may receive **external beam radiation therapy** delivered by a machine outside the body, or

internal radiation therapy (brachytherapy) from a radioactive substance that has been introduced into the body. Note that **chemotherapy** is similar to internal radiation therapy in that the cancer treatment is injected into the body, but differs in that chemotherapy uses chemical rather than radioactive substances to kill the cancer cells.

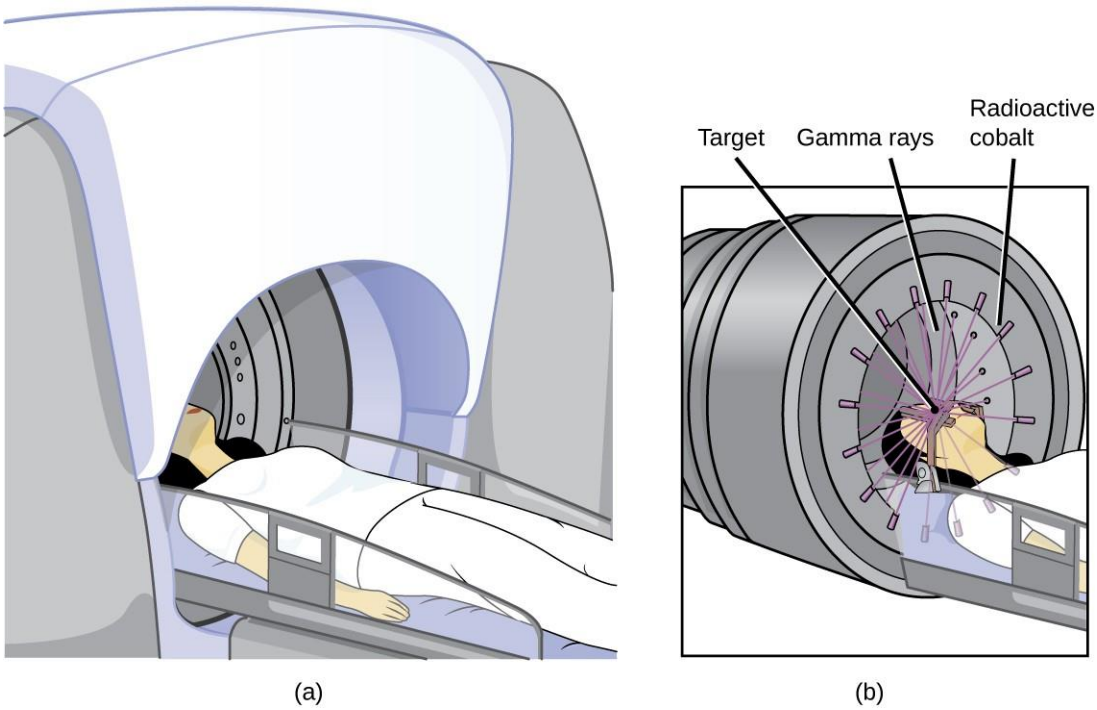


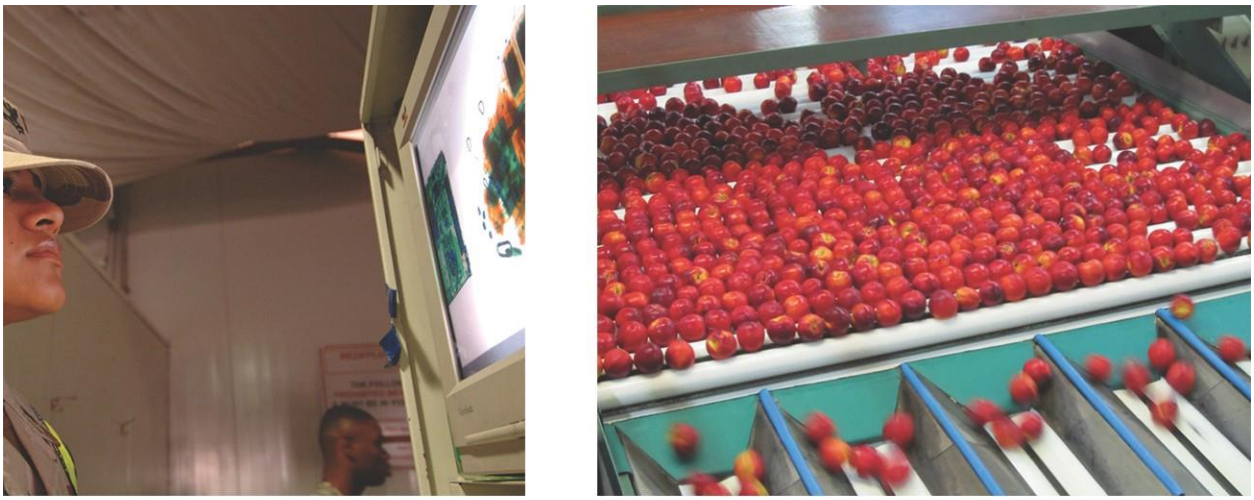
Figure 4.26 The cartoon in (a) shows a cobalt-60 machine used in the treatment of cancer. The diagram in (b) shows how the gantry of the Co-60 machine swings through an arc, focusing radiation on the targeted region (tumor) and minimizing the amount of radiation that passes through nearby regions.

Cobalt-60 is a synthetic radioisotope produced by the neutron activation of Co-59, which then undergoes β decay to form Ni-60, along with the emission of γ radiation. The overall process is:

$$^{59}_{27}CO + ^{1}_{0}n \rightarrow ^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}\beta + 2^{0}_{0}y$$

The γ emissions are used for radiation therapy.

Commercial applications of radioactive materials are equally diverse (**Figure 4.28**). They include determining the thickness of films and thin metal sheets by exploiting the penetration power of various types of radiation. Flaws in metals used for structural purposes can be detected using high-energy gamma rays from cobalt-60 in a fashion similar to the way X-rays are used to examine the human body. In one form of pest control, flies are controlled by sterilizing male flies with γ radiation so that females breeding with them do not produce offspring. Many foods are preserved by radiation that kills microorganisms that cause the foods to spoil.



(a) (b)

Figure 4.28 Common commercial uses of radiation include (a) X-ray examination of luggage at an airport and (b) preservation of food. (credit a: modification of work by the Department of the Navy; credit b: modification of work by the US Department of Agriculture)

Americium-241, an α emitter with a half-life of 458 years, is used in tiny amounts in ionization-type smoke detectors (**Figure 4.29**). The α emissions from Am-241 ionize the air between two electrode plates in the ionizing chamber. A battery supplies a potential that causes movement of the ions, thus creating a small electric current. When smoke enters the chamber, the movement of the ions is impeded, reducing the conductivity of the air. This causes a marked drop in the current, triggering an alarm.

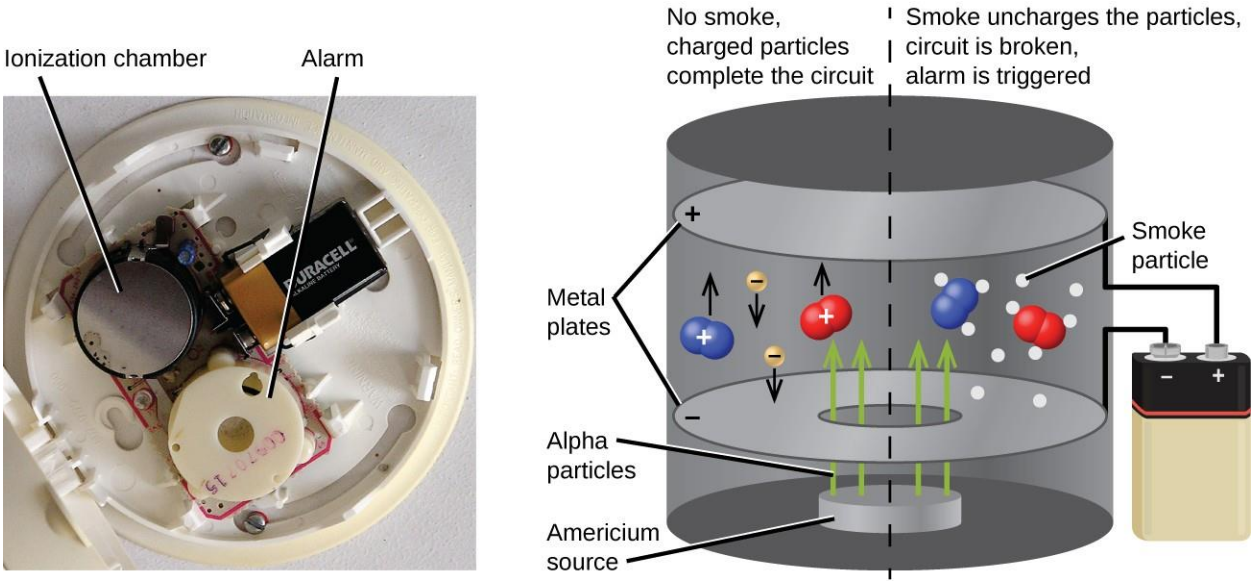


Figure 4.29 Inside a smoke detector, Am-241 emits α particles that ionize the air, creating a small electric current.

During a fire, smoke particles impede the flow of ions, reducing the current and triggering an alarm. (credit a: modification of work by “Muffet”/Wikimedia Commons)

4.5 Biological Effects of Radiation

By the end of this section, you will be able to:

4.2.2 Describe the biological impact of ionizing radiation

4.2.3 Define units for measuring radiation exposure

4.2.4 Explain the operation of common tools for detecting radioactivity

4.2.5 List common sources of radiation exposure in the US

The increased use of radioisotopes has led to increased concerns over the effects of these materials on biological systems (such as humans). All radioactive nuclides emit high-energy particles or electromagnetic waves. When this radiation encounters living cells, it can cause heating, break chemical bonds, or ionize molecules. The most serious biological damage results when these radioactive emissions fragment or ionize molecules. For example, alpha and beta particles emitted from nuclear decay reactions possess much higher energies than ordinary chemical bond energies. When these particles strike and penetrate matter, they produce ions and molecular fragments that are extremely reactive. The damage this does to biomolecules in living organisms can cause serious malfunctions in normal cell processes, taxing the organism’s repair mechanisms and possibly causing illness or even death (**Figure 4.30**).

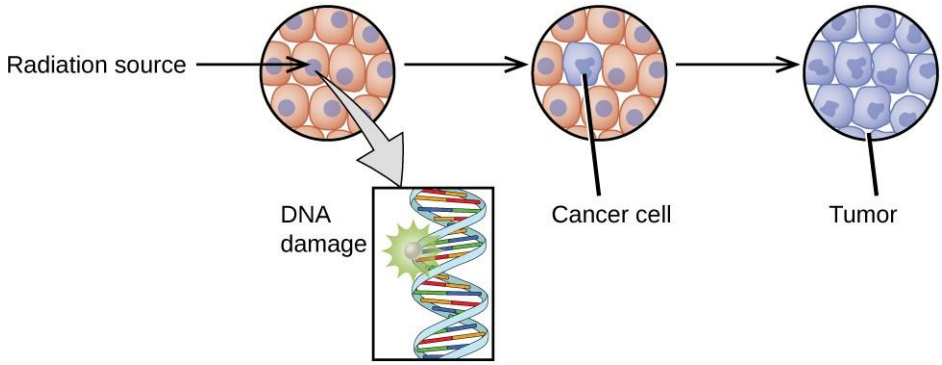


Figure 4.30 Radiation can harm biological systems by damaging the DNA of cells. If this damage is not properly repaired, the cells may divide in an uncontrolled manner and cause cancer.

Ionizing and Nonionizing Radiation

There is a large difference in the magnitude of the biological effects of **nonionizing radiation** (for example, light and microwaves) and **ionizing radiation**, emissions energetic enough to knock electrons out of molecules (for example,

α and β particles, γ rays, X-rays, and high-energy ultraviolet radiation).

Energy absorbed from nonionizing radiation speeds up the movement of atoms and molecules, which is equivalent to heating the sample. Although biological systems are sensitive to heat (as we might know from touching a hot stove or spending a day at the beach in the sun), a large amount of nonionizing radiation is necessary before dangerous levels are reached. Ionizing radiation, however, may cause much more severe damage by breaking bonds or removing electrons in biological molecules, disrupting their structure and function. The damage can also be done indirectly, by first ionizing H_2O (the most abundant molecule in living organisms), which forms a H_2O^+ ion that reacts with water, forming a hydronium ion and a hydroxyl radical:

$$H_2O + \text{radiation} \xrightarrow{e^-} H_2O^+ + H_2O \longrightarrow H_3O^+ + OH^\bullet$$

Because the hydroxyl radical has an unpaired electron, it is highly reactive. (This is true of any substance with unpaired electrons, known as a **free radical**.) This hydroxyl radical can react with all kinds of biological molecules (DNA, proteins, enzymes, and so on), causing damage to the molecules and disrupting physiological processes. Examples of direct and indirect damage are shown in **Figure 4.32**.

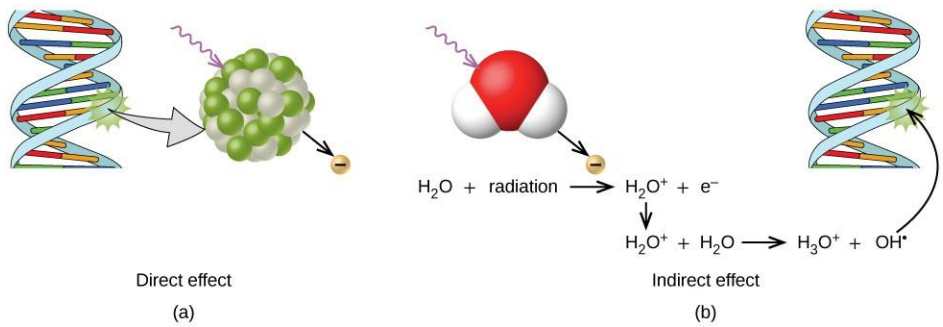


Figure 4.32 Ionizing radiation can (a) directly damage a biomolecule by ionizing it or breaking its bonds, or (b) create an H_2O^+ ion, which reacts with H_2O to form a hydroxyl radical, which in turn reacts with the biomolecule, causing damage indirectly.

Self-assessment 4.6

What subatomic particle is lost from an atom that has been subjected to ionizing radiation?

Answer: Ionizing radiation removes a valence electron from an atom.

Biological Effects of Exposure to Radiation

Radiation can harm either the whole body (somatic damage) or eggs and sperm (genetic damage). Its effects are more pronounced in cells that reproduce rapidly, such as the stomach lining, hair follicles, bone marrow, and embryos. This is why patients undergoing radiation therapy often feel nauseous or sick to their stomach, lose hair, have bone aches,

and so on, and why particular care must be taken when undergoing radiation therapy during pregnancy.

Different types of radiation have differing abilities to pass through material (**Figure 4.33**). A very thin barrier, such as a sheet or two of paper, or the top layer of skin cells, usually stops alpha particles. Because of this, alpha particle sources are usually not dangerous if outside the body, but are quite hazardous if ingested or inhaled (see the Chemistry in Everyday Life feature on Radon Exposure). Beta particles will pass through a hand, or a thin layer of material like paper or wood, but are stopped by a thin layer of metal. Gamma radiation is very penetrating and can pass through a thick layer of most materials. Some high-energy gamma radiation is able to pass through a few feet of concrete. Certain dense, high atomic number elements (such as lead) can effectively attenuate gamma radiation with thinner material and are used for shielding. The ability of various kinds of emissions to cause ionization varies greatly, and some particles have almost no tendency to produce ionization. Alpha particles have about twice the ionizing power of fast-moving neutrons, about 10 times that of β particles, and about 20 times that of γ rays and X-rays.

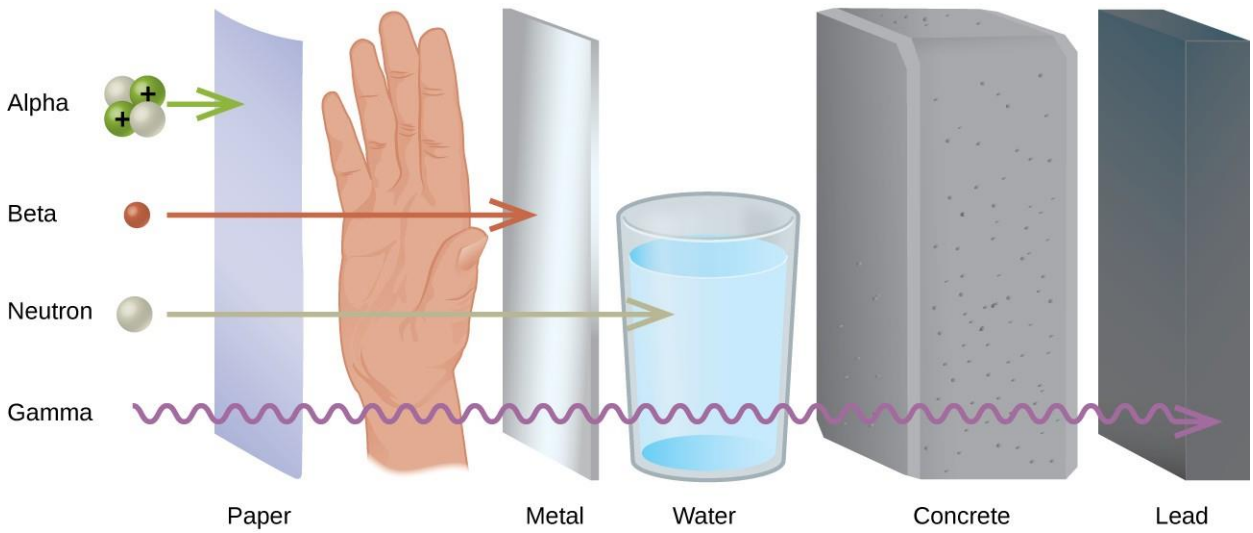


Figure 4.33 The ability of different types of radiation to pass through material is shown. From least to most penetrating, they are alpha < beta < neutron < gamma.

Self-assessment 4.7

If you didn't have protection, which would cause more damage: alpha particles or gamma rays? If you were standing behind a wood door, which would cause more damage: an alpha emitter or a gamma ray emitter?

Answer: Without protection, alpha particles cause more damage because they have more energy. With a wooden door, gamma rays would cause more damage because they can penetrate the wood door.

Chemistry in everyday life

Radon Exposure

For many people, one of the largest sources of exposure to radiation is from radon gas (Rn-222). Radon-222 is an α

emitter with a half–life of 3.82 days. It is one of the products of the radioactive decay series of U-238 (**Figure 4.9**), which is found in trace amounts in soil and rocks. The radon gas that is produced slowly escapes from the ground and gradually seeps into homes and other structures above. Since it is about eight times more dense than air, radon gas accumulates in basements and lower floors, and slowly diffuses throughout buildings (**Figure 4.34**).

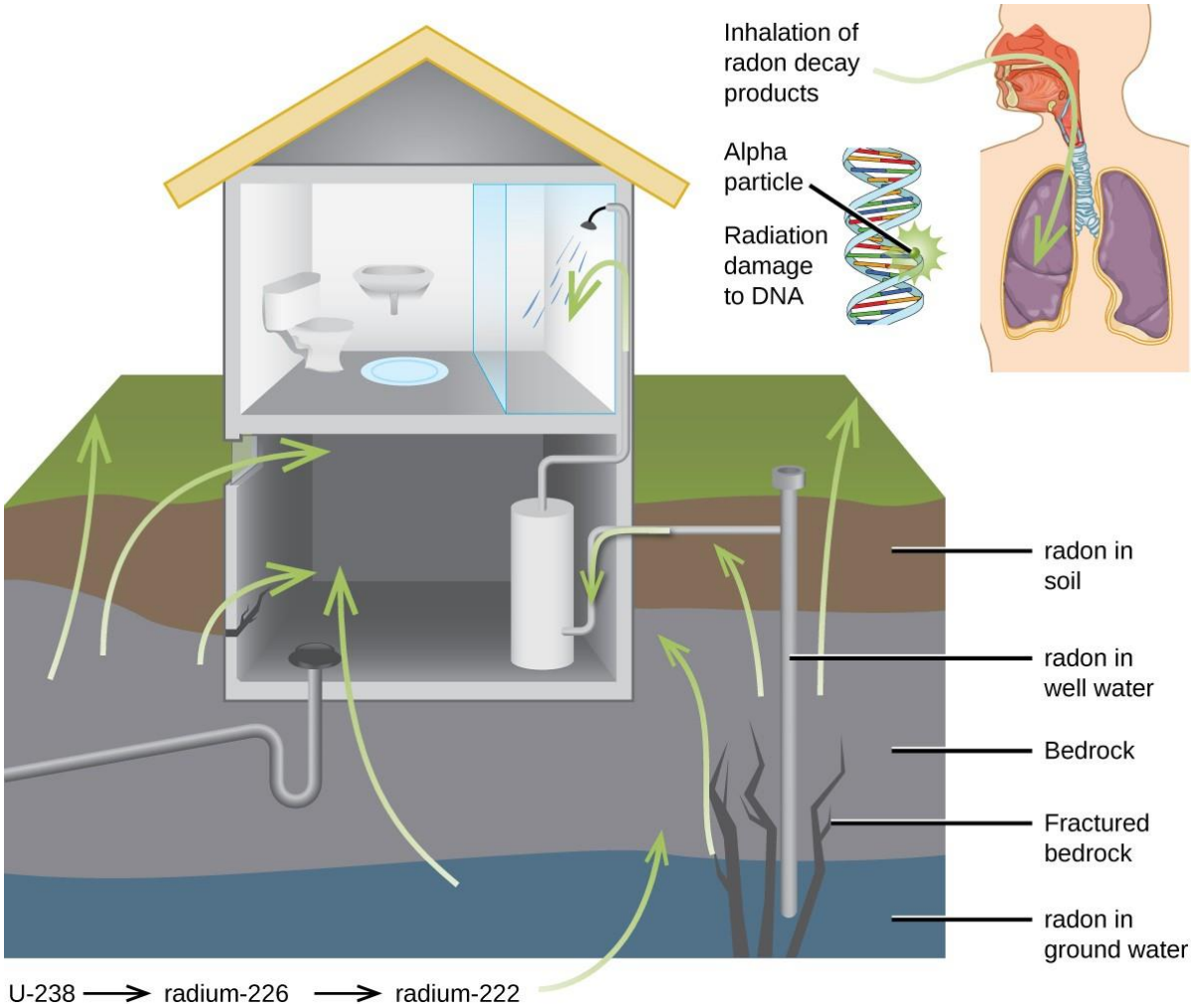
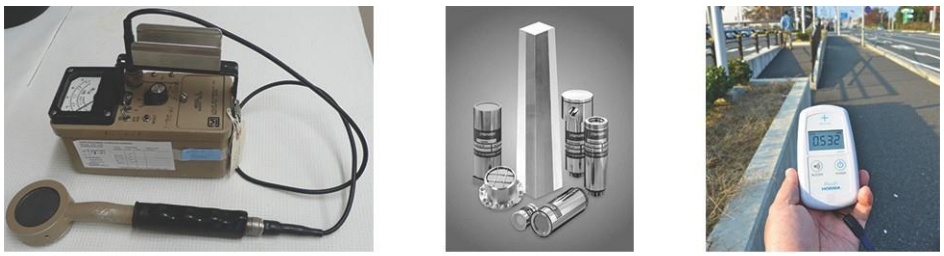


Figure 4.34 Radon-222 seeps into houses and other buildings from rocks that contain uranium-238, a radon emitter. The radon enters through cracks in concrete foundations and basement floors, stone or porous cinderblock foundations, and openings for water and gas pipes.

Radon is found in buildings across the country, with amounts depending on where you live. The average concentration of radon inside houses in the US (1.25 pCi/L) is about three times the levels found in outside air, and about one in six houses have radon levels high enough that remediation efforts to reduce the radon concentration are recommended. Exposure to radon increases one's risk of getting cancer (especially lung cancer), and high radon levels can be as bad for health as smoking a carton of cigarettes a day. Radon is the number one cause of lung cancer in nonsmokers and the second leading cause of lung cancer overall. Radon exposure is believed to cause over 20,000 deaths in the US per year.

Measuring Radiation Exposure

Several different devices are used to detect and measure radiation, including Geiger counters, scintillation counters (scintillators), and radiation dosimeters (**Figure 4.35**). Probably the best-known radiation instrument, the **Geiger counter** (also called the Geiger-Müller counter) detects and measures radiation. Radiation causes the ionization of the gas in a Geiger-Müller tube. The rate of ionization is proportional to the amount of radiation. A **scintillation counter** contains a scintillator—a material that emits light (luminesces) when excited by ionizing radiation—and a sensor that converts the light into an electric signal. **Radiation dosimeters** also measure ionizing radiation and are often used to determine personal radiation exposure. Commonly used types are electronic, film badge, thermoluminescent, and quartz fiber dosimeters.



(a) (b) (c)

Figure 4.35 Devices such as (a) Geiger counters, (b) scintillators, and (c) dosimeters can be used to measure radiation. (credit c: modification of work by "osaMu"/Wikimedia commons)

A variety of units are used to measure various aspects of radiation (**Figure 4.36**). The SI unit for rate of radioactive decay is the **becquerel (Bq)**, with 1 Bq = 1 disintegration per second. The **curie (Ci)** and **millicurie (mCi)** are much larger units and are frequently used in medicine (1 curie = 1 Ci = 3.7×10^{10} disintegrations per second). The SI unit for measuring radiation dose is the **gray (Gy)**, with 1 Gy = 1 J of energy absorbed per kilogram of tissue. In medical applications, the **radiation absorbed dose (rad)** is more often used (1 Gy= 100 rad); 1 rad results in the absorption of 0.01 J/kg of tissue). The SI unit measuring tissue damage caused by radiation is the **sievert (Sv)**. This takes into account both the energy and the biological effects of the type of radiation involved in the radiation dose. The **roentgen equivalent for man (rem)** is the unit for radiation damage that is used most frequently in medicine (100 rem = 1 Sv). Note that the tissue damage units (rem or Sv) includes the energy of the radiation dose (rad or Gy) along with a biological factor referred to as the **RBE** (for **relative biological effectiveness**) that is an approximate measure of the relative damage done by the radiation. These are related by:

number of rems = RBE × number of rads

with RBE approximately 10 for α radiation, 2(+) for protons and neutrons, and 1 for β and γ radiation.

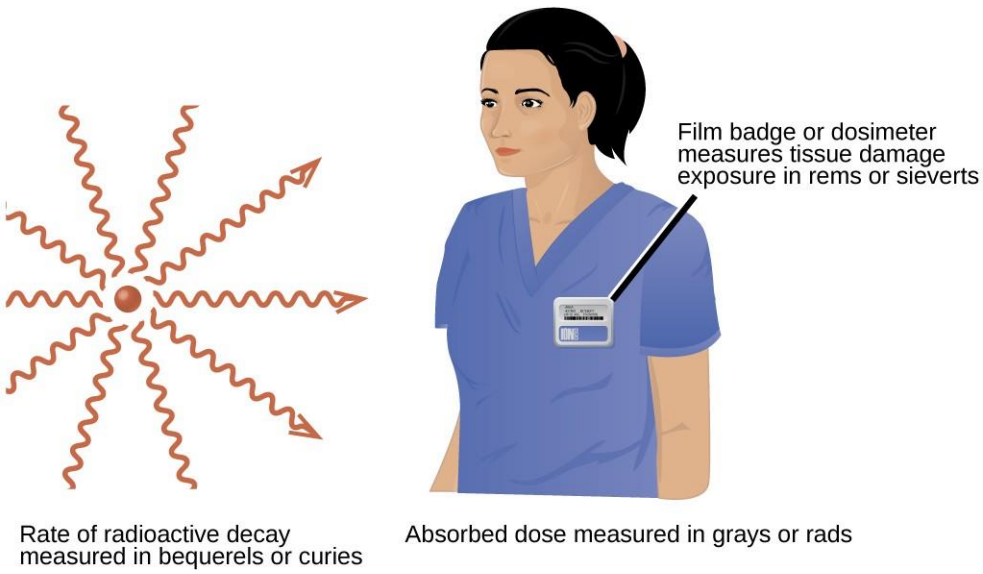


Figure 4.36 Different units are used to measure the rate of emission from a radioactive source, the energy that is absorbed from the source, and the amount of damage the absorbed radiation does **Table 4.4** summarizes the units used for measuring radiation.

Units Used for Measuring Radiation

Measurement Purpose	Unit	Quantity Measured	Description
activity of source	becquerel (Bq)	radioactive decays or emissions	amount of sample that undergoes 1 decay/second
	curie (Ci)		amount of sample that undergoes 3.7×10^{10} decays/second
absorbed dose	gray (Gy)	energy absorbed per kg of tissue	1 Gy = 1 J/kg tissue
	radiation absorbed dose (rad)		1 rad = 0.01 J/kg tissue
biologically effective dose	sievert (Sv)	tissue damage	Sv = RBE × Gy
	roentgen equivalent for man (rem)		Rem = RBE × rad

Table 4.4 Units Used for Measuring Radiation

Example 4.8

Amount of Radiation: Two sample of a radioisotope were received at a laboratory. The activity of one sample was 8 kBq and the other 15 mCi. Which sample produces the higher amount of radiation?

Solution:

In order to answer the question we need to have the activity in the same units.

Since 1 Ci = 3.7 x 10^{10} $\frac{\text{decay}}{\text{s}}$ and 1 Bq = 1 $\frac{\text{decay}}{\text{s}}$ we can convert the two units

The activity of 15 mCi in kBq is:

$$15 \text{ mCi} \times \frac{1 \text{ Ci}}{1000\text{mCi}} \times \frac{3.7\text{x}10^{10}\text{decay/s}}{1 \text{ Ci}} \times \frac{1 \text{ Bq}}{1 \text{ decay/s}} \times \frac{1\text{kBq}}{1000\text{Bq}} = 550{,}000 \text{ kBq}$$

Therefor 15 mCi is larger than 8 kBq

Check Your Learning

Two technicians were exposed to radiation. If one was exposed to 8 mGy and the other 5 rad, which technician received more radiation?

Answer: the technician exposed to 5 rad received more radiation

Self-assessment 4.7

The radiation in rads absorbed by tissue from an α emitter was the same as that absorbed from a β-emitter. The radiation absorbed from the b emitter was determined to be 15.2 mrem. What was the absorbed dose in rem form the α-emitter?

Answer: $rems = rads\ x\ RBE$; RBE of α-absorption = 10 and β-absorption = 1

$15.2\ mrems\ (\alpha\ radiation) = mrads\ x\ 10$

$mrads\ (\alpha\ radiation) = 1.52 = mrads\ (\beta\ radiation)$

$mrems\ (\beta\ radiation) = 1.52\ x\ 1$

$= 1.52$

The effects of radiation depend on the type, energy, and location of the radiation source, and the length of exposure. As shown in **Figure 4.37**, the average person is exposed to background radiation, including cosmic rays from the sun and radon from uranium in the ground (see the Chemistry in Everyday Life feature on Radon Exposure); radiation from medical exposure, including CAT scans, radioisotope tests, X-rays, and so on; and small amounts of radiation from other human activities, such as airplane flights (which are bombarded by increased numbers of cosmic rays in the upper atmosphere), radioactivity from consumer products, and a variety of radionuclides that enter our bodies when we breathe (for example, carbon-14) or through the food chain (for example, potassium-40, strontium-90, and iodine-131).

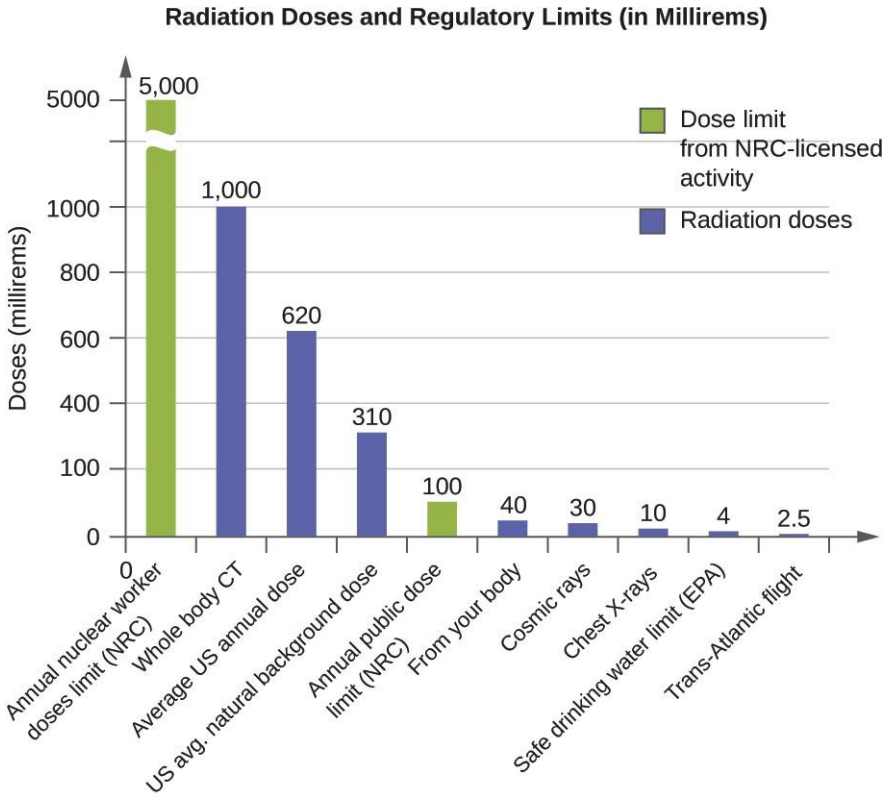


Figure 4.37 The total annual radiation exposure for a person in the US is about 620 mrem. The various sources and their relative amounts are shown in this bar graph. (source: U.S. Nuclear Regulatory Commission)

A short-term, sudden dose of a large amount of radiation can cause a wide range of health effects, from changes in blood chemistry to death. Short-term exposure to tens of rems of radiation will likely cause very noticeable symptoms or illness; a dose of about 500 rems is estimated to have a 50% probability of causing the death of the victim within 30 days of exposure. Exposure to radioactive emissions has a cumulative effect on the body during a person's lifetime, which is another reason why it is important to avoid any unnecessary exposure to radiation. Health effects of short-term exposure to radiation are shown in **Table 4.5**.

Health Effects of Radiation [2]

Exposure (rem)	Health Effect	Time to Onset (without treatment)
5–10	changes in blood chemistry	—
50	nausea	hours
55	fatigue	—
70	vomiting	—
75	hair loss	2–3 weeks

90	diarrhea	—
100	hemorrhage	—
400	possible death	within 2 months
1000	destruction of intestinal lining	—
	internal bleeding	—
	death	1–2 weeks
2000	damage to central nervous system	—
	loss of consciousness;	minutes
	death	hours to days

Table 4.5 Health effects of radiation

It is impossible to avoid some exposure to ionizing radiation. We are constantly exposed to background radiation from a variety of natural sources, including cosmic radiation, rocks, medical procedures, consumer products, and even our own atoms. We can minimize our exposure by blocking or shielding the radiation, moving farther from the source, and limiting the time of exposure.

Self-assessment 4.8

What symptoms can you expect from exposure to 75 rem of radiation?

Answer: hair loss, nausea, fatigue and vomiting

4.6 Nuclear Fission and Fusion

By the end of this section, you will be able to:

4.6.1 Explain nuclear fission and fusion processes

After the discovery of radioactivity, the field of nuclear chemistry was created and developed rapidly during the early twentieth century. A slew of new discoveries in the 1930s and 1940s, along with World War II, combined to usher in the Nuclear Age in the mid-twentieth century. Scientists learned how to create new substances, and certain isotopes of certain elements were found to possess the capacity to produce unprecedented amounts of energy, with the potential to cause tremendous damage during war, as well as produce enormous amounts of power for society's needs during peace.

Nuclear Fission

In 1939 three German scientists bombarded uranium-235 with neutrons and discovered that the U-235 nucleus splits into two smaller nuclei and produces a great amount of energy. This was the discovery of nuclear **fission**, the breaking of a large nucleus into smaller pieces with great amounts of energy. The breaking is rather random with the formation of a large number of different products. Fission usually does not occur naturally, but is induced by bombardment with neutrons. Fission has been observed in many other isotopes. A typical nuclear fission reaction is shown in **Figure 4.14**.

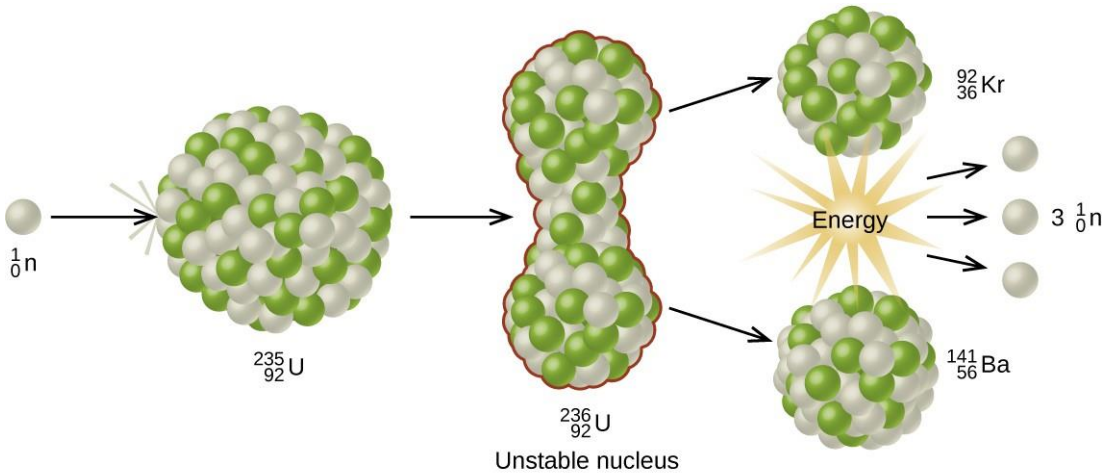


Figure 4.14 When a slow neutron hits a fissionable U-235 nucleus, it is absorbed and forms an unstable U-236 nucleus. The U-236 nucleus then rapidly breaks apart into two smaller nuclei (in this case, Ba-141 and Kr-92) along with several neutrons (usually two or three), and releases a very large amount of energy.

Nuclear fission reactions produce incredibly large amounts of energy compared to chemical reactions. The fission of 1 kilogram of uranium-235, for example, produces about 2.5 million times as much energy as is produced by burning 1 kilogram of coal.

Link to Learning

View this **link (http://openstaxcollege.org/l/16fission)** to see a simulation of

When undergoing fission U-235 produces two “medium-sized” nuclei, and two or three neutrons. These neutrons may then cause the fission of other uranium-235 atoms, which in turn provide more neutrons that can cause fission of even

more nuclei, and so on. If this occurs, we have a nuclear **chain reaction** (see **Figure 4.16**). On the other hand, if too many neutrons escape the bulk material without interacting with a nucleus, then no chain reaction will occur. Nuclear fission becomes self-sustaining when the number of neutrons produced by fission equals or exceeds the number of neutrons absorbed by splitting nuclei plus the number that escape into the surroundings.

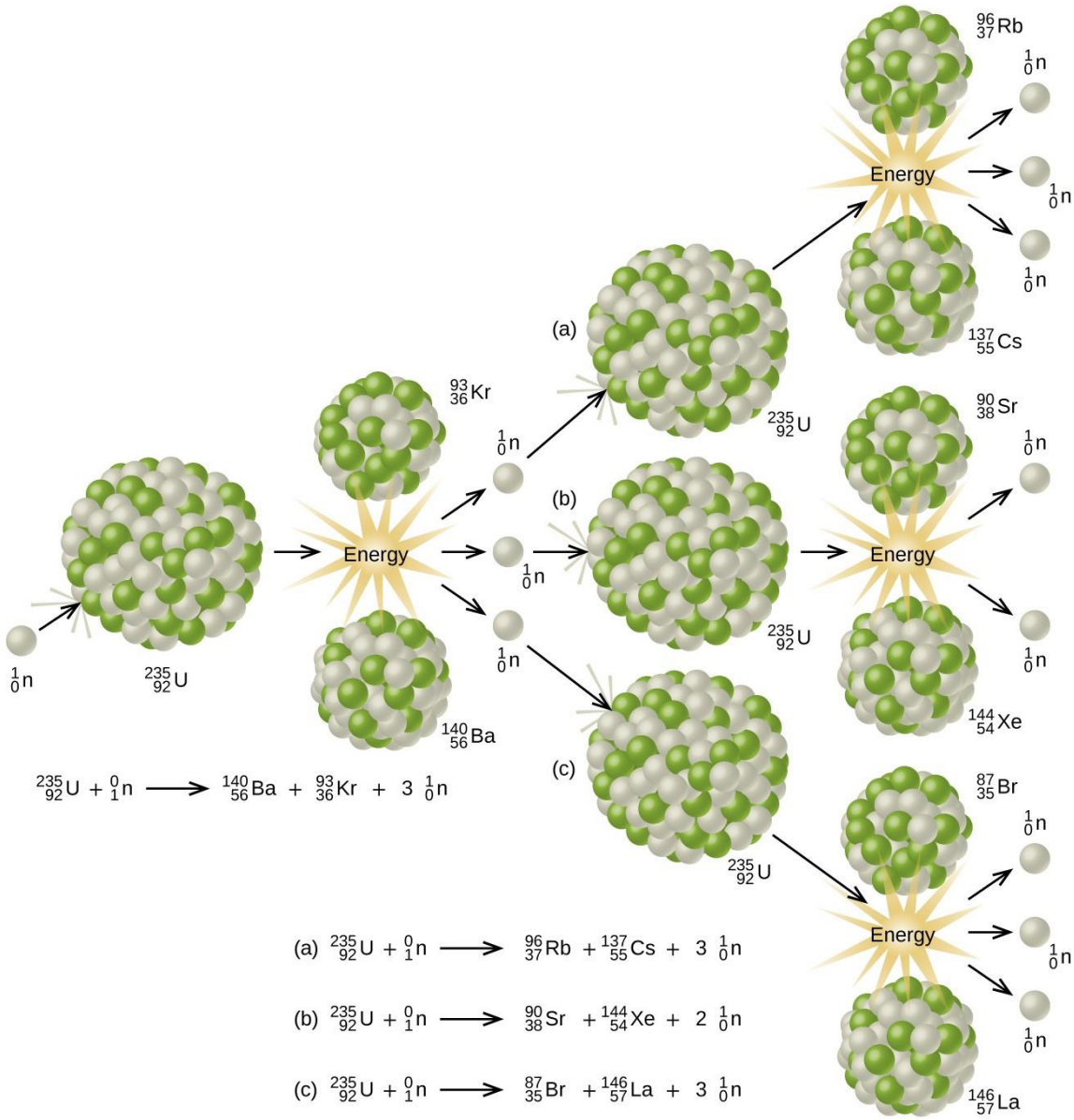
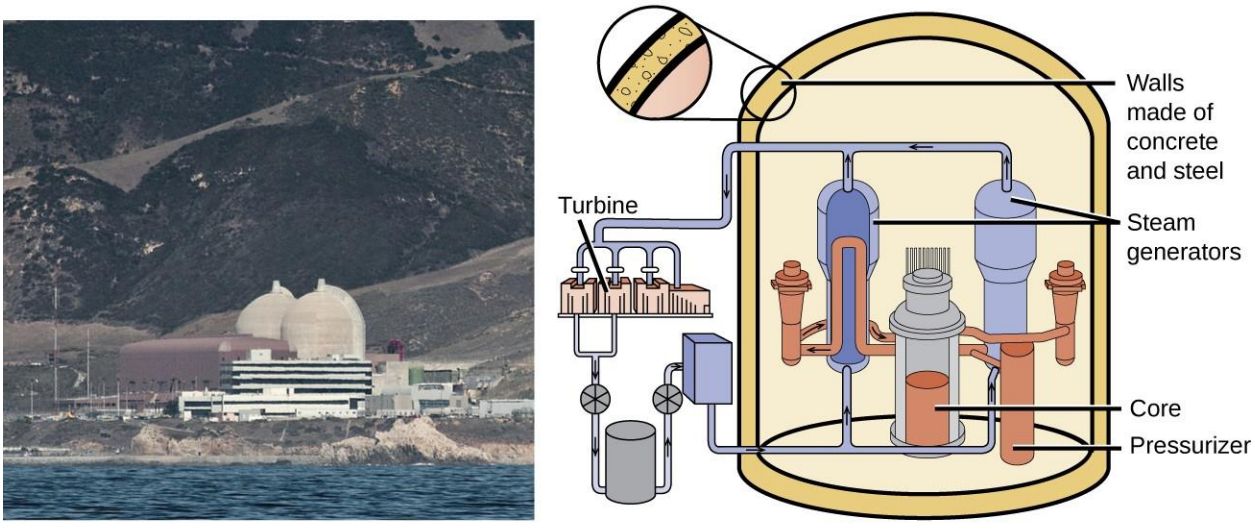


Figure 4.16 The fission of a large nucleus, such as U-235, produces two or three neutrons, each of which is capable of causing fission of another nucleus by the reactions shown. If this process continues, a nuclear chain reaction occurs.

Fission Reactors

Chain reactions of fissionable materials can be controlled and sustained without an explosion in a **nuclear reactor** (**Figure 4.19**). Any nuclear reactor that produces power via the fission of uranium or plutonium by bombardment with neutrons must have at least five components: nuclear fuel consisting of fissionable material, a nuclear moderator, reactor coolant, control rods, and a shield and containment system. We will discuss these components in greater detail later in the section. The reactor works by separating the fissionable nuclear material such that a critical mass cannot be formed, controlling both the flux and absorption of neutrons to allow shutting down the fission reactions. In a nuclear reactor used for the production of electricity, the energy released by fission reactions is trapped as thermal energy and used to boil water and produce steam. The steam is used to turn a turbine, which powers a generator for the production of electricity.



(a) (b)

Figure 4.19 (a) The Diablo Canyon Nuclear Power Plant near San Luis Obispo is the only nuclear power plant currently in operation in California. The domes are the containment structures for the nuclear reactors, and the brown building houses the turbine where electricity is generated. Ocean water is used for cooling. (b) The Diablo Canyon uses a pressurized water reactor, one of a few different fission reactor designs in use around the world, to produce electricity. Energy from the nuclear fission reactions in the core heats water in a closed, pressurized system. Heat from this system produces steam that drives a turbine, which in turn produces electricity. (credit a: modification of work by "Mike" Michael L. Baird; credit b: modification of work by the Nuclear Regulatory Commission)

Self-assessment 4.9

Why are nuclear fission reactions characterized as chain reactions?

Answer: Neutron-induced fission reactions of heavy elements have as their products two or more neutrons of high energy. These neutrons can each cause a fission reaction releasing more neutrons. This multiplies the effect of the initial neutron leading to a chain reaction.

Nuclear Fusion

The process of converting very light nuclei into heavier nuclei is also accompanied by the conversion of mass into large amounts of energy, a process called **fusion**. The principal source of energy in the sun is a net fusion reaction in which four hydrogen nuclei fuse and produce one helium nucleus and two positrons. This is a net reaction of a more complicated series of events:

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e$$

Useful fusion reactions require very high temperatures for their initiation—about 15,000,000 K or more. At these temperatures, all molecules dissociate into atoms, and the atoms ionize, forming plasma. These conditions occur in an extremely large number of locations throughout the universe—stars are powered by fusion. Humans have already figured out how to create temperatures high enough to achieve fusion on a large scale in thermonuclear weapons. A thermonuclear weapon such as a hydrogen bomb contains a nuclear fission bomb that, when exploded, gives off enough energy to produce the extremely high temperatures necessary for fusion to occur.

Self-assessment 4.10

Does nuclear fusion occur naturally?

Answer: Yes, the reactions occur in stars like our sun.

Key Terms

alpha (α) decay loss of an alpha particle during radioactive decay,

alpha particle $(\boldsymbol{\alpha\ or\ {}^{4}_{2}He\ or\ {}^{4}_{2}\alpha})$ high-energy helium nucleus; a helium atom that has lost two electrons and contains two protons and two neutron

antimatter particles with the same mass but opposite properties (such as charge) of ordinary particles

becquerel (Bq) SI unit for rate of radioactive decay; 1 Bq = 1 disintegration/s

beta (β) decay breakdown of a neutron into a proton, which remains in the nucleus, and an electron, which is emitted as a beta particle

beta particle $(\boldsymbol{\beta\ or\ {}^{0}_{-1}e\ \ or\ {}^{0}_{-1}\beta})$ high-energy electron

binding energy per nucleon total binding energy for the nucleus divided by the number of nucleons in the nucleus

chain reaction repeated fission caused when the neutrons released in fission bombard other atoms

chemotherapy similar to internal radiation therapy, but chemical rather than radioactive substances are introduced into the body to kill cancer cells

containment system (also, shield) a three-part structure of materials that protects the exterior of a nuclear fission reactor and operating personnel from the high temperatures, pressures, and radiation levels inside the reactor

control rod material inserted into the fuel assembly that absorbs neutrons and can be raised or lowered to adjust the rate of a fission reaction

curie (Ci) larger unit for rate of radioactive decay frequently used in medicine; 1 Ci = 3.7×10^{10} disintegrations/s

daughter nuclide nuclide produced by the radioactive decay of another nuclide; may be stable or may decay further

electron capture combination of a core electron with a proton to yield a neutron within the nucleu

electron volt (eV) measurement unit of nuclear binding energies, with 1 eV equaling the amount energy due to the moving an electron across an electric potential difference of 1 volt

external beam radiation therapy radiation delivered by a machine outside the body

fissile (or fissionable) when a material is capable of sustaining a nuclear fission reaction

fission splitting of a heavier nucleus into two or more lighter nuclei, usually accompanied by the conversion of mass into large amounts of energy

fusion combination of very light nuclei into heavier nuclei, accompanied by the conversion of mass into large amounts of energy

fusion reactor nuclear reactor in which fusion reactions of light nuclei are controlled

gamma (γ) emission decay of an excited-state nuclide accompanied by emission of a gamma ray

Gamma ray ($\boldsymbol{\gamma}$ ***or*** $\boldsymbol{^{0}_{0}\gamma}$) Short wavelength, high- energy electromagnetic radiation that exhibits wave-particle duality

Geiger counter instrument that detects and measures radiation via the ionization produced in a Geiger-Müller tube

gray (Gy) SI unit for measuring radiation dose; 1 Gy = 1 J absorbed/kg tissu

half-life ($t_{1/2}$) time required for half of the atoms in a radioactive sample to decay

internal radiation therapy kill cancer cells (also, brachytherapy) radiation from a radioactive substance introduced into the body to

ionizing radiation radiation that can cause a molecule to lose an electron and form an ion

magic number nuclei with specific numbers of nucleons that are within the band of stability

mass defect difference between the mass of an atom and the summed mass of its constituent subatomic particles (or the mass "lost" when nucleons are brought together to form a nucleus)

mass-energy equivalence equation Albert Einstein's relationship showing that mass and energy are equivalent

millicurie (mCi) larger unit for rate of radioactive decay frequently used in medicine; 1 Ci = 3.7×10^{10} disintegrations/s

nonionizing radiation radiation that speeds up the movement of atoms and molecules; it is equivalent to heating a sample, but is not energetic enough to cause the ionization of molecules

nuclear binding energy energy lost when an atom's nucleons are bound together (or the energy needed to break a nucleus into its constituent protons and neutrons)

nuclear chemistry study of the structure of atomic nuclei and processes that change nuclear structure

nuclear fuel fissionable isotope present in sufficient quantities to provide a self-sustaining chain reaction in a nuclear reactor

nuclear moderator substance that slows neutrons to a speed low enough to cause fission

nuclear reaction change to a nucleus resulting in changes in the atomic number, mass number, or energy state

nuclear reactor environment that produces energy via nuclear fission in which the chain reaction is controlled and sustained without explosion

nuclear transmutation conversion of one nuclide into another nuclide

nucleon collective term for protons and neutrons in a nucleus

nuclide nucleus of a particular isotope

parent nuclide unstable nuclide that changes spontaneously into another (daughter) nuclide

particle accelerator device that uses electric and magnetic fields to increase the kinetic energy of nuclei used in transmutation reactions

positron $(_{+1}^{0}\boldsymbol{\beta}\ \ or\ _{+1}^{0}\boldsymbol{e})$ antiparticle to the electron; it has identical properties to an electron, except for having the opposite (positive) charge

positron emission (also, β^+ decay) conversion of a proton into a neutron, which remains in the nucleus, and a positron, which is emitted

radiation absorbed dose (rad) SI unit for measuring radiation dose, frequently used in medical applications; 1 rad = 0.01 Gy

radiation dosimeter device that measures ionizing radiation and is used to determine personal radiation exposure

radiation therapy use of high-energy radiation to damage the DNA of cancer cells, which kills them or keeps them from dividing

radioactive decay spontaneous decay of an unstable nuclide into another nuclide

radioactive decay series chains of successive disintegrations (radioactive decays) that ultimately lead to a stable end-product

radioactive tracer (also, radioactive label) radioisotope used to track or follow a substance by monitoring its radioactive emissions

radioactivity phenomenon exhibited by an unstable nucleon that spontaneously undergoes change into a nucleon that is more stable; an unstable nucleon is said to be radioactive

radiocarbon dating highly accurate means of dating objects 30,000–50,000 years old that were derived from once-living matter; achieved by calculating the ratio of $^{14}_{6}C:\ ^{12}_{6}C$ in the object vs. the ratio of $^{14}_{6}C:\ ^{12}_{6}C$ in the present-day atmosphere

radioisotope isotope that is unstable and undergoes conversion into a different, more stable isotope

radiometric dating use of radioisotopes and their properties to date the formation of objects such as archeological artifacts, formerly living organisms, or geological formations

reactor coolant assembly used to carry the heat produced by fission in a reactor to an external boiler and turbine where it is transformed into electricity

relative biological effectiveness (RBE) measure of the relative damage done by radiation

roentgen equivalent man (rem) unit for radiation damage, frequently used in medicine; 100 rem = 1 Sv

scintillation counter instrument that uses a scintillator—a material that emits light when excited by ionizing radiation—to detect and measure radiation

sievert (Sv) SI unit measuring tissue damage caused by radiation; takes into account energy and biological effects of radiation

strong nuclear force force of attraction between nucleons that holds a nucleus together

subcritical mass amount of fissionable material that cannot sustain a chain reaction; less than a critical mass

supercritical mass amount of material in which there is an increasing rate of fission

transmutation reaction bombardment of one type of nuclei with other nuclei or neutrons

transuranium element element with an atomic number greater than 92; these elements do not occur in nature

Key Equations

- $A = \frac{A_{t=0}}{2^n}$
- rem = RBE × rad
- Sv = RBE × Gy

Summary

4.1 Nuclear Structure and Stability

An atomic nucleus consists of protons and neutrons, collectively called nucleons. Although protons repel each other, the nucleus is held tightly together by a short-range, but very strong, force called the strong nuclear force. Of the many nuclides that exist, only a small number are stable.

4.2 Nuclear Equations

Nuclei can undergo reactions that change their number of protons, number of neutrons, or energy state. Many different particles can be involved in nuclear reactions. The most common are protons, neutrons, positrons (which are positively charged electrons), alpha (α) particles (which are high-energy helium nuclei), beta (β) particles (which are high-energy electrons), and gamma (γ) rays (which compose high-energy electromagnetic radiation). As with chemical reactions, nuclear reactions are always balanced. When a nuclear reaction occurs, the total mass (number) and the total charge remain unchanged.

4.3Radioactive Decay

Nuclei that have unstable n:p ratios undergo spontaneous radioactive decay. The most common types of radioactivity are α decay, β decay, γ emission, positron emission, and electron capture. Nuclear reactions

also often involve γ rays, and some nuclei decay by electron capture. Each of these modes of decay leads to the formation of a new nucleus with a more stable n:p ratio. Some substances undergo radioactive decay series, proceeding through multiple decays before ending in a stable isotope. All nuclear decay processes follow first-order kinetics, and each radioisotope has its own characteristic half-life, the time that is required for half of its atoms to decay. Because of the large differences in stability among nuclides, there is a very wide range of half-lives of radioactive substances. Many of these substances have found useful applications in medical diagnosis and treatment, determining the age of archaeological and geological objects, and more.

4.4 Transmutation and Nuclear Energy

It is possible to produce new atoms by bombarding other atoms with nuclei or high-speed particles. The products of these transmutation reactions can be stable or radioactive. A number of artificial elements, including technetium, astatine, and the transuranium elements, have been produced in this way.Nuclear power as well as nuclear weapon detonations can be generated through fission (reactions in which a heavy nucleus is split into two or more lighter nuclei and several neutrons). Because the neutrons may induce additional fission reactions when they combine with other heavy nuclei, a chain reaction can result. Useful power is obtained if the fission process is carried out in a nuclear reactor. The conversion of light nuclei into heavier nuclei (fusion) also produces energy. At present, this energy has not been contained adequately and is too expensive to be feasible for commercial energy production.

4.5 Uses of Radioisotopes

Compounds known as radioactive tracers can be used to follow reactions, track the distribution of a substance, diagnose and treat medical conditions, and much more. Other radioactive substances are helpful for controlling pests, visualizing structures, providing fire warnings, and for many other applications. Hundreds of millions of nuclear

medicine tests and procedures, using a wide variety of radioisotopes with relatively short half-lives, are performed every year in the US. Most of these radioisotopes have relatively short half-lives; some are short enough that the radioisotope must be made on-site at medical facilities. Radiation therapy uses high-energy radiation to kill cancer cells by damaging their DNA. The radiation used for this treatment may be delivered externally or internally.

4.6 Biological Effects of Radiation

We are constantly exposed to radiation from a variety of naturally occurring and human-produced sources. This radiation can affect living organisms. Ionizing radiation is the most harmful because it can ionize molecules or break chemical bonds, which damages the molecule and causes malfunctions in cell processes. It can also create reactive hydroxyl radicals that damage biological molecules and disrupt physiological processes. Radiation can cause somatic or genetic damage, and is most harmful to rapidly reproducing cells.

Types of radiation differ in their ability to penetrate material and damage tissue, with alpha particles the least penetrating but potentially most damaging and gamma rays the most penetrating.

Various devices, including Geiger counters, scintillators, and dosimeters, are used to detect and measure radiation, and monitor radiation exposure. We use several units to measure radiation: becquerels or curies for rates of radioactive decay; gray or rads for energy absorbed; and rems or sieverts for biological effects of radiation. Exposure to radiation can cause a wide range of health effects, from minor to severe, and including death. We can minimize the effects of radiation by shielding with dense materials such as lead, moving away from the source, and limiting time of exposure.

Exercises

4.1 Nuclear Structure and Stability

1. Write the following isotopes in hyphenated form (e.g., "carbon-14")

a. $^{24}_{11}Na$

b. $^{29}_{13}Al$

c. $^{73}_{36}Kr$

d. $^{194}_{77}Ir$

2. Write the following isotopes in nuclide notation (e.g. $^{14}_{6}C$)

(a) oxygen-14

(b) copper-70

(c) tantalum-175

(d) francium-217

3. For the following isotopes that have missing information, fill in the missing information to complete the notation

a. $^{34}_{14}X$

b. $^{36}_{X}P$

c. $^{57}_{X}Mn$

d. $^{121}_{56}X$

4. For each of the isotopes in **Exercise4.1**, determine the numbers of protons, neutrons, and electrons in a neutral atom of the isotope.

5. Write the nuclide notation, including charge if applicable, for atoms with the following characteristics:

(a) 25 protons, 20 neutrons, 24 electrons

(b) 45 protons, 24 neutrons, 43 electrons

(c) 53 protons, 89 neutrons, 54 electrons

(d) 97 protons, 146 neutrons, 97 electrons

4.2 Nuclear Equations

Write a brief description or definition of each of the following:

(a) radioactivity

(b) α particle

(c) β particle

(d) positron

(e) γ ray

(f) nuclide

(g) mass number

(h) atomic number

Which of the various particles (α particles, β particles, and so on) that may be produced in a nuclear reaction are actually nuclei?

Complete each of the following equations by adding the missing species:

(a) ${}^{27}_{13}Al + {}^{4}_{2}He \rightarrow ? + {}^{1}_{0}n$

(b) ${}^{239}_{94}Pu + ? \rightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$

(c) ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow ? + {}^{1}_{1}H$

(d) ${}^{235}_{92}U \rightarrow ? + {}^{135}_{55}Cs + 4\,{}^{1}_{0}n$

Complete each of the following equations:

(a) ${}^{7}_{3}Li + ? \rightarrow 2\,{}^{4}_{2}He$

(b) ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + ?$

(c) ${}^{27}_{13}Al + {}^{4}_{2}He \rightarrow ? + {}^{1}_{0}n$

(d) ${}^{250}_{96}Cm \rightarrow ? + {}^{98}_{38}Sr + 4\,{}^{1}_{0}n$

Write a balanced equation for each of the following nuclear reactions:

(a) the production of ${}^{17}O$ from ${}^{14}N$ by α particle bombardment

(b) the production of ${}^{14}C$ from ${}^{14}N$ by neutron bombardment

(c) the production of ${}^{233}Th$ from ${}^{232}Th$ by neutron bombardment

(d) the production of ${}^{239}U$ from ${}^{238}U$ by H bombardment

4.3 Radioactive Decay

6. What are the types of radiation emitted by the nuclei of radioactive elements?

7. What changes occur to the atomic number and mass of a nucleus during each of the following decay scenarios?

(a) an α particle is emitted

(b) a β particle is emitted

(c) γ radiation is emitted

(d) a positron is emitted

(e) an electron is captured

8. What is the change in the nucleus that results from the following decay scenarios?

(a) emission of a β particle

(b) emission of a β^+ particle

(c) capture of an electron

27. Define the term half-life and illustrate it with an example.

The isotope ^{208}Tl undergoes β decay with a half-life of 3.1 min.

(a) What isotope is produced by the decay?

(b) How long will it take for the radiation level of thallium-208 to drop to one-forth its original level?

28. Technetium-99 is often used for assessing heart, liver, and lung damage because certain technetium compounds

are absorbed by damaged tissues. It has a half-life of 6.0 h. If 120 mg sample was used for a diagnostic test, how many milligrams remain 24 h after the test?

29. Co-60 has a half-life of 5.3 years. If the initial sample of Co-60 has an activity of 1200 Ci, what is the activity after 15.9 years?

30. What is the age of mummified primate skin that contains 8.25% of the original quantity of ^{14}C?

31. The radioisotope fluorine-18 is used for medical imaging. If the half-life of 110 min. Approximately, what percentage of the original sample activity is left after 4 hr.

32. Sodium-24 is used to treat leukemia. A 36-kg patient is prescribed 145 μCi/kg and it is supplied to the hospital in a vial containing 250 μCi/mL. What volume should be given to the patient?

33. Using information from the previous question and knowing the half-life of Na-24 is 15 hours, calculate the total dose in μCi given to the patient. How long will it take for the radioactivity to be approximately 80 μCi?

34. Write a balanced equation for each of the following nuclear reactions:

(a) bismuth-212 decays into polonium-212

(b) beryllium-8 and a positron are produced by the decay of an unstable nucleus

(c) neptunium-239 forms from the reaction of uranium-238 with a neutron and then spontaneously converts into plutonium-239

(d) strontium-90 decays into yttrium-90

35. Write a balanced equation for each of the following nuclear reactions:

(a) mercury-180 decays into platinum-176

(b) zirconium-90 and an electron are produced by the decay of an unstable nucleus

(c) thorium-232 decays and produces an alpha particle and a radium-228 nucleus, which decays into actinium-228 by beta decay

(d) neon-19 decays into fluorine-19

4.4 Transmutation and Nuclear Energy

36. Write the balanced nuclear equation for the production of the following transuranium elements:

(a) berkelium-244, made by the reaction of Am-241 and He-4

(b) fermium-254, made by the reaction of Pu-239 with a large number of neutrons

(c) lawrencium-257, made by the reaction of Cf-250 and B-11

(d) dubnium-260, made by the reaction of Cf-249 and N-15

37. How does nuclear fission differ from nuclear fusion? Why are both of these processes exothermic?

4.5 Uses of Radioisotopes

38. Technetium-99m has a half-life of 6.01 hours. If a patient injected with technetium-99m is safe to leave the hospital once 75% of the dose has decayed, when is the patient allowed to leave?

39. Iodine that enters the body is stored in the thyroid gland from which it is released to control growth and metabolism. The thyroid can be imaged if iodine-131 is injected into the body. In larger doses, I-133 is also used as a means of treating cancer of the thyroid. I-131 has a half-life of 8.70 days and decays by β^- emission.

(a) Write an equation for the decay.

(b) How long will it take for 95.0% of a dose of I-131 to decay?

4.6 Biological Effects of Radiation

40. Which penetrates matter more deeply—alpha particles or beta particles? Suggest ways to protect yourself against both particles.

41. If a hospital were storing radioisotopes, what is the minimum containment needed to protect against:

(a) cobalt-60 (a strong γ emitter used for irradiation)

(b) molybdenum-99 (a beta emitter used to produce technetium-99 for imaging)

42. Based on what is known about Radon-222's primary decay method, why is inhalation so dangerous?