Al-Rasheed University College
Department of Dentistry
1st Stage

MEDICAL CHEMISTRY

lecture 4
Radioactivity

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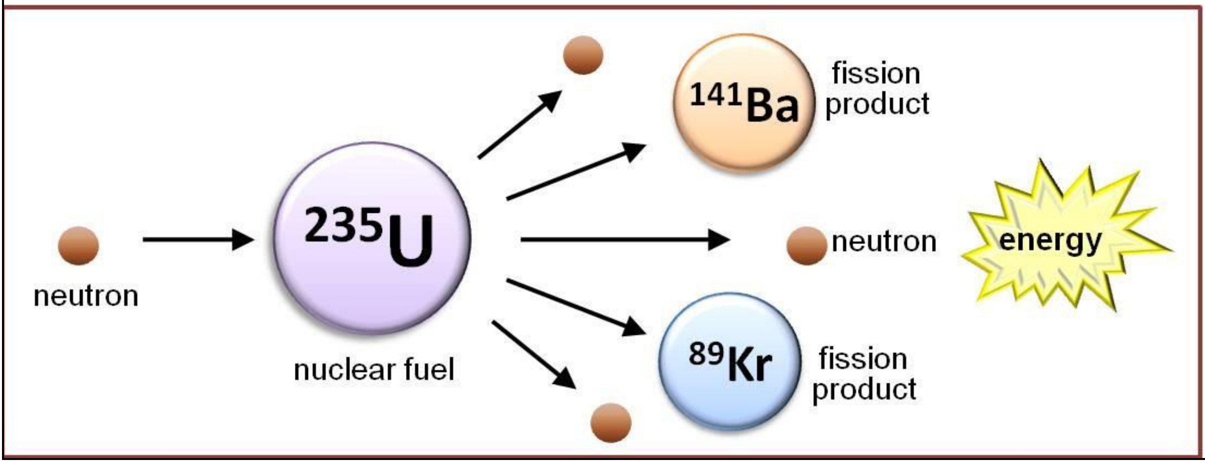


Introduction

Thus far our study of reactions has concentrated on processes that involve the valence electrons of atoms. In these reactions, bonds that join atoms are broken and new bonds between atoms are formed, but the identity of the atoms does not change. In this lecture, we turn our attention to nuclear reactions, processes that involve changes in the nucleus of an atom.

Although most reactions involve valence electrons, a small but significant group of reactions, nuclear reactions, involves the subatomic particles of the nucleus.

Isotopes

The nucleus of an atom is composed of protons and neutrons.

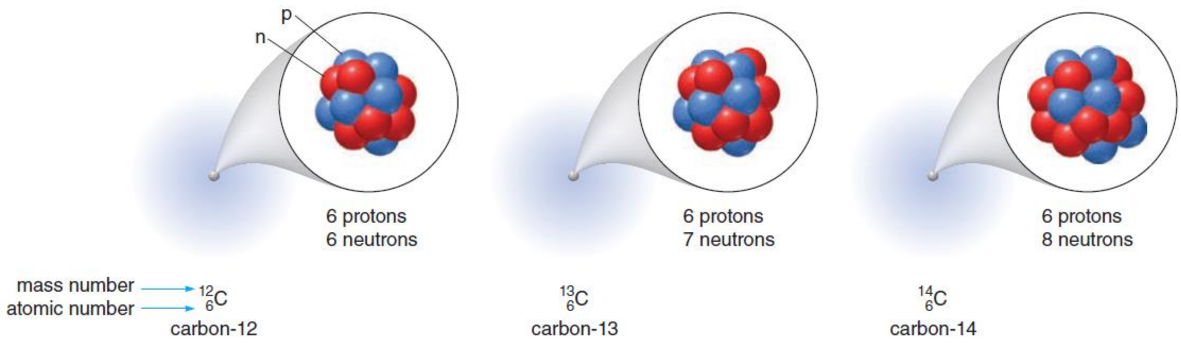
- ***The atomic number (Z)*** = the number of protons in the nucleus.
- ***The mass number (A)*** = the number of protons and neutrons in the nucleus.

Atoms of the same type of element have the same atomic number, but the number of neutrons may vary.

- ***Isotopes*** are atoms of the same element having a different number of neutrons.

As a result, isotopes have the same atomic number (Z) but different mass numbers (A).

Carbon, for example, has three naturally occurring isotopes. Each isotope has six protons in the nucleus (i.e., Z = 6), but the number of neutrons may be six, seven, or eight. Thus, the mass numbers (A) of these isotopes are 12, 13, and 14, respectively. We can refer to these isotopes as carbon-12, carbon-13, and carbon-14. Isotopes are also written with the mass number to the upper left of the element symbol and the atomic number to the lower left.



Many isotopes are stable, but a larger number are not.

☒ A *radioactive isotope,* called a *radioisotope,* is unstable and spontaneously emits energy to form a more stable nucleus.

☒ ***Radioactivity*** is the nuclear radiation emitted by a radioactive isotope

Types of Radiation

Different forms of radiation are emitted when a radioactive nucleus is converted to a more stable nucleus, including **alpha particles, beta particles, positrons,** and **gamma radiation.**

A. An alpha particle is a high-energy particle that contains two protons and two neutrons.

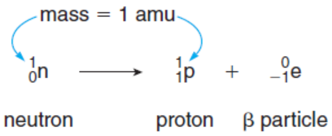
alpha particle: α or $^{4}_{2}He$

An alpha particle, symbolized by the Greek letter alpha (**α**) or the element symbol for helium, has a +2 charge and a mass number of 4.

B. A beta particle is a high-energy electron.

beta particle: β or $^{0}_{-1}e$

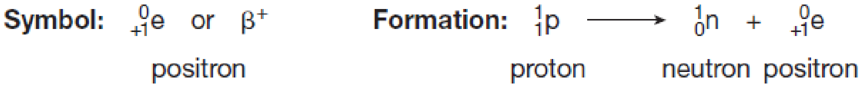
An electron has a –1 charge and a negligible mass compared to a proton. A beta particle, symbolized by the Greek letter beta (**β**), is also drawn with the symbol for an electron, **e**, with a mass number of 0.



C. Positron is called an antiparticle of a **β** particle, since their charges are different but their masses are the same.

Symbol: $^{0}_{+1}e$ or β^{+}

Thus, a positron has a negligible mass like a β particle, but is opposite in charge, +1. A positron, symbolized as β+, is also drawn with the symbol for an electron, e, with a mass number of 0.



D. Gamma rays are high-energy radiation released from a radioactive nucleus.

gamma ray: γ

Gamma rays, symbolized by the Greek letter gamma (**γ**), are a form of energy and thus they have no mass or charge.

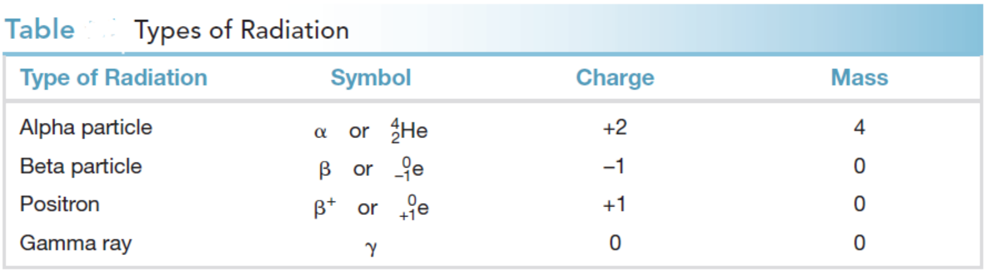


Table Types of Radiation

Type of Radiation	Symbol	Charge	Mass
Alpha particle	α or $^{4}_{2}He$	+2	4
Beta particle	β or $^{0}_{-1}e$	−1	0
Positron	β^{+} or $^{0}_{+1}e$	+1	0
Gamma ray	γ	0	0

The Effects of Radioactivity

- Radioactivity cannot be **seen, smelled, tasted, heard, or felt**, and yet it can have powerful effects Because it is high in energy, ***nuclear radiation penetrates the surface of an object or living organism where it can damage or kill cells***. The cells that are most sensitive to radiation are those that undergo **rapid cell division**, such as those in bone marrow, reproductive organs, skin, and the intestinal tract. Since cancer cells also rapidly divide, they are also particularly sensitive to radiation.

- Alpha (α) particles, β particles, and γ rays differ in the extent to which they can penetrate a surface.

- **Alpha particles** are the **heaviest of the radioactive particles**, and as a result they move the **slowest** and **penetrate the least**.

- **Gamma rays** travel the **fastest** and **readily penetrate body tissue**.

- That **γ** rays kill cells is used to an advantage in the food industry. To decrease the incidence of harmful bacteria in foods, certain fruits and vegetables are irradiated with **γ** rays that kill any bacteria contained in them.

- Individuals who work with radioisotopes that emit α particles wear lab coats and gloves that provide a layer of sufficient protection. Beta particles move much faster since they have negligible mass, and they can penetrate into body tissue. Lab workers and health professionals must wear heavy lab coats and gloves when working with substances that give off β particles. Gamma rays travel the fastest and readily penetrate body tissue. Working with substances that emit γ rays is extremely hazardous, and a thick lead shield is required to halt their penetration.

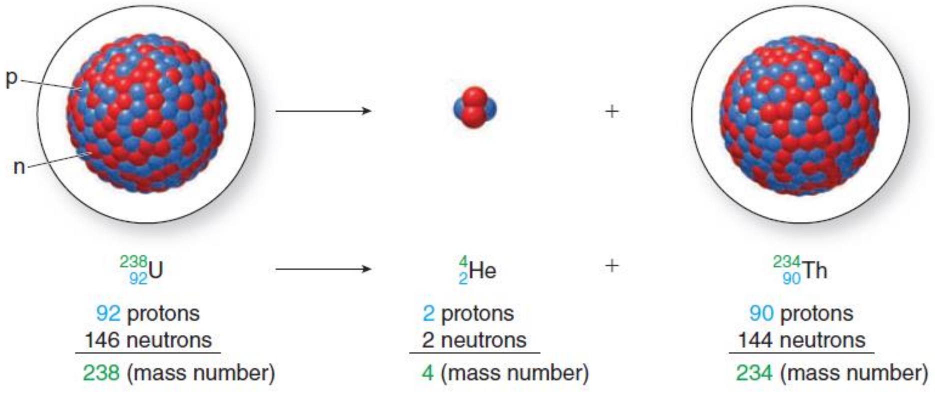
Nuclear Reactions

Radioactive decay is the process by which an unstable radioactive nucleus emits radiation, forming a nucleus of new composition. A nuclear equation can be written for this process, which contains the original nucleus, the new nucleus, and the radiation emitted. Unlike a chemical equation that balances atoms, in a nuclear equation the mass numbers and the atomic numbers of the nuclei must be balanced.

- ✓ The sum of the mass numbers (A) must be equal on both sides of a nuclear equation.
- ✓ The sum of the atomic numbers (Z) must be equal on both sides of a nuclear equation.

A. Alpha Emission

Alpha emission is the decay of a nucleus by emitting an **α** particle. For example, uranium-238 decays to thorium-234 by loss of an α particle.

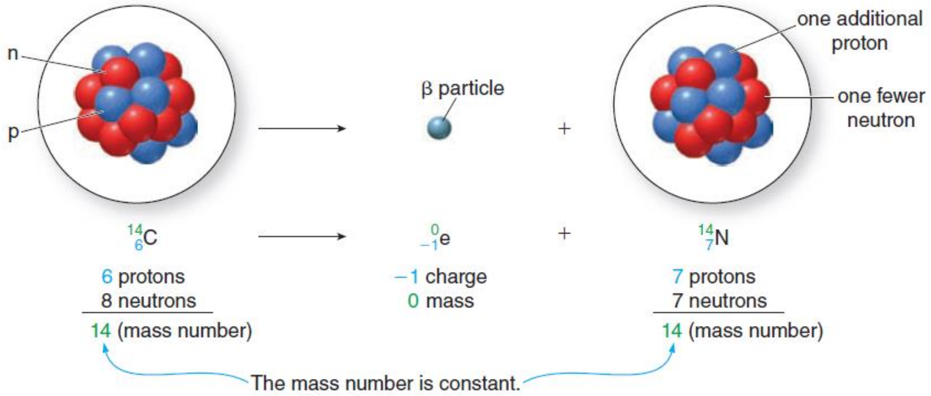


Since an α particle has two protons, **the new nucleus has *two fewer protons* than the original nucleus.** Because it has a *different* number of protons, the new nucleus represents a *different* element. Uranium-238 has 92 protons, so loss of two forms the element thorium with 90 protons. The thorium nucleus has a mass number that is four fewer than the original—234—because it has been formed by loss of an α particle with a mass number of four.

- As a result, the sum of the mass numbers is equal on both sides of the equation—238 = 4 + 234.
- The sum of the atomic numbers is also equal on both sides of the equation—92 = 2 + 90.

B. Beta Emission

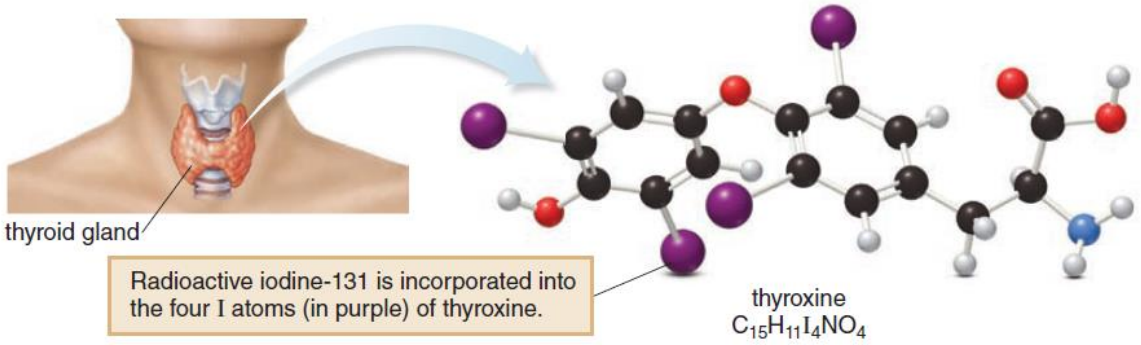
Beta emission is the decay of a nucleus by emitting a **β** particle. For example, carbon-14 decays to nitrogen-14 by loss of a β particle. The decay of carbon-14 is used to date archaeological specimens.



In β emission, one neutron of the original nucleus decays to a β particle and a proton. As a result, the **new nucleus has *one more proton* and *one fewer neutron* than the original nucleus.** In this example, a carbon atom with six protons decays to a nitrogen atom with seven protons. Since the total number of particles in the nucleus does not change, the **mass number is constant.**

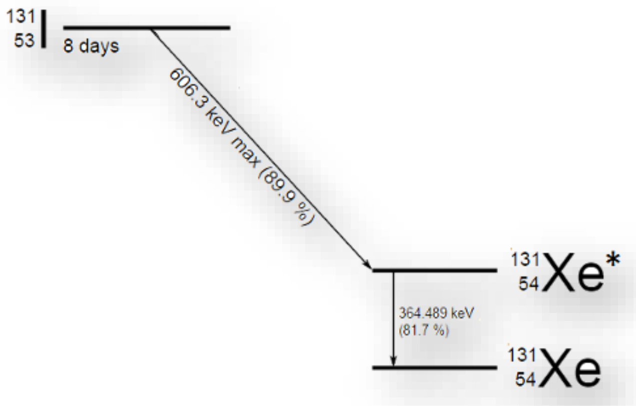
The subscripts that represent the atomic numbers are balanced because the β particle has a charge of –1. Seven protons on the right side plus a –1 charge for the β particle gives a total "charge" of +6, the atomic number of carbons on the left. The mass numbers are also balanced since a β particle has zero mass, and both the original nucleus and the new nucleus contain 14 subatomic particles (protons + neutrons).

☒ Radioactive elements that emit β radiation are widely used in medicine. Iodine-131, a radioactive element that emits β radiation, is used to treat hyperthyroidism, a condition resulting from an overactive thyroid gland (Bellow Figure). Moreover, since β radiation is composed of high-energy electrons that penetrate tissue in a small, localized region, radioactive elements situated in close contact with tumor cells kill them. Although both healthy and diseased cells are destroyed by this internal radiation therapy, rapidly dividing tumor cells are more sensitive to its effects and therefore their growth and replication are affected the most.



Iodine-131 is incorporated into the thyroid hormone thyroxine. Beta radiation emitted by the radioactive isotope destroys nearby thyroid cells, thus decreasing the activity of the thyroid gland and bringing the disease under control.

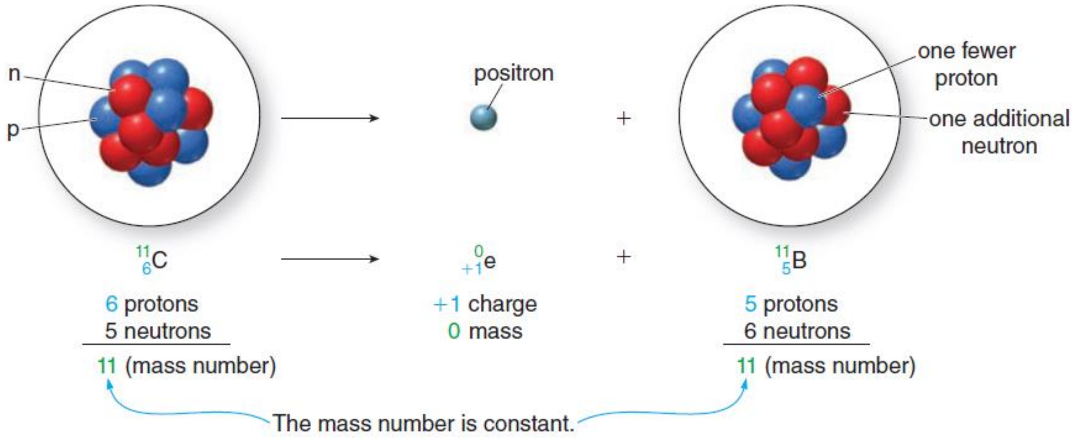
- Iodine-131 is readily absorbed by the follicular cells of the thyroid gland via the sodium/iodine symporter. As the atoms of iodine-131 accumulate in the thyroid, they eventually undergo a two-step radioactive decay process that releases high energy electrons and electromagnetic radiation in the form of gamma rays. These highly energetic electrons can penetrate and damage surrounding tissue within 2 mm from the source of emission. Roughly 90 percent of iodine-131 atoms decay into xenon-131



C. Positron Emission

Positron emission is the decay of a nucleus by emitting a positron (**β**+). For example, carbon-11, an artificial radioactive isotope of carbon, decays to boron-11 by loss of a β+ particle. Positron emitters are used in a relatively new diagnostic technique, positron emission tomography (PET)

In positron emission, one proton of the original nucleus decays to a β+ particle and a neutron. As a result, the new nucleus has one fewer proton and one more neutron than the original nucleus.



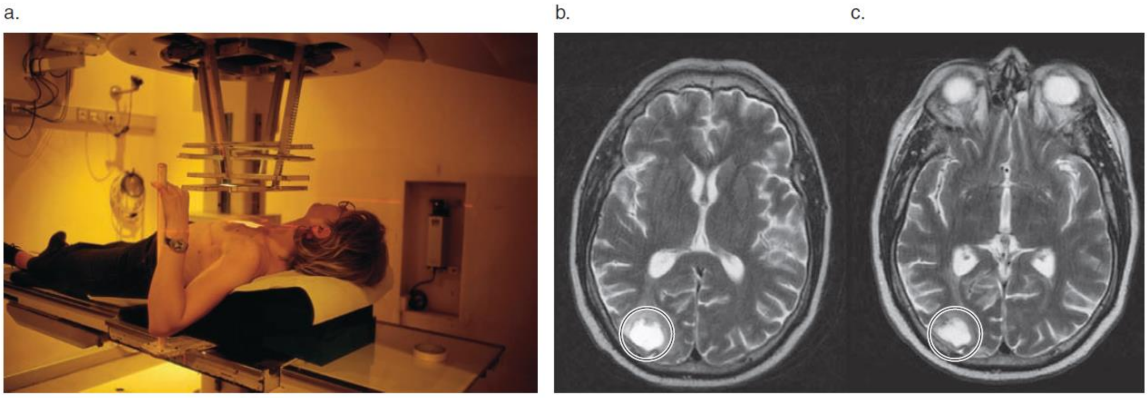
D. Gamma Emission

Gamma emission is the decay of a nucleus by emitting **γ** radiation. Since γ rays are simply a form of energy, their emission causes no change in the atomic number or mass number of a radioactive nucleus. Gamma emission sometimes occurs alone. For example, one form of technetium-99, written as technetium-99m, is an energetic form of the technetium nucleus that decays with emission of γ rays to technetium-99, a more stable but still radioactive element.

$$^{99m}_{43}\mathrm{Tc} \longrightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$$

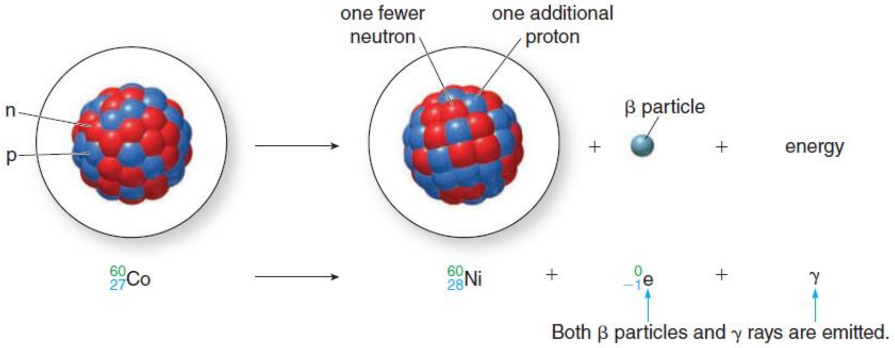
The mass number and atomic number are the same.

Technetium-99m is a widely used radioisotope in medical imaging. Because it emits high-energy **γ** rays but decays in a short period of time, it is used to image the brain, thyroid, lungs, liver, skeleton, and many other organs. It has also been used to detect ulcers in the gastrointestinal system, and combined with other compounds, it is used to map the circulatory system and gauge damage after a heart attack.



a. Gamma radiation from the decay of cobalt-60 is used to treat a variety of tumors, especially those that cannot be surgically removed.
b. A tumor (bright area in circle) before radiation treatment
c. A tumor (bright area in circle) that has decreased in size after six months of radiation treatment

More commonly, γ emission accompanies α or β emission. For example, cobalt-60 decays with both β and γ emission. Because a β particle is formed, decay generates an element with the *same* mass but a *different* number of protons, and thus a new element, nickel-60.

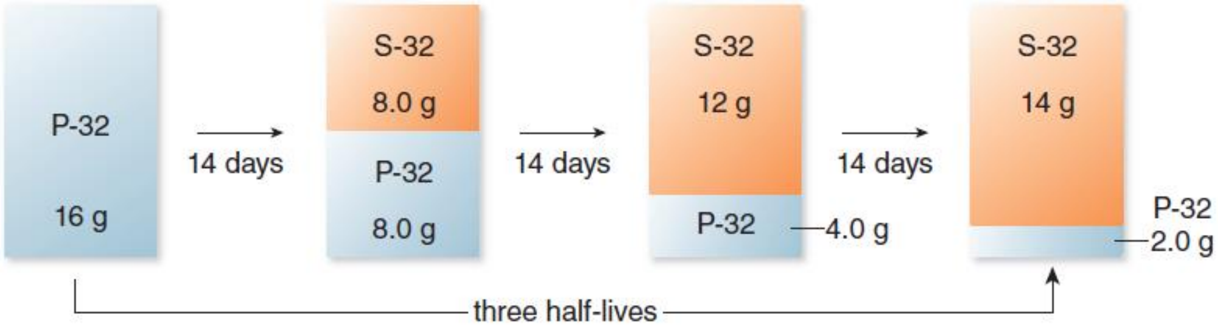


Both β particles and γ rays are emitted.

Cobalt-60 is used in external radiation treatment for cancer. Radiation generated by cobalt-60 decay is focused on a specific site in the body that contains cancerous cells. By directing the radiation on the tumor, damage to surrounding healthy tissues is minimized.

Half-Life

- How fast do radioactive isotopes decay? It depends on the isotope.
- The half-life (t1/2) **of a radioactive isotope is the time it takes for one-half of the sample to decay.**
- Suppose we have a sample that contains 16 g of phosphorus-32, a radioactive isotope that decays to sulfur-32 by β emission. Phosphorus-32 has a half-life of approximately 14 days. Thus, after 14 days, the sample contains only half the amount of P-32—8.0 g. After another 14 days (a total of two half-lives), the 8.0 g of P-32 is again halved to 4.0 g. After another14 days (a total of three half-lives), the 4.0 g of P-32 is halved to 2.0 g, and so on. Every 14 days, half of the P-32 decays.



Many naturally occurring isotopes have long half-lives. Examples include carbon-14 (5,730 years) and uranium-235 (7.0 × 108 years). Radioisotopes that are used for diagnosis and imaging in medicine have short half-lives so they do not linger in the body. Examples include technetium-99m (6.0 hours) and iodine-131 (8.0 days). The half-lives of several elements are given in Table 9.2.

The half-life of a radioactive isotope is a property of a given isotope and is independent of the amount of sample, temperature, and pressure. Thus, if the half-life and amount of a sample are known, it is possible to predict how much of the radioactive isotope will remain after a period of time.

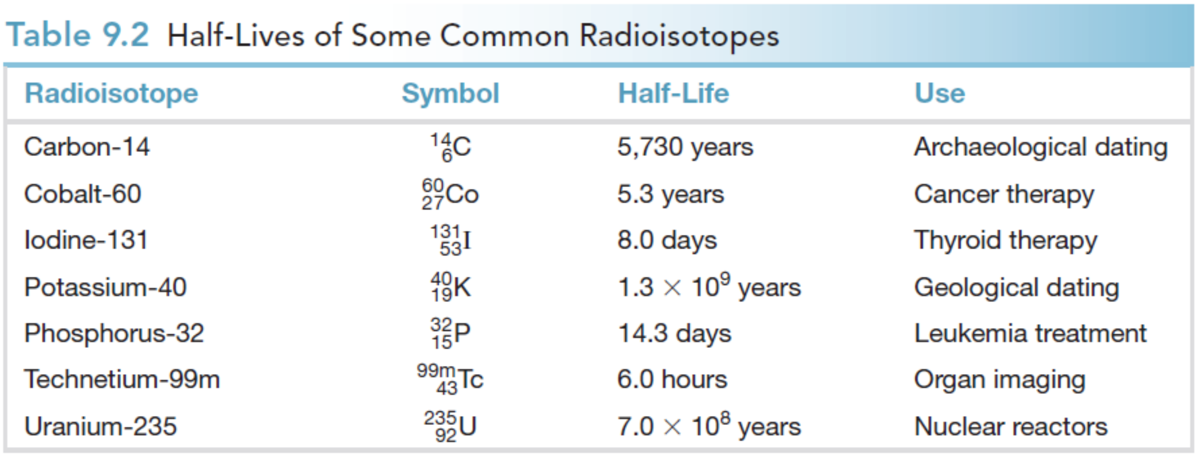


Table 9.2 Half-Lives of Some Common Radioisotopes

Radioisotope	Symbol	Half-Life	Use
Carbon-14	$^{14}_{6}C$	5,730 years	Archaeological dating
Cobalt-60	$^{60}_{27}Co$	5.3 years	Cancer therapy
Iodine-131	$^{131}_{53}I$	8.0 days	Thyroid therapy
Potassium-40	$^{40}_{19}K$	1.3×10^9 years	Geological dating
Phosphorus-32	$^{32}_{15}P$	14.3 days	Leukemia treatment
Technetium-99m	$^{99m}_{43}Tc$	6.0 hours	Organ imaging
Uranium-235	$^{235}_{92}U$	7.0×10^8 years	Nuclear reactors

Detecting and Measuring Radioactivity

- We all receive a miniscule daily dose of radiation from cosmic rays and radioactive substances in the soil. Additional radiation exposure comes from television sets, dental X-rays, and other man-made sources.
- Moreover, we are still exposed to nuclear fallout, residual radiation resulting from the testing of nuclear weapons in the atmosphere decades ago. Although this background radiation is unavoidable and minute, higher levels can be harmful and life-threatening because radiation is composed of high-energy particles and waves that damage cells and disrupt key biological processes, often causing cell death.
- **How can radiation be detected and measured when it can’t be directly observed by any of the senses?**
- A ***Geiger counter*** is a small portable device used for measuring radioactivity. It consists of a tube filled with argon gas that is ionized when it comes into contact with nuclear radiation. This in turn generates an electric current that produces a clicking sound on a meter. Geiger counters are used to locate a radiation source or a site that has become contaminated by radioactivity.

A Geiger counter is a device used to detect radiation.

Individuals who work with radioactivity wear badges to monitor radiation levels.

- The amount of radioactivity in a sample is measured by the number of nuclei that decay per unit time-disintegrations per second. **The most common unit is the curie (Ci)**, and smaller units derived from it, the millicurie (mCi) and the microcurie (μCi). One curie equals 3.7 × 10^{10} disintegrations/second, which corresponds to the decay rate of 1 g of the element radium.
- The becquerel (Bq), an SI unit, is also used to measure radioactivity; 1 Bq = 1 disintegration/second. Since each nuclear decay corresponds to one becquerel, 1 Ci = 3.7 × 10^{10} Bq.

Often a dose of radiation is measured in the number of millicuries that must be administered. For example, a diagnostic test for thyroid activity uses sodium iodide that contains iodine-131—that is, $Na^{131}I$. The radioisotope is purchased with a known amount of radioactivity per milliliter, such as 3.5 mCi/mL. By knowing the amount of radioactivity, a patient must be given, as well as the concentration of radioactivity in the sample, one can calculate the volume of radioactive isotope that must be administered.

Measuring Human Exposure to Radioactivity

Several units are used to measure the amount of radiation absorbed by an organism.

- ✓ The rad—radiation absorbed dose—is the amount of radiation absorbed by one gram of a substance. The amount of energy absorbed varies with both the nature of the substance and the type of radiation.
- ✓ The rem—radiation equivalent for man—is the amount of radiation that also factors in its energy and potential to damage tissue. Using rem as a measure of radiation, 1 rem of any type of radiation produces the same amount of tissue damage.

Other units to measure absorbed radiation include the gray (1 Gy = 100 rad) and the sievert (1 Sv = 100 rem).

Although background radiation varies with location, the average radiation dose per year for an individual is estimated at 0.27 rem. Generally, no detectable biological effects are noticed when the dose of radiation is less than 25 rem. A single dose of 25–100 rem causes a temporary decrease in white blood cell count. The symptoms of radiation sickness—nausea, vomiting, fatigue, and prolonged decrease in white blood cell count—are visible at a dose of more than 100 rem.

Death results at still higher doses of radiation. ***The LD_{50}—the lethal dose that kills 50% of a population—is 500 rem in humans***, and exposure to 600 rem of radiation is fatal for an entire population.

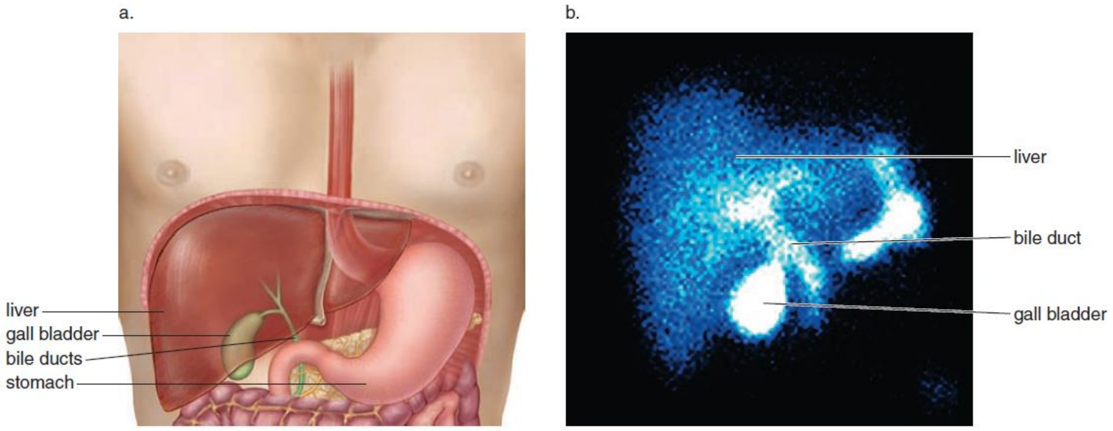
Medical Uses of Radioisotopes

Radioactive isotopes are used for both diagnostic and therapeutic procedures in medicine. In a diagnostic test to measure the function of an organ or to locate a tumor, low doses of radioactivity are generally given. When the purpose of using radiation is therapeutic, such as to kill diseased cells or cancerous tissue, a much higher dose of radiation is required.

A. Radioisotopes Used in Diagnosis

- Radioisotopes are routinely used to determine if an organ is functioning properly or to detect the presence of a tumor. The isotope is ingested or injected and the radiation it emits can be used to produce a scan.
- The radioactive atom is bonded to a larger molecule that targets a specific organ. An organ that has increased or decreased uptake of the radioactive element can indicate disease, the presence of a tumor, or other conditions.
- A HIDA scan (hepatobiliary iminodiacetic acid scan) uses a technetium-99m-labeled molecule to evaluate the functioning of the gall bladder and bile ducts After injection, the technetium-99m travels through the bloodstream and into the liver, gall bladder, and bile ducts, where, in a healthy individual, the organs are all clearly visible on a scan. When the gall bladder is inflamed or the bile ducts are obstructed by gallstones, uptake of the radioisotope does not occur and these organs are not visualized because they do not contain the radioisotope.
- Red blood cells tagged with technetium-99m are used to identify the site of internal bleeding in an individual.
- Bone scans performed with technetium-99m can show the location of metastatic cancer, so that specific sites can be targeted for radiation therapy.

Figure 9.4 HIDA Scan Using Technetium-99m



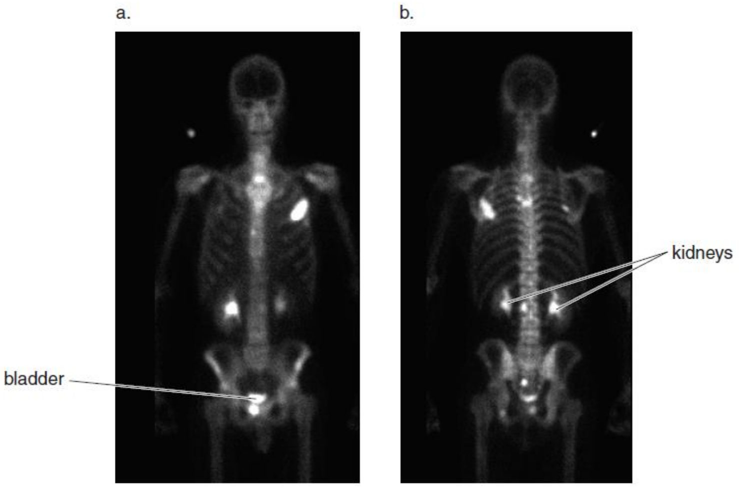
a. Schematic showing the location of the liver, gall bladder, and bile ducts

b. A scan using technetium-99m showing bright areas for the liver, gall bladder, and bile ducts, indicating normal function

- Thallium-201 is used in stress tests to diagnose coronary artery disease. Thallium injected into a vein crosses cell membrane into normal heart muscle. Little radioactive thallium is found in areas of the heart that have a poor blood supply. This technique is used to identify individuals who may need bypass surgery or other interventions because of blocked coronary arteries.

Figure 9.5

Bone Scan Using Technetium-99m



The bone scan of a patient whose lung cancer has spread to other organs. The anterior view [from the front in (a)] shows the spread of disease to the ribs, while the posterior view [from the back in (b)] shows spread of disease to the ribs and spine. The bright areas in the mid-torso and lower pelvis are due to a collection of radioisotope in the kidneys and bladder, before it is eliminated in the urine.

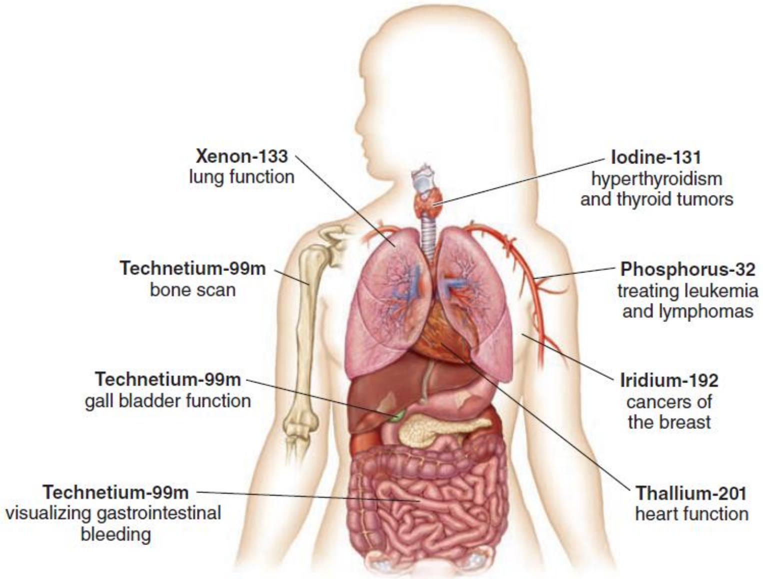
B. *Radioisotopes Used in Treatment*

- The high-energy radiation emitted by radioisotopes can be used to kill rapidly dividing tumor cells. Two techniques are used. Sometimes the radiation source is external to the body.
- For example, a beam of radiation produced by decaying cobalt-60 can be focused at a tumor. Such a radiation source must have a much longer half-

life—5.3 years in this case—than radioisotopes that are ingested for diagnostic purposes. **With this method some destruction of healthy tissue often occurs, and a patient may experience some signs of radiation sickness, including vomiting, fatigue, and hair loss.**

Figure 9.6

Common Radioisotopes Used in Medicine



Medical Imaging Without Radioactivity

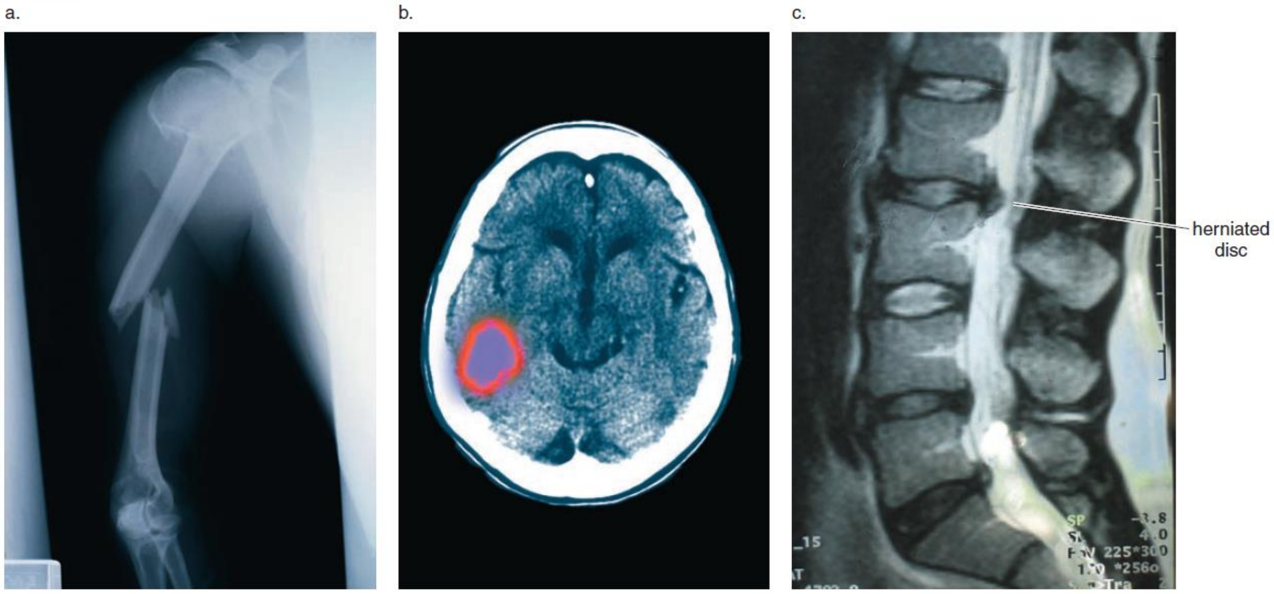
- **X-rays, CT scans**, and **MRIs** are also techniques that provide an image of an organ or extremity that is used for diagnosis of a medical condition. Unlike PET scans and other procedures discussed thus far, however, these procedures are not based on nuclear reactions and they do not utilize radioactivity. In each technique, an energy source is directed towards a specific region in the body, and a scan is produced that is analyzed by a trained medical professional.

☒ **X-rays** are a high-energy type of radiation called electromagnetic radiation. Tissues of different density interact differently with an X-ray beam, and so a map of bone and internal organs is created on an X-ray film. Dense bone is clearly visible in an X-ray, making it a good diagnostic technique for finding fractures (Figure 9.9a). Although X-rays are a form of high-energy radiation, they are lower in energy than the γ rays produced in nuclear reactions. Nonetheless, X-rays still cause adverse biological effects on the cells with which they come in contact, and the exposure of both the patient and X-ray technician must be limited.

☒ **CT (computed tomography) scans**, which also use X-rays, provide high resolution images of "slices" of the body. Historically, CT images have shown a slice of tissue perpendicular to the long axis of the body. Modern CT scanners can now provide a three-dimensional view of the body's organs. CT scans of the head are used to diagnose bleeding and tumors in the brain (Figure 9.9b).

☒ **MRI (magnetic resonance imaging)** uses low-energy radio waves to visualize internal organs. Unlike methods that use high-energy radiation, MRIs do not damage cells. An MRI is a good diagnostic method for visualizing soft tissue (Figure 9.9c), and thus it complements X-ray techniques.

Figure 9.9 Imaging the Human Body



a. X-ray of a broken humerus in a patient's arm
b. A color-enhanced CT scan of the head showing the site of a stroke
c. MRI of the spinal cord showing spinal compression from a herniated disc