# Chapter 9 Nuclear Radiation

## 9.1

## Natural Radioactivity

# Radioactive Isotopes

A **radioactive isotope**

- has an unstable nucleus.
- emits radiation to become more stable.
- can be one or more of the isotopes of an element

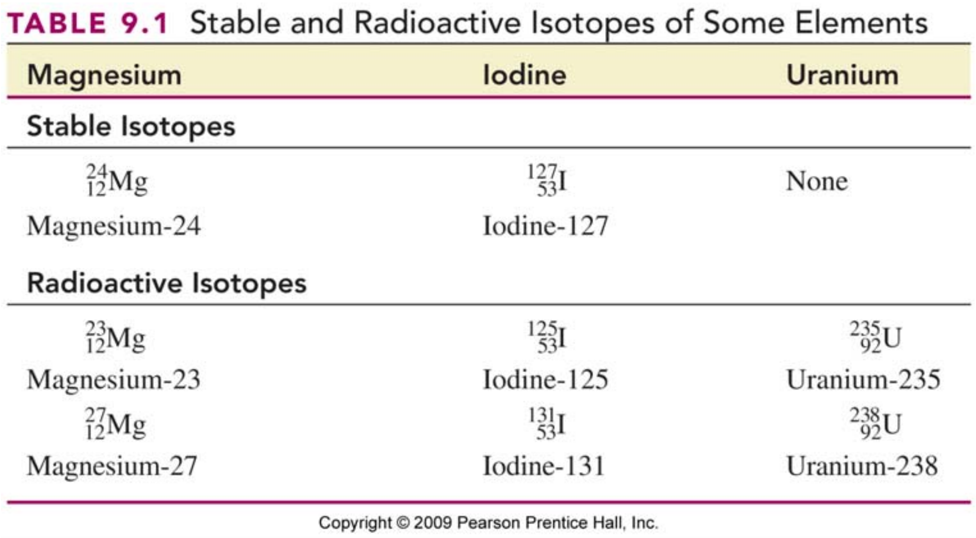


**TABLE 9.1** Stable and Radioactive Isotopes of Some Elements

| Magnesium | Iodine | Uranium |
|---|---|---|
| **Stable Isotopes** | | |
| $^{24}_{12}\text{Mg}$<br>Magnesium-24 | $^{127}_{53}\text{I}$<br>Iodine-127 | None |
| **Radioactive Isotopes** | | |
| $^{23}_{12}\text{Mg}$<br>Magnesium-23 | $^{125}_{53}\text{I}$<br>Iodine-125 | $^{235}_{92}\text{U}$<br>Uranium-235 |
| $^{27}_{12}\text{Mg}$<br>Magnesium-27 | $^{131}_{53}\text{I}$<br>Iodine-131 | $^{238}_{92}\text{U}$<br>Uranium-238 |

# Nuclear Radiation

**Nuclear radiation**

- is the radiation emitted by an unstable atom.
- takes the form of alpha particles, neutrons, beta particles, positrons, or gamma rays.

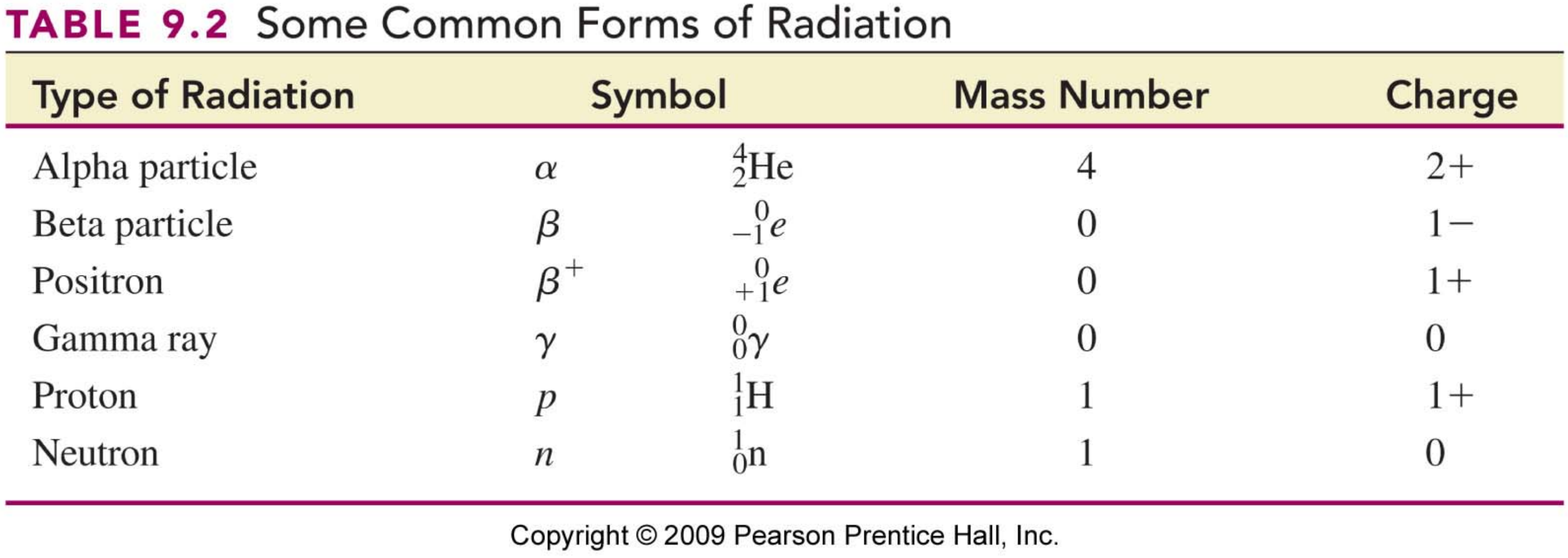
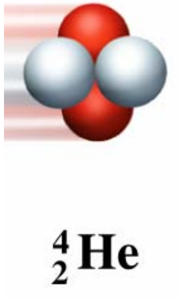


**TABLE 9.2** Some Common Forms of Radiation

| Type of Radiation | Symbol | | Mass Number | Charge |
|---|---|---|---|---|
| Alpha particle | $\alpha$ | $^{4}_{2}\mathrm{He}$ | 4 | 2+ |
| Beta particle | $\beta$ | $^{0}_{-1}e$ | 0 | 1− |
| Positron | $\beta^{+}$ | $^{0}_{+1}e$ | 0 | 1+ |
| Gamma ray | $\gamma$ | $^{0}_{0}\gamma$ | 0 | 0 |
| Proton | $p$ | $^{1}_{1}\mathrm{H}$ | 1 | 1+ |
| Neutron | $n$ | $^{1}_{0}\mathrm{n}$ | 1 | 0 |

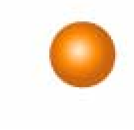
# Types of Radiation

**Alpha (α) particle** is two protons and two neutrons.



**Beta (β) particle** is a high-energy electron. $^{0}_{-1}e$

**Positron (β+)** is a positive electron. $^{0}_{+1}e$



**Gamma ray** is high-energy radiation released from a nucleus. $\gamma$

# Radiation Protection

**Radiation protection** requires

- paper and clothing for alpha particles.
- a lab coat or gloves for beta particles.
- a lead shield or a thick concrete wall for gamma rays.
- limiting the amount of time spent near a radioactive source.
- increasing the distance from the source.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# Shielding for Radiation Protection

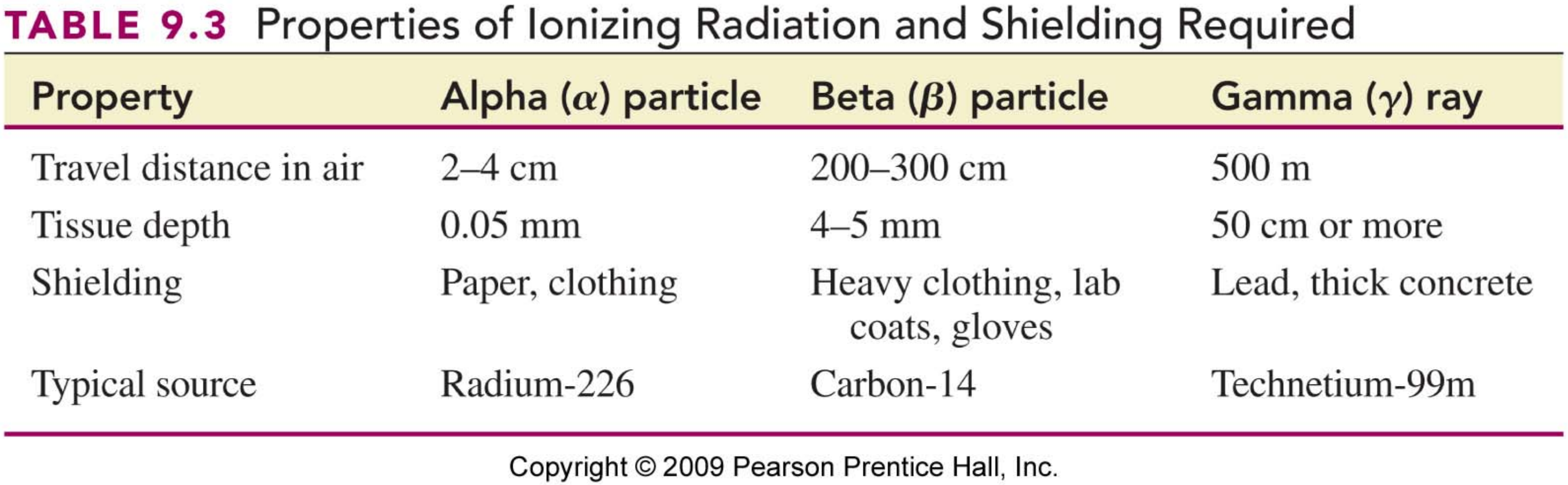


**TABLE 9.3** Properties of Ionizing Radiation and Shielding Required

| Property | Alpha ($\alpha$) particle | Beta ($\beta$) particle | Gamma ($\gamma$) ray |
|---|---|---|---|
| Travel distance in air | 2–4 cm | 200–300 cm | 500 m |
| Tissue depth | 0.05 mm | 4–5 mm | 50 cm or more |
| Shielding | Paper, clothing | Heavy clothing, lab coats, gloves | Lead, thick concrete |
| Typical source | Radium-226 | Carbon-14 | Technetium-99m |

# Chapter 9 Nuclear Radiation

## 9.2

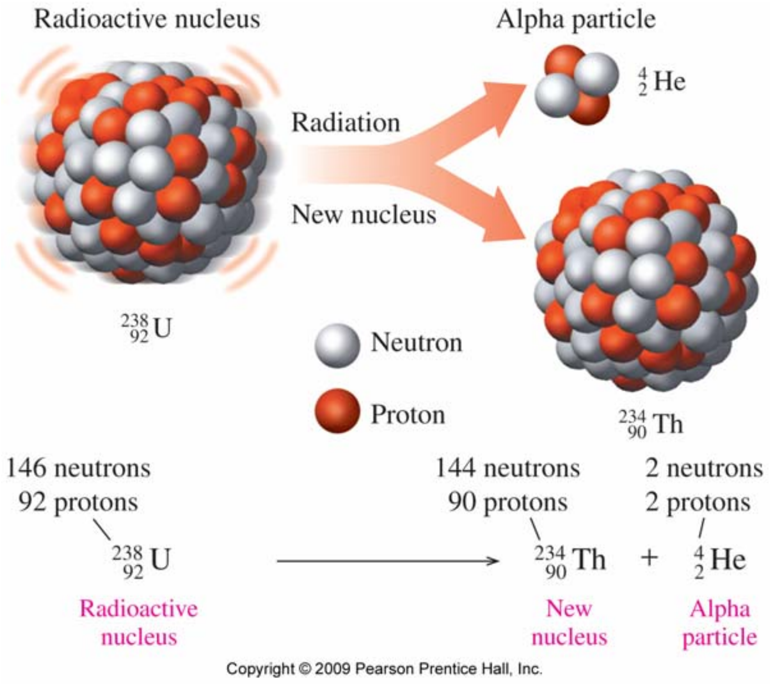
## Nuclear Reactions

$$\underset{\text{Radioactive nucleus}}{{}^{238}_{92}\text{U}} \longrightarrow \underset{\text{New nucleus}}{{}^{234}_{90}\text{Th}} + \underset{\text{Alpha particle}}{{}^{4}_{2}\text{He}}$$

# Alpha Decay

When a radioactive nucleus emits an **alpha particle**, a new nucleus forms that has

- a mass number that is decreased by 4.
- an atomic number that is decreased by 2.



# Balancing Nuclear Equations

In a balanced nuclear equation, the sum of the mass numbers and the sum of the atomic numbers are equal for the nuclei of the reactants and the products.

**MASS NUMBERS**

Total = 251 = 251

$$^{251}_{98}\text{Cf} \longrightarrow {}^{247}_{96}\text{Cm} + {}^{4}_{2}\text{He}$$

Total = 98 = 98

**ATOMIC NUMBERS**

# Changes in Nuclear Particles Due to Radiation

When radiation occurs,

- particles are emitted from the nucleus.
- mass number may change.
- atomic number may change.

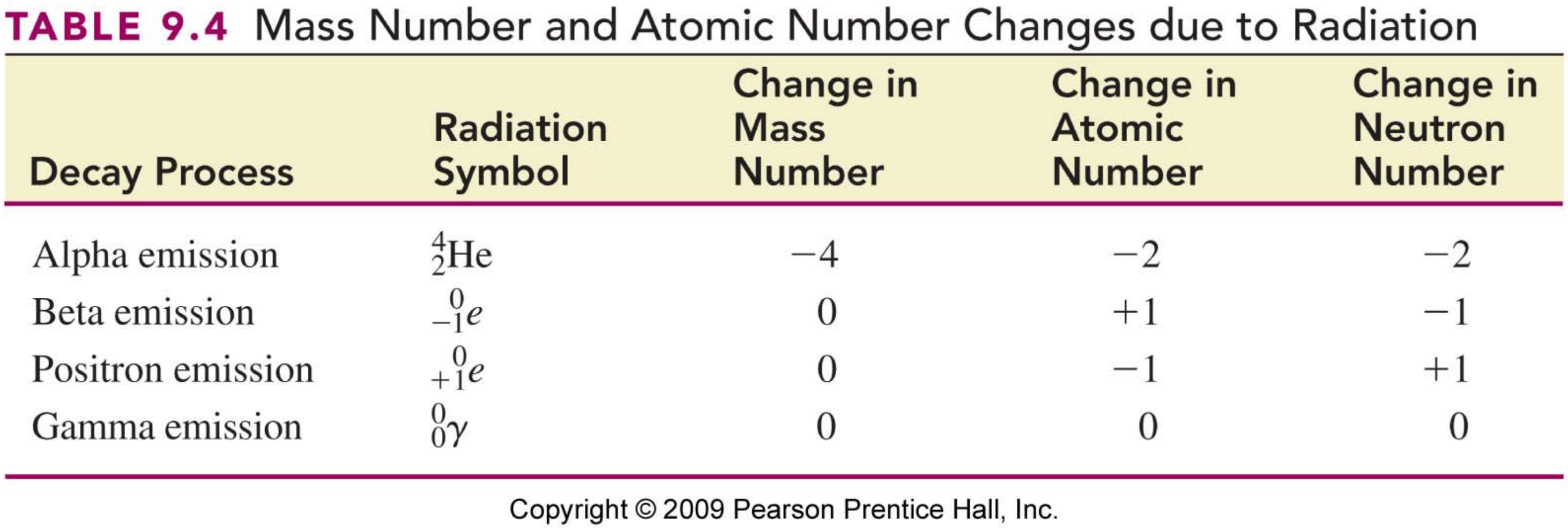
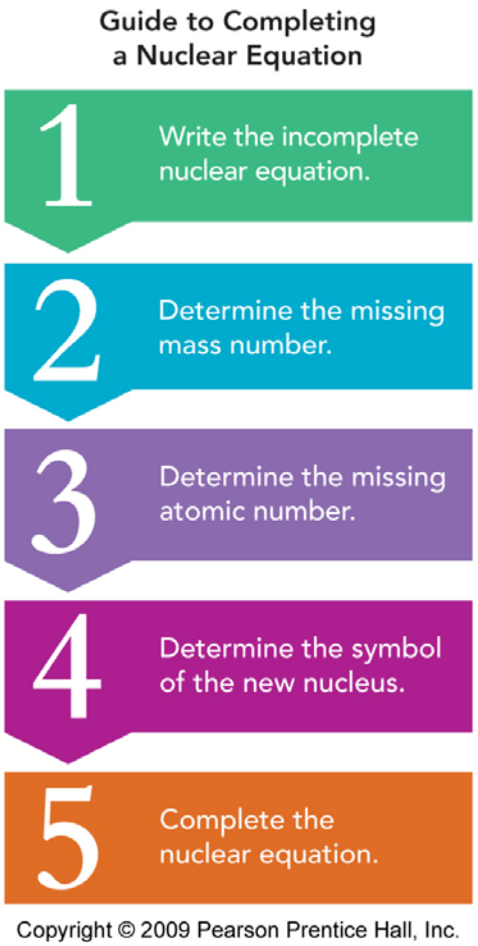


**TABLE 9.4** Mass Number and Atomic Number Changes due to Radiation

| Decay Process | Radiation Symbol | Change in Mass Number | Change in Atomic Number | Change in Neutron Number |
|---|---|---|---|---|
| Alpha emission | ${}^{4}_{2}\mathrm{He}$ | −4 | −2 | −2 |
| Beta emission | ${}^{0}_{-1}e$ | 0 | +1 | −1 |
| Positron emission | ${}^{0}_{+1}e$ | 0 | −1 | +1 |
| Gamma emission | ${}^{0}_{0}\gamma$ | 0 | 0 | 0 |

# Guide to Balancing a Nuclear Equation



Guide to Completing a Nuclear Equation

1. Write the incomplete nuclear equation.
2. Determine the missing mass number.
3. Determine the missing atomic number.
4. Determine the symbol of the new nucleus.
5. Complete the nuclear equation.

# Equation for Alpha Emission

Write an equation for the alpha decay of Rn-222.

**STEP 1:** Write the incomplete equation

$$^{222}_{86}\text{Rn} \longrightarrow ? + {}^{4}_{2}\text{He}$$

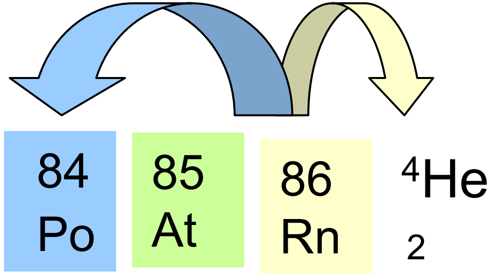
**STEP 2:** Determine the mass number $222 - 4 = 218$

**STEP 3:** Determine the atomic number $86 - 2 = 84$

**STEP 4:** Determine the symbol of element $84 = \text{Po}$

**STEP 5:** Complete the equation

$$^{222}_{86}\text{Rn} \longrightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$$

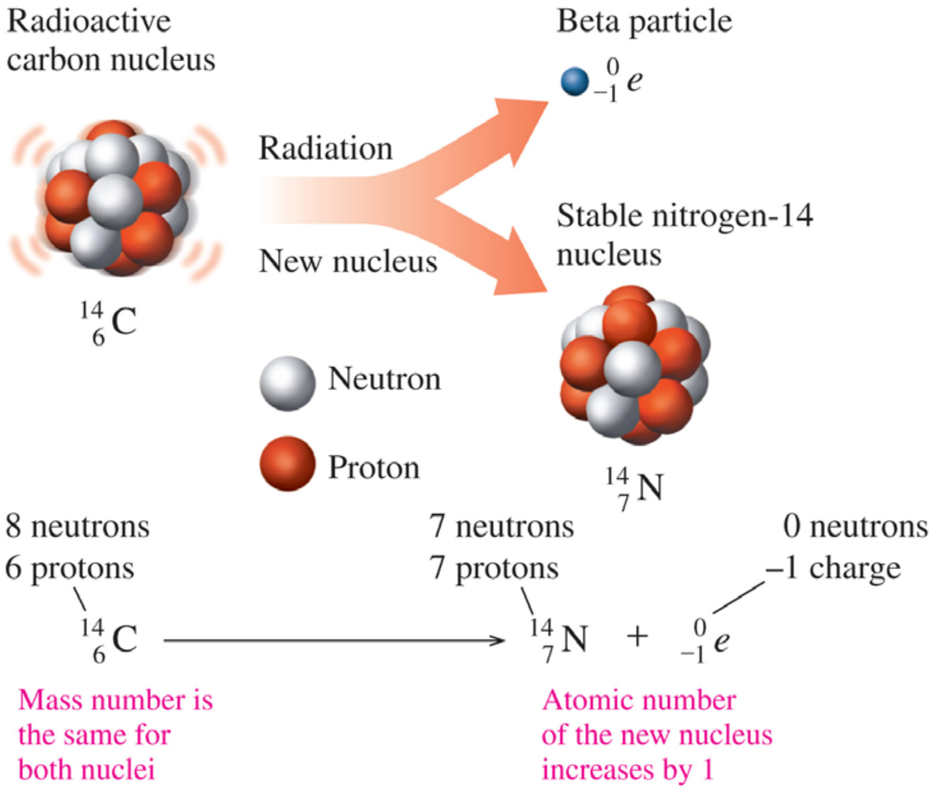


# Beta Emission

A **beta particle**

- is an electron emitted from the nucleus.
- forms when a neutron in the nucleus breaks down.

$${}^{1}_{0}n \longrightarrow {}^{0}_{-1}e + {}^{1}_{1}H$$



# Writing An Equation for a Beta Emitter

**STEP 1:** Write an equation for the decay of ${}^{42}$potassium, a beta emitter.

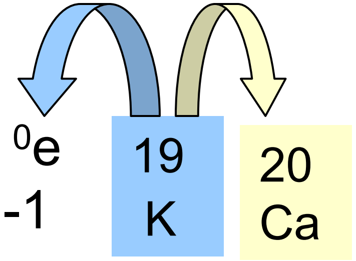
$${}^{42}_{19}\text{K} \longrightarrow \text{new nucleus} + {}^{0}_{-1}\text{e}$$

**STEP 2:** Mass number : (same) = 42

**STEP 3:** Atomic number: 19 + 1 = 20

**STEP 4:** Symbol of element: 20 = Ca

**STEP 5** ${}^{42}_{19}\text{K} \longrightarrow {}^{42}_{20}\text{Ca} + {}^{0}_{-1}\text{e}$



# Learning Check

Write the nuclear equation for the beta decay of $^{60}$Co.

# Solution

$$^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}e$$

**beta particle**

# Positron Emission

In **positron emission**,

- a proton is converted to a neutron and a positron.

$$ {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}e $$

- the mass number of the new nucleus is the same, but the atomic number decreases by 1.

$$ {}^{49}_{25}\mathrm{Mn} \longrightarrow {}^{49}_{24}\mathrm{Cr} + {}^{0}_{+1}e $$

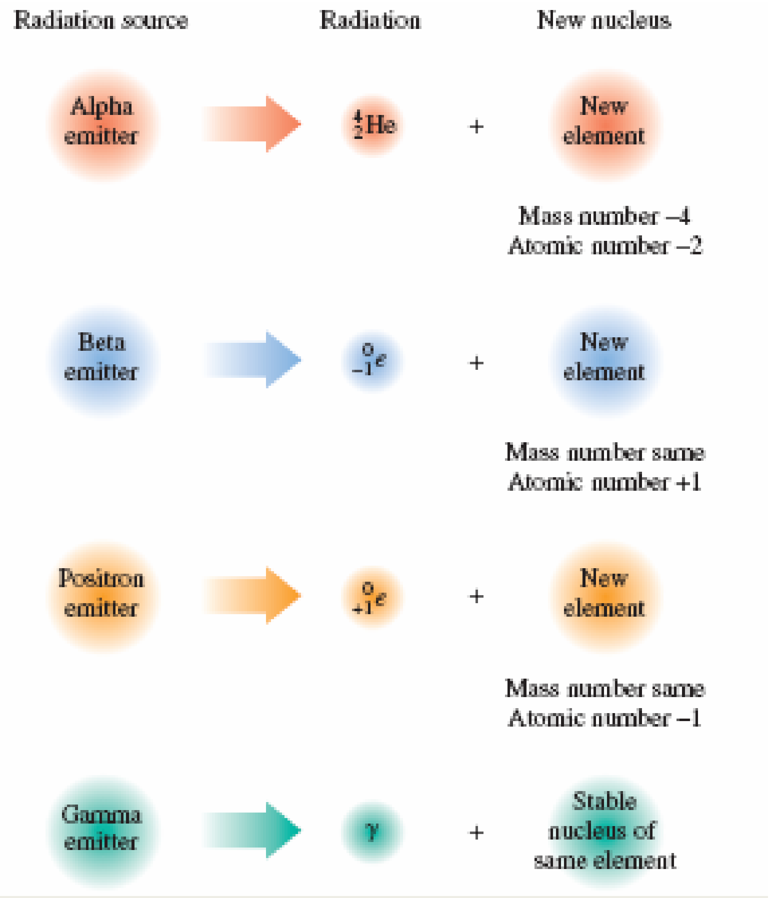
# Gamma Radiation

In **gamma radiation**,

- energy is emitted from an unstable nucleus, indicated by *m* following the mass number.
- the mass number and the atomic number of the new nucleus are the same.

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

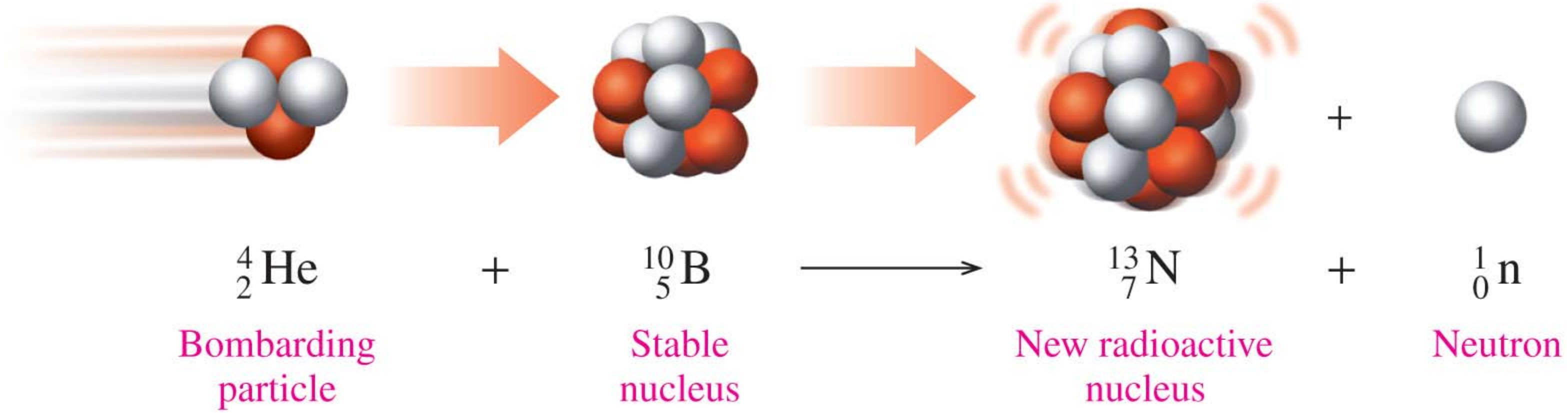
# Summary of Types of Radiation



# Producing Radioactive Isotopes

**Radioactive isotopes** are produced

- when a stable nucleus is converted to a radioactive nucleus by bombarding it with a small particle.
- in a process called **transmutation**.



$$^{4}_{2}\text{He} + ^{10}_{5}\text{B} \longrightarrow ^{13}_{7}\text{N} + ^{1}_{0}\text{n}$$

# Learning Check

What radioactive isotope is produced when a neutron bombards $^{59}Co$?

$$^{59}_{27}\mathrm{Co} \quad + \quad ^{1}_{0}n \quad \longrightarrow \quad ? \quad + \quad ^{4}_{2}\mathrm{He}$$

# Solution

**mass numbers**

60 = 60

$$^{59}_{27}\text{Co} + {}^{1}_{0}n \longrightarrow {}^{56}_{25}\text{Mn} + {}^{4}_{2}\text{He}$$

27 = 27

**atomic numbers**

# Chapter 9 Nuclear Radiation

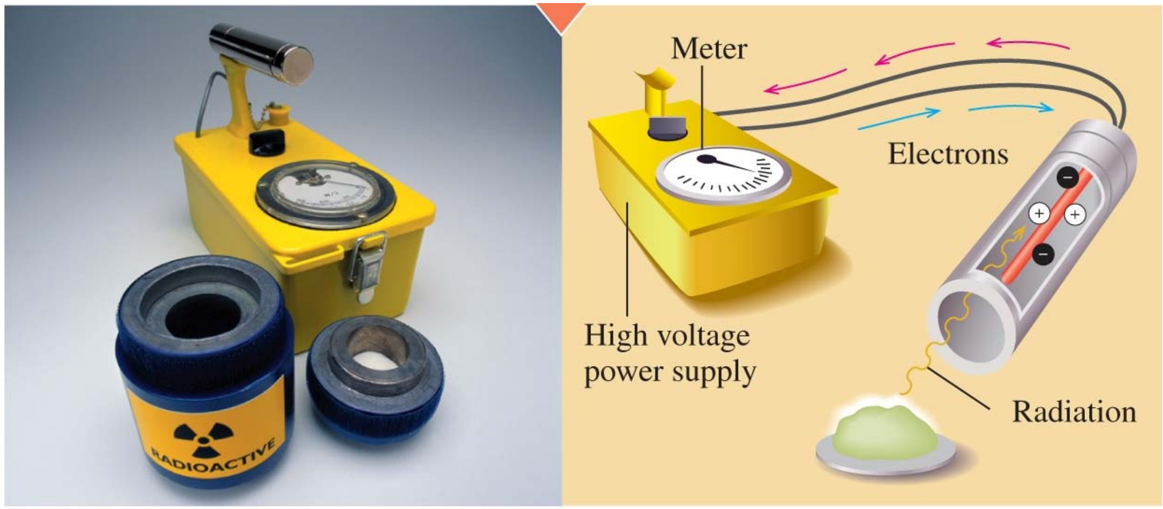
## 9.3

## Radiation Measurement

# Radiation Measurement

A **Geiger counter**

- detects beta and gamma radiation.
- uses ions produced by radiation to create an electrical current.



# Radiation Units

Units of radiation include

- **Curie**
  - measures activity as the number of atoms that decay in 1 second.
- **rad** (radiation absorbed dose)
  - measures the radiation absorbed by the tissues of the body.
- **rem** (radiation equivalent)
  - measures the biological damage caused by different types of radiation.

# Units of Radiation Measurement

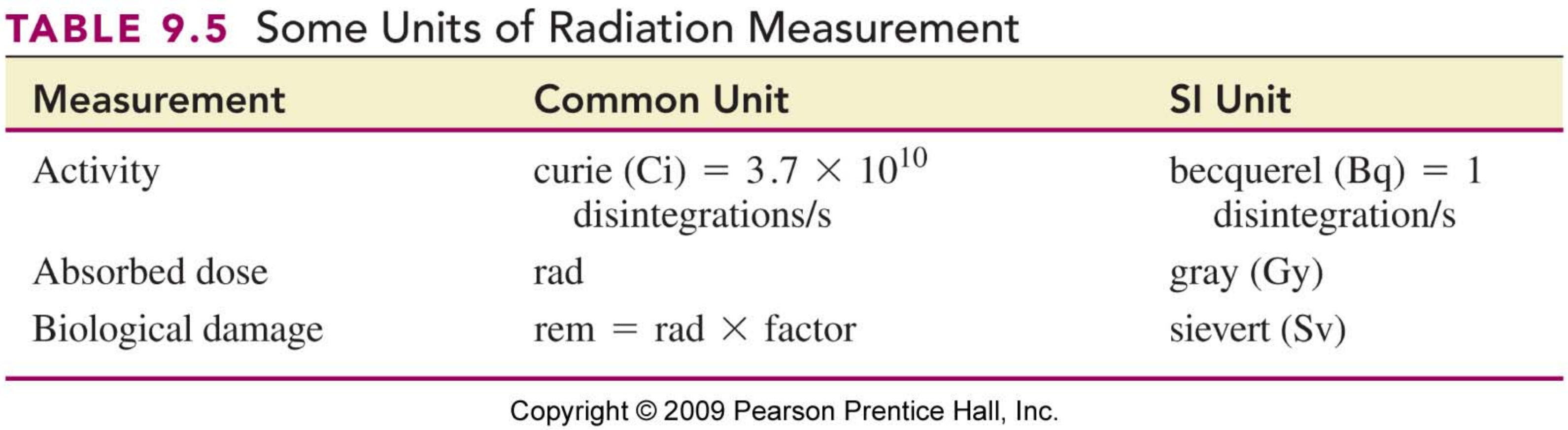


**TABLE 9.5** Some Units of Radiation Measurement

| Measurement | Common Unit | SI Unit |
|---|---|---|
| Activity | curie (Ci) = $3.7 \times 10^{10}$ disintegrations/s | becquerel (Bq) = 1 disintegration/s |
| Absorbed dose | rad | gray (Gy) |
| Biological damage | rem = rad × factor | sievert (Sv) |

# Exposure to Radiation

Exposure to radiation occurs from

- naturally occurring radioisotopes.
- medical and dental procedures.
- air travel, radon, and smoking cigarettes.

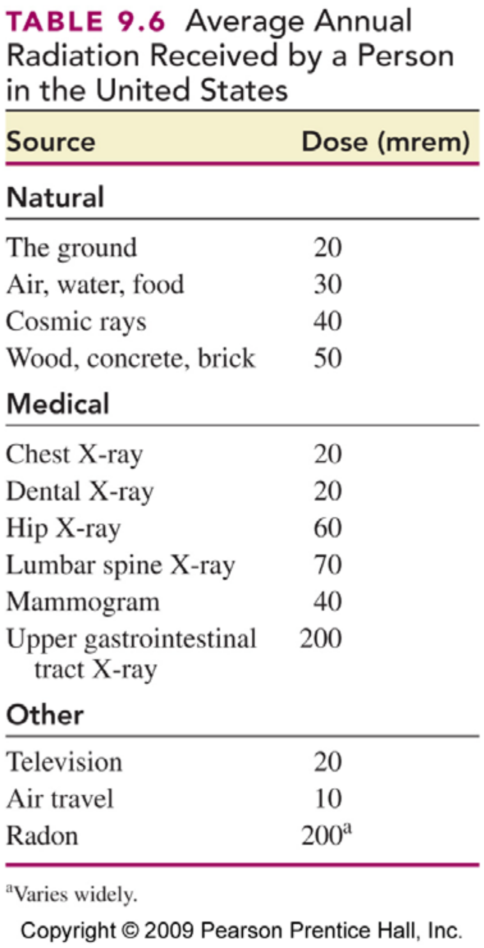


**TABLE 9.6** Average Annual Radiation Received by a Person in the United States

| Source | Dose (mrem) |
|---|---|
| **Natural** | |
| The ground | 20 |
| Air, water, food | 30 |
| Cosmic rays | 40 |
| Wood, concrete, brick | 50 |
| **Medical** | |
| Chest X-ray | 20 |
| Dental X-ray | 20 |
| Hip X-ray | 60 |
| Lumbar spine X-ray | 70 |
| Mammogram | 40 |
| Upper gastrointestinal tract X-ray | 200 |
| **Other** | |
| Television | 20 |
| Air travel | 10 |
| Radon | 200[a] |

[a] Varies widely.

# Learning Check

A typical intravenous dose of I-125 for a thyroid diagnostic test is 100 μ Ci. What is this dosage in megabecquerels (MBq)? ($3.7 \times 10^{10}$ Bq = 1 Ci)

1) 3.7 MBq

2) $3.7 \times 10^{6}$ MBq

3) $2.7 \times 10^{2}$ MBq

# Solution

A typical intravenous does of I-125 for a thyroid diagnostic test is 100 μ Ci. What is this dosage in megabecquerels (MBq)? ($3.7 \times 10^{10}$ Bq = 1 Ci)

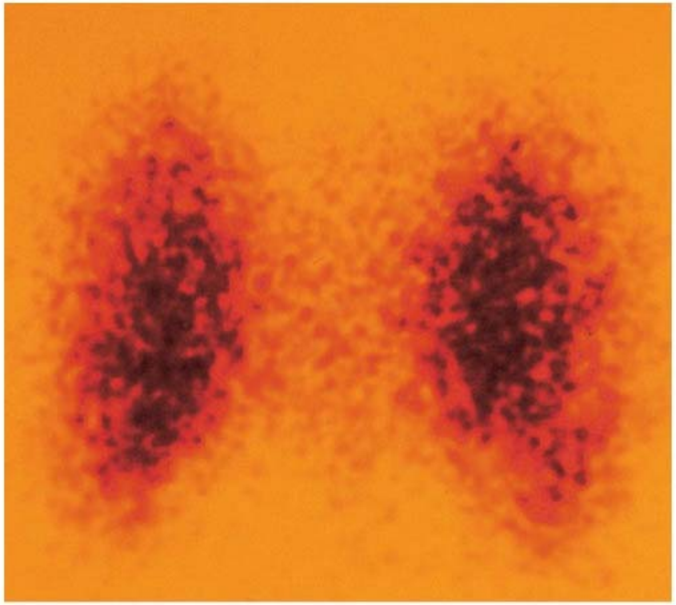
1) 3.7 MBq

$$100\ \cancel{\mu\ \mathrm{Ci}} \times \frac{1\ \cancel{\mathrm{Ci}}}{1 \times 10^{6}\ \cancel{\mu\ \mathrm{Ci}}} \times \frac{3.7 \times 10^{10}\ \cancel{\mathrm{Bq}}}{1\ \cancel{\mathrm{Ci}}} \times \frac{1\ \cancel{\mathrm{MBq}}}{1 \times 10^{6}\ \cancel{\mathrm{Bq}}} =$$

3.7 MBq

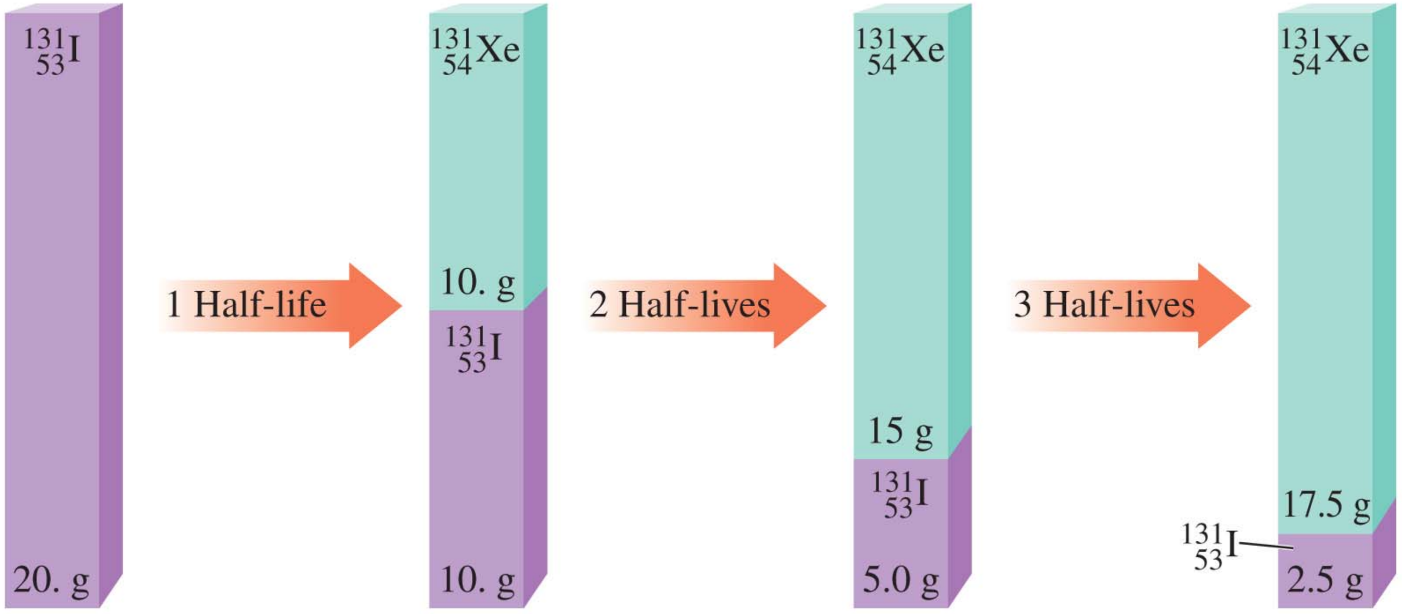
# Chapter 9 Nuclear Radiation

## 9.4 Half-Life of a Radioisotope
## 9.5 Medical Applications Using Radioactivity



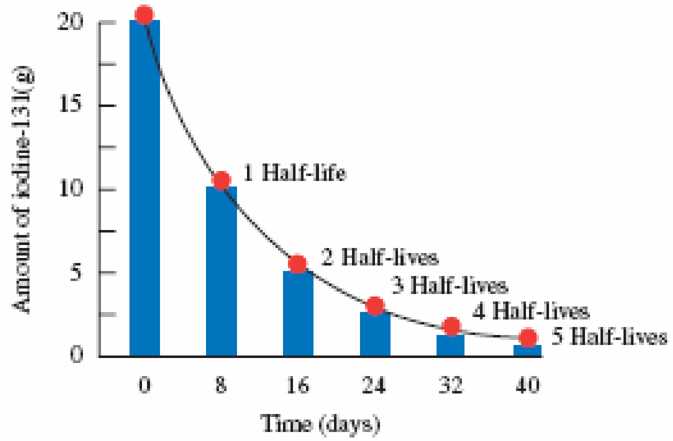
# Half-Life

The **half-life** of a radioisotope is the time for the radiation level to decrease (decay) to one half of the original value.



# Decay Curve

A **decay curve** shows the decay of radioactive atoms and the remaining radioactive sample.



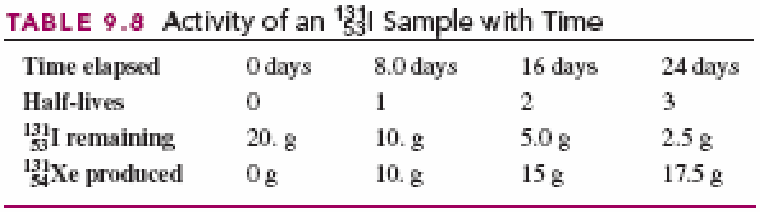


**TABLE 9.8** Activity of an $^{131}_{53}I$ Sample with Time

| Time elapsed | 0 days | 8.0 days | 16 days | 24 days |
|---|---|---|---|---|
| Half-lives | 0 | 1 | 2 | 3 |
| $^{131}_{53}I$ remaining | 20. g | 10. g | 5.0 g | 2.5 g |
| $^{131}_{54}Xe$ produced | 0 g | 10. g | 15 g | 17.5 g |

# Half-Lives of Some Radioisotopes

**Radioisotopes**

- that are naturally occurring tend to have long half-lives.
- used in nuclear medicine have short half-lives.

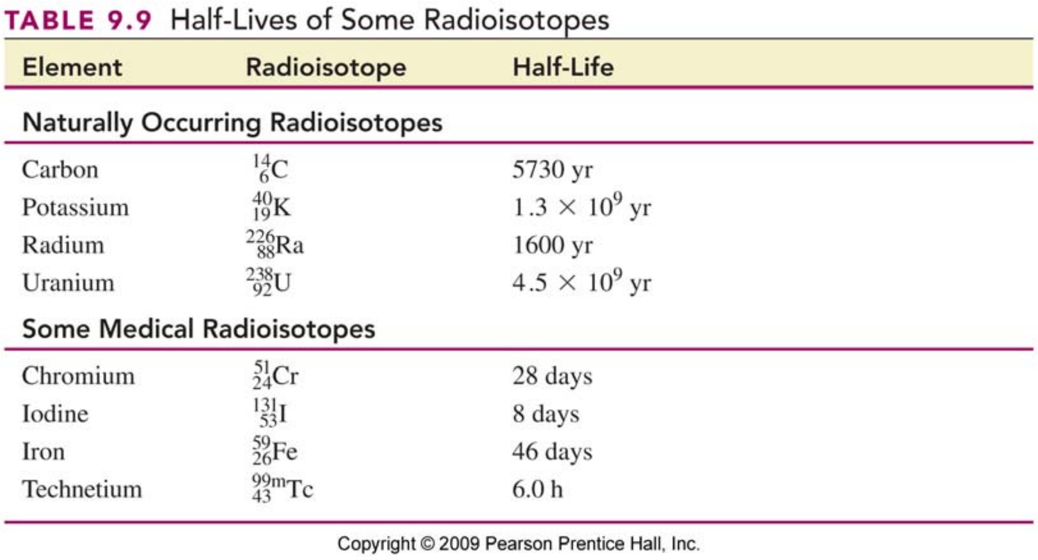


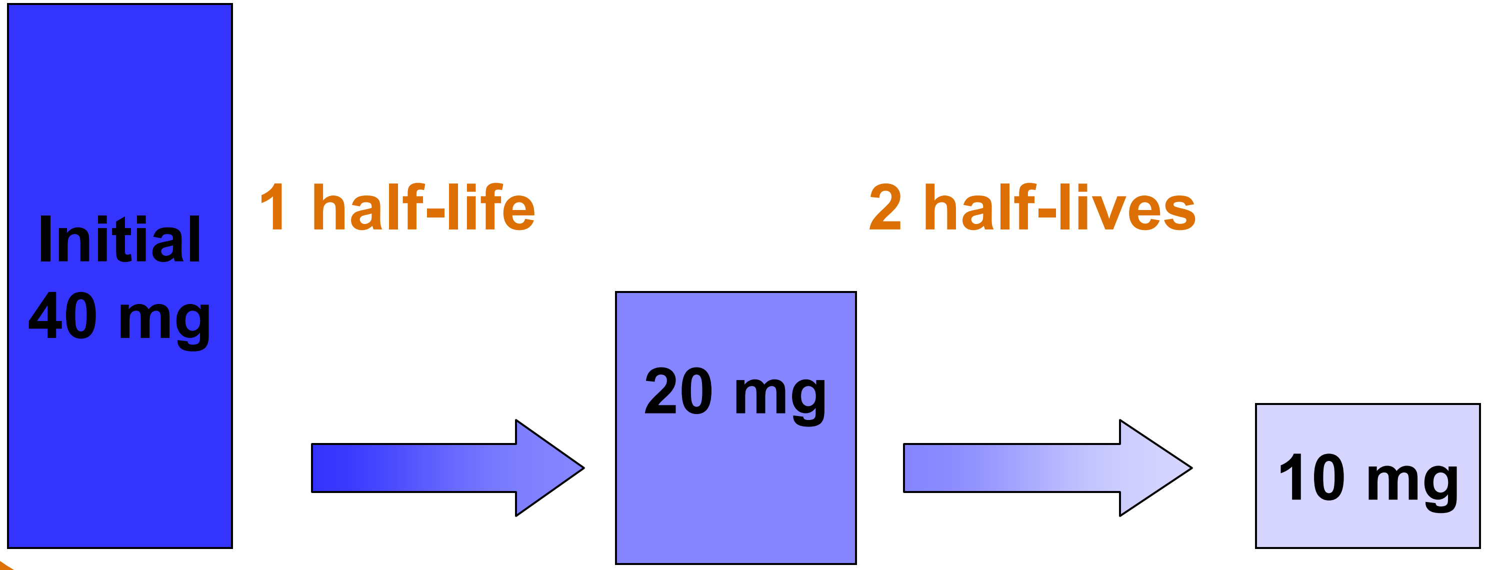
**TABLE 9.9** Half-Lives of Some Radioisotopes

| Element | Radioisotope | Half-Life |
|---|---|---|
| **Naturally Occurring Radioisotopes** | | |
| Carbon | ${}^{14}_{6}\text{C}$ | 5730 yr |
| Potassium | ${}^{40}_{19}\text{K}$ | $1.3 \times 10^{9}$ yr |
| Radium | ${}^{226}_{88}\text{Ra}$ | 1600 yr |
| Uranium | ${}^{238}_{92}\text{U}$ | $4.5 \times 10^{9}$ yr |
| **Some Medical Radioisotopes** | | |
| Chromium | ${}^{51}_{24}\text{Cr}$ | 28 days |
| Iodine | ${}^{131}_{53}\text{I}$ | 8 days |
| Iron | ${}^{59}_{26}\text{Fe}$ | 46 days |
| Technetium | ${}^{99m}_{43}\text{Tc}$ | 6.0 h |

# Half-Life Calculations

In one half-life, 40 mg of a radioisotope decays to 20 mg. After two half-lives, 10 mg of radioisotope remain.

$$40 \text{ mg} \times \frac{1}{2} \times \frac{1}{2} = 10 \text{ mg}$$



**Initial 40 mg**

**1 half-life**

**20 mg**

**2 half-lives**

**10 mg**

# Learning Check

The half-life of $^{123}I$ is 13 hr. How much of a 64 mg sample of $^{123}I$ is left after 26 hours?

1) 32 mg
2) 16 mg
3) 8 mg

# Solution

2) 16 mg

**STEP 1** **Given** 64 g; 26 h; 13 hr/half-life

**STEP 2** **Plan** 26 hours $\xrightarrow{\text{Half-life}}$ Number of half-lives

**STEP 3** **Equalities** 1 half-life = 13 h

**STEP 4** **Set Up Problem**

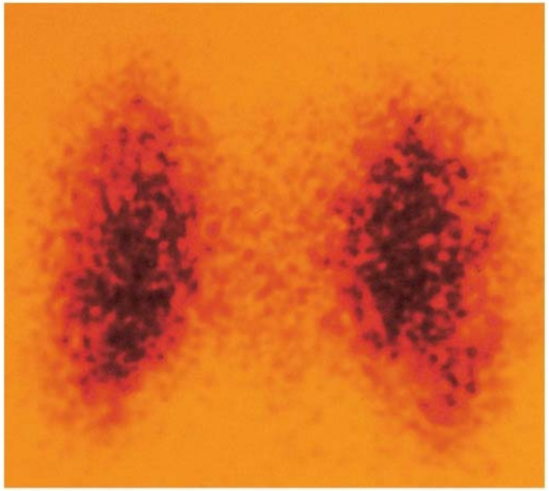
$$\text{Number of half-lives} = 26\ \cancel{\text{h}} \times \frac{1\ \text{half-life}}{13\ \cancel{\text{h}}} = 2\ \text{half-lives}$$

$$64\ \text{mg} \xrightarrow{13\ \text{hr}} 32\ \text{mg} \xrightarrow{13\ \text{hr}} 16\ \text{mg}$$

# Medical Applications

Radioisotopes with short half-lives are used in nuclear medicine because

- they have the same chemistry in the body as the nonradioactive atoms.
- in the organs of the body, they give off radiation that exposes a photographic plate (scan), giving an image of an organ.



Thyroid scan

# Some Radioisotopes Used in Nuclear Medicine

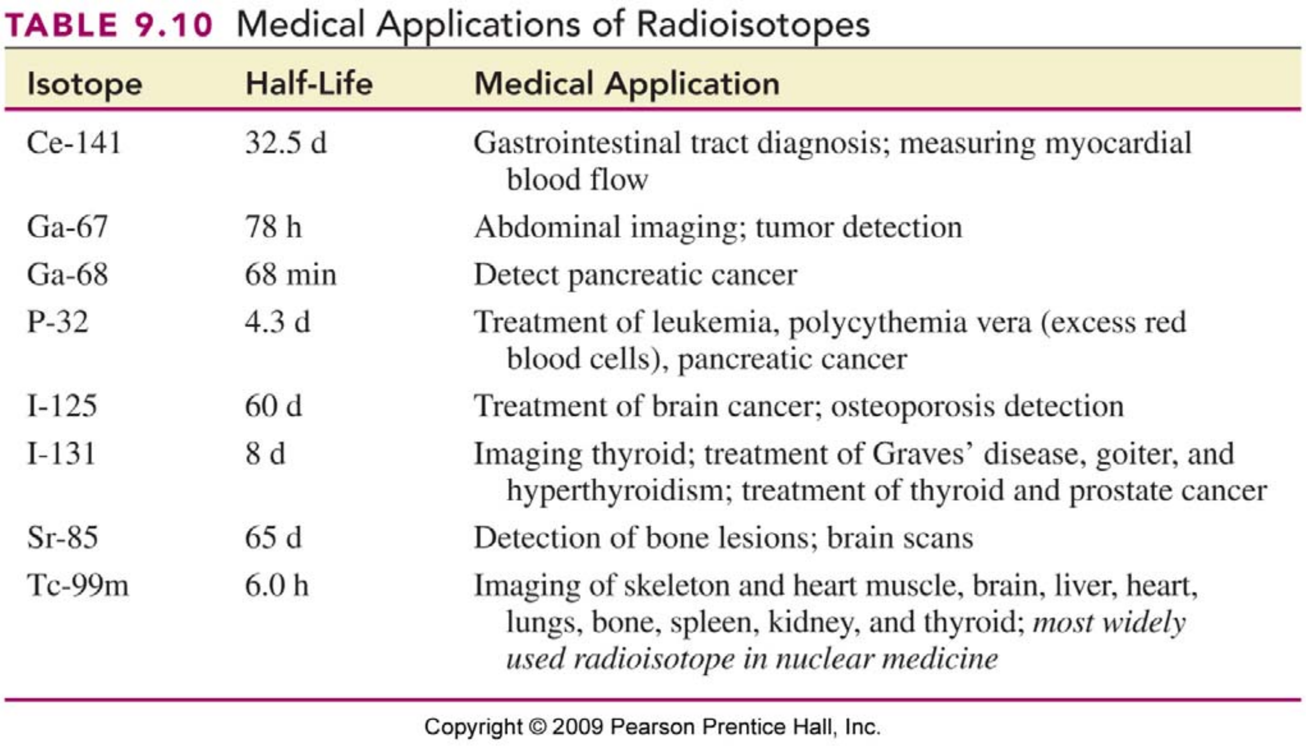


**TABLE 9.10** Medical Applications of Radioisotopes

| Isotope | Half-Life | Medical Application |
|---|---|---|
| Ce-141 | 32.5 d | Gastrointestinal tract diagnosis; measuring myocardial blood flow |
| Ga-67 | 78 h | Abdominal imaging; tumor detection |
| Ga-68 | 68 min | Detect pancreatic cancer |
| P-32 | 4.3 d | Treatment of leukemia, polycythemia vera (excess red blood cells), pancreatic cancer |
| I-125 | 60 d | Treatment of brain cancer; osteoporosis detection |
| I-131 | 8 d | Imaging thyroid; treatment of Graves' disease, goiter, and hyperthyroidism; treatment of thyroid and prostate cancer |
| Sr-85 | 65 d | Detection of bone lesions; brain scans |
| Tc-99m | 6.0 h | Imaging of skeleton and heart muscle, brain, liver, heart, lungs, bone, spleen, kidney, and thyroid; *most widely used radioisotope in nuclear medicine* |

# Learning Check

Which of the following radioisotopes are most likely to be used in nuclear medicine?

1) $^{40}K$ half-life 1.3 x $10^9$ years
2) $^{42}K$ half-life 12 hours
3) $^{131}I$ half-life 8 days

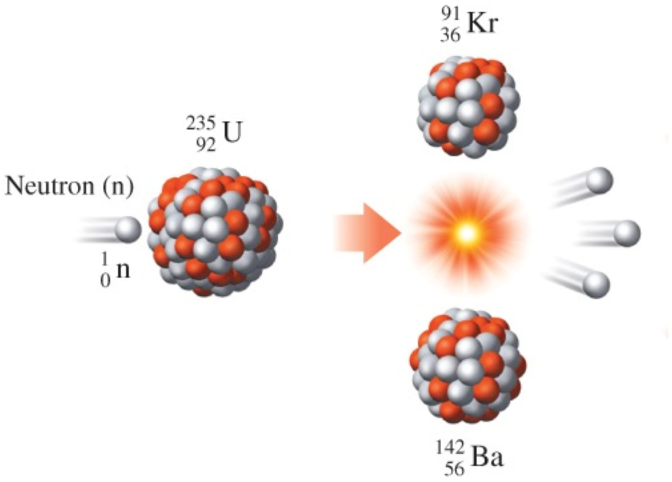
# Solution

Which of the following radioisotopes are most likely to be used in nuclear medicine?

Radioisotopes with short half-lives are used in nuclear medicine.

2) $^{42}K$ half-life 12 hours
3) $^{131}I$ half-life 8 days

# 9.6
# Nuclear Fission and Fusion



# Nuclear Fission

In **nuclear fission**,

- a large nucleus is bombarded with a small particle.
- the nucleus splits into smaller nuclei and several neutrons.
- large amounts of energy are released.

# Nuclear Fission

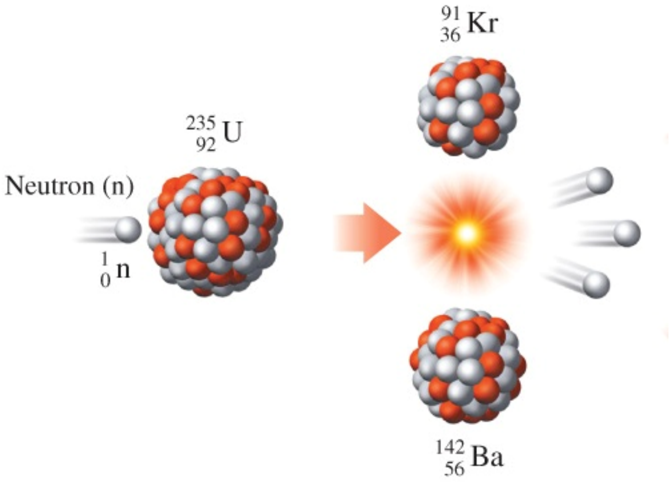
When a neutron bombards $^{235}U$,

- an unstable nucleus of $^{236}U$ undergoes fission (splits).
- smaller nuclei are produced, such as Kr-91 and Ba-142.
- neutrons are released to bombard more $^{235}U$.

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U \longrightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3\,{}^{1}_{0}n + \text{Energy} $$

# Nuclear Fission Diagram

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{236}_{92}\mathrm{U} \longrightarrow {}^{91}_{36}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}n + \text{energy} $$



# Learning Check

Supply the missing atomic symbol to complete the equation for the following nuclear fission reaction.

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{137}_{52}\mathrm{Te} + {}^{?}_{?}\mathbf{X} + 2\,{}^{1}_{0}n + \text{energy} $$

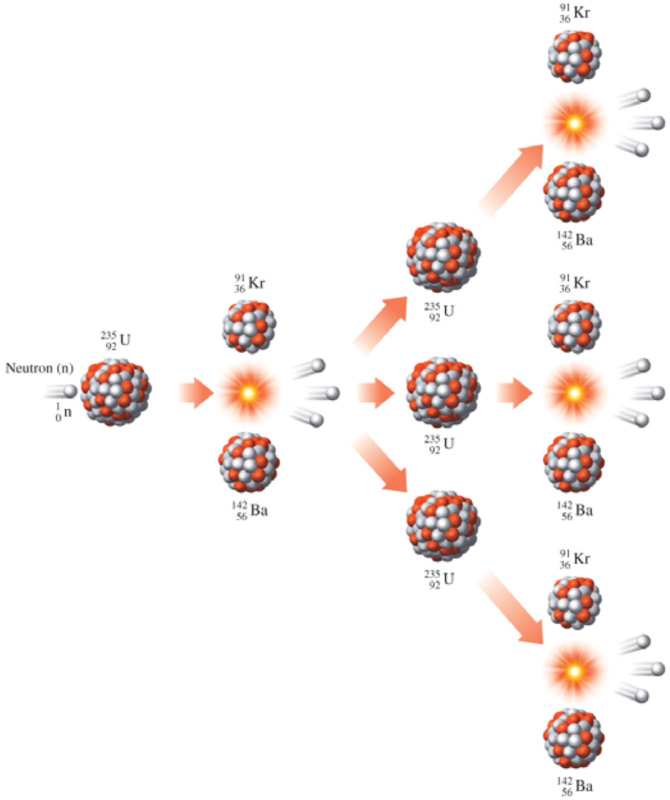
# Solution

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{137}_{52}\mathrm{Te} + {}^{\mathbf{97}}_{\mathbf{40}}\mathbf{Zr} + 2\,{}^{1}_{0}n + \text{energy} $$

# Chain Reaction

A **chain reaction** occurs

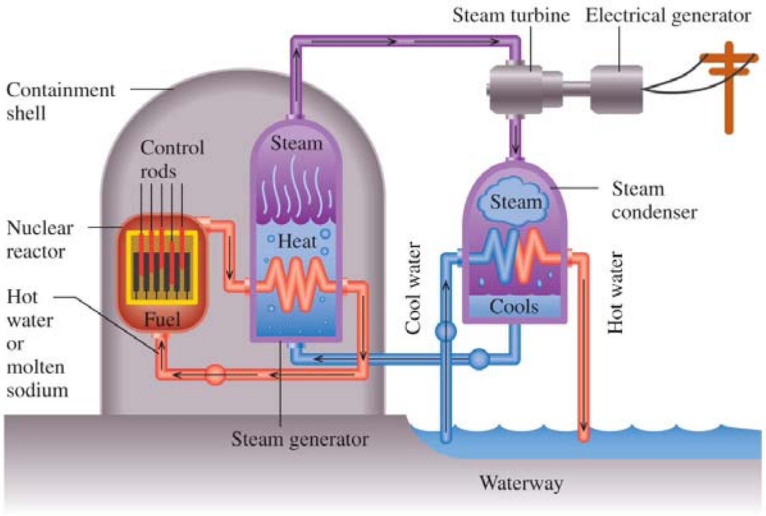
- when a critical mass of uranium undergoes fission.
- releasing a large amount of heat and energy that produces an atomic explosion.



# Nuclear Power Plants

In nuclear power plants,

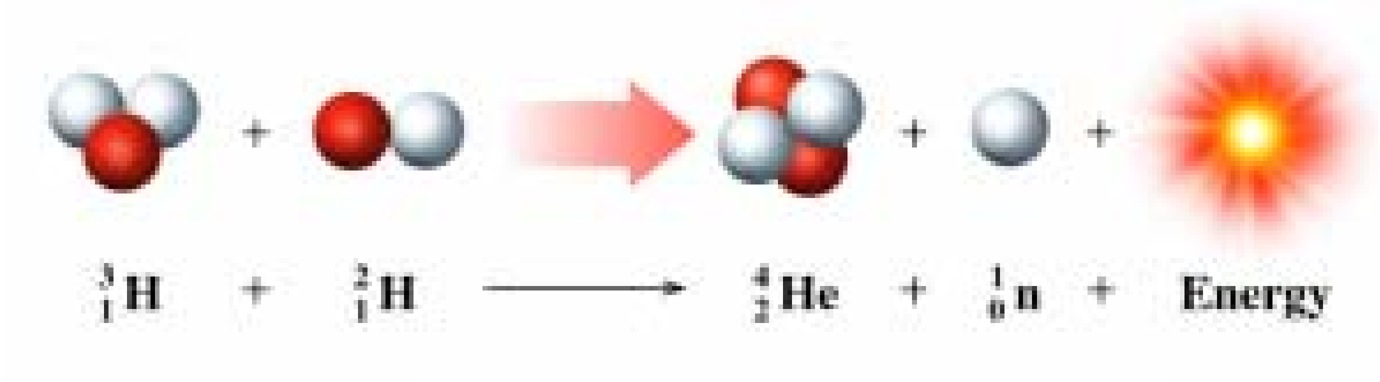
- fission is used to produce energy.
- control rods in the reactor absorb neutrons to slow and control the chain reactions of fission.



# Nuclear Fusion

**Fusion**

- occurs at extremely high temperatures (100 000 000 °C).
- combines small nuclei into larger nuclei.
- releases large amounts of energy.
- occurs continuously in the sun and stars.



# Learning Check

Indicate if each of the following describes
1) nuclear fission or 2) nuclear fusion.

____ A. a nucleus splits.
____ B. large amounts of energy are released.
____ C. small nuclei form larger nuclei.
____ D. hydrogen nuclei react.
____ E. several neutrons are released.

# Solution

Indicate if each of the following is
1) nuclear fission or 2) nuclear fusion.

_1_ A. a nucleus splits.
_1, 2_ B. large amounts of energy are released.
_2_ C. small nuclei form larger nuclei.
_2_ D. hydrogen nuclei react.
_1_ E. several neutrons are released.