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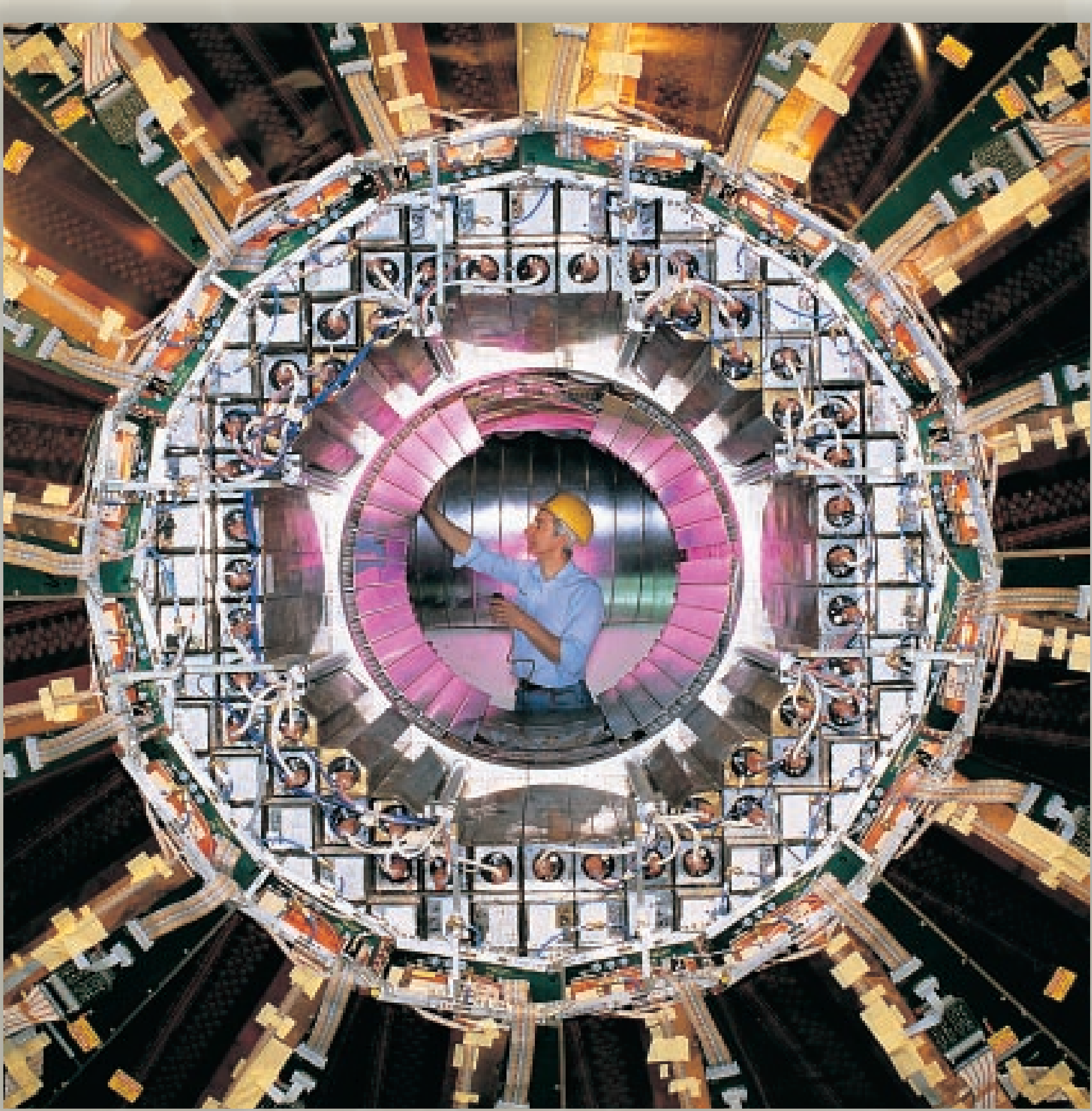
CHAPTER 22

Nuclear Chemistry



Particle detectors are important tools in the study of nuclear chemistry.

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The Nucleus

SECTION 22-1

OBJECTIVES

- Explain what a nuclide is, and describe the different ways nuclides can be represented.
- Define and relate the terms *mass defect* and *nuclear binding energy*.
- Explain the relationship between nucleon number and stability of nuclei.
- Explain why nuclear reactions occur, and know how to balance a nuclear equation.

Atomic nuclei are made of *protons and neutrons, which are collectively called* **nucleons.** In nuclear chemistry, *an atom is referred to as a* **nuclide** *and is identified by the number of protons and neutrons in its nucleus*. Nuclides can be represented in two ways: when a symbol such as $^{228}_{88}Ra$ is used, the superscript is the mass number and the subscript is the atomic number; the same nuclide can also be written as radium-228.

Mass Defect and Nuclear Stability

Because an atom is made of protons, neutrons, and electrons, you might expect the mass of an atom to be the same as the mass of an equal number of isolated protons, neutrons, and electrons. However, this is not the case. Let's consider a $^{4}_{2}He$ atom as an example. The combined mass of two protons, two neutrons, and two electrons is calculated below.

$$\begin{aligned}
&\text{2 protons:} && (2 \times 1.007\ 276\ \text{amu}) = 2.014\ 552\ \text{amu}\\
&\text{2 neutrons:} && (2 \times 1.008\ 665\ \text{amu}) = 2.017\ 330\ \text{amu}\\
&\text{2 electrons:} && (2 \times 0.000\ 5486\ \text{amu}) = \underline{0.001\ 097\ \text{amu}}\\
& && \text{total combined mass: } 4.032\ 979\ \text{amu}
\end{aligned}$$

However, the atomic mass of a $^{4}_{2}He$ atom has been measured to be 4.002 60 amu. The measured mass, 4.002 60 amu, is 0.030 38 amu *less* than the calculated mass, 4.032 98 amu. *The difference between the mass of an atom and the sum of the masses of its protons, neutrons, and electrons is called the* **mass defect.**

Nuclear Binding Energy

What causes the loss in mass? According to Albert Einstein's equation $E = mc^2$, mass can be converted to energy, and energy to mass. The mass defect is caused by the conversion of mass to energy upon formation of the nucleus. The mass units of the mass defect can be converted to energy units by using Einstein's equation. First, convert 0.030 38 amu to kilograms to match the units for energy, kg•m^2/s^2.

$$0.030\ 38\ \text{amu} \times \frac{1.6605 \times 10^{-27}\ \text{kg}}{1\ \text{amu}} = 5.0446 \times 10^{-29}\ \text{kg}$$

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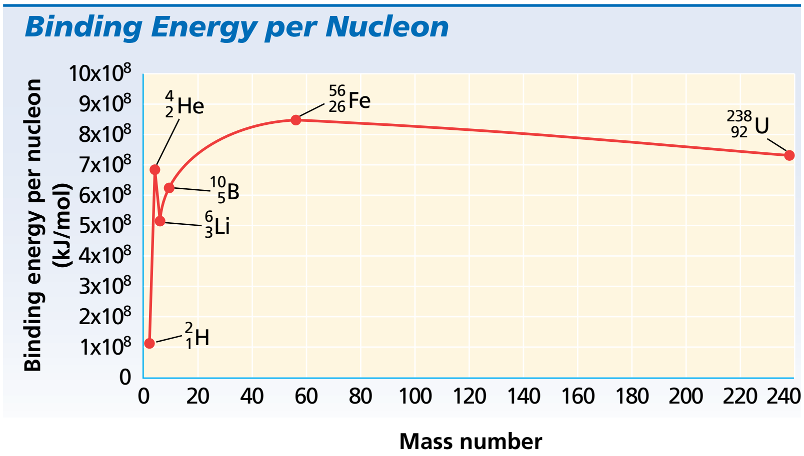

FIGURE 22-1 This graph shows the relationship between binding energy per nucleon and mass number. The binding energy per nucleon is a measure of the stability of a nucleus.

The energy equivalent can now be calculated.

$$E = mc^2$$
$$E = (5.0446 \times 10^{-29}\ \text{kg})(3.00 \times 10^8\ \text{m/s})^2$$
$$= 4.54 \times 10^{-12}\ \text{kg•m}^2/\text{s}^2 = 4.54 \times 10^{-12}\ \text{J}$$

This is the **nuclear binding energy,** *the energy released when a nucleus is formed from nucleons*. This energy can also be thought of as the amount of energy required to break apart the nucleus. Therefore, the nuclear binding energy is also a measure of the stability of a nucleus.

Binding Energy per Nucleon

The binding energy per nucleon is used to compare the stability of different nuclides, as shown in Figure 22-1. *The* **binding energy per nucleon** *is the binding energy of the nucleus divided by the number of nucleons it contains*. The higher the binding energy per nucleon, the more tightly the nucleons are held together. Elements with intermediate atomic masses have the greatest binding energies per nucleon and are therefore the most stable.

Nucleons and Nuclear Stability

Stable nuclides have certain characteristics. When the number of protons in stable nuclei is plotted against the number of neutrons, as shown in Figure 22-2, a beltlike graph is obtained. *This stable nuclei cluster over a range of neutron-proton ratios is referred to as the* **band of stability.** Among atoms having low atomic numbers, the most stable nuclei are those with a neutron-proton ratio of approximately 1:1. For example, $^{4}_{2}He$, a stable isotope of helium with two neutrons and two protons, has a neutron-proton ratio of 1:1. As the atomic number increases, the stable neutron-proton ratio increases to about 1.5:1. For example, $^{206}_{82}Pb$, with 124 neutrons and 82 protons, has a neutron-proton ratio of 1.51:1.

This trend can be explained by the relationship between the nuclear force and the electrostatic forces between protons. Protons in a nucleus repel all other protons through electrostatic repulsion, but the short

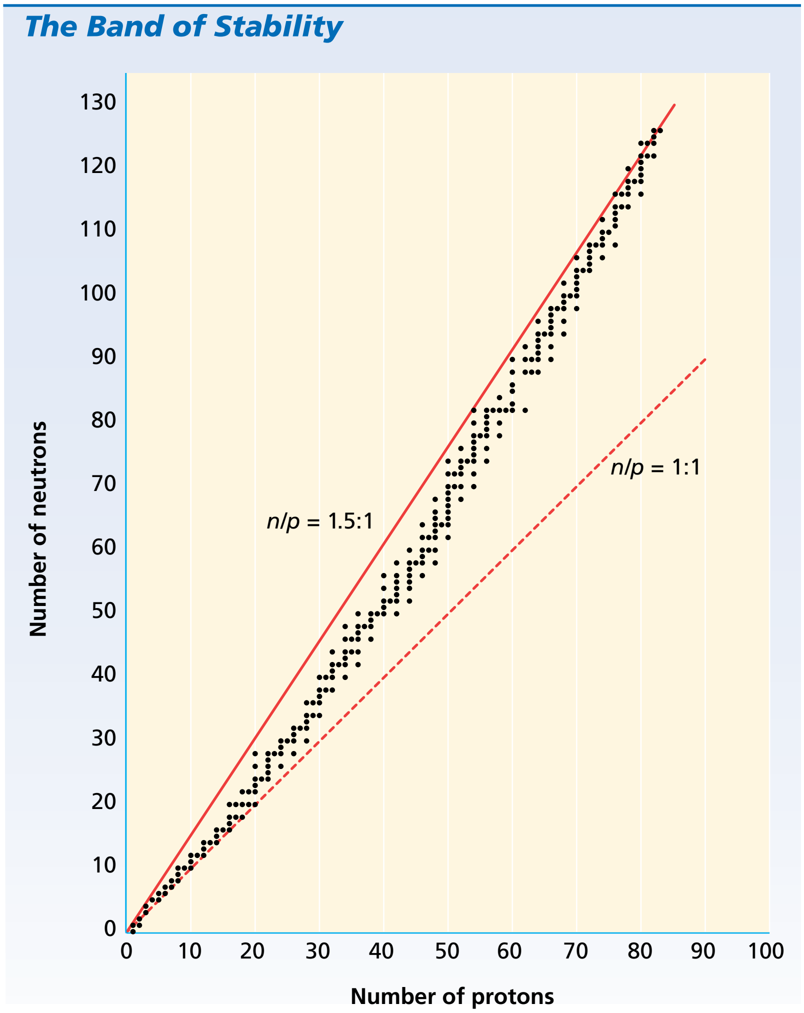

FIGURE 22-2 The neutron-proton ratios of stable nuclides cluster together in a region known as the band of stability. As the number of protons increases, the ratio increases from 1:1 to about 1.5:1.

range of the nuclear force allows them to attract only protons very close to them, as shown in Figure 22-3. So as the number of protons in a nucleus increases, the electrostatic force between protons increases faster than the nuclear force. More neutrons are required to increase the nuclear force and stabilize the nucleus. Beyond the atomic number 83, bismuth, the repulsive force of the protons is so great that no stable nuclides exist.

Stable nuclei tend to have even numbers of nucleons. Out of 265 stable nuclides, 159 have even numbers of both protons and neutrons. Only four nuclides have odd numbers of both. This indicates that stability of a nucleus is greatest when the nucleons—like electrons—are paired.

The most stable nuclides are those having 2, 8, 20, 28, 50, 82, or 126 protons, neutrons, or total nucleons. This extra stability at certain numbers supports a theory that nucleons—like electrons—exist at certain energy levels. According to the **nuclear shell model,** *nucleons exist in different energy levels, or shells, in the nucleus. The numbers of nucleons that represent completed nuclear energy levels—2, 8, 20, 28, 50, 82, and 126—are called* **magic numbers.**

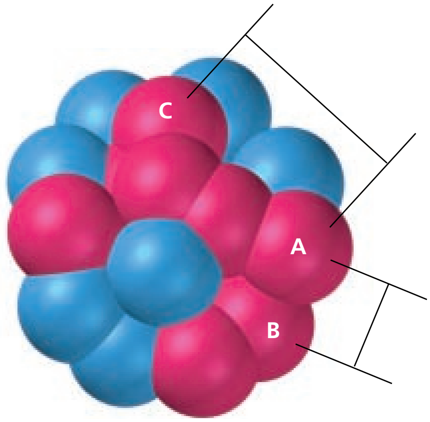

FIGURE 22-3 Proton A attracts proton B through the nuclear force but repels it through the electrostatic force. Proton A mainly repels proton C through the electrostatic force because the nuclear force reaches only a few nucleon diameters.

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Nuclear Reactions

Unstable nuclei undergo spontaneous changes that change their number of protons and neutrons. In this process, they give off large amounts of energy and increase their stability. These changes are a type of nuclear reaction. *A* **nuclear reaction** *is a reaction that affects the nucleus of an atom.* In equations representing nuclear reactions, the total of the atomic numbers and the total of the mass numbers must be equal on both sides of the equation. An example is shown below.

$$^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \longrightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}n$$

Notice that when the atomic number changes, the identity of the element changes. *A* **transmutation** *is a change in the identity of a nucleus as a result of a change in the number of its protons.*

SAMPLE PROBLEM 22-1

Identify the product that balances the following nuclear reaction: $^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + \underline{\ ?\ }$

SOLUTION

1. The total mass number and atomic number must be equal on both sides of the equation.

$$^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + \underline{\ ?\ }$$

mass number: $212 - 4 = 208$

atomic number: $84 - 2 = 82$

2. The nuclide has a mass number of 208 and an atomic number of 82, $^{208}_{82}\mathrm{Pb}$.
3. The balanced nuclear equation is $^{212}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + ^{208}_{82}\mathrm{Pb}$

PRACTICE

Complete the following nuclear equations:

1. $^{218}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + \underline{\ ?\ }$ — *Answer* $^{218}_{84}\mathrm{Po} \longrightarrow ^{4}_{2}\mathrm{He} + ^{214}_{82}\mathrm{Pb}$
2. $^{253}_{99}\mathrm{Es} + ^{4}_{2}\mathrm{He} \longrightarrow ^{1}_{0}n + \underline{\ ?\ }$ — *Answer* $^{253}_{99}\mathrm{Es} + ^{4}_{2}\mathrm{He} \longrightarrow ^{1}_{0}n + ^{256}_{101}\mathrm{Md}$
3. $^{142}_{61}\mathrm{Pm} + \underline{\ ?\ } \longrightarrow ^{142}_{60}\mathrm{Nd}$ — *Answer* $^{142}_{61}\mathrm{Pm} + ^{0}_{-1}e \longrightarrow ^{142}_{60}\mathrm{Nd}$

SECTION REVIEW

1. Define the following terms:
   a. nuclide
   b. nucleon
   c. mass defect
   d. nuclear binding energy
2. How is nuclear stability related to the neutron-proton ratio?
3. Why do unstable nuclides undergo nuclear reactions?
4. Complete and balance the following nuclear equations:
   a. $^{187}_{75}\mathrm{Re} + \underline{\ ?\ } \longrightarrow ^{188}_{75}\mathrm{Re} + ^{1}_{1}\mathrm{H}$
   b. $^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \longrightarrow \underline{\ ?\ } + ^{1}_{0}n$
   c. $^{22}_{11}\mathrm{Na} + \underline{\ ?\ } \longrightarrow ^{22}_{10}\mathrm{Ne}$

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Radioactive Decay

SECTION 22-2

OBJECTIVES

- Define and relate the terms *radioactive decay* and *nuclear radiation.*
- Describe the different types of radioactive decay and their effects on the nucleus.
- Define the term *half-life*, and explain how it relates to the stability of a nucleus.
- Define and relate the terms *decay series, parent nuclide,* and *daughter nuclide.*
- Explain how artificial radioactive nuclides are made, and discuss their significance.

In 1896, Henri Becquerel was studying the possible connection between light emission of some uranium compounds after exposure to sunlight and X-ray emission. He wrapped a photographic plate in a lightproof covering and placed a uranium compound on top of it. He then placed them in sunlight. The photographic plate was exposed even though it was protected from visible light, suggesting exposure by X rays. When he tried to repeat his experiment, cloudy weather prevented him from placing the experiment in sunlight. To his surprise, the plate was still exposed. This meant that sunlight was not needed to produce the rays that exposed the plate. The rays were produced by radioactive decay. **Radioactive decay** *is the spontaneous disintegration of a nucleus into a slightly lighter nucleus, accompanied by emission of particles, electromagnetic radiation, or both.* The radiation that exposed the plate was **nuclear radiation,** *particles or electromagnetic radiation emitted from the nucleus during radioactive decay.*

Uranium is a **radioactive nuclide,** *an unstable nucleus that undergoes radioactive decay*. Studies by Marie Curie and Pierre Curie found that of the elements known in 1896, only uranium and thorium were radioactive. In 1898, the Curies discovered two new radioactive metallic elements, polonium and radium. Since that time, many other radioactive nuclides have been identified. In fact, all of the nuclides beyond atomic number 83 are unstable and thus radioactive.

Types of Radioactive Decay

A nuclide's type and rate of decay depend on the nucleon content and energy level of the nucleus. Some common types of radioactive nuclide emissions are summarized in Table 22-1.

TABLE 22-1 *Radioactive Nuclide Emissions*

Type	Symbol	Charge	Mass (amu)
Alpha particle	${}^{4}_{2}He$	2+	4.002 60
Beta particle	${}^{0}_{-1}\beta$	1–	0.000 5486
Positron	${}^{0}_{+1}\beta$	1+	0.000 5486
Gamma ray	γ	0	0

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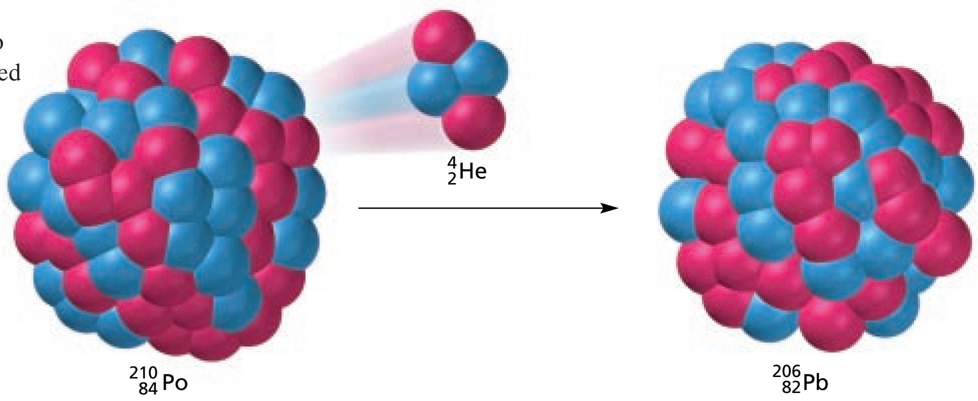

FIGURE 22-4 An alpha particle, identical to a helium nucleus, is emitted during the radioactive decay of some very heavy nuclei.

Alpha Emission

An **alpha particle** *(α) is two protons and two neutrons bound together and is emitted from the nucleus during some kinds of radioactive decay.* Alpha particles are helium nuclei and have a charge of 2+. They are often represented with the symbol $^{4}_{2}He$. Alpha emission is restricted almost entirely to very heavy nuclei. In these nuclei, both the number of neutrons and the number of protons need to be reduced in order to increase the stability of the nucleus. An example of alpha emission is the decay of $^{210}_{84}Po$ into $^{206}_{82}Pb$, shown in Figure 22-4. The atomic number decreases by two, and the mass number decreases by four.

$$^{210}_{84}Po \longrightarrow ^{206}_{82}Pb + ^{4}_{2}He$$

Beta Emission

Elements above the band of stability are unstable because they have too many neutrons. To decrease the number of neutrons, a neutron can be converted into a proton and an electron. The electron is emitted from the nucleus as a beta particle. *A* **beta particle** *(β) is an electron emitted from the nucleus during some kinds of radioactive decay.*

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

An example of beta emission, shown in Figure 22-5, is the decay of $^{14}_{6}C$ into $^{14}_{7}N$. Notice that the atomic number increases by one and the mass number stays the same.

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}\beta$$

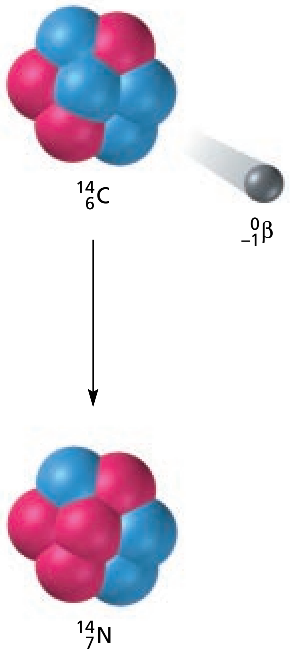

FIGURE 22-5 Beta emission causes the transmutation of $^{14}_{6}C$ into $^{14}_{7}N$. Beta emission is a type of radioactive decay in which a proton is converted to a neutron with the emission of a beta particle.

Positron Emission

Elements below the band of stability have too many protons to be stable. To decrease the number of protons, a proton can be converted into a neutron by emitting a positron. *A* **positron** *is a particle that has the same mass as an electron, but has a positive charge, and is emitted from the nucleus during some kinds of radioactive decay.*

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

An example of positron emission is the decay of $^{38}_{19}K$ into $^{38}_{18}Ar$. Notice that the atomic number decreases by one but the mass number stays the same.

$$^{38}_{19}K \longrightarrow {}^{38}_{18}Ar + {}^{0}_{+1}\beta$$

Electron Capture

Another type of decay for nuclides with too many protons is electron capture. *In* **electron capture,** *an inner orbital electron is captured by the nucleus of its own atom.* The inner orbital electron combines with a proton, and a neutron is formed.

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

An example of electron capture is the radioactive decay of $^{106}_{47}Ag$ into $^{106}_{46}Pd$. Just as in positron emission, the atomic number decreases by one but the mass number stays the same.

$$^{106}_{47}Ag + {}^{0}_{-1}e \longrightarrow {}^{106}_{46}Pd$$

Gamma Emission

Gamma rays (γ) *are high-energy electromagnetic waves emitted from a nucleus as it changes from an excited state to a ground energy state.* The position of gamma rays in the electromagnetic spectrum is shown in Figure 22-6. The emission of gamma rays is another piece of evidence supporting the nuclear shell model. According to the nuclear shell model, gamma rays are produced when nuclear particles undergo transitions in nuclear-energy levels. This is similar to the emission of light when an electron drops to a lower-energy level, which was covered in Chapter 4. Gamma emission usually occurs immediately following other types of decay, when other types of decay leave the nucleus in an excited state.

FIGURE 22-6 Gamma rays, like visible light, are a form of electromagnetic radiation, but they have a much shorter wavelength and are much higher in energy than visible light.

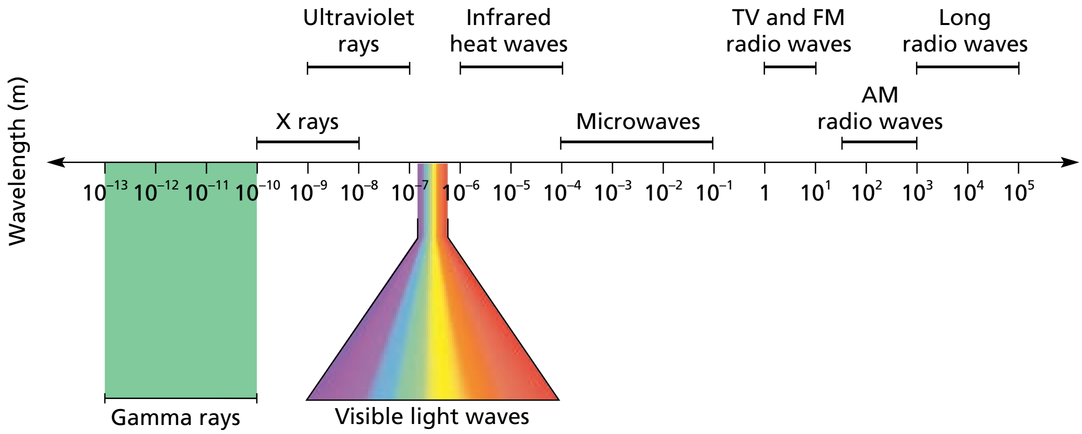

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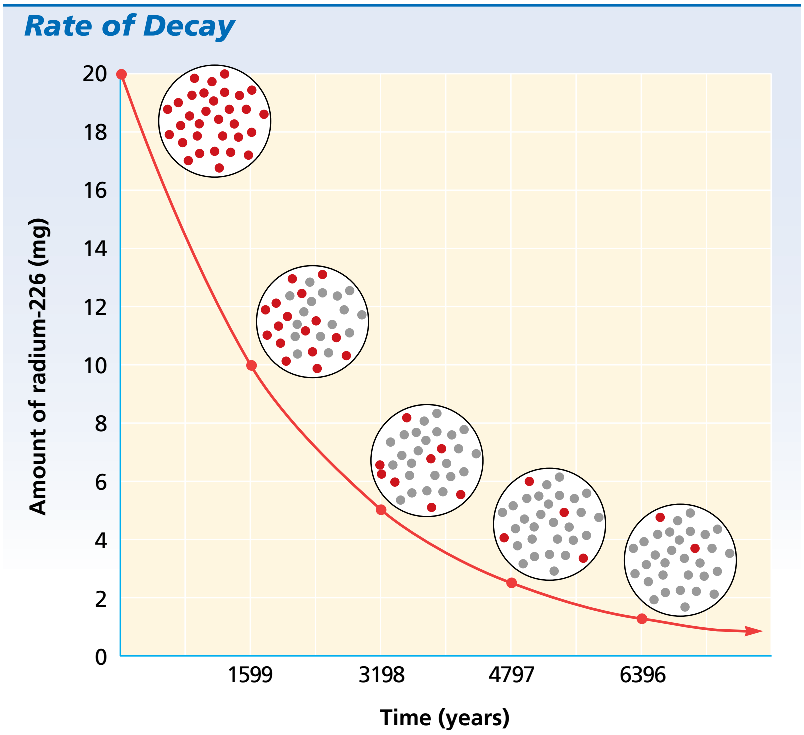
FIGURE 22-7 The half-life of radium-226 is 1599 years. Half of the remaining radium-226 decays by the end of each additional half-life.



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Half-Life

No two radioactive isotopes decay at the same rate. **Half-life,** $t_{1/2}$, *is the time required for half the atoms of a radioactive nuclide to decay.* Look at the graph of the decay of radium-226 in Figure 22-7. Radium-226 has a half-life of 1599 years. Half of a given amount of radium-226 decays in 1599 years. In another 1599 years, half of the remaining radium-226 decays. This process continues until there is a negligible amount of radium-226. Each radioactive nuclide has its own half-life. More-stable nuclides decay slowly and have longer half-lives. Less-stable nuclides decay very quickly and have shorter half-lives, sometimes just a fraction of a second. Some representative radioactive nuclides, along with their half-lives and types of decay, are given in Table 22-2.

TABLE 22-2 ***Representative Radioactive Nuclides and Their Half-Lives***

Nuclide	Half-life	Nuclide	Half-life
$^{3}_{1}H$	12.32 years	$^{214}_{84}Po$	163.7 μs
$^{14}_{6}C$	5715 years	$^{218}_{84}Po$	3.0 min
$^{32}_{15}P$	14.28 days	$^{218}_{85}At$	1.6 s
$^{40}_{19}K$	1.3×10^{9} years	$^{238}_{92}U$	4.46×10^{9} years
$^{60}_{27}Co$	10.47 min	$^{239}_{94}Pu$	2.41×10^{4} years

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SAMPLE PROBLEM 22-2

Phosphorus-32 has a half-life of 14.3 days. How many milligrams of phosphorus-32 remain after 57.2 days if you start with 4.0 mg of the isotope?

SOLUTION

1 ANALYZE

Given: original mass of phosphorus-32 = 4.0 mg
half-life of phosphorus-32 = 14.3 days
time elapsed = 57.2 days

Unknown: mass of phosphorus-32 remaining after 57.2 days

2 PLAN

To determine the number of milligrams of phosphorus-32 remaining, we must first find the number of half-lives that have passed in the time elapsed. Then the amount of phosphorus-32 is determined by reducing the original amount by half for every half-life that has passed.

$$\text{number of half-lives} = \text{time elapsed (days)} \times \frac{1 \text{ half-life}}{14.3 \text{ days}}$$

amount of phosphorus-32 remaining =
original amount of phosphorus-32 × $\frac{1}{2}$ for each half-life

3 COMPUTE

$$\text{number of half-lives} = 57.2 \text{ days} \times \frac{1 \text{ half-life}}{14.3 \text{ days}} = 4 \text{ half-lives}$$

$$\text{amount of phosphorus-32 remaining} = 4.0 \text{ mg} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 0.25 \text{ mg}$$

4 EVALUATE

A period of 57.2 years is four half-lives for phosphorus-32. At the end of one half-life, 2.0 mg of phosphorus-32 remains; 1.0 mg remains at the end of two half-lives; 0.50 mg remains at the end of three half-lives; and 0.25 mg remains at the end of four half-lives.

PRACTICE

1. The half-life of polonium-210 is 138.4 days. How many milligrams of polonium-210 remain after 415.2 days if you start with 2.0 mg of the isotope? — *Answer* 0.25 mg
2. Assuming a half-life of 1599 years, how many years will be needed for the decay of $\frac{15}{16}$ of a given amount of radium-226? — *Answer* 6396 years
3. The half-life of radon-222 is 3.824 days. After what time will one-fourth of a given amount of radon remain? — *Answer* 7.648 days
4. The half-life of cobalt-60 is 10.47 min. How many milligrams of cobalt-60 remain after 104.7 min if you start with 10.0 mg? — *Answer* 0.00977 mg
5. A sample contains 4.0 mg of uranium-238. After 4.46×10^9 years, the sample will contain 2.0 mg of uranium-238. What is the half-life of uranium-238? — *Answer* 4.46×10^9 years
6. A sample contains 16 mg of polonium-218. After 12 min, the sample will contain 1.0 mg of polonium-218. What is the half-life of polonium-218? — *Answer* 3.0 min

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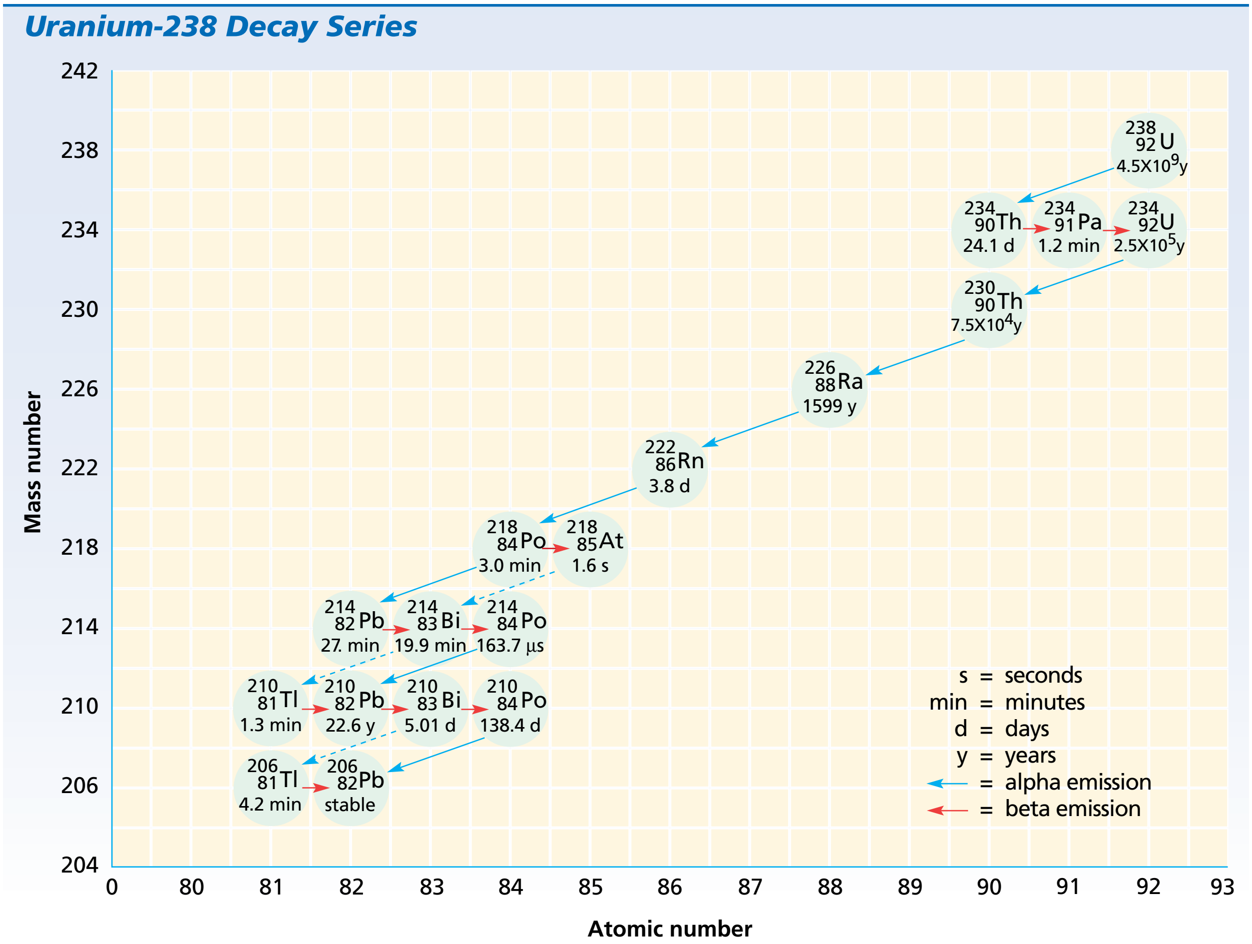
Decay Series

One nuclear reaction is not always enough to produce a stable nuclide. *A* **decay series** *is a series of radioactive nuclides produced by successive radioactive decay until a stable nuclide is reached. The heaviest nuclide of each decay series is called the* **parent nuclide.** *The nuclides produced by the decay of the parent nuclides are called* **daughter nuclides.** All naturally occurring nuclides with atomic numbers greater than 83 are radioactive and belong to one of three natural decay series. The parent nuclides are uranium-238, uranium-235, and thorium-232. The transmutations of the uranium-238 decay series are charted in Figure 22-8.

Locate the parent nuclide, uranium-238, on the chart. As the nucleus of uranium-238 decays, it emits an alpha particle. The mass number of the nuclide, and thus the vertical position on the graph, decreases by four. The atomic number, and thus the horizontal position, decreases by two. The daughter nuclide is an isotope of thorium.

$$^{238}_{92}U \longrightarrow \, ^{234}_{90}Th + \, ^{4}_{2}He$$

FIGURE 22-8 This chart shows the transmutations that occur as $^{238}_{92}U$ decays to the final, stable nuclide, $^{206}_{82}Pb$. Decay usually follows the solid arrows. The dotted arrows represent alternative routes of decay.



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The half-life of $^{234}_{90}Th$, about 24 days, is indicated on the chart. It decays by giving off beta particles. This increases its atomic number, and thus its horizontal position, by one. The mass number, and thus its vertical position, remains the same.

$$^{234}_{90}\text{Th} \longrightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$$

The remaining atomic number and mass number changes shown on the decay chart are also explained in terms of the particles given off. In the final step, $^{210}_{84}Po$ loses an alpha particle to form $^{206}_{82}Pb$. This is a stable, nonradioactive isotope of lead. Notice that $^{206}_{82}Pb$ contains 82 protons, a magic number. It contains the extra-stable nuclear configuration of a completed nuclear shell.

Artificial Transmutations

Artificial radioactive nuclides are radioactive nuclides not found naturally on Earth. They are made by **artificial transmutations,** *bombardment of stable nuclei with charged and uncharged particles.* Because neutrons have no charge, they can easily penetrate the nucleus of an atom. However, positively charged alpha particles, protons, and other ions are repelled by the nucleus. Because of this repulsion, great quantities of energy are required to bombard nuclei with these particles. The necessary energy may be supplied by accelerating these particles in the magnetic or electrical field of a particle accelerator. An example of an accelerator is shown in Figure 22-9.

FIGURE 22-9 This is an aerial view of the Fermi International Accelerator Laboratory (Fermilab), in Illinois. The particle accelerators are underground. The Tevatron ring, the larger particle accelerator, has a circumference of 4 mi. The smaller ring in the background is a new accelerator, the Main Injector.

TABLE 22-3 Reactions for the First Preparation of Several Transuranium Elements

Atomic number	Name	Symbol	Nuclear reaction
93	neptunium	Np	${}^{238}_{92}\text{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{92}\text{U}$ ${}^{239}_{92}\text{U} \longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\beta$
94	plutonium	Pu	${}^{238}_{93}\text{Np} \longrightarrow {}^{238}_{94}\text{Pu} + {}^{0}_{-1}\beta$
95	americium	Am	${}^{239}_{94}\text{Pu} + 2{}^{1}_{0}n \longrightarrow {}^{241}_{95}\text{Am} + {}^{0}_{-1}\beta$
96	curium	Cm	${}^{239}_{94}\text{Pu} + {}^{4}_{2}\text{He} \longrightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}n$
97	berkelium	Bk	${}^{241}_{95}\text{Am} + {}^{4}_{2}\text{He} \longrightarrow {}^{243}_{97}\text{Bk} + 2{}^{1}_{0}n$
98	californium	Cf	${}^{242}_{96}\text{Cm} + {}^{4}_{2}\text{He} \longrightarrow {}^{245}_{98}\text{Cf} + {}^{1}_{0}n$
99	einsteinium	Es	${}^{238}_{92}\text{U} + 15{}^{1}_{0}n \longrightarrow {}^{253}_{99}\text{Es} + 7{}^{0}_{-1}\beta$
100	fermium	Fm	${}^{238}_{92}\text{U} + 17{}^{1}_{0}n \longrightarrow {}^{255}_{100}\text{Fm} + 8{}^{0}_{-1}\beta$
101	mendelevium	Md	${}^{253}_{99}\text{Es} + {}^{4}_{2}\text{He} \longrightarrow {}^{256}_{101}\text{Md} + {}^{1}_{0}n$
102	nobelium	No	${}^{246}_{96}\text{Cm} + {}^{12}_{6}\text{C} \longrightarrow {}^{254}_{102}\text{No} + 4{}^{1}_{0}n$
103	lawrencium	Lr	${}^{252}_{98}\text{Cf} + {}^{10}_{5}\text{B} \longrightarrow {}^{258}_{103}\text{Lr} + 4{}^{1}_{0}n$

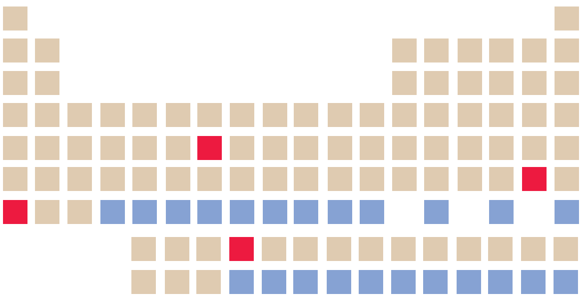

FIGURE 22-10 Artificial transmutations filled the gaps in the periodic table, shown in red, and extended the periodic table with the transuranium elements, shown in blue.

Artificial Radioactive Nuclides

Radioactive isotopes of all the natural elements have been produced by artificial transmutation. In addition, production of technetium, astatine, francium, and promethium by artificial transmutation has filled gaps in the periodic table. Their positions are shown in Figure 22-10.

Artificial transmutations are also used to produce the transuranium elements. **Transuranium elements** *are elements with more than 92 protons in their nuclei.* All of these elements are radioactive. The nuclear reactions for the synthesis of several transuranium elements are shown in Table 22-3. Currently, 17 artificially prepared transuranium elements have been reported. The positions of the transuranium elements in the periodic table are also shown in Figure 22-10.

SECTION REVIEW

1. Define *radioactive decay.*
2. a. What are the different types of radioactive decay?
   b. List the types of radioactive decay that involve conversion of particles.
3. What fraction of a given sample of a radioactive nuclide remains after four half-lives?
4. When does a decay series end?
5. Distinguish between natural and artificial radioactive nuclides.

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Nuclear Radiation

SECTION 22-3

Objectives

- Compare the penetrating ability and shielding requirements of alpha particles, beta particles, and gamma rays.
- Define the terms *roentgen* and *rem,* and distinguish between them.
- Describe three devices used in radiation detection.
- Discuss applications of radioactive nuclides.

In Becquerel's experiment, nuclear radiation from the uranium compound penetrated the lightproof covering and exposed the film. Different types of nuclear radiation have different penetrating abilities. Nuclear radiation includes alpha particles, beta particles, and gamma rays.

Alpha particles have a range of only a few centimeters in air and have a low penetrating ability due to their large mass and charge. They cannot penetrate skin. However, they can cause damage if ingested or inhaled. Beta particles travel at speeds close to the speed of light and have a penetrating ability about 100 times greater than that of alpha particles. They have a range of a few meters in air. Gamma rays have the greatest penetrating ability. The penetrating abilities and shielding requirements of different types of nuclear radiation are shown in Figure 22-11.

Radiation Exposure

Nuclear radiation can transfer its energy to the electrons of atoms or molecules and cause ionization. *The* **roentgen** *is a unit used to measure nuclear radiation; it is equal to the amount of radiation that produces* 2×10^9 *ion pairs when it passes through 1* cm^3 *of dry air.* Ionization can damage living tissue. Radiation damage to human tissue is measured in rems (roentgen equivalent, man). *One* **rem** *is the quantity of ionizing radiation that does as much damage to human tissue as is done by 1 roentgen of high-voltage X rays.* Cancer and genetic effects caused by DNA mutations are long-term radiation damage to living tissue. DNA

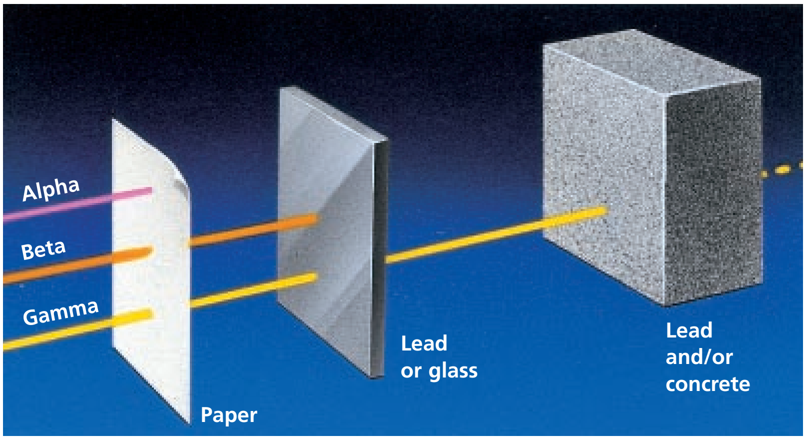

FIGURE 22-11 The different penetrating abilities of alpha particles, beta particles, and gamma rays require different levels of shielding. Alpha particles can be shielded with just a sheet of paper. Lead or glass is often used to shield beta particles. Gamma rays are the most penetrating and require shielding with thick layers of lead or concrete, or both.

can be mutated directly by interaction with radiation or indirectly by interaction with previously ionized molecules.

Everyone is exposed to environmental background radiation. Average exposure for people living in the United States is estimated to be about 0.1 rem per year. However, actual exposure varies. The maximum permissible dose of radiation exposure for a person in the general population is 0.5 rem per year. Airline crews and people who live at high altitudes have increased exposure levels because of increased cosmic-ray levels at high altitudes. Radon-222 trapped inside homes may also cause increased exposure. Because it is a gas, radon can move up from the soil into homes through cracks and holes in the foundation. Radon trapped in homes increases the risk of lung cancer among smokers.

Radiation Detection

Film badges, Geiger-Müller counters, and scintillation counters are three devices commonly used to detect and measure nuclear radiation. A film badge and a Geiger-Müller counter are shown in Figure 22-12. As previously mentioned, nuclear radiation exposes film just as visible light does. This property is used in film badges. **Film badges** *use exposure of film to measure the approximate radiation exposure of people working with radiation*. **Geiger-Müller counters** *are instruments that detect radiation by counting electric pulses carried by gas ionized by radiation.* Geiger-Müller counters are typically used to detect beta-particle radiation. Radiation can also be detected when it transfers its energy to substances that *scintillate,* or absorb ionizing radiation and emit visible light. **Scintillation counters** *are instruments that convert scintillating light to an electric signal for detecting radiation.*

(a) (b)

FIGURE 22-12 Film badges (a) and Geiger-Müller counters (b) are both used to detect nuclear radiation.

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Applications of Nuclear Radiation

Many applications are based on the fact that the physical and chemical properties of stable isotopes are essentially the same as those of radioactive isotopes of the same element. A few uses of radioactive nuclides are discussed below.

Radioactive Dating

Radioactive dating *is the process by which the approximate age of an object is determined based on the amount of certain radioactive nuclides present.* Such an estimate is based on the fact that radioactive substances decay with known half-lives. Age is estimated by measuring either the accumulation of a daughter nuclide or the disappearance of the parent nuclide.

Carbon-14 is radioactive and has a half-life of approximately 5715 years. It can be used to estimate the age of organic material up to about 50 000 years old. Nuclides with longer half-lives are used to estimate the age of older objects; methods using nuclides with long half-lives have been used to date minerals and lunar rocks more than 4 billion years old.

Radioactive Nuclides in Medicine

In medicine, radioactive nuclides, such as the artificial radioactive nuclide cobalt-60, are used to destroy certain types of cancer cells. Many radioactive nuclides are also used as **radioactive tracers,** *which are radioactive atoms that are incorporated into substances so that movement of the substances can be followed by radiation detectors.* Detection of radiation from radioactive tracers can be used to diagnose cancer and other diseases. See Figure 22-13.

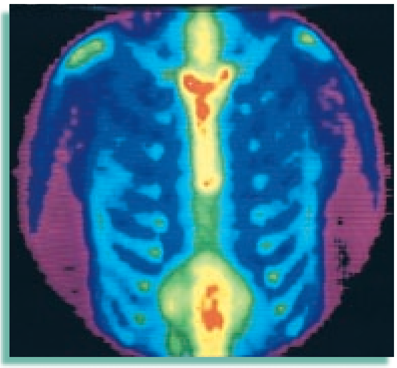

FIGURE 22-13 Radioactive nuclides, such as technetium-99, can be used to detect bone cancer. In this procedure, technetium-99 accumulates in areas of abnormal bone metabolism. Detection of the nuclear radiation then shows the location of bone cancer.

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Radioactive Nuclides in Agriculture

In agriculture, radioactive tracers in fertilizers are used to determine the effectiveness of the fertilizer. The amount of radioactive tracer absorbed by a plant indicates the amount of fertilizer absorbed. Nuclear radiation is also used to prolong the shelf life of food. For example, gamma rays from cobalt-60 can be used to kill bacteria and insects that spoil and infest food.

Nuclear Waste

Nuclear Fission and Nuclear Fusion

In nuclear fission, the nucleus of a very heavy atom, such as uranium, is split into two or more nuclei. The products of the fission include the nuclei as well as the nuclides formed from the fragments' radioactive decay. Fission is the primary system powering nuclear reactors, nuclear missiles, and nuclear-powered submarines and aircraft carriers. Fusion is the opposite process of fission. In fusion, very high temperatures and pressures are used to combine light atoms, such as hydrogen, to make heavier atoms, such as helium. Fusion is the primary process that fuels

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our sun and the stars. Creating and maintaining a fusion reaction is more complex and expensive than performing fission. Both fission and fusion release enormous amounts of energy that can be converted into heat and electricity, and both produce **nuclear waste.** Fission produces more waste than fusion. As new processes are developed to use energy from fission and fusion, a more vexing question arises: how to contain, store, and dispose of nuclear waste.

Containment of Nuclear Waste

Every radioactive substance has a half-life, which is the amount of time needed for half of a given material to decay into a stable nuclear form and lose its radioactivity. Radioactive waste from medical research, for example, has a half-life of a few months. Waste that is produced in a nuclear reactor will take hundreds of thousands of years to decay, and it needs to be contained so that living organisms can be shielded from radioactivity. There are two main types of containment: on-site storage and off-site disposal.

Storage of Nuclear Waste

The most common form of nuclear waste is spent fuel rods from nuclear power plants. These fuel rods can be contained above the ground by placing them in water pools or in dry casks. Each nuclear reactor in the United States has large pools of water where spent rods can be stored, and some of the radioactive materials will decay. When these pools are full, the rods are moved to dry casks, which are usually made of concrete and steel. Both storage pools and casks are meant for only temporary storage before the waste is moved to permanent underground storage facilities.

Disposal of Nuclear Waste

Disposal of nuclear waste is done with the intention of never retrieving the materials. Because of this, building disposal sites takes careful planning. Currently, there are 77 disposal sites around the United States. The U. S. Department of Energy is considering a new site near Las Vegas, Nevada, called Yucca Mountain, for the permanent disposal of much of this waste. This plan, however, is controversial—some organizations oppose the idea of the disposal site, and others have alternate plans. If the Yucca Mountain site is approved, nuclear waste will be transported there by truck and train beginning in 2010.

SECTION REVIEW

1. What is required to shield alpha particles? Why are these materials effective?
2. a. What is the average exposure of people living in the United States to environmental background radiation?
   b. How does this relate to the maximum permissible dose?
3. What device is used to measure the radiation exposure of people working with radiation?
4. Explain why nuclear radiation can be used to preserve food.
5. Explain how nuclear waste is contained, stored, and disposed of, and how each method affects the environment.

Nuclear Fission and Nuclear Fusion

SECTION 22-4

OBJECTIVES

- Define *nuclear fission, chain reaction,* and *nuclear fusion,* and distinguish between them.
- Explain how a fission reaction is used to generate power.
- Discuss the possible benefits and the current difficulty of controlling fusion reactions.

Nuclear Fission

Review Figure 22-1 on page 702, which shows that nuclei of intermediate mass are the most stable. *In* **nuclear fission,** *a very heavy nucleus splits into more-stable nuclei of intermediate mass.* This process releases enormous amounts of energy. Nuclear fission can occur spontaneously or when nuclei are bombarded by particles. When uranium-235 is bombarded with slow neutrons, a uranium nucleus may capture one of the neutrons, making it very unstable. The nucleus splits into medium-mass parts with the emission of more neutrons. The mass of the products is less than the mass of the reactants. The missing mass is converted to energy.

Nuclear Chain Reaction

When fission of an atom bombarded by neutrons produces more neutrons, a chain reaction can occur. *A* **chain reaction** *is a reaction in which the material that starts the reaction is also one of the products and can start another reaction.* As shown in Figure 22-14, two or three neutrons can be given off when uranium-235 fission occurs. These neutrons can cause the fission of other uranium-235 nuclei. Again neutrons are emitted, which

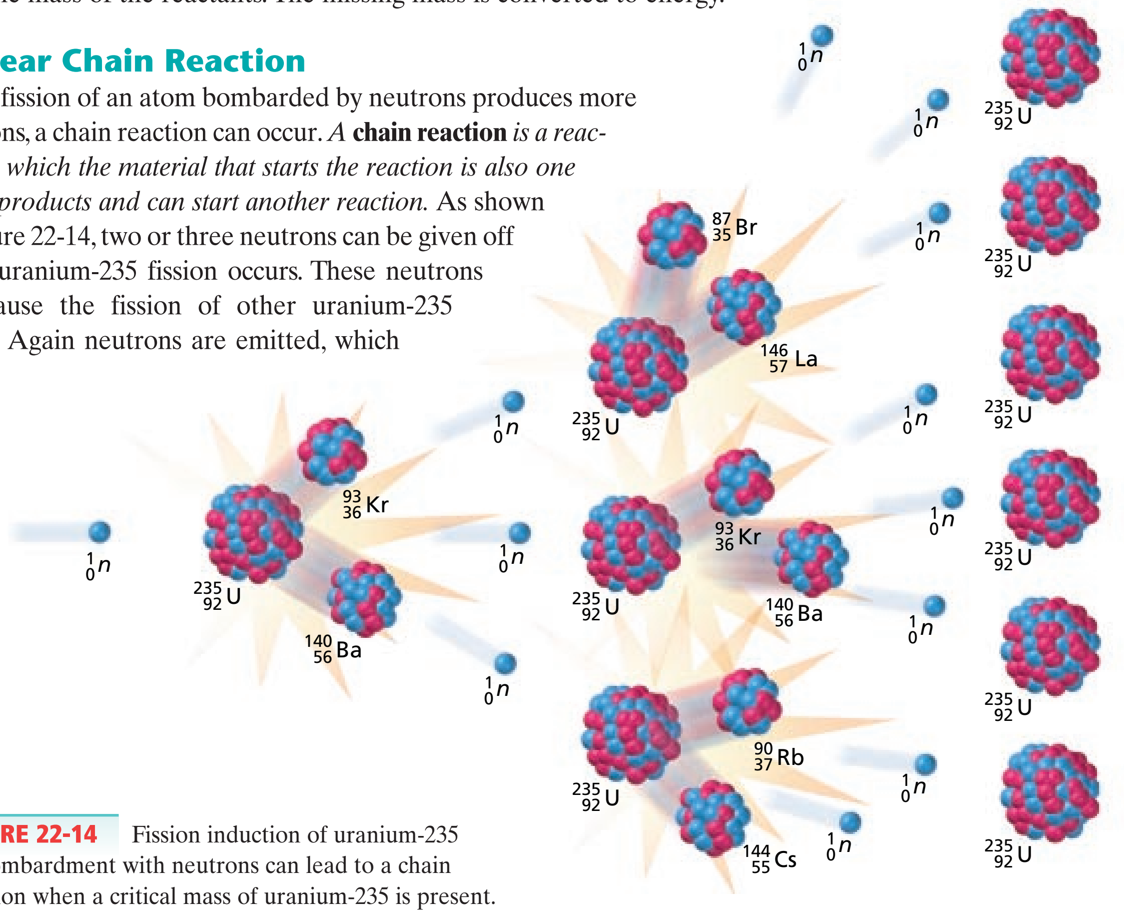

FIGURE 22-14 Fission induction of uranium-235 by bombardment with neutrons can lead to a chain reaction when a critical mass of uranium-235 is present.

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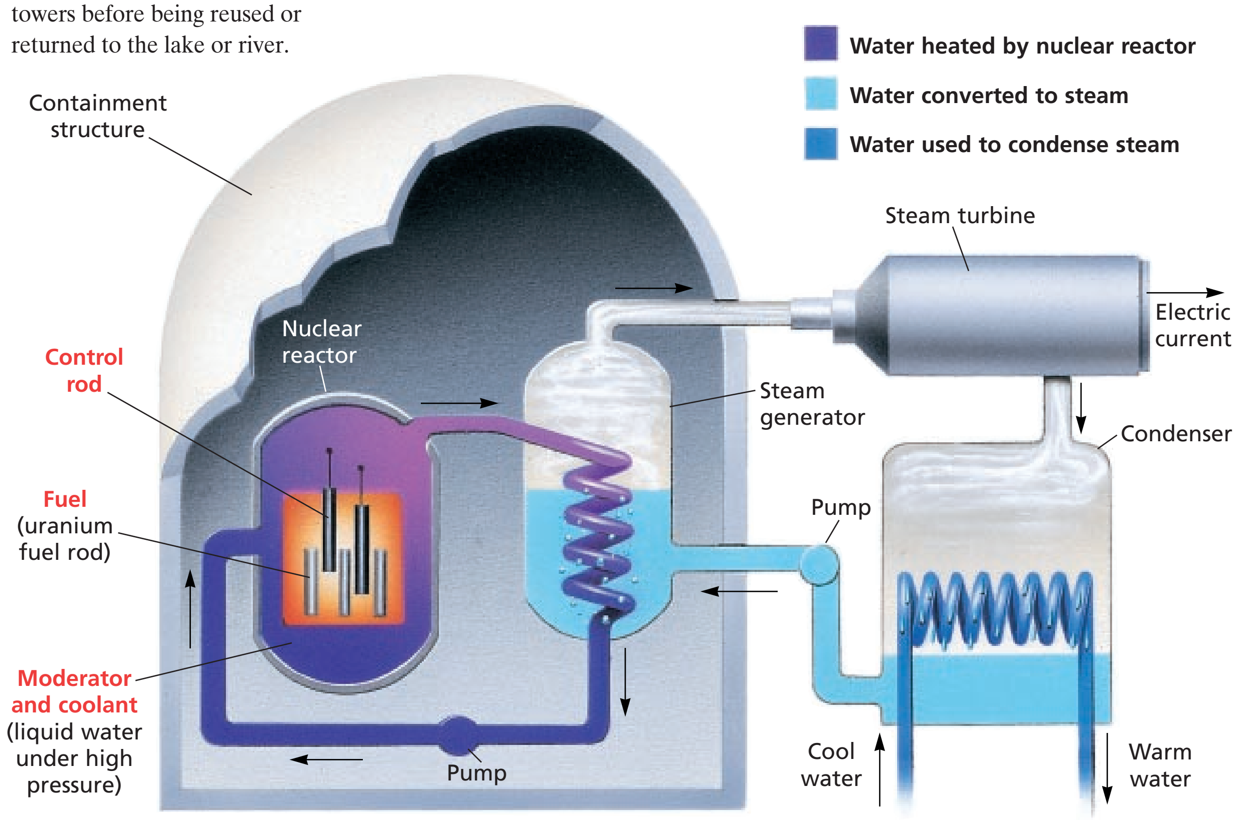
can cause the fission of still other uranium-235 nuclei. This chain reaction continues until all of the uranium-235 atoms have split or until the neutrons fail to strike uranium-235 nuclei. If the mass of uranium-235 is below a certain minimum, too many neutrons will escape without striking other nuclei, and the chain reaction will stop. *The minimum amount of nuclide that provides the number of neutrons needed to sustain a chain reaction is called the* **critical mass.** Uncontrolled chain reactions provide the explosive energy of atomic bombs. **Nuclear reactors** *use controlled-fission chain reactions to produce energy or radioactive nuclides*.

Nuclear Power Plants

Nuclear power plants *use heat from nuclear reactors to produce electrical energy*. They have five main components: shielding, fuel, control rods, moderator, and coolant. The components, shown in Figure 22-15, are surrounded by shielding. **Shielding** *is radiation-absorbing material that is used to decrease exposure to radiation, especially gamma rays, from nuclear reactors*. Uranium-235 is typically used as the fissionable fuel to produce heat, which is absorbed by the coolant. **Control rods** *are neutron-absorbing rods that help control the reaction by limiting the number of free neutrons.* Because fission of uranium-235 is more efficiently induced by slow neutrons, a **moderator** *is used to slow down the fast neutrons produced by fission*. Current problems with nuclear power plant development include environmental requirements, safety of operation, plant construction costs, and storage and disposal of spent fuel and radioactive wastes.

FIGURE 22-15 In this model of a nuclear power plant, pressurized water is heated by fission of uranium-235. This water is circulated to a steam generator. The steam drives a turbine to produce electricity. Cool water from a lake or river is then used to condense the steam into water. The warm water from the condenser may be cooled in cooling towers before being reused or returned to the lake or river.



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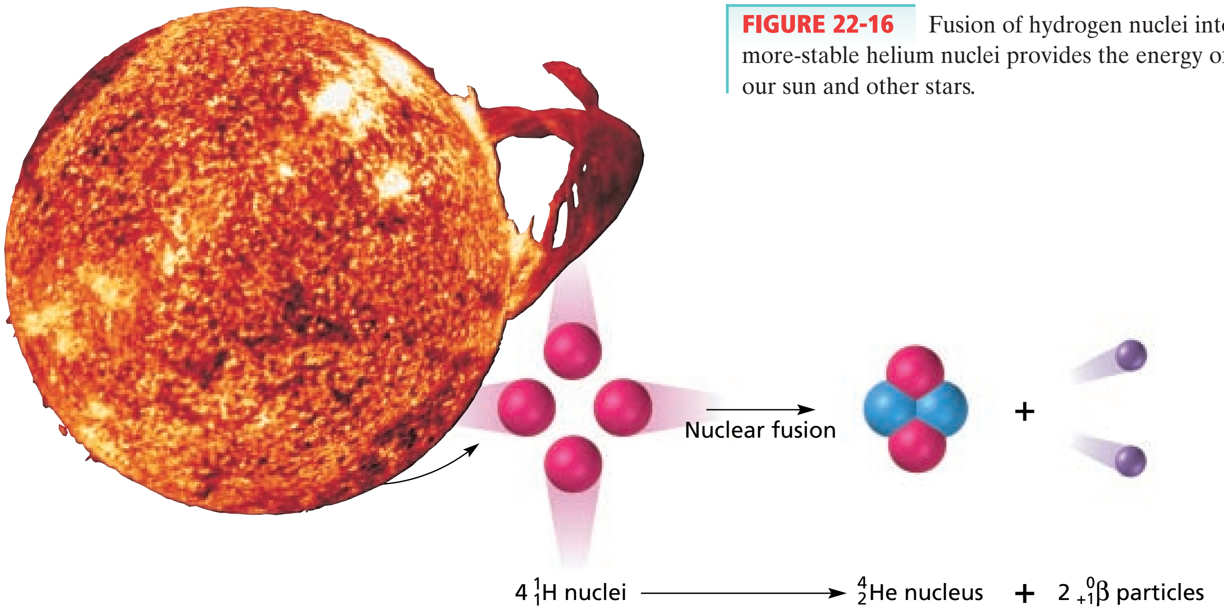


FIGURE 22-16 Fusion of hydrogen nuclei into more-stable helium nuclei provides the energy of our sun and other stars.

Nuclear Fusion

The high stability of nuclei with intermediate masses can also be used to explain nuclear fusion. *In* **nuclear fusion,** *light-mass nuclei combine to form a heavier, more stable nucleus.* Nuclear fusion releases even more energy per gram of fuel than nuclear fission. In our sun and other stars, four hydrogen nuclei combine at extremely high temperature and pressure to form a helium nucleus with a loss of mass and release of energy. This reaction is illustrated in Figure 22-16.

Uncontrolled fusion reactions of hydrogen are the source of energy for the hydrogen bomb, as shown in Figure 22-17. A fission reaction is used to provide the heat and pressure necessary to trigger the fusion of nuclei. Current research indicates that fusion reactions may be controllable if some major problems can be overcome. One of the problems is that no known material can withstand the initial temperatures, about 10^8 K, required to induce fusion at high temperatures. Methods that contain the fusion reactions within a magnetic field or induce fusion at lower temperatures are being investigated.

FIGURE 22-17 The enormous amount of energy released by fusion reactions is illustrated by this explosion of a hydrogen bomb.

SECTION REVIEW

1. Distinguish between nuclear fission and nuclear fusion.
2. Define *chain reaction.*
3. List the five main components of a nuclear power plant.
4. Explain how fusion is one of our sources of energy.

An Unexpected Finding

HISTORICAL PERSPECTIVE

The discovery of the artificial transmutation of uranium in 1934 triggered great excitement in science. Chemists preoccupied with identifying what they thought were the final missing elements of the periodic table suddenly had to consider the existence of elements beyond atomic number 92, while physicists began to probe the stability of the nucleus more deeply. By 1939, nuclear investigators in both fields had collaborated to provide a stunning explanation for the mysterious results of uranium's forced transformation.

Neutrons in Italy

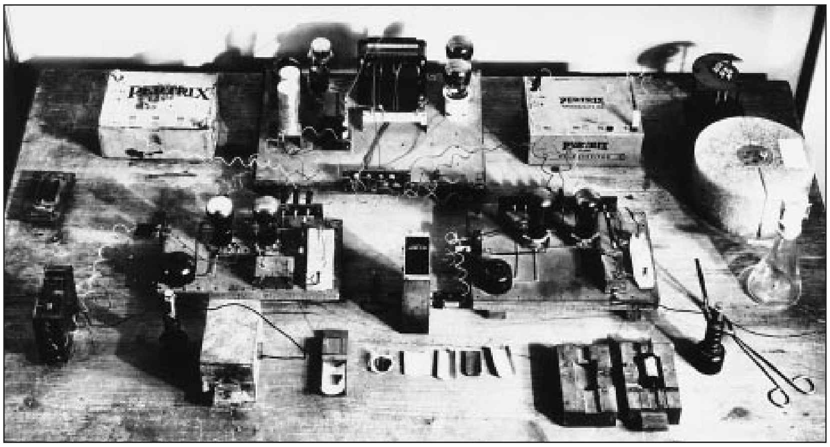
In 1934, uranium had the most protons of any known element, 92. But that year, Italian physicist Enrico Fermi believed he had synthesized elements with even higher atomic numbers. After bombarding a sample of uranium with neutrons, Fermi and co-workers recorded measurements that seemed to indicate that some uranium nuclei had absorbed neutrons and then undergone beta decay:

$$^{238}_{92}\mathrm{U} + ^{1}_{0}n \longrightarrow ^{239}_{92}\mathrm{U} \longrightarrow ^{239}_{93}? + ^{0}_{-1}\beta$$

His report noted further, subsequent beta decays, by which he hypothesized the existence of a whole new series of "transuranic" elements:

$$^{238}_{92}\mathrm{U} \longrightarrow ^{238}_{93}? + ^{0}_{-1}\beta \longrightarrow ^{238}_{94}?? + ^{0}_{-1}\beta \longrightarrow ^{238}_{95}??? + ^{0}_{-1}\beta$$

Unfortunately, the Italian group could not verify the existence of the transuranes because, as Fermi put it, "We did not know enough chemistry to separate the products of uranium disintegration from one another."



This apparatus from Otto Hahn's lab was used to produce fission reactions.

Curiosity in Berlin

Fermi's experiments caught the attention of a physicist in Berlin, Lise Meitner. Knowing that she could not perform the difficult task of chemically separating radionuclides either, Meitner persuaded a colleague, radiochemist Otto Hahn, to help her explain Fermi's results. Joined by expert chemical analyst Fritz Strassman, the team began investigating neutron-induced uranium decay at the end of 1934.

From the onset, the Berlin team, along with all other scientists at the time, operated under two false assumptions. The first involved the makeup of the bombarded nuclei. In every nuclear reaction observed previously, the resulting nucleus had never differed from the original by more than a few protons or neutrons. Thus, it was assumed that the products of neutron bombardment were radioisotopes of elements at most a few places in the periodic table before or beyond the atoms being bombarded (as Fermi had presumed in hypothesizing the transuranes).

The second assumption concerned the periodicity of the transuranes. Because the elements Ac, Th, Pa, and U chemically resembled the third-row transition elements, La, Hf, Ta, and W, it was believed that elements beyond U would correspondingly resemble those following W. Thus, the transuranes were thought to be homologues of Re, Os, Ir, Pt, and so on. This belief was generally unquestioned and seemed to be confirmed. In fact, by 1937 Hahn was sure of the chemical evidence of transuranes:

> *. . . the chemical behavior of the transuranes . . . is such that their position in the periodic system is no longer in doubt. . . . their chemical distinction from all previously known elements needs no further discussion.*

Meitner's Exile

By 1938, the political situation in Germany had become dangerous for Meitner. Because she was of Jewish descent, she was being targeted by the Nazis and fled to Sweden to escape persecution. Meanwhile in Berlin, the anti-Nazi Hahn and Strassman had to be careful of every move they made under the watchful eyes of the fascists around them.

Despite censorship, the Berlin team continued to communicate through letters. Meitner could not come up with a satisfying physical explanation for the chemical results of Hahn and Strassman, and she insisted that her partners re-examine their findings. As Strassman later recalled, Meitner

> *. . . requested that [the] experiments be scrutinized . . . one more time. . . . Fortunately L. Meitner's opinion and judgment carried so much weight . . . the necessary control experiments were immediately undertaken.*

The politics of World War II prevented Lise Meitner from receiving the Nobel Prize in physics for explaining nuclear fission.

A Shocking Discovery

Prompted by Meitner, Hahn and Strassman realized they had been looking in the wrong place to find the cause of their results. In analyzing a fraction of a solution assay that they had previously ignored, they found the critical evidence they had been seeking.

The analysis indicated that barium appeared to be a result of neutron bombardment of uranium. Suspecting the spectacular truth but lacking confidence, Hahn wrote to Meitner for an explanation. After consultation with her nephew, Otto Frisch, Meitner proposed that the uranium nuclei had been broken apart into elemental fragments, one of which was Ba. On January 3, 1939, she wrote to Hahn:

> *. . . the two of you really do have a splitting to Ba . . . a truly beautiful result, for which I most heartily congratulate you and Strassman.*

Thus, the transuranes turned out to be merely radioisotopes of known elements—atomic fragments of uranium atoms that had burst apart on being struck by neutrons.

For the discovery of this unexpected phenomenon, which Meitner named nuclear fission, the talented Hahn was awarded the 1944 Nobel Prize in chemistry. Due to wartime politics, however, Lise Meitner did not receive the corresponding award in physics, and she was not popularly recognized until well after her death in 1968 for her role in clarifying the process that she first explained and named.

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CHAPTER 22 REVIEW

CHAPTER SUMMARY

22-1

- The difference between the sum of the masses of the nucleons and electrons in an atom and the actual mass of an atom is the mass defect, or nuclear binding energy.
- Nuclear stability tends to be greatest when nucleons are paired, when there are magic numbers of nucleons, and when there are certain neutron-proton ratios.
- Nuclear reactions, represented by nuclear equations, can involve the transmutation of nuclides.

Vocabulary

band of stability (702)
binding energy per nucleon (702)
magic numbers (703)
mass defect (701)
nuclear binding energy (702)
nuclear reaction (704)
nuclear shell model (703)
nucleons (701)
nuclide (701)
transmutation (704)

22-2

- Radioactive nuclides become more stable by radioactive decay, a type of nuclear reaction.
- Alpha, beta, positron, and gamma emission, and electron capture are all types of radioactive decay. A nuclide's type of decay is related to its nucleon content and the energy level of the nucleus.
- The half-life of a radioactive nuclide is the length of time that it takes for half of a given number of atoms of the nuclide to decay.
- A decay series starts with a parent nuclide and ends with a stable daughter nuclide.
- Artificial transmutations are used to produce artificial radioactive nuclides, including the transuranium elements.

Vocabulary

alpha particle (706)
artificial transmutations (711)
beta particle (706)
daughter nuclides (710)
decay series (710)
electron capture (707)
gamma ray (707)
half-life (708)
nuclear radiation (705)
parent nuclide (710)
positron (706)
radioactive decay (705)
radioactive nuclide (705)
transuranium elements (712)

22-3

- Alpha particles, beta particles, and gamma rays have different penetrating abilities and therefore different shielding requirements.
- Film badges, Geiger-Müller counters, and scintillation detectors are used to detect radiation.
- Everyone is exposed to environmental background radiation. Exposure levels vary.
- Radioactive nuclides have many uses, including radioactive dating and cancer detection.
- Nuclear waste must be contained, stored, and disposed of in a way that does not harm people or the environment.

Vocabulary

film badges (714)
Geiger-Müller counters (714)
nuclear waste (716)
radioactive dating (715)
radioactive tracers (715)
rem (713)
roentgen (713)
scintillation counters (714)

22-4

- Nuclear fission and nuclear fusion are nuclear reactions in which the splitting and fusing of nuclei produce more stable nuclei and release enormous amounts of energy.
- Controlled fission reactions are used to produce energy and radioactive nuclides.
- Fusion reactions produce the sun's heat and light. If fusion reactions could be controlled, they would produce more usable energy per gram of fuel than fission reactions.

Vocabulary

chain reaction (717)
control rods (718)
critical mass (718)
moderator (718)
nuclear fission (717)
nuclear fusion (719)
nuclear power plant (718)
nuclear reactors (718)
shielding (718)

REVIEWING CONCEPTS

1. a. How does mass defect relate to nuclear binding energy?
   b. How does binding energy per nucleon vary with mass number?
   c. How does binding energy per nucleon affect the stability of a nucleus? (22-1)
2. Describe three ways in which the number of protons and the number of neutrons in a nucleus affect its stability. (22-1)
3. Where on the periodic table are most of the natural radioactive nuclides located? (22-2)
4. What changes in atomic number and mass number occur in each of the following types of radioactive decay?
   a. alpha emission
   b. beta emission
   c. positron emission
   d. electron capture (22-2)
5. Which types of radioactive decay cause the transmutation of a nuclide? (Hint: Review the definition of *transmutation*.) (22-2)
6. Explain how beta emission, positron emission, and electron capture affect the neutron-proton ratio. (22-2)
7. Write out the nuclear reactions that show particle conversion for the following types of radioactive decay:
   a. beta emission
   b. positron emission
   c. electron capture (22-2)
8. Compare and contrast electrons, beta particles, and positrons. (22-2)
9. a. What are gamma rays?
   b. How do scientists think they are produced? (22-2)
10. How does the half-life of a nuclide relate to its stability? (22-2)
11. List the three parent nuclides of the natural decay series. (22-2)
12. How are artificial radioactive isotopes produced? (22-2)
13. Neutrons are more effective than protons or alpha particles for bombarding atomic nuclei. Why? (22-2)
14. Why are all of the transuranium elements radioactive? (Hint: See Section 22-1.) (22-2)
15. Why can a radioactive material affect photographic film even though the film is well wrapped in black paper? (22-3)
16. How does the penetrating ability of gamma rays compare with that of alpha particles and beta particles? (22-3)
17. How does nuclear radiation damage biological tissue? (22-3)
18. Explain how film badges, Geiger-Müller counters, and scintillation detectors are used to detect radiation and measure radiation exposure. (22-3)
19. How is the age of an object containing a radioactive nuclide estimated? (22-3)
20. How is the fission of a uranium-235 nucleus induced? (22-4)
21. How does the fission of uranium-235 produce a chain reaction? (22-4)
22. Describe the purposes of the five major components of a nuclear power plant. (22-4)
23. Describe the reaction that produces the sun's energy. (22-4)
24. What is one problem that must be overcome before energy-producing controlled fusion reactions are a reality? (22-4)

PROBLEMS

Mass Defect

25. The mass of a $^{20}_{10}$Ne atom is 19.992 44 amu. Calculate its mass defect.
26. The mass of a $^{7}_{3}$Li atom is 7.016 00 amu. Calculate its mass defect.

Nuclear Binding Energy

27. Calculate the nuclear binding energy of one lithium-6 atom. The measured atomic mass of lithium-6 is 6.015 amu.
28. Calculate the binding energies of the following two nuclei, and indicate which releases more

energy when formed. You will need information from the periodic table and the text.
a. atomic mass 34.988011 amu, ${}^{35}_{19}K$
b. atomic mass 22.989767 amu, ${}^{23}_{11}Na$

29. a. What is the binding energy per nucleon for each nucleus in the previous problem?
b. Which nucleus is more stable?

30. The mass of ${}^{7}_{3}Li$ is 7.016 00 amu. Calculate the binding energy per nucleon for ${}^{7}_{3}Li$. Convert the mass in amu to binding energy in joules.

Neutron-Proton Ratio

31. Calculate the neutron-proton ratios for the following nuclides:
a. ${}^{12}_{6}C$
b. ${}^{3}_{1}H$
c. ${}^{206}_{82}Pb$
d. ${}^{134}_{50}Sn$

32. a. Locate the nuclides in problem 31 on the graph in Figure 22-2. Which ones lie on the band of stability?
b. For the stable nuclides, determine whether their neutron-proton ratio tends toward 1:1 or 1.5:1.

Nuclear Equations

33. Balance the following nuclear equations. (Hint: See Sample Problem 22-1.)
a. ${}^{43}_{19}K \longrightarrow {}^{43}_{20}Ca + \underline{\ ?\ }$
b. ${}^{233}_{92}U \longrightarrow {}^{229}_{90}Th + \underline{\ ?\ }$
c. ${}^{11}_{6}C + \underline{\ ?\ } \longrightarrow {}^{11}_{5}B$
d. ${}^{13}_{7}N \longrightarrow {}^{0}_{+1}\beta + \underline{\ ?\ }$

34. Write the nuclear equation for the release of an alpha particle by ${}^{210}_{84}Po$.

35. Write the nuclear equation for the release of a beta particle by ${}^{210}_{82}Pb$.

Half-Life

36. The half-life of plutonium-239 is 24 110 years. Of an original mass of 100.g, how much remains after 96 440 years? (Hint: See Sample Problem 22-2.)

37. The half-life of thorium-227 is 18.72 days. How many days are required for three-fourths of a given amount to decay?

38. Exactly $\frac{1}{16}$ of a given amount of protactinium-234 remains after 26.76 hours. What is the half-life of protactinium-234?

39. How many milligrams remain of a 15.0 mg sample of radium-226 after 6396 years? The half-life of radium-226 is 1599 years.

MIXED REVIEW

40. Balance the following nuclear reactions;
a. ${}^{239}_{93}Np \longrightarrow {}^{0}_{-1}\beta + \underline{\ ?\ }$
b. ${}^{9}_{4}Be + {}^{4}_{2}He \longrightarrow \underline{\ ?\ }$
c. ${}^{32}_{15}P + \underline{\ ?\ } \longrightarrow {}^{33}_{15}P$
d. ${}^{236}_{92}U \longrightarrow {}^{94}_{36}Kr + \underline{\ ?\ } + 3\,{}^{1}_{0}n$

41. After 4797 years, how much of an original 0.250 g of radium-226 remains? Its half-life is 1599 years.

42. The parent nuclide of the thorium decay series is ${}^{232}_{90}Th$. The first four decays are as follows: alpha emission, beta emission, beta emission, and alpha emission. Write the nuclear equations for this series of emissions.

43. The half-life of radium-224 is 3.66 days. What was the original mass of radium-224 if 0.0500 g remains after 7.32 days?

44. Calculate the neutron-proton ratios for the following nuclides, and determine where they lie in relation to the band of stability.
a. ${}^{235}_{92}U$
b. ${}^{16}_{8}O$
c. ${}^{56}_{26}Fe$
d. ${}^{156}_{60}Nd$

45. Calculate the binding energy per nucleon of ${}^{238}_{92}U$ in joules. The atomic mass of a ${}^{238}_{92}U$ nucleus is 238.050 784 amu.

46. The energy released by the formation of a nucleus of ${}^{56}_{26}Fe$ is 7.89×10^{-11} J. Use Einstein's equation, $E = mc^2$, to determine how much mass is lost (in kilograms) in this process.

47. Calculate the binding energy for one mole of deuterium atoms. The measured mass of deuterium is 2.0140 amu.

CRITICAL THINKING

48. Why do we compare binding energy per nuclear particle of different nuclides instead of the total binding energy per nucleus?

49. Why is the constant rate of decay of radioactive nuclei so important in radioactive dating?

50. Which of the following nuclides of carbon is most likely to be stable? State reasons for your answer.
a. $^{11}_{6}C$ b. $^{12}_{6}C$

51. Which of the following nuclides of iron are most likely to be stable? State reasons for your answer.
a. $^{56}_{26}Fe$ b. $^{59}_{26}Fe$

52. Use the data in the table shown to determine
a. which isotopes would be best for dating ancient rocks.
b. which isotopes could be used as tracers.
State reasons for your answers.

Element	Half-Life
Potassium-40	1.28×10^9 yr
Potassium-42	12.36 h
Uranium-238	4.468×10^9 yr
Uranium-239	23.47 min

RESEARCH & WRITING

53. Investigate the history of the Manhattan Project.

54. Research the 1986 nuclear reactor accident at Chernobyl, Ukraine. What factors combined to cause the accident?

55. Find out about the various fusion-energy research projects that are being conducted in the United States and other parts of the world. How close are the researchers to finding an economical method of producing energy? What obstacles must still be overcome?

ALTERNATIVE ASSESSMENT

56. Using the library, research the medical uses of radioactive isotopes such as cobalt-60 and technetium-99. Evaluate the benefits and risks of using radioisotopes in the diagnosis and treatment of medical conditions. Report your findings to the class.