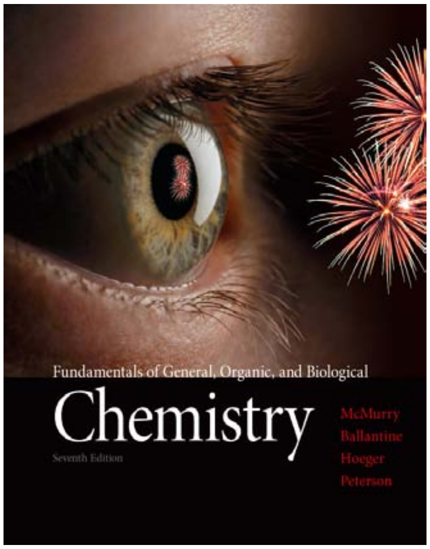
Chapter 11 Lecture



Fundamentals of General, Organic, and Biological Chemistry

7th Edition

McMurry, Ballantine, Hoeger, Peterson

Chapter Eleven

Nuclear Chemistry

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ALWAYS LEARNING PEARSON

Outline

Goals

1. **What is a nuclear reaction, and how are equations for nuclear reactions balanced?**
   Be able to write and balance equations for nuclear reactions.
2. **What are the different kinds of radioactivity?**
   Be able to list the characteristics of three common kinds of radiation—*α*, *β*, and *γ* (alpha, beta, and gamma).
3. **How are the rates of nuclear reactions expressed?**
   Be able to explain half-life and calculate the quantity of a radioisotope remaining after a given number of half-lives
4. **What is ionizing radiation?**
   Be able to describe the properties of the different types of ionizing radiation and their potential for harm to living tissue.
5. **How is radioactivity measured?**
   Be able to describe the common units for measuring radiation
6. **What is transmutation?**
   Be able to explain nuclear bombardment and balance equations for nuclear bombardment reactions.
7. **What are nuclear fission and nuclear fusion?**
   Be able to explain nuclear fission and nuclear fusion.

11.1 Nuclear Reactions

- An atom is characterized by its *atomic number, Z*, and its *mass number, A*.
- The mass number gives the total number of **nucleons**, a general term for both protons (p) and neutrons (n).
- Atoms with identical atomic numbers but different mass numbers are called *isotopes*, and the nucleus of a specific isotope is called a **nuclide**.

11.1 Nuclear Reactions

- A reaction involves a change in an atom's nucleus.
- A reaction involves a change in distribution of the outer-shell electrons around the atom and never changes the nucleus or produces a different element.
- Different isotopes have the same behavior in chemical reactions but often have completely different behavior in nuclear reactions.
- The rate of a nuclear reaction is unaffected by a change in temperature or pressure or by the addition of a catalyst.

11.1 Nuclear Reactions

- The nuclear reaction of an atom is the same whether it is in a chemical compound or in elemental form.
- The energy change accompanying a nuclear reaction can be several million times greater than that accompanying a chemical reaction.
  - The nuclear transformation of 1.0 g of uranium-235 releases 3.4×10^8 kcal.
  - The chemical combustion of 1.0 g of methane releases12 kcal.

11.2 The Discovery and Nature of Radioactivity

- In 1896, French physicist Henri Becquerel made a remarkable observation.
- Becquerel placed a uranium-containing mineral on top of a photographic plate.
- On developing the plate, Becquerel found a silhouette of the mineral.
- He concluded that the mineral was producing some kind of unknown radiation.

11.2 The Discovery and Nature of Radioactivity

- Marie Sklodowska Curie and her husband, Pierre found that the source of the radioactivity was the element uranium (U).
- Two previously unknown elements, which they named polonium and radium, are also radioactive.
- Becquerel and the Curies shared the 1903 Nobel Prize in physics.
- Further work by Ernest Rutherford established that there were two types of radiation, which he named *alpha* and *beta*.
- Soon thereafter, a third type of radiation was found and named for the third Greek letter, *gamma*.

11.2 The Discovery and Nature of Radioactivity

- When the three kinds of radiation are passed between plates with opposite electrical charges, each is affected differently.
  - Alpha radiation is deflected toward the negative plate;
  - Beta radiation is deflected toward the positive plate;
  - Gamma radiation is not deflected.
- Another difference is their mass:
  - **Gamma radiation** consists of high-energy electromagnetic waves and has no mass;
  - A **beta particle** is an electron;
  - An **alpha particle** is a helium nucleus.

11.2 The Discovery and Nature of Radioactivity

- A third difference is penetrating power:
  - Alpha particles move slowly (up to about one-tenth the speed of light) and can be stopped by a few sheets of paper or by the top layer of skin.
  - Beta particles move at up to nine-tenths the speed of light and have about 100 times the penetrating power of alpha particles.
  - Gamma rays move at the speed of light and have about 1000 times the penetrating power of alpha particles. A lead block several inches thick is needed to stop gamma radiation, which can otherwise penetrate and damage the body's internal organs.

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11.2 The Discovery and Nature of Radioactivity

TABLE 11.1 Characteristics of α, β, and γ Radiation

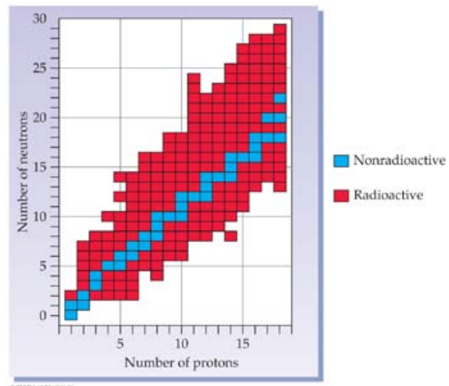
Type of Radiation	Symbol	Charge	Composition	Mass (AMU)	Velocity	Relative Penetrating Power
Alpha	α, ${}^{4}_{2}He$	+2	Helium nucleus	4	Up to 10% speed of light	Low (1)
Beta	β, ${}^{0}_{-1}e$	−1	Electron	1/1823	Up to 90% speed of light	Medium (100)
Gamma	γ, ${}^{0}_{0}\gamma$	0	High-energy radiation	0	Speed of light (3.00×10^{8} m/s)	High (1000)

11.3 Stable and Unstable Isotopes

- Every element in the periodic table has at least one radioactive isotope, or **radioisotope**.
- Radioactivity is the result of unstable nuclei, although the exact causes of this instability are not fully understood.
- Radiation is emitted when an unstable **radionuclide** spontaneously changes into a more stable one.

11.3 Stable and Unstable Isotopes

- In the first few rows of the periodic table, stability is associated with a roughly equal number of neutrons and protons.
- As elements get heavier, the number of neutrons relative to protons in stable nuclei increases.



11.3 Stable and Unstable Isotopes

- Most of the more than 3300 known radioisotopes have been made in high-energy particle accelerators.
- All isotopes of the transuranium elements (those heavier than uranium) are artificial.
- The much smaller number of radioactive isotopes found in the earth's crust are called *radioisotopes*.
- Radioisotopes have the same chemical properties as stable isotopes, which accounts for their great usefulness as *tracers*.

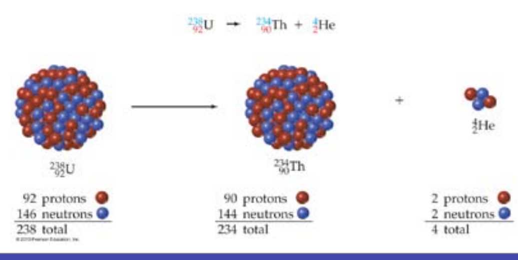
11.4 Nuclear Decay

- The spontaneous emission of a particle from an unstable nucleus is called **nuclear decay** or *radioactive decay*.
- The resulting change of one element into another is called **transmutation**.
- The equation for a nuclear reaction is not balanced in the usual sense because the k atoms are not the same on both sides.
- A nuclear equation is balanced when the number of nucleons is the same on both sides of the equation and when the sums of the charges are the same on both sides.

11.4 Nuclear Decay

Alpha Emission

- When an atom of uranium-238 emits an alpha particle, the nucleus loses two protons and two neutrons.
- Because the number of protons in the nucleus has now changed from 92 to 90, the *identity* of the atom has changed from uranium to thorium.



11.4 Nuclear Decay

Beta Emission

- Beta emission involves the *decomposition* of a neutron to yield an electron and a proton.
- The electron is ejected as a beta particle, and the proton is retained by the nucleus.
- The atomic number of the atom increases by 1 because there is a new proton.
- The mass number of the atom remains the same.

11.4 Nuclear Decay

Gamma Emission

- Emission of gamma rays causes no change in mass or atomic number because gamma rays are simply high-energy electromagnetic waves.
- It usually accompanies transmutation as a mechanism for the new nucleus to get rid of some extra energy.
- Emission affects neither mass number nor atomic number, so is often omitted from nuclear equations.
- Gamma rays' penetrating power makes them the most dangerous kind of external radiation and also makes them useful in medical applications.

11.4 Nuclear Decay

Positron Emission

- *Positron emission* involves the conversion of a proton in the nucleus into a neutron plus an ejected **positron**.
- A positron, which can be thought of as a "positive electron," has the same mass as an electron but a positive charge.
- The result of positron emission is a decrease in the atomic number of the product nucleus because a proton has changed into a neutron, but no change in the mass number.

11.4 Nuclear Decay

Electron Capture

- **Electron capture** is a process in which the nucleus captures an inner-shell electron from the surrounding electron cloud.
- A proton is converted into a neutron, and energy is released in the form of gamma rays.
- The mass number of the product nucleus is unchanged, but the atomic number decreases by 1.

11.4 Nuclear Decay

- Unstable isotopes that have more protons than neutrons are more likely to undergo β decay to convert a proton to a neutron.
- Unstable isotopes having more neutrons than protons are more likely to undergo either positron emission or electron capture to convert a neutron to a proton.
- Very heavy isotopes (Z>83) will most likely undergo α-decay to lose both neutrons and protons to decrease the atomic number.

11.4 Nuclear Decay

TABLE 11.2 A Summary of Radioactive Decay Processes

Process	Symbol	Change in Atomic Number	Change in Mass Number	Change in Number of Neutrons
α emission	${}^{4}_{2}He$ or α	−2	−4	−2
β emission	${}^{0}_{-1}e$ or β^{-}*	+1	0	−1
γ emission	${}^{0}_{0}\gamma$ or γ	0	0	0
Positron emission	${}^{0}_{1}e$ or β^{+}*	−1	0	+1
Electron capture	E.C.	−1	0	+1

*Superscripts are used to indicate the charge associated with the two forms of beta decay; β^{-}, or a beta particle, carries a −1 charge, while β^{+}, or a positron, carries a +1 charge.

11.5 Radioactive Half-Life

- The rate of radioactive decay varies greatly from one radioisotope to another.
- Rates of nuclear decay are measured in units of **half-life** ($t_{1/2}$) defined as the amount of time required for one-half of a radioactive sample to decay.
- Fraction remaining = $(0.5)^n$ where *n* is the number of half-lives that have elapsed.

11.5 Radioactive Half-Life

- Carbon-14 atoms are produced in the upper atmosphere.
- Carbon-14 is then taken up by plants during photosynthesis. When plants are eaten by animals, carbon-14 enters the food chain.
- The ratio of C-14 to C-12 in a living organism is the same as that in the atmosphere—about 1 part in 10^{12}.
- When the plant or animal dies, the ratio slowly decreases as C-14 undergoes radioactive decay. At 5730 years (one half-life) after the death of the organism, the ratio has decreased by a factor of 2.
- By measuring the amount of C-14 remaining in the traces of any once-living organism, archaeologists can determine how long ago the organism died.

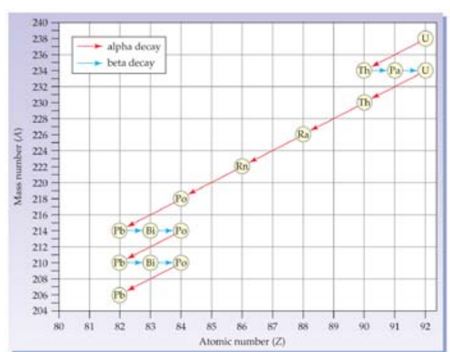
11.5 Radioactive Half-Life

Medical Uses of Radioactivity

- **In Vivo Procedures:**
  - In vivo studies take place inside the body and are carried out to assess the functioning of a particular organ or body system. A *radiopharmaceutical* agent is administered, and its path determined by analysis of blood or urine samples.
- **Therapeutic Procedures:**
  - External radiation therapy for the treatment of cancer is often carried out with γ rays emanating from a cobalt-60 source.
  - To treat some tumors a radioactive source is placed physically close to the tumor for a specific amount of time.
  - In boron neutron-capture therapy (BNCT), boron-containing drugs are administered to a patient and concentrate in the tumor site. The tumor is then irradiated with a neutron beam from a nuclear reactor. The boron absorbs a neutron and undergoes transmutation to produce an alpha particle and a lithium nucleus.

11.6 Radioactive Decay Series

- When a radioactive isotope decays, nuclear change occurs and a different element is formed.
- Sometimes the product nucleus is radioactive and undergoes further decay.
- Some radioactive nuclei undergo a whole **decay series** of nuclear disintegrations before they ultimately reach a nonradioactive product.



11.6 Radioactive Decay Series

- One of the intermediate radionuclides in the uranium-238 decay series is radium-226.
- Radium-226 has a half-life of 1600 years and undergoes decay to produce radon-222, a gas.
- Radon is a gas that passes in and out of the lungs without being incorporated into body tissue.
- If a radon-222 atom should decay while in the lungs, the solid decay product polonium-218 results. Further decay emits alpha particles, which can damage lung tissue.

11.7 Ionizing Radiation

- High-energy radiation of all kinds is also called **ionizing radiation**.
- This includes alpha particles, beta particles, gamma rays, and also *X rays* and *cosmic rays*.
- **X rays** have no mass and consist of high-energy electromagnetic radiation. The energy of X rays is somewhat less than that of gamma rays.
- **Cosmic rays** are a mixture of high-energy particles that shower the earth from outer space. They consist primarily of protons, along with some alpha and beta particles.

11.7 Ionizing Radiation

- The interaction of ionizing radiation with a molecule converts the molecule into an extremely reactive ion.
- The reactive ion can react with other molecules nearby, creating other fragments that can cause further reactions.
- A large dose of ionizing radiation can destroy the delicate balance of chemical reactions in living cells, ultimately causing the death of an organism.

11.7 Ionizing Radiation

- A small dose of ionizing radiation can be dangerous if it strikes a cell nucleus and damages the genetic machinery inside.
- The resultant changes might lead to a genetic mutation, to cancer, or to cell death.
- The nuclei of rapidly dividing cells, such as those in bone marrow, the lymph system, the lining of the intestinal tract, or an embryo, are the most readily damaged.
- Because cancer cells are also rapidly dividing, they are highly susceptible to the effects of ionizing radiation, which is why radiation therapy is an effective treatment.

11.7 Ionizing Radiation

TABLE 11.4 Some Properties of Ionizing Radiation

Type of Radiation	Energy Range*	Penetrating Distance in Water**
α	3–9 MeV	0.02–0.04 mm
β	0–3 MeV	0–4 mm
X	100 eV–10 keV	0.01–1 cm
γ	10 keV–10 MeV	1–20 cm

* The energies of subatomic particles are often measured in electron volts (eV): 1 eV = 6.703×10^{-19} cal, or 2.805×10^{-18} J.
** Distance at which one-half of the radiation is stopped.

11.7 Ionizing Radiation

- The effects of ionizing radiation on the human body vary with the energy of the radiation, its distance from the body, the length of exposure, and the location of the source.
- When coming from outside the body, gamma rays and X rays are most harmful because they pass through clothing and skin.
- Alpha and beta particles are much more dangerous when emitted within the body because all their radiation energy is given up to the immediately surrounding tissue.

11.7 Ionizing Radiation

- Health professionals who work with ionizing radiation protect themselves by surrounding the source with a thick layer of lead or other dense material.
- Protection from radiation is also afforded by controlling the distance between the worker and the radiation source because radiation intensity (*I*) decreases with the square of the distance from the source.

11.8 Detecting Radiation

- Radiation is invisible, no matter how high the dose. Radiation can be detected by taking advantage of its ionizing properties.
- The simplest device for detecting exposure to radiation is the photographic film badge.
- The film is protected from exposure to light, but radiation causes the film to fog.

11.8 Detecting Radiation

- The most versatile method for measuring radiation is the *scintillation counter*. A *phosphor* emits a flash of light when struck by radiation. The number of flashes are counted electronically and converted into an electrical signal.
- A *Geiger counter* is an argon-filled tube containing two electrodes. Radiation ionizes argon atoms, which briefly conduct a tiny electric current between the walls and the center electrode.
- The current is detected and used to produce a clicking sound or to register on a meter.

11.8 Detecting Radiation

Irradiated Food

- In the 1940s, U.S. Army scientists found that irradiation increased the shelf-life of ground beef.
- Exposure of contaminated food to ionizing radiation destroys the genetic material of any bacteria or other organisms present.
- Irradiation will not kill viruses or prions.
- The food itself undergoes little if any change when irradiated and does not become radioactive.
- One of the major concerns in the United States is the possible generation of *radiolytic products*, compounds formed in food by exposure to ionizing radiation.
- The U.S. Food and Drug Administration has declared that food irradiation is safe and does not appreciably alter the vitamin or other nutritional content of food

11.9 Measuring Radiation

TABLE 11.5 Common Units for Measuring Radiation

Unit	Quantity Measured	Description
Curie (Ci)	Decay events	Amount of radiation equal to 3.7×10^{10} disintegrations per second
Roentgen (R)	Ionizing intensity	Amount of radiation producing 2.1×10^{9} charges per cubic centimeter of dry air
Rad	Energy absorbed per gram of tissue	1 rad = 1 R
Rem	Tissue damage	Amount of radiation producing the same damage as 1 R of X rays
Sievert (Sv)	Tissue damage	1 Sv = 100 rem

11.9 Measuring Radiation

- **Curie:** The *curie* (Ci), the *millicurie* (mCi), and the *microcurie* measure the number of radioactive disintegrations occurring each second in a sample.
- The dosage of a radioactive substance is usually given in millicuries. Because the emitter concentration is constantly decreasing as it decays, the activity must be measured immediately before administration.

11.9 Measuring Radiation

- The ***roentgen*** (R) is a unit for measuring the ionizing intensity of γ or X radiation; the capacity of the radiation for affecting matter.
- The ***rad*** (radiation absorbed dose) is the absorption of 1×10^{-5} J per gram. The energy absorbed varies with the type of material irradiated and the type of radiation.
- The roentgen and the rad are so close that they can be considered identical when used for X rays and γ rays.

11.9 Measuring Radiation

- The ***rem*** (roentgen equivalent for man) measures the amount of tissue damage caused by radiation. Rems are the preferred units for medical purposes because they measure equivalent doses of different kinds of radiation.

$$\text{Rems} = \text{rads} \times \text{RBE}$$

- RBE is a *relative biological effectiveness* factor, which takes into account the differences in energy and of the different types of radiation.

11.9 Measuring Radiation

- **SI Units**:
  - The *becquerel* (Bq) is defined as one disintegration per second.
  - The SI unit for energy absorbed is the *gray* (Gy; 1 Gy = 100 rad.).
  - For radiation dose, the SI unit is the *sievert* (Sv), which is equal to 100 rem.
- The radiation dose received annually by most people is only about 0.27 rem. About 80% of this *background radiation* comes from natural sources; the remaining 20% comes from consumer products and medical procedures.

11.9 Measuring Radiation

TABLE 11.6 Biological Effects of Short-Term Radiation on Humans

Dose (rem)	Biological Effects
0–25	No detectable effects
25–100	Temporary decrease in white blood cell count
100–200	Nausea, vomiting, longer-term decrease in white blood cells
200–300	Vomiting, diarrhea, loss of appetite, listlessness
300–600	Vomiting, diarrhea, hemorrhaging, eventual death in some cases
Above 600	Eventual death in nearly all cases

11.10 Artificial Transmutation

Body Imaging

- An X-ray image is produced when X rays pass through the body and the intensity of the radiation that exits is recorded on film.
- Diagnostic information can be obtained by analyzing the distribution pattern of a radioactively tagged substance in the body.
- In *CT* scanning (computerized tomography), an X-ray source and an array of detectors move rapidly in a circle around a patient's body, collecting up to 90,000 readings. CT scans can detect structural abnormalities without the use of radioactive materials.
- *Positron emission tomography* (PET), combines tomography with radioisotope imaging utilizes radioisotopes that emit positrons and ultimately yield γ rays.
- Magnetic resonance imaging (MRI) is a medical imaging technique that uses powerful magnetic and radio-frequency fields to interact with specific nuclei in the body to generate images in which the contrast between soft tissues is much better than that seen with CT.

11.11 Nuclear Fission and Nuclear Fusion

- **Nuclear fusion** is the joining together of light nuclei.
- **Nuclear fission** is the fragmenting of heavy nuclei.
- The huge amounts of energy that accompany these processes are the result of mass-to-energy conversions.
- They are predicted by Einstein's equation:

$$E = mc^2$$

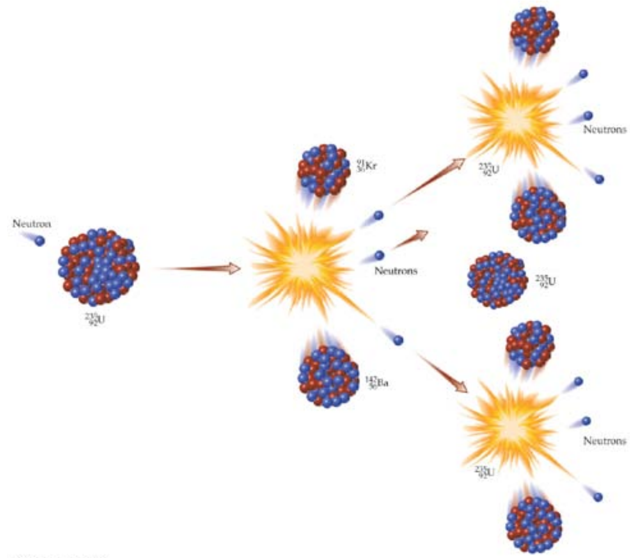
11.11 Nuclear Fission and Nuclear Fusion

- **NUCLEAR FISSION**
  - Uranium-235 is the only naturally occurring isotope that undergoes nuclear fission.
  - When this isotope is bombarded by a stream of relatively slow-moving neutrons, its nucleus splits to give isotopes of other elements.
  - The split can take place in more than 400 ways, and more than 800 different fission products have been identified.
  - One of the pathways generates barium-142 and krypton-91, along with two additional neutrons plus the one neutron that initiated the fission.

11.11 Nuclear Fission and Nuclear Fusion

- **NUCLEAR FISSION (*Continued*)**
  - *One* neutron is used to initiate fission of a ^{235}U nucleus, but *three* neutrons are released. Thus, a nuclear **chain reaction** can be started.
  - If the sample size is small, many of the neutrons escape, and the chain reaction stops.
  - If a **critical mass** is present then the chain reaction becomes self-sustaining, a nuclear explosion results.

11.11 Nuclear Fission and Nuclear Fusion



11.11 Nuclear Fission and Nuclear Fusion

- An enormous quantity of heat is released during nuclear fission.
- The fission of just 1.0 g of uranium-235 produces 3.4×10^8 kcal.
- This heat can be used to convert water to steam, which can be harnessed to turn huge generators and generate electricity.
- There is a potential radiation hazard should an accident rupture the containment vessel.
- Many of the wastes from power generation have such long half-lives that hundreds or even thousands of years must elapse before they will be safe for humans to approach.

11.11 Nuclear Fission and Nuclear Fusion

- Very light nuclei such as the isotopes of hydrogen release enormous amounts of energy when they undergo *fusion*.
- It is a fusion reaction of hydrogen nuclei to produce helium that powers our sun and other stars.
- In stars, where the temperature is 2×10^7 K and pressures approach 10^5 atmospheres, nuclei are stripped of their electrons and have enough kinetic energy that nuclear fusion readily occurs.
- On earth, however, the necessary conditions for nuclear fusion are not easily created.

Chapter Summary

1. What is a nuclear reaction, and how are equations for nuclear reactions balanced?

- A *nuclear reaction* is one that changes an atomic nucleus, causing the change of one element into another. Loss of an α particle leads to a new atom whose atomic number is 2 less than that of the starting atom. Loss of a β particle leads to an atom whose atomic number is 1 greater than that of the starting atom.

$$\alpha \text{ emission}: {}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

$$\beta \text{ emission}: {}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e}$$

- A nuclear reaction is balanced when the sum of the *nucleons* (protons and neutrons) is the same on both sides of the reaction arrow and when the sum of the charges on the nuclei plus any ejected subatomic particles is the same.

Chapter Summary

2. What are the different kinds of radioactivity?

- *Radioactivity* is the spontaneous emission of radiation from the nucleus of an unstable atom. The three major kinds of radiation are called *alpha* (α), *beta* (β), and *gamma* (γ).
- Alpha radiation consists of helium nuclei, small particles containing two protons and two neutrons; beta radiation consists of electrons; and gamma radiation consists of high-energy light waves. Every element in the periodic table has at least one radioactive isotope, or *radioisotope*.

3. How are the rates of nuclear reactions expressed?

- The rate of a nuclear reaction is expressed in units of *half-life* where one half-life is the amount of time necessary for one half of the radioactive sample to decay.

Chapter Summary, *Continued*

4. What is ionizing radiation?

- High-energy radiation of all types—α particles, β particles, γ rays, and X rays—is called *ionizing radiation*. When any of these kinds of radiation strikes an atom, it dislodges an electron and gives a reactive ion that can be lethal to living cells.
- Gamma rays and X rays are the most penetrating and most harmful types of external radiation, and α particles are the most dangerous types of internal radiation because of their high energy and the resulting damage to surrounding tissue.

Chapter Summary, *Continued*

5. How is radioactivity measured?

- Radiation intensity is expressed in different ways according to the property being measured.
- The *curie* (*Ci*) measures the number of radioactive disintegrations per second in a sample; the *roentgen* (*R*) measures the ionizing ability of radiation; the *rad* measures the amount of radiation energy absorbed per gram of tissue; and the *rem* measures the amount of tissue damage caused by radiation.
- Radiation effects become noticeable with a human exposure of 25 rem and become lethal at an exposure above 600 rem.

Chapter Summary, *Continued*

6. What is transmutation?

- *Transmutation* is the change of one element into another brought about by a nuclear reaction.
- Most known radioisotopes do not occur naturally but are made by bombardment of an atom with a high-energy particle. In the ensuing collision between particle and atom, a nuclear change occurs and a new element is produced by *artificial transmutation*.

7. What are nuclear fission and nuclear fusion?

- With a very few isotopes, including $^{235}_{92}U$, the nucleus is split apart by neutron bombardment to give smaller fragments. A large amount of energy is released during this *nuclear fission*, leading to use of the reaction for generating electric power.
- *Nuclear fusion* results when small nuclei such as those of tritium and deuterium combine to give a heavier nucleus.