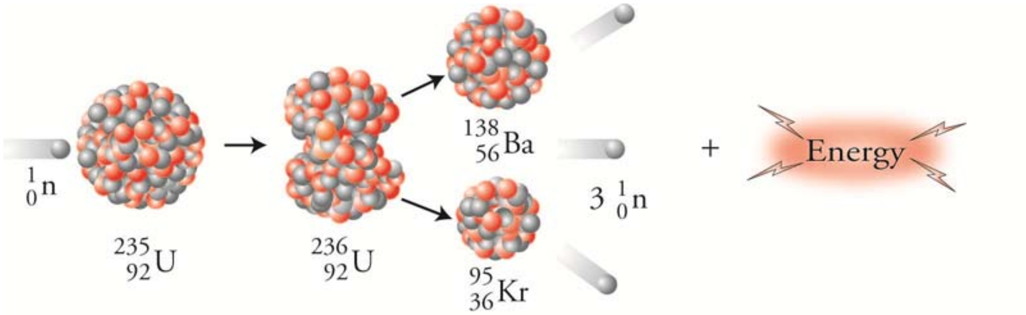
Chapter 16
Nuclear Chemistry



♦ Review Skills

16.1 The Nucleus and Radioactivity

- Nuclear Stability
- Types of Radioactive Emissions
- Nuclear Reactions and Nuclear Equations
- Rates of Radioactive Decay
- Radioactive Decay Series
- The Effect of Radiation on the Body

16.2 Uses of Radioactive Substances

- Medical Uses
- Carbon-14 Dating
- Other Uses for Radioactive Nuclides

16.3 Nuclear Energy

- Nuclear Fission and Electric Power Plants
- Nuclear Fusion and the Sun

Special Topic 16.1: A New Treatment for Brain Cancer

Special Topic 16.2: The Origin of the Elements

♦ Chapter Glossary

Internet: Glossary Quiz

♦ Chapter Objectives

Review Questions

Key Ideas

Chapter Problems

Section Goals and Introductions

Section 16.1 The Nucleus and Radioactivity

Goals

- *To introduce the new terms nucleon, nucleon number, and nuclide.*
- *To show the symbolism used to represent nuclides.*
- *To explain why some nuclei are stable and others not.*
- *To provide you with a way of predicting nuclear stability.*
- *To describe the different types of radioactive decay.*
- *To show how nuclear reactions are different from chemical reactions.*
- *To show how nuclear equations are different from chemical equations.*
- *To show how the rates of radioactive decay can be described with half-life.*
- *To explain why short-lived radioactive atoms are in nature.*
- *To describe how radiation affects our bodies..*

This section provides the basic information that you need to understand radioactive decay. It will also help you understand the many uses of radioactive atoms, including how they are used in medicine and in electricity generation.

Section 16.2 Uses of Radioactive Substances

Goal: To describe many of the uses of radioactive atoms, including medical uses, archaeological dating, smoke detectors, and food irradiation.

Radiation and radioactive substances have often been viewed as dangerous and things that create problems rather than solving them, but there are actually many important and beneficial uses of radioactive atoms. Some of them are described in this section.

Section 16.3 Nuclear Energy

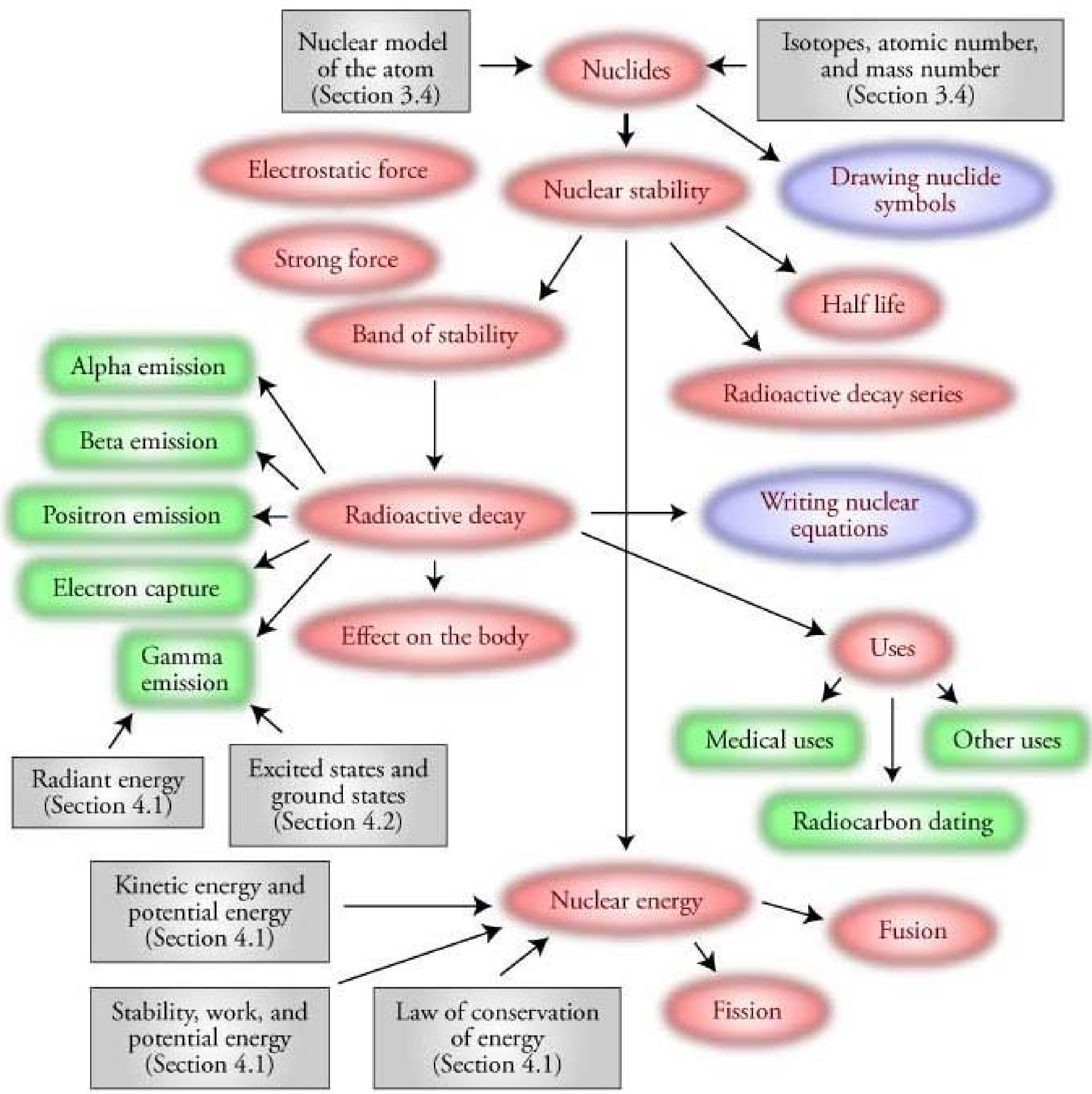
Goals

- *To describe nuclear fission (the splitting of larger atoms into smaller atoms) and nuclear fusion (the combination of smaller atoms into larger atoms) and to explain why energy is released by each.*
- *To describe briefly how nuclear power plants work.*
- *To show how the sun gets its energy.*

The potential energy stored in the nuclei of atoms can be converted into other forms of energy in the fission reactions in nuclear power plants and in the fusion reactions in the sun. This section tells you why this energy conversion takes place.

Nuclear power is a major source of energy for electrical generation worldwide. Nuclear power plants are found in over 30 countries and generate a significant percentage of the world’s electricity. This section will help you to understand how these plants work.

Chapter 16 Map



Chapter Checklist

- ☐ Read the Review Skills section. If there is any skill mentioned that you have not yet mastered, review the material on that topic before reading this chapter.
- ☐ Read the chapter quickly before the lecture that describes it.
- ☐ Attend class meetings, take notes, and participate in class discussions.
- ☐ Work the Chapter Exercises, perhaps using the Chapter Examples as guides.
- ☐ Study the Chapter Glossary and test yourself on our Web site:

  Internet: Glossary Quiz
- ☐ Study all of the Chapter Objectives. You might want to write a description of how you will meet each objective.
- ☐ Memorize the following.

  Be sure to check with your instructor to determine how much you are expected to know of the following.
  - For the types of radioactive decay, know the symbols, changes in the numbers of protons and neutrons, and changes in the atomic number and mass number described in Table 16.2.
- ☐ To get a review of the most important topics in the chapter, fill in the blanks in the Key Ideas section.
- ☐ Work all of the selected problems at the end of the chapter, and check your answers with the solutions provided in this chapter of the study guide.
- ☐ Ask for help if you need it.

Web Resources

Internet: Glossary Quiz

Exercises Key

Exercise 16.1 – Nuclide Symbols: One of the nuclides used in radiation therapy for the treatment of cancer has 39 protons and 51 neutrons. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to represent this nuclide. *(Objs 2, 3, & 4)*

Because this nuclide has 39 protons, its atomic number, Z, is 39. This identifies the element as yttrium. This nuclide of yttrium has 90 total nucleons (39 protons + 51 neutrons), so its nucleon number, A, is 90.

$\mathbf{{}^{90}_{39}Y}$ $\mathbf{{}^{90}Y}$ **yttrium - 90**

Exercise 16.2 – Nuclide Symbols: A nuclide with the symbol ^{201}Tl can be used to assess a patient's heart in a stress test. What is its atomic number and mass number? How many protons and how many neutrons are in the nucleus of each atom? Write two other ways to represent this nuclide. *(Objs 2, 3, & 4)*

The periodic table shows us that the atomic number for thallium is 81, so each thallium atom has 81 protons. The superscript in the symbol ^{201}Tl is this nuclide's mass number. The difference between the mass number (the sum of the numbers of protons and neutrons) and the atomic number (the number of protons) is equal to the number of neutrons, so this nuclide has 120 neutrons (201 – 81).

Atomic number = 81 mass number = 201 81 protons 120 neutrons

$$\mathbf{{}^{201}_{81}Tl \quad thallium - 201}$$

Exercise 16.3 - Nuclear Equations: Write nuclear equations for (a) alpha emission by plutonium-239, one of the substances formed in nuclear power plants, (b) beta emission by sodium-24, used to detect blood clots, (c) positron emission by oxygen-15, used to assess the efficiency of the lungs, and (d) electron capture by copper-64, used to diagnose lung disease. *(Obj 12)*

a. $\mathbf{{}^{239}_{94}Pu \rightarrow {}^{235}_{92}U + {}^{4}_{2}He}$

b. $\mathbf{{}^{24}_{11}Na \rightarrow {}^{24}_{12}Mg + {}^{0}_{-1}e}$

c. $\mathbf{{}^{15}_{8}O \rightarrow {}^{15}_{7}N + {}^{0}_{+1}e}$

d. $\mathbf{{}^{64}_{29}Cu + {}^{0}_{-1}e \rightarrow {}^{64}_{28}Ni}$

Exercise 16.4 - Nuclear Equations: Complete the following nuclear equations. *(Obj 13)*

a. ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow \mathbf{{}^{17}_{8}O} + {}^{1}_{1}H$

b. ${}^{238}_{92}U + \mathbf{{}^{14}_{7}N} \rightarrow {}^{247}_{99}Es + 5{}^{1}_{0}n$

c. $\mathbf{{}^{238}_{92}U} + {}^{2}_{1}H \rightarrow {}^{239}_{93}Np + {}^{1}_{0}n$

Exercise 16.5 - Half-life: One of the radioactive nuclides formed in nuclear power plants is hydrogen-3, called tritium, which has a half-life of 12.26 years. How long before a sample decreases to 1/8 of its original amount? *(Obj 14)*

In each half-life of a radioactive nuclide, the amount diminishes by one-half. The fraction 1/8 is ½ × ½ × ½, so it takes three half-lives to diminish to 1/8 remaining. Therefore, it will take **36.78 years** *for tritium to decrease to 1/8 of what was originally there.*

Exercise 16.6 - Half-life: Uranium-238 is one of the radioactive nuclides sometimes found in soil. It has a half-life of 4.51×10^9 years. What fraction of a sample is left after 9.02×10^9 years? *(Obj 15)*

The length of time divided by the half-life yields the number of half-lives.

$$\frac{9.02\times10^9 \text{ years}}{4.51\times10^9 \text{ years}} = 2 \text{ half - lives}$$

Therefore, the fraction remaining would be **1/4** *(½ × ½).*

Review Questions Key

1. Describe the nuclear model of the atom, including the general location of the protons, neutrons, and electrons, the relative size of the nucleus compared to the size of the atom, and the modern description of the electron.

   Protons and neutrons are in a tiny core of the atom called the nucleus, which has a diameter about 1/100,000 the diameter of the atom. The position and motion of the electrons are uncertain, but they generate a negative charge that is felt in the space that surrounds the nucleus.

2. With reference to both their particle and their wave nature, describe the similarities and differences between gamma radiation and radio waves. Which has higher energy?

   In the particle view, radiant energy is a stream of tiny, massless packets of energy called photons. Different forms of radiant energy differ with respect to the energy of each of their photons. The energies of the photons of radio waves are much lower than for gamma radiation.

   In the wave view, as radiant energy moves away from the source, it has an effect on the space around it that can be described as a wave consisting of an oscillating electric field perpendicular to an oscillating magnetic field. Different forms of radiant energy differ with respect to the wavelengths and frequencies of these oscillating waves. The waves associated with radio waves have much longer wavelength than the waves associated with gamma radiation.

Complete the following statements by writing the word or phrase in each blank that best completes the thought.

3. Atoms that have the same number of protons but different numbers of neutrons are called **isotopes**. They have the same atomic number but different mass numbers.
4. The **atomic number** for an atom is equal to the number of protons in an atom’s nucleus. It establishes the element’s identity.
5. The **mass number** for an atom is equal to the sum of the numbers of protons and neutrons in an atom’s nucleus.
6. **Energy** is the capacity to do work.
7. **Kinetic energy** is the capacity to do work due to the motion of an object.
8. The **Law of Conservation of Energy** states that energy can neither be created nor destroyed, but it can be transferred from one system to another and changed from one form to another.
9. **Potential energy** is a retrievable, stored form of energy an object possesses by virtue of its position or state.
10. The more stable a system is, the **lower** (higher or lower) its potential energy.
11. When a system shifts from a less stable to a more stable state, energy is **released** (absorbed or released).
12. The **ground state** of an atom is the condition in which its electrons are in the orbitals that give it the lowest possible potential energy.
13. The **excited state** of an atom is the condition in which one or more of its electrons are in orbitals that do not represent the lowest possible potential energy.

Key Ideas Answers

14. Because **protons** and **neutrons** reside in the nucleus of atoms, they are called nucleons.
16. There are two forces among the particles within the nucleus. The first, called the **electrostatic** force, is the force between electrically charged particles. The second force, called the **strong** force, holds nucleons (protons and neutrons) together.
18. Larger atoms with more protons in their nuclei require a greater **ratio** of neutrons to protons to balance the increased repulsion between protons.
20. One of the ways that heavy nuclides change to move back into the band of stability is to release two protons and two neutrons in the form of a helium nucleus, called an **alpha** particle.
22. When a radioactive nuclide has a neutron to proton ratio that is **too low**, it can move toward stability in one of two ways, positron emission or electron capture. In positron emission (β^+), a proton becomes a neutron and a positron. The neutron stays in the nucleus, and the positron speeds out of the nucleus at high velocity.
24. Because radioactive decay leads to more stable products, it always **releases** energy, some in the form of kinetic energy of the moving product particles, and some in the form of gamma rays. Gamma rays can be viewed as a stream of high-energy **photons**.
26. Different isotopes of the same element, which share the same chemical characteristics, often undergo very **different** nuclear reactions.
28. Nuclear reactions, in general, give off a lot more **energy** than chemical reactions.
30. Rates of radioactive decay are described in terms of half-life, the time it takes for **one-half** of a sample to disappear.
32. As alpha particles, which move at up to 10% the speed of light, move through the tissues of our bodies, they **pull** electrons away from the tissue's atoms.
34. Gamma photons are ionizing radiation, because they can **excite** electrons enough to actually remove them from atoms.
36. Because beta particles are smaller than alpha particles, and because they can move up to 90% the speed of light, they are about **100** times as penetrating as alpha particles.
38. Gamma photons that penetrate the body do more damage to **rapidly reproducing** cells than to others.
40. To date an artifact, a portion of it is analyzed to determine the **$^{14}C/^{12}C$ ratio**, which can be used to determine its age.
42. It takes about **10,000** times as much energy to remove a proton or a neutron from the nucleus of a hydrogen-2 atom as to remove its one electron.
44. There appears to be something stable about having 2, 8, 20, 28, 50, 82, or 126 protons or neutrons. The nuclides with **double magic numbers** have very high stability.
46. For atoms **larger than** iron-56, splitting larger atoms to form more stable, smaller atoms releases energy.
48. The nuclear reactor in a nuclear power plant is really just a big **furnace** that generates heat to convert liquid water to steam that turns a steam turbine generator to produce electricity.

Problems Key

Section 16.1: The Nucleus and Radioactivity

50. A radioactive nuclide that has an atomic number of 88 and a mass (nucleon) number of 226 is used in radiation therapy. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to represent this nuclide. *(Objs 2 & 4)*

    $^{226}_{88}Ra$ ^{226}Ra radium - 226

52. A radioactive nuclide that has 6 protons and 5 neutrons is used to generate positron emission tomography (PET) brain scans. Write its nuclide symbol in the form of $^{A}_{Z}X$. Write two other ways to represent this nuclide. *(Objs 3 & 4)*

    $^{11}_{6}C$ ^{11}C carbon - 11

54. A radioactive nuclide with the symbol $^{40}_{19}K$ is used for geologic dating. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide. *(Objs 2 & 4)*

    atomic number = 19 mass number = 40 ^{40}K potassium - 40

56. A radioactive nuclide with the symbol $^{111}_{49}In$ is used to label blood platelets. How many protons and how many neutrons does each atom have? Write two other ways to represent this nuclide. *(Objs 3 & 4)*

    49 protons 62 neutrons ^{111}In indium - 111

58. Barium-131 is used to detect bone tumors. What is its atomic number and mass number? How many protons and how many neutrons are in the nuclei of each atom? Write two other ways to represent this nuclide. *(Objs 2, 3, & 4)*

    atomic number = 56 mass number = 131 56 protons 75 neutrons $^{131}_{56}Ba$ ^{131}Ba

60. The radioactive nuclide with the symbol ^{75}Se is used to measure the shape of the pancreas. What is its atomic number and mass number? How many protons and how many neutrons are in the nuclei of each atom? Write two other ways to represent this nuclide. *(Objs 2, 3, & 4)*

    atomic number = 34 mass number = 75 34 protons 41 neutrons $^{75}_{34}Se$ selenium - 75

62. Describe the two opposing forces between particles in the nucleus, and with reference to these forces, explain why the ratio of neutrons to protons required for a stable nuclide increases as the number of protons in a nucleus increases. *(Obj 5)*

The first force among the particles in the nucleus is called the electrostatic force (or electromagnetic force). It is the force between electrically charged particles. Opposite charges attract each other, and like charges repel each other, so the positively charged protons in the nucleus of an atom have an electrostatic force pushing them apart. The second force, called the strong force, holds nucleons (protons and neutrons) together.

You can think of neutrons as the nuclear glue that allows protons to stay together in the nucleus. Because neutrons are uncharged, there are no electrostatic repulsions among them and other particles, but each neutron in the nucleus of an atom is attracted to other neutrons and to protons by the strong force. Therefore, adding neutrons to a nucleus leads to more attractions holding the particles of the nucleus together without causing increased repulsion between those particles.

Larger atoms with more protons in their nuclei require a greater ratio of neutrons to protons to balance the increased electrostatic repulsion between protons.

64. Write a general description of the changes that take place in alpha emission. Write the two symbols used for an alpha particle. Write the general equation for alpha emission, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number. *(Objs 6 & 7)*

One of the ways that heavy nuclides change to move back into the band of stability is to release two protons and two neutrons in the form of a helium nucleus, called an alpha particle. In nuclear equations for alpha emission, the alpha particle is described as either α *or* ${}^{4}_{2}He$. *In alpha emission, the radioactive nuclide changes into a different element that has an atomic number that is two lower and a mass number that is four lower.*

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

66. Write a general description of the changes that take place in positron emission. Write the three symbols used for a positron. Write the general equation for positron emission, using X for the reactant element symbol, Y for the product element symbol, Z for atomic number, and A for mass number. *(Objs 6 & 7)*

In positron emission (β^+*), a proton becomes a neutron and an anti-electron. The neutron stays in the nucleus, and the positron speeds out of the nucleus at high velocity.*

$$p \rightarrow n + e^+$$

In nuclear equations for positron emission, the electron is described as either β^+, ${}^{0}_{+1}e$, *or* ${}^{0}_{1}e$. *In positron emission, the radioactive nuclide changes into a different element that has an atomic number that is one lower but that has the same mass number.*

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$$

68. Consider three isotopes of bismuth, $^{202}_{83}Bi$, $^{209}_{83}Bi$, and $^{215}_{83}Bi$. Bismuth-209 is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes electron capture. Identify the isotope that makes each of these changes, and explain your choices. *(Obj 8)*

    Bismuth-202, which has a lower neutron to proton ratio than the stable bismuth-209, undergoes electron capture, which increases the neutron to proton ratio. Bismuth-215, which has a higher neutron to proton ratio than the stable bismuth-209, undergoes beta emission, which decreases the neutron to proton ratio.

71. What nuclear process or processes lead to each of the results listed below? The possibilities are alpha emission, beta emission, positron emission, electron capture, and gamma emission. *(Obj 6)*

    a. Atomic number increases by 1. **beta emission**
    b. Mass number decreases by 4. **alpha emission**
    c. No change in atomic number or mass number **gamma emission**
    d. The number of protons decreases by 1. **positron emission or electron capture**
    e. The number of neutrons decreases by 1. **beta emission**
    f. The number of protons decreases by 2. **alpha emission**

73. Describe the differences between nuclear reactions and chemical reactions. *(Obj 10)*

    - *Nuclear reactions involve changes in the nucleus, as opposed to chemical reactions that involve the loss, gain, and sharing of electrons.*
    - *Different isotopes of the same element often undergo very different nuclear reactions, whereas they all share the same chemical characteristics.*
    - *Unlike chemical reactions, the rates of nuclear reactions are unaffected by temperature, pressure, and the other atoms to which the radioactive atom is bonded.*
    - *Nuclear reactions, in general, give off a lot more energy than chemical reactions.*

74. Explain why $^{38}_{17}Cl$ and $^{38}_{17}Cl^-$ are very different chemically and why they each undergo identical nuclear reactions.

    These two particles differ only in the number of their electrons. Because chemical reactions involve the loss, gain, and sharing of electrons, the number of electrons for an atom is very important for chemical changes. The attractions between charges are also very important for chemical changes, so the different charges of these particles change how they act chemically.

    Nuclear reactions are determined by the stability of nuclei, which is related to the number of protons and neutrons in the nuclei. They are unaffected by the number of electrons and unaffected by the overall charge of the particles. Therefore, these particles, which both have 17 protons and 21 neutrons in their nuclei, have the same nuclear stability and undergo the same nuclear changes.

76. Marie Curie won the Nobel Prize for physics in 1903 for her study of radioactive nuclides, including polonium-218 (which was named after her native country, Poland). Polonium-218 undergoes alpha emission. Write the nuclear equation for this change. *(Obj 12)*

    $$^{218}_{84}\mathbf{Po} \rightarrow {}^{214}_{82}\mathbf{Pb} + {}^{4}_{2}\mathbf{He}$$

78. Cobalt-60, which is the most common nuclide used in radiation therapy for cancer, undergoes beta emission. Write the nuclear equation for this reaction. *(Obj 12)*

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

80. Carbon-11 is used in PET brain scans because it emits positrons. Write the nuclear equation for the positron emission of carbon-11. *(Obj 12)*

$$\mathbf{{}^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e}$$

82. Mercury-197 was used in the past for brain scans. Its decay can be detected, because this nuclide undergoes electron capture, which forms an excited atom that then releases a gamma photon that escapes the body and strikes a detector. Write the nuclear equation for the electron capture by mercury-197. *(Obj 12)*

$$\mathbf{{}^{197}_{80}Hg + {}^{0}_{-1}e \rightarrow {}^{197}_{79}Au}$$

84. Complete the following nuclear equations. *(Obj 13)*

a. ${}^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + \mathbf{{}^{0}_{-1}e}$

b. ${}^{17}_{9}F \rightarrow {}^{17}_{8}O + \mathbf{{}^{0}_{+1}e}$

c. ${}^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + \mathbf{{}^{4}_{2}He}$

d. ${}^{18}_{9}F + \mathbf{{}^{0}_{-1}e} \rightarrow {}^{18}_{8}O$

e. ${}^{235}_{92}U \rightarrow \mathbf{{}^{231}_{90}Th} + {}^{4}_{2}He$

f. ${}^{7}_{4}Be + {}^{0}_{-1}e \rightarrow \mathbf{{}^{7}_{3}Li}$

g. ${}^{52}_{26}Fe \rightarrow \mathbf{{}^{52}_{25}Mn} + {}^{0}_{+1}e$

h. ${}^{3}_{1}H \rightarrow \mathbf{{}^{3}_{2}He} + {}^{0}_{-1}e$

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

j. $\mathbf{{}^{118}_{54}Xe} \rightarrow {}^{118}_{53}I + {}^{0}_{+1}e$

k. $\mathbf{{}^{204}_{84}Po} + {}^{0}_{-1}e \rightarrow {}^{204}_{83}Bi$

l. $\mathbf{{}^{238}_{92}U} \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

86. Silver-117 atoms undergo three beta emissions before they reach a stable nuclide. What is the final product?

$${}^{117}_{47}Ag \rightarrow {}^{117}_{48}Cd \rightarrow {}^{117}_{49}In \rightarrow \mathbf{{}^{117}_{50}Sn}$$

88. Tellurium-116 atoms undergo two electron captures before they reach a stable nuclide. What is the final product?

$${}^{116}_{52}Te \rightarrow {}^{116}_{51}Sb \rightarrow \mathbf{{}^{116}_{50}Sn}$$

90. Samarium-142 atoms undergo two positron emissions before they reach a stable nuclide. What is the final product?

$${}^{142}_{62}Sm \rightarrow {}^{142}_{61}Pm \rightarrow \mathbf{{}^{142}_{60}Nd}$$

92. Bismuth-211 atoms undergo an alpha emission and beta emission before they reach a stable nuclide. What is the final product?

$${}^{211}_{83}Bi \rightarrow {}^{207}_{81}Tl \rightarrow \mathbf{{}^{207}_{82}Pb}$$

94. Complete the following nuclear equations describing the changes that led to the formation of previously undiscovered nuclides. *(Obj 13)*

a. $^{246}_{96}\text{Cm} + ^{12}_{6}\text{C} \rightarrow \mathbf{^{252}_{102}No} + 6\,^{1}_{0}\text{n}$

b. $\mathbf{^{249}_{98}Cf} + ^{16}_{8}\text{O} \rightarrow ^{263}_{106}\text{Sg} + 2\,^{1}_{0}\text{n}$

c. $^{240}_{95}\text{Am} + ^{4}_{2}\text{He} \rightarrow ^{243}_{97}\text{Bk} + \mathbf{^{1}_{0}n}$

d. $^{252}_{98}\text{Cf} + \mathbf{^{10}_{5}B} \rightarrow ^{257}_{103}\text{Lr} + 5\,^{1}_{0}\text{n}$

96. In February 1981, the first atoms of the element Bohrium-262, $^{262}_{107}\text{Bh}$, were made from the bombardment of bismuth-209 atoms by chromium-54 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.) *(Obj 13)*

$\mathbf{^{209}_{83}Bi + ^{54}_{24}Cr \rightarrow ^{262}_{107}Bh + ^{1}_{0}n}$

98. Cesium-133, which is used in radiation therapy, has a half-life of 30 years. How long before a sample decreases to 1/4 of what was originally there? *(Obj 14)*

It takes two half-lives for a radioactive nuclide to decay to ¼ of its original amount (½ × ½). Therefore, it will take **60 years** *for cesium-133 to decrease to ¼ of what was originally there.*

100. Phosphorus-32, which is used for leukemia therapy, has a half-life of 14.3 days. What fraction of a sample is left in 42.9 days? *(Obj 15)*

The 42.9 days is three half-lives (42.9/14.3), so the fraction remaining would be **1/8** *(½× ½ × ½).*

102. Explain why short-lived radioactive nuclides are found in nature. *(Obj 16)*

Although short-lived radioactive nuclides disappear relatively quickly once they form, they are constantly being replenished because they are products of other radioactive decays. There are three long-lived radioactive nuclides (uranium-235, uranium-238, and thorium-232) that are responsible for many of the natural radioactive isotopes.

105. The first six steps of the decay series for uranium-235 consist of the changes alpha emission, beta emission, alpha emission, beta emission, alpha emission, and alpha emission. Write the products formed after each of these six steps.

$^{235}_{92}\text{U} \rightarrow \mathbf{^{231}_{90}Th} \rightarrow \mathbf{^{231}_{91}Pa} \rightarrow \mathbf{^{227}_{89}Ac} \rightarrow \mathbf{^{227}_{90}Th} \rightarrow \mathbf{^{223}_{88}Ra} \rightarrow \mathbf{^{219}_{86}Rn}$

107. In the first five steps of the decay series for thorium-232, the products are $^{228}_{88}\text{Ra}$, $^{228}_{89}\text{Ac}$, $^{228}_{90}\text{Th}$, $^{224}_{88}\text{Ra}$, and $^{220}_{86}\text{Rn}$. Identify each of these steps as alpha emissions or beta emissions.

alpha, beta, beta, alpha, alpha

109. Explain why alpha particles are considered ionizing radiation. *(Obj 19)*

As alpha particles, which move at up to 10% the speed of light, move through the tissues of our bodies, they drag electrons away from the tissue's atoms. Remember that alpha particles are helium nuclei, so they each have a +2 charge. Thus, as the alpha particle moves past an atom or molecule, it attracts the particle's electrons. One of the electrons might be pulled toward the passing alpha particle enough to escape, but it might not be able to catch up to the fast moving alpha particle. The electron lags behind the alpha particle and is quickly incorporated into another atom or molecule, forming an anion, and the particle that lost the electron becomes positively charged. The alpha particle continues on its way creating many ions before it is slowed enough for electrons to catch up to it and neutralize its charge.

111. Explain why gamma photons are considered ionizing radiation. *(Obj 19)*

Gamma photons can excite electrons enough to actually remove them from atoms.

113. What types of tissues are most sensitive to emission from radioactive nuclides? Why do radiation treatments do more damage to cancer cells than to regular cells? Why are children more affected by radiation than adults are? *(Obj 21)*

The greatest effect is on tissues with rapidly reproducing cells where there are more frequent chemical changes. This is why nuclear emissions have a greater effect on cancerous tumors with their rapidly reproducing cells and on children, who have more rapidly reproducing cells than adults.

115. Why do you think radium-226 concentrates in our bones?

Because both radium and calcium are alkaline earth metals in group 2 on the periodic table, they combine with other elements in similar ways. Therefore, if radioactive radium-226 is ingested, it concentrates in the bones in substances that would normally contain calcium.

117. Why are alpha particles more damaging to tissues when the source is ingested than gamma rays would be? *(Obj 24)*

Alpha and beta particles lose all of their energy over a very short distance, so they can do more damage to localized areas in the body than the same number of gamma photons would.

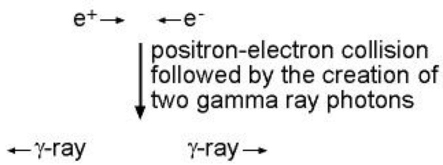
Section 16.2: Uses of Radioactive Substances

118. Describe how cobalt-60 is used to treat cancer. *(Obj 25)*

Cobalt-60 emits ionizing radiation in the form of beta particles and gamma photons. Gamma photons penetrate the body and do more damage to rapidly reproducing cells that others. Typically, a focused beam of gamma photons from cobalt-60 is directed at a cancerous tumor. The gamma photons enter the tumor and create ions and free radicals that damage the tumor cells to shrink the tumor.

120. Explain how PET can show dynamic processes in the body, such as brain activity and blood flow. *(Obj 27)*

To get a PET scan of a patient, a solution that contains a positron-emitting substance is introduced into the body. The positrons that the radioactive atoms emit collide with electrons, and they annihilate each other, creating two gamma photons that move out in opposite directions.



These photons can be detected, and the data can be computer-analyzed to yield images that show where in the body the radioactive substances collected. Depending on the nuclide used and the substance into which it is incorporated, the radioactive substance will move to a specific part of the body.

122. Describe how carbon-14 (radiocarbon) dating of artifacts is done. *(Obj 29)*

Carbon-14 atoms are constantly being produced in our upper atmosphere through neutron bombardment of nitrogen atoms.

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

The carbon-14 formed is quickly oxidized to form carbon dioxide, CO_2, which is converted into many different substances in plants. When animals eat the plants, the carbon-14 becomes part of the animal too. For these reasons, carbon-14 is found in all living things. The carbon-14 is a beta-emitter with a half-life of 5730 years (±40 years), so as soon as it becomes part of a plant or animal, it begins to disappear.

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

As long as a plant or animal is alive, the intake of carbon-14 balances the decay so that the ratio of ^{14}C to ^{12}C remains constant at about 1 in 1,000,000,000,000. When the plant or animal dies, it stops taking in fresh carbon, but the carbon-14 it contains continues to decay. Thus the ratio of ^{14}C to ^{12}C drops steadily. Therefore, to date an artifact, a portion of it is analyzed to determine the $^{14}C/^{12}C$ ratio, which can be used to calculate its age.

Initially, it was thought that determination of the age of something using this technique would be simple. For example, if the $^{14}C/^{12}C$ ratio had dropped to one-half of the ratio found in the air today, it would be considered to be about 5730 years old. A $^{14}C/^{12}C$ ratio of one-fourth of the ratio found in the air today would date it as 11,460 years old (two half-lives). This only works if we can assume that the $^{14}C/^{12}C$ ratio in the air was the same when the object died as it is now, and scientists have discovered that this is not strictly true.

Study of very old trees, such as the bristlecone pines in California, have allowed researchers to develop calibration curves that adjust the results of radiocarbon dating experiments for the variation in the $^{14}C/^{12}C$ ratio that go back about 10,000 years. These calibration curves are now used to get more precise dates for objects.

124. Describe how iridium-192 can be used to find leaks in welded pipe joints. *(Obj 31)*

The radioactive iridium-192 is introduced to the pipe, and the connection is wrapped on the outside with film. If there is a crack in the connection, radiation leaks out and exposes the film.

126. Explain how scientists use radioactive tracers. *(Obj 33)*

Unstable nuclides have been used as radioactive tracers that help researchers discover a wide range of things. For example, incorporating carbon-14 into molecules helped scientists to study many of the aspects of photosynthesis. Because the radiation emitted from the carbon-14 atoms can be detected outside of the system into which the molecules are placed, the changes that involve carbon can be traced. Phosphorus-32 atoms can be used to trace phosphorus-containing chemicals as they move from the soil into plants under various conditions. Carbon-14, hydrogen-3, and sulfur-35 have been used to trace the biochemical changes that take place in our bodies.

Section 16.3: Nuclear Energy

128. Explain how the binding energy per nucleon can be used to compare the stability of nuclides. *(Obj 35)*

The greater the strengths of the attractions between nucleons, the more stable the nucleus and the greater the difference in potential energy between the separate nucleons and the nucleus. This is reflected in a greater binding energy per nucleon.

130. Explain why ${}^{4}_{2}He$, ${}^{12}_{6}C$, ${}^{16}_{8}O$, and ${}^{20}_{10}Ne$ are especially stable. *(Obj 37)*

This can be explained by the fact that they have an even number of protons and an even number of the neutrons. Paired nucleons (like paired electrons) are more stable than unpaired ones.

132. Give two reasons why ${}^{16}_{8}O$ is more stable than ${}^{15}_{8}O$.

Paired nucleons are more stable than unpaired ones, and oxygen-16 with 8 protons and 8 neutrons would have its nucleons paired. Oxygen-15 with an odd number of neutrons (7) would be less stable. Oxygen-16 also has double magic numbers, making it especially stable. Finally, oxygen-15 has too few neutrons to be stable.

134. Describe how heat is generated in a nuclear power plant. *(Obj 40)*

Heat is generated by the chain reaction of uranium-235, which is initiated by the bombardment of uranium fuel that is about 3% uranium-235. The products are significantly more stable than the initial reactants, so the system shifts from higher potential energy to lower potential energy, releasing energy as increased kinetic energy of the product particles. Higher kinetic energy means higher temperature.

136. Describe the role of the moderator in a nuclear reactor. *(Obj 42)*

Both uranium-235 and uranium-238 absorb fast neutrons, but if the neutrons are slowed down, they are much more likely to be absorbed by uranium-235 atoms than uranium-238 atoms. Therefore, in a nuclear reactor, the fuel rods are surrounded by a substance called a moderator, which slows the neutrons as they pass through it. Several substances have been used as moderators, but normal water is most common.

138. Nuclear wastes must be isolated from the environment for a very long time because they contain relatively long-lived radioactive nuclides, such as technetium-99 with a half-life of over 2.1×10^5 years. One proposed solution is to bombard the waste with neutrons so as to convert the long-lived nuclides into nuclides that decay more quickly. When technetium-99 absorbs a neutron, it forms technetium-100, which has a half-life of 16 seconds and forms stable ruthenium-100 by emitting a beta particle. Write the nuclear equations for these two changes.

$$\mathbf{{}^{99}_{43}Tc + {}^{1}_{0}n \rightarrow {}^{100}_{43}Tc}$$

$$\mathbf{{}^{100}_{43}Tc \rightarrow {}^{100}_{44}Ru + {}^{0}_{-1}e}$$

Additional Problems

141. A radioactive nuclide that has an atomic number of 53 and a mass (nucleon) number of 131 is used to measure thyroid function. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to symbolize this nuclide.

$^{131}_{53}$I ^{131}I iodine - 131

143. A radioactive nuclide that has 11 protons and 13 neutrons is used to detect blood clots. Write its nuclide symbol in the form of ${}^{A}_{Z}X$. Write two other ways to symbolize this nuclide.

$^{24}_{11}$Na ^{24}Na sodium - 24

145. A radioactive nuclide with the symbol ${}^{133}_{55}Cs$ is used in radiation therapy. What is its atomic number and mass (nucleon) number? Write two other ways to represent this nuclide.

atomic number = 55 mass number = 133 ^{133}Cs cesium - 133

147. A radioactive nuclide with the symbol ${}^{51}_{24}Cr$ is used to determine blood volume. How many protons and neutrons does each atom have? Write two other ways to represent this nuclide.

24 protons 27 neutrons ^{51}Cr chromium - 51

149. Gallium-67 is used to diagnose lymphoma. What is its atomic number and mass number? How many protons and how many neutrons are in the nuclei of each atom? Write two other ways to represent this nuclide.

atomic number = 31 mass number = 67 31 protons 36 neutrons $^{67}_{31}$Ga ^{67}Ga

151. The radioactive nuclide with the symbol ${}^{32}P$ is used to detect eye tumors. What is its atomic number and mass number? How many protons and how many neutrons are in the nuclei of each atom? Write two other ways to represent this nuclide.

atomic number = 15 mass number = 32 15 protons 17 neutrons $^{32}_{15}$P phosphorus - 32

153. Consider three isotopes of neon, ${}^{18}_{10}Ne$, ${}^{20}_{10}Ne$, and ${}^{24}_{10}Ne$. Neon-20, which is the most abundant isotope of neon, is stable. One of the other nuclides undergoes beta emission, and the remaining nuclide undergoes positron emission. Identify the isotope that makes each of these changes, and explain your choices.

Neon-18, which has a lower neutron to proton ratio than the stable neon-20, undergoes positron emission, which increases the neutron to proton ratio. Neon-24, which has a higher neutron to proton ratio than the stable neon-20, undergoes beta emission, which decreases the neutron to proton ratio.

155. Write the nuclear equation for the alpha emission of bismuth-189.

$$\mathbf{{}^{189}_{83}Bi \rightarrow {}^{185}_{81}Tl + {}^{4}_{2}He}$$

157. Phosphorus-32, which is used to detect breast cancer, undergoes beta emission. Write the nuclear equation for this reaction.

$$\mathbf{{}^{32}_{15}P \rightarrow {}^{32}_{16}S + {}^{0}_{-1}e}$$

159. Write the nuclear equation for the positron emission of potassium-40.

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

161. Radioactive selenium-75, used to determine the shape of the pancreas, shifts to a more stable nuclide via electron capture. Write the nuclear equation for this change.

$$\mathbf{{}^{75}_{34}Se + {}^{0}_{-1}e \rightarrow {}^{75}_{33}As}$$

163. Germanium-78 atoms undergo two beta emissions before they reach a stable nuclide. What is the final product?

$${}^{78}_{32}Ge \rightarrow {}^{78}_{33}As \rightarrow \mathbf{{}^{78}_{34}Se}$$

165. Iron-52 atoms undergo one positron emission and one electron capture before they reach a stable nuclide. What is the final product?

$${}^{52}_{26}Fe \rightarrow {}^{52}_{25}Mn \rightarrow \mathbf{{}^{52}_{24}Cr}$$

167. Arsenic-69 atoms undergo one positron emission and one electron capture before they reach a stable nuclide. What is the final product?

$${}^{69}_{33}As \rightarrow {}^{69}_{32}Ge \rightarrow \mathbf{{}^{69}_{31}Ga}$$

170. Complete the following nuclear equations.

a. ${}^{249}_{98}Cf + {}^{15}_{7}N \rightarrow \mathbf{{}^{259}_{105}Db} + 5\,{}^{1}_{0}n$

b. $\mathbf{{}^{249}_{98}Cf} + {}^{10}_{5}B \rightarrow {}^{257}_{103}Lr + 2\,{}^{1}_{0}n$

c. ${}^{121}_{51}Sb + {}^{1}_{1}H \rightarrow {}^{121}_{52}Te + \mathbf{{}^{1}_{0}n}$

172. Nitrogen-containing explosives carried by potential terrorists can be detected at airports by bombarding suspicious luggage with low-energy neutrons. The nitrogen-14 atoms absorb the neutrons, forming nitrogen-15 atoms. The nitrogen-15 atoms emit gamma photons of a characteristic wavelength that can be detected outside the luggage. Write a nuclear equation for the reaction that forms nitrogen-15 from nitrogen-14.

$$\mathbf{{}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{15}_{7}N}$$

174. In March 1984, the nuclide hassium-265, $^{265}_{108}Hs$, was made from the bombardment of lead-208 atoms with iron-58 atoms. Write a nuclear equation for this reaction. (One or more neutrons may be released in this type of nuclear reaction.)

$$\mathbf{^{208}_{82}Pb + ^{58}_{26}Fe \rightarrow ^{265}_{108}Hs + ^{1}_{0}n}$$

176. Krypton-79, which is used to assess cardiovascular function, has a half-life of 34.5 hours. How long before a sample decreases to 1/8 of what was originally there?

*It takes three half-lives for a radioactive nuclide to decay to 1/8 of its original amount (½ × ½ × ½). Therefore, it will take 103.5 hours (***104 hours** *to three significant figures) for krypton-79 to decrease to 1/8 of what was originally there.*

178. Iron-59, which is used to diagnose anemia, has a half-life of 45 days. What fraction of it is left in 90 days?

The 90 days is two half-lives (90/45), so the fraction remaining would be **1/4** *(½ × ½).*