CHAPTER 24 Nuclear Chemistry

Section 1 Nuclear Radiation

Section 1 Review

page 864

1. **List** the different types of radiation and their charges.

   Alpha (2+), beta (1–), and gamma (0).

2. **Compare** the subatomic particles involved in nuclear and chemical reactions.

   Protons, electrons, and neutrons may be involved in nuclear change; only electrons are involved in chemical change.

3. **Explain** how you know whether the reaction is a chemical or nuclear reaction when an atom undergoes a reaction and attains a more stable form.

   If the new, more stable form of the atom has an identity different from the original atom or gamma radiation has been released, a nuclear process has occurred.

4. **Calculate** Table 2 gives approximate energy values in units of MeV. Convert each value into Joules using the following conversion factor: $1\text{MeV} = 1.6 \times 10^{-13}$ J.

   alpha $= 1.6 \times 10^{-13} \times 5 = 8 \times 10^{-13}$ J

   beta $= 1.6 \times 10^{-13} \times 0.05 = 8 \times 10^{-15}$ to $1.6 \times 10^{-13} \times 1 = 1.6 \times 10^{-13}$ J

   gamma $= 1.6 \times 10^{-13} \times 1 = 1.6 \times 10^{-13}$ J

5. **Summarize** Make a time line that summarizes the major events described in this lesson that led to the understanding of alpha, beta, and gamma radiation.

   Time lines should include Roentgen's 1895 discovery of X-rays, Becquerel's discovery that uranium exposes photographic film, the Curie's conclusion that uranium atoms emit radiation, and Rutherford's identification of alpha, beta, and gamma radiation.

Section 2 Radioactive Decay

Practice Problems

6. Write a balanced nuclear equation for the reaction in which oxygen-15 undergoes positron emission.

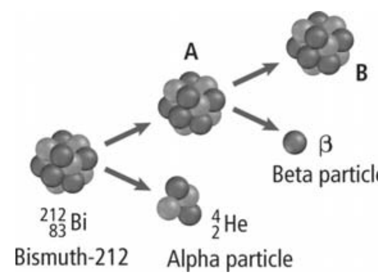
   $^{15}_{8}\text{O} \rightarrow {}^{0}_{1}\beta + {}^{15}_{7}\text{N}$

7. Thorium-229 is used to increase the lifetime of fluorescent bulbs. What type of decay occurs when thorium-229 decays to form radium-225?

   $^{229}_{90}\text{Th} \rightarrow {}^{4}_{2}\text{He} + {}^{225}_{88}\text{Ra}$

   Alpha decay

8. **Challenge** The figure shows one way that bismuth-212 can decay, producing isotopes **A** and **B.**



   a. Write a balanced nuclear equation for this decay.

   $^{212}_{83}\text{Bi} \rightarrow {}^{208}_{81}\text{Tl} + {}^{4}_{2}\text{He}$

   $^{208}_{81}\text{Tl} \rightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}\beta$

   b. Identify the isotopes **A** and **B** that are produced.

   Isotope A is thallium-208. Isotope B is lead-208.

9. Bandages can be sterilized by exposure to gamma radiation from cobalt-60, which has a half-life of 5.27 years. How much of a 10.0-mg sample of cobalt-60 is left after one half-life? Two half-lives? Three half-lives?

5.00 mg; 2.50 mg; 1.25 mg

For one half-life, amount remaining =

$$\text{(initial amount)}\left(\frac{1}{2}\right)^{n} = (10.0\text{ mg})\left(\frac{1}{2}\right)^{1}$$

$= 5.00$ **mg.**

For two half-lives, amount remaining =

$$\text{(initial amount)}\left(\frac{1}{2}\right)^{n} = (10.0\text{ mg})\left(\frac{1}{2}\right)^{2}$$

$= 2.50$ **mg.**

For three half-lives, amount remaining =

$$\text{(initial amount)}\left(\frac{1}{2}\right)^{n} = (10.0\text{ mg})\left(\frac{1}{2}\right)^{3}$$

$= 1.25$ **mg.**

10. If the passing of five half-lives leaves 25.0 mg of a strontium-90 sample, how much was present in the beginning?

$$\text{initial amount} = \frac{25.0}{(1/2)^5} = 8.00\times10^2\text{ mg}$$

11. Challenge The table shows the amounts of radioisotopes in three different samples. To the nearest gram, how much will be in Sample B and Sample C when Sample A has 16.2 grams remaining?

Sample	Radioisotope	Half-Life	Amount (g)
A	cobalt-60	5.27 y	64.8
B	tritium	12.32 y	58.4
C	strontium-90	28.79 y	37.6

Sample A will have 16.2 grams remaining after two half-lives, or 10.54 years.

Sample A: $16.2\text{ g} = 64.8\text{ g }(1/2)^n;\ n = 2$

$t = 2 \times 5.27\text{ years} = 10.54\text{ years}$

For Sample B,

$$\text{Amount remaining} = \text{(Initial amount)}\left(\frac{1}{2}\right)^{t/T}$$

$$= (58.4\text{ g})\left(\frac{1}{2}\right)^{\frac{10.54\text{ y}}{12.32\text{ y}}} \approx 32.3\text{ g}$$

For Sample C,

$$\text{Amount remaining} = \text{(Initial amount)}\left(\frac{1}{2}\right)^{t/T}$$

$$= (37.6\text{ g})\left(\frac{1}{2}\right)^{\frac{10.54\text{ y}}{28.79\text{ y}}} \approx 29.2\text{ g}$$

Section 2 Assessment

12. Describe what happens to unstable nuclei.

Unstable nuclei decay by emitting alpha or beta radiation until they form a stable element.

13. Explain how you can predict whether or not an isotope is likely to be stable if you know its number of neutrons and protons.

Isotopes are likely to be stable if their n/p ratio is within the range of 1:1 to 1.5:1. The lightest isotopes have n/p ratios close to 1:1, while the heaviest isotopes have ratios close to 1.5:1.

14. Describe the forces acting on the particles within a nucleus and identify the force - responsible for nuclear stability.

Protons are positively charged and repel each other. Neutrons do not repel each other or protons. The strong nuclear force is an attractive force that acts on both protons and neutrons in the nucleus. The greater the number of neutrons in the nucleus, the greater the strong nuclear force.

15. Predict the nuclear equation for the alpha decay of radium-226 used on the tips of older lightning rods.

$${}^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$$

16. Calculate how much of a 10.0 g sample of Americium-241 remains after four half-lives. Americium-241 is a radioisotope commonly used in smoke detectors and has a half-life of 430 y.

0.625 g

$$\text{Amount remaining} = \text{(Initial amount)}\left(\frac{1}{2}\right)^{n}$$

$$= (10.0\text{ g})\left(\frac{1}{2}\right)^{4} = 0.625\text{ g}$$

17. **Radioactive Isotopes** After 2.00 y, 1.986 g of a radioisotope remains from a sample that had an original mass of 2.000 g.

a. Calculate the half-life.

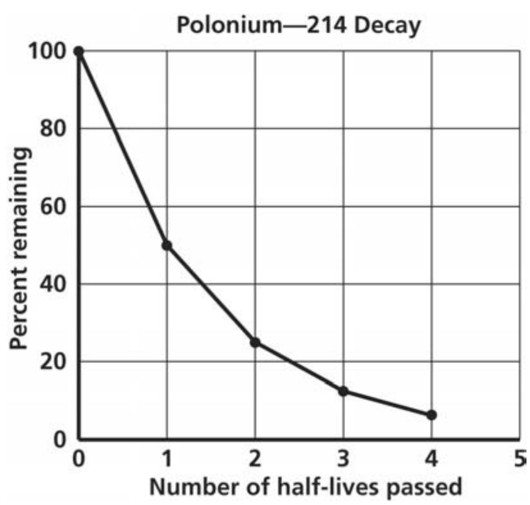
$$\mathbf{1.986\ g = 2.000\ g \times (1/2)^{(2.00\ y)/T}}$$
$$\mathbf{\frac{1.986}{2.000} = (1/2)^{2.00/T}}$$
$$\mathbf{0.9930 = 0.5^{2.00/T}}$$
$$\mathbf{\log 0.9930 = \log (0.5^{2.00/T})}$$
$$\mathbf{\log 0.9930 = \log 0.5 \times (2.00/T)}$$
$$\mathbf{T = \frac{\log 0.5 \times 2.00}{\log 0.9930} = 197\ years}$$

b. How much of the radioisotope remains after 10.00 years?

$$\mathbf{2.000 \times (1/2)^{10/197} = 1.931\ g}$$

18. **Graph** A sample of polonium-214 originally has a mass of 1.0 g. Express the mass remaining as a percent of the original sample after a period of one, two, and three half-lives. Graph the percent remaining versus the number of half-lives. Approximately how much time has elapsed when 20% of the original sample remains?

Each half-life corresponds to a 50% reduction in the amount remaining.



According to table 24.5, polonium has a half-life of 163.7 μs. From the graph, at 2.3 half-lives, approximately 20% remains. $t = 2.3 \times 163.7 = 380\ \mu s$

Section 3 Nuclear Reactions

Practice Problems

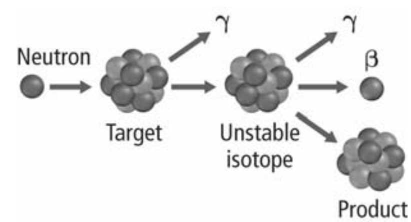
19. Write the balanced nuclear equation for the induced transmutation of aluminum-27 into sodium-24 by neutron bombardment. An alpha particle is released in the reaction.

$$\mathbf{{}^{27}_{13}Al + {}^{1}_{0}n \rightarrow {}^{24}_{11}Na + {}^{4}_{2}He}$$

20. Write the balanced nuclear equation for the alpha particle bombardment of ${}^{239}_{94}\mathbf{Pu}$. One of the reaction products is a neutron.

$$\mathbf{{}^{239}_{94}Pu + {}^{4}_{2}He \rightarrow {}^{1}_{0}n + {}^{242}_{96}Cm}$$

21. **Challenge** Archeologists sometimes use a procedure called neutron activation analysis to identify elements in artifacts. The figure shows one type of reaction that can occur when they bombard an artifact with neutrons. If the product of the process is cadmium-110, what was the target and unstable isotope? Write balanced nuclear equations for the process to support your answer.



Let T = target and I = unstable isotope. Then,

$$\mathbf{{}^{1}_{0}n + T = I}$$

and

$$\mathbf{I = {}^{0}_{-1}\beta + {}^{110}_{48}Cd}$$

Balancing the second equation gives:

$$\mathbf{{}^{110}_{47}Ag = {}^{0}_{-1}\beta + {}^{110}_{48}Cd}$$

The first equation must then be:

$$\mathbf{{}^{1}_{0}n + T = {}^{110}_{47}Ag}$$

Balancing this equation gives:

$$\mathbf{{}^{1}_{0}n + {}^{109}_{47}Ag = {}^{110}_{47}Ag}$$

The target, then, was silver -109, and the unstable isotope was silver -110.

Problem-solving Strategy

Calculate the mass defect and binding energy of lithium-7. The mass of lithium is 7.016003 amu.

mass defect = (mass of isotope) – (number of protons)m_H – (number of neutrons)m_n
= 7.016003 amu – 3(1.007825 amu)
–4(1.008665 amu)
= –0.042132 amu

Binding energy = (mass defect) (931.49 MeV/amu)
= (–0.042132 amu) (931.49 MeV/amu)
= –39.246 MeV

Section 3 Review

22. **Compare and contrast** nuclear fission and nuclear fusion reactions. Describe the particles that are involved in each type of reaction and the changes they undergo.

    In fission, heavy nuclei break down into smaller nuclei, releasing large amounts of energy. In fusion, two or more light nuclei join together to form a more stable nucleus and release large amounts of energy.

23. **Describe** the process that occurs during a nuclear chain reaction and explain how to monitor a chain reaction in a nuclear reactor.

    A neutron strikes a target nucleus such as U-235, which then splits into multiple fission fragments and releases several neutrons. These neutrons collide with other nuclei, causing additional fissions and sustaining the reaction. To control the chain reaction in a nuclear reactor, control rods made of cadmium or boron are used to absorb some of the neutrons released during the reaction.

24. **Explain** how nuclear fission can be used to generate electrical power.

    Fission reactions heat water and form steam. The steam spins turbines that produce electrical power.

25. **Formulate** an argument supporting or opposing nuclear power as your state's primary power source. Assume the primary source of power currently is the burning of fossil fuels.

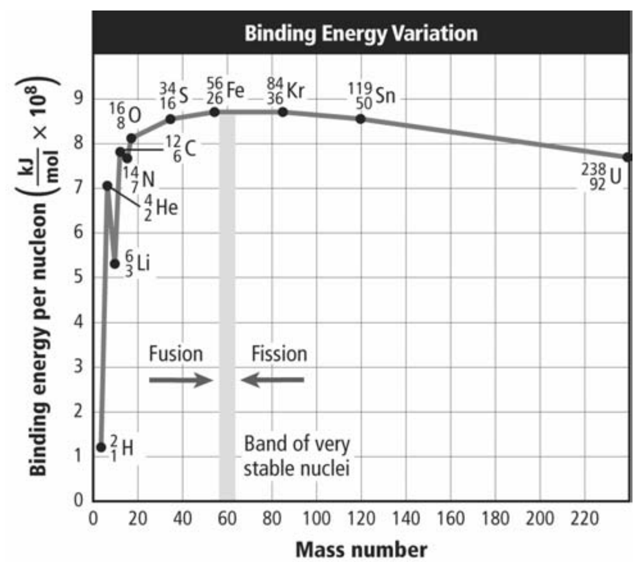
    Answers will vary. Supporting: students might mention that the burning of fossil fuels contribute to global warming and that the resources of fossil fuels are limited. Opposing: students might mention the problem of recycling nuclear wastes and the risk of accidents at a nuclear power plant.

26. **Calculate** What is the energy change (ΔE) associated with a change in mass (Δm) of 1.00 mg?

    $\boldsymbol{\Delta E = (1.00 \times 10^{-6}\ kg)(3.00 \times 10^{8}\ m/s)^2}$

    $\boldsymbol{= 9.00 \times 10^{10}\ J\ (kg{\cdot}m^2/s^2)}$

27. **Interpret a Graph** Use the graph in **Figure 24** to answer the following questions.



a. Why is the isotope ${}^{56}_{26}Fe$ highest on the curve? ${}^{56}_{26}Fe$ has the greatest binding energy.

b. Are more stable isotopes located higher or lower on the curve?

   higher

c. Compare the stability of Li-6 and He-4.

   The stability of He-4 is greater.

Problem-Solving Lab

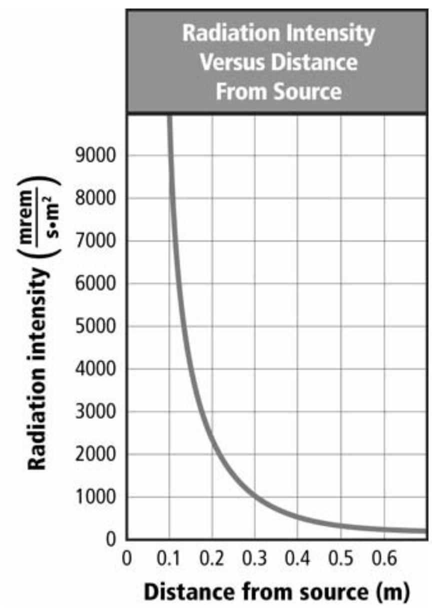
1. **Evaluate** How does the radiation exposure change as the distance doubles from 0.1 m to 0.2 m? How does it change as the distance quadruples from 0.1 m to 0.4 m?

   The level at 0.2, is one-quarter the level at 0,1 m. The level at 0.4 m is one-sixteenth the level at 0.1 m.

2. **Formulate** in words the mathematical relationship described in your answer to question 1.

   The radiation decreases with the square of the distance from the source.

3. **Interpret graphs** Determine the distance from the source at which the radiation decreased to 0.69 mrem/s·m^2. This intensity is the maximum radiation exposure intensity considered safe. (*Hint: Use the equation* $I_1/I_2 = d_2^2/d_1^2$.)



   Set up an inverse square relationship. $\frac{I_1}{d_2^2} = \frac{I_2}{d_2^1}$.

   Substitute values for I_1 and I_2 from the data given in the graph. Then substitute 0.69 mrem/m^2 for I_2 and solve for d_2. The result is $d_2 = 12$ m.

Section 4 Review

28. **Explain** one way in which nuclear chemistry is used to diagnose or treat disease.

    Explanations will vary, but might include radiotracers, PET scans, or radiation treatment to kill cancer cells.

29. **Describe** several methods used to detect and measure radiation.

    Geiger counters, scintillation counters, and film badges may be described.

30. **Compare** and contrast somatic and genetic biological damage.

    Somatic damage affects the body cells of the organism and will have effects only on that organism in its lifetime. Genetic damage affects the DNA of the organism, and could be transferred to later generations.

31. **Explain** why it is safe to use radioisotopes for the diagnosis of medical problems.

    Radioisotopes used in medical diagnosis have short half-lives, thereby minimizing the patient's exposure.

32. **Calculate** A lab worker receives an average radiation dose of 21 mrem each month. Her allowed dose is 5000 mrem/y. On average, what fraction of her yearly dose does she receive?

    Average yearly dose = 12 × (average monthly dose) = 12 × (21 mrem) = 252 mrem. The fraction of her yearly dose is (252 mrem/5,000 mrem) × 100% = 5.0%

33. **Interpret Data** Look at the data in **Table 7.** Suppose someone is exposed to the maximum values listed for average annual radiation from the ground, from buildings, and from the air. What fraction would the person receive of the minimum short-term dose (25 rem) that causes temporary decrease in white blood cell population?

    The total annual dose the person receives from the ground, buildings, and air would be 170 mrem + 160 mrem + 260 mrem = 590 mrem. (590 mrem ÷ 25,000 mrem) × 100% = 2.4%.

Chapter 24 Assessment

Section 1

Mastering Concepts

34. Compare and contrast chemical reactions and nuclear reactions in terms of energy changes and the particles involved.

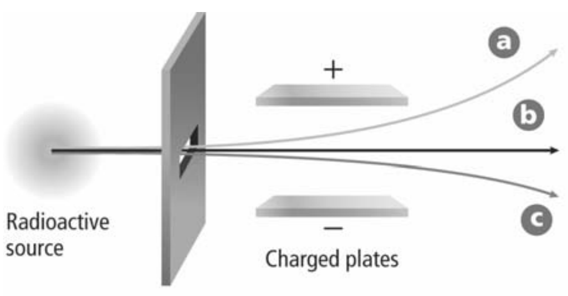
Nuclear reactions release more energy per mole. Nuclear reactions involve neutrons and protons, whereas chemical reactions involve electrons.

35. Match each numbered choice on the right with the correct radiation type on the left.

a. alpha	**1.** high speed electrons
b. beta	**2.** 2 + charge, blocked easily
c. gamma	**3.** no charge, electromagnetic radiation

a. 2 **b. 1** **c. 3**

36. The figure above shows alpha particles, beta particles, and gamma rays passing through a screen and between two charged plates. What can you infer about the identity of A, B, and C? Explain your answer.



Radiation "a" must be beta particles because their negative charge would cause them to be deflected away from the negatively-charged plate and towards the positive plate. Radiation "b" must be gamma rays because they have no charge and would not be deflected by the charged plates. Radiation "c" must be alpha particles because their positive charge would cause them to be deflected away from the positively-charged plate and towards the negative plate.

37. What is the difference between X-rays and gamma rays?

X-rays are produced by materials that are in an excited electron state. Gamma rays are produced by radioactive sources.

Mastering Problems

38. Dental Crown Uranium-234 is used to make dental crowns appear brighter. The alpha decay of uranium-234 produces what isotope?

$^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} + \alpha$

39. Detecting Material Flaws Flaws in welded metal parts of airplanes can be identified by placing the isotope iridium-192 on one side of the weld and photographic film on the other side to detect gamma rays that pass through. How does the gamma ray emission affect the atomic number and mass number of the iridium?

The atomic number and mass number do not change.

40. Colored Glass Thorium-230 can be used to provide coloring in glass objects. One method of producing thorium-230 is through the radioactive decay of actinium-230. Is this an example of alpha decay or beta decay? How do you know?

Beta decay; the mass number does not change.

$^{230}_{89}\text{Ac} \rightarrow {}^{230}_{90}\text{Th} + {}^{0}_{-1}\beta$

41. Plastic Bags Thin sheets of plastic are used to make items such as grocery bags. The sheets move under a source of promethium-147 emitting beta particles. The radiation intensity, measured under the plastic sheets, is used to monitor the thickness of the plastic. During this process, promethium changes to what element?

$^{147}_{61}\text{Pm} \rightarrow {}^{147}_{62}\text{Sm} + {}^{0}_{-1}\beta$

samarium

Section 2

Mastering Concepts

42. What is the strong nuclear force? On which particles does it act?

The strong nuclear force binds nucleons together. Protons and neutrons.

43. Explain the difference between positron emission and electron capture.

In positron emission, a proton turns into a neutron: $^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}\beta$. In electron capture, a proton merges with an inner-shell electron: $^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n$.

44. Categorize each type of radioactive decay.

a. Mass number and atomic number are unchanged.

gamma emission

b. Mass number remains the same and atomic number decreases.

The decay involved is either positron emission or electron capture.

45. What is the significance of the band of stability?

Isotopes lying outside the band will spontaneously decay.

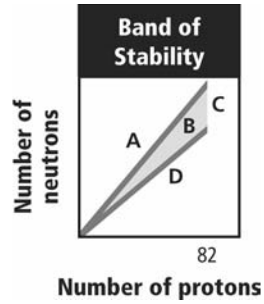
46. What is a radioactive decay series? When does it end?

A family of decay reactions that continue until a stable, non-radioactive isotope is formed.

47. Radioisotopes What are the factors that determine the amount of a given radioisotope in nature?

Its half-life and how much of the isotope is produced.

48. In which region(s) in **Figure 31** are you likely to find



a. stable nuclei?

region B

b. Nuclei that undergo alpha decay?

region C

c. Nuclei that undergo beta decay?

region A

d. Nuclei that undergo positron emission?

region D

49. Carbon-14 Dating Carbon-14 dating makes use of a specific ratio of two different radioisotopes. Define the ratio used in carbon-14 dating. Why is this ratio constant in living organisms?

C-14 : C-12; Ratio is constant in living organisms because they assimilate new C-14 into their cells, thus replenishing C-14 lost to decay.

Mastering Problems

50. Calculate the neutron-to-proton ratio for each of the following atoms.

a. tin-134

$(134–50)/50 = 1.68$

b. silver-107

$(107–47)/47 = 1.28$

c. carbon-12

$(12–6)/6 = 1.0$

d. carbon-14

$(14–6)/6 = 1.33$

51. Complete the following equations:

a. $^{214}_{83}\text{Bi} \rightarrow ^{4}_{2}\text{He} + ?$

$^{210}_{81}\text{Tl}$

b. $^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ?$

$^{0}_{-1}\beta$

52. Write a balanced nuclear equation for the alpha decay of americium-241.

$^{241}_{95}\text{Am} \rightarrow ^{4}_{2}\text{He} + ^{237}_{93}\text{Np}$

53. Write a balanced nuclear equation for the beta decay of cesium-137.

$^{137}_{55}\text{Cs} \rightarrow ^{137}_{56}\text{Ba} + ^{0}_{-1}\beta$

54. **Bone Formation** The electron capture of strontium-85 can be used by physicians to study bone formation. Write a balanced nuclear equation for this reaction.

$^{0}_{-1}\text{e} + ^{85}_{38}\text{Sr} \rightarrow ^{85}_{37}\text{Rb}$

55. **Nuclear Mishap** The half-life of tritium ($^{3}_{1}$H)is 12.3 y. If 48.0 mg of tritium is released from a nuclear power plant during the course of a mishap, what mass of the nuclide will remain after 49.2 years? After 98.4 years?

$t/T = 49.2 \text{ y}/12.3 \text{ y} = 4 \text{ half-lives}$

$48.0 \text{ mg } (1/2)^4 = 48.0 \text{ mg}/16 = 3.00 \text{ mg}$

$t/T = 98.4 \text{ y}/12.3 \text{ y} = 8 \text{ half-lives}$

$48.0 \text{ mg } (1/2)^8 = 48.0 \text{ mg}/256 = 0.188 \text{ mg.}$

56. **Static Charge** The buildup of static charge can interfere with the production and labeling of plastic products by attracting dust and dirt. To reduce it, manufacturers expose the area to polonium-210, which has a half-life of 138 days. How much of a 25.0 g sample will remain after one year (365 days)?

$$\text{Amount remaining} = (\text{Initial amount})\left(\frac{1}{2}\right)^{t/T}$$

$$= (25.0 \text{ g})\left(\frac{1}{2}\right)^{365 \text{ d}/138 \text{ d}}$$

$$= 4.00 \text{ g}$$

57. The half-life of polonium-218 is 3.0 min. If you start with 20.0 g, how long will it be before only 1.0 g remains?

$$1.0 \text{ g} = 20.0 \text{ g} \times (1/2)^{t/3.0 \text{ min}}$$

$$\frac{1.0}{20.0} = (0.5)^{t/3.0 \text{ min}}$$

$$0.050 = (0.5)^{t/3.0 \text{ min}}$$

$$\log 0.050 = \log 0.5 \times t/3.0 \text{ min}$$

$$t = \frac{\log 0.05 \times 3.0 \text{ min}}{\log 0.5} = 13 \text{ min}$$

58. An unknown radioisotope exhibits 8540 decays per second. After 350.0 minutes, the number of decays has decreased to 1250 per second. What is the half-life?

$$1250 \text{ dps} = 8540 \text{ dps} \times (1/2)^{350.0 \text{ min}/T}$$

$$\frac{1250}{8540} = 0.5^{350.0 \text{ min}/T}$$

$$\log 0.146 = \log 0.5 \times (350 \text{ min}/T)$$

$$T = \frac{\log 0.5 \times 350.0 \text{ min}}{\log 0.146} = 126 \text{ min}$$

Section 3

Mastering Concepts

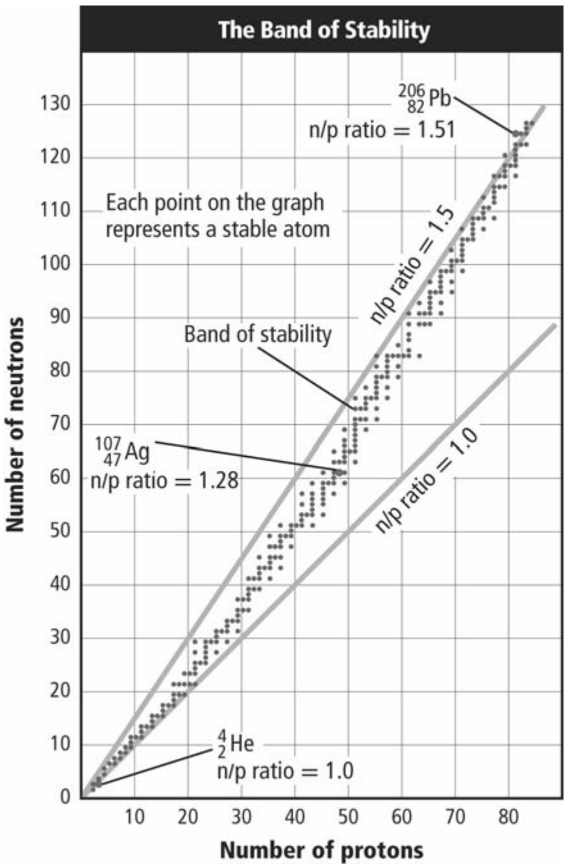
59. Define transmutation. Are all nuclear reactions also transmutation reactions? Explain.

Transmutation is the changing of an atom's nucleus such that a new element is formed. Most, but not all nuclear reactions are transmutations.

60. Relate binding energy per nucleon to mass number.

The binding energy per nucleon reaches a maximum value for mass numbers around 60 amu.

61. Referring to **Figure 7** would you expect $^{39}_{20}$**Ca** to be radioactive? Explain.



Ca-39 is likely to be radioactive, since it lies just below the band of stability.

62. What is a chain reaction? Give an example of a nuclear chain reaction.

A chain reaction occurs when a reaction produces one or more of the particles needed as a reactant. An example is the fission of U-235 by absorption of a neutron.

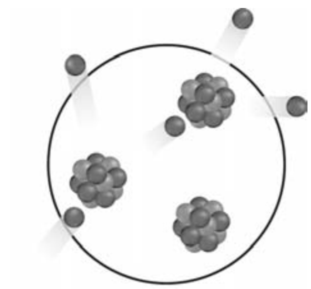
63. Explain the purpose of control rods in a nuclear reactor.

Control rods absorb neutrons from the fission reaction, allowing the rate of reaction to be controlled.

64. Why is the fuel of a nuclear reactor enriched?

Enriching the fuel means increasing the concentration of the fissionable isotope in order to ensure that the chain reaction can be sustained.

65. Describe what is meant by the terms critical mass, subcritical mass, and supercritical mass. Which is shown in **Figure 32**? How can you tell?



Critical mass is the minimum mass of a sample of fissionable material needed to sustain a nuclear chain reaction. The mass is subcritical if most of the neutrons escape the material instead of hitting other nuclei. The mass is superciritcal if most neutrons hit other material, causing more and more fissions to occur. The figure shows subcritical mass because most neutrons are escaping the material.

66. Explain how it is possible that both fission, the splitting of a nucleus, and fusion, the combining of nuclei, both release tremendous amounts of energy.

With fission, a large nucleus splits into smaller nuclei. The binding energy of the large nucleus is greater than the sum of the binding energies of the smaller nuclei. The difference in energy is released. With fusion, two smaller nuclei combine to form a larger nucleus. The sum of the binding energies of the smaller nuclei is greater than the binding energy of the larger nucleus. Again, the difference in energy is released.

67. Describe the current limitations of fusion as a power source.

Answers might include generation of sufficient temperature and containing the reaction. A lot of energy is required to initiate and sustain the reaction. No materials so far are capable of withstanding the very high temperature reached during such a reaction.

68. Why does nuclear fusion require so much heat? How is heat contained within a tokamak reactor?

Extremely high temperatures are needed to overcome electrostatic repulsion and fuse the positively charged nuclei together. Magnetic fields contain the hot fusion reaction.

Mastering Problems

69. **Smoke Detectors** Americium-241, a radioisotope commonly used in smoke detectors, is produced by bombarding plutonium-238 with neutrons to produce plutonium-240 which is bombarded with neutrons to produce plutonium-241. The plutonium-241 decays to americium-241. Write the balanced nuclear equations for all three steps in this transmutation.

$${}^{238}_{94}\mathbf{Pu} + 2\,{}^{1}_{0}\mathbf{n} \rightarrow {}^{240}_{94}\mathbf{Pu}$$
$${}^{240}_{94}\mathbf{Pu} + {}^{1}_{0}\mathbf{n} \rightarrow {}^{241}_{94}\mathbf{Pu}$$
$${}^{241}_{94}\mathbf{Pu} \rightarrow {}^{241}_{95}\mathbf{Am} + {}^{0}_{-1}\beta$$

70. **Exit Signs** Exit signs are coated with a paint containing phosphors. These phosphors are -activated by the radioisotope tritium (${}^{3}_{1}H$) which is produced by bombarding lithium-6 with neutrons to produce lithium-7. The lithium-7 then undergoes alpha decay to produce the tritium. Write balanced nuclear equations for both steps.

$${}^{6}_{3}\mathbf{Li} + {}^{1}_{0}\mathbf{n} \rightarrow {}^{3}_{7}\mathbf{Li}$$
$${}^{7}_{3}\mathbf{Li} \rightarrow {}^{3}_{1}\mathbf{H} + {}^{4}_{2}\mathbf{He}$$

71. **Control Rods** Bombarding uranium-235 with neutrons produces samarium-149, a radioisotope used in nuclear reactor control rods. What other element is produced?

$${}^{235}_{92}\mathbf{U} + {}^{1}_{0}\mathbf{n} \rightarrow {}^{149}_{62}\mathbf{Sm} + {}^{86}_{30}\mathbf{Zn}$$

72. *The Sun* ${}^{1}_{1}\mathbf{H} + {}^{2}_{1}\mathbf{H} \rightarrow {}^{3}_{2}\mathbf{He} + {}^{0}_{0}\gamma$ is one of the fusion reactions in the Sun. The mass of ${}^{1}_{1}\mathbf{H}$ is 1.007825 amu, the mass of ${}^{2}_{1}\mathbf{H}$ is 2.014102 amu, and the mass of ${}^{3}_{1}\mathbf{H}$ is 3.016029.

a. What is the mass defect of ${}^{3}_{2}\mathbf{H}$?

$\Delta m = m_f - m_i$

= 3.016029 amu − (1.007825 amu + 2.014102 amu)
= 0.005898 amu

b. What energy is released by the process? (Hint: A mass of 1 amu corresponds to an energy of 931.49 MeV.)

ΔE = Δm × (931.49 MeV/amu)
= 0.005898 amu × (931.49 MeV/amu)
= 5.4939 MeV

Section 4

Mastering Concepts

73. What property of isotopes allows radiotracers to be useful in studying chemical reactions?

Radiotracers have the same chemical properties as the stable isotopes of that element.

74. Which unit of radiation dose, rem or rad, is most useful for describing the effect of radiation on living tissue? Why?

The rem is most effective because it accounts for the energy of the radiation, the type of living tissue, and the time of the exposure.

75. **PET Scans** In PET scans, the radiotracer emits positrons, which can travel a few millimeters before interacting with electrons. How, can the original radiotracer be detected?

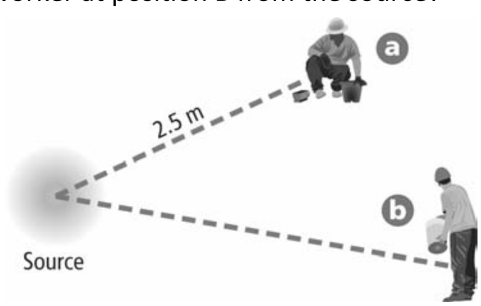
The positron/electron interaction forms gamma rays emissions that can be detected.

76. Figure 33 shows a simplified graph of radiation intensity versus distance from source. Explain this graph and what it implies about a method of reducing the effects of radiation exposure.

The graph shows that radiation intensity decreases rapidly with increasing distance from the source of the radiation. You can decrease the effects of radiation by increasing your distance from the source.

Mastering Problems

77. **Figure 34** shows the position of two workers near a radioactive gamma source. The worker at position A is standing 2.5 m from the source and receives an exposure of 0.98 mrem/s·m^2. The worker at position B receives an exposure of 0.50 mrem/s·m^2. What is the distance of the worker at position B from the source?



$$d_2 = \sqrt{\frac{I_1 d_1^2}{I_2}}$$
$$= \sqrt{\frac{(0.98\ \text{mrem/s}\cdot\text{m}^2)(2.5\ \text{m})^2}{0.50\ \text{mrem/s}\cdot\text{m}^2}}$$
$$= \mathbf{3.5\ m}$$

78. A worker stands near a machine that uses a cobalt-60 gamma source to sterilize medical equipment. The worker's dose 2.0 m from the source is 0.85 mrem/s·m^2. What is the worker's dose at a distance of 3.5 m from the source?

$$I_2 = \frac{I_1 d_1^2}{d_2^2}$$
$$= \frac{(0.85\ \text{mrem/s}\cdot\text{m}^2)(2.0\ \text{m})^2}{(3.5\ \text{m})^2}$$
$$= \mathbf{0.28\ mrem/s\cdot m^2}$$

79. **Safe Exposure** The intensity of a radioactive source is 1.15 mrem/s·m^2 at a distance of 0.50 m. What is the minimum distance a person could be from the source to have a maximum exposure of 0.65 mrem/s·m^2?

$$d_2 = \sqrt{\frac{I_1 d_1^2}{I_2}}$$
$$= \sqrt{\frac{(1.15\ \text{mrem/s}\cdot\text{m}^2)(0.50\ \text{m})^2}{0.65\ \text{mrem/s}\cdot\text{m}^2}}$$
$$= \mathbf{0.66\ m}$$

Mixed Review

80. Technetium-104 has a half-life of 18.0 minutes. How much of a 165.0 g sample remains after 90.0 minutes have passed?

t/T = 90.0 min/18.0 min = 5.00 half-lives
165.0 g × $(1/2)^{5.00}$ = 5.16 g.

81. A bromine-80 nucleus can decay by gamma emission, positron emission, or electron capture. What is the product nucleus in each case?

$$^{80}_{35}\text{Br} \rightarrow {}^{80}_{35}\text{Br} + \gamma$$
$$^{80}_{35}\text{Br} \rightarrow {}^{80}_{34}\text{Se} + {}^{0}_{1}\text{e}^+$$
$$^{80}_{35}\text{Br} + {}^{0}_{-1}\text{e}^- \rightarrow {}^{80}_{34}\text{Se}$$

82. The half-life of plutonium-239 is 24,000 years. How much nuclear waste generated today will remain in 1000 years?

amount remaining = $(1/2)^{1000/24000}$ = 0.97 or 97%

83. Red Blood Cells A medical researcher is using a chromium-51 source to study red blood cells. The gamma emission intensity at a distance of 1.0 m is 0.75 mrem/s·m^2. At what distance would the intensity drop to 0.15 mrem/s·m^2?

$$\boldsymbol{d_2 = \sqrt{\frac{I_1 d_1^2}{I_2}}}$$
$$\boldsymbol{= \sqrt{\frac{(0.75\ \text{mrem/s}\cdot\text{m}^2)(1.0\ \text{m})^2}{0.15\ \text{mrem/s}\cdot\text{mw}^2}}}$$
$$\boldsymbol{= 2.2\ \text{m}}$$

84. The binding energy per nucleon reaches a maximum around what mass number? Explain how this number is related to fission and fusion processes.

Mass number 60; light nuclei can become more stable by undergoing fusion, and heavier nuclei can become more stable by undergoing fission.

85. You have an alpha source, a beta source, and a gamma source. Design a plan to use a Geiger counter, paper, and foil to determine the identity of each source.

You could place each source behind the paper and use the Geiger counter to identify the source emitting alpha particles, which are blocked by paper. You could then place the remaining two sources behind the foil. The beta particles would be blocked by the foil. Then the remaining source is gamma.

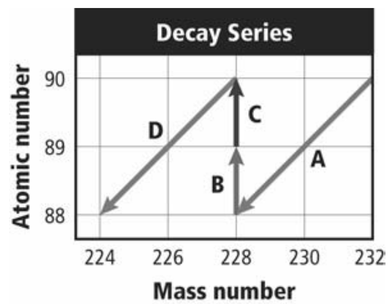
86. What is the half-life of radon-222 if *a* sample initially contains 150.0 mg and only 18.7 mg after 11.4 days?

$$\boldsymbol{18.7\ \text{mg} = 150.0\ \text{mg} \times (1/2)^{11.4\ \text{days}/T}}$$
$$\boldsymbol{\frac{18.7\ \text{mg}}{150.0\ \text{mg}} = (0.5)^{11.4\ \text{days}/T}}$$
$$\boldsymbol{\log 0.125 = \log 0.5 \times (11.4\ \text{days}/T\ )}$$
$$\boldsymbol{T = \frac{\log 0.5 \times 11.4}{\log 0.125} = 3.80\ \text{days}}$$

87. Sheet metal A company plans to monitor the thickness of sheet metal during production. What would you recommend the company do to determine a safe distance for workers from the gamma source?

Possible answer: The company could use a Geiger counter to determine the intensity of the source at a certain distance. They could move the Geiger counter until they reach a safe distance based on the maximum recommended exposure intensity for the source.

88. Figure 35 shows part of the decay series of a radioisotope. For each segment on the graph, tell whether alpha decay or beta decay occurs, and identify the change in atomic number and mass number.



A and D: alpha decay, atomic number decreases by 2, mass number decreases by 4; B and C: beta decay, atomic number increases by 1, mass number does not change

a. $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$

b. $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta$

c. $^{228}_{89}\text{Ac} \rightarrow {}^{228}_{90}\text{Th} + {}^{0}_{-1}\beta$

d. $^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + {}^{4}_{2}\text{He}$

Think Critically

89. Make and Use Graphs Thorium-231 decays to lead-207 by emitting the following particles in successive steps: b, a, a, b, a, a, a, b, b, a. Plot each step of the decay series on a graph of mass number versus atomic number. Label each plotted point with the symbol of the radioisotope.

$$^{231}_{90}\text{Th} \rightarrow ^{231}_{91}\text{Pa} + ^{0}_{-1}\beta$$

$$^{231}_{91}\text{Pa} \rightarrow ^{227}_{89}\text{Ac} + ^{4}_{2}\text{He}$$

$$^{227}_{89}\text{Ac} \rightarrow ^{223}_{87}\text{Fr} + ^{4}_{2}\text{He}$$

$$^{223}_{87}\text{Fr} \rightarrow ^{223}_{88}\text{Ra} + ^{0}_{-1}\beta$$

$$^{223}_{88}\text{Ra} \rightarrow ^{219}_{86}\text{Rn} + ^{4}_{2}\text{He}$$

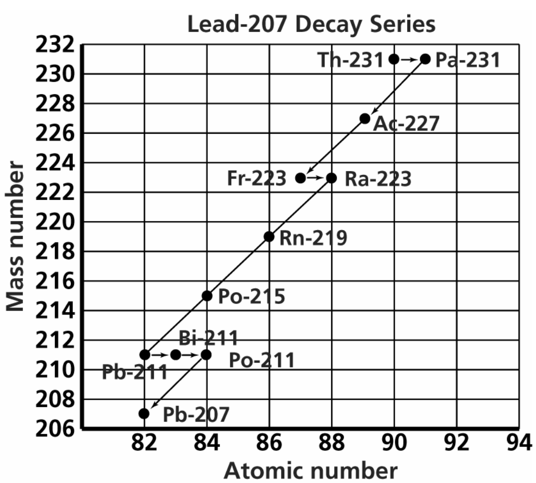
$$^{219}_{86}\text{Rn} \rightarrow ^{215}_{84}\text{Po} + ^{4}_{2}\text{He}$$

$$^{215}_{84}\text{Po} \rightarrow ^{211}_{82}\text{Pb} + ^{4}_{2}\text{He}$$

$$^{211}_{82}\text{Pb} \rightarrow ^{211}_{83}\text{Bi} + ^{0}_{-1}\beta$$

$$^{211}_{83}\text{Bi} \rightarrow ^{211}_{84}\text{Po} + ^{0}_{-1}\beta$$

$$^{211}_{84}\text{Po} \rightarrow ^{207}_{82}\text{Pb} + ^{4}_{2}\text{He}$$



90. Apply Chemical treatment is often used to destroy harmful chemicals. For example, bases neutralize acids. Why can't chemical treatment be applied to destroy the fission products produced in a nuclear reactor?

Chemical reactions do not affect nuclei, thus, the radioisotopes would continue to emit radiation.

91. Compare A biological concern about working around some radioactive materials is the radioactive dust a person might inhale. Compare the effect of alpha radiation outside the body and inside the body.

Outside the body, alpha radiation is not harmful because it cannot penetrate the skin. Inside the body, alpha radiation is far more damaging because it can directly affect tissue more fragile than the outer layer of the skin.

92. Interpret Small radioactive sources are often used for laboratory experiments. The radioactive substance is enclosed in a metal container with a small window. A gamma source might be covered with a stainless steel window. What would you expect the window of an alpha source to be like? Why?

An alpha source would have an open window to prevent absorption of the alpha particles.

93. Analyze Some radioisotopes used for medical imaging have half-lives as short as several hours. Why is a short half-live beneficial? Why is it a problem?

A short half-life is beneficial because it reduces the long-range exposure to the patient. A short half-life is a problem because it means the radioisotope must be frequently replaced and shipped to the medical facility soon after production or produced directly at the medical facility.

94. Infer The production of electricity at nuclear fission reactor facilities is controversial. Think about benefits and dangers of this technology. Explain your opinion about whether nuclear reactors should be used.

Those in favor of nuclear facilities might argue that it is a clean source of energy. They might point out that safeguards during the Three Mile Island accident show dangers can be contained and minimized. Opponents might argue that nuclear reactors produce nuclear waste that can pollute the environment and cause storage problems or that safeguards don't always work.

Challenge Problem

95. Use the information in **Table 8** to calculate the mass defect and binding energy of deuterium ($^{2}_{1}\mathbf{H}$), a hydrogen isotope involved in fusion reactions in the Sun.

Particle	Mass (amu)
hydrogen	1.007941
deuterium	2.014102
neutron	1.008665

a. Find the mass of the the nucleons.

mass of nucleons = mass of hydrogen + mass of neutron = 1.007941 amu + 1.008665 amu = 2.016606 amu

b. Find the mass defect by subtracting the mass of the nucleons from the mass of the deuterium.

mass defect = mass of deuterium – mass of nucleons = 2.014102 amu – 2.016606 amu = –0.002504 amu

c. Find the binding energy using the conversion 1 amu = 931.49 MeV.

binding energy = (mass defect) (931.49 MeV/amu) = (–0.002504 amu)(931.49 MeV/amu) = –2.332 MeV

Cumulative Review

96. Identify each of the following as a chemical property or a physical property.

a. The element mercury has a high density.

physical

b. Solid carbon dioxide sublimes at room temperature.

physical

c. Zinc oxidizes when exposed to air.

chemical

d. Sucrose is a white crystalline solid.

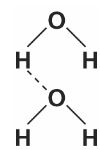
physical

97. Why does the second period of the periodic table contains eight elements?

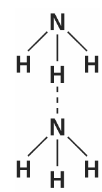
Because there are eight electrons in the 2s and 2p orbitals in the second energy level, the period contains 8 elements.

98. Draw the following molecules and show the locations of hydrogen bonds between the molecules.

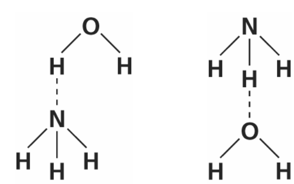
a. two water molecules



b. two ammonia molecules



c. one water molecule and one ammonia molecule



99. What process takes place in each situation

a. a solid air freshener cube getting smaller and smaller

sublimation

b. dewdrops forming on leaves in the morning

condensation

c. steam rising from a hot spring

evaporation

d. a crust of ice forming on top of a pond

solidification

100. If the volume of a sample of chlorine gas is 4.5 L at 0.65 atm and 321 K, what volume will the gas occupy at STP?

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$V_2 = \frac{(0.65\ \cancel{\text{atm}})(4.5\ \text{L})(273\ \cancel{\text{K}})}{(1.0\ \cancel{\text{atm}})(321\ \cancel{\text{K}})} = 2.5\ \text{L}$$

101. The temperature of 756 g of water in a calorimeter increses from 23.28C to 37.68C. How much heat was given off by the reaction in the calorimeter?

$$q = c \times m \times \Delta T$$

$$= 4.184 \times 756 \times (37.6 - 23.2) = 45.5\ \text{kJ}$$

102. Explain what a buffer is and why buffers are found in body fluids.

A buffer is a solution containing a mixture of an acid and its conjugate base that is able to resist changes in pH. Because many biochemical reactions are sensitive to changes in pH, buffers are needed in the body fluids.

103. Explain how the structure of benzene can be used to explain its unusually high stability compared to other unsaturated cyclic hydrocarbons.

The electron pairs in benzene's double bonds are shared among all six carbon atoms in the ring. Thus, the electrons cannot be pulled away as easily as electrons that are held by only two nuclei.

Additional Assessment

Writing in Chemistry

104. Marie Curie and Irene Curie Joliot Research and report on the lives of Marie Curie and her daughter, Irene Curie Joliot. What kind of scientific training did each receive? What was it like to be a female chemist in their time? What discoveries did each make?

Student answers will vary and might be extensive. For example, Marie Curie and her husband, Pierre, made possible many medical diagnostic techniques that we take for granted today. Marie and her oldest daughter, Irene Curie Joliot, developed and pioneered the use of x-radiography on the battlefields of World War I. Irene Curie Joliot won a Nobel Prize in Chemistry in 1935.

105. Nuclear Waste Evaluate environmental issues associated with nuclear wastes. Research the Yucca Mountain nuclear waste disposal plan, the Hanford nuclear site, or a local nuclear facility. Prepare a poster or multimedia presentation on your findings.

Answers will vary according to chosen nuclear site or facility. Projects should include the location and function of the facility, the nature of the issues, and what has been done to remedy the issue.

106. Radioactive Sources Students in your school might not realize how beneficial radioactive sources can be. Create a poster showing common, beneficial uses of radioactive sources. Be sure to point out safeguards that are taken to ensure the sources are safe.

Answers might include the use of radiation to treat cancer, x-ray radiography, radiocarbon dating, and others.

Document-Based Questions

Half-Lives The National Institute of Standards and Technology (NIST) maintains a database of radionuclide half-lives. In 1992, researchers at NIST measured the half-lives shown in **Table 9.**

Data obtained from: Unterweger, M.P., Hoppes, D.O., and Schima, F.J. 1992. New and revised half-life measurements results. Nucl. Instrum. Meth. Phys. Res. A3 12: 349–352.

Half-lives	
Radionuclide	**Half-Life**
Fluorine-18	1.82951 h
Molybdenum-99	65.9239 h
Samarium-153	46.2853 h

107. Fluorine-18 is used in medical imaging. If a lab has a sample containing 15 g of fluorine-18, how much fluorine-18 will remain in the sample after 8.0 h?

$$\textbf{Amount remaining} = \textbf{(Initial amount)}\left(\frac{1}{2}\right)^{t/T}$$

$$= (15.0\ \text{g})\left(\frac{1}{2}\right)^{8.0\ \text{h}/1.8295\ 1\text{h}}$$

$$= 0.72\ \text{g}$$

108. Technetium-99 can be used for diagnostic tests of the heart and lungs. Because of technetium-99's very short half-life, medical facilities produce it from molybdenum-99. If the facility has a 25-g sample of molybdenum-99, how much will it have a week (168 h) later?

$$\textbf{Amount remaining} = \textbf{(Initial amount)}\left(\frac{1}{2}\right)^{t/T}$$

$$= (25.0\ \text{g})\left(\frac{1}{2}\right)^{168\ \text{h}/65.9239\ \text{h}}$$

$$= 4.27\ \text{g}$$

109. Samarium-153 is used in the production of a drug to treat pain from bone tumors. Radiation released by the samarium hinders the tumor growth, thereby reducing pain. How much of a 1.0 g sample of samarium-153 is left after 4 days (96 h)?

$$\textbf{Amount remaining} = \textbf{(Initial amount)}\left(\frac{1}{2}\right)^{t/T}$$

$$= (1.0\ \text{g})\left(\frac{1}{2}\right)^{96\ \text{h}/46.2853\ \text{h}}$$

$$= 0.24\ \text{g}$$

Standardized Test Practice

Multiple Choice

1. Geologists use the decay of potassium-40 in volcanic rocks to determine their ages. Potassium-40 has a half-life of 1.26×10^9 years, so it can be used to date very old rocks. If a sample of rock 3.15×10^8 years old contains 2.73×10^{-7} g of potassium-40 today, how much potassium-40 was originally present in the rock?

a. 1.71×10^{-8} g
b. 2.30×10^{-7} g
c. 3.25×10^{-7} g
d. 4.37×10^{-6} g

Solution:

$$\textbf{amount remaining} = \textbf{original amount} \times (1/2)^{t/T}$$

$$t/T = \frac{3.15\times10^8\ \text{y}}{1.26\times10^9\ \text{y}} = 0.250$$

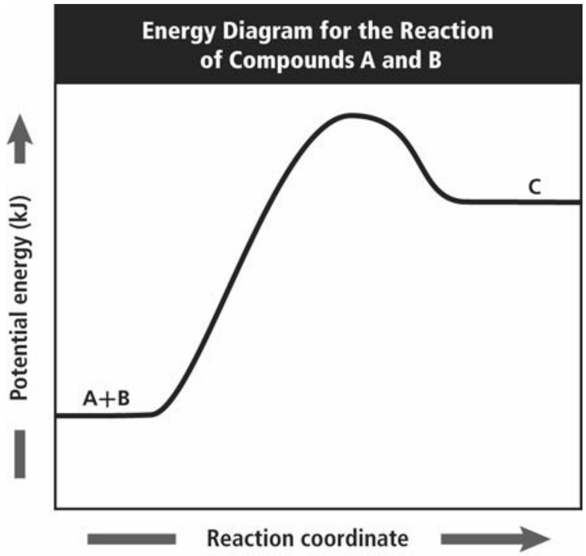
$$2.73\times10^{-7}\ \text{g} = \text{original amount} \times (1/2)^{0.250}$$

$$\text{original amount} = \frac{2.73\times10^{-7}\ \text{g}}{0.841} = 3.25\times10^{-7}\ \text{g}$$

2. In the early 1930s, van de Graaf generators were used to generate neutrons by bombarding stable beryllium atoms with deuterons ($^2_1$H), the nuclei of deuterium atoms. A neutron is released in the reaction. Which is the balanced nuclear equation describing this induced transmutation?

a. $^9_4\text{Be} + {^2_1}\text{H} \rightarrow {^{10}_5}\text{B} + \text{n}$
b. $^6_4\text{Be} + {^2_1}\text{H} \rightarrow {^8_5}\text{B} + \text{n}$
c. $^9_4\text{Be} \rightarrow {^{10}_5}\text{B} + {^2_1}\text{H} + \text{n}$
d. $^9_4\text{Be} + {^2_1}\text{H} \rightarrow {^{11}_5} + \text{n}$

Use the figure below to answer question 3.



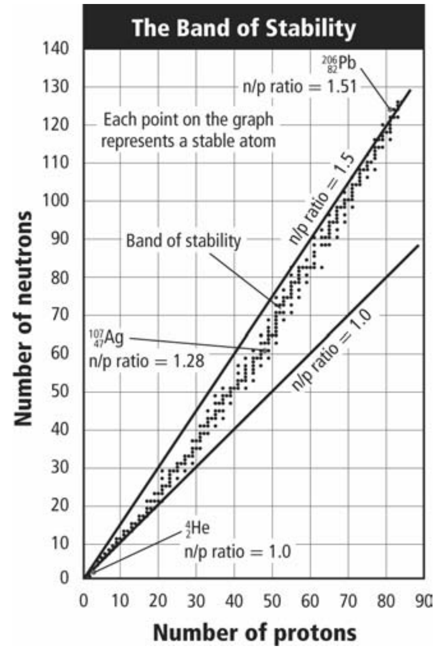
3. Which is NOT a correct description of this reaction?

a. This is a synthesis reaction.
b. This reaction releases energy.
c. This reaction is endothermic.
d. This reaction will occur spontaneously.

4. Which statement is NOT true of alpha particles?

a. They carry a charge of 2+.
b. They are represented by the symbol $^4_2$H.
c. They are more penetrating than β particles.
d. They have the same composition as helium nuclei.

Use the figure below to answer questions 5 and 6.



5. Why will calcium-35 undergo positron emission?

a. It lies above the line of stability.
b. It lies below the line of stability.
c. It has a high neutron-to-proton ratio.
d. It has an overabundance of neutrons.

6. Based on its position relative to the band of stability, which process will $^{70}_{30}$**Zn** undergo?

a. beta decay
b. electron capture
c. nuclear fusion
d. positron emission nuclear fusion

7. A solution of 0.600*M* HCl is used to titrate 15.00 mL of KOH solution. The end point of the titration is reached after the addition of 27.13 mL of HCl. What is the concentration of the KOH solution?

   a. 9.00*M*
   b. 1.09*M*
   c. 0.332*M*
   d. 0.0163*M*

   Solution:

   Calculate moles of HCl used.

   $$27.13\ \cancel{mL} \times \frac{1\ L}{1000\ \cancel{mL}} = 0.02713\ L\ HCl$$

   $$0.02713\ \cancel{L} \times \frac{0.600\ mol}{1\ \cancel{L}} = 0.0613\ mol\ HCl$$

   $$HCl(aq) + KOH(aq) \rightarrow H_2O(l) + KCl$$

   The ratio of mol HCl : mol KOH is 1:1

   Thus, mol KOH = 0.0163 mol

   $$\frac{0.0163\ mol\ KOH}{0.0150\ L\ KOH} = 1.09M$$

Short Answer

Use the figure below to answer questions 8 to 10.

8. Identify the anode and cathode of this apparatus.

   The anode is where oxidation takes place and electrons are lost, which is the zinc electrode. The cathode is the copper electrode.

9. Write the oxidation half reaction.

   $$Zn \rightarrow Zn^{2+} + 2e^-$$

10. Explain the function of the salt bridge in this apparatus.

    It allows ions to pass from one solution to the other, completing the electrical circuit and preventing the buildup of positive or negative ions.

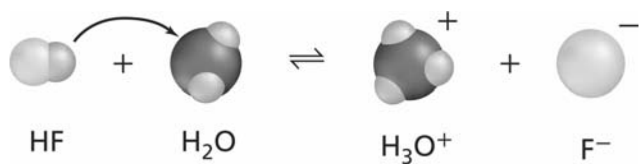
11. Predict the products of this reaction.

    $$Al(NO_3)_3 + CaSO_4 \rightarrow$$

    $$Al_2(SO_4)_3 + Ca(NO_3)_2$$

Extended Response

Use the figure below to answer questions 12 and 13.



12. Identify the acid and the base for the forward reaction. Explain how you can tell.

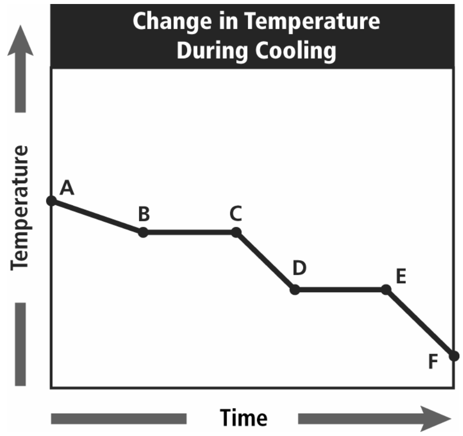
    The acid is HF because it is donating its proton. The base is H_2O because it is accepting the proton.

13. Explain how you can identify the conjugate acid and conjugate base for the forward reaction. What are they?

    The conjugate acid is what remains after the base accepts the proton, and will act as the acid in the reverse reaction by giving up its proton. In this reaction, it is H_3O^+. The conjugate base is what remains after the acid gives up its proton and will serve as the proton acceptor in the reverse reaction. It is the F^- ion in this reaction.

SAT Subject Test: Chemistry

Use the figure below to answer Questions 14 and 15.



14. During which segments are particles changing states of matter?

a. AB, CD, EF
b. AB, EF
c. BC, CD, DE
d. BC, EF
e. BC, DE

15. During which segments are particles losing kinetic energy?

a. BC, DE
b. AB, DE
c. AB, CD, EF
d. BC, DE, EF
e. AB, CD, DE

16. In the first steps of its radioactive decay series, thorium-232 decays to radium-228, which then decays to actinium-228, What are the balanced nuclear equations describing these first two decay steps?

a. $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + e^{-}$, $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + e^{+}$
b. $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$, $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + e^{-}$
c. $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + e^{+}$, $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + e^{-}$
d. $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$, $^{228}_{88}\text{Ra} + e^{-} \rightarrow {}^{228}_{89}\text{Ac}$
e. $^{232}_{90}\text{Th} + e^{-} \rightarrow {}^{228}_{88}\text{Ra}$, $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + e^{-}$