CHAPTER

16

Key Concepts

In this chapter, you will learn about:

- half-life
- nuclear decay
- nuclear reactions

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- describe the nature and properties of nuclear radiation
- write nuclear equations for alpha, beta-negative, and beta-positive decays
- perform half-life calculations
- use conservation laws to predict the particles emitted by a nucleus
- compare and contrast fission and fusion reactions
- relate the mass defect of the nucleus to the energy released in nuclear reactions

Science, Technology, and Society

- explain that the goal of science is knowledge about the natural world
- explain that technology meets given needs but should be assessed for each potential application

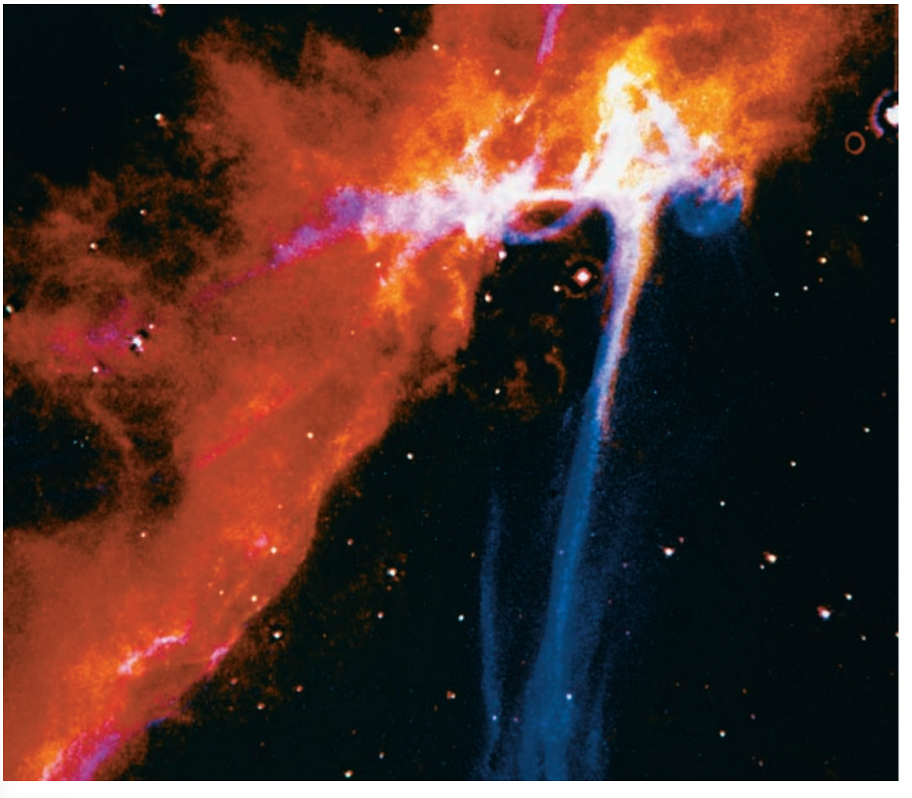
Nuclear reactions are among the most powerful energy sources in nature.

"*I believe a leaf of grass is no less than the journey-work of the stars*"

— from *Leaves of Grass* by Walt Whitman

When the American poet Walt Whitman wrote this line in 1855, the reactions within stars were unknown, the nucleus had not been discovered, and there was no clear proof that atoms exist. By the late 1950s, however, a new interpretation of Whitman's words was possible. Astrophysicists had developed a theory that nuclear reactions inside massive stars created the heavy elements essential to life. Some of these stars exploded into supernovae, scattering heavy elements throughout the galaxy.

This chapter describes nuclear reactions, the enormous potential energy in some nuclei, and the hazards and benefits of radioactive materials. You will learn about the processes that power the stars and how every leaf of grass may indeed be "the journey-work of the stars."



▲ **Figure 16.1** A portion of the Cygnus Loop, an expanding cloud of hot gas formed by a supernova explosion about 15 000 years ago. This composite image was made using photographs from the Hubble Space Telescope. The blue colour is light from oxygen, green is light from hydrogen, and red is light from sulfur.

16-1 Inquiry Lab

Radiation Intensity

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question
Does the intensity of radiation depend on the distance from the source of the radiation?

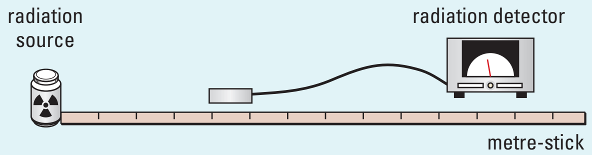
Hypothesis
There is a mathematical relationship between the intensity of radiation and the distance from the radiation source.

Variables
- distance between radiation source and detector
- reading on radiation detector

Materials and Equipment
cobalt-60 radiation source
radiation detector
metre-stick
masking tape
optional: interface for computer or graphing calculator

CAUTION: The radioactive material is enclosed in a durable casing to prevent accidental absorption into the body. Do not damage this casing.

Procedure
1. Make sure the radiation source is at least 3 m away from the radiation detector. Switch on the detector and measure the background radiation level for 5 min or more. Record this measurement, including the units. If you are using an interface with a computer or graphing calculator, check with your teacher about recording your data electronically.
2. Centre the cobalt-60 radiation source over the zero mark on the metre-stick, and tape the source in place. If your radiation source is shielded so that it emits radiation only from one side, align the source to direct the radiation along the metre-stick (Figure 16.2).
3. Place the radiation detector on the metre-stick within a few centimetres of the radiation source. Measure the radiation level for at least 1 min. Record the radiation level and the distance between the source and the detector.
4. Increase the separation between the radiation source and the detector in steps of 5 cm. Measure the radiation level for at least 1 min at each distance. Record measurements for at least six distances.



▲ **Figure 16.2**

Analyzing and Interpreting
1. Which variable is the manipulated variable in this experiment?
2. Explain why you need to know the background radiation level in order to determine how the intensity of the radiation varies with distance.
3. Graph your data. What type of relationship do you think the graph shows?
4. Discuss with your lab partners how you could use a different graph to determine the exact relationship between the radiation intensity and the distance from the radiation source. Produce a graph using the method that you think will work best. Explain your choice.
5. List any assumptions you made when analyzing your data.

Forming Conclusions
6. Do your data support the hypothesis? Explain.

Think About It
1. What is radioactivity?
2. Where does the energy released in a nuclear reaction come from?
3. How can stars create elements?

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes in your ideas.

16.1 The Nucleus

Section 15.3 described how scattering experiments directed by Rutherford showed that more than 99.9% of the mass of an atom is concentrated in a nucleus that is typically only a few **femto**metres (10^{-15} m) in diameter. In 1918, Rutherford began a new series of experiments in which he bombarded nitrogen gas with alpha particles. He found that some of the nitrogen transmuted into oxygen and that the process also produced hydrogen nuclei. Rutherford concluded that the hydrogen nucleus was a fundamental particle that is a constituent of all nuclei. He called these particles **protons**, from *protos*, the Greek word for "first."

femto: metric prefix meaning 10^{-15}

proton: a positively charged particle found in all nuclei

However, protons could not account for all of the mass of nuclei. For example, the charge-to-mass ratio for protons is twice that of helium nuclei. In 1920, Rutherford suggested that nuclei might also contain **neutrons**, neutral particles with about the same mass as a proton. Neutral particles are difficult to detect or measure because they do not interact with electric or magnetic fields. A variety of experiments over the next decade failed to find any neutrons. The breakthrough came in 1932 when James Chadwick showed that alpha rays striking a beryllium target produced radiation consisting of neutral particles. In a similar experiment with a boron target, he determined that the mass of a neutron is about 0.1% greater than the mass of a proton.

neutron: a neutral particle found in nuclei

info **BIT**

Chadwick made two earlier attempts to discover the neutron, in 1923 and 1928. In 1935, he received the Nobel Prize in physics for his discovery.

Nuclear Terms and Notation

Protons and neutrons are called **nucleons** because they are both components of nuclei. Three numbers describe the composition of a nucleus:

nucleon: a proton or neutron

Atomic Number, Z: the number of protons in a nucleus

Neutron Number, N: the number of neutrons in the nucleus

Atomic Mass Number, A: the number of nucleons in the nucleus, $Z + N$

Scientists often indicate the composition of a nucleus with the notation ${}^{A}_{Z}\mathrm{X}$, where X is the chemical symbol for the element. For example, a carbon nucleus with 6 protons and 6 neutrons has $Z = 6$, $N = 6$, and $A = 6 + 6 = 12$. The notation for the carbon nucleus is ${}^{12}_{6}\mathrm{C}$. Apply these terms and concepts in the next example.

Example 16.1

How many neutrons are contained in a gold nucleus $^{197}_{79}Au$?

Given
$Z = 79$ $A = 197$

Required
neutron number (N)

Analysis and Solution
Since $A = Z + N$,
$$N = A - Z = 197 - 79 = 118$$

Paraphrase
There are 118 neutrons in a nucleus of $^{197}_{79}Au$.

Practice Problems

1. How many neutrons are in a nucleus of $^{24}_{12}Mg$?
2. Find the atomic mass number for a uranium atom that contains 92 protons and 146 neutrons.

Answers

1. 12
2. 238

Concept Check

How do the nuclei $^{12}_{6}C$, $^{13}_{6}C$, and $^{14}_{6}C$ differ? How are they the same?

Isotopes

Many elements have two or more **isotopes** — forms that have the same number of protons (Z) but differing numbers of neutrons (N). For example, ordinary hydrogen ($^{1}_{1}H$), deuterium ($^{2}_{1}H$), and tritium ($^{3}_{1}H$) are all isotopes of the element hydrogen. Specific isotopes can be indicated by the element name and the atomic mass number. For example, carbon-12 is another way of writing $^{12}_{6}C$.

isotopes: atoms that have the same number of protons, but different numbers of neutrons

All the isotopes of a particular element have the same number of protons and electrons. So, these isotopes have almost identical chemical properties. However, the physical properties can differ dramatically. In particular, one isotope of an element may be highly radioactive, while another is quite stable. Bombarding materials with electrons, neutrons, or other particles can create radioactive isotopes.

Atomic Mass Units

Atoms and nuclei are much, much smaller than everyday objects. So, even though a kilogram may be a convenient unit for expressing the mass of apples or oranges, it is not particularly useful for measuring the mass of a proton or a carbon nucleus. For calculations involving nuclei and subatomic particles, it is often convenient to use a mass unit that is much smaller than the kilogram. The **atomic mass unit (u)** is defined as exactly $\frac{1}{12}$ of the mass of the carbon-12 atom:

$$1\ u = 1.660\ 539 \times 10^{-27}\ kg$$

Table 16.1 lists the masses of electrons and nucleons, in both kilograms and atomic mass units.

Table 16.1 Some Properties of Subatomic Particles (to Six Decimal Places)

Particle	Charge (C)	Mass (kg)	Mass (u)
Electron	$-1.602\ 177 \times 10^{-19}$	$9.109\ 383 \times 10^{-31}$	$5.485\ 799 \times 10^{-4}$
Proton	$+1.602\ 177 \times 10^{-19}$	$1.672\ 622 \times 10^{-27}$	1.007 276
Neutron	0	$1.674\ 927 \times 10^{-27}$	1.008 665

Forces in the Nucleus

Aside from hydrogen, all nuclei consist of two or more protons and a number of neutrons (Figure 16.3). Like charges repel each other, so what keeps these nuclei from flying apart?

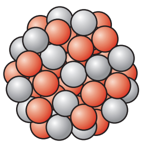


Figure 16.3 Any nucleus heavier than hydrogen has protons and neutrons packed closely together.

Example 16.2

Can gravitational force bind two protons in a nucleus together?

Given

Rounding the values listed in Table 16.1 gives
proton mass $m = 1.67 \times 10^{-27}$ kg and proton charge $q = 1.60 \times 10^{-19}$ C.

Required

Determine if gravitational force can bind two protons in a nucleus together.

Analysis and Solution

Compare the gravitational and electrostatic forces between two protons in a nucleus.
The magnitude of the gravitational force is $|\vec{F}_g| = \dfrac{Gm_1m_2}{r^2}$.

The magnitude of the electrostatic force is $|\vec{F}_e| = \dfrac{kq_1q_2}{r^2}$.

$$\text{So, } \frac{|\vec{F}_g|}{|\vec{F}_e|} = \frac{\dfrac{Gm_1m_2}{\cancel{r^2}}}{\dfrac{kq_1q_2}{\cancel{r^2}}} = \frac{Gm_1m_2}{kq_1q_2}.$$

This ratio shows that the relative strength of the two forces does not depend on the distance between the protons. In order for the gravitational attraction between the protons to overcome the electrostatic repulsion, the ratio $\dfrac{|\vec{F}_g|}{|\vec{F}_e|}$ would have to be greater than 1.

Substituting the known values into the ratio of the forces gives

$$\frac{|\vec{F}_g|}{|\vec{F}_e|} = \frac{(6.67 \times 10^{-11}\ \cancel{\text{N}}\bullet\cancel{\text{m}^2}/\cancel{\text{kg}^2})(1.67 \times 10^{-27}\ \cancel{\text{kg}})^{\cancel{2}}}{(8.99 \times 10^{9}\ \cancel{\text{N}}\bullet\cancel{\text{m}^2}/\cancel{\text{C}^2})(1.60 \times 10^{-19}\ \cancel{\text{C}})^{\cancel{2}}}$$

$$= 8.08 \times 10^{-37}$$

Paraphrase

The gravitational attraction is vastly weaker than the electrostatic repulsion, so gravity cannot be the force that holds a nucleus together.

Practice Problems

1. Calculate the gravitational force that two protons exert on each other when they are 5 fm apart.
2. Calculate the electrostatic force that two protons exert on each other when they are 5 fm apart.

Answers

1. 7×10^{-36} N
2. 9 N

Since gravity is far too weak, there must be some other force that holds the particles in a nucleus together. Physicists call this force the **strong nuclear force,** and think that it is a fundamental force of nature, like gravity and the electrostatic force. The strong nuclear force has a very short range. Although it is more powerful than the electrostatic force within a nucleus, the strong nuclear force has a negligible effect on particles that are more than a few femtometres apart. The strong nuclear force acts on both neutrons and protons, but does not affect electrons. Chapter 17 describes fundamental forces in more detail.

strong nuclear force: the force that binds together the protons and neutrons in a nucleus

PHYSICS INSIGHT

Measurements of interactions between subatomic particles suggest that there is a fourth fundamental force, the weak nuclear force. This force acts on electrons.

Binding Energy and Mass Defect

Removing a nucleon from a stable nucleus requires energy because work has to be done on the nucleon in order to overcome the strong nuclear force. The **binding energy**, E_b, of a nucleus is the energy required to separate all of its protons and neutrons and move them infinitely far apart. In other words, the binding energy is the difference between the total energy of the separate nucleons and the energy of the nucleus with the nucleons bound together:

binding energy: the net energy required to liberate all of the protons and neutrons in a nucleus

$$E_b = E_{\text{nucleons}} - E_{\text{nucleus}}$$

where E_{nucleons} is the sum of the energies of the nucleons when they are free of the nucleus and E_{nucleus} is the energy of the nucleus.

Mass-energy Equivalence

The equivalence of mass and energy is part of the theory of relativity that Albert Einstein developed in 1905. This theory correctly predicted that mass and energy are related by the equation

$$E = mc^2$$

where E is energy, m is mass, and c is the speed of light.

Earlier in this section, you learned that physicists commonly use the atomic mass unit, u, for calculations involving nuclei and subatomic particles. For nuclear calculations, it is useful to know the energy equivalent for 1 u:

$$\begin{aligned}
E &= 1\ \text{u} \times c^2 \\
&= (1.660\,539 \times 10^{-27}\ \text{kg})(2.997\,925 \times 10^{8}\ \text{m/s})^2 \\
&= 1.492\,418 \times 10^{-10}\ \text{J} \\
&= 1.492\,418 \times 10^{-10}\ \cancel{\text{J}} \times \frac{1\ \text{eV}}{1.602\,177 \times 10^{-19}\ \cancel{\text{J}}} \\
&= 931.494\,1\ \text{MeV}
\end{aligned}$$

Thus, 1 u is equivalent to about 149.2 pJ or 931.5 MeV. The binding energy of most nuclei is equivalent to only a small fraction of an atomic mass unit.

Nuclear reactions can involve conversions between mass and energy. The law of conservation of energy still applies if the conversions are taken into account. For any closed system, the total of the energy and the energy equivalent of the mass in the system is constant.

Example 16.3

Calculate the energy equivalent for 0.0034 u of mass, in joules and in electron volts.

Analysis and Solution

Simply multiply 0.0034 u by the appropriate equivalence factors:

$$0.0034\ \cancel{\mathrm{u}} \times \frac{1.492 \times 10^{-10}\ \mathrm{J}}{1\ \cancel{\mathrm{u}}} = 5.1 \times 10^{-13}\ \mathrm{J}$$

$$0.0034\ \cancel{\mathrm{u}} \times \frac{931.5\ \mathrm{MeV}}{1\ \cancel{\mathrm{u}}} = 3.2\ \mathrm{MeV}$$

Paraphrase

The energy equivalent for 0.0034 u is 5.1×10^{-13} J or 3.2 MeV.

Practice Problems

1. Find the energy equivalent, in electron volts, for 0.221 u.
2. Find the mass equivalent to 250 MeV.

Answers

1. 206 MeV
2. 0.268 u

Mass Defect

Rearranging Einstein's equation for mass-energy equivalence gives $m = \dfrac{E}{c^2}$. Dividing the equation for binding energy by c^2 leads to a formula for the **mass defect**, Δm, of a nucleus:

mass defect: difference between the sum of the masses of the separate nucleons and the mass of the nucleus

$$\frac{E_\mathrm{b}}{c^2} = \frac{E_\mathrm{nucleons}}{c^2} - \frac{E_\mathrm{nucleus}}{c^2}$$

$$\Delta m = m_\mathrm{nucleons} - m_\mathrm{nucleus}$$

where m_nucleons is the sum of the masses of the separate nucleons and m_nucleus is the mass of the nucleus.

Thus, the mass of a nucleus is equal to the total mass of its constituents, less the mass corresponding to the binding energy.

Physicists have determined the masses of atoms and nucleons with great accuracy. Tables of atomic data generally list the masses of neutral atoms rather than the masses of nuclei alone without any electrons. The following formula uses atomic masses to calculate the mass defect for a nucleus:

PHYSICS INSIGHT

Nuclear calculations often involve very small differences in mass. Such calculations can require data with six or more significant digits.

$$\Delta m = Zm_{^1_1\mathrm{H}} + Nm_\mathrm{neutron} - m_\mathrm{atom}$$

where $m_{^1_1\mathrm{H}}$ is the mass of a neutral hydrogen atom, Z is the atomic number, and N is the neutron number.

Since $m_{^1_1\mathrm{H}}$ includes the masses of both a proton and an electron, the term $Zm_{^1_1\mathrm{H}}$ includes the mass of Z electrons, matching the mass of the electrons included in m_atom. The differences in the binding energy of the electrons are small enough to ignore in most nuclear calculations.

Concept Check

Show that $\Delta m = Zm_{\text{proton}} + Nm_{\text{neutron}} - m_{\text{nucleus}}$.

Example 16.4

Find the mass defect, expressed in kilograms, and the binding energy for a carbon-12 nucleus.

Given

$Z = 6$ $A = 12$ $m = 12.000\ 000$ u

Required

mass defect (Δm) binding energy (E_b)

Analysis and Solution

The formula $N = A - Z$ gives the number of neutrons in the nucleus:

$$N = 12 - 6 = 6$$

Thus, the $^{12}_{6}C$ nucleus consists of 6 neutrons and 6 protons. Now, use $\Delta m = Zm_{^1_1H} + Nm_{\text{neutron}} - m_{\text{atom}}$ to find the mass defect. Use mass data from Tables 7.5 and 7.6 on page 881. Recall that $1\text{ u} = 1.660\ 539 \times 10^{-27}$ kg (page 791).

$$\begin{aligned}\Delta m &= Zm_H + Nm_{\text{neutron}} - m_{\text{atom}} \\ &= 6(1.007\ 825\text{ u}) + 6(1.008\ 665\text{ u}) - 12.000\ 000\text{ u} \\ &= 0.098\ 940\ \cancel{\text{u}} \times \frac{1.660\ 539 \times 10^{-27}\text{ kg}}{1\ \cancel{\text{u}}} \\ &= 1.6429 \times 10^{-28}\text{ kg}\end{aligned}$$

Use the mass-energy equivalence to calculate the binding energy from the mass defect.

$$1\text{ u} = 1.492 \times 10^{-10}\text{ J} = 931.5\text{ MeV}$$

$$E_b = 0.098\ 940\ \cancel{\text{u}} \times \frac{1.492 \times 10^{-10}\text{ J}}{1\ \cancel{\text{u}}} \quad \text{or} \quad 0.098\ 940\ \cancel{\text{u}} \times \frac{931.5\text{ MeV}}{1\ \cancel{\text{u}}}$$

$$= 1.476 \times 10^{-11}\text{ J} \qquad = 92.16\text{ MeV}$$

Paraphrase

The mass defect for $^{12}_{6}C$ is 1.6429×10^{-28} kg. The binding energy of the carbon-12 nucleus is 1.476×10^{-11} J or 92.16 MeV.

Practice Problems

1. Sodium $^{23}_{11}Na$ has an atomic mass of 22.989 769 u. Find the mass defect for this nucleus.
2. Find the binding energy for $^{23}_{11}Na$.

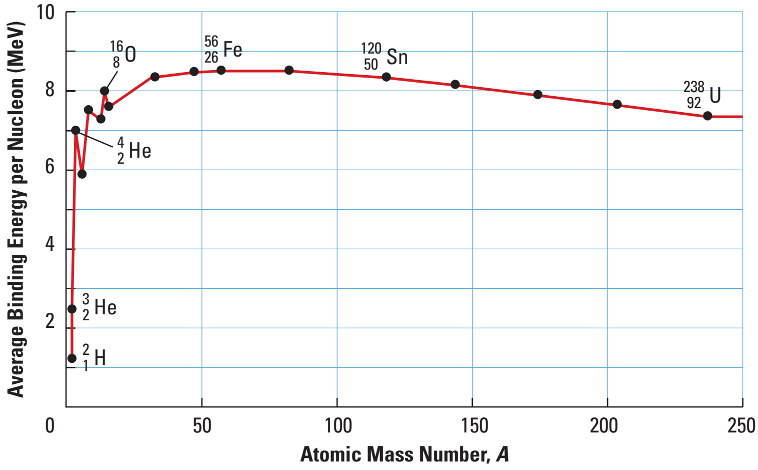
Answers

1. 0.200 286 u
2. 186.6 MeV

Binding Energy per Nucleon

You can compare the stability of different nuclei by dividing the binding energy of each nucleus by the number of nucleons it contains. The greater the binding energy per nucleon $\left(\frac{E_b}{A}\right)$, the more stable the nucleus is. Figure 16.4 is a graph of binding energy per nucleon versus atomic mass number for stable nuclei. This graph peaks at about 8.79 MeV per nucleon. The three most stable isotopes are nickel $^{62}_{28}Ni$, iron $^{58}_{26}Fe$, and iron $^{56}_{26}Fe$.

▶ **Figure 16.4** Binding energy per nucleon for stable isotopes



The graph also gives a hint about the process that causes the stars to shine. The binding energy per nucleon is much less for hydrogen than for helium. If hydrogen atoms combine to form helium, the nucleons move to a lower energy level and give off the difference in energy. In section 16.4, you will learn more about such nuclear reactions.

16.1 Check and Reflect

Knowledge

1. How many protons and neutrons do each of the following nuclei contain?

(a) ${}^{90}_{38}\text{Sr}$ (b) ${}^{13}_{6}\text{C}$ (c) ${}^{56}_{26}\text{Fe}$ (d) ${}^{1}_{1}\text{H}$

2. Convert 1.6×10^{-10} J to electron volts.

3. Calculate the energy equivalent of 0.25 u.

4. How much mass is converted into energy by a nuclear reaction that produces 5.00 GJ of energy?

5. Define the term *isotope*.

6. Explain why the mass of a stable nucleus is a bit less than $Zm_{\text{proton}} + Nm_{\text{neutron}}$.

Applications

7. Determine the binding energy for ${}^{22}_{10}\text{Ne}$. The atomic mass of ${}^{22}_{10}\text{Ne}$ is 21.991 385 u.

8. The ${}^{40}_{19}\text{K}$ isotope of potassium has an atomic mass of 39.963 998 u.

(a) Determine the mass defect for ${}^{40}_{19}\text{K}$.

(b) Calculate the binding energy per nucleon for this isotope.

9. Use Figure 16.4 to estimate the binding energy for each of these nuclei:

(a) ${}^{13}_{6}\text{C}$ (b) ${}^{56}_{26}\text{Fe}$ (c) ${}^{238}_{92}\text{U}$

10. Show that MeV/c^2 has the dimensions of mass.

Extensions

11. (a) Contrast the strength and range of the electromagnetic force and the strong nuclear force.

(b) Explain how the nature of these forces limits the maximum possible size for nuclei.

12. Suppose that the electrostatic force were much stronger. Describe how this change would affect the stability of nuclei.

13. Experiments have shown that most nuclei are approximately spherical with a radius of $r = r_0 A^{\frac{1}{3}}$, where $r_0 = 1.20$ fm and A is the atomic mass number. Use this formula to determine the radius of the nucleus of a ${}^{90}_{38}\text{Sr}$ atom. Then estimate the distance between adjacent nucleons in this nucleus. What can you conclude about the size of protons and neutrons?

eTEST

To check your understanding of nuclei, follow the eTEST links at www.pearsoned.ca/school/physicssource.

16.2 Radioactive Decay

The French physicist, Antoine Henri Becquerel (1852–1908), discovered radioactive decay in 1896 while conducting an experiment to see if a fluorescent compound of uranium would emit X rays when exposed to sunlight. During a period of cloudy weather, Becquerel put the uranium compound away in a drawer along with a photographic plate wrapped in black paper. When he developed the plate several days later, he was surprised to find that it was fogged even though the fluorescent compound had not been exposed to sunlight. Becquerel realized that the radiation that fogged the plate must be coming from the uranium in the compound. He also found that a magnetic field would deflect some of this radiation.

The husband and wife team of Marie Curie (1867–1934) and Pierre Curie (1859–1906) began an extensive study of this radiation. They showed that thorium was also radioactive, and discovered two new elements, radium and polonium, that were both much more radioactive than uranium. Indeed, Marie coined the term *radioactive*. She also demonstrated that the intensity of radiation from uranium compounds was not affected by the other elements in the compound or by processes such as being heated, powdered, or dissolved. The intensity depended only on the quantity of uranium. Therefore, the radioactivity must result from a process within the uranium nucleus.

info BIT

Marie Curie was the first person to win two Nobel Prizes. She died of leukemia, almost certainly the result of years of exposure to radiation in her laboratory.

Rutherford and others identified three forms of nuclear radiation:

Alpha (α): the emission of a helium nucleus

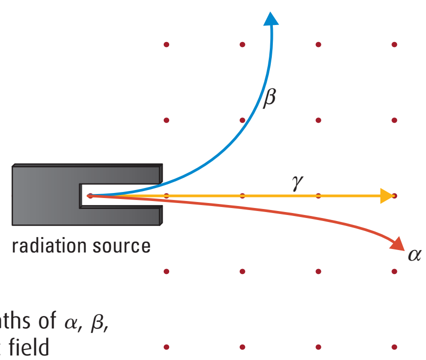
Beta (β): the emission of a high-energy electron

Gamma (γ): the emission of a high-energy photon

Initially, this classification was based on how much material each type of radiation could penetrate. In radiation from naturally occurring isotopes, the alpha particles typically do not penetrate much more than a thin metal foil or sheet of paper, whereas beta particles can pass through up to 3 mm of aluminium, and gamma rays can penetrate several centimetres of lead. The three types of radiation result from different processes within nuclei.

Concept Check

Figure 16.5 shows the paths that α, β, and γ rays take when passing through a magnetic field. What can you conclude about the electrical properties of these rays?



▶ **Figure 16.5** The paths of α, β, and γ rays in a magnetic field

16-2 Design a Lab

Radiation Shielding

The Question

What common materials provide effective shielding against α, β, and γ radiation?

▲ **Figure 16.6** Radiation meters

Design and Conduct Your Investigation

Check with your teacher about the radiation sources and radiation meters (Figure 16.6) available for this investigation. Then design your experiment. List the materials you will need and outline the procedure.

Try this procedure and modify it if necessary. Keep careful records of your results. Then analyze your data, and explain your conclusions.

Conservation Laws and Radioactive Decay

In addition to conserving momentum and energy, all radioactive decay processes obey these additional conservation laws:

- **Charge:** The net electrical charge cannot change in a decay process. Any change in the electrical charge of the nucleus must be exactly offset by an opposite change elsewhere in the system. For example, if the charge on a nucleus decreases by +2e, then a particle with a charge of +2e must be emitted.
- **Atomic Mass Number:** The total of the atomic mass numbers for the final products must equal the atomic mass number of the original nucleus. In other words, the total number of nucleons remains constant.

Example 16.5

Determine which of these radioactive decay processes are possible.

(a) ${}^{214}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\alpha$

(b) ${}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$

(c) ${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{1}_{0}\text{n}$ (${}^{1}_{0}\text{n}$ represents a neutron)

Analysis and Solution

Compare the charge and atomic mass number of the original nucleus to those of the decay products.

(a) Charge: $84 = 82 + 2$
Atomic mass number: $214 \neq 208 + 4$
The decay process ${}^{214}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\alpha$ is not possible.

(b) Charge: $90 = 88 + 2$
Atomic mass number: $230 = 226 + 4$
The decay process ${}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$ is possible.

(c) Charge: $27 \neq 28 + 0$
Atomic mass number: $60 \neq 60 + 1$
The decay process ${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{1}_{0}\text{n}$ is not possible.

Practice Problems

Determine whether these decay processes are possible.

1. ${}^{212}_{84}\text{Po} \rightarrow {}^{210}_{86}\text{Rn} + {}^{4}_{2}\alpha$
2. ${}^{233}_{91}\text{Pa} \rightarrow {}^{233}_{92}\text{U} + {}^{0}_{-1}\beta$
3. ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{1}_{1}\text{H}$

Answers

1. Impossible
2. Possible
3. Impossible

Concept Check

Why are electrons *not* considered when applying the conservation law for atomic mass number?

Alpha Decay

In 1908, Rutherford showed that alpha particles are helium nuclei spontaneously emitted by unstable large nuclei. In these nuclei, the electromagnetic force repelling the outer protons is almost as great as the attractive strong nuclear force. Such nuclei can spontaneously emit alpha particles. Because a cluster of two protons and two neutrons forms a highly stable helium nucleus, these unstable large nuclei decay by emitting alpha particles rather than separate protons and neutrons.

The emission of an alpha particle decreases the atomic number by 2 and the atomic mass number by 4. For example, alpha decay of uranium-238 produces thorium:

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

In this example, uranium is the **parent element** and thorium is the **daughter element**. Applying the conservation laws gives this general form for alpha decays:

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

where X is the chemical symbol for the parent element and Y is the symbol for the daughter element. Here, A is the atomic mass number of the *parent* element and Z is its atomic number.

parent element: the original element in a decay process

daughter element: the element produced by a decay process

Example 16.6

Predict the daughter element that results from alpha decay of radium-226.

Analysis and Solution

From a periodic table, you can see that the atomic number for radium is 88. So, the parent element is $^{226}_{88}\text{Ra}$.

Since the alpha particle carries away four nucleons, including two protons, A decreases by 4 and Z decreases by 2:

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

So, the daughter element is $^{226-4}_{88-2}\text{Y} = {}^{222}_{86}\text{Y}$.

The periodic table shows that the element with $Z = 86$ is radon.

Paraphrase

For alpha decay, the daughter element of radium-226 is radon-222.

Practice Problems

Write the α-decay process for these elements, and name the parent and daughter elements.

1. $^{230}_{90}\text{Th}$
2. $^{238}_{92}\text{U}$
3. $^{214}_{84}\text{Po}$

Answers

1. $^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$; thorium, radium
2. $^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$; uranium, thorium
3. $^{214}_{84}\text{Po} \rightarrow {}^{210}_{82}\text{Pb} + {}^{4}_{2}\alpha$; polonium, lead

Energy Released During Alpha Decay

You can apply the concepts of energy conservation and mass-energy equivalence to alpha decay, using a method similar to the calculation of nuclear binding energy.

The mass-energy of the parent nucleus is equal to the sum of the mass-energy and the kinetic energies of both the daughter nucleus and the alpha particle:

$$m_{\text{parent}}c^2 = m_{\text{daughter}}c^2 + m_{\alpha}c^2 + \Delta E$$

The difference in energy, ΔE, appears as the total kinetic energy of the alpha particle and of the daughter nucleus. If the parent nucleus was at rest, the law of conservation of momentum requires the momentum of the alpha particle to be equal in magnitude and opposite in direction to the momentum of the daughter nucleus. Usually, the mass of the daughter nucleus is much greater than the mass of the alpha particle. So, the speed of the alpha particle is correspondingly greater than the speed at which the daughter nucleus recoils:

$$m_{\alpha}v_{\alpha} = m_{\text{daughter}}v_{\text{daughter}}$$

$$v_{\alpha} = \frac{m_{\text{daughter}}v_{\text{daughter}}}{m_{\alpha}}$$

The kinetic energy of the alpha particle is also correspondingly greater than the kinetic energy of the daughter nucleus:

$$\begin{aligned} E_\alpha &= \frac{1}{2} m_\alpha v_\alpha^2 \\ &= \frac{1}{2} m_\alpha \left(\frac{m_{\text{daughter}} v_{\text{daughter}}}{m_\alpha} \right)^2 \\ &= \frac{m_{\text{daughter}}}{m_\alpha} \times \frac{1}{2} m_{\text{daughter}} v_{\text{daughter}}^2 \\ &= \frac{m_{\text{daughter}}}{m_\alpha} \times E_{\text{daughter}} \end{aligned}$$

Concept Check

Explain why ΔE must be positive in order for α-decay to occur.

Example 16.7

Show that α-decay of radium-226 is possible, and estimate the maximum kinetic energy of the emitted alpha particle.

Given
Parent atom is radium-226.

Required
maximum kinetic energy of the alpha particle

Analysis and Solution
Example 16.6 showed that the daughter element is radon-222. The energy released is equivalent to the difference between the mass of the parent atom and the total mass of the products.

$\Delta m = m_{\text{parent}} - m_{\text{products}}$

Table 7.5 on page 881 lists the atomic masses for radium-226, radon-222, and helium-4. As in section 16.1, you can use atomic masses instead of nuclear masses because the masses of the electrons will balance out. A radon nucleus has over 50 times the mass of an alpha particle. So, the alpha particle will have over 98% of the total kinetic energy, ΔE.

$$\begin{aligned} \Delta m &= m_{{}^{226}_{88}\text{Ra}} - (m_{{}^{222}_{86}\text{Rn}} + m_{{}^{4}_{2}\alpha}) \\ &= 226.025\ 410\ \text{u} - 222.017\ 578\ \text{u} - 4.002\ 603\ \text{u} \\ &= 0.005\ 229\ \text{u} \end{aligned}$$

$$\Delta E = 0.005\ 229\ \cancel{\text{u}} \times \frac{1.492 \times 10^{-10}\ \text{J}}{1\ \cancel{\text{u}}} \quad \text{or} \quad 0.005\ 229\ \cancel{\text{u}} \times \frac{931.5\ \text{MeV}}{1\ \cancel{\text{u}}}$$

$$= 7.802 \times 10^{-13}\ \text{J} \qquad\qquad = 4.871\ \text{MeV}$$

Paraphrase
Since $\Delta E > 0$, alpha decay of radium-226 is possible. The maximum kinetic energy of the alpha particle when emitted is about 7.802×10^{-13} J or 4.871 MeV.

Practice Problems

Calculate the energy released during α-decay of these nuclei:

1. ${}^{230}_{90}\text{Th}$
2. ${}^{238}_{92}\text{U}$
3. ${}^{214}_{84}\text{Po}$

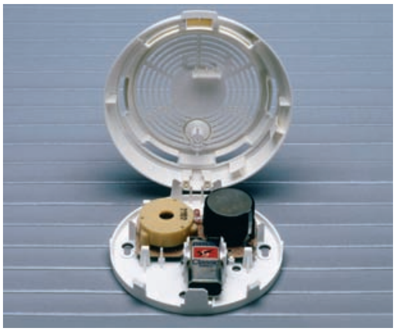
Answers

1. 7.641×10^{-13} J
2. 6.839×10^{-13} J
3. 1.255×10^{-12} J

THEN, NOW, AND FUTURE — Ionization Smoke Detectors

Most household smoke detectors (Figure 16.7) contain a small amount of americium-241. This isotope emits α-particles, which ionize air molecules between two metal plates within the smoke detector. One of the plates has a positive charge, and the other plate has a negative charge. The plates attract the ions, so a small current flows between the plates.

If smoke particles enter the smoke detector, they absorb some of the α-particles. So, the alpha radiation ionizes fewer air molecules and the current between the metal plates decreases. This drop in current triggers the alarm circuit in the smoke detector.



▲ **Figure 16.7** This smoke detector uses alpha radiation to sense smoke particles.

Questions

1. Why is it safer for a smoke detector to use alpha radiation, instead of beta or gamma radiation?
2. Suggest reasons why most manufacturers of smoke detectors recommend replacing them after 10 years.

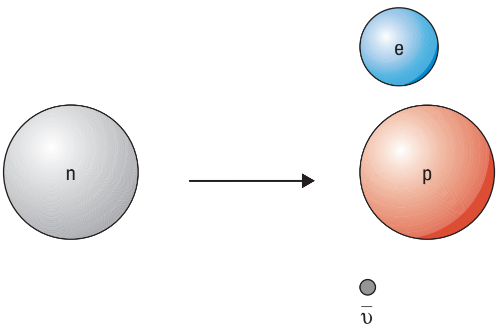
Beta Decay

beta-negative (β^-) decay: nuclear decay involving emission of an electron

beta (β) particle: electron emitted by a nucleus

Sometimes, a nucleus decays by emitting an electron. This process is termed **beta-negative** or **β^- decay**. During β^- decay, a neutron in the nucleus transforms into a proton, electron, and an extremely small neutral particle known as antineutrino, symbol $\bar{\upsilon}$ (Figure 16.8). So, the atomic number of the atom increases by 1, but the atomic mass number does not change. Charge is conserved because the charge on the new proton balances the charge on the electron emitted from the nucleus. This electron is often called a **beta (β) particle**, a name that originates from the early classification of types of radiation. It is often written as ${}_{-1}^{0}\beta$ in equations. For example, β^- decay of thallium-208 produces lead, and the equation is:

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



▲ **Figure 16.8** During β^- decay, a neutron changes into a proton, electron, and antineutrino.

Concept Check

Why is the mass of the neutron slightly larger than the sum of the proton and electron masses?

Example 16.8

What element will the β^- decay of thorium produce?

Analysis and Solution

A periodic table shows that the atomic number for thorium is 90.

β^- decay increases the atomic number by 1, so $A_{\text{daughter}} = 91$.

The element with an atomic number of 91 is protactinium, the element immediately after thorium in the periodic table.

Paraphrase

For β^- decay of thorium, the daughter element is protactinium.

Practice Problems

1. Find the elements produced by β^- decay of
   (a) ${}^{228}_{88}\text{Ra}$
   (b) ${}^{212}_{82}\text{Pb}$

Answers

1. (a) ${}^{228}_{89}\text{Ac}$
   (b) ${}^{212}_{83}\text{Bi}$

As with alpha decays, you can use atomic masses to calculate how much energy a beta decay will release.

Example 16.9

How much energy would you expect the β^- decay of a thorium-234 nucleus to release?

Given

Parent element is ${}^{234}_{90}\text{Th}$.

Required

Energy released by β^- decay (ΔE)

Analysis and Solution

As shown in Example 16.8, the daughter element is protactinium. However, this daughter atom has only the 90 electrons from the original thorium atom because the electron emitted by the thorium nucleus leaves the atom as beta radiation. The result is a positive ion, ${}^{234}_{91}\text{Pa}^+$. The energy released is equivalent to the difference between the mass of the parent atom and the total mass of the decay products. Together, the masses of the protactinium ion and the beta particle equal the mass of a neutral protactinium atom. Table 7.5 on page 881 lists the atomic masses.

$$\begin{aligned}
\Delta m &= m_{\text{parent}} - m_{\text{products}} \\
&= m_{{}^{234}_{90}\text{Th}} - (m_{{}^{234}_{91}\text{Pa}^+} + m_{{}^{0}_{-1}\beta}) \\
&= m_{{}^{234}_{90}\text{Th}} - m_{{}^{234}_{91}\text{Pa}} \\
&= 234.043\ 601\ \text{u} - 234.043\ 308\ \text{u} \\
&= 0.000\ 293\ \text{u}
\end{aligned}$$

1 u is equivalent to about 931.5 MeV, so

$$\begin{aligned}
\Delta E &= 0.000\ 293\ \cancel{\text{u}} \times \frac{931.5\ \text{MeV}}{1\ \cancel{\text{u}}} \\
&= 0.2729\ \text{MeV}
\end{aligned}$$

Paraphrase

The β^- decay of a ${}^{234}_{90}\text{Th}$ nucleus should release 0.2729 MeV.

Practice Problems

1. (a) What element does the β^- decay of cobalt-60 produce?
   (b) How much energy would you expect the decay of a cobalt-60 nucleus to release?

Answers

1. (a) ${}^{60}_{28}\text{Ni}$
   (b) 2.823 MeV

PHYSICS INSIGHT

In calculating energy produced in nuclear decay, it is common to use atomic masses because these data are readily available. You see this being done in Examples 16.9 and 16.10. In both of these examples, as an intermediate step an ion notation has been used to account for the change in nuclear charge that happens during beta decay. In reality, in beta decay it is most likely that the atom will not end up ionized. The atom will either lose or gain an electron as appropriate.

info BIT

The name *neutrino* comes from the Italian word for "little, neutral one." The word was coined by Enrico Fermi, a renowned physicist who developed a theory to explain beta decay.

The Elusive Neutrino

Since the daughter nucleus has vastly more mass than an electron, there is practically no recoil of the daughter nucleus during beta decay. Consequently, physicists expected that virtually all of the energy released during β^- decay would appear as the kinetic energy of the electron emitted by the nucleus. However, measurements found that most electrons emitted during β^- decay had somewhat less kinetic energy than expected, and a few had almost no kinetic energy. During β^- decay, small portions of the mass of the parent nuclei seemed to just disappear!

neutrino: an extremely small neutral subatomic particle

In 1930, the Austrian physicist Wolfgang Pauli (1900–1958) suggested that the missing energy in beta decay was carried away by a tiny, as-yet-undiscovered neutral particle, now called the **neutrino**, ν. Neutrinos are so small that physicists have yet to determine their size and mass. These "ghost-like" particles can pass through Earth with only a slight chance of being absorbed! Indeed, it was 1956 before an experiment using the intense radiation at a nuclear power plant finally proved conclusively that neutrinos actually exist. Eventually physicists discovered that there are actually two kinds of neutrinos given off in beta decay. In β^- decay an antineutrino is released. As you will soon see, in β^+ decay a neutrino is released. The neutrino and antineutrino are identical in all respects except for their opposite spins. Many astrophysicists now think that neutrinos play a critical role in the cores of stars and perhaps in the structure of the cosmos as well.

e WEB

To learn more about the Sudbury Neutrino Observatory, follow the links at www.pearsoned.ca/school/physicssource.

Concept Check

How did physicists know that the neutrino must be neutral?

info BIT

Each second, more than 100 trillion neutrinos pass through your body! Almost all of these neutrinos were formed by nuclear reactions in the core of the Sun.

Beta Decay, the Weak Nuclear Force, and Antimatter

Careful study of beta decays revealed two further important differences from alpha decay.

weak nuclear force: fundamental force that acts on electrons and neutrinos

antimatter: form of matter that has a key property, such as charge, opposite to that of ordinary matter

positron (e^+ or ${}^{0}_{1}\beta$): an anti-electron; a positively charged particle with its other properties the same as those of an electron

First, the transformation of a neutron into a proton involves a fundamental force called the **weak nuclear force**. Although it is less powerful than the strong nuclear force, the weak nuclear force acts on electrons and neutrinos, whereas the strong nuclear force does not.

The second difference is that beta decay involves **antimatter**. An antimatter particle has a key property, such as charge, opposite to that of the corresponding particle of ordinary matter. For example, an anti-electron, or **positron (e^+ or ${}^{0}_{1}\beta$)**, has a positive charge but the same mass as an electron. Section 17.2 presents antimatter in more detail.

In β^- decay, the transformation of a neutron into a proton produces an *antineutrino* rather than a neutrino:

$$n \rightarrow p^+ + {}^{0}_{-1}\beta + \overline{\nu}$$

where $\overline{\nu}$ is the symbol for the antineutrino.

Thus, β^- decays have the general form

$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}\beta + \overline{\nu} \qquad (Z \text{ increases by } 1)$$

A second form of beta decay also produces an antiparticle. In **β^+ decay**, a proton transforms into a neutron, and the parent nucleus emits a positron and a neutrino:

$${}^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + {}^{0}_{1}\beta + \nu \quad (Z \text{ decreases by } 1)$$

Sometimes, you will see the electron in these decay processes represented by the symbol e^-. To distinguish this electron from those orbiting the nucleus, this chapter uses the symbol ${}^{0}_{-1}\beta$ to represent an electron emitted by a nucleus. Similarly, the symbol ${}^{0}_{1}\beta$ is used to represent an emitted positron.

beta-positive (β^+) decay: nuclear decay involving emission of a positron

Example 16.10

Nitrogen-13 (${}^{13}_{7}N$) transmutes into carbon-13 (${}^{13}_{6}C$) by β^+ decay.

$${}^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{1}\beta + \nu$$

Calculate the energy released if the atomic masses are 13.005 739 for nitrogen-13 and 13.003 355 for carbon-13.

Given
Nitrogen-13 transmutes into carbon-13 by β^+ decay.
Atomic masses: 13.005 739 for nitrogen-13, 13.003 355 for carbon-13

Required
Energy released in the decay

Analysis and Solution
The energy released is equivalent to the difference between the mass of the parent atom and the total mass of the products.

$$\begin{aligned}\Delta m &= m_{\text{parent}} - m_{\text{products}}\\ &= m_{{}^{13}_{7}N} - (m_{{}^{13}_{6}C^-} + m_{{}^{0}_{1}\beta})\\ &= m_{{}^{13}_{7}N} - (m_{{}^{13}_{6}C} + m_{{}^{0}_{-1}\beta} + m_{{}^{0}_{1}\beta})\end{aligned}$$

Note that again we use an ion notation indicating the presence of a carbon ion. In fact, at the end of the decay process, the carbon ion will lose an electron, and its mass can be written as $(m_{{}^{13}_{6}C} + m_{{}^{0}_{-1}\beta})$ as shown above.

Since electrons and positrons have the same mass, $m_{{}^{0}_{-1}\beta} = m_{{}^{0}_{1}\beta}$. Therefore,

$$\begin{aligned}\Delta m &= m_{{}^{13}_{7}N} + (m_{{}^{13}_{6}C} + 2m_{{}^{0}_{-1}\beta})\\ &= 13.005\ 739\ \text{u} - [13.003\ 355\ \text{u} + 2(0.000\ 549)\ \text{u}]\\ &= 0.001\ 286\ \text{u}\end{aligned}$$

1 u is equivalent to 931.5 MeV, so

$$\begin{aligned}\Delta E &= 0.001\ 286\ \cancel{\text{u}} \times \frac{931.5\ \text{MeV}}{1\ \cancel{\text{u}}}\\ &= 1.198\ \text{MeV}\end{aligned}$$

Paraphrase
The β^+ decay of a ${}^{13}_{7}N$ nucleus should release 1.198 MeV of energy.

Practice Problems

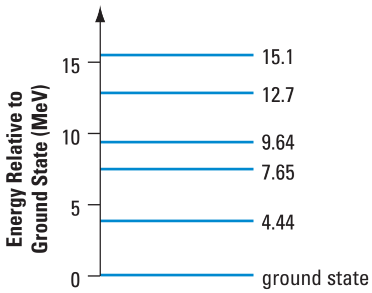
1. (a) What isotope will β^+ decay of thallium-202 produce?
   (b) Write the process for this decay.
   (c) How much energy will be released by the decay of the thallium-202 nucleus if the mass of the thallium nucleus decreases by 0.001 463 u?

Answers

1. (a) mercury-202
   (b) ${}^{202}_{81}Tl \rightarrow {}^{202}_{80}Hg + {}^{0}_{1}\beta + \nu$
   (c) 0.3400 MeV

PHYSICS INSIGHT

In Example 16.10, the energy released when a nitrogen-13 nucleus decays to form carbon-13 is calculated to be 1.198 MeV. Most nuclear decay data tables, however, will indicate that *the total energy released* in this decay is 2.221 MeV. Both are correct! When a β^+ decay occurs, a positron is emitted. This positron could combine with an electron to release the energy equivalence of 2 electron masses, an additional 1.023 MeV.



▲ **Figure 16.9** Nuclear energy levels for carbon-12: How do these energy levels differ from those for electrons in hydrogen?

gamma (γ) decay: emission of a high-energy photon by a nucleus

Gamma Decay (γ-decay)

Many nuclei have a series of energy levels that correspond to different configurations of the nucleons. In the excited states, the nucleons are farther apart. As a result, their binding energy is less than when in the ground state, and the total energy of the nucleus is greater. When making a transition to a lower-energy state, a nucleus emits a gamma-ray photon, similar to the photon emitted when an electron in an atom moves to a lower energy level (Figure 16.9). However, the difference in energy is much greater for a nucleus.

Gamma (γ) decay does not change the atomic number or the atomic mass number. Gamma decays can be written using this general form:

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

where * indicates an excited state and γ represents a gamma ray.

Often, alpha or beta decay leaves the daughter nucleus in a highly excited state. The excited nucleus then makes a transition to its ground state, and emits a gamma ray. For example, when β^- decay of boron-12 produces carbon-12, the carbon nucleus is highly excited and quickly emits a gamma ray:

$$^{12}_{5}B \rightarrow {}^{12}_{6}C^{*} + {}^{0}_{-1}\beta + \overline{\nu}$$

$$^{12}_{6}C^{*} \rightarrow {}^{12}_{6}C + \gamma$$

The energy of a gamma ray depends on the energy levels and the degree of excitation of the particular nucleus. Gamma rays can have energies ranging from thousands to millions of electron volts.

e **WEB**

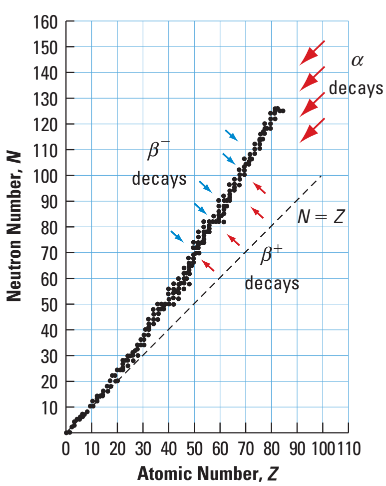
To learn more about nuclear energy levels, follow the links at www.pearsoned.ca/school/physicssource.

Stability of Isotopes

Figure 16.10 shows that stable isotopes form a relatively narrow band when plotted by their proton and neutron numbers. Other than hydrogen, all stable isotopes have at least as many neutrons as protons. As Z increases, the isotopes require an increasing ratio of neutrons to protons in order to be stable. There are no completely stable isotopes with more than 83 protons.

The stable isotopes have greater binding energies than the unstable isotopes. Radioactive decay **transmutes** unstable nuclei into nuclei with higher binding energies. For example, heavy nuclei above and to the right of the stable band will emit alpha particles (larger red arrows), heavy nuclei below and to the right of the band will emit positrons, or β^+ particles (small red arrows), and lighter nuclei to the left of the band will emit electrons, or β^- particles (blue arrows). All of these decay processes produce isotopes that are either in the stable band or closer to it. A nucleus may undergo several successive decays before it reaches the stable band.

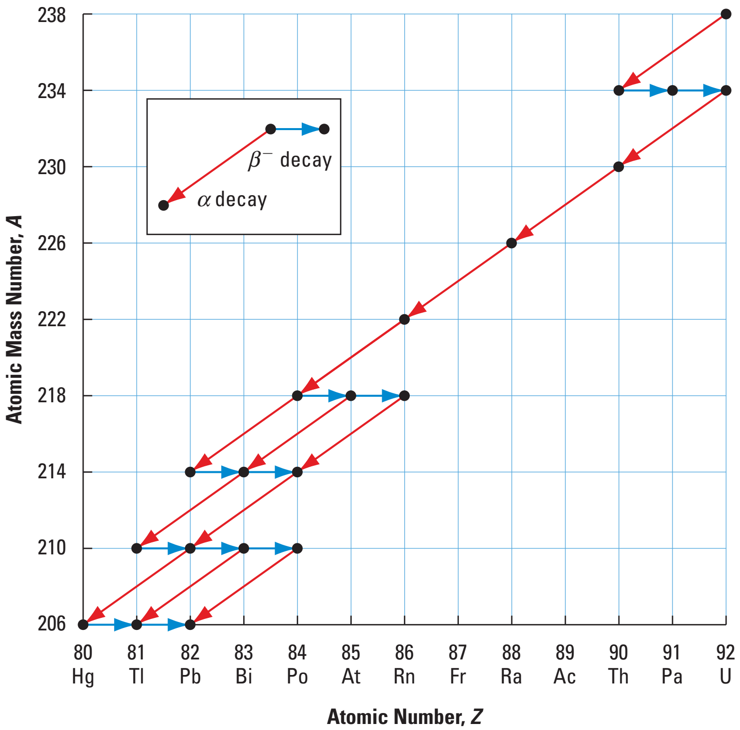
transmute: change into a different element



▲ **Figure 16.10** The black dots represent the band of stable isotopes.

Radioactive Decay Series

Often, a radioactive nucleus will decay into a daughter nucleus that is itself radioactive. The daughter nucleus may then decay into yet another unstable nucleus. This process of successive decays continues until it creates a stable nucleus. Such a process is called a **radioactive decay series**.



▲ **Figure 16.11** Radioactive decay series beginning with $^{238}_{92}U$ and ending with $^{206}_{82}Pb$. How many different decay paths are there from uranium-238 to lead-206?

The dots in Figure 16.11 represent nuclei that are part of the decay series. A decay series can have several branches that lead to the same final product. Figure 16.11 shows that $^{218}_{84}Po$ can transmute into $^{214}_{84}Po$ by three different combinations of decays. All of the intermediate isotopes in a decay series are unstable, but the degree of instability is different for each isotope. For example, $^{218}_{86}Rn$ usually lasts for only a fraction of a second whereas $^{222}_{86}Rn$ takes several days to decay and $^{230}_{90}Th$ takes thousands of years. Although not shown in Figure 16.11, many of the intermediate isotopes undergo gamma decay.

Concept Check

Explain why gamma decays cannot be shown as paths on a decay series graph like the one in Figure 16.11.

Potential Hazards of Nuclear Radiation

info **BIT**

Both Marie and Pierre Curie suffered from radiation sickness. Some of Marie's laboratory notebooks are still dangerously radioactive.

Alpha, beta, and gamma radiation are all invisible, and most of their effects on the human body are not immediately apparent. As a result, it was not until years after the discovery of radioactive decay that researchers realized how dangerous radiation can be. Radiation poses two major types of risk:

- **Radiation Sickness:** Radiation can ionize cellular material. This ionization disrupts the intricate biochemistry of the body, resulting in radiation sickness. Large doses of ionizing radiation can kill cells. Blood cells and the lining of the intestine are particularly vulnerable. Symptoms include nausea, vomiting, diarrhea, headache, inflammation, and bleeding. Severe radiation sickness is often fatal.
- **Genetic Damage:** High-energy particles and gamma rays can alter DNA, and lead to the development of cancers or harmful mutations. These effects often appear 10 to 15 years after radiation exposure.

radioisotope: an isotope that is radioactive

Everywhere on Earth, there is some naturally occurring radiation from cosmic rays and from **radioisotopes** in the ground. This background radiation causes some minor damage, but normally the body can repair such damage without any lasting harm.

The effect of radiation on living organisms depends on the energy it carries, its ability to ionize atoms and molecules, and the depth to which it can penetrate living tissue. The charge and energy of the radiation determine how ionizing it is. The energy also affects how far the radiation can penetrate. The energy that a radiation has depends on the process that produces it. Table 16.2 compares the hazards posed by typical radiations from natural sources.

▼ **Table 16.2** Radiation Hazards from Natural Sources Outside the Body

Radiation	Typical Penetration	Ionization	Hazard
alpha	Travels about 5 cm in air. Cannot penetrate skin.	high	low
beta	Travels about 30–50 cm in air. Penetrates about 1 cm into the body.	moderate	low
gamma	Travels great distances in air. Penetrates right through the body.	low	high

Although α and β particles are much less penetrating than gamma radiation, they can still be extremely harmful if emitted by material absorbed into the body, because the nearby tissue has a continuing exposure to the radiation. For example, health scientists have calculated that breathing in a speck of dust containing just 1 μg of plutonium is virtually certain to cause lung cancer within 30 years.

The introduction of radioactive isotopes into the food chain is also a serious concern because these materials can accumulate in the body. For example, strontium-90, a by-product of nuclear weapons and power reactors, is absorbed into bones because it is chemically similar to calcium. Radiation from strontium damages bone marrow, reduces the production of blood cells, and can lead to bone cancer and leukemia.

Despite its potential hazards, nuclear radiation is not always harmful. As you will see in section 16.3, nuclear radiation has many beneficial industrial and medical applications.

Measuring Radiation Exposure

The effects of a given dose of radiation depend on the type of radiation. For example, a dose of infrared radiation that delivered 1 J/kg to living tissue would do little more than heat the tissue slightly. The same quantity of energy from X rays would ionize some molecules within the tissue, whereas the same quantity of energy from alpha radiation would be far more ionizing and disruptive. For this reason, SI has two units for measuring radiation exposure: The gray is the unit for absorbed dose and the sievert is the unit for equivalent absorbed dose.

Gray (Gy): 1 gray is the dose of ionizing radiation that delivers 1 J of energy to each kilogram of material absorbing the radiation.

Sievert (Sv): 1 sievert is the absorbed dose of ionizing radiation that has the same effect on a person as 1 Gy of photon radiation, such as X rays or gamma rays. The absorbed dose in sieverts is equal to the dose in grays multiplied by the **relative biological effectiveness (RBE)**, a measure of how harmful the particular kind of radiation is. For example, the RBE for high-energy alpha particles is about 20, so an absorbed dose of 1 Gy of alpha radiation is equivalent to 20 Sv.

relative biological effectiveness (RBE): a factor indicating how much a particular type of radiation affects the human body

An equivalent dose of 6 Sv in a short time is usually fatal. Typical radiation exposure for North Americans is less than 0.5 mSv annually. Table 16.3 summarizes some common sources of radiation exposure.

▼ **Table 16.3** Common Sources of Radiation Exposure

Source	Typical Exposure (μSv/year)
Natural	
Radon from ground	200
Cosmic rays	44
Radioactive rocks/minerals, common building materials	40
Ingested from natural sources	18
Artificial	
Medical/dental X rays	73
Nuclear weapons testing	4
Consumer products	1
All other	2
Total	<400

▲ **Figure 16.12** Dosimeters: How do these devices measure exposure to radiation?

16.2 Check and Reflect

Knowledge

1. What are the three basic radioactive decay processes and how do they differ from each other?
2. What is the ratio of neutrons to protons for the heaviest stable isotopes?
3. (a) Write the alpha-decay process for $^{234}_{91}\text{Pa}$.
   (b) Identify the parent and daughter nuclei in this decay.
4. (a) Which type of beta decay transmutes carbon-14 into nitrogen?
   (b) Write the process for this decay.
5. (a) Which type of beta decay transmutes the sodium isotope $^{22}_{11}\text{Na}$ into $^{22}_{10}\text{Ne}$?
   (b) Write the process for this decay.
6. Explain why the daughter nucleus in an alpha decay often emits a gamma ray.
7. Which form of radioactive decay has the greatest penetrating power?

Applications

8. How much energy is released when $^{22}_{11}\text{Na}$ decays to $^{22}_{10}\text{Ne}$? The mass of $^{22}_{11}\text{Na}$ is 21.994 436 u and the mass of $^{22}_{10}\text{Ne}$ is 21.991 385 u.
9. Explain whether the atomic number can increase during nuclear decay. Support your answer with an example.
10. Compare the annual average radiation exposure from natural sources with the dose you would receive from a dental X ray.
11. Identify each type of decay in this series, and name the parent and daughter elements.
    (a) $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra}^* + {}^{4}_{2}\alpha$
    (b) $^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{1}\beta + \nu$
    (c) $^{228}_{88}\text{Ra}^* \rightarrow {}^{228}_{88}\text{Ra} + \gamma$
    (d) $^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta + \bar{\nu}$
    (e) $^{228}_{89}\text{Ac} \rightarrow {}^{228}_{90}\text{Th} + {}^{0}_{-1}\beta + \bar{\nu}$
    (f) $^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + {}^{4}_{2}\alpha$
    (g) $^{0}_{1}\text{p} \rightarrow {}^{0}_{0}\text{n} + {}^{0}_{1}\beta + \nu$

Extensions

12. In a process called electron capture, a nucleus absorbs an electron and emits a neutrino.
    (a) What effect does electron capture have on the atomic number?
    (b) Use nuclear notation to write the general form for electron capture.
    (c) Compare electron capture with beta decay.
13. Devise an experiment to test the hypothesis that gamma rays are emitted by nucleons jumping from higher energy levels to lower ones, similar to the energy-level transitions of electrons in an atom. What would you expect the spectrum of gamma rays emitted by a nucleus to look like?
14. Use library or Internet resources to learn how radon forms in the ground. Explain how radon can accumulate in basements in some areas. Why is this accumulation a health concern?

eTEST

To check your understanding of radioactive decay, follow the eTEST links at www.pearsoned.ca/school/physicssource.

16.3 Radioactive Decay Rates

How can an archaeologist confidently tell you that a bison head found in southern Alberta provides evidence that First Nations peoples were here more than 5000 years ago? Why do doctors sometimes inject patients with radioactive dyes? In this section, you will be introduced to the concepts of radioactive decay rate and half-life, and begin to see how understanding the behaviour of radioactive elements can provide us with a glimpse into the past or give us powerful techniques to diagnose and combat disease.

16-3 QuickLab

Simulating Radioactive Decay

Problem

How can decay rates of atoms be predicted?

Materials

container with 100 pennies
graph paper

Procedure

Work in groups of two or three.

1. (a) Pour the pennies onto a flat surface and spread them out. Put aside any pennies that are tails up. These pennies have "decayed."
   (b) Count the remaining pennies and put them back into the container. Record this count in a table.
2. Predict how many pennies will remain if you repeat step 1 two more times.
3. Repeat step 1 a total of eight times.
4. Pool your results with the other groups in the class.
5. Use the pooled data to draw a graph of how the number of pennies remaining varies with time.

Questions

1. How many pennies were left after you had done step 1 three times? Does this result match your prediction?
2. If you repeat the experiment, will you get exactly the same results each time? Explain.
3. Suppose that step 1 takes 2 min each time.
   (a) How long would it take for the number of pennies remaining to decrease by half? How long will it take until only about an eighth of the pennies remain? How are these two time intervals related?
   (b) Try to find a formula to predict how many pennies will remain at any given time.

Activity and Decay Constant

The radioactive decay of a specific nucleus is unpredictable. The nucleus could decay in the next minute, or tomorrow, or thousands of years from now. However, you can accurately predict how many nuclei in a sample will decay in a given time.

The **decay constant (λ)** is the probability of any given nucleus decaying in a unit of time. The decay constant is a property of each particular isotope. For example, radium-226 has a decay constant of 1.4×10^{-11} s^{-1}, indicating that each individual nucleus in a sample of radium-226 has a probability of 1.4×10^{-11} of decaying in 1 s. The greater the decay constant, the faster an isotope will decay.

decay constant: probability of a nucleus decaying in a given time

activity or **decay rate:** the number of nuclei in a sample that decay within a given time

becquerel (Bq): unit of activity, equal to 1 decay per second

The **activity (A)** or **decay rate** is the number of nuclei in a sample that decay within a given time. Activity is usually measured in decays per second, or **becquerels (Bq).** A highly radioactive sample has many radioactive decays each second. Activity and the decay constant are related by this formula:

$$A = \frac{\Delta N}{\Delta t} = -\lambda N$$

where N is the number of radioactive nuclei, Δt is the time interval, and λ is the decay constant.

Example 16.11

Carbon-14 has a decay constant of $3.8 \times 10^{-12}\ \text{s}^{-1}$. What is the activity of a sample that contains 2.0×10^{15} carbon-14 nuclei?

Given
$\lambda = 3.8 \times 10^{-12}\ \text{s}^{-1}$
$N = 2.0 \times 10^{15}$ atoms

Required
activity (A)

Analysis and Solution
Substitute the given values into the formula for activity:

$$\begin{aligned} A &= -\lambda N \\ &= -(3.8 \times 10^{-12}\ \text{s}^{-1})(2.0 \times 10^{15}) \\ &= -7.6 \times 10^{3}\ \text{Bq} \end{aligned}$$

The negative sign indicates that the number of carbon-14 nuclei is decreasing.

Paraphrase
The initial activity of the sample is 7.6 kBq.

Practice Problems

1. Cobalt-60 has a decay constant of $4.1 \times 10^{-9}\ \text{s}^{-1}$. Find the activity of a sample containing 1.01×10^{22} cobalt-60 atoms.
2. A sample containing 5.00×10^{20} atoms has an activity of 2.50×10^{12} Bq. Find the decay constant of this sample.

Answers

1. 4.1×10^{13} Bq
2. $5.00 \times 10^{-9}\ \text{s}^{-1}$

The activity of a radioactive material decreases over time. The reason is simple: Radioactive decay "uses up" the unstable nuclei in the sample.

Half-life

half-life: the time it takes for half of the radioactive nuclei in a sample to decay

Half-life is the time required for one-half of the radioactive nuclei in a sample to decay. For example, to diagnose thyroid problems, doctors sometimes inject patients with the radioactive isotope iodine-131, which has a half-life of about 192 h. Out of a dose of 20 μg of iodine-131, 10 μg will decay within 192 h. Only 5 μg of iodine-131 will remain after the next 192 h, then 2.5 μg after the next 192 h, and so on (see Figure 16.13). A common symbol for half-life is $t_{1/2}$.

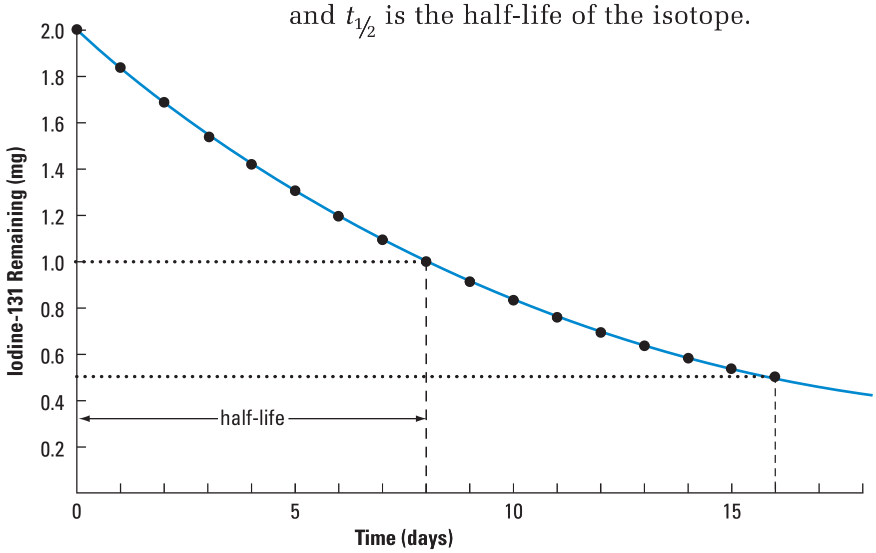
eSIM

To see a simulation of half-life, follow the links at www.pearsoned.ca/school/physicssource.

The number of nuclei of the original radioisotope left in a sample is given by the equation

$$N = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

where t is the time elapsed, N_0 is the number of nuclei of the original radioisotope when $t = 0$, and $t_{1/2}$ is the half-life of the isotope.



▲ **Figure 16.13** A graph showing the radioactive decay of iodine-131

Example 16.12

Carbon-14 has a half-life of 5730 years. How long will it take for the quantity of carbon-14 in a sample to drop to one-eighth of the initial quantity?

Given

$t_{1/2} = 5730$ years

$N = \frac{1}{8}N_0$

Required

time (t)

Analysis and Solution

$$N = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} = \frac{1}{8}N_0$$

In 3 half-lives, N will decrease to $N_0 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}N_0$

$$\begin{aligned}
\text{Therefore, } \frac{t}{t_{1/2}} &= 3 \\
t &= 3t_{1/2} \\
&= 3 \times 5730 \text{ years} \\
&= 1.719 \times 10^4 \text{ years}
\end{aligned}$$

Paraphrase

It will take just over 17 thousand years for the amount of carbon-14 in a sample to drop to one-eighth of its original value.

Practice Problems

1. Astatine-218 has a half-life of only 1.6 s. About how long will it take for 99% of a sample of astatine-218 to decay?
2. Radium-226 has a half-life of 1600 years. What percentage of a sample of radium-226 will remain after 8000 years?

Answers

1. about 11 s
2. 3.125%

Example 16.13

Radon-222 has a half-life of 3.82 days. What percent of a sample of this isotope will remain after 2 weeks?

Given

$t_{1/2} = 3.82$ days

$t = 14$ days

Required

percent remaining after 14 days

Analysis and Solution

The percent remaining is calculated from the ratio $\frac{N}{N_0}$.

$$\begin{aligned} N &= N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} \\ &= N_0\left(\frac{1}{2}\right)^{\frac{14}{3.82}} \\ &= N_0\left(\frac{1}{2}\right)^{3.66} \\ &= 0.079N_0 \\ \frac{N}{N_0} &= 0.079 \text{ or } 7.9\% \end{aligned}$$

Note that you can use the exponent or ^ key on a scientific or graphing calculator to evaluate powers of $\frac{1}{2}$. On a graphing calculator, you could enter (1/2)^(14/3.82).

Paraphrase

Only 7.9% of a sample of radon-222 will remain after 2 weeks.

Practice Problems

1. Strontium-90 has a half-life of 29.1 years. What percent of a sample of this isotope will be left after 100 years?
2. Tritium ($^3_1$H) has a half-life of 12.3 years. How much of a 100-mg sample of tritium will be left after 5.0 years?

Answers

1. 9.24%
2. 75%

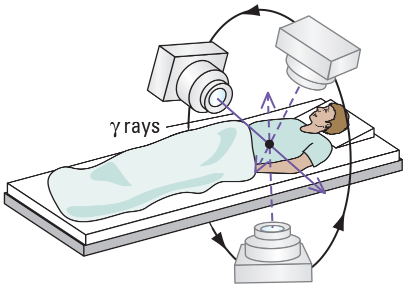
Applications of Radiation

The Rutherford gold-foil experiment that you learned about in Chapter 15 was one of the first examples of the use of nuclear energy (the release of alpha particles in the decay of radium nuclei) to study the inner working of atoms. Scientists apply radioactive decay in many other fields of scientific research, including archaeology. Radioactive compounds also have numerous industrial applications and are routinely used to diagnose and treat diseases.

THEN, NOW, AND FUTURE Radiotherapy

During their first experiments with radium, Pierre and Marie Curie noticed that its radiation could burn the skin, but the wound would heal without forming scar tissue. They realized that radium could therefore be used to treat cancer. To ensure that this treatment was readily available to cancer patients, the Curies refused to patent their discovery.

Radiotherapy is particularly useful for treating cancer because cancer cells are more susceptible to the effects of radiation than healthy tissue is. Also, the radiation is concentrated on the cancer, and kept away from the surrounding tissue as much as possible (Figure 16.14).



▲ **Figure 16.14** Rotating the radiation source around the patient minimizes damage to normal tissue.

There is now a wide variety of radiation treatments. Often, a carefully focussed beam of gamma rays is directed at the tumour. Another common method is to inject the tumour with a short-lived radioisotope that emits alpha-particles.

Questions

1. Give two reasons why gamma rays are used for the beam type of radiotherapy.
2. Why does injected radiotherapy use an isotope that undergoes alpha decay rather than one that gives off beta or gamma radiation?

Radioactive Dating

Nearly 6000 years ago, First Nations people of southwestern Alberta devised an ingenious method for hunting the vast herds of bison on the plains. By setting up barriers along a carefully chosen route, the First Nations people funnelled the bison toward a hidden cliff and then drove them over the edge. There were about 150 buffalo jumps in Alberta. The most famous, Head-Smashed-In Buffalo Jump, is now a United Nations World Heritage Site (see Chapter 2, Figure 2.68). By carefully measuring the ratio of carbon-12 to carbon-14 in bones found at this site, archaeologists have shown that it was used continuously for over 5500 years.

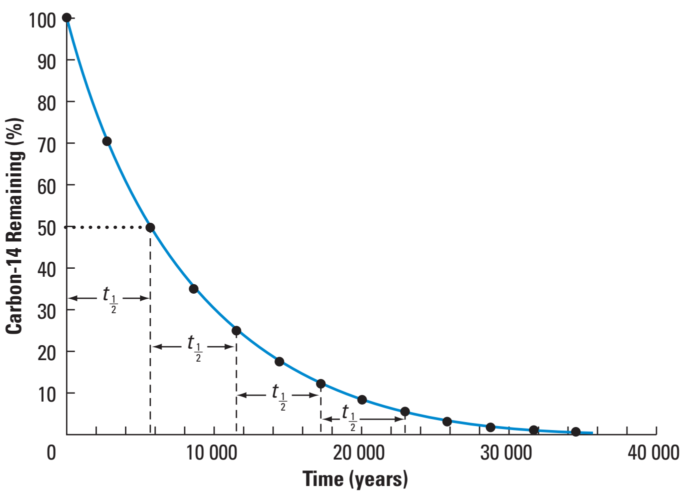
e MATH

To plot the decay rate of carbon-14 and other radioactive elements, and to learn how to mathematically determine a radioactive sample's age based on the percentage of the sample remaining, visit www.pearsoned.ca/school/physicssource.

How did this carbon ratio indicate the age of these bones? High-energy neutrons in cosmic rays produce the radioisotope carbon-14 by colliding with nitrogen atoms high in the atmosphere:

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

This carbon-14 diffuses throughout the atmosphere. Some of it is absorbed by plants and enters the food chain. So, a small proportion of all the carbon metabolized by plants and animals is carbon-14. Carbon-14 undergoes β^- decay to form nitrogen-14, whereas carbon-12 is completely stable. When living matter dies, it stops absorbing carbon, and the proportion of carbon-14 gradually decreases as it decays (see Figure 16.15). The half-life of carbon-14 is 5730 years.



▲ **Figure 16.15** Carbon-14 content as a function of the age of an artifact

For archaeologists, bone fragments and other artifacts found at Head-Smashed-In Buffalo Jump are like clocks that show when the living matter stopped absorbing carbon. Suppose, for example, that the proportion of carbon-14 in a bone fragment is about 40% of that in living tissue. Since $\left(\frac{1}{2}\right)^{1.32} = 40\%$, the carbon-14 has been decaying for about 1.3 half-lives, provided that the ratio of carbon-14 to carbon-12 in the atmosphere is the same now as when the buffalo was alive. Thus, the age of the bone fragment is roughly $1.3 \times 5730 \approx 7500$ years. Accurate estimates require more detailed calculations that take into account factors such as variations in the proportion of carbon-14 in the atmosphere through the ages.

Geologists estimate the age of rocks and geological formations with calculations based on isotopes with much longer half-lives. Such calculations are one of the methods that scientists use to estimate the age of Earth.

e WEB

To learn more about radioisotope dating, follow the links at www.pearsoned.ca/school/physicssource.

Industrial Applications

Manufacturers of sheet materials such as paper, plastics, and metal foils often monitor the thickness of the material with a gauge that measures how much of the beta radiation from a calibrated source passes through the material. Unlike mechanical thickness gauges, such gauges need not touch the material they measure, so they do not get worn down and have less risk of marking the material. Gamma rays can pass through thick metal parts to expose a photographic plate. The resulting image can reveal hidden air bubbles or hairline cracks, similar to the way X rays produce images of the inside of a patient's body. Gamma-ray photographs are a non-destructive way of testing items that X rays cannot penetrate, including structural materials, jet engines, and welded joints in pipelines. Radioactive tracers are also used in pipelines to measure flow and to detect underground leaks.

Some uses of radiation are controversial. For example, beta radiation from tritium powers runway lights and emergency exit signs that require no electricity. However, several people have received harmful doses of radiation when tritium lights have been damaged. Critics of these lights argue that other technologies can provide reliable lighting during power failures without any risk of radiation exposure. Perhaps the most controversial application is the irradiation of food to kill bacteria, insects, and parasites. Although this process sterilizes the food and thereby prolongs its shelf life, there are concerns that the radiation might also alter the food in ways that make it harmful or less nutritious.

Concept Check

Why is beta radiation used for measuring the thickness of sheet materials, whereas gamma radiation is used for testing structural materials?

16.3 Check and Reflect

Knowledge

1. What fraction of a radioactive material remains after four half-lives?

2. How many decays per second occur in a radioactive sample containing 6.4×10^{23} atoms of a material that has a decay constant of $5.8 \times 10^{-12}\ s^{-1}$?

3. Which has the greater activity, 1 g of material with a half-life of 1 ms or 1 g of material with a half-life of 1 year? Explain your answer.

Applications

4. Analysis of a rock sample shows that only $\frac{1}{16}$ of the original amount of chlorine-36 remains in the rock. Estimate the age of the rock given that the half-life of chlorine-36 is 3.0×10^5 years.

5. A radioactive tracer used in a medical test has a half-life of 2.6 h. What proportion of this tracer will remain after 24 h?

6. An archaeologist finds a wooden arrow shaft with a proportion of carbon-14 that is about 25% of that in a living tree branch. Estimate the age of the arrow.

7. A radioactive sample has an activity of 2.5 MBq and a half-life of 12 h. What will be the activity of the sample a week later?

8. Graph the data in this table. Then use your graph to estimate
   (a) the half-life of the material
   (b) the activity of the sample at time $t = 0$

Time (h)	Activity (decays/min)
1	3027
2	2546
4	1800
6	1273
8	900
10	636

Extensions

9. A dealer in antiquities offers to sell you an "authentic" dinosaur bone for a mere $100. He shows you a certificate indicating that carbon-14 dating determined that the bone is 65 million years old. Why should you be suspicious?

10. Do a Web search on use of irradiation in food production and distribution. Prepare a summary of the arguments for and against this technology.

11. (a) What is depleted uranium?
    (b) Why is depleted uranium used in armour-piercing shells and in ballast for aircraft?
    (c) Why are these applications controversial?

eTEST

To check your understanding of radioactive decay, follow the eTEST links at www.pearsoned.ca/school/physicssource.

16.4 Fission and Fusion

▲ **Figure 16.16** The doomsday clock from the *Bulletin of the Atomic Scientists*

In 1945, a group of the scientists who had designed and built the atomic bomb founded a magazine as part of an ongoing campaign to prevent this weapon from ever being used again. The *Bulletin of the Atomic Scientists* features a doomsday clock that symbolizes their estimate of the risk of a nuclear war (Figure 16.16). Since 2002, the clock has showed just seven minutes to midnight — a sobering reminder of the dangers posed by the enormous energy that nuclear reactions can release.

The graph in Figure 16.4 (page 796) shows that binding energy per nucleon has a maximum value of about 8.7 MeV when the atomic mass number, A, is from 58 to 62 — the values for isotopes of iron and nickel. Up to this maximum, the binding energy per nucleon generally increases as A increases. Then, as A increases further, the binding energy per nucleon gradually decreases. The shape of this graph indicates that two distinct types of reactions can release energy from nuclei.

Fission: When a nucleus with $A > 120$ splits into smaller nuclei, they have greater binding energy per nucleon. This fission reaction gives off energy equal to the difference between the binding energy of the original nucleus and the total binding energy of the products.

Fusion: When two low-mass nuclei combine to form a single nucleus with $A < 60$, the resulting nucleus is more tightly bound. This fusion reaction gives off energy equal to the difference between the total binding energy of the original nuclei and the binding energy of the product.

For both nuclear fission and fusion, the energy released, ΔE, is

$$\Delta E = E_{b_f} - E_{b_i} = (\text{net change in mass defect}) \times c^2$$

where E_{b_i} is the total binding energy of the original nucleus or nuclei, and E_{b_f} is the total binding energy of the product(s).

Since the binding energies correspond to the mass defects for the nuclei, the energy released corresponds to the decrease in the total mass defect. This change in the total mass defect equals the change in the total mass. Thus, the energy released corresponds to the mass that the reaction transforms into energy:

$$\Delta E = (m_f - m_i) \times c^2$$

where m_i is the total mass of the original nucleus or nuclei, and m_f is the total mass of the product(s).

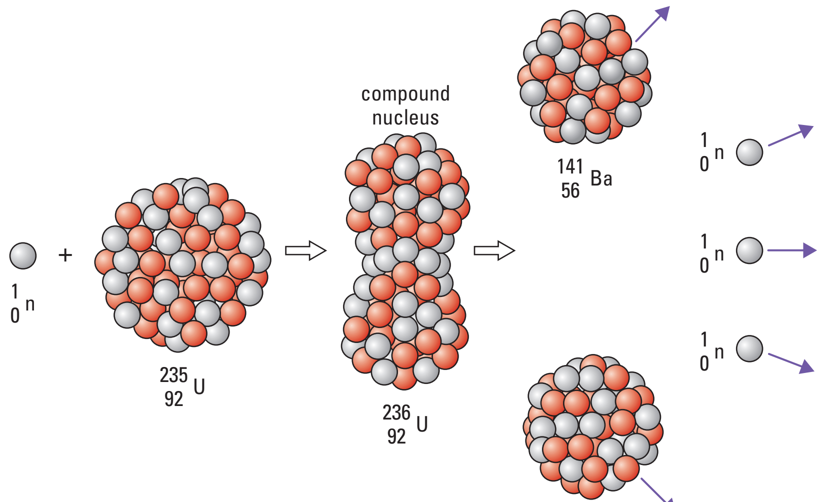
Concept Check

Why does a nuclear reaction that increases the binding energy per nucleon release energy? Use an analogy to help explain this release of energy.

Nuclear Fission

Often, fission results from a free neutron colliding with a large nucleus. The nucleus absorbs the neutron, forming a highly unstable isotope that breaks up almost instantly. Figure 16.17 shows one of the ways that uranium-235 can split into two lighter nuclei.

In the next example, you will calculate the energy released during a fission reaction.



▶ **Figure 16.17** Absorbing a neutron causes uranium-235 to undergo fission in a CANDU nuclear reactor.

Example 16.14

Calculate the energy released by the fission reaction $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n$.

Given

Initial mass: $^{235}_{92}U$ plus one neutron

Final mass: $^{141}_{56}Ba$, $^{92}_{36}Kr$, and three neutrons

Required

energy released (ΔE)

Analysis and Solution

First, use the atomic mass data on page 881 to calculate the net change in mass resulting from the reaction.

$$\begin{aligned} m_i &= m_{^{235}_{92}U} + m_n \\ &= 235.043\ 930\ u + 1.008\ 665\ u \\ &= 236.052\ 595\ u \end{aligned}$$

$$\begin{aligned} m_f &= m_{^{141}_{56}Ba} + m_{^{92}_{36}Kr} + 3m_n \\ &= 140.914\ 412\ u + 91.926\ 156\ u + 3(1.008\ 665\ u) \\ &= 235.866\ 563\ u \end{aligned}$$

$$\begin{aligned} m_i - m_f &= 236.052\ 595\ u - 235.886\ 563\ u \\ &= 0.186\ 032\ u \end{aligned}$$

Now, use mass-energy equivalence to calculate the energy released.

1 u is equivalent to 931.5 MeV, so

$$\begin{aligned} \Delta E &= 0.186\ 032\ \cancel{u} \times \frac{931.5\ \text{MeV}}{1\ \cancel{u}} \\ &= 173.3\ \text{MeV} \end{aligned}$$

Paraphrase

The fission of an atom of uranium-235 into barium-141 and krypton-92 releases 173.3 MeV of energy.

Practice Problems

1. Calculate the energy released by the reaction $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{94}_{40}Zr + ^{139}_{52}Te + 3\ ^{1}_{0}n$.
2. A uranium-235 nucleus absorbs a neutron and then splits into a bromine nucleus ($^{87}_{35}Br$), a lanthanum nucleus ($^{146}_{57}La$), and additional neutrons. How many neutrons are released in this fission reaction? Express this reaction as a balanced equation.
3. How much energy is released in the reaction in question 2?

Answers

1. 172.9 MeV
2. $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{87}_{35}Br + ^{146}_{57}La + 3\ ^{1}_{0}n$
3. 167.8 MeV

Comparing Chemical Energy with Nuclear Energy

When you sit by a campfire, the warmth that you feel is due to the chemical energy released by the combustion of wood. All chemical processes, including combustion, involve electrons moving from one energy level to another. In Chapter 15, you learned that such transitions typically release no more than a few tens of electron volts. Example 16.15 shows that a nuclear process can release a vastly greater amount of energy.

Example 16.15

Burning 1 kg of gasoline releases about 4.4×10^7 J. Compare this energy to the energy released by the fission of 1 kg of uranium-235 into barium-141 and krypton-92.

Given

chemical energy content of gasoline = 4.4×10^7 J/kg

Required

ratio of the energy content of gasoline to that of uranium-235

Analysis and Solution

From Example 16.14, you know that uranium-235 has about 173.3 MeV of nuclear potential energy per atom, assuming fission into barium and krypton.

Use the atomic mass of uranium-235 to calculate the number of atoms in 1 kg of this isotope. Then calculate the potential energy per kilogram for comparison with gasoline.

$$m_{^{235}_{92}\mathrm{U}} = 235.043\ 930\ \cancel{\mathrm{u}} \times \frac{1.660\ 539 \times 10^{-27}\ \mathrm{kg}}{1\ \cancel{\mathrm{u}}}$$

$$= 3.902\ 996 \times 10^{-25}\ \mathrm{kg}$$

$$\text{Number of atoms in 1 kg of } ^{235}_{92}\mathrm{U} = \frac{1\ \cancel{\mathrm{kg}}}{3.902\ 996 \times 10^{-25}\ \cancel{\mathrm{kg}}}$$

$$= 2.562\ 134 \times 10^{24}$$

$$\text{Energy content of } ^{235}_{92}\mathrm{U} = \left(2.562\ 134 \times 10^{24}\ \frac{\cancel{\text{atoms}}}{\mathrm{kg}}\right)\left(173.3\ \frac{\mathrm{MeV}}{\cancel{\text{atom}}}\right)$$

$$= 4.4402 \times 10^{26}\ \mathrm{MeV/kg}$$

$$= 4.4402 \times 10^{32}\ \frac{\cancel{\mathrm{eV}}}{\mathrm{kg}} \times \frac{1.60 \times 10^{-19}\ \mathrm{J}}{1\ \cancel{\mathrm{eV}}}$$

$$= 7.10 \times 10^{13}\ \mathrm{J/kg}$$

$$\frac{\text{Energy content of } ^{235}_{92}\mathrm{U}}{\text{Energy content of gasoline}} = \frac{7.10 \times 10^{13}\ \cancel{\mathrm{J/kg}}}{4.4 \times 10^{7}\ \cancel{\mathrm{J/kg}}}$$

$$= 1.6 \times 10^{6}$$

Paraphrase

The nuclear potential energy of 1 kg of uranium-235 is about 1.6 million times greater than the chemical potential energy of 1 kg of gasoline.

Practice Problems

1. A typical family car requires approximately 1600 MJ of energy to travel 500 km.
   (a) How many kilograms of gasoline does it take to provide this energy?
   (b) What mass of uranium-235 would provide the same energy?

Answers

1. (a) 36 kg
   (b) 22 mg

Concept Check

A nucleus is much smaller than an atom. How does this difference in size make nuclear reactions much more energetic than chemical reactions?

Fusion

What powers the Sun? The discovery of the nucleus and of mass-energy equivalence provided the key to this question, which had puzzled scientists for thousands of years. In the early 1920s, the British-American astrophysicist Cecilia Payne-Gaposchkin (1900–1979) showed that the Sun consists primarily of hydrogen (about 73%) and helium (about 27%). Noting that four protons have 0.7% more mass than a helium nucleus, the British astrophysicist Arthur Stanley Eddington (1882–1944) suggested that a fusion process might power the stars.

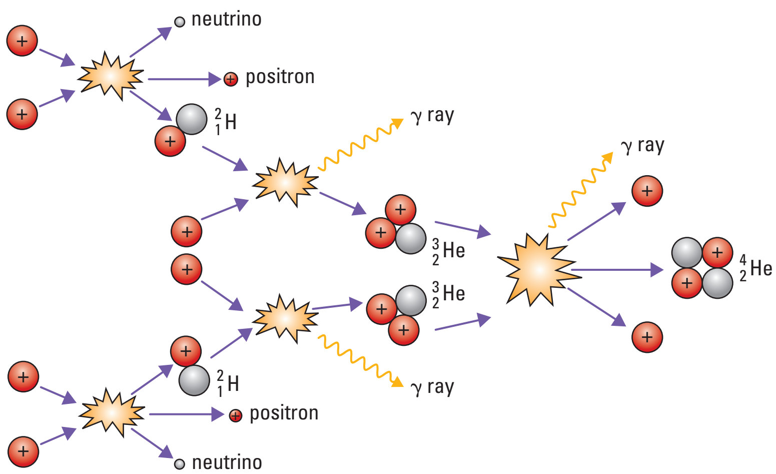
info BIT

In the mid-1930s, Hans Bethe won a $500 prize for a paper on fusion in stars. He used the money to get his mother out of Nazi Germany. Bethe won the Nobel Prize for physics in 1967 and helped found the *Bulletin of the Atomic Scientists*.

In the 1930s, the young German physicist Hans Bethe (1906–2005) worked out the details of how hydrogen nuclei could release energy by fusing together to form helium. In the Sun and smaller stars, the process, called the **proton-proton chain** (Figure 16.18), has four steps. First, two hydrogen nuclei combine to form deuterium (an isotope of hydrogen with one neutron), an antielectron, and a neutrino. Next, another hydrogen nucleus combines with the deuterium nucleus to produce a helium-3 nucleus and a gamma ray. Then, two of the helium-3 nuclei combine to produce a helium-4 nucleus, two hydrogen nuclei, and a gamma ray. In the final step, annihilation of two positron-electron pairs occurs. Each of these annihilations produces a pair of gamma photons. In order for these reactions to occur, the nuclei must have enough kinetic energy to overcome the electrostatic repulsion between them.

proton-proton chain: fusion process in which four hydrogen nuclei combine to form a helium nucleus

Step	Reaction	Energy Released
1	$2\ {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + {}^0_1\beta + \nu$ (twice)	0.42 MeV (twice)
2	${}^1_1\mathrm{H} + {}^2_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma$ (twice)	5.49 MeV (twice)
3	$2\ {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + 2\ {}^1_1\mathrm{H} + \gamma$	12.85 MeV
4	${}^0_1\beta + {}^0_{-1}\beta \rightarrow 2\gamma$ (twice)	1.02 MeV (twice)
Total	$4\ {}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2\ {}^0_1\beta + 2\nu + 7\gamma$	26.71 MeV



◀ **Figure 16.18** The proton-proton chain

Example 16.16

The Sun radiates about 4×10^{26} W and has a mass of 1.99×10^{30} kg. Astronomers estimate that the Sun can convert only the innermost 10% of its hydrogen into helium. Estimate how long the Sun can continue to shine at its present intensity.

Given

Power = 4×10^{26} W $\quad$ $m_{Sun} = 1.99 \times 10^{30}$ kg

Hydrogen available for conversion = 10% of total hydrogen

Required

Time the Sun will take to convert 10% of its hydrogen into helium (t)

Analysis and Solution

The fusion of four hydrogen atoms produces 26.71 MeV. To find the rate at which helium nuclei are produced, divide the Sun's power by the energy released during the formation of each helium nucleus:

$$\text{Rate of helium production} = \frac{\text{power of Sun}}{\text{energy released per helium atom}}$$

$$= \frac{4 \times 10^{26}\ \text{W}}{26.71\ \text{MeV/atom}}$$

$$= \frac{4 \times 10^{26}\ \frac{\cancel{\text{J}}}{\text{s}}}{\left(26.71\ \frac{\cancel{\text{MeV}}}{\text{atom}}\right)\left(\frac{1.60 \times 10^{-13}\ \cancel{\text{J}}}{1\ \cancel{\text{MeV}}}\right)}$$

$$= 9.36 \times 10^{37}\ \text{atoms/s}$$

Practice Problems

1. (a) How many helium nuclei does a star with a power of 1.6×10^{25} W produce every second?
   (b) Estimate how much helium this star has produced if it is 4 billion years old.

Answers

1. (a) 4.1×10^{36}
   (b) 3.4×10^{27} kg

Since 4 hydrogen atoms are needed for each helium produced, multiply by 4 to find the rate at which the Sun converts hydrogen atoms into helium. Then, convert this rate to mass per second by multiplying it by the mass of a hydrogen atom:

$$\text{Rate of hydrogen conversion} = 4\left(9.36 \times 10^{37}\ \frac{\cancel{\text{atoms}}}{\text{s}}\right)\left(1.67 \times 10^{-27}\ \frac{\text{kg}}{\cancel{\text{atom}}}\right)$$

$$= 6.25 \times 10^{11}\ \text{kg/s}$$

Hydrogen makes up 73% of the mass of the Sun, but only 10% of this hydrogen can be converted into helium.

The lifespan of the Sun approximately equals the amount of hydrogen that can be converted divided by the conversion rate.

$$t = \frac{\text{amount of hydrogen available}}{\text{rate of conversion}}$$

$$= \frac{1.99 \times 10^{30}\ \text{kg} \times 73\% \times 10\%}{6.25 \times 10^{11}\ \text{kg/s}}$$

$$= 2.32 \times 10^{17}\ \text{s} \quad \text{or about} \quad 7 \times 10^{9}\ \text{years}$$

Paraphrase

The Sun can continue to produce energy at its present rate for about 7 billion years.

Concept Check

Why can fusion reactions occur only at extremely high temperatures?

The cores of massive stars can reach temperatures high enough for helium nuclei to combine to form carbon and oxygen. In some stars, these elements can undergo further fusion. The extent of this **nucleosynthesis** depends on the star's density, temperature, and the concentration of the various elements. Current theory suggests that synthesis of elements heavier than iron and nickel occurs only during the explosion of **supernovae**. Such explosions distribute these elements throughout the cosmos. So, the uranium fuel for today's nuclear power stations may have come from the explosion of a massive star billions of years ago.

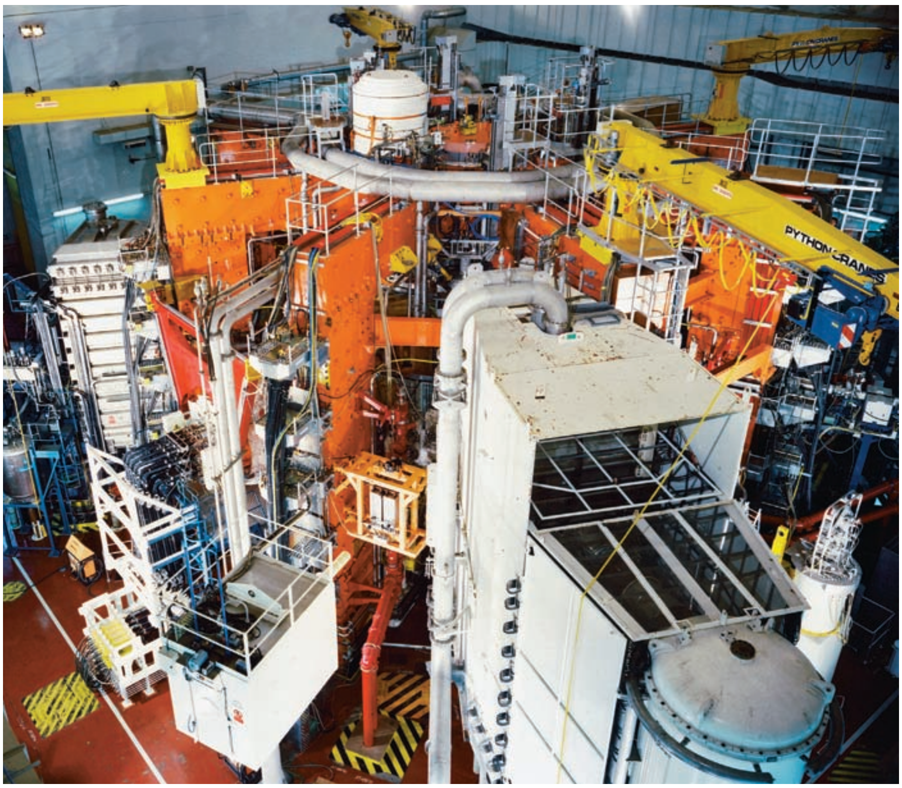
nucleosynthesis: formation of elements by the fusion of lighter elements

supernova: sudden, extremely powerful explosion of a massive star

A hydrogen-fusion reactor might be an almost ideal energy source. Hydrogen is the most abundant of elements, and the end product, helium-4, is harmless. However, controlling and sustaining a fusion reaction for generating power is extremely difficult. To start the fusion process, the hydrogen has to be heated to a temperature between 45 million and 400 million kelvins, depending on which isotopes are used. Then, this extremely hot gas has to be contained so that the fusion reactions can continue. Some researchers are using powerful lasers to generate the necessary temperatures and magnetic fields to contain the fusion reactions. However, the latest experiments have sustained fusion for only a few seconds and produced only slightly more energy than it took to run the reactor (see Figure 16.19). It will take major technological advances to make fusion power practical.

e **WEB**

To learn more about fusion reactors, follow the links at www.pearsoned.ca/school/physicssource.



▲ **Figure 16.19** The Joint European Toroid (JET) fusion reactor

Concept Check

There are concerns that tritium could leak from a fusion reactor. Why would tritium be a serious environmental hazard?

16.4 Check and Reflect

Knowledge

1. (a) Complete this nuclear reaction:
   ${}^{235}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + ? + 2\,{}^{1}_{0}\mathrm{n}$
   (b) Does this reaction involve fission or fusion? Justify your answer.
2. What happens to the binding energy per nucleon in a nuclear reaction that releases energy?
3. An iron nucleus of binding energy 492 MeV fuses with a silicon nucleus of binding energy 237 MeV to form a nucleus with binding energy 718 MeV. Will this reaction release energy? Explain why or why not.
4. (a) Which elements are most likely to undergo fission?
   (b) Which elements are most likely to undergo fusion?
5. A neutron is emitted when aluminium-27 absorbs an alpha particle.
   (a) What isotope does this reaction create?
   (b) Write the process for the reaction.

Applications

6. (a) Write the reaction formula for the fusion of helium-4 with oxygen-16.
   (b) How much energy does this reaction release?
7. (a) What particle is emitted when deuterium (${}^{2}_{1}\mathrm{H}$) and tritium (${}^{3}_{1}\mathrm{H}$) fuse to form helium?
   (b) How much energy does this reaction release?
8. A CANDU-6 nuclear reactor can generate 700 MW of electrical power. A CANDU power plant transforms about 27% of its nuclear energy into electrical energy, with the rest being lost primarily as heat.
   (a) If the plant uses uranium-235 as fuel and the average energy released per uranium nucleus is 200 MeV, how many nuclei undergo fission each second when the reactor is running at full power?
   (b) Estimate how many kilograms of uranium-235 a CANDU-6 reactor uses in a year. List any assumptions you make.

Extensions

9. (a) In stars much more massive than the Sun, iron-56 will eventually be produced in their centres. Suppose that two iron-56 nuclei fuse. Complete the following reaction and identify the element produced: ${}^{56}_{26}\mathrm{Fe} + {}^{56}_{26}\mathrm{Fe} \rightarrow$
   (b) The element formed in the reaction in (a) has a mass of 111.917 010 u. Show that this reaction absorbs rather than releases energy.
   (c) Explain why stars like the Sun do not produce elements heavier than iron.
10. (a) Research the radioactive wastes produced by nuclear reactors. List the major isotopes produced and their half-lives.
    (b) Briefly outline some of the methods for storing and disposing of these wastes.
11. Compare and contrast the risks and benefits of generating electricity with coal and with nuclear reactors.

e TEST

To check your understanding of fission and fusion, follow the eTest links at www.pearsoned.ca/school/physicssource.

CHAPTER 16 SUMMARY

Key Terms and Concepts

femto
proton
neutron
nucleon
atomic number
neutron number
atomic mass number
isotope
atomic mass unit (u)
strong nuclear force
binding energy
mass defect
alpha radiation
beta radiation
gamma radiation
transmute
parent element
daughter element
beta-negative (β^-) decay
beta (β) particle
neutrino
weak nuclear force
antimatter
positron (e+ or ${}^{0}_{1}\beta$)
beta-positive (β+) decay
gamma (γ) decay
radioactive decay series
radiation sickness
genetic damage
radioisotope
gray (Gy)
sievert (Sv)
relative biological effectiveness (RBE)
decay constant
activity (A) or decay rate
becquerel (Bq)
half-life
fission
fusion
proton-proton chain
nucleosynthesis
supernova

Key Equations

Binding energy: $E_b = E_{nucleons} - E_{nucleus}$

Mass defect: $\Delta m = m_{nucleons} - m_{nucleus} = Zm_{{}^1_1H} + Nm_{neutron} - m_{atom}$

α decay: ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$

β^- decay: ${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}\beta + \bar{\nu}$

γ decay: ${}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$

β^+ decay: ${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}^{0}_{1}\beta + \nu$

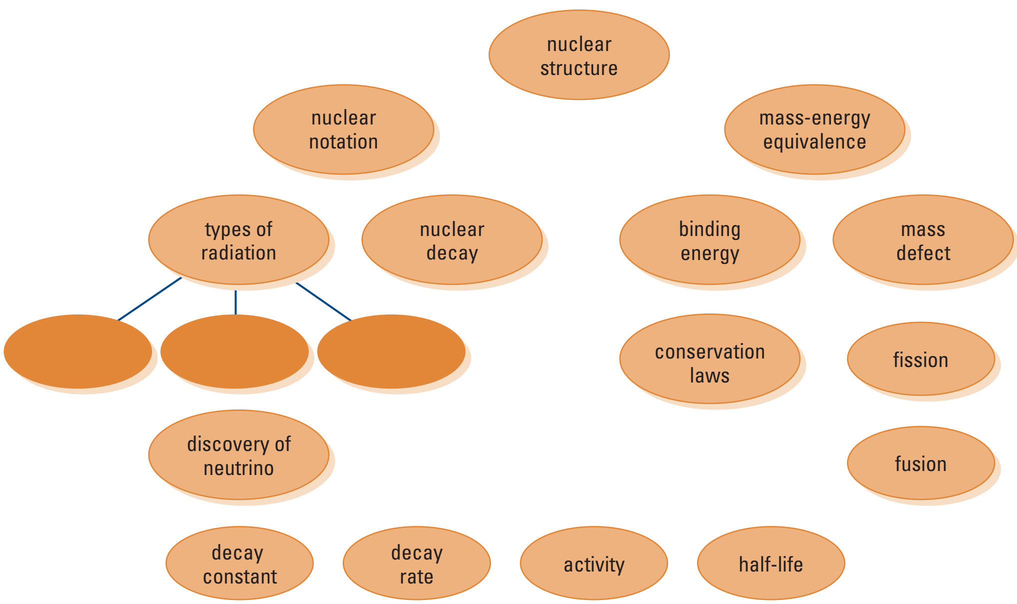
Activity: $A = \dfrac{\Delta N}{\Delta t} = -\lambda N$

Half-life: $N = N_0\left(\dfrac{1}{2}\right)^{\frac{t}{t_{1/2}}}$

Nuclear energy released: $\Delta E = (m_i - m_f) \times c^2$

Conceptual Overview

Summarize this chapter by copying and completing this concept map.



CHAPTER 16 REVIEW

Knowledge

1. (16.1) Do all nuclei contain more neutrons than protons? Justify your answer.
2. (16.1) Is the atomic mass number for an atom always greater than the atomic number? Justify your answer.
3. (16.1) What is the term for elements that have the same atomic number but different neutron numbers?
4. (16.1) Explain how these nuclei are similar and how they differ: ${}^{233}_{92}U$, ${}^{235}_{92}U$, ${}^{238}_{92}U$.
5. (16.1) How many neutrons are in a nucleus of ${}^{115}_{55}Cs$? How many protons?
6. (16.1) Convert 50 MeV to joules.
7. (16.1) Calculate the energy equivalent for 1 g of matter.
8. (16.1) Calculate the energy equivalent for 2.3 u of mass.
9. (16.1) Calculate the mass equivalent for 300 MeV.
10. (16.1) Calculate the binding energy for a nucleus that has a mass defect of 0.022 u.
11. (16.2) Which decay processes do not change the atomic number of a nucleus?
12. (16.2) What is the charge on
    (a) a beta particle?
    (b) an alpha particle?
    (c) a gamma ray?
13. (16.2) Explain how each of these decay processes changes nuclear structure:
    (a) alpha decay
    (b) beta decay
    (c) gamma decay
14. (16.2) Describe this decay in words, identifying the parent element, the daughter element, and the type of decay: ${}^{43}_{19}K \rightarrow {}^{43}_{20}Ca + {}^{0}_{-1}\beta + \overline{\nu}$.
15. (16.2) Which of α, β, and γ radiation is the most penetrating, and which is the least penetrating?
16. (16.2) Explain why physicists think that radioactivity originates from nuclei.
17. (16.2) Compare the radiation dose that North Americans typically receive each year from radon and from diagnostic X rays. Which of these sources poses the greater health hazard?
18. (16.3) What is the activity of a sample that contains 1.5×10^{20} nuclei of an element with a decay constant of 1.2×10^{-12} s^{-1}?
19. (16.3) After 1.5 h, the number of radioactive nuclei in a sample has dropped from 5.0×10^{20} to 2.5×10^{20}. How many of these nuclei will remain after another 6 h?
20. (16.3) Explain why carbon-14 dating is not useful for determining the age of a rock sample.
21. (16.4) Why do all of the elements used as fuel in nuclear power plants have $A > 200$?
22. (16.4) What is the primary energy source for most stars?
23. (16.4) List the steps in the proton-proton chain.

Applications

24. Calculate the binding energy per nucleon for the following nuclei:
    (a) ${}^{4}_{2}He$
    (b) ${}^{28}_{14}Si$
    (c) ${}^{58}_{26}Fe$
    (d) ${}^{235}_{92}U$
25. (a) Write the process for the β^{+} decay of ${}^{52}_{26}Fe$.
    (b) Show that this process conserves charge and atomic mass number.
26. (a) What parent element decays into lead-208 by emitting an alpha particle?
    (b) Estimate the kinetic energy of the alpha particle.
27. (a) Write a complete decay process for the transmutation of ${}^{30}_{15}P$ into ${}^{30}_{14}Si$.
    (b) Calculate the energy released in this decay.
28. In the oldest campsites yet discovered in Alberta, archaeologists have found materials that contain about a quarter of their original carbon-14. Estimate the age of these campsites. Give your answer to two significant digits.

29. Until the early 1950s, a paint containing radium-226 was used to make the dials on some clocks, watches, and aircraft instruments glow in the dark. Radium-226 has a decay constant of $1.98 \times 10^{-11}\ \text{s}^{-1}$.

(a) If the activity of one of these clocks is 0.10 MBq, how many atoms of radium-226 are on the dial?

(b) Calculate the mass of radium on the dial.

(c) The half-life of radium is 1600 years. Calculate the activity that the clock will have in 5000 years.

30. Graph the data in this table. Use your graph to estimate

(a) the activity of the sample when $t = 5$ h

(b) the half-life of the radioactive material in the sample

Time (h)	Activity (Bq)	Time (h)	Activity (Bq)
0	1000.0	14	80.5
2	697.7	16	56.1
4	486.8	18	39.2
6	339.6	20	27.3
8	236.9	22	19.1
10	165.3	24	13.3
12	115.3		

31. Calculate the energy released when three helium-4 nuclei combine to form a carbon-12 nucleus.

32. You are designing a thermoelectric power supply for a space probe. The probe will need 20 W of electricity for 14.5 years. The efficiency of thermal to electrical energy conversion is 15%. You are considering using polonium-208 as the fuel for the power supply.

(a) What is the key advantage of polonium over a chemical fuel?

(b) How much polonium will you need? Polonium-208 has a decay constant of $7.57 \times 10^{-9}\ \text{s}^{-1}$ and a half-life of 2.9 years. $^{208}_{84}\text{Po}$ decays into $^{204}_{82}\text{Pb}$.

Extensions

33. In 1918, Rutherford observed that bombarding nitrogen atoms with alpha particles produced oxygen and hydrogen. Use nuclear notation to write two reactions that could account for these products. Which reaction is more likely to occur? Explain your reasoning. How could you check your conclusion?

34. There have been over 2000 tests of nuclear weapons, including 711 conducted in the atmosphere or in the ocean. What radioactive products did these tests release? What health hazards result from this radioactive fallout?

35. Research nucleosynthesis in stars. List a sequence of fusion reactions that produces iron-56, and explain why smaller stars do not complete this sequence. How are the fusion reactions in the Sun likely to end?

Consolidate Your Understanding

1. Explain how atomic number, atomic mass number, and neutron number are related to the structure of the nucleus.

2. Use the concept of binding energy to explain why some nuclei are more stable than others.

3. Describe the differences between the alpha, beta, and gamma decays.

4. Explain how you can use conservation principles to predict the daughter elements created by a radioactive decay.

5. Distinguish between nuclear fission and nuclear fusion, and explain how to calculate the energy yield from either process.

Think About It

Review your answers to the Think About It questions on page 789. How would you answer each question now?

eTEST

To check your understanding of nuclear reactions, follow the eTEST links at www.pearsoned.ca/school/physicssource.