Chapter 30

Nuclear Physics

What You'll Learn

- You will describe the components of a nucleus and how radioactive decay affects these components.
- You will calculate the energy released in nuclear reactions.
- You will examine how radioactive isotopes and nuclear energy are produced and used.
- You will understand the building blocks of matter.

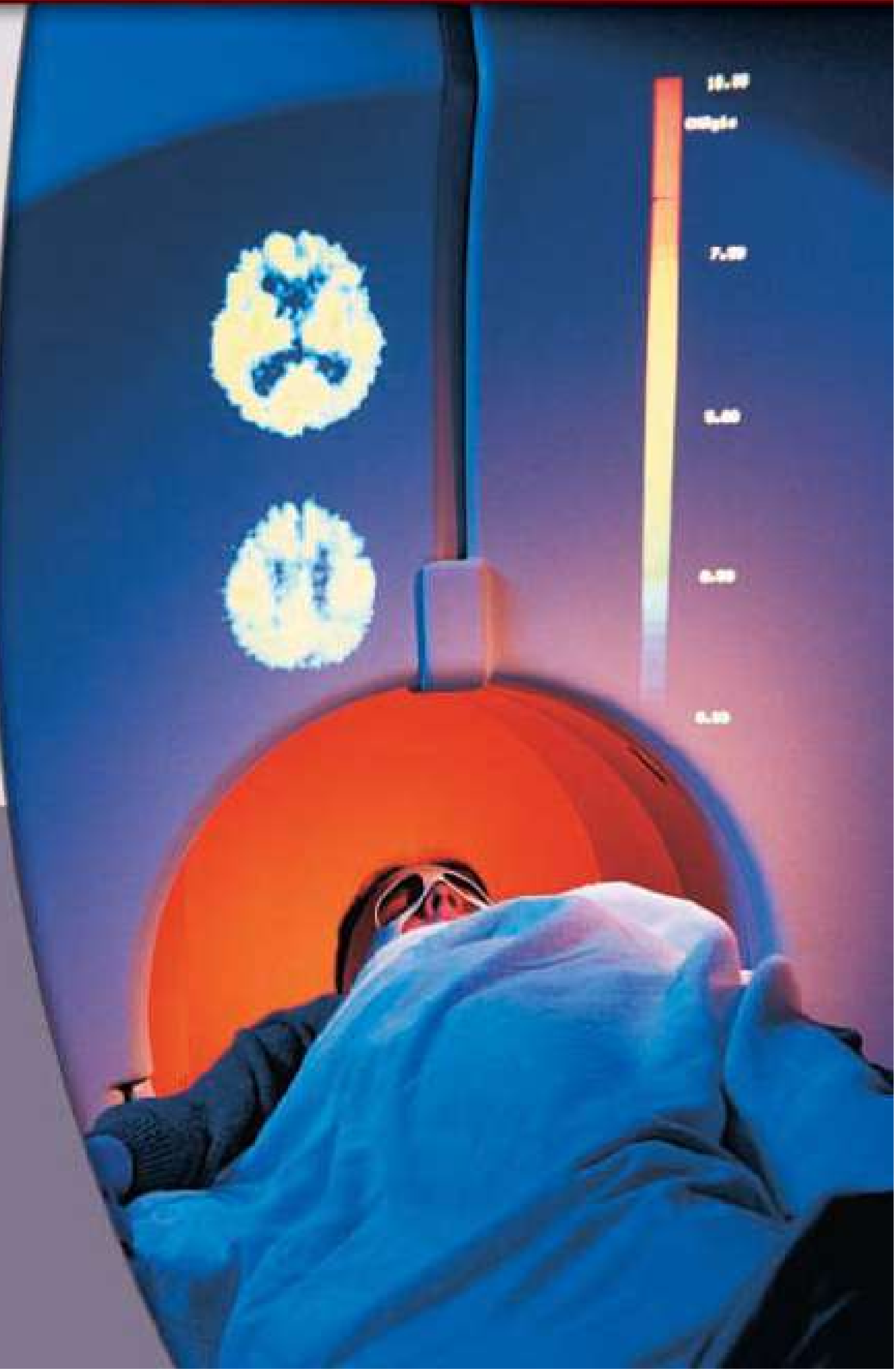
Why It's Important

Nuclear physics has many applications, including medical research, energy production, and studying the structure of matter.

Medicine Radioactive isotopes are used to create images of the brain and other organs at work for medical diagnoses and research.

Think About This ▶

How does the radiation that is emitted by radioactive isotopes allow scientists and doctors to trace the operations of the human body?



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Kay Chernush

LAUNCH Lab

How can you model the nucleus?

Question

How is the force exerted by double-sided tape similar to the strong force?

Procedure

1. Cover the outer edges of 3–6 disk magnets with double-sided tape. Do the same thing to 3–6 disks of wood or aluminum of the same size. The magnets represent protons. The other disks represent neutrons.
2. Arrange the magnets with all the north poles facing up.
3. **Describe** the force exerted on one "proton" when another "proton" is brought closer, until they finally touch.
4. **Describe** the force exerted on a "neutron" by either another "neutron" or a "proton" when they are brought together, until they finally touch.

Analysis

The strong force drops to zero when the centers of two nucleons are farther apart than their diameters. How does that compare with the range of the force of the tape? The strong force is the same for neutrons and protons. Does this model behave this way?

Critical Thinking Stable nuclei usually have more neutrons than protons. Why would this model behave the same way?

30.1 The Nucleus

Ernest Rutherford not only established the existence of the nucleus, but he also conducted some of the early experiments to discover its structure. It is important to realize that neither Rutherford's experiments, nor the experiments of those who followed, offered the opportunity to observe the atom directly. Instead, inferences were drawn from the observations that researchers made. Recall from Chapter 28 that Rutherford's team made careful measurements of the deflection of alpha particles as they hit gold foil. These deflections could be explained if the atom was mostly empty space. The experiment showed that the atom had a small, dense, positively charged center surrounded by nearly massless electrons.

After the discovery of radioactivity by Becquerel in 1896, he and others looked at the effects produced when a nucleus breaks apart in natural radioactive decay. Marie and Pierre Curie discovered the new element radium and made it available to researchers all over the world, thereby increasing the study of radioactivity. Scientists discovered that through radioactivity one kind of atom could change into another kind, and thus, atoms must be made up of smaller parts. Ernest Rutherford and Fredrick Soddy used radioactivity to probe the center of the atom, the nucleus.

Objectives

- **Determine** the number of neutrons and protons in nuclides.
- **Define** the binding energy of the nucleus.
- **Relate** the energy released in a nuclear reaction to the change in binding energy during the reaction.

Vocabulary

atomic number
atomic mass unit
mass number
nuclide
strong nuclear force
nucleons
binding energy
mass defect

Description of the Nucleus

Are nuclei made up only of positively charged particles? At first, only the mass of the nucleus and the fact that the charge was positive were known. The magnitude of the charge of the nucleus was found as a result of X-ray scattering experiments done by Henry Moseley, a member of Rutherford's team. The results showed that the positively charged protons accounted for roughly half the mass of the nucleus. One hypothesis was that the extra mass was the result of protons, and that electrons in the nucleus reduced the charge to the observed value. This hypothesis, however, had some fundamental problems. In 1932, English physicist James Chadwick solved the problem when he discovered a neutral particle that had a mass approximately that of the proton. This particle, known as the neutron, accounted for the missing mass of the nucleus without increasing its charge.

Mass and charge of the nucleus The only charged particle in the nucleus is the proton. The **atomic number,** Z, of an atom is the number of protons. The total charge of the nucleus is the number of protons times the elementary charge, e.

$$\text{nuclear charge} = Ze$$

Both the proton and the neutron have a mass that is about 1800 times the mass of an electron. The proton and neutron masses are approximately equal to 1 u, where u is the **atomic mass unit,** 1.66×10^{-27} kg. To determine the approximate mass of the nucleus, multiply the number of neutrons and protons, or **mass number,** A, by u.

$$\text{nuclear mass} \cong A(\text{u})$$

Size of the nucleus Rutherford's experiments produced the first measurements of the size of the nucleus. He found that the nucleus has a diameter of about 10^{-14} m. A typical atom might have a radius 10,000 times larger than the size of the nucleus. Although the nucleus contains nearly all of the mass of an atom, proportionally the nucleus occupies less space in the atom than the Sun does in the solar system. The nucleus is incredibly dense—about 1.4×10^{18} kg/m^3. If a nucleus could be one cubic centimeter, it would have a mass of about one billion tons.

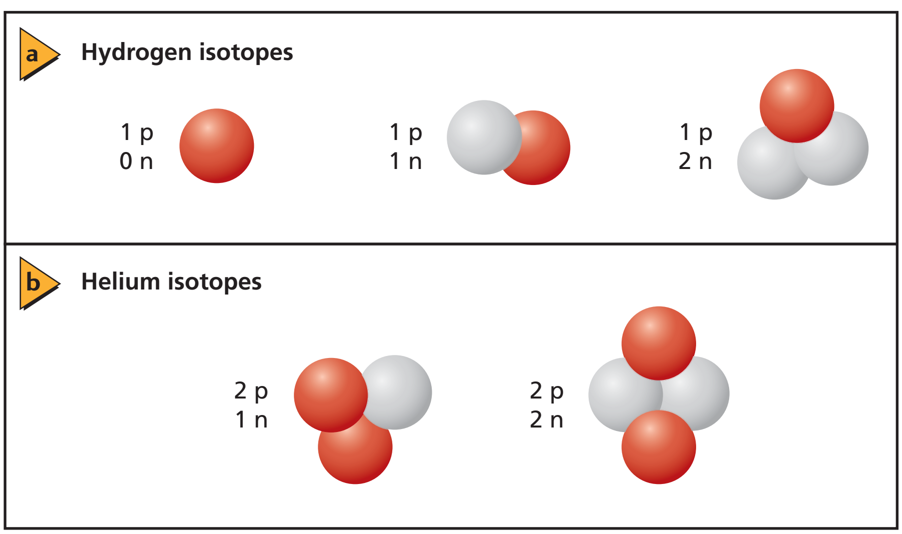

Figure 30-1 The nuclides of hydrogen **(a)** and helium **(b)** illustrate that all the nuclides of an element have the same numbers of protons, but have different numbers of neutrons. Protons are red and neutrons are gray in this drawing.

Do all elements have the same mass numbers?

Looking at the periodic table on page 916, you might notice that the first four elements all have an atomic mass, A, near a whole number. Boron, on the other hand, has a mass of 10.8 u. If the nucleus is made up of only protons and neutrons, each with a mass of approximately 1 u, shouldn't the total mass of any atom be near a whole number?

The puzzle of atomic masses that were not whole numbers was solved with the mass spectrometer. You learned in Chapter 26 how the mass spectrometer demonstrated that an element could have atoms with different masses. For example, in an analysis of a pure sample of neon, not one, but two spots appeared on the film of the spectrometer. The two spots were produced by neon atoms of different masses. One variety of the neon atom was found to have a mass of 20 u, while the second type had a mass of 22 u. All neutral neon atoms have 10 protons in the nucleus and 10 electrons in the atom. One kind of neon atom, however, has 10 neutrons in its nucleus, while the other has 12 neutrons. The two kinds of atoms are called *isotopes* of neon. The nucleus of an isotope is called a **nuclide.**

All nuclides of an element have the same number of protons, but have different numbers of neutrons, as illustrated by the hydrogen and helium nuclides shown in **Figure 30-1.** All isotopes of a neutral element have the same number of electrons around the nucleus and behave chemically in the same way.

Average mass The measured mass of neon gas is 20.183 u. This figure is now understood to be the average mass of the naturally occurring isotopes of neon. Thus, while the mass of an individual atom of neon is close to a whole number of mass units, the atomic mass determined from an average sample of neon atoms is not. Most elements have several isotopic forms that occur naturally. The mass of one isotope of carbon, carbon-12, is now used to define the mass unit. One u is defined to be $\frac{1}{12}$ the mass of the carbon-12 isotope.

A special method of notation is used to describe an isotope. A subscript representing the atomic number, or charge, Z, is written to the left of the symbol for the element. A superscript written to the left of the symbol is the mass number, A. This notation takes the form ${}^{A}_{Z}X$, where X is any element. For example, carbon-12 is ${}^{12}_{6}\text{C}$, and the two isotopes of neon, with atomic number 10, are written as ${}^{20}_{10}\text{Ne}$ and ${}^{22}_{10}\text{Ne}$.

PRACTICE Problems

Additional Problems, Appendix B

1. Three isotopes of uranium have mass numbers of 234, 235, and 238. The atomic number of uranium is 92. How many neutrons are in the nuclei of each of these isotopes?
2. An isotope of oxygen has a mass number of 15. How many neutrons are in the nucleus of this isotope?
3. How many neutrons are in the mercury isotope ${}^{200}_{80}\text{Hg}$?
4. Write the symbols for the three isotopes of hydrogen that have zero, one, and two neutrons in the nucleus.

What holds the nucleus together?

The negatively charged electrons that surround the positively charged nucleus of an atom are held in place by the attractive electromagnetic force. Because the nucleus consists of positively charged protons and neutral neutrons, the repulsive electromagnetic force among the protons might be expected to cause them to fly apart. Because this does not happen, an even stronger attractive force must exist within the nucleus.

The Strong Nuclear Force

APPLYING PHYSICS

► **Forces** A positron is a positively charged electron. The electromagnetic attraction of an electron and a positron is 4.2×10^{42} times stronger than their gravitational attraction. ◄

The **strong nuclear force,** also called the strong force, acts between protons and neutrons that are close together, as they are in a nucleus. This force is more than 100 times stronger than the electromagnetic force. The range of the strong force is short, only about the radius of a proton, 1.4×10^{-15} m. It is attractive and is of the same strength among protons and protons, protons and neutrons, and neutrons and neutrons.

Both neutrons and protons are called **nucleons.** The strong nuclear force holds the nucleons in the nucleus. If a nucleon were to be pulled out of a nucleus, work would have to be done to overcome the attractive force. Doing work adds energy to the system. Thus, the assembled nucleus has less energy than the separate protons and neutrons that make it up. The difference is the **binding energy** of the nucleus. Because the assembled nucleus has less energy, all binding energies are negative.

Binding Energy of the Nucleus

Einstein showed that mass and energy are equivalent, so the binding energy can be expressed in the form of an equivalent amount of mass, according to the following equation.

Energy Equivalent of Mass $E = mc^2$

The energy contained in matter is equal to the mass times the square of the speed of light in a vacuum.

Because energy has to be added to take a nucleus apart, the mass of the assembled nucleus is less than the sum of the masses of the nucleons that compose it.

For example, the helium nucleus, ${}^{4}_{2}He$, consists of two protons and two neutrons. The mass of a proton is 1.007276 u. The mass of a neutron is 1.008665 u. If the mass of the helium nucleus were equal to the sum of the masses of the two protons and the two neutrons, you would expect that the mass of the nucleus would be 4.031882 u. Careful measurement, however, shows that the mass of a helium nucleus is only 4.002603 u. The actual mass of the helium nucleus is less than the mass of its constituent parts by 0.029279 u. The difference between the sum of the masses of the individual nucleons and the actual mass is called the **mass defect.**

Mass spectrometers usually measure the masses of isotopes; that is, the nuclides with all their electrons. When calculating the mass defect of a nucleus, one must make sure that the mass of the electrons is accounted for properly. Thus, the mass of hydrogen (one proton and one electron) usually is given in mass-defect problems.

Masses normally are measured in atomic mass units. It will be useful, then, to determine the energy equivalent of 1 u (1.6605×10^{-27} kg). To determine the energy, you must multiply the mass by the square of the speed of light in a vacuum (2.9979×10^{8} m/s). This is expressed to five significant digits.

$$\begin{aligned} E &= mc^2 \\ &= (1.6605\times10^{-27}\ \text{kg})(2.9979\times10^{8}\ \text{m/s})^2 \\ &= 1.4924\times10^{-10}\ \text{kg}\cdot\text{m}^2/\text{s}^2 \\ &= 1.4924\times10^{-10}\ \text{J} \end{aligned}$$

The most convenient unit of energy to use is the electron volt.

$$\begin{aligned} E &= (1.4924\times10^{-10}\ \text{J})(1\ \text{eV}/1.60217\times10^{-19}\ \text{J}) \\ &= 9.3149\times10^{8}\ \text{eV} \\ &= 931.49\ \text{MeV} \end{aligned}$$

Hence, 1 u of mass is equivalent to 931.49 MeV of energy. **Figure 30-2** shows how the binding energy per nucleon depends on the mass of the nucleus. Heavier nuclei are bound more strongly than lighter nuclei. Except for a few nuclei, the binding energy per nucleon becomes more negative as the mass number, A, increases to a value of 56, which is that of iron, Fe. The most tightly bound nucleus is $^{56}_{26}\text{Fe}$; thus, nuclei become more stable as their mass numbers approach that of iron. Nuclei whose mass numbers are larger than that of iron are less strongly bound, and are therefore less stable.

A nuclear reaction will occur naturally if energy is released by the reaction; that is, if the nucleus is transformed into one closer to the lowpoint of the graph at $A = 56$. At lower mass numbers, below $^{56}_{26}\text{Fe}$, a nuclear reaction will occur naturally if it increases the atomic mass. In the Sun and other stars, hydrogen is converted into helium, carbon, and other heavier elements in a reaction that releases energy, causing the electromagnetic radiation that you experience as visible light.

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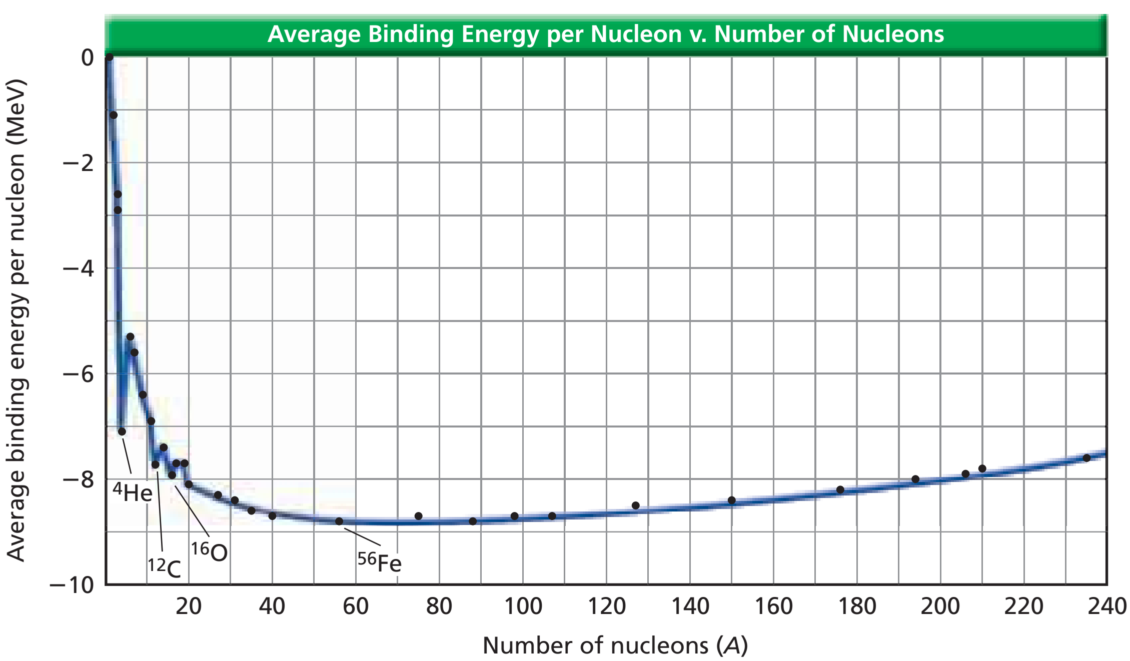
Personal Tutor For an online tutorial on joule and electron volt, visit physicspp.com.



■ **Figure 30-2** The binding energy per nucleon depends on the number of nucleons, *A*.

At mass numbers above 56, a nuclear reaction will occur naturally if it decreases the atomic mass. When uranium-238 decays to thorium-234, the resulting thorium nucleus is more stable than the uranium nucleus. Energy is released in the form of a radioactive particle with mass and kinetic energy. Thorium will not spontaneously transform into uranium because energy would have to be added to the nucleus. The heaviest nuclei in the periodic table are created in this way, by slamming together smaller nuclei in particle accelerators. In general, such heavy elements can exist only for fractions of a second before the nuclei decay into smaller, more stable nuclei. In contrast, when small nuclei gain nucleons, the binding energy of the larger nucleus is more negative, and thus, more stable than the sum of the binding energies of the smaller nuclei.

In the next section, calculations of binding energy will be used to understand nuclear reactions. The binding energy explains the energy released when small nuclei fuse, as in stars, and large nuclei split, as in the decay of radioactive elements.

EXAMPLE Problem 1

Mass Defect and Nuclear Binding Energy **Find the mass defect and binding energy of tritium, ${}^{3}_{1}H$. The mass of the tritium isotope is 3.016049 u, the mass of a hydrogen atom is 1.007825 u, and the mass of a neutron is 1.008665 u.**

1 Analyze the Problem

Known:

mass of 1 hydrogen atom = 1.007825 u
mass of 1 neutron = 1.008665 u
mass of tritium = 3.016049 u
binding energy of 1 u = 931.49 MeV

Unknown:

total mass of nucleons and electron = ?
mass defect = ?
binding energy of tritium = ?

2 Solve for the Unknown

Add the masses of the hydrogen atom (one proton and one electron) and two neutrons.

mass of 1 hydrogen atom:	1.007825 u
plus mass of 2 neutrons:	+ 2.017330 u
total mass of nucleons:	3.025155 u

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Operations with Significant Digits
pages 835–836

The mass defect is equal to the actual mass of tritium less the mass of the sum of its parts.

mass of tritium:	3.016049 u
less mass of nucleons:	− 3.025155 u
mass defect:	− 0.009106 u

The binding energy is the energy equivalent of the mass defect.

E = (mass defect in u)(binding energy of 1 u)

$E = (-0.009106\ \text{u})(931.49\ \text{MeV/u})$ Substitute mass defect = −0.009106 u, binding energy per u = 931.49 MeV

$= -8.4821\ \text{MeV}$

3 Evaluate the Answer

- **Are the units correct?** Mass is measured in u, and energy is measured in MeV.
- **Does the sign make sense?** Binding energy should be negative.
- **Is the magnitude realistic?** According to Figure 30-2, binding energies per nucleon in this range are between −2 MeV and −3 MeV, so the answer for three nucleons is reasonable.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

Use these values to solve the following problems:
mass of hydrogen = 1.007825 u, mass of neutron = 1.008665 u,
1 u = 931.49 MeV.

5. The carbon isotope ${}^{12}_{6}\mathrm{C}$ has a mass of 12.0000 u.

a. Calculate its mass defect.

b. Calculate its binding energy in MeV.

6. The isotope of hydrogen that contains one proton and one neutron is called deuterium. The mass of the atom is 2.014102 u.

a. What is its mass defect?

b. What is the binding energy of deuterium in MeV?

7. A nitrogen isotope, ${}^{15}_{7}\mathrm{N}$, has seven protons and eight neutrons. It has a mass of 15.010109 u.

a. Calculate the mass defect of this nucleus.

b. Calculate the binding energy of the nucleus.

8. An oxygen isotope, ${}^{16}_{8}\mathrm{O}$, has a nuclear mass of 15.994915 u.

a. What is the mass defect of this isotope?

b. What is the binding energy of its nucleus?

In few areas of physics has basic knowledge led to applications as quickly as in the field of nuclear physics. The medical use of the radioactive element radium began within 20 years of its discovery. Proton accelerators were used for medical applications less than one year after being invented. In the case of nuclear fission (splitting nuclei), the military application was under development before the basic physics was even known. Peaceful applications followed in less than ten years.

30.1 Section Review

9. Nuclei Consider these two pairs of nuclei: ${}^{12}_{6}\mathrm{C}$ and ${}^{13}_{6}\mathrm{C}$ and ${}^{11}_{5}\mathrm{B}$ and ${}^{11}_{6}\mathrm{C}$. In which way are the two alike? In which way are they different?

10. Binding Energy When tritium, ${}^{3}_{1}\mathrm{H}$, decays, it emits a beta particle and becomes ${}^{3}_{2}\mathrm{He}$. Which nucleus would you expect to have a more negative binding energy?

11. Strong Nuclear Force The range of the strong nuclear force is so short that only nucleons that are adjacent to each other are affected by the force. Use this fact to explain why, in large nuclei, the repulsive electromagnetic force can overcome the strong attractive force and make the nucleus unstable.

12. Mass Defect Which of the two nuclei in problem 10 has the larger mass defect?

13. Mass Defect and Binding Energy The radioactive carbon isotope ${}^{14}_{6}\mathrm{C}$ has a mass of 14.003074 u.

a. What is the mass defect of this isotope?

b. What is the binding energy of its nucleus?

14. Critical Thinking In old stars, not only are helium and carbon produced by joining more tightly bound nuclei, but so are oxygen ($Z = 8$) and silicon ($Z = 14$). What is the atomic number of the heaviest nucleus that could be formed in this way? Explain.

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30.2 Nuclear Decay and Reactions

▶ **Objectives**

- **Describe** three forms of radioactive decay.
- **Solve** nuclear equations.
- **Calculate** the amount remaining and activity of radioactive material after a given time.
- **Define** nuclear fission and fusion.
- **Describe** the operation of a nuclear reactor.

▶ **Vocabulary**

radioactive
alpha decay
beta decay
gamma decay
nuclear reaction
half-life
activity
fission
chain reaction
fusion

In 1896, Henri Becquerel was working with compounds containing the element uranium. To his surprise, he found that photographic plates that had been covered to keep out light became fogged, or partially exposed, when these uranium compounds were anywhere near the plates. This fogging suggested that some kind of ray from the uranium had passed through the plate coverings. Several materials other than uranium or its compounds also were found to emit these penetrating rays. Materials that emit this kind of radiation are now said to be **radioactive.** Because particles are emitted from the material, it is said to decay. Nuclei decay from a less stable form to a more stable form. Radioactivity is a natural process.

Radioactive Decay

In 1899, Ernest Rutherford and his colleagues discovered that the element radon spontaneously splits into a lighter nucleus and a light helium nucleus. The same year, Rutherford also discovered that uranium compounds produce three different kinds of radiation. He separated the types of radiation according to their penetrating ability and named them α (alpha), β (beta), and γ (gamma) radiation. Alpha radiation can be stopped by a thick sheet of paper, while 6 mm of aluminum is needed to stop most beta particles. Several centimeters of lead are required to stop gamma rays.

Alpha decay An alpha particle is the nucleus of a helium atom, ${}^{4}_{2}\text{He}$. The emission of an α particle from a nucleus is a process called **alpha decay.** The mass number of an α particle, ${}^{4}_{2}\text{He}$, is 4, and the atomic number is 2. When a nucleus emits an α particle, the mass number, A, of the decaying nucleus is reduced by 4, and the atomic number of the nucleus, Z, is reduced by 2. The element changes, or transmutes, into a different element. For example, ${}^{238}_{92}\text{U}$ transmutes into ${}^{234}_{90}\text{Th}$ through alpha decay.

Beta decay Beta particles are electrons emitted by the nucleus. The nucleus contains no electrons, however, so where do these electrons come from? **Beta decay** occurs when a neutron is changed to a proton within the nucleus. In all reactions, charge must be conserved. That is, the charge before the reaction must equal the charge after the reaction. In beta decay, when a neutron, charge 0, changes to a proton, charge $+1$, an electron, charge -1, also appears. In beta decay, a nucleus with N neutrons and Z protons ends up as a nucleus of $N-1$ neutrons and $Z+1$ protons. Another particle, an antineutrino, also is emitted in beta decay.

Gamma decay A redistribution of the energy within the nucleus results in **gamma decay.** The γ ray is a high-energy photon. Neither the mass number nor the atomic number is changed in gamma decay. Gamma radiation often accompanies alpha and beta decay. The three types of radiation are summarized in **Table 30-1.**

Radioactive elements often go through a series of successive decays until they form a stable nucleus. For example, ${}^{238}_{92}\text{U}$ undergoes 14 separate decays before the stable lead isotope ${}^{206}_{82}\text{Pb}$ is produced.

Table 30-1		
The Three Types of Radiation		
Alpha Particle	**Beta Particle**	**Gamma Ray**
Charge +2	Charge −1	No charge
Least penetration	Middle energy	Highest penetration
Transmutes nucleus: $A \rightarrow A - 4$ $Z \rightarrow Z - 2$ $N \rightarrow N - 2$	Transmutes nucleus: $A \rightarrow A$ $Z \rightarrow Z + 1$ $N \rightarrow N - 1$	Changes only energy: $A \rightarrow A$ $Z \rightarrow Z$ $N \rightarrow N$

Nuclear Reactions and Equations

A **nuclear reaction** occurs whenever the energy or number of neutrons or protons in a nucleus changes. Just as in chemical reactions, some nuclear reactions occur with a release of energy, while others occur only when energy is added to a nucleus.

One form of nuclear reaction is the emission of particles by radioactive nuclei. The reaction releases excess energy in the form of the kinetic energy of the emitted particles. Two such reactions are shown in **Figure 30-3.**

Nuclear reactions can be described by words, diagrams, or equations. The symbols used for the nuclei in nuclear equations make the calculation of atomic number and mass number in nuclear reactions simpler. For example, the equation for the reaction in **Figure 30-3a** is as follows.

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

The total number of nuclear particles stays the same during the reaction, so the sum of the superscripts on each side must be equal: $238 = 234 + 4$. The total charge also is conserved, so the sum of the subscripts on each side must be equal: $92 = 90 + 2$.

In beta decay, an electron, ${}^{0}_{-1}\text{e}$, and an antineutrino, ${}^{0}_{0}\bar{\nu}$, are produced. (The symbol for the antineutrino is the Greek letter *nu* with a bar over it; the bar denotes a particle of antimatter.) The transmutation of a thorium atom by the emission of a β particle is shown in **Figure 30-3b.**

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\bar{\nu}$$

Note that the sum of the superscripts on the left-hand side of the equation equals the sum of the superscripts on the right-hand side. Equality also exists between the subscripts on the two sides of the equation.

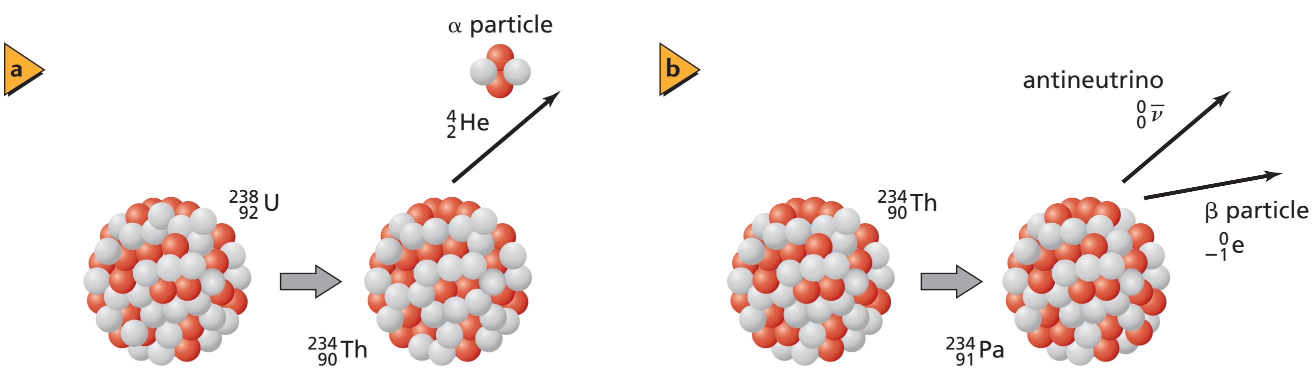

Figure 30-3 The emission of an alpha particle by uranium-238 results in the formation of thorium-234 **(a).** The emission of a beta particle by thorium-234 results in the formation of protactinium-234 **(b).**

Concepts In Motion

Interactive Figure To see an animation on alpha decay and beta decay, visit physicspp.com.

EXAMPLE Problem 2

Alpha and Beta Decay Write the nuclear equation for each radioactive process.

a. A radioactive radium isotope, $^{226}_{88}\text{Ra}$, emits an α particle and becomes the radon isotope $^{222}_{86}\text{Rn}$.

b. A radioactive lead isotope, $^{209}_{82}\text{Pb}$, decays into the bismuth isotope, $^{209}_{83}\text{Bi}$, by the emission of a β particle and an antineutrino.

1 Analyze the Problem

Known:

a. $^{226}_{88}\text{Ra} \rightarrow \alpha$ particle $+ \,^{222}_{86}\text{Rn}$

α particle $= \,^{4}_{2}\text{He}$

b. $^{209}_{82}\text{Pb} \rightarrow \,^{209}_{83}\text{Bi} + \beta$ particle + antineutrino

β particle $= \,^{0}_{-1}\text{e}$

antineutrino $= \,^{0}_{0}\bar{\nu}$

Unknown:

Is the decay possible?

Is the decay possible?

2 Solve for the Unknown

a. $^{226}_{88}\text{Ra} \rightarrow \,^{4}_{2}\text{He} + \,^{222}_{86}\text{Rn}$ — **Substitute $^{4}_{2}\text{He}$ for α particle**

b. $^{209}_{82}\text{Pb} \rightarrow \,^{209}_{83}\text{Bi} + \,^{0}_{-1}\text{e} + \,^{0}_{0}\bar{\nu}$ — **Substitute $^{0}_{-1}\text{e}$ for β particle and $^{0}_{0}\bar{\nu}$ for antineutrino**

3 Evaluate the Answer

- **Is the number of nucleons conserved?**
  a. 226 = 222 + 4, so mass number is conserved.
  b. 209 = 209 + 0 + 0, so mass number is conserved.
- **Is charge conserved?**
  a. 88 = 86 + 2, so charge is conserved.
  b. 82 = 83 − 1 + 0, so charge is conserved.

PRACTICE Problems

- Additional Problems, Appendix B
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15. Write the nuclear equation for the transmutation of a radioactive uranium isotope, $^{234}_{92}\text{U}$, into a thorium isotope, $^{230}_{90}\text{Th}$, by the emission of an α particle.

16. Write the nuclear equation for the transmutation of a radioactive thorium isotope, $^{230}_{90}\text{Th}$, into a radioactive radium isotope, $^{226}_{88}\text{Ra}$, by the emission of an α particle.

17. Write the nuclear equation for the transmutation of a radioactive radium isotope, $^{226}_{88}\text{Ra}$, into a radon isotope, $^{222}_{86}\text{Rn}$, by α decay.

18. A radioactive lead isotope, $^{214}_{82}\text{Pb}$, can change to a radioactive bismuth isotope, $^{214}_{83}\text{Bi}$, by the emission of a β particle and an antineutrino. Write the nuclear equation.

19. A radioactive carbon isotope, $^{14}_{6}\text{C}$, undergoes β decay to become the nitrogen isotope $^{14}_{7}\text{N}$. Write the nuclear equation.

In alpha and beta decay, one nucleus, shown on the left of the equation, decays to another nucleus and one or more radioactive particles, shown on the right of the equation. Another example of transmutation occurs when a particle collides with the nucleus, often resulting in the emission of other particles, as in $^{12}_{6}\text{C} + \,^{1}_{1}\text{H} \rightarrow \,^{13}_{7}\text{N}$. Such reactions are illustrated in the next Example Problem, and in the discussion of fission later in the section.

EXAMPLE Problem 3

Solve Nuclear Equations When nitrogen gas is bombarded with α particles, high-energy protons are emitted. What new isotope is created?

1 Analyze the Problem

Known:	Unknown:
nitrogen = $^{14}_{7}N$, α = $^{4}_{2}He$	What isotope belongs on the
proton = $^{1}_{1}H$	right side of the equation?

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Solving Equations
page 844

2 Solve for the Unknown

Write the equation for the nuclear reaction.

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{1}_{1}H + ^{A}_{Z}X$$

Solve for Z and for A.

$$Z = 2 + 7 - 1 = 8 \qquad A = 4 + 14 - 1 = 17$$

Use the periodic table on page 916. The element with $Z = 8$ is oxygen.
The isotope must be $^{17}_{8}O$.

3 Evaluate the Answer

- **Does the equation balance?** The number of nucleons is conserved: $4 + 14 = 1 + 17$. The charge is conserved: $2 + 7 = 1 + 8$.

PRACTICE Problems

• Additional Problems, Appendix B
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20. Use the periodic table on page 916 to complete the following.

a. $^{14}_{6}C \rightarrow ? + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$

b. $^{55}_{24}Cr \rightarrow ? + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$

21. Write the nuclear equation for the transmutation of a seaborgium isotope, $^{263}_{106}Sg$, into a rutherfordium isotope, $^{259}_{104}Rf$, by the emission of an alpha particle.

22. A proton collides with the nitrogen isotope $^{15}_{7}N$, forming a new isotope and an alpha particle. What is the isotope? Write the nuclear equation.

23. Write the nuclear equations for the beta decay of the following isotopes.

a. $^{210}_{82}Pb$ **b.** $^{210}_{83}Bi$ **c.** $^{234}_{90}Th$ **d.** $^{239}_{93}Np$

Half-Life

The time required for half of the atoms in any given quantity of a radioactive isotope to decay is the **half-life** of that element. After each half-life, the number of undecayed nuclei is cut in half, as shown in **Figure 30-4.** Each particular isotope has its own half-life.

For example, the half-life of the radium isotope $^{226}_{88}Ra$ is 1600 years. That is, in 1600 years, half of a given quantity of $^{226}_{88}Ra$ decays into another element, radon. In a second 1600 years, half of the remaining sample of radium will have decayed. In other words, one-fourth of the original amount still will remain after 3200 years. In contrast, a sample of polonium-210 will decay to one-fourth the original amount in just 276 days.

■ **Figure 30-4** Radioactive nuclei decay to more stable forms.

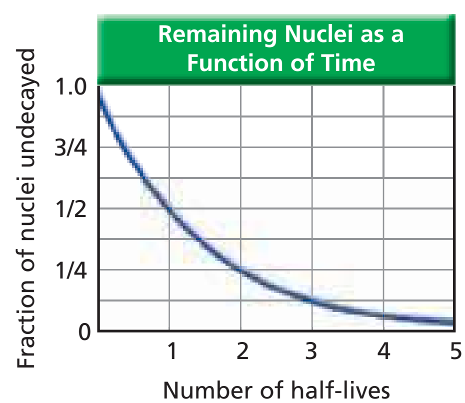


Table 30-2			
Half-Lives of Selected Isotopes			
Element	**Isotope**	**Half-Life**	**Radiation Produced**
Hydrogen	${}^{3}_{1}H$	12.3 years	β
Carbon	${}^{14}_{6}C$	5730 years	β
Cobalt	${}^{60}_{27}Co$	30 years	β, γ
Iodine	${}^{131}_{53}I$	8.07 days	β, γ
Lead	${}^{212}_{82}Pb$	10.6 hours	β
Polonium	${}^{194}_{84}Po$	0.7 seconds	α
Polonium	${}^{210}_{84}Po$	138 days	α, γ
Uranium	${}^{235}_{92}U$	7.1×10^{8} years	α, γ
Uranium	${}^{238}_{92}U$	4.51×10^{9} years	α, γ
Plutonium	${}^{236}_{94}Pu$	2.85 years	α
Plutonium	${}^{242}_{94}Pu$	3.79×10^{5} years	α, γ

The half-lives of selected isotopes are shown in **Table 30-2.** If you know the original amount of a radioactive substance and its half-life, you can calculate the amount remaining after a given number of half-lives.

Half-Life $\quad \text{remaining} = \text{original}\left(\frac{1}{2}\right)^{t}$

The amount of a radioactive isotope remaining in a sample equals the original amount times $\frac{1}{2}$ to the t, where t is the number of half-lives that have passed.

Half-lives of radioactive isotopes are used to date objects. The age of a sample of organic material can be found by measuring the amount of carbon-14 remaining. The age of Earth was calculated based on the decay of uranium into lead.

Physics Online

Personal Tutor For an online tutorial on half-life, visit physicspp.com.

The decay rate, or number of decays per second, of a radioactive substance is called its **activity.** Activity is proportional to the number of radioactive atoms present. Therefore, the activity of a particular sample also is reduced by one-half in one half-life. Consider ${}^{131}_{53}I$, with a half-life of 8.07 days. If the activity of a certain sample of iodine-131 is 8×10^{5} decays/s, then 8.07 days later, its activity will be 4×10^{5} decays/s. After another 8.07 days, its activity will be 2×10^{5} decays/s. The activity of a sample also is related to its half-life. The shorter the half-life, the higher the activity. Consequently, if you know the activity of a substance and the amount of that substance, you can determine its half-life. The SI unit for decays per second is a Becquerel (Bq).

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

Refer to Figure 30-4 and Table 30-2 to solve the following problems.

24. A sample of 1.0 g of tritium, ${}^{3}_{1}H$, is produced. What will be the mass of the tritium remaining after 24.6 years?

25. The isotope ${}^{238}_{93}Np$ has a half-life of 2.0 days. If 4.0 g of neptunium is produced on Monday, what will be the mass of neptunium remaining on Tuesday of the next week?

26. A sample of polonium-210 is purchased for a physics class on September 1. Its activity is 2×10^{6} Bq. The sample is used in an experiment on June 1. What activity can be expected?

27. Tritium, ${}^{3}_{1}H$, once was used in some watches to produce a fluorescent glow so that the watches could be read in the dark. If the brightness of the glow is proportional to the activity of the tritium, what would be the brightness of such a watch, in comparison to its original brightness, when the watch is six years old?

Artificial Radioactivity

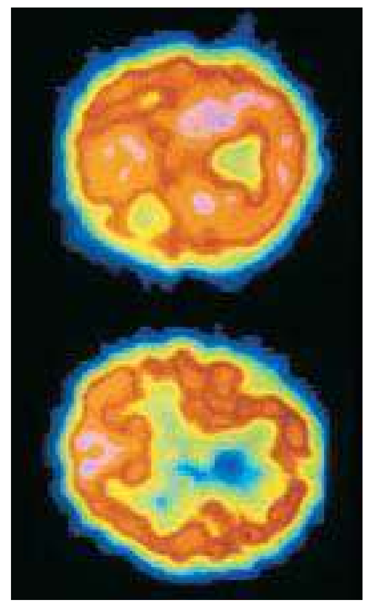
Radioactive isotopes can be formed from stable isotopes by bombardment with α particles, protons, neutrons, electrons, or gamma rays. The resulting unstable nuclei emit radiation until they are converted into stable isotopes. The radioactive nuclei may emit alpha, beta, and gamma radiation, as well as neutrinos, antineutrinos, and positrons. (A positron is a positively charged electron, ${}^{0}_{+1}e$.)

Artificially produced radioactive isotopes often are used in medicine and medical research. In many medical applications, patients are given radioactive isotopes of elements that are absorbed by specific parts of the body. A physician uses a radiation counter to monitor the activity in the region in question. A radioactive isotope also can be attached to a molecule that will be absorbed in the area of interest, as is done in positron emission tomography, better known as the PET scan. A PET scan of a brain is shown in **Figure 30-5.**

Radiation often is used to destroy cancer cells. These cells are more sensitive to the damaging effects of radiation because they divide more often than normal cells. Gamma rays from the isotope ${}^{60}_{27}Co$ are used to treat cancer patients. Radioactive iodine is injected to target thyroid cancer. In a third method, particles produced in a particle accelerator are beamed into tissue in such a way that they decay in the cancerous tissue and destroy the cells.

APPLYING PHYSICS

▶ **Radiation Treatment** Gamma rays destroy both cancerous cells and healthy cells; thus, the beams of radiation must be directed only at cancerous cells. ◀



■ **Figure 30-5** For a PET scan, physicians inject a solution in which a radioactive isotope, such as ${}^{18}_{9}F$, is attached to a molecule that will concentrate in the target tissues. When the ${}^{18}_{9}F$ decays, it produces positrons, which annihilate nearby electrons, producing gamma rays. The PET scanner detects the gamma rays. A computer then makes a three-dimensional map of the isotope distribution. Here, a normal brain (top), and the brain of a person suffering from dementia (bottom) are contrasted.

Nuclear Fission

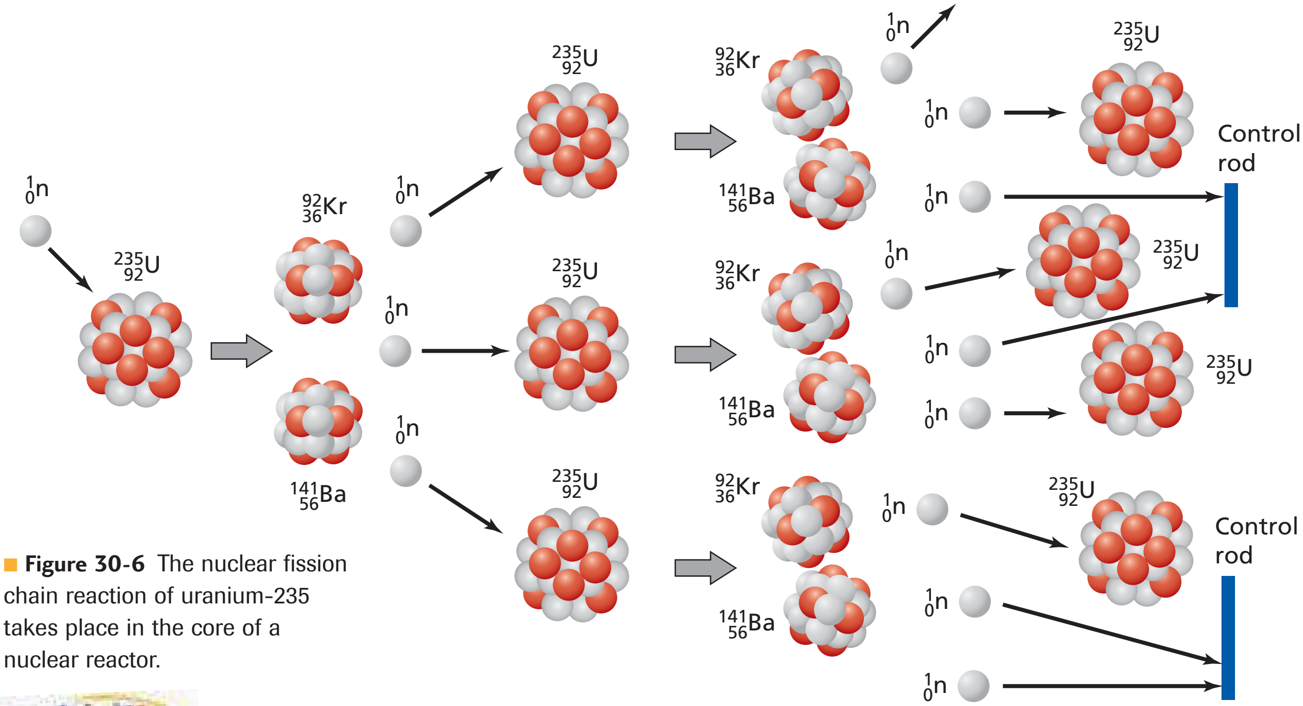
The possibility of obtaining useful forms of energy from nuclear reactions was discussed in the 1930s. The most promising results came from bombarding substances with neutrons. In Italy, in 1934, Enrico Fermi and Emilio Segré produced many new radioactive isotopes by bombarding uranium with neutrons. German chemists Otto Hahn and Fritz Strassmann showed in 1939 that the resulting atoms acted chemically like barium. One week later, Lise Meitner and Otto Frisch proposed that the neutrons had caused a division of the uranium into two smaller nuclei, resulting in a large release of energy. Such a division of a nucleus into two or more fragments is called **fission.** The possibility that fission could be not only a source of energy, but also an explosive weapon, was immediately realized by many scientists.

Fission occurs when a nucleus is divided into two or more fragments, releasing neutrons and energy. The uranium isotope, ${}^{235}_{92}U$, undergoes fission when it is bombarded with neutrons. The elements barium and krypton are typical results of fission. The reaction is illustrated with the following equation.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3\,{}^{1}_{0}n + 200\text{ MeV} $$

The energy released by each fission can be found by calculating the masses of the atoms on each side of the equation. In the uranium-235 reaction, the total mass on the right side of the equation is 0.215 u smaller than that on the left. The energy equivalent of this mass is 3.21×10^{-11} J, or 2.00×10^{2} MeV. This energy appears as the kinetic energy of the products of the fission.

CNRI/Photo Researchers



■ **Figure 30-6** The nuclear fission chain reaction of uranium-235 takes place in the core of a nuclear reactor.

Concepts In Motion

Interactive Figure To see an animation on chain reaction, visit **physicspp.com**.

The neutrons needed to cause the fission of additional $^{235}_{92}$U nuclei can be the neutrons produced once the fission process is started. If one or more of the neutrons cause a fission, that fission releases three more neutrons, each of which can cause more fission. This continual process of repeated fission reactions caused by the release of neutrons from previous fission reactions is called a **chain reaction.** The process is illustrated in **Figure 30-6.**

Nuclear Reactors

To create a controlled chain reaction and make use of the energy produced, the neutrons need to interact with the fissionable uranium at the right rate. Most of the neutrons released by the fission of $^{235}_{92}$U atoms are moving at high speeds. These are called fast neutrons. In addition, naturally occurring uranium consists of less than one percent $^{235}_{92}$U and more than 99 percent $^{238}_{92}$U. When a $^{238}_{92}$U nucleus absorbs a fast neutron, it does not undergo fission, but becomes a new isotope, $^{239}_{92}$U. The absorption of neutrons by $^{238}_{92}$U keeps most of the neutrons from reaching the fissionable $^{235}_{92}$U atoms. Thus, most neutrons released by the fission of $^{235}_{92}$U are unable to cause the fission of another $^{235}_{92}$U atom.

To control the reaction, the uranium is broken up into small pieces and placed in a *moderator,* a material that can slow down, or moderate, the fast neutrons. When a neutron collides with a light atom it transfers momentum and energy to the atom. In this way, the neutron loses energy. The moderator thus slows many fast neutrons to speeds at which they can be absorbed more easily by $^{235}_{92}$U than by $^{238}_{92}$U. The larger number of slow neutrons greatly increases the probability that a neutron released by the fission of a $^{235}_{92}$U nucleus will cause another $^{235}_{92}$U nucleus to fission. If there is enough $^{235}_{92}$U in the sample, a chain reaction can occur. To increase the amount of fissionable uranium, the uranium may be enriched by adding more $^{235}_{92}$U. Both types of uranium are used in nuclear reactors.

■ **Figure 30-7** The glow is due to the Cerenkov effect, which occurs when high speed particles entering the water exceed the speed of light in water. The electrons emit photons, which cause the water to glow when fuel rods are placed in it. This glow is not the result of radioactivity.

Science VU/Visuals Unlimited

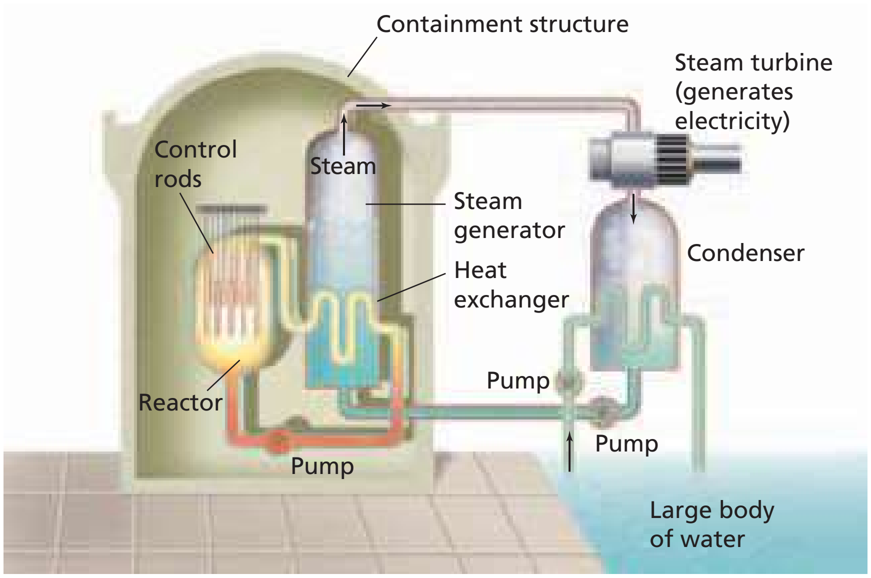


Figure 30-8 In a nuclear power plant, the thermal energy released in nuclear reactions is converted to electric energy.

The type of nuclear reactor used in the United States, the pressurized water reactor, contains about 200 metric tons of uranium sealed in hundreds of metal rods. The rods are immersed in water, as shown in **Figure 30-7.** Water not only is the moderator, but also transfers thermal energy away from the fission of uranium. Rods of cadmium metal are placed between the uranium rods. Cadmium absorbs neutrons easily and also acts as a moderator. The cadmium rods are moved in and out of the reactor to control the rate of the chain reaction. Thus, the rods are called control rods. When the control rods are inserted completely into the reactor, they absorb enough of the neutrons released by the fission reactions to prevent any further chain reaction. As the control rods are removed from the reactor, the rate of energy release increases, with more free neutrons available to continue the chain reaction.

Energy released by the fission heats the water surrounding the uranium rods. The water itself doesn't boil because it is under high pressure, which increases its boiling point. As shown in **Figure 30-8,** this water is pumped to a heat exchanger, where it causes other water to boil, producing steam that turns turbines. The turbines are connected to generators that produce electrical energy.

Fission of ${}^{235}_{92}\mathrm{U}$ nuclei produces Kr, Ba, and other atoms in the fuel rods. Most of these atoms are radioactive. About once a year, some of the uranium fuel rods must be replaced. The old rods no longer can be used in the reactor, but they are still extremely radioactive and must be stored in a location that can be secured. Methods of permanently storing these radioactive waste products currently are being developed.

Nuclear Fusion

In nuclear **fusion,** nuclei with small masses combine to form a nucleus with a larger mass, as shown in **Figure 30-9** on the next page. In the process, energy is released. You learned earlier in this chapter that the larger nucleus is more tightly bound, so its mass is less than the sum of the masses of the smaller nuclei. This loss of mass corresponds to a release of energy.

MINI LAB

Modeling Radioactive Decay

You will need 50 pennies to represent 50 atoms of a radioactive isotope. In this simulation, heads indicates that a nucleus has not decayed.

1. Record 50 heads as the starting point.

2. Shake all the pennies in a large cup and pour them out. Remove all the tails and set them aside. Count and record the number of heads.

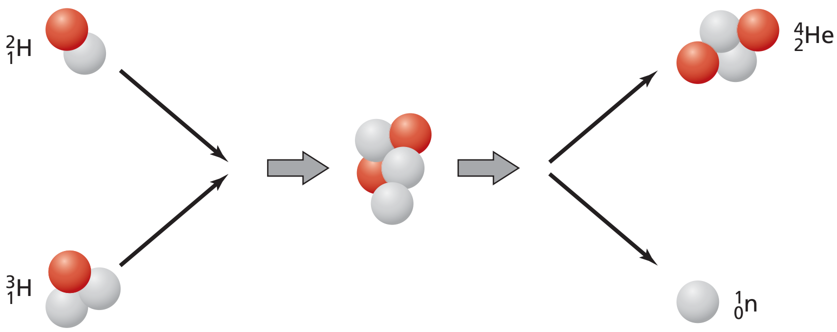
3. Repeat step 2 with the pennies that were heads in the last throw. Each throw simulates one half-life.

Analyze and Conclude

4. Graph the number of pennies as a function of the number of half-lives.

5. Collect the results from other students and use the totals to make a new graph.

6. Compare this graph with the individual ones. Which more closely matches the theoretical graph in Figure 30-4?



■ **Figure 30-9** The fusion of deuterium and tritium produces helium. Protons are red and neutrons are gray in the figure.

An example of fusion is the process that occurs in the Sun. Four hydrogen nuclei (protons) fuse in several steps to form one helium nucleus. The mass of the four protons is greater than the mass of the helium nucleus that is produced. The energy equivalent of this mass difference appears as the kinetic energy of the resultant particles. The energy released by the fusion that produces one helium-4 nucleus is 25 MeV. In comparison, the energy released when one dynamite molecule reacts chemically is about 20 eV, about 1 million times smaller.

There are several processes by which fusion occurs in the Sun. The most important process is the proton-proton chain.

$$^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + {}^{\ 0}_{+1}\text{e} + {}^0_0\nu$$
$$^1_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$$
$$^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2{}^1_1\text{H}$$

The first two reactions must occur twice to produce the two $^3_2$He particles needed for the final reaction. The net result (subtracting out the two protons produced in the final step) is that four protons produce one $^4_2$He, two positrons, and two neutrinos.

The repulsive force between the charged nuclei requires the fusing nuclei to have high energies. Thus, fusion reactions take place only when the nuclei have large amounts of thermal energy. The proton-proton chain requires a temperature of about 2×10^7 K, such as that found in the center of the Sun. Fusion reactions also occur in a hydrogen, or thermonuclear, bomb. In this device, the high temperature necessary to produce the fusion reaction is produced by exploding a uranium fission, or atomic, bomb.

30.2 Section Review

28. Beta Decay How can an electron be expelled from a nucleus in beta decay if the nucleus has no electrons?

29. Nuclear Reactions The polonium isotope $^{210}_{84}$Po undergoes alpha decay. Write the equation for the reaction.

30. Half-Life Use Figure 30-4 and Table 30-2 to estimate in how many days a sample of $^{131}_{53}$I would have three-eighths its original activity.

31. Nuclear Reactor Lead often is used as a radiation shield. Why is it not a good choice for a moderator in a nuclear reactor?

32. Fusion One fusion reaction involves two deuterium nuclei, $^2_1$H. A deuterium molecule contains two deuterium atoms. Why doesn't this molecule undergo fusion?

33. Energy Calculate the energy released in the first fusion reaction in the Sun, $^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + {}^{\ 0}_{+1}\text{e} + {}^0_0\nu$.

34. Critical Thinking Alpha emitters are used in smoke detectors. An emitter is mounted on one plate of a capacitor, and the α particles strike the other plate. As a result, there is a potential difference across the plates. Explain and predict which plate has the more positive potential.

Physics Online physicspp.com/self_check_quiz

30.3 The Building Blocks of Matter

The first physicists who studied the nucleus with high speed particles had to make do with α particles from radioactive sources. Other experimenters used cosmic rays, produced by not-yet-understood processes in stars and galaxies. In the early 1930s, the first laboratory devices that could accelerate protons and α particles to energies high enough to penetrate the nucleus were developed. Two devices, the linear accelerator and the synchrotron, are regularly used today.

▶ **Objectives**

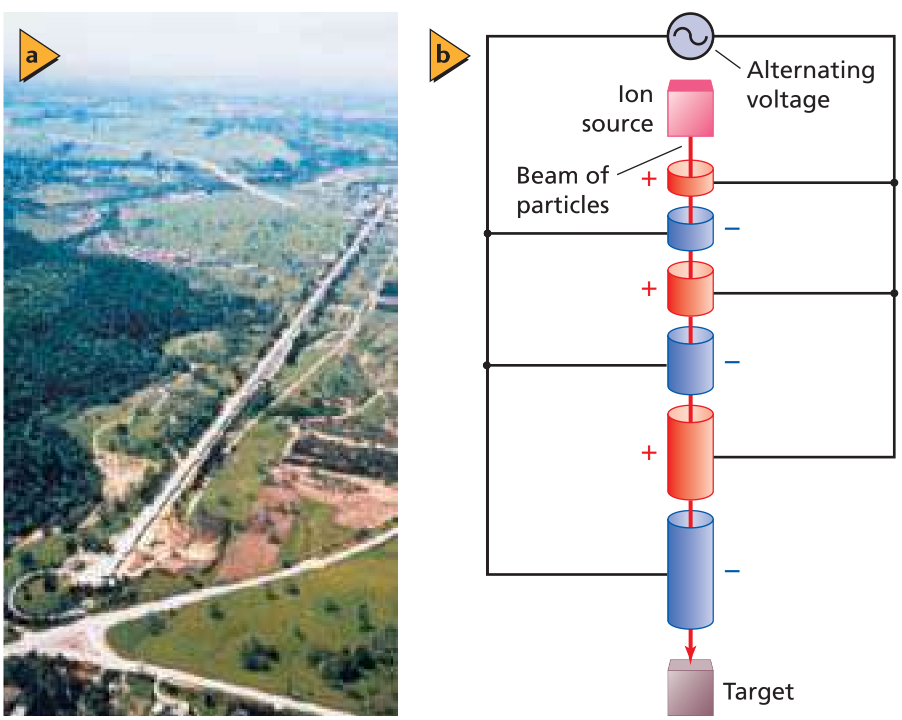
- **Describe** the operation of particle accelerators and particle detectors.
- **Describe** the Standard Model of matter and explain the role of force carriers.

▶ **Vocabulary**

quarks
leptons
Standard Model
force carriers
pair production
weak nuclear force

Linear Accelerators

A linear accelerator can be used to accelerate protons or electrons. It consists of a series of hollow tubes within a long, evacuated chamber. The tubes are connected to a source of high-frequency alternating voltage, as illustrated in **Figure 30-10.** Protons are produced in an ion source similar to that described in Chapter 26. When the first tube has a negative potential, protons are accelerated into it. There is no electric field within the tube, so the protons move at a constant velocity. The length of the tube and the frequency of the voltage are adjusted so that when the protons have reached the far end of the tube, the potential of the second tube is negative in relation to that of the first. The resulting electric field in the gap between the tubes accelerates the protons into the second tube. This process continues, with the protons receiving an acceleration between each pair of tubes. The energy of the protons is increased by 10^5 eV with each acceleration. The protons ride along the crest of an electric field wave, much as a surfboard moves on the ocean. At the end of the accelerator, the protons can have energies of many millions or billions of electron volts. A similar method is used to accelerate electrons. Note that one can accelerate only charged particles.

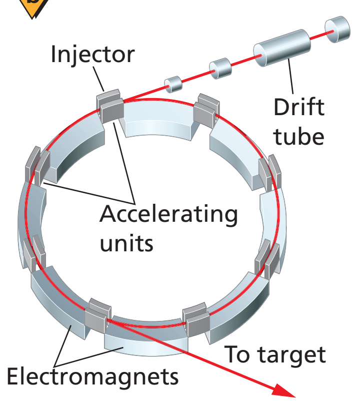


■ **Figure 30-10** The linear accelerator at Stanford University is 3.3 km long and accelerates electrons to energies of 50 GeV **(a).** Protons in a linear accelerator are accelerated by changing the charge on the tubes as the protons move **(b).** (Not to scale)

Interactive Figure To see an animation on a linear accelerator, visit physicspp.com.

Stanford Linear Accelerator Center/Photo Researchers a

b



■ **Figure 30-11** Fermi Laboratory's synchrotron has a diameter of 2 km **(a).** The synchrotron is a circular accelerator. Magnets are used to control the path and acceleration of the particles **(b).**

The Synchrotron

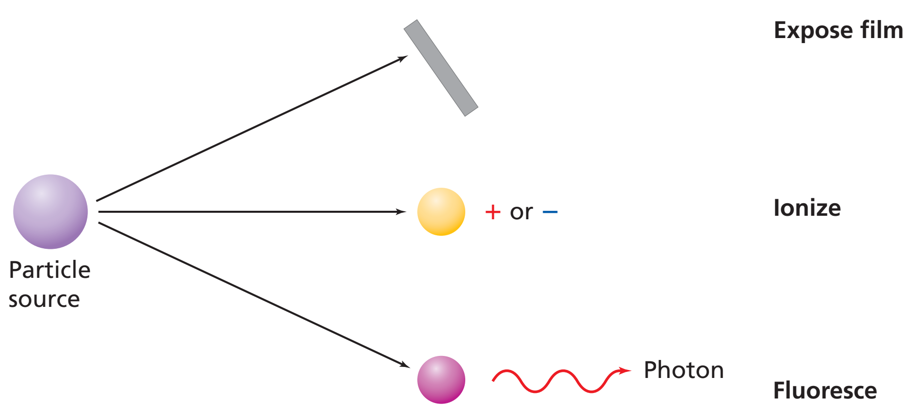
An accelerator may be made smaller by using a magnetic field to bend the path of the particles into a circle. In a synchrotron, the bending magnets are separated by accelerating regions, as shown in **Figure 30-11b.** In the straight regions, high-frequency alternating voltage accelerates the particles. The strength of the magnetic field and the length of the path are chosen so that the particles reach the location of the alternating electric field precisely when the field's polarity will accelerate them. One of the largest synchrotrons in operation is at the Fermi National Accelerator Laboratory near Chicago, shown in **Figure 30-11a.** Protons there reach energies of 1 TeV (10^{12} eV). A proton beam and an antiproton beam travel the circle in opposite directions. (An antiproton is the antimatter pair to a proton; it has the same mass and opposite charge.) The beams collide in several interaction regions and the results are studied.

Particle Detectors

Once particles are produced, the results of the collision need to be detected. In other words, they need to interact with matter in such a way that we can sense them with our relatively limited human senses. Your hand will stop an α particle, yet you will have no idea that the particle struck you. And as you read this sentence, billions of solar neutrinos pass through your body without so much as a twitch from you. Over the past century, scientists have devised tools to detect and distinguish the products of nuclear reactions.

In the last section, you learned that uranium samples fogged photographic plates. When α particles, β particles, or gamma rays strike photographic film, the film becomes fogged, or exposed. Thus, photographic film can be used to detect radiation. Many other devices are used to detect charged particles and gamma rays. Most of these devices make use of the fact that a collision with a high-speed particle will remove electrons from atoms. That is, the high-speed particles ionize the matter that they bombard. In addition, some substances fluoresce, or emit photons, when they are exposed to certain types of radiation. Thus, fluorescent substances also can be used to detect radiation. These three means of detecting radiation are illustrated in **Figure 30-12.**

■ **Figure 30-12** Particles can be detected when they interact with matter, exposing film, charging the matter, or causing the matter to emit a photon.



courtesy of Fermilab

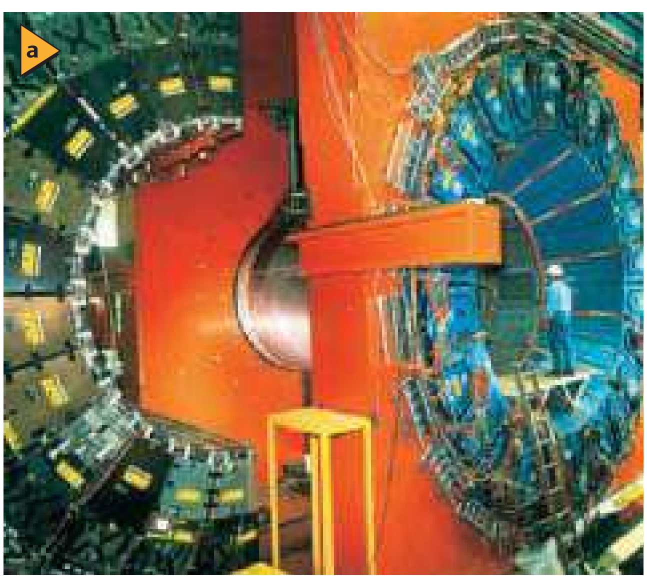
Geiger counter A Geiger-Mueller tube contains a copper cylinder with a negative charge. Down the center of this cylinder runs a rigid wire with a positive charge. The voltage across the wire and cylinder is kept just below the point at which a spontaneous discharge, or spark, occurs. When a charged particle or gamma ray enters the tube, it ionizes a gas atom between the copper cylinder and the wire. The positive ion that is produced is accelerated toward the copper cylinder by the potential difference, and the electron is accelerated toward the positive wire. As these charged particles move toward the electrodes, they create an avalanche of charged particles, and a pulse of current goes through the tube.

Condensation trails A device once used to detect particles was the Wilson cloud chamber. The chamber contained an area supersaturated with water vapor or ethanol vapor. When charged particles traveled through the chamber, leaving a trail of ions in their paths, vapor condensed into small droplets on the ions. In this way, visible trails of droplets, or fog, were formed. In a similar detector still used today, the bubble chamber, charged particles pass through a liquid held just above the boiling point. In this case, the trails of ions cause small vapor bubbles to form, marking the particles' trajectories, as shown in **Figure 30-13.**

Recent technology has produced detection chambers called wire chambers that are like giant Geiger-Mueller tubes. Huge plates are separated by a small gap filled with a low-pressure gas. A discharge is produced in the path of a particle passing through the chamber. A computer locates the discharge and records its position for later analysis.

Neutral particles do not leave trails because they do not produce discharges. The laws of conservation of energy and momentum in collisions can be used to tell if any neutral particles were produced. Other detectors measure the energy of the particles. The entire array of detectors used in high-energy accelerator experiments, such as the Collider Detector at Fermilab (CDF), can be up to three stories high, as shown in **Figure 30-14a.** The CDF is designed to monitor a quarter-million particle collisions each second, as though the detector functioned as a 5000-ton camera, creating a computer picture of the collision events, as shown in **Figure 30-14b.**

Figure 30-13 This false-color bubble chamber photograph shows the tracks of charged particles.



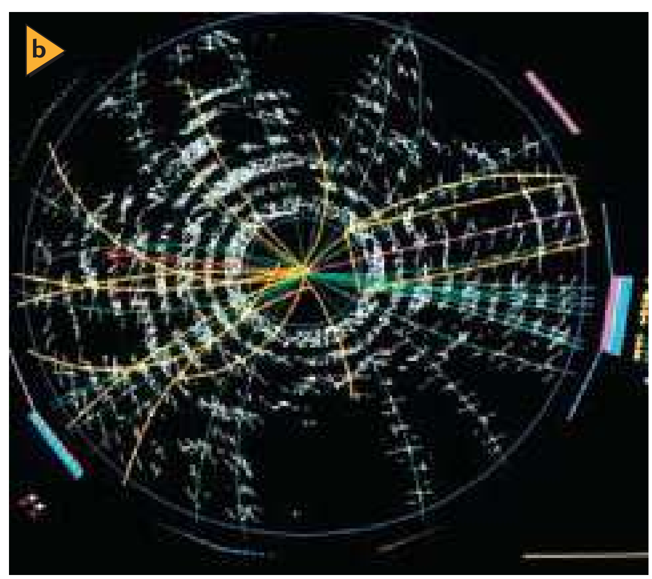
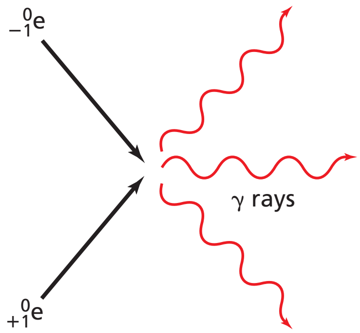
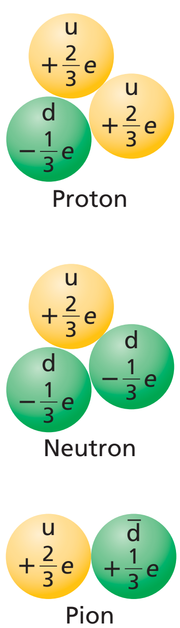


Figure 30-14 The Collider Detector at Fermilab (CDF) records the tracks from billions of collisions **(a).** A CDF computer image of a top quark event is shown **(b).**



■ **Figure 30-15** The collision of a positron and an electron results in gamma ray production.

■ **Figure 30-16** Even though quarks have fractional charges, all the particles they make have whole-number charges.



Antimatter

In the late 1920s, Paul Dirac pradicted the existence of an antiparticle associated with each kind of particle. The positive electron, called a positron, is an example of an antiparticle, a particle of antimatter. The electron and positron have the same mass and charge magnitude; however, the signs of their charges are opposite. When a positron and an electron collide, the two can annihilate each other, resulting in energy in the form of gamma rays, as shown in **Figure 30-15.** The positron was not discovered until 1932.

Particles

The model of the atom in 1930 was fairly simple: protons and neutrons surrounded by electrons. More detailed studies of radioactive decay disturbed this simple picture. While the α particles and gamma rays emitted by radioactive nuclei have single energies that depend on the decaying nucleus, β particles are emitted with a wide range of energies. One might expect the energy of the β particles to be equal to the difference between the energy of the nucleus before decay and the energy of the nucleus produced by the decay. In fact, the wide range of energies of electrons emitted during beta decay suggested to Niels Bohr that another particle might be involved in nuclear reactions that carries away energy. Wolfgang Pauli in 1931 and Enrico Fermi in 1934 suggested that an unseen neutral particle was emitted with the β particle. Named the neutrino ("little neutral one" in Italian) by Fermi, the particle, which is actually an antineutrino, was not directly observed until 1956.

Other studies discovered more particles. The muon, which seemed to be a heavy electron, was discovered in 1937. In 1935, a remarkable hypothesis by Japanese physicist Hideki Yukawa spurred much research in the years to follow. Yukawa hypothesized the existence of a new particle that could carry the nuclear force through space, just as the photon carries the electromagnetic force. In 1947 a possible particle, the pion, was dicovered. While it was not the carrier of the strong force, it was a new type of matter.

Experiments with particle accelerators resulted in the identification of more and more particles, some with intermediate masses, others much more massive than the proton. They had positive and negative charges, or none at all. Some lifetimes were 10^{-23} s, while others had no detectable decays. At one point Enrico Fermi, asked to identify a particle track, replied "If I could remember the names of all these particles, I'd be a botanist!"

The Standard Model

By the late 1960s it became clear that neither protons, nor neutrons, nor pions are elementary particles. They are made up of a family of particles called **quarks,** as shown in **Figure 30-16.** Electrons and neutrinos belong to a different family, called **leptons.** Physicists now believe that there are three families of elementary particles: quarks, leptons, and **force carriers,** also called gauge bosons. This model of the building blocks of matter is called the **Standard Model.** Particles such as protons and neutrons, made of three quarks, are called baryons. A pair made of a

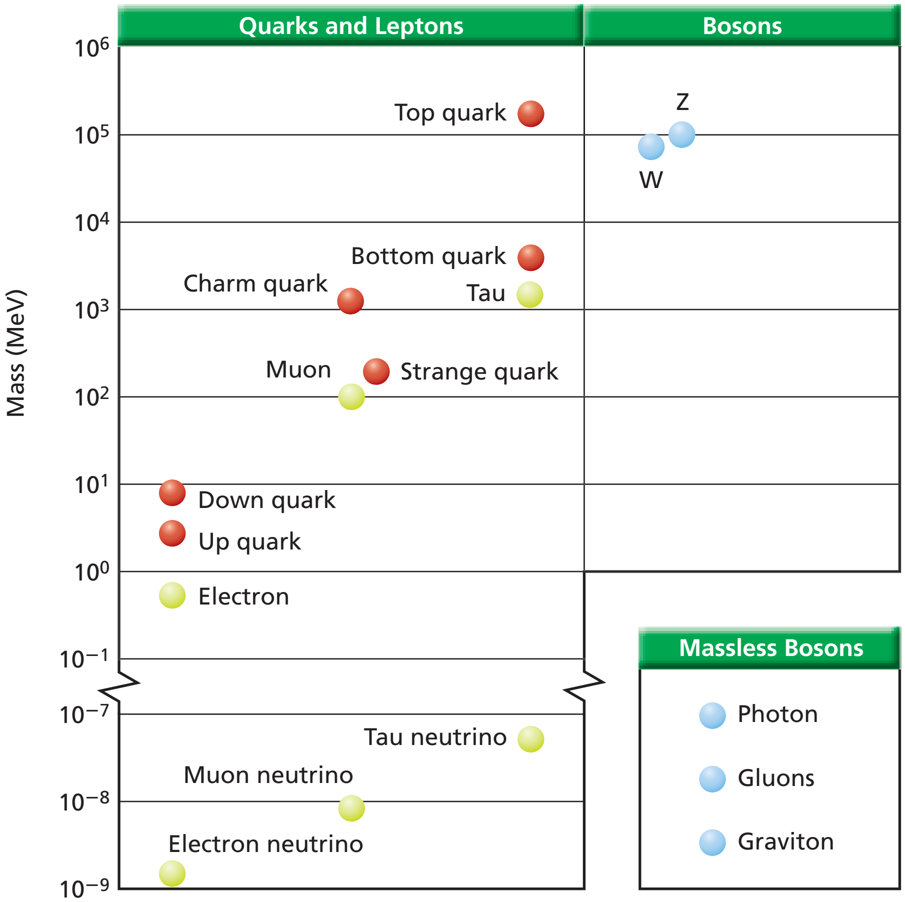


Figure 30-17 The known quarks and leptons are divided into three families. The everyday world is made from particles in the left-hand family (u, d, e). Particles in the middle group (c, s, μ) are found in cosmic rays and are routinely produced in particle accelerators. Particles in the right-hand family (b, t, τ) are believed to have existed briefly during the earliest moments of the Big Bang and are created in high-energy collisions. The gauge bosons carry the weak, electromagnetic, strong, and gravitational forces. Masses are stated as energy equivalents, given by Einstein's formula $E = mc^2$.

quark and an antiquark, like the pion, is called a meson. A new type of particle, made of four quarks and one antiquark, is called a pentaquark and might have been observed recently. There are six quarks and six leptons. Quarks and leptons form matter, while force carriers are particles that transmit forces. For example, photons carry the electromagnetic force. The eight gluons carry the strong nuclear force that binds quarks in baryons and mesons. Three weak gauge bosons are involved in β decay. The graviton is the name given to the yet-undetected carrier of gravitational force. The properties of elementary particles, which are the basis of the Standard Model, are summarized in **Figure 30-17.**

Protons and Neutrons

The quark model describes nucleons, the proton and the neutron, as an assembly of quarks. The nucleons each are made up of three quarks. The proton has two up quarks, u, (charge $+\frac{2}{3}e$) and one down quark, d, (charge $-\frac{1}{3}e$). A proton is described as p = uud. The charge on the proton is the sum of the charges of the three quarks, $(\frac{2}{3} + \frac{2}{3} + -\frac{1}{3})e = +e$. The neutron is made up of one up quark and two down quarks, n = udd. The charge of the neutron is zero, $(\frac{2}{3} + -\frac{1}{3} + -\frac{1}{3})e = 0$.

Individual free quarks cannot be observed, because the strong force that holds them together becomes larger as the quarks are pulled farther apart. In this case, the strong force acts like the force of a spring. It is unlike the electric force, which becomes weaker as charged particles are moved farther apart. In the quark model, the strong force is transmitted by gluons.

Conversions Between Mass and Energy

The amount of energy created in particle annihilation can be calculated using Einstein's equation for the energy equivalent of mass, $E = mc^2$. The mass of the electron is 9.11×10^{-31} kg. The mass of the positron is the same. Therefore, the energy equivalent of the positron and the electron together can be calculated as follows.

$$E = 2(9.11\times10^{-31}\text{ kg})(3.00\times10^{8}\text{ m/s})^2$$
$$E = (1.64\times10^{-13}\text{ J})(1\text{ eV} / 1.60\times10^{-19}\text{ J})$$
$$E = 1.02\times10^{6}\text{ eV or } 1.02\text{ MeV}$$

When a positron and an electron at rest annihilate each other, the sum of the energies of the gamma rays emitted is 1.02 MeV.

The inverse of annihilation also can occur. That is, energy can be converted directly into matter. If a gamma ray with at least 1.02 MeV of energy passes close by a nucleus, a positron and electron pair can be produced.

$$\gamma \rightarrow e^- + e^+$$

The conversion of energy into a matter-antimatter pair of particles is called **pair production.** Individual reactions, such as $\gamma \rightarrow e^-$ and $\gamma \rightarrow e^+$, however, cannot occur, because such events would violate the law of conservation of charge. Reactions such as $\gamma \rightarrow e^- +$ proton also do not occur; the pair must be a particle and its corresponding antiparticle.

■ **Figure 30-18** When a particle is produced, its corresponding antimatter particle is also produced. Here, a gamma ray decays into an electron-positron pair.

Matter and antimatter particles come in pairs The production of a positron-electron pair is shown in **Figure 30-18.** A magnetic field around the bubble chamber causes the oppositely charged particles' tracks to curve in opposite directions. The gamma ray produced no track. If the gamma ray's energy is larger than 1.02 MeV, the excess energy goes into the kinetic energy of the positron and electron. The positron soon collides with another electron and they are both annihilated, resulting in two or three gamma rays with a total energy of no less than 1.02 MeV.

Particle conservation Each quark and each lepton also has its antiparticle. The antiparticles are identical to the particles except that for charged particles, an antiparticle will have the opposite charge. For example, an up quark, u, has a charge of $+\frac{2}{3}$, while an anti-up quark, $\bar{u}$, has a charge of $-\frac{2}{3}$. A proton, uud, has a charge of $+1$ and the antiproton, $\bar{u}\bar{u}\bar{d}$, has a charge of $-\frac{2}{3} - \frac{2}{3} + \frac{1}{3} = -1$. When a particle and its antiparticle collide, they annihilate each other and are transformed into photons, or lighter particle-antiparticle pairs and energy. The total number of quarks and the total number of leptons in the universe is constant. That is, quarks and leptons are created or destroyed only in particle-antiparticle pairs. On the other hand, force carriers such as gravitons, photons, gluons, and weak bosons can be created or destroyed if there is enough energy.

Antiprotons also can be created. An antiproton has a mass equal to that of the proton but is negatively charged. Protons have 1836 times as much mass as electrons. Thus, the energy needed to create proton-antiproton pairs is comparably larger. The first proton-antiproton pair was produced and observed at Berkeley, California in 1955. Neutrons also have an antiparticle, called an antineutron.

PRACTICE Problems

- Additional Problems, Appendix B
- Solutions to Selected Problems, Appendix C

35. The mass of a proton is 1.67×10^{-27} kg.

a. Find the energy equivalent of the proton's mass in joules.

b. Convert this value to eV.

c. Find the smallest total γ-ray energy that could result in a proton-antiproton pair.

36. A positron and an electron can annihilate and form three gammas. Two gammas are detected. One has an energy of 225 keV, the other 357 keV. What is the energy of the third gamma?

37. The mass of a neutron is 1.008665 u.

a. Find the energy equivalent of the neutron's mass in MeV.

b. Find the smallest total γ-ray energy that could result in the production of a neutron-antineutron pair.

38. The mass of a muon is 0.1135 u. It decays into an electron and two neutrinos. What is the energy released in this decay?

Beta Decay and the Weak Interaction

The high energy electrons emitted in the beta decay of a radioactive nucleus do not exist in the nucleus. From where do they come? In the decay process a neutron is transformed into a proton. While in a stable nucleus, the neutron does not decay. A free neutron, or one in an unstable nucleus, however, can decay into a proton by emitting a β particle. Sharing the outgoing energy with the proton and β particle is an antineutrino, ${}^{0}_{0}\overline{\nu}$. The antineutrino has a very small mass and is uncharged, but like the photon, it carries momentum and energy. The neutron decay equation is written as follows.

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

When an isotope decays by emission of a positron, or antielectron, a process like beta decay occurs. While the decay of a free proton has never been observed, a proton within the nucleus can change into a neutron with the emission of a positron, ${}^{0}_{+1}\mathrm{e}$, and a neutrino, ${}^{0}_{0}\nu$.

$$ {}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e} + {}^{0}_{0}\nu $$

The decay of neutrons into protons and protons into neutrons cannot be explained by the strong force. The existence of beta decay indicates that there must be another interaction, the **weak nuclear force,** acting in the nucleus. This force is much weaker than the strong nuclear force.

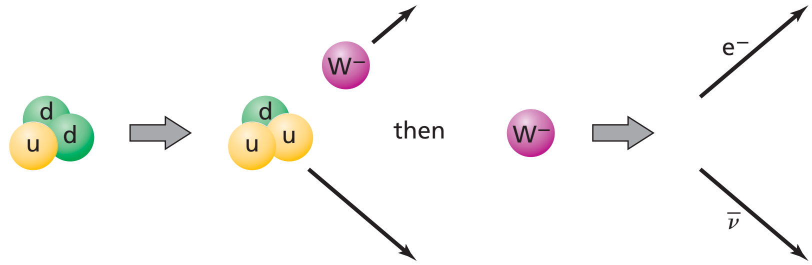
CHALLENGE PROBLEM

${}^{238}_{92}\mathrm{U}$ decays by α emission and two successive β emissions back into uranium again.

1. Show the three nuclear decay equations.

2. Predict the atomic mass number of the uranium formed.

■ **Figure 30-19** Beta decay of a neutron to a proton can be represented with the quark model: $d \rightarrow u + W^-$, then $W^- \rightarrow e^- + \bar{\nu}$.



Quark model of beta decay The difference between a proton, uud, and a neutron, udd, is only one quark. Beta decay in the quark model occurs in two steps, as shown in **Figure 30-19.** First, one d quark in a neutron changes to a u quark with the emission of a W^- boson. The W^- boson is one of the three carriers of the weak force. In the second step, the W^- boson decays into an electron and an antineutrino. Similarly, in the decay of a proton within a nucleus, a neutron and a W^+ boson would be emitted. The W^+ boson then decays into a positron and a neutrino.

The emission of the third weak force carrier, the Z^0 boson, is not accompanied by a change from one quark to another. The Z^0 boson produces an interaction between the nucleons and the electrons in atoms that is similar to, but much weaker than, the electromagnetic force holding the atom together. The interaction first was detected in 1979. The W^+, W^-, and Z^0 bosons first were observed directly in 1983.

While neutrinos and antineutrinos have long been thought to be massless, recent experiments that detect neutrinos from the Sun and from distant accelerators show that neutrinos do have mass, although these masses are much smaller than those of any other known particles.

Testing the Standard Model

You can see in Figure 30-16 that the quarks and leptons are separated into three families. The everyday world is made from particles in the left-hand family: protons, neutrons, and electrons. Particles in the middle group are found in cosmic rays and are routinely produced in particle accelerators. Particles in the right-hand family are believed to have existed briefly during the earliest moments of the Big Bang and are created in high-energy collisions.

What determines the masses of the quarks and leptons? The Higgs boson, which has been hypothesized as the particle that determines the masses of the leptons and quarks, has not yet been discovered. The Standard Model is not a theory; it does not explain the masses of particles, nor why there are three families of quarks and leptons.

Why are there four forces? The differences among the four fundamental interactions are evident: the forces may act on different quantities such as charge or mass, they may have different dependencies on distance, and the force carriers have different properties. There are, however, some similarities among the interactions. For instance, the force between charged particles, the electromagnetic interaction, is carried by photons in much the same way as weak bosons carry the weak interaction. The electric force acts over a long range because the photon has zero mass, while the weak force acts over short distances because the W and Z bosons are relatively massive. The mathematical structures of the theories of the weak interaction and electromagnetic interaction, however, are similar.

■ **Figure 30-20** In a supernova, the electromagnetic and weak forces are indistinguishable. The increased light and neutrinos from supernova 1987A, shown here, reached Earth at the same time, demonstrating that neutrinos travel near the speed of light and are produced in supernovas, as predicted. Supernova 1987A is shown before exploding **(a),** during explosion **(b),** and in a close-up from *Hubble* **(c).**

Astrophysical theories of supernovae indicate that during massive stellar explosions, such as the one shown in **Figure 30-20,** the two interactions are identical. Present theories of the origin of the universe suggest that the two forces were identical during the early moments of the cosmos as well. For this reason, the electromagnetic and weak forces are said to be unified into a single force, called the electroweak force.

In the same way that the electromagnetic and weak forces were unified into the electroweak force during the 1970s, physicists presently are developing theories that include the strong force as well. Work is still incomplete. Theories are being improved, and experiments to test these theories are being planned. A fully unified theory that includes gravitation will require even more work.

Even more perplexing are the results of studies of the galaxies that suggest that matter described by the Standard Model makes up only a small fraction of the mass in the universe. A much larger amount is formed of dark matter, so called because it doesn't interact with photons or ordinary matter, except through the gravitational force. In addition, there appears to be dark energy, an unknown force that accelerates the expansion of the universe.

Thus the studies of the tiniest particles that make up nuclei are connected directly to investigations of the largest systems, the galaxies that make up the universe. Elementary particle physicists and cosmologists used to be at opposite ends of the length scale; now they question together "What IS the world made of?" Perhaps you will be able to answer that question.

30.3 Section Review

39. Nucleus Bombardment Why would a proton require more energy than a neutron when used to bombard a nucleus?

40. Particle Accelerator Protons in the Fermi Laboratory accelerator, Figure 30-11, move counterclockwise. In what direction is the magnetic field of the bending magnets?

41. Pair Production Figure 30-18 shows the production of two electron/positron pairs. Why does the bottom set of tracks curve less than the top pair of tracks?

42. The Standard Model Research the limitations of the Standard Model and possible replacements.

43. Critical Thinking Consider the following equations.

$$u \rightarrow d + W^+ \quad \text{and} \quad W^+ \rightarrow e^+ + \nu$$

How could they be used to explain the radioactive decay of a nucleon that results in the emission of a positron and a neutrino? Write the equation involving nucleons rather than quarks.

PHYSICS LAB • Design Your Own

Exploring Radiation

Alternate CBL instructions can be found on the Web site.
physicspp.com

Radiation detectors use various means to detect radiation. One common type of detector in use is a Geiger-Mueller tube. It consists of a metal tube filled with gas at a low pressure and a long wire along the tube's axis. The wire is at a high potential difference, such as 400–800 V, relative to the metal tube. At one end of the tube is a thin, fragile window. When a high-energy photon or charged particle enters the tube through the window, some of the gas becomes ionized. The ionized electrons are attracted to the wire and speed up. Then they ionize additional atoms creating a pulse of charge striking the wire. This charge pulse is converted to a voltage pulse, amplified, and counted or sent to a speaker.

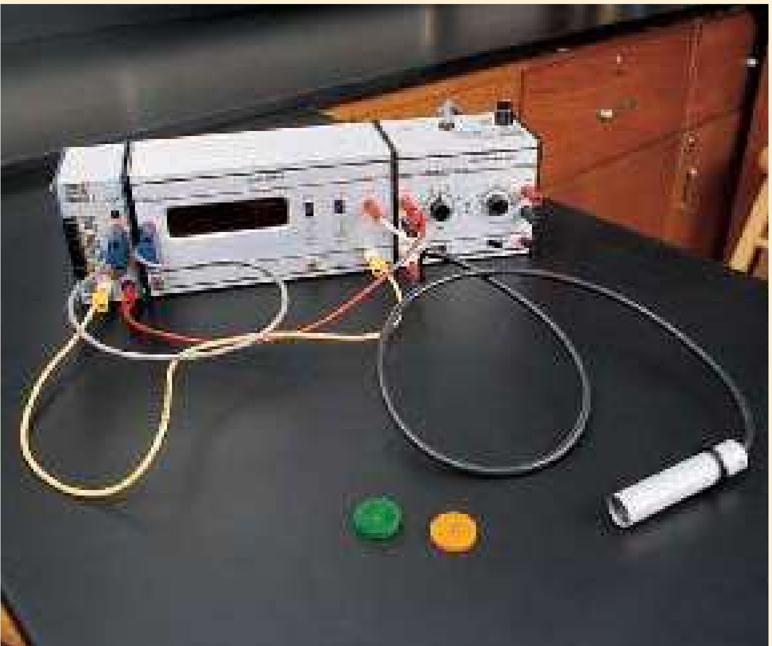
Previously, you learned that light and other electromagnetic radiation travels in all directions in straight lines from a source, such as the Sun. In this lab you will explore the relationship between distance from a radioactive gamma and beta source, and the measured radiation intensity.

QUESTION

What is the relationship between distance and radiation intensity from a gamma and a beta source?

Objectives

- **Measure** radiation.
- **Use variables, constants, and controls** to design your experiment.
- **Collect and organize data** from gamma and beta radiation activity compared to the distance from the source.
- **Compare and contrast** beta and gamma radiation activity.



Horizons Companies

Safety Precautions

- **If a Geiger counter is used, keep hands, pencils, etc. away from the end of the Geiger tube as the tube window is very thin and fragile.**
- **Plug equipment into only GFCI-protected receptacles to prevent shock hazard.**
- **Do not eat, drink, or apply makeup when working with radioactive materials.**
- **Be careful not to crack open the protective plastic case over the radioactive material. Inform your teacher immediately if this exposure happens.**

Materials

gamma and beta sources
radiation counter or student radiation monitor
meterstick
masking tape
stopwatch

Data Table

Background Radiation (cpm = counts per minute)	cpm

Distance (cm)	Beta-Measured Count Rate (cpm)	Beta-Corrected Count Rate (cpm)	Gamma-Measured Count Rate (cpm)	Gamma-Corrected Count Rate (cpm)
2				
4				
6				
8				
10				
12				
14				

Procedure

1. The type of radiation counter or Geiger-Mueller tube and counter that is available in schools varies dramatically. Your procedure should take into consideration how to assemble and handle the type of equipment that is available for your use—both the detector and the radioactive material.
2. With the detector at least 1 m away from the radioactive materials, turn on the detector and measure the radiation. This is called background radiation. Record your data in the data table.
3. Measure the beta and gamma radiation from your sources at various distances.
4. Subtract the background count rate from the count rate recorded to obtain the corrected activity.
5. Be sure to check with your teacher and have your design approved before you proceed with the lab.

Analyze

1. **Observe and Infer** What is the background radiation source in this experiment?
2. **Make and Use Graphs** Make a plot of gamma count rate versus distance, placing distance on the horizontal axis and corrected sample count rate on the vertical axis. If the count rates are similar, plot the beta count rate on the same graph, and label the graph for each set of data.
3. **Make and Use Graphs** Make a plot of the corrected sample count rate versus $1/d^2$ for the beta and gamma data.

Conclude and Apply

1. **Explain** how the two graphs compare. What relationship exists between distance and count rate?
2. **Explain** how the background count rate would compare if you were at sea level, such as along the coast, compared to the level in the Rocky Mountains.
3. **Describe** what happens to the beta count rate when the Geiger-Mueller tube is moved back to three times the initial distance; for example, 18 cm as compared to 6 cm.

Going Further

What other physics phenomena follow similar patterns?

Real-World Physics

Explain how closeness to radioactive materials is a potential hazard for you or others.

Physics Online

To find out more about radiation, visit the Web site: **physicspp.com**

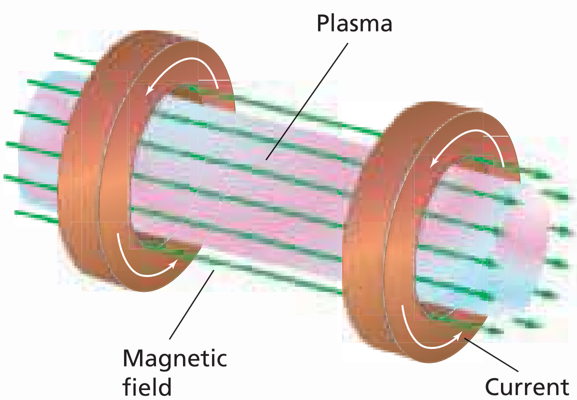
Future Technology

Thermonuclear Fusion

For several decades, physicists have been seeking to create and sustain a fusion reaction that will generate more energy than it consumes. A thermonuclear reactor would generate great heat from small amounts of deuterium, $^{2}_{1}H$, and tritium, $^{3}_{1}H$, which can be extracted from seawater.

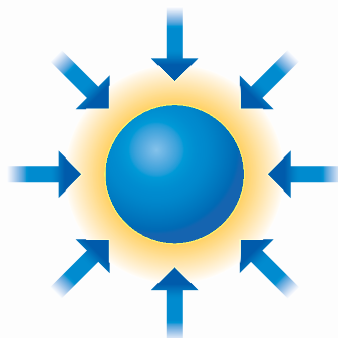
To initiate a fusion reaction, a mixture of deuterium and tritium must be heated and compressed under conditions typical of those in the Sun. The required temperature would destroy the sort of containers used in fission plants. Confining the plasma is one of the chief design problems for fusion reactors.

Magnetic Confinement In a magnetic confinement reactor, a strong current is passed through a container of deuterium and tritium gas so that the plasma is compressed within the arc. Additional magnetic fields shape the plasma stream, as shown in the diagram, confining it away from the container walls. One promising configuration keeps the plasma in a toroid, or donut shape, which has the great advantage of having no ends to seal.



Magnetic confinement: the hot plasma is compressed and confined by the magnetic field.

Inertial Confinement If you look at the rapid, string-like motion of a continuous electric arc, you'll see that it's very difficult to form plasma into a stable shape. In the inertial confinement reactor, a microscopic pellet of frozen deuterium-tritium is illuminated on all sides by powerful laser beams. These lasers heat the outer layer of the pellet so quickly that it explodes. Simultaneously the remainder of the pellet is compressed and heated so greatly that a fusion reaction starts. The energy from the fusion of the pellet exceeds the energy used to heat the pellet. A stream of pellets is fused one after another to obtain a sustained reaction, and the obtained heat is captured to create steam for turbines.



In inertial confinement, beams of light or X rays from a laser rapidly heat the surface of the pellet, forming a surrounding plasma envelope. The rest of the fuel is compressed by the blowoff of the hot surface material.

The Future While thermonuclear fusion has been sustained in both types of reactors, researchers have had trouble achieving a breakeven reaction (one in which the energy produced in the reaction exceeds the energy needed to sustain the reaction). Progress toward a practical thermonuclear reactor has been expensive and slow, but the promise is great. A fusion reactor is not completely free of radiation hazards because neutrons are produced in fusion reactions. But because the fuel itself is not radioactive, the amount of nuclear waste would be negligible.

Going Further

1. **Analyze** Why does the thermonuclear reactor appear to be such an attractive source of energy?
2. **Compare** You have seen three types of 'thermal' electric power plants. What features do they all have in common?

Chapter 30

Study Guide

30.1 The Nucleus

Vocabulary

- atomic number (p. 800)
- atomic mass unit (p. 800)
- mass number (p. 800)
- nuclide (p. 801)
- strong nuclear force (p. 802)
- nucleon (p. 802)
- binding energy (p. 802)
- mass defect (p. 802)

Key Concepts

- The number of protons in a nucleus is given by the atomic number, Z.
- The sum of the numbers of protons and neutrons in a nucleus is equal to the mass number, A.
- Atoms having nuclei with the same number of protons but different numbers of neutrons are called isotopes.
- The strong nuclear force binds the nucleus together.
- The energy released in a nuclear reaction can be calculated by finding the mass defect, the difference in mass of the particles before and after the reaction.

$$E = mc^2$$

- The binding energy is the energy equivalent of the mass defect.

30.2 Nuclear Decay and Reactions

Vocabulary

- radioactive (p. 806)
- alpha decay (p. 806)
- beta decay (p. 806)
- gamma decay (p. 806)
- nuclear reaction (p. 807)
- half-life (p. 809)
- activity (p. 810)
- fission (p. 811)
- chain reaction (p. 812)
- fusion (p. 813)

Key Concepts

- An unstable nucleus decays, transmuting into another element.
- Radioactive decay produces three kinds of particles. Alpha, α, particles are helium nuclei, beta, β, particles are high-speed electrons, and gamma, γ, rays are high-energy photons.
- In nuclear reactions, the sums of the mass number, A, and the total charge, Z, are not changed.
- The half-life of a radioactive isotope is the time required for half of the nuclei to decay. After t half-lives:

$$\text{remaining} = \text{original}\left(\frac{1}{2}\right)^t$$

- The number of decays of a radioactive sample per second is the activity.
- In nuclear fission, the uranium nucleus is split into two smaller nuclei with a release of neutrons and energy.
- Nuclear reactors use the energy released in fission to generate electrical energy.
- The fusion of hydrogen nuclei into a helium nucleus releases the energy that causes stars to shine.

30.3 The Building Blocks of Matter

Vocabulary

- quarks (p. 818)
- leptons (p. 818)
- Standard Model (p. 818)
- force carriers (p. 818)
- pair production (p. 820)
- weak nuclear force (p. 821)

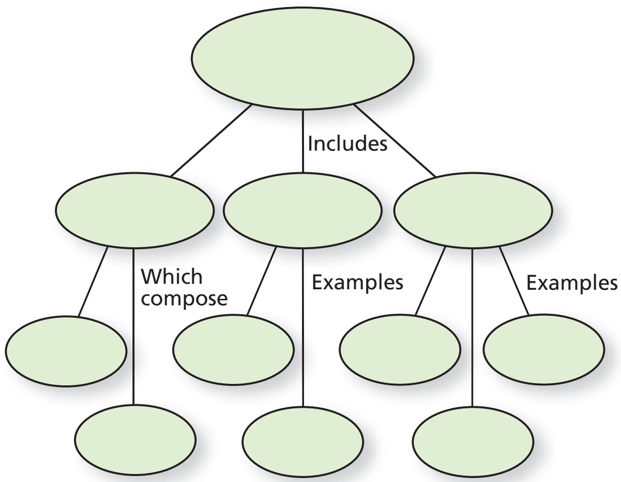
Key Concepts

- Linear accelerators and synchrotrons produce high-energy particles.
- The Geiger-Mueller counter, cloud chamber, and other particle detectors use the ionization caused by charged particles passing through matter.
- All matter appears to be made up of quarks and leptons.
- Matter interacts with other matter through particles called force carriers.
- The Standard Model includes the quarks, leptons, and force carriers.
- When corresponding antimatter and matter particles combine, their mass and energy are converted into energy or lighter matter-antimatter particle pairs.
- By pair production, energy is transformed into a matter-antimatter pair.

Chapter 30 Assessment

Concept Mapping

44. Organize the following terms into the concept map: *Standard Model, quarks, gamma rays, force carriers, protons, neutrons, leptons, W bosons, neutrinos, electrons, gluons.*



Mastering Concepts

45. What force inside a nucleus acts to push the nucleus apart? What force inside the nucleus acts to hold the nucleus together? (30.1)

46. Define the mass defect of a nucleus. To what is it related? (30.1)

47. Which are generally more unstable, small or large nuclei? (30.1)

48. Which isotope has the greater number of protons, uranium-235 or uranium-238? (30.1)

49. Define the term *transmutation* as used in nuclear physics and give an example. (30.2)

50. **Radiation** What are the common names for an α particle, β particle, and γ radiation? (30.2)

51. What two quantities must always be conserved in any nuclear equation? (30.2)

52. **Nuclear Power** What sequence of events must occur for a chain reaction to take place? (30.2)

53. **Nuclear Power** What role does a moderator play in a fission reactor? (30.2)

54. Fission and fusion are opposite processes. How can each release energy? (30.2)

55. **High-Energy Physics** Why would a linear accelerator not work with a neutron? (30.3)

56. **Forces** In which of the four interactions (strong, weak, electromagnetic, and gravitational) do the following particles take part? (30.3)
- **a.** electron
- **b.** proton
- **c.** neutrino

57. What happens to the atomic number and mass number of a nucleus that emits a positron? (30.3)

58. **Antimatter** What would happen if a meteorite made of antiprotons, antineutrons, and positrons landed on Earth? (30.3)

Applying Concepts

59. **Fission** A Web site claims that scientists have been able to cause iron nuclei to undergo fission. Is the claim likely to be true? Explain.

60. Use the graph of binding energy per nucleon in Figure 30-2 to determine whether the reaction ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He$ is energetically possible.

61. **Isotopes** Explain the difference between naturally and artificially produced radioactive isotopes.

62. **Nuclear Reactor** In a nuclear reactor, water that passes through the core of the reactor flows through one loop, while the water that produces steam for the turbines flows through a second loop. Why are there two loops?

63. The fission of a uranium nucleus and the fusion of four hydrogen nuclei to produce a helium nucleus both produce energy.
- **a.** Which produces more energy?
- **b.** Does the fission of a kilogram of uranium nuclei or the fusion of a kilogram of hydrogen produce more energy?
- **c.** Why are your answers to parts **a** and **b** different?

Mastering Problems

30.1 The Nucleus

64. What particles, and how many of each, make up an atom of ${}^{109}_{47}Ag$?

65. What is the isotopic symbol (the one used in nuclear equations) of a zinc atom composed of 30 protons and 34 neutrons?

66. The sulfur isotope ${}^{32}_{16}S$ has a nuclear mass of 31.97207 u.
- **a.** What is the mass defect of this isotope?
- **b.** What is the binding energy of its nucleus?
- **c.** What is the binding energy per nucleon?

67. A nitrogen isotope, $^{12}_{7}N$, has a nuclear mass of 12.0188 u.

a. What is the binding energy per nucleon?

b. Does it require more energy to separate a nucleon from a $^{14}_{7}N$ nucleus or from a $^{12}_{7}N$ nucleus? $^{14}_{7}N$ has a mass of 14.00307 u.

68. The two positively charged protons in a helium nucleus are separated by about 2.0×10^{-15} m. Use Coulomb's law to find the electric force of repulsion between the two protons. The result will give you an indication of the strength of the strong nuclear force.

69. The binding energy for $^{4}_{2}He$ is -28.3 MeV. Calculate the mass of a helium isotope in atomic mass units.

30.2 Nuclear Decay and Reactions

70. Write the complete nuclear equation for the alpha decay of $^{222}_{86}Rn$.

71. Write the complete nuclear equation for the beta decay of $^{89}_{36}Kr$.

72. Complete each nuclear reaction.

a. $^{225}_{89}Ac \rightarrow {}^{4}_{2}He + \_\_\_\_\_$

b. $^{227}_{88}Ra \rightarrow {}^{0}_{-1}e + \_\_\_\_\_ + \_\_\_\_\_$

c. $^{65}_{29}Cu + {}^{1}_{0}n \rightarrow \_\_\_\_\_ \rightarrow {}^{1}_{1}p + \_\_\_\_\_$

d. $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{96}_{40}Zr + 3({}^{1}_{0}n) + \_\_\_\_\_$

73. An isotope has a half-life of 3.0 days. What percent of the original material will be left after

a. 6.0 days?

b. 9.0 days?

c. 12 days?

74. In an accident in a research laboratory, a radioactive isotope with a half-life of three days is spilled. As a result, the radiation is eight times the maximum permissible amount. How long must workers wait before they can enter the room?

75. When a boron isotope, $^{11}_{5}B$, is bombarded with protons, it absorbs a proton and emits a neutron.

a. What element is formed?

b. Write the nuclear equation for this reaction.

c. The isotope formed is radioactive and decays by emitting a positron. Write the complete nuclear equation for this reaction.

76. The first atomic bomb released an energy equivalent of 2.0×10^{1} kilotons of TNT. One kiloton of TNT is equivalent to 5.0×10^{12} J. Uranium-235 releases 3.21×10^{-11} J/atom. What was the mass of the uranium-235 that underwent fission to produce the energy of the bomb?

77. During a fusion reaction, two deuterons, $^{2}_{1}H$, combine to form a helium isotope, $^{3}_{2}He$. What other particle is produced?

78. $^{209}_{84}Po$ has a half-life of 103 years. How long would it take for a 100-g sample to decay so that only 3.1 g of Po-209 was left?

30.3 The Building Blocks of Matter

79. What would be the charge of a particle composed of three up quarks?

80. The charge of an antiquark is opposite that of a quark. A pion is composed of an up quark and an anti-down quark, $u\bar{d}$. What would be the charge of this pion?

81. Pions are composed of a quark and an antiquark. Find the charge of a pion made up of the following.

a. $u\bar{u}$

b. $d\bar{u}$

c. $d\bar{d}$

82. Baryons are particles that are made of three quarks. Find the charge on each of the following baryons.

a. neutron: ddu

b. antiproton: $\bar{u}\bar{u}\bar{d}$

83. The synchrotron at the Fermi Laboratory has a diameter of 2.0 km. Protons circling in it move at approximately the speed of light in a vacuum.

a. How long does it take a proton to complete one revolution?

b. The protons enter the ring at an energy of 8.0 GeV. They gain 2.5 MeV each revolution. How many revolutions must they travel before they reach 400.0 GeV of energy?

c. How long does it take the protons to be accelerated to 400.0 GeV?

d. How far do the protons travel during this acceleration?

84. **Figure 30-21** shows tracks in a bubble chamber. What are some reasons one track might curve more than another?

■ **Figure 30-21**

Mixed Review

85. Each of the following nuclei can absorb an α particle. Assume that no secondary particles are emitted by the nucleus. Complete each equation.

a. ${}^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow$ _____

b. ${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow$ _____

86. ${}^{211}_{86}\text{Rn}$ has a half-life of 15 h. What fraction of a sample would be left after 60 h?

87. One of the simplest fusion reactions involves the production of deuterium, ${}^{2}_{1}\text{H}$(2.014102 u), from a neutron and a proton. Write the complete fusion reaction and find the amount of energy released.

88. A ${}^{232}_{92}\text{U}$ nucleus, mass = 232.0372 u, decays to ${}^{228}_{90}\text{Th}$, mass = 228.0287 u, by emitting an α particle, mass = 4.0026 u, with a kinetic energy of 5.3 MeV. What must be the kinetic energy of the recoiling thorium nucleus?

Thinking Critically

89. Infer Gamma rays carry momentum. The momentum of a gamma ray of energy E is equal to E/c, where c is the speed of light. When an electron-positron pair decays into two gamma rays, both momentum and energy must be conserved. The sum of the energies of the gamma rays is 1.02 MeV. If the positron and electron are initially at rest, what must be the magnitude and direction of the momentum of the two gamma rays?

90. Infer An electron-positron pair, initially at rest, also can decay into three gamma rays. If all three gamma rays have equal energies, what must be their relative directions? Make a sketch.

91. Estimate One fusion reaction in the Sun releases about 25 MeV of energy. Estimate the number of such reactions that occur each second from the luminosity of the Sun, which is the rate at which it releases energy, 4×10^{26} W.

92. Interpret Data An isotope undergoing radioactive decay is monitored by a radiation detector. The number of counts in each five-minute interval is recorded. The results are shown in **Table 30-3.** The sample is then removed and the radiation detector records 20 counts resulting from cosmic rays in 5 min. Find the half-life of the isotope. Note that you should first subtract the 20-count background reading from each result. Then plot the counts as a function of time. From your graph, determine the half-life.

Table 30-3
Radioactive Decay Measurements

Time (min)	Counts (per 5 min)
0	987
5	375
10	150
15	70
20	40
25	25
30	18

Writing in Physics

93. Research the present understanding of dark matter in the universe. Why is it needed by cosmologists? Of what might it be made?

94. Research the hunt for the top quark. Why did physicists hypothesize its existence?

Cumulative Review

95. An electron with a velocity of 1.7×10^{6} m/s is at right angles to a 0.91-T magnetic field. What is the force on the electron produced by the magnetic field? (Chapter 24)

96. An *EMF* of 2.0 mV is induced in a wire that is 0.10 m long when it is moving perpendicularly across a uniform magnetic field at a velocity of 4.0 m/s. What is the magnetic induction of the field? (Chapter 25)

97. An electron has a de Broglie wavelength of 400.0 nm, the shortest wavelength of visible light. (Chapter 27)

a. Find the velocity of the electron.

b. Calculate the energy of the electron in eV.

98. A photon with an energy of 14.0 eV enters a hydrogen atom in the ground state and ionizes it. With what kinetic energy will the electron be ejected from the atom? (Chapter 28)

99. A silicon diode (V = 0.70 V)that is conducting 137 mA is in series with a resistor and a 6.67-V power source. (Chapter 29)

a. What is the voltage drop across the resistor?

b. What is the value of the resistor?

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

Multiple Choice

1. How many protons, neutrons, and electrons are in the isotope nickel-60, $^{60}_{28}\text{Ni}$?

	Protons	Neutrons	Electrons
A	28	32	28
B	28	28	32
C	32	32	28
D	32	28	28

2. What has occurred in the following reaction? $^{212}_{82}\text{Pb} \rightarrow {}^{212}_{83}\text{Bi} + e^- + \overline{\nu}$

   A alpha decay
   B beta decay
   C gamma decay
   D loss of a proton

3. What is the product when pollonium-210, $^{210}_{84}\text{Po}$, undergoes alpha decay?

   A $^{206}_{82}\text{Pb}$
   B $^{208}_{82}\text{Pb}$
   C $^{210}_{85}\text{Pb}$
   D $^{210}_{80}\text{Pb}$

4. A sample of radioactive iodine-131 emits beta particles at the rate of 2.5×10^8 Bq. The half-life is 8 days. What will be the activity after 16 days?

   A 1.6×10^7 Bq
   B 6.3×10^7 Bq
   C 1.3×10^8 Bq
   D 2.5×10^8 Bq

5. Identify the unknown isotope in this reaction: neutron + $^{14}_{7}\text{N} \rightarrow {}^{14}_{6}\text{C}$ + ?

   A $^{1}_{1}\text{H}$
   B $^{2}_{1}\text{H}$
   C $^{3}_{1}\text{H}$
   D $^{4}_{2}\text{He}$

6. Which type of decay does not change the number of protons or neutrons in the nucleus?

   A positron
   B alpha
   C beta
   D gamma

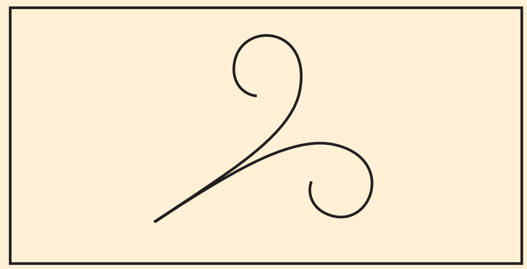
7. Polonium-210 has a half-life of 138 days. How much of a 2.34-kg sample will remain after four years?

   A 0.644 mg
   B 1.50 mg
   C 1.51 g
   D 10.6 g

8. An electron and a positron collide, annihilate one another, and release their energy as a gamma ray. What is the minimum energy of the gamma ray? (The energy equivalent of the mass of an electron is 0.51 MeV.)

   A 0.51 MeV
   B 1.02 MeV
   C 931.49 MeV
   D 1863 MeV

9. The illustration below shows the tracks in a bubble chamber produced when a gamma ray decays into a positron and an electron. Why doesn't the gamma ray leave a track?



   A Gamma rays move too quickly for their tracks to be detected.
   B Only pairs of particles can leave tracks in a bubble chamber.
   C A particle must have mass to interact with the liquid and leave a track, and the gamma ray is virtually massless.
   D The gamma ray is electrically neutral, so it does not ionize the liquid in the bubble chamber.

Extended Answer

10. The fission of a uranium-235 nucleus releases about 3.2×10^{-11} J. One ton of TNT releases about 4×10^9 J. How many uranium-235 nuclei are in a nuclear fission weapon that releases energy equivalent to 20,000 tons of TNT?

✓ Test-Taking TIP

Do Some Reconnaissance

Find out what the conditions will be for taking the test. Is it timed or untimed? Can you use a calculator or other tools? Will those tools be provided? Will mathematical constants be given? Know these things in advance so that you can practice taking tests under the same conditions.