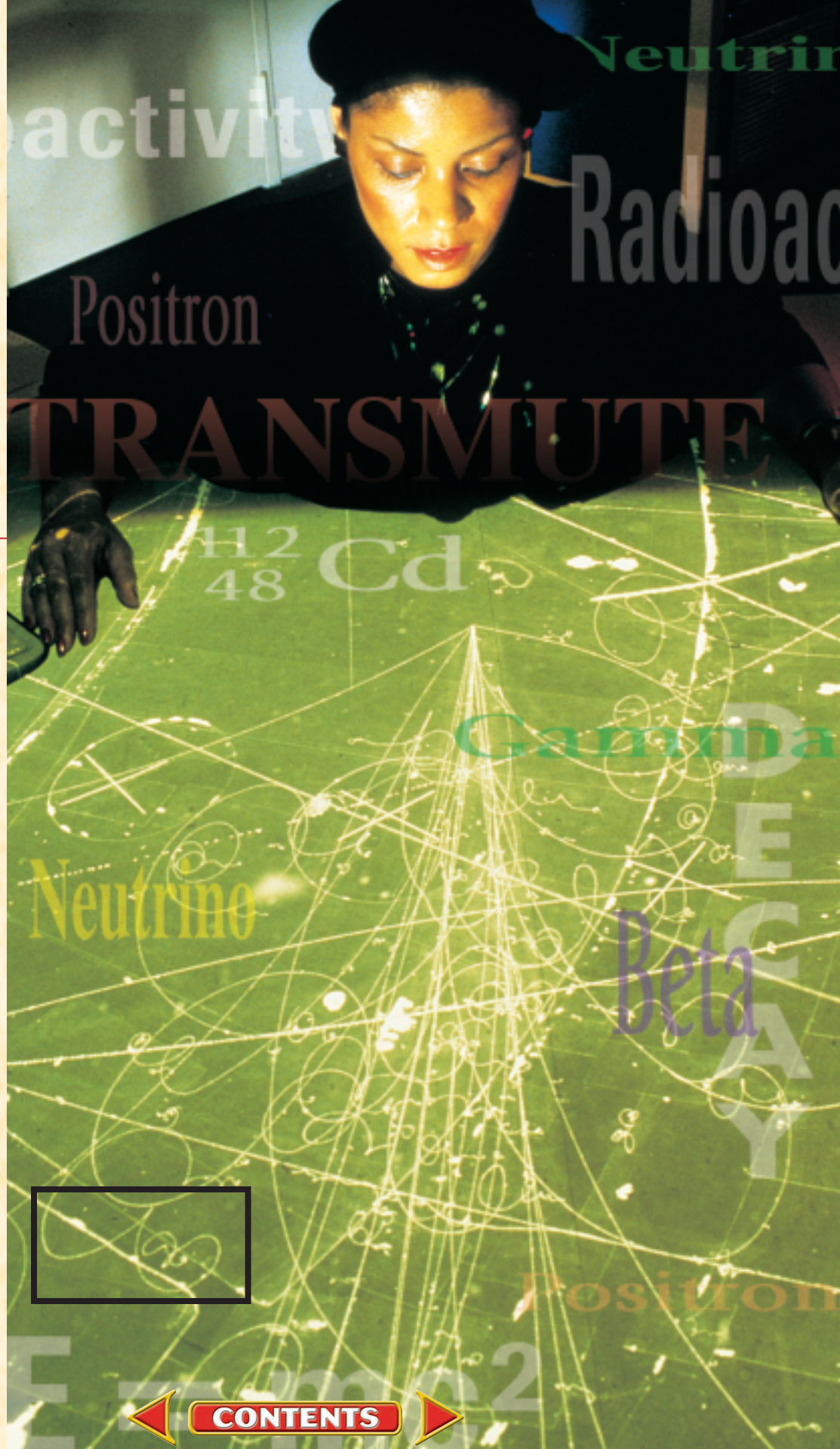


Phantom Tracks

This technician's work seeks clues into the nature of the atomic nucleus. In the highlighted box are two particles moving in opposite spiral paths. The curvatures are about the same, so their momenta must be equal. What might cause this pair of paths?

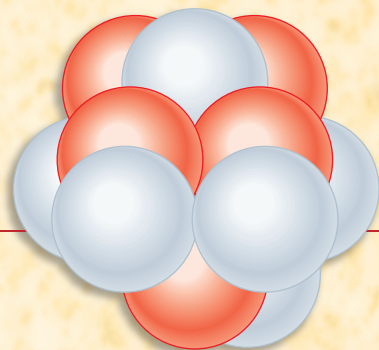
➡ Look at the text on page 708 for the answer.



CHAPTER

30

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's important to realize that Rutherford's experiments, and the experiments of those who followed, did not offer the opportunity to directly observe the atom. Instead, hypotheses were tailored to fit the direct observations that researchers made. As you may recall from Chapter 28, Rutherford's direct observations centered in the deflection of alpha particles as they hit gold foil. These deflections could be explained if the atom was mostly empty space. That is, if the atom had a small, dense, positively charged center surrounded by nearly massless electrons.

Later researchers looked at the effects produced when a nucleus breaks apart in natural radioactive decay. Soon scientists found ways to break apart certain nuclei on demand, allowing the study of the products of "atom smashing." Today modern accelerators and detectors have given researchers the ability to study nuclei and the particles that compose them with much greater precision than was possible during Rutherford's time.

In the photo at the left, a technician is measuring the tracks of subatomic particles moving through a bubble chamber. A bubble chamber is a radiation detector. Charged particles speeding through the chamber leave strings of tiny bubbles in their wake. In addition, the bubble chamber is subject to a magnetic field so the paths of any charged particles will be bent. The faster the particles move, the less they will bend. Thus, their momenta can be determined. The direction of the curve also indicates the charge of the particle. In this chapter, you'll learn how bubble chambers and other tools have expanded our knowledge of not only the nucleus, but of a whole new class of particles that may be the ultimate building blocks of matter.

WHAT YOU'LL LEARN

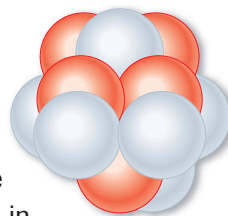
- You will describe the components of a nucleus and how radioactive decay affects these components.
- You will compare the various tools that physicists use to study the nucleus and nuclear reactions.

WHY IT'S IMPORTANT

- Atomic nuclei are used in various ways to determine what is happening inside the human body, from utilizing nuclei in magnetic resonance imaging (MRI) to using radioactive particles in positron emission tomography (PET).



To find out more about the nucleus, visit the Glencoe Science Web site at science.glencoe.com



OBJECTIVES

- **Determine** the number of neutrons and protons in nuclides.
- **Describe** three forms of radioactive decay and **solve** nuclear equations.
- **Define** half-life and **calculate** the amount of material and its activity remaining after a given number of half-lives.



FIGURE 30–1 Nuclear physicist Dr. Sekazi Mtingwa served as president of the National Society of Black Physicists from 1992 to 1994.

After the discovery of radioactivity by Becquerel in 1896, many scientists studied this new phenomenon. French scientists Marie and Pierre Curie discovered the new elements polonium and radium in samples of radioactive uranium. In Canada, Ernest Rutherford and Fredrick Soddy used radioactivity to probe the center of the atom, the nucleus.

Description of the Nucleus

Recall from Chapter 28 how the nucleus was discovered. Ernest Rutherford directed a beam of α particles at metal foil and noticed that a few α particles were scattered at large angles. To explain the results, he hypothesized that the nucleus consisted of massive, positively charged particles. Around 1921, the name proton was adopted for these particles and each was defined as possessing one unit of elementary charge, e . In Chapter 20, you learned that elementary charge is the magnitude of charge existing on one electron, $e = 1.60 \times 10^{-19}$ C.

How was the other component of the nucleus, the neutron, discovered? Again, the scattering experiment played a key role. In 1909, only the mass of the nucleus was known. The charge of the nucleus was found as a result of X-ray scattering experiments done by 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 had some fundamental problems, however. 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, 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. Therefore, the total charge of the nucleus is the number of protons, Z , times the elementary charge, e .

$$\text{nuclear charge} = Z \times e$$

Both the proton and the neutron have mass that is approximately equal to 1u, 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, A , by u.

$$\text{nuclear mass} \approx A \times u$$

The symbols Z and A are **atomic number** and **mass number**, respectively.

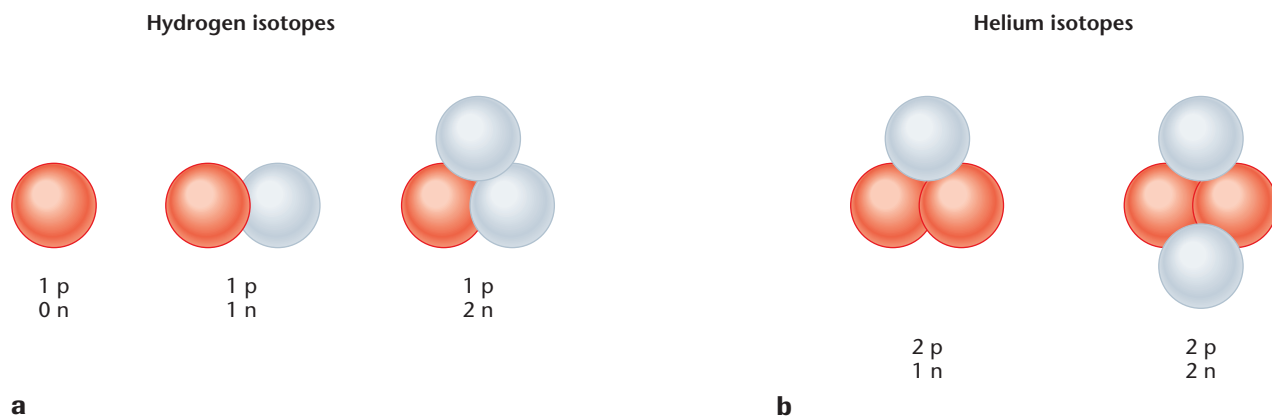
Size of the nucleus As you know, the electrical force between positively charged protons is repulsive. The neutrons are not affected by the electrical force. What, then, holds the nucleus together? An attractive **strong nuclear force** is exerted by one proton on any other proton or neutron that is near it. This force, which also exists between neutrons, is stronger than the electrostatic repulsing force. Because of the strong nuclear force, the nucleus is held together at a diameter of about 10 fm (10^{-14} m). Typical atomic radii are on the order of 0.1 nm, which is 10 000 times larger than the size of the nucleus.

Isotopes

Looking at the periodic table, you might notice that the first four elements all have mass number near a whole number. Boron, on the other hand, has a mass of 10.8 u. If, as was thought, the nucleus is made up of only protons and neutrons, each with a mass of approximately 1 u, then the total mass of any atom should 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 neon atom was found to have a mass of 20 u, the second type a mass of 22 u. All neutral neon atoms have ten protons in the nucleus and ten 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 30–2**. All isotopes of a neutral element have the same number of electrons around the nucleus and chemically behave the same way.

FIGURE 30–2 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.



F.Y.I.

For naturally occurring carbon, 98.9% is $^{12}_6\text{C}$ and about 1.1% is $^{13}_6\text{C}$, with a trace amount of $^{14}_6\text{C}$.

HELP WANTED NUCLEAR ENGINEER

Several federal departments need bright, conscientious nuclear engineers to continue to work on refining the production and distribution process of nuclear energy to make it the world's best and safest energy source. The key word is safety. If you have an advanced degree, a creative yet logical approach to problem solving, a desire to be part of an exciting team, and the ability to help convince the public about the future of our industry, Uncle Sam wants you! For information contact:

American Nuclear Society
555 North Kensington Ave.
LaGrange Park, IL 60526

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 of an average sample of neon atoms is not. Most elements have several isotopic forms that occur naturally. The mass of one isotope of carbon, $^{12}_6\text{C}$, is now used to define the mass unit. One u is defined to be 1/12 the mass of the $^{12}_6\text{C}$ isotope.

A special method of notation is used to describe an isotope. A subscript representing the atomic number, 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, the two isotopes of neon, with atomic number 10, are written as $^{20}_{10}\text{Ne}$ and $^{22}_{10}\text{Ne}$.

Practice Problems

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 nuclei 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 which have zero, one, and two neutrons in the nucleus.

Radioactive Decay

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 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** and to undergo radioactive decay.

In 1899, Rutherford 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, which have proved to be high-energy photons. Gamma rays are the most penetrating of the three

because they have no charge. Rutherford determined that an alpha particle is the nucleus of helium atoms, ${}^4_2\text{He}$. By having a +2 charge, alpha particles interact strongly with matter, in fact, just a few centimeters of air are enough to absorb them. Beta particles were later identified as high-speed electrons. Moving faster and having less charge allows beta particles a greater penetrating ability. **Figure 30–3** illustrates the difference in charge of these three particles.

Alpha decay The emission of an α particle is a process called **alpha decay**. Because α particles consist of two protons and two neutrons, they must come from the nucleus of an atom. The nucleus that results from α decay will have a mass and charge different from those of the original nucleus. A change in nuclear charge means that the element has been changed, or **transmuted**, into a different element. The mass number of an α particle, ${}^4_2\text{He}$, is 4, so the mass number, A , of the decaying nucleus is reduced by 4. The atomic number of ${}^4_2\text{He}$ is 2, and therefore the atomic number of the nucleus, Z , is reduced by 2.

For example, when ${}^{238}_{92}\text{U}$ emits an α particle, the atomic number, Z , changes from 92 to 90. From **Table F–6** of the Appendix, we find that $Z = 90$ is thorium. The mass number of the newly formed nucleus is $A = 238 - 4 = 234$. A thorium isotope, ${}^{234}_{90}\text{Th}$, is formed. The uranium isotope has been transmuted into thorium.

Beta decay Beta particles are electrons emitted by the nucleus. However, the nucleus contains no electrons, so where do the 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. Charge conservation is satisfied. Consequently, as a result of beta decay, a nucleus with N neutrons and Z protons ends up with a nucleus of $N-1$ neutrons and $Z+1$ protons. Another particle, an antineutrino, is also emitted in beta decay. The reason for the appearance of this small, massless, chargeless particle will be discussed in the next section. The symbol for an antineutrino is the Greek letter nu with a bar over it, ${}^0_0\bar{\nu}$.

Gamma decay Gamma radiation results from the redistribution of the charge within the nucleus. The γ ray is a high-energy photon. Neither the mass number nor the atomic number is changed when a nucleus emits a γ ray in **gamma decay**. Gamma radiation often accompanies alpha and beta decay.

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

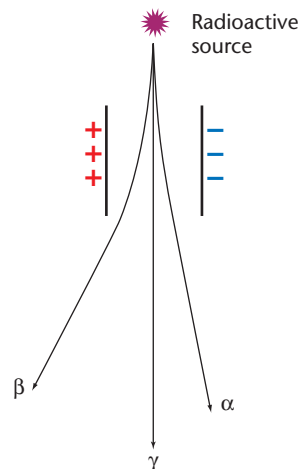


FIGURE 30–3 Alpha, beta, and gamma emissions behave differently in an electric field. Alpha and beta particles are deflected because of their charge.

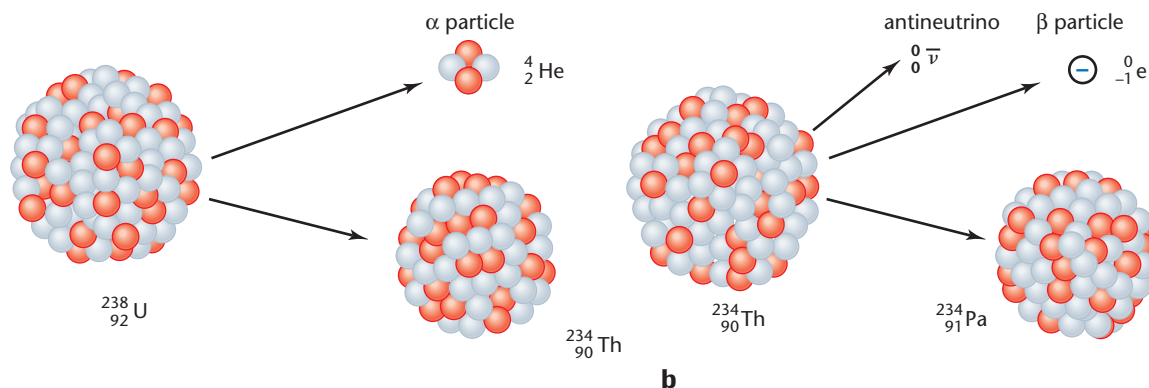


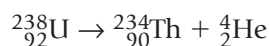
FIGURE 30-4 The emission of an alpha particle by uranium-238 results in the formation of thorium-234 **(a)**. The emission of a beta particle by thorium-234 results in the formation of protactinium-234 **(b)**.

Nuclear Reactions and Equations

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

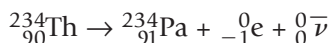
One form of nuclear reaction is the emission of particles by radioactive nuclei. The reaction releases excess energy in the form of the kinetic energy of the emitted particles. One such reaction is the thorium-234 decaying into protactinium-234 by the emission of a high-speed electron and antineutrino, as shown in **Figure 30-4b**.

While nuclear reactions can be described in words or in pictures, as in **Figure 30-4**, they can be written more easily in equation form. The symbols used for the nuclei in nuclear equations make the calculation of atomic number and mass number in nuclear reactions simpler. For example, this is the word equation for the change of uranium to thorium resulting from α decay: uranium-238 yields thorium-234 plus an α particle. The nuclear equation for this reaction is as follows.



The total number of nuclear particles stays the same during the nuclear reaction. Thus, the sum of the superscripts on the right side of the equation must equal the sum of the superscripts on the left side of the equation. The sum of the superscripts on both sides of the equation is 238. Electric charge also is conserved. Thus, the sum of the subscripts on the right is equal to the sum of the subscripts on the left.

A β particle is an electron and is represented by the symbol $^0_{-1}\text{e}$. This indicates that the electron has one negative charge and a mass number of 0. The transmutation of a thorium atom by the emission of a β particle is shown in **Figure 30-4b**.



Note that the sum of the left-side superscripts equals the sum of the right-side superscripts. Equality must also exist between the left-side subscripts and the right-side subscripts.

Example Problem

Nuclear Equations: Alpha Decay

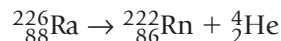
Write the equation for the process by which a radioactive radium isotope, $^{226}_{88}\text{Ra}$, emits an α particle and becomes the radon isotope $^{222}_{86}\text{Rn}$.

Calculate your Answer

Strategy:

The sum of the superscripts, A , and the sum of the subscripts, Z , must be equal on the two sides of the equation.

Calculations:



Check your Answer

- Sum of A : $226 = 222 + 4$
- Sum of Z : $88 = 86 + 2$

Example Problem

Nuclear Equations: Beta Decay

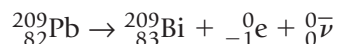
Write the equation for the decay of the radioactive lead isotope, $^{209}_{82}\text{Pb}$, into the bismuth isotope, $^{209}_{83}\text{Bi}$, by the emission of a β particle and an antineutrino.

Calculate your Answer

Strategy:

The sum of the superscripts, A , and the sum of the subscripts, Z must be equal on the two sides of the equation.

Calculations:



Check your Answer

- Sum of A : $209 = 209 + 0 + 0$
- Sum of Z : $82 = 83 - 1 + 0$

Practice Problems

5. 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.
6. 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.

Continued on next page

Pocket Lab

Background Radiation



Place a Geiger counter on the lab table far away from any sources of radiation. Turn the counter on and record the number of counts for a three-minute interval. Tape a piece of paper around the tube to cover the window and repeat the measurements.

Analyze and Conclude Did the count go down? What type of radiation could the counter be receiving? Explain.

7. 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.
8. 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.

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. Each particular isotope has its own half-life. For example, the half-life of the radium isotope $^{226}_{88}\text{Ra}$ is 1600 years. That is, in 1600 years, half of a given quantity of $^{226}_{88}\text{Ra}$ decays into another element. In a second 1600 years, half of the remaining sample will have decayed. In other words, one fourth of the original amount still will remain after 3200 years.

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 is also reduced by one half in one half-life. Consider $^{131}_{53}\text{I}$, with a half-life of 8.07 days. If the activity of a certain sample is 8×10^5 decays per second when the $^{131}_{53}\text{I}$ is produced, then 8.07 days later its activity will be 4×10^5 decays per second. After another 8.07 days, its activity will be 2×10^5 decays per second. The activity of a sample is also 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.

TABLE 30-1

Half-Life of Selected Isotopes

Element	Isotope	Half-Life	Radiation Produced
hydrogen	^3_1H	12.3 years	β
carbon	$^{14}_6\text{C}$	5730 years	β
cobalt	$^{60}_{27}\text{Co}$	30 years	β, γ
iodine	$^{131}_{53}\text{I}$	8.07 days	β, γ
lead	$^{212}_{82}\text{Pb}$	10.6 hours	β
polonium	$^{194}_{84}\text{Po}$	0.7 seconds	α
polonium	$^{210}_{84}\text{Po}$	138 days	α, γ
uranium	$^{235}_{92}\text{U}$	7.1×10^8 years	α, γ
uranium	$^{238}_{92}\text{U}$	4.51×10^9 years	α, γ
plutonium	$^{236}_{94}\text{Pu}$	2.85 years	α
plutonium	$^{242}_{94}\text{Pu}$	3.79×10^5 years	α, γ



Practice Problems

Refer to **Figure 30-5** and **Table 30-1** to solve the following problems.

- A sample of 1.0 g of tritium, ${}^3_1\text{H}$, is produced. What will be the mass of the tritium remaining after 24.6 years?
- The isotope ${}^{238}_{93}\text{Np}$ 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?
- 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?
- Tritium, ${}^3_1\text{H}$, was once 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?

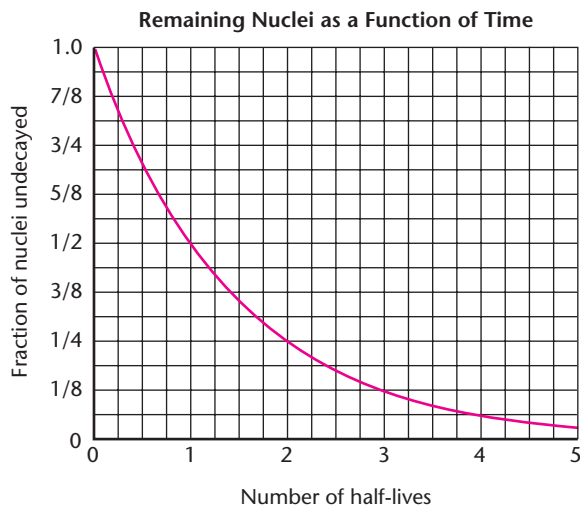


FIGURE 30-5

30.1 Section Review

- Consider these two pairs of nuclei: ${}^{12}_6\text{C}$ and ${}^{13}_6\text{C}$ and ${}^{11}_5\text{B}$ and ${}^{12}_6\text{C}$. In which way are the two alike? In which way are they different?
- How can an electron be expelled from a nucleus in β decay if the nucleus has no electrons?
- Use **Figure 30-5** and **Table 30-1** to estimate in how many days a sample of ${}^{131}_{53}\text{I}$ would have $3/8$ its original activity.
- 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.

Heads Up

Problem

How does the activity of radioactive materials decrease over time? Devise a model of the radioactive decay system.

Materials

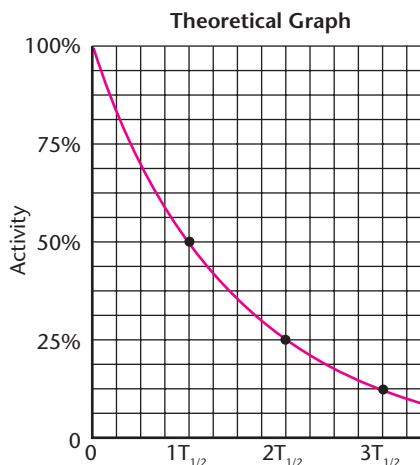
20 pennies
graph paper

Procedure

1. Set up a data table as shown, or use a spreadsheet. Turn the pennies so that they are all heads. In this simulation, a heads indicates that the nucleus has not decayed.
2. Flip each coin separately and put the heads and tails into separate piles.
3. Record the number of heads on your data sheet or spreadsheet. Remove the pennies that came up tails.
4. Flip all remaining coins and separate the heads and tails. Count the number of heads and record the value.
5. Repeat steps 2–4 one more time.
6. Share your data with four other students and copy their data onto your data sheet or spreadsheet.

Analyze and Conclude

1. **Comparing Data** Did each person have the same number of heads after each trial?
2. **Analyzing Data** Is the number of heads close to what you expected?
3. **Graphing Results** Total the number of heads remaining for each trial. Make a graph of the number of heads (vertical) verses the trial (horizontal). If possible, use a graphing calculator or a computer plotting program.

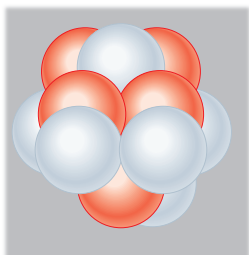


Data and Observations						
	you	other students				total
Begin	20	20	20	20	20	100
Trial 1						
Trial 2						
Trial 3						

4. **Interpreting Graphs** Evaluate and compare your results to the theoretical graph shown in the lab. Propose explanations for any differences you notice.
5. **Understanding Procedures** Explain the rationale for collecting the results from other students and using the sum of all the results for graphing and analysis.

Apply

1. Radioactive materials are often used in medicine for diagnostic purposes. Are these radioisotopes likely to have a short or a long half-life? Explain.
2. Laws mandate that hospitals keep radioactive materials for 10 half-lives before disposing of them. Calculate the fraction of the original activity left at the end of 10 half-lives.



The Building Blocks of Matter

30.2

Why are some isotopes radioactive while others are stable? What holds the nucleus together against the repulsive force of the charged protons? These questions and many others motivated some of the best physicists to study the nucleus. The tiny size of the nucleus meant that new tools had to be developed for this study. Studies of nuclei have also led to an understanding of the structure of the particles found in the nucleus, the proton and the neutron, and the nature of the forces that hold the nucleus together.

Nuclear Bombardment

The first tool used to study the nucleus was the product of radioactivity. Rutherford bombarded many elements with α particles, using them to cause a nuclear reaction. For example, when nitrogen gas was bombarded, Rutherford noted that high-energy protons were emitted from the gas. A proton has a charge of 1, while an α particle has a charge of 2. Rutherford hypothesized that the nitrogen had been artificially transmuted by the α particles. The unknown results of the transmutation can be written A_ZX , and the nuclear reaction can be written as follows.



Simple arithmetic shows that the atomic number of the unknown isotope is $Z = 2 + 7 - 1 = 8$. The mass number is $A = 4 + 14 - 1 = 17$. From **Table F-6** in the Appendix, you can see that the isotope must be ${}^{17}_8\text{O}$. The transmutation of nitrogen to oxygen is shown in **Figure 30-6**. The identity of this ${}^{17}_8\text{O}$ isotope was confirmed with a mass spectrometer several years after Rutherford's experiment.

Bombarding ${}^9_4\text{Be}$ with α particles produced a radiation more penetrating than any that had been discovered previously. In 1932, Irene Joliot-Curie (daughter of Marie and Pierre Curie) and her husband, Frederic Joliot, discovered that high-speed protons were expelled from paraffin wax that was exposed to this new radiation from beryllium. In the same year, James Chadwick showed that the particles emitted from

OBJECTIVES

- **Describe** the operation of particle detectors and particle accelerators.
- **Define** antiparticles and **calculate** the energy of γ rays emitted when particles and their antiparticles annihilate one another.
- **Describe** the quark and lepton model of matter and **explain** the role of force carriers.

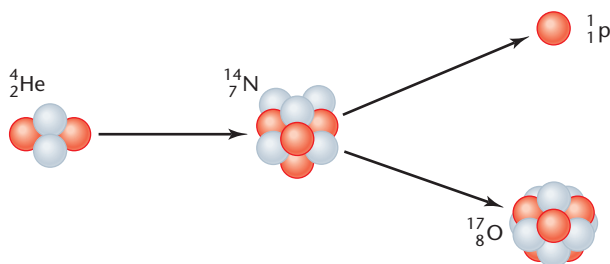
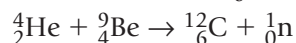


FIGURE 30-6 Oxygen-17 can be produced from the artificial transmutation of nitrogen.

beryllium were uncharged, but they had approximately the same mass as protons. This is how he discovered the neutron. The reaction can be written using the symbol for the neutron, ${}_0^1\text{n}$.



Neutrons, being uncharged, are not repelled by the nucleus. As a result, neutrons often are used to bombard nuclei.

As Rutherford had showed, alpha particles are useful in producing nuclear reactions. Alpha particles from radioactive materials, however, have fixed energies. In addition, sources that emit a large number of particles per second are difficult to produce. Thus, methods of artificially accelerating particles to high energies are needed. Energies of several million electron volts are required to produce nuclear reactions. Consequently, several types of particle accelerators have been developed. The linear accelerator, the cyclotron, and the synchrotron are the accelerator types in greatest use today.

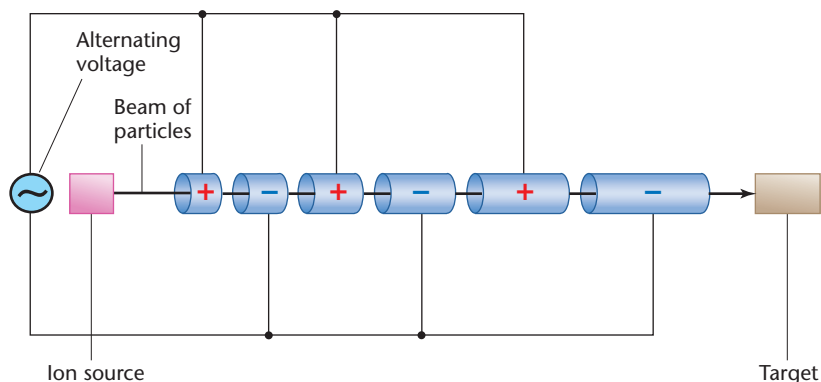
Linear Accelerators

A linear accelerator 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 30–7b**. 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 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.

FIGURE 30–7 The linear accelerator at Stanford University is 3.3 km long **(a)**. Protons are accelerated by changing the charge on the tubes as the protons move **(b)**. (Not drawn to scale.)



a



b

Linear accelerators can be used with both electrons and protons. The largest linear accelerator, at Stanford University in California, is shown in **Figure 30–7a**. It is 3.3 km long and accelerates electrons to energies of 20 GeV (2×10^{10} eV).

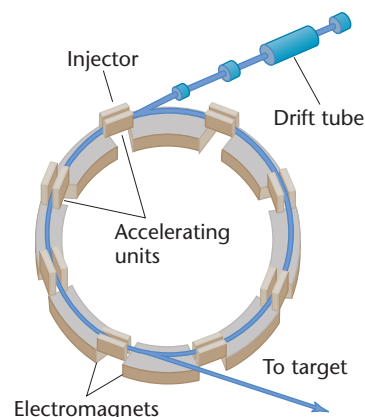
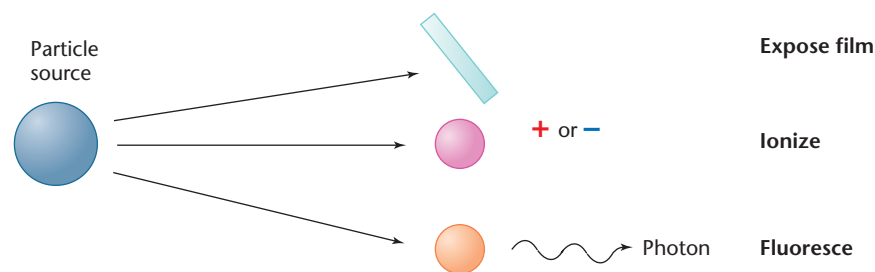
The Synchrotron

An accelerator may be made smaller by using a magnetic field to bend the path of the particles into a circle. In a device known as a synchrotron, the bending magnets are separated by accelerating regions, as shown in **Figure 30–8a**. 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 30–8b**. Protons there reach energies of 1 TeV (10^{12} eV). Two proton beams travel the circle in opposite directions. The beams collide in an interaction region and the results are studied.

Particle Detectors

Once particles are produced, they 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 weak human senses. Your hand will stop an alpha 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. Fortunately, scientists have devised tools to detect and distinguish the products of nuclear reactions.

In the last section you read how uranium samples fogged photographic plates. When α particles, β particles, or γ particles strike photographic film, the film becomes fogged, or exposed. Thus, photographic film can be used to detect these particles and rays. Many other devices are used to detect charged particles and γ 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 30–9**.



a

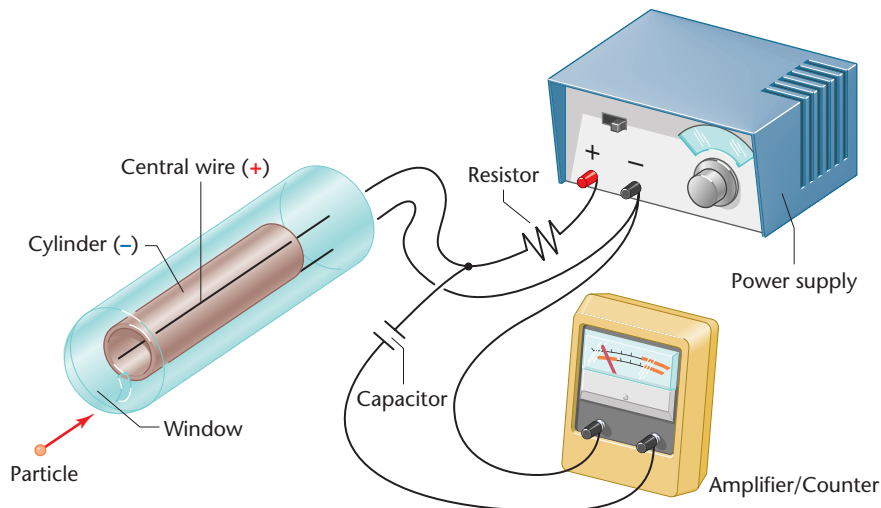


b

FIGURE 30–8 The synchrotron is a circular accelerator. Magnets are used to control the path and acceleration of the particles (**a**). Fermi Laboratory's synchrotron has a diameter of 2 km (**b**).

FIGURE 30–9 Particles can be detected when they interact with matter, exposing film, charging the matter, or causing the matter to emit a photon.

FIGURE 30–10 Gamma rays from a radioactive source ionize the low-pressure gas in the Geiger-Mueller tube, allowing a pulse of current to flow between the central wire and the copper tube.



In the Geiger-Mueller tube, particles ionize gas atoms, as illustrated in **Figure 30–10**. The tube contains a gas at low pressure (10 kPa). At one end of the tube is a very thin window through which charged particles or gamma rays pass. Inside the tube is a copper cylinder with a negative charge. A rigid wire with a positive charge runs down the center of this cylinder. 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 produced is accelerated toward the copper cylinder by the potential difference. The electron is accelerated toward the positive wire. As these charged particles move toward the electrodes, they strike other atoms and form even more ions in their path.

Thus, an avalanche of charged particles is created and a pulse of current flows through the tube. The current causes a potential difference across a resistor in the circuit. The voltage is amplified and registers the arrival of a particle by advancing a counter or producing an audible signal, such as a click. The potential difference across the resistor then lowers the voltage across the tube so that the current flow stops. Thus, the tube is ready for the beginning of a new avalanche when another particle or gamma ray enters it.

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, the vapor tended to condense into small droplets on the ions. In this way, visible trails of droplets, or fog, were formed, as shown in **Figure 30–11**. In another detector, the bubble chamber, charged particles would pass through a liquid held just above the boiling point. In this case, the trails of ions would cause small vapor bubbles to form, marking the particle's trajectory.

Modern experiments use detection chambers that are like giant Geiger-Mueller tubes. Huge plates are separated by a small gap filled

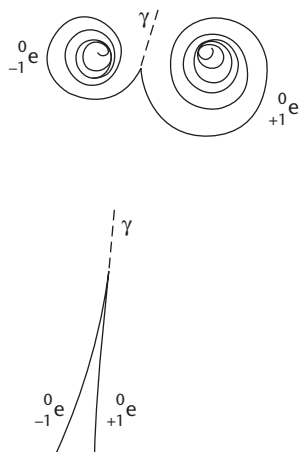


FIGURE 30–11 False-color bubble chamber photograph shows the symmetrical production of matter and antimatter.

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 produce discharges, and thus they do not leave tracks. 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 30–12a**. 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 30–12b**.

The Elementary Particles

The model of the hydrogen atoms in 1930 was fairly simple: a proton, a neutron, and orbiting electrons. There also was a particle with no mass called a gamma particle (photon). Different combinations of these four **elementary particles** seemed to describe the contents of the universe quite well. Yet there were other elementary particles that needed to be explained, such as the antineutrino and a positive electron that was found in 1932. Physicists tried to answer the questions: Of what is matter composed? What holds matter together? by devising more sophisticated particle detectors and accelerators.

In 1935, a remarkable hypothesis by Japanese physicist Hideki Yukawa spurred much research in the years to follow. Recall from Chapter 27 how the electric field propagates through space by means of an electromagnetic wave, that is, a photon. The interaction of the field on a charge produces an electrical force. In essence, the electrical force is carried through space by a photon. Could a particle carry the nuclear force as well? Yukawa hypothesized the existence of a new particle that could carry the nuclear force through space. He predicted that this new particle would have a mass intermediate between the electron and the proton; hence, it was called the mesotron, later shortened to meson. In 1947 this particle was discovered and is called π -meson or simply pion.

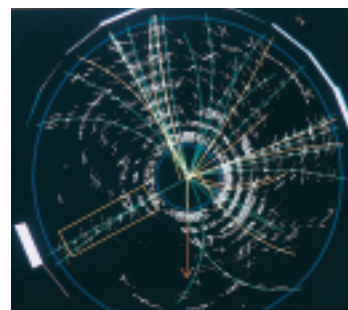
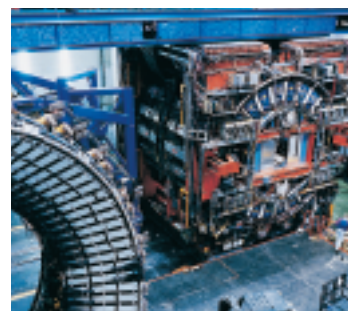


FIGURE 30–12 The Collider Detector at Fermilab (CDF) records the tracks from billions of collisions **(a)**. A CDF computer image of a top quark event **(b)**.

Pocket Lab

Follow the Tracks



Caution: Avoid extended contact with a radioactive source. Handle with extreme caution.

Prepare a cloud chamber by soaking the cloth ring in alcohol. Place the radioactive needle into the side of the cloud chamber and then place the chamber on a block of dry ice. After the chamber cools down, you should be able to observe the tracks of the radiation.

Analyze and Conclude Predict what might happen when you place a small neodymium magnet in the bottom of the center of the chamber. Try it. Describe the results.

Fundamental types of elementary particles Can the elementary particles be grouped or classified according to shared characteristics? Physicists now believe that all elementary particles can be grouped into three families labeled **quarks**, **leptons**, and **force carriers**. Quarks make up protons, neutrons, and mesons. Leptons are particles like electrons and antineutrinos. Quarks and leptons make up all the matter in the universe, whereas force carriers are particles that carry, or transmit, forces between matter. For example, photons carry the electromagnetic interaction. Eight particles, called gluons, carry the strong nuclear interaction that binds quarks into protons and the protons and neutrons into nuclei. Three particles, the weak bosons, are involved in the weak nuclear interaction, which operates in beta decay. The graviton is the name given to the yet-undetected carrier of the gravitational interaction. The properties of particles are summarized in **Table 30–2**.

Charges are given in units of the elementary charge, and masses are stated as energy equivalents, given by Einstein's formula, $E = mc^2$. The energy equivalent of these particles is much larger than the electron volt, and so is shown in MeV (mega-electron volts, or 10^6 eV) and GeV (giga-electron volts, or 10^9 eV).

Particles and Antiparticles

The α particles and γ rays emitted by radioactive nuclei have single energies that depend on the decaying nucleus. For example, the energy of the α particle emitted by thorium-234 is always 4.2 MeV. Beta particles, however, 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 β decay suggested to Niels Bohr that energy might not be conserved in

TABLE 30–2

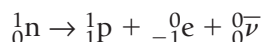
Quarks				Leptons			
Name	Symbol	Mass	Charge	Name	Symbol	Mass	Charge
down	d	333 MeV	$-1/3 e$	electron	e	0.511 MeV	$-e$
up	u	330 MeV	$2/3 e$	neutrino	ν_e	0	0

Force Carriers				
Force	Name	Symbol	Mass	Charge
Electromagnetic	photon	γ	0	0
Weak	Weak boson	W^+	80.2 GeV	$+e$
		W^-	80.2 GeV	$-e$
		Z^0	91.2 GeV	0
Strong	Gluon (8)	g	0	0
Gravitational	graviton (?)	G	0	0

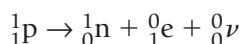


nuclear reactions. Wolfgang Pauli in 1931 and Enrico Fermi in 1934 suggested that an unseen neutral particle was emitted with the β particle. Named the **neutrino** ("little neutral one" in Italian) by Fermi, the particle, which is actually an antineutrino, was not directly observed until 1956.

In a stable nucleus, the neutron does not decay. A free neutron, or one in an unstable nucleus, can decay into a proton by emitting a β particle. Sharing the outgoing energy with the proton and β particle is an antineutrino, ${}^0_0\bar{\nu}$. The antineutrino has zero mass and is uncharged, but like the photon, it carries momentum and energy. The neutron decay equation is written as follows.



When an isotope decays by emission of a **positron**, or antielectron, a process like β decay occurs. A proton within the nucleus changes into a neutron with the emission of a positron, ${}^0_1\text{e}$, and a neutrino, ${}^0_0\nu$



The weak nuclear interaction The decay of neutrons into protons and protons into neutrons cannot be explained by the strong force. The existence of β decay indicates that there must be another interaction, the **weak nuclear force**, acting in the nucleus. This second type of nuclear force is much weaker than the strong nuclear force, and it can be detected only in certain types of radioactive decay.

Annihilation and production The positron is an example of an **antiparticle**, a particle of antimatter. The electron and positron have the same mass and charge magnitude; however, the sign of their charge is opposite. When a positron and an electron collide, the two can annihilate each other, resulting in energy in the form of γ rays, as shown in **Figure 30–13**. Matter is converted directly into energy. The amount of energy can be calculated using Einstein's equation for the energy equivalent of mass.

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.

$$E = 2(9.11 \times 10^{-31} \text{ kg})(3.00 \times 10^8 \text{ m/s})^2$$

$$E = 1.64 \times 10^{-13} \text{ J} \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} \right)$$

$$E = 1.02 \times 10^6 \text{ eV or } 1.02 \text{ MeV}$$

Recall from Chapter 27 that $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. When a positron and an electron at rest annihilate each other, the sum of the energies of the γ rays emitted is 1.02 MeV.

F.Y.I.

If I could remember the names of all these particles, I'd be a botanist.

Enrico Fermi

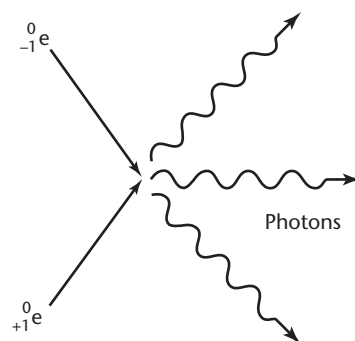


FIGURE 30–13 The collision of a positron and an electron results in gamma ray production.

Phantom Tracks

➡ Answers question from page 690.



F.Y.I.

The electromagnetic attraction of an electron and a positron is 4.2×10^{42} times stronger than their gravitational attraction.

—Isaac Asimov's
Book of Facts

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

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

This 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. Matter and antimatter particles must always be produced in pairs.

The production of a positron-electron pair is shown in the chapter-opening photograph of bubble chamber tracks. A magnetic field around the bubble chamber causes the oppositely charged particles to curve in opposite directions. The γ ray that produced the pair produced no track. If the energy of the γ ray is larger than 1.02 MeV, the excess energy goes into kinetic energy of the positron and electron. The positron soon collides with another electron and they are both annihilated, resulting in the production of two or three γ rays with a total energy of no less than 1.02 MeV.

Particle conservation Each quark particle and each lepton particle also has its antiparticle. The antiparticles are identical to the particles except that for charged particles, an antiparticle will have the opposite charge. 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. Consequently, the number of charge carriers is not conserved; the total charge, however, is conserved. 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, aptly named an antineutron.

Practice Problems

13. The mass of a proton is 1.67×10^{-27} kg.
- Find the energy equivalent of the proton's mass in joules.
 - Convert this value to eV.
 - Find the smallest total γ ray energy that could result in a proton-antiproton pair.

How It Works

Smoke Detectors

A smoke detector is a sensing device that sounds an alarm when it detects the presence of smoke particles in the air. Two types are commonly available. One uses photons to detect the smoke; the other uses alpha particles and is more popular because it is less expensive and more sensitive.

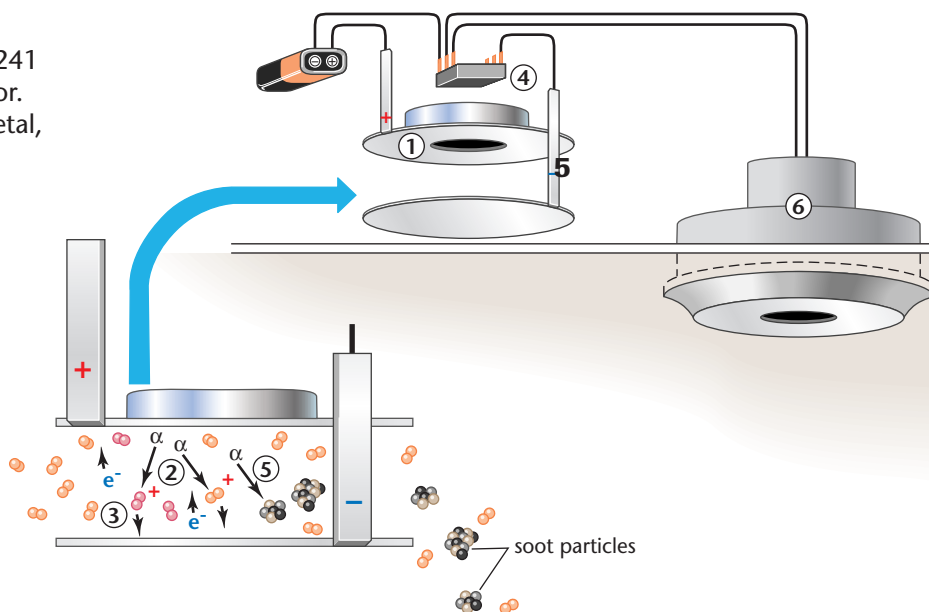


1 A small quantity, about 0.2 mg, of Americium-241 is housed in the detector. Americium, a silvery metal, is radioactive with a half-life of 432 years. As $^{241}_{95}\text{Am}$ decays, it emits alpha particles and low-energy gamma rays.

2 Alpha particles emitted by Am-241 collide with the oxygen and nitrogen in the air in the detector's chamber to produce ions.

3 A low-level electric voltage is applied across two electrodes in the chamber. The ions move in response to the voltage, causing a small electric current to flow.

4 A battery-operated microchip monitors this current. Any decrease in the current is detected by the microchip.



5 As smoke enters the detector's chamber, soot particles absorb some of the alpha particles.

6 Fewer alpha particles means fewer ionized air molecules, and consequently there is less current across the electrodes. The microchip senses this change and activates the alarm.

Thinking Critically

1. Why do ionizing smoke detectors contain an isotope that undergoes alpha decay rather than beta or gamma decay?
2. Explain how ions permit an electric current in the detection chamber.

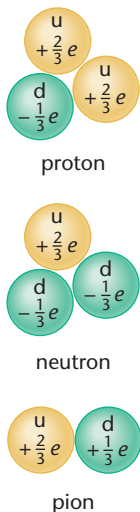


FIGURE 30–14 Even though quarks have fractional charge, all the particles they make have whole-number charge.

The Quark Model of Nucleons

The quark model describes nucleons, the proton and the neutron, as an assembly of quarks. The nucleons are each made up of three quarks. The proton has two up quarks, u , (charge $+2/3 e$) and one down quark, d , (charge $-1/3 e$), as shown in **Figure 30–14**. A proton is described as $p = uud$. The charge on the proton is the sum of the charges of the three quarks, $(2/3 + 2/3 + -1/3)e = +e$. The neutron is made up of one up quark and two down quarks, $n = udd$. The charge of the neutron is zero, $(2/3 + -1/3 + -1/3)e = 0$.

Individual quarks cannot be observed, because the strong force that holds them together becomes larger as the quarks are pulled farther apart. In this sense, 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 the result of the emission and absorption of gluons that carry the force.

Quark model of beta decay The weak interaction involves three force carriers: W^+ , W^- , and Z^0 bosons. The weak force exhibits itself in beta decay, the decay of a neutron into a proton, electron, and antineutrino. As was shown before, only one quark in the neutron and the proton is different. Beta decay in the quark model occurs in two steps, as shown in **Figure 30–15b**. First, one d quark in a neutron changes to a u quark with the emission of a W^- boson.

$$d \rightarrow u + W^-$$

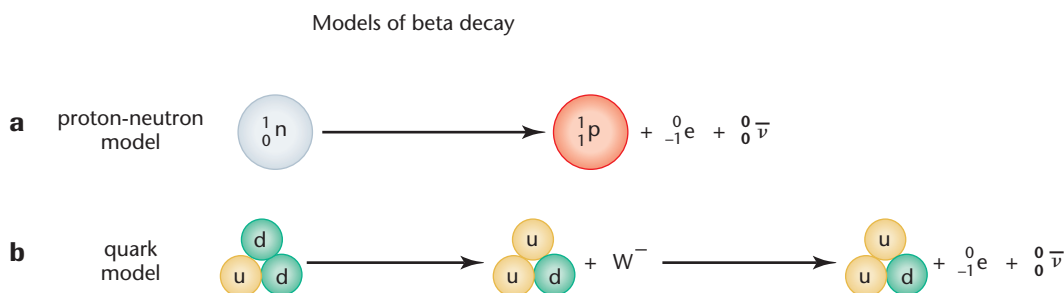
Then the W^- boson decays into an electron and an antineutrino.

$$W^- \rightarrow e^- + \bar{\nu}$$

Similarly, in the decay of a proton, a neutron and a W^+ boson are emitted. The weak boson then decays into a positron and a neutrino.

The emission of a 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 was first detected in 1979. The W^+ , W^- , and Z^0 bosons were first observed directly in 1983.

FIGURE 30–15 Beta decay can be represented by two different models, proton-neutron or quark.



Unification theories The differences between 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. However, there are some similarities among the interaction. 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. In the high-energy collisions produced in accelerators, the electromagnetic and weak interactions have the same strength and range.

Astrophysical theories of supernovae indicate that during massive stellar explosions, 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 are presently trying to create a **grand unification theory** that includes 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.

Additional quarks and leptons Bombardment of particles at high energies creates many particles of medium and large mass that have very short lifetimes. Some of these particles are combinations of two or three u or d quarks or a quark-antiquark pair. Combinations of the u and d quarks and antiquarks, however, cannot account for all the particles produced. Combinations of four other quarks are necessary to form all known particles. Two additional pairs of leptons also are produced in high-energy collisions. The additional quarks and leptons are listed in **Table 30-3**.

No one knows why there are six quarks and six leptons or whether there are still other undiscovered particles. Physicists are planning to build higher-energy accelerators to attempt to answer this question. **Figure 30-16** describes the fundamental building blocks of matter and where they might be found.

The branch of physics that is involved in the study of these particles is called elementary particle physics. The field is very exciting because new discoveries occur almost every week. Each new discovery, however, seems to raise as many questions as it answers. The question of what makes up the universe does not yet have a complete answer.

TABLE 30-3

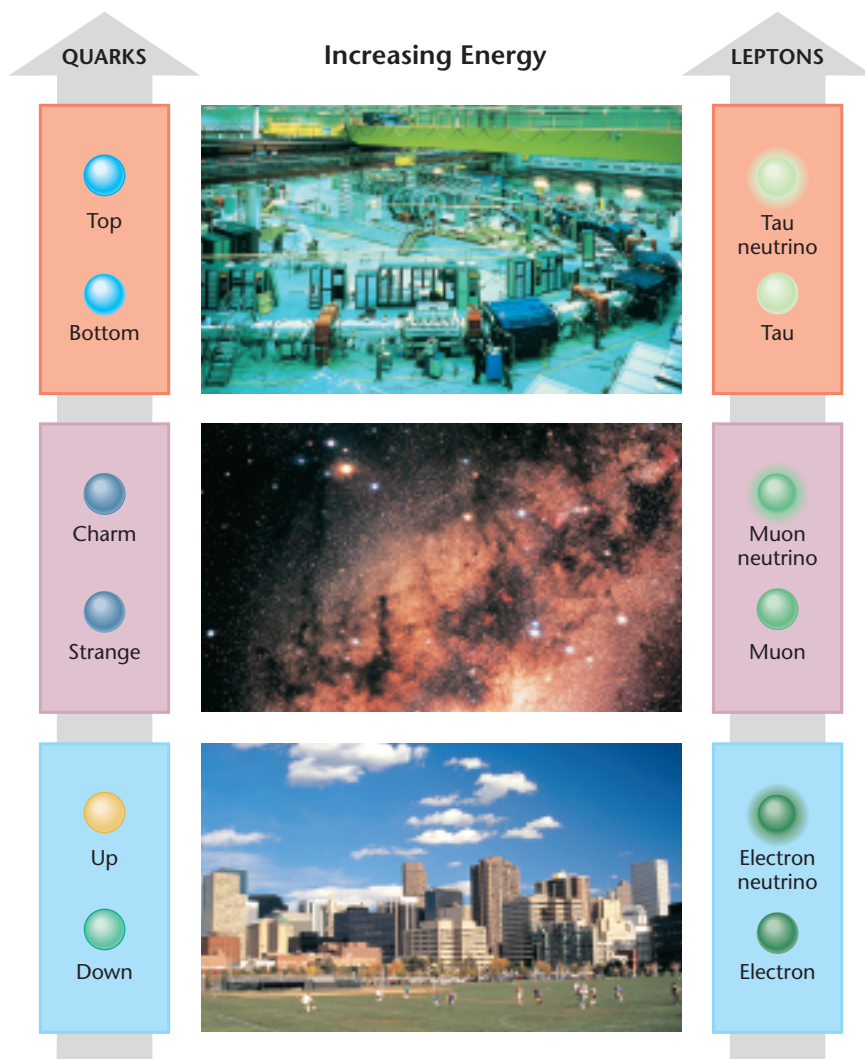
Additional Quarks

Name	Mass
strange	110 MeV
charm	1500 MeV
bottom	4250 MeV
top	180 GeV

Additional Leptons

Name	Mass
muon	105.7 MeV
muon neutrino	0
tau	1777 MeV
tau neutrino	0

FIGURE 30–16 The known quarks and leptons are divided into three families. The everyday world is made from particles in the bottom family. Particles in the middle group are found in cosmic rays and are routinely produced in particle accelerators. Particles in the top family are believed to have existed briefly during the earliest moments of the Big Bang and are created in high-energy collisions.

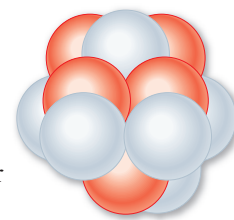


30.2 Section Review

1. Why would a more energetic proton than a neutron be required to produce a nuclear reaction?
2. Protons in the Fermi Laboratory accelerator, **Figure 30–8**, move counterclockwise. In what direction is the magnetic field of the bending magnets?
3. Research and critique the quark model.
4. **Figure 30–11** shows the production of two electron/positron pairs. Why does the bottom set of tracks curve less than the top pair of tracks?
5. **Critical Thinking** Write an equation for beta decay in which you write the quarks comprising both the neutron and the proton. Include both steps in the decay.

CHAPTER 30 REVIEW

Summary



Key Terms

30.1

- atomic mass unit
- atomic number
- mass number
- strong nuclear force
- nuclide
- radioactive
- alpha decay
- transmute
- beta decay
- gamma decay
- nuclear reaction
- half-life
- activity

30.2

- elementary particle
- quark
- lepton
- force carrier
- neutrino
- positron
- weak nuclear force
- antiparticle
- pair production
- grand unification theory

30.1 Radioactivity

- The number of protons in a nucleus is given by the atomic number.
 - The sum of the numbers of protons and neutrons in a nucleus is equal to the mass number.
 - Atoms having nuclei with the same number of protons but different numbers of neutrons are called isotopes.
 - An unstable nucleus undergoes radioactive decay, 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 sum 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.
 - The number of decays of a radioactive sample per second is the activity.
- gamma rays, or other nuclei can produce a nuclear reaction.
- Linear accelerators and synchrotrons produce high-energy particles.
 - The Geiger-Mueller counter and other particle detectors use the ionization caused by charged particles passing through matter.
 - When antimatter and matter combine, all mass is converted into energy or lighter matter-antimatter particle pairs.
 - By pair production, energy is transformed into a matter-antimatter particle pair.
 - The weak interaction, or weak force, operates in beta decay. The strong force binds the nucleus together.
 - All matter appears to be made up of two families of particles, quarks and leptons.
 - Matter interacts with other matter through a family of particles called force carriers.

30.2 The Building Blocks of Matter

- Bombardment of nuclei by protons, neutrons, alpha particles, electrons,

Key Equation

30.2

$$E = mc^2$$

Reviewing Concepts

Section 30.1

1. Define the term *transmutation* as used in nuclear physics and give an example.
2. What are the common names for an α particle, β particle, and γ radiation?
3. What happens to the atomic number and mass number of a nucleus that emits an alpha particle?
4. What happens to the atomic number and mass number of a nucleus that emits a beta particle?

5. What two quantities must always be conserved in any nuclear equation?

Section 30.2

6. Why would a linear accelerator not work with a neutron?
7. In which of the four interactions (strong, weak, electromagnetic, and gravitational) do the following particles take part?
 - a. electron
 - b. proton
 - c. neutrino

8. What happens to the atomic number and mass number of a nucleus that emits a positron?
9. Give the symbol, mass, and charge of the following particles.
 - a. proton
 - b. positron
 - c. α particle
 - d. neutron
 - e. electron

Applying Concepts

10. Which are generally more unstable, small or large nuclei?
11. Which isotope has the greater number of protons, uranium-235 or uranium-238?
12. Which is usually larger, A or Z ? Explain.
13. Which is most like an X ray: alpha particles, beta particles, or gamma particles?
14. Could a deuteron, ${}^2_1\text{H}$, decay through alpha decay? Explain.
15. Which will give a higher reading on a radiation detector: a radioactive substance that has a short half-life or an equal amount of a radioactive substance that has a long half-life?
16. Why is carbon dating useful in establishing the age of campfires but not the age of a set of knight's armor?
17. What would happen if a meteorite made of antiprotons, antineutrons, and positrons landed on Earth?
21. Find the symbols for the elements that are shown by the following symbols, where X replaces the symbol for the element.
 - a. ${}^{18}_9X$
 - b. ${}^{241}_{95}X$
 - c. ${}^{21}_{10}X$
 - d. 7_3X
22. A radioactive bismuth isotope, ${}^{214}_{83}\text{Bi}$, emits a β particle. Write the complete nuclear equation, showing the element formed.
23. A radioactive polonium isotope, ${}^{210}_{84}\text{Po}$, emits an α particle. Write the complete nuclear equation, showing the element formed.
24. An unstable chromium isotope, ${}^{56}_{24}\text{Cr}$, emits a β particle. Write a complete equation showing the element formed.
25. During a reaction, two deuterons, ${}^2_1\text{H}$, combine to form a helium isotope, ${}^3_2\text{He}$. What other particle is produced?
26. On the sun, the nuclei of four ordinary hydrogen atoms combine to form a helium isotope, ${}^4_2\text{He}$. What particles are missing from the following equation for this reaction?
$$4{}^1_1\text{H} \rightarrow {}^4_2\text{He} + ?$$
27. Write a complete nuclear equation for the transmutation of a uranium isotope, ${}^{227}_{92}\text{U}$, into a thorium isotope, ${}^{223}_{90}\text{Th}$.
28. 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?
29. If the half-life of an isotope is two years, what fraction of the isotope remains after six years?
30. The half-life of strontium-90 is 28 years. After 280 years, how would the intensity of a sample of strontium-90 compare to the original intensity of the sample?
31. ${}^{238}_{92}\text{U}$ decays by α emission and two successive β emissions back into uranium again. Show the three nuclear decay equations and predict the atomic mass number of the uranium formed.
32. A Geiger-Mueller counter registers an initial reading of 3200 counts while measuring a radioactive substance. It registers 100 counts 30 hours later. What is the half-life of this substance?

Problems

Section 30.1

18. An atom of an isotope of magnesium has an atomic mass of about 24 u. The atomic number of magnesium is 12. How many neutrons are in the nucleus of this atom?
19. An atom of an isotope of nitrogen has an atomic mass of about 15 u. The atomic number of nitrogen is 7. How many neutrons are in the nucleus of this isotope?
20. List the number of neutrons in an atom of each of the following isotopes.
 - a. ${}^{112}_{48}\text{Cd}$
 - b. ${}^{209}_{83}\text{Bi}$
 - c. ${}^{208}_{83}\text{Bi}$
 - d. ${}^{80}_{35}\text{Br}$
 - e. ${}^1_1\text{H}$
 - f. ${}^{40}_{18}\text{Ar}$

33. A 14-g sample of $^{14}_6\text{C}$ contains Avogadro's number, 6.02×10^{23} , of nuclei. A 5.0 g-sample of C-14 will have how many nondecayed nuclei after 11 460 years?
34. A 1.00- μg sample of a radioactive material contains 6.0×10^{14} nuclei. After 48 hours, 0.25 μg of the material remains.
- What is the half-life of the material?
 - How could one determine the activity of the sample at 24 hours using this information?

Section 30.2

35. What would be the charge of a particle composed of three u quarks?
36. The charge of an antiquark is opposite that of a quark. A pion is composed of a u quark and an anti-d quark. What would be the charge of this pion?
37. Find the charge of a pion made up of
- u and anti-u quark pair.
 - d and anti-u quarks.
 - d and anti-d quarks.
38. The synchrotron at the Fermi Laboratory has a diameter of 2.0 km. Protons circling in it move at approximately the speed of light.
- How long does it take a proton to complete one revolution?
 - 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?
 - How long does it take the protons to be accelerated to 400.0 GeV?
 - How far do the protons travel during this acceleration?



Extra Practice For more practice solving problems, go to **Extra Practice Problems, Appendix B.**

Critical Thinking Problems

39. Gamma rays carry momentum. The momentum of a gamma ray of energy E_γ is equal to E_γ/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?
40. 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?

Going Further



Using a Graphing Calculator An archaeological expedition group in Jerusalem finds three wooden bowls, each in a different part of the city. An analysis of the levels of carbon-14 reveals that the three bowls have 90%, 75%, and 60% of the carbon-14 one would expect to find in a similar bowl made today. The equation for the decay of carbon-14 is $y = 100 \times 2^{(-x/5730)}$ where y is the percentage of carbon-14 remaining and x is the age of the object in years. Graph this equation on a graphing calculator with axes scaled from 0 to 5000 years and from 100% to 50%. Trace along the equation to find the age of the three objects.

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