CHAPTER

30 The Nucleus

Phantom Tracks

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?

Chapter Outline

Rutherford not only established the existence of the nucleus, but he did some of the early experiments to discover its structure. Modern accelerators and detectors have given physicists the ability to study nuclei and the particles that compose them with much greater precision. The chapter-opening photo shows trails of subatomic particles moving to the left in a bubble chamber. These charged particles are bent by a magnetic field. The direction of the curve shows their charge. The faster they are moving, the less the bend. Thus their momentum can be determined as well. We will see how this and other tools have enlarged our knowledge of the ultimate building-blocks of matter.

Concept Check

The following terms or concepts from earlier chapters are important for a good understanding of this chapter. If you are not familiar with them, you should review them before studying this chapter.

- conservation of energy, Chapter 11
- electric force on charged particles, Chapter 20
- magnetic force on charged particle, Chapter 24
- Rutherford scattering, structure of the atom, Chapter 24

Objectives

- define atomic number and mass number; find the charge and mass of a nucleus.
- define an isotope and a nuclide; calculate the number of neutrons, protons, and electrons in an isotope.
- describe three modes of radioactive decay; explain the changes in atomic number or mass number for each mode; write equations for the three forms of radioactive decay.
- define half-life; calculate the amount of material and its activity remaining after a given number of half-lives.

30.1 RADIOACTIVITY

After the discovery of radioactivity by Becquerel in 1896, many scientists studied this new phenomenon. In Canada, Ernest Rutherford and Frederick Soddy discovered that uranium atoms were changed, or transmuted, to other atoms. The French scientists Marie and Pierre Curie discovered the new elements polonium and radium in samples of radioactive uranium. One of the first results of radioactivity studies was an understanding of the composition of the atomic nucleus.

Description of the Nucleus

Rutherford's analysis of his scattering experiments predicted that the number of α particles deflected through a given angle should be proportional to the square of the charge of the nucleus of the atom. At that time, only the mass of an atom was known. The number of electrons, and thus the charge of the nucleus, was unknown.

Rutherford and his co-workers experimented with sheets of carbon, aluminum, and gold. In each case, the charge of the nucleus was found to be roughly half the atomic mass times the elementary unit of charge. Since each electron carries one elementary charge, the number of electrons in an atom is equal to roughly half the atomic mass number. The carbon nucleus has a charge of 6, so the carbon atom must contain 6 electrons. Using a similar argument, aluminum contains 13 electrons and gold 79 electrons.

Protons are the positively-charged particles in a nucleus.

The atom is neutral, so the nucleus must contain positive charge. The **proton** is the name given to the nucleus of the hydrogen atom. The proton is positively charged with one unit of elementary charge. Its mass is approximately one **atomic mass unit**, u. The number of protons in a nucleus, which, in a neutral atom, is equal to the number of electrons surrounding the nucleus, is called the atom's **atomic number**, Z. All atoms of a given element contain the same number of protons. Thus carbon always has 6 protons and aluminum 13. Their atomic numbers are $Z = 6$ for carbon and $Z = 13$ for aluminum.

The atomic number is the number of protons in the nucleus.

FIGURE 30–1. Many countries have issued commemorative stamps documenting the history of radioactivity.

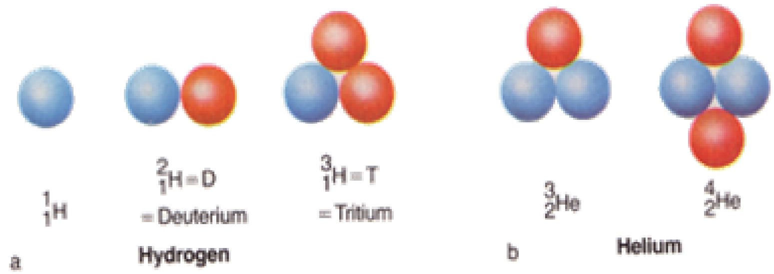

FIGURE 30–2. The isotopes of hydrogen (a) and helium (b). Protons are blue and neutrons are red.

The mass of the carbon atom, however, is the mass of 12 protons, not 6. To account for the excess mass in the nucleus, Rutherford postulated the existence of a neutral particle with a mass of a proton. In 1932 James Chadwick, a student of Rutherford, demonstrated the existence of this particle, called the neutron. A **neutron** is a particle with no charge and with a mass almost equal to that of the proton.

Neutrons are uncharged particles in the nucleus.

The nucleus of every atom except hydrogen contains both neutrons and protons. The sum of the numbers of protons and neutrons is equal to the **mass number**, *A*. The mass of the nucleus is approximately equal to the mass number, *A*, multiplied by the atomic mass unit (u), 1.66×10^{-27} kg. The mass of the nucleus in atomic mass units is approximately equal to the atomic mass number. The mass number of carbon is 12, while that of aluminum is 27. Elements with 20 or fewer protons have roughly equal numbers of protons and neutrons. Heavier elements, however, contain more neutrons than protons.

The mass number is the sum of the numbers of protons and neutrons in a nucleus.

How large is the nucleus? Rutherford had found that the nucleus is a very small body in the centre of the atom. Today it is known that the nucleus is almost spherical and has a diameter ranging from 2.6 fm (2.6×10^{-15} m) in hydrogen to 16 fm in uranium.

Atoms with the same atomic number but different mass numbers are called isotopes.

Isotopes

Careful measurements of the mass of boron atoms consistently yielded 10.8 u. If, as was thought, the nucleus is made up of protons and neutrons, each with a mass of approximately 1 u, then the total mass of any atom should be near a whole number.

The puzzle of atomic masses that were not integral numbers of atomic mass units was solved with the mass spectrometer. The mass spectrometer demonstrated that an element could have atoms with different masses. For example, when analysing 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 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 different numbers of neutrons, Figure 30–2. All isotopes of an element have the same number of electrons around the nucleus and behave the same chemically.

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.

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. For information contact:

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

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 many isotopic forms that occur naturally. The mass of the isotope of carbon, ${}^{12}_{6}C$, is now used to define the mass unit. One u is defined to be 1/12 the mass of the ${}^{12}_{6}C$ isotope.

A special method of notation is used to describe an isotope. A subscript representing the atomic number, Z, is written to the lower left of the symbol for the element. A superscript written to the upper 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 ${}^{20}_{10}Ne$ and ${}^{22}_{10}Ne$.

Practice Problems

1. An isotope of oxygen has a mass number of 15. The atomic number of oxygen is 8. How many neutrons are in the nuclei of this isotope?
2. Three isotopes of uranium have mass numbers of 234, 235, and 238 respectively. The atomic number of uranium is 92. How many neutrons are in the nuclei of each of these isotopes?
3. How many neutrons are in an atom of the mercury isotope ${}^{200}_{80}Hg$?
4. ▶ Write the symbols for the three isotopes of hydrogen in Figure 30–2 with 0, 1, and 2 neutrons in the nucleus.

Radioactive Decay

Nuclei that decay are radioactive.

In 1896 Henri Becquerel was working with compounds containing the element uranium. To his surprise, he found that photographic plates 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 were also found to emit these penetrating rays. Materials that emit this kind of radiation are said to be **radioactive** and to undergo **radioactive decay**.

The decay of nuclei can produce α-, β-, or γ-particles.

In 1899 Rutherford discovered that uranium compounds produce three different kinds of radiation. He separated the radiations according to their penetrating ability and named them α (alpha), β (beta), and γ (gamma) radiation.

The α radiation can be stopped by a thick sheet of paper. Rutherford later showed that an α particle is the nucleus of a helium atom, ${}^{4}_{2}He$. Beta particles were later identified as high-speed electrons. Six millimetres of aluminum are needed to stop most β particles. Several centimetres of lead are required to stop γ rays, which proved to be high-energy photons. Alpha particles and γ rays are emitted with a specific energy that depends on the radioactive isotope. Beta particles, however, are emitted with a wide range of energies.

The emission of an α particle is a process called **α decay**. Since α particles contain protons and 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, A, of an α particle,

F.Y.I.

. . . science is awash with serendipity; science is hard work when done properly, but in the hard work there is joy and in the discovery there is abundant reward. . . .

Sherwin B. Nuland
Doctors: The Biography of Medicine, 1988

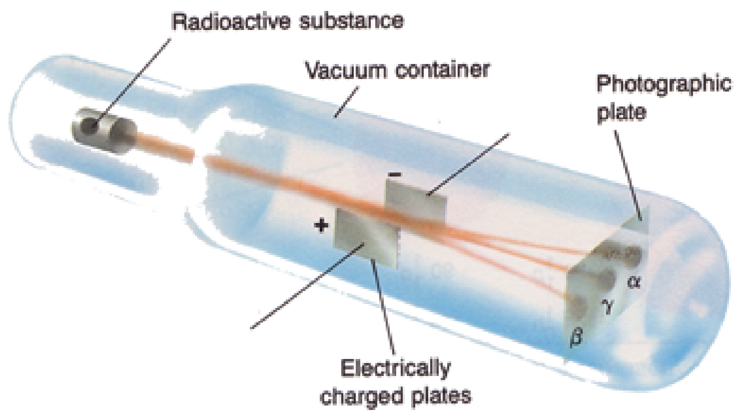


FIGURE 30–3. Alpha, beta, and gamma emissions behave differently in an electric field. Alpha and beta particles are deflected because of their charge.

^4_2He, is four, so the mass number, A, of the decaying nucleus is reduced by four. The atomic number, Z, of ^4_2He is two, and therefore the atomic number of the nucleus, the number of protons, is reduced by two. For example, when $^{238}_{92}U$ emits an α particle, the atomic number, Z, changes from 92 to 90. From Table D–5 of the Appendix, we find that $Z = 90$ is thorium. The mass number of the nucleus is $A = 238 - 4 = 234$. A thorium isotope, $^{234}_{90}Th$, is formed. The uranium isotope has been transmuted into thorium.

In α decay, the nucleus loses two charge units and four mass units.

Beta particles are negative electrons emitted by the nucleus. Since the mass of an electron is a tiny fraction of an atomic mass unit, the atomic mass of a nucleus that undergoes **β decay** is changed only a tiny amount. The mass number is unchanged. The nucleus contains no electrons. Rather, β decay occurs when a neutron is changed to a proton within the nucleus. An unseen neutrino accompanies each β decay. Neutrinos will be discussed later. The number of protons, and thus the atomic number, is increased by one. For example, the isotope $^{234}_{90}Th$, produced by the α decay of $^{238}_{92}U$, is unstable and emits a β particle. The $^{234}_{90}Th$ then becomes a protactinium isotope, $^{234}_{91}Pa$.

β particles are high speed electrons.

In β-decay, the atomic number is increased by one while the mass number is not changed.

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 **γ decay**.

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

In gamma decay, neither the atomic number nor the mass number is changed.

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.

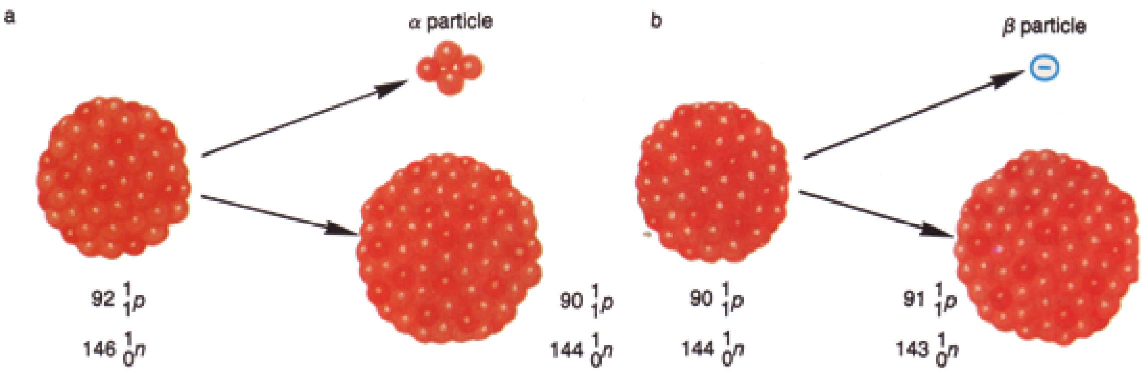


FIGURE 30–4. The emission of an alpha particle (a) by uranium-238 results in the formation of thorium-234. The emission of a beta particle (b) by thorium-234 results in the formation of protactinium-234.

While nuclear reactions can be described in words, or in pictures, such as Figure 30–4a, 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, the word equation for the change of uranium to thorium due to α decay is: uranium 238 yields thorium 234 plus an α particle. The nuclear equation for this reaction is

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

When writing nuclear equations, be sure the atomic numbers and mass numbers are the same before and after the reaction.

No nuclear particles are destroyed 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 is also conserved. Thus, the sum of the subscripts on the right is equal to the sum of the subscripts on the left.

Example Problem

Nuclear Equations—Alpha Decay

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 the emission of an α particle.

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

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

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

The symbol $^{0}_{0}\bar{\nu}$ represents an antineutrino that is emitted with the β particle. The sum of the superscripts on the right side of the equation equals the sum of the superscripts on the left side of the equation. Also, the sum of the subscripts on the right side of the equation equals the sum of the subscripts on the left side of the equation.

Example Problem

Nuclear Equations—Beta Decay

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

Solution: ${}^{209}_{82}Pb \rightarrow {}^{209}_{83}Bi + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$

Practice Problems

5. Write the nuclear equation for the transmutation of a radioactive uranium isotope, ${}^{234}_{92}U$, into a thorium isotope, ${}^{230}_{90}Th$, by the emission of an α particle.
6. Write the nuclear equation for the transmutation of a radioactive thorium isotope, ${}^{230}_{90}Th$, into a radioactive radium isotope, ${}^{226}_{88}Ra$, by the emission of an α particle.
7. Write the nuclear equation for the transmutation of a radioactive radium isotope, ${}^{226}_{88}Ra$, into a radon isotope, ${}^{222}_{86}Rn$, by the emission of an α particle.
8. A radioactive lead isotope, ${}^{214}_{82}Pb$, can change to a radioactive bismuth isotope, ${}^{214}_{83}Bi$, 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 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. In a second 1600 years, half of the remaining sample will have decayed. Only one fourth of the original amount will remain after 3200 years.

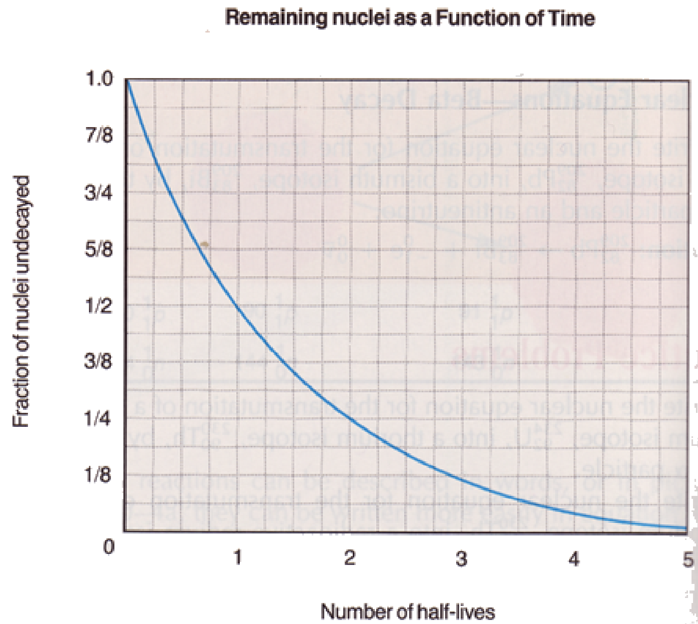
In a time interval equal to one half-life, half the mass of the radioactive element decays.

Table 30–1

Half-Life of Selected Isotopes

Element	Isotope	Half-life	Radiation produced
hydrogen	${}^{3}_{1}H$	12.3 a	β
carbon	${}^{14}_{6}C$	5730 a	β
iodine	${}^{131}_{53}I$	80.7 d	β
lead	${}^{212}_{82}Pb$	10.6 h	β
polonium	${}^{194}_{84}Po$	0.7 s	α
polonium	${}^{210}_{84}Po$	138 d	α
uranium	${}^{227}_{92}U$	1.1 min	α
uranium	${}^{235}_{92}U$	7.1×10^{8} a	α
uranium	${}^{238}_{92}U$	4.51×10^{9} a	α
plutonium	${}^{236}_{94}Pu$	2.85 a	α
plutonium	${}^{242}_{94}Pu$	3.79×10^{5} a	α

FIGURE 30–5. Use this half-life graph with Practice Problems 9 through 12.



Activity, or decays per second, is proportional to the number of radioactive atoms.

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 $^{131}_{53}I$ with a half-life of 8.07d. If the activity of a certain sample is 8×10^5 decays per second when the $^{131}_{53}I$ is produced, 8.07 d later its activity will be 4×10^5 decays per second. After another 8.07 d, its activity will be 2×10^5 decays per second. The SI unit for decays per second is a Bequerel, Bq.

Practice Problems

These problems require the use of Figure 30–5 and Table 30–1.

9. A sample of 1.0 g of tritium, ^3_1H, is produced. What will be the mass of tritium remaining after 24.6 years?

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

11. A sample of $^{210}_{84}Po$ is purchased for a physics class on September 1. Its activity is 2×10^6 decays per second. The sample is used in an experiment on June 1. What activity can be expected?

▶ **12.** Tritium, ^3_1H, was once used in some watches to produce a fluorescent glow so the watch 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 the watch, in comparison to its original brightness, when the watch is six years old?

PHYSICS LAB: Heads Up

Purpose

To formulate a model of radioactive decay.

Materials

- 20 pennies
- graph paper

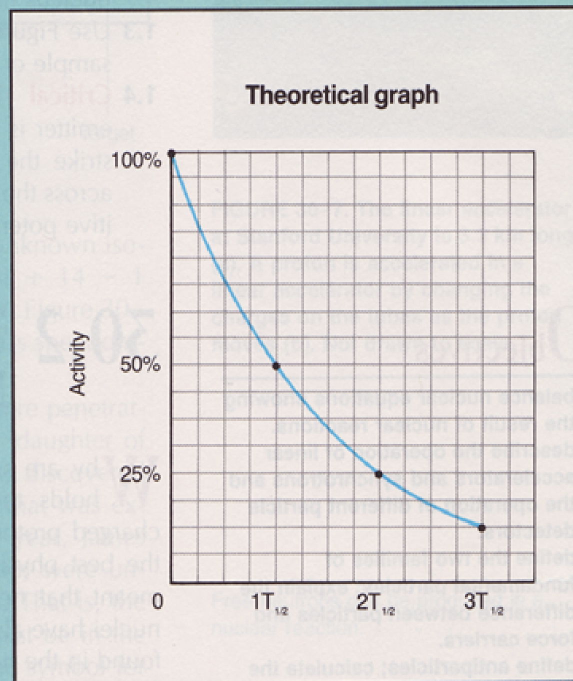
Procedure

1. Set up a data table as shown below. 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 separate the heads and tails.
3. Record the number of heads on your data sheet. 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.

Observations and Data

Data Table

Student	1	2	3	4	5	Total
Beginning Number	20	20	20	20	20	100
After Trial 1						
After Trial 2						
After Trial 3						



1. Did each person have the same number of heads after each trial?
2. Is the number of heads close to what you expected?

Analysis

1. Total the number of heads remaining for each trial. Make a graph of the number of heads (vertical) versus the trial (horizontal).
2. Compare your results to the theoretical graph shown in the lab.

Applications

1. 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.

CONCEPT REVIEW

1.1 Consider the pairs of nuclei: first, ${}^{12}_{6}C$ and ${}^{13}_{6}C$; second, ${}^{11}_{5}B$ and ${}^{12}_{6}C$. In which way is the first pair like the second? In which way are they different?

1.2 How can an electron be expelled from a nucleus in β decay if the nucleus has no electrons?

1.3 Use Figure 30–5 and Table 30–1 to estimate in how many days a sample of ${}^{131}_{53}I$ would have 3/8 its original activity.

1.4 **Critical Thinking:** An α emitter is used in smoke detectors. The 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.

Objectives

- **balance nuclear equations showing the result of nuclear reactions.**
- **describe the operation of linear accelerators and synchrotrons and the operation of different particle detectors.**
- **define the two families of fundamental particles; explain the difference between particles and force carriers.**
- **define antiparticles; calculate the energy of γ rays emitted when particles annihilate with their antiparticles.**
- **describe the quark content of the proton and neutron; understand the place of additional quark and lepton families in the quark model.**

30.2 THE BUILDING BLOCKS OF MATTER

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 more motivated many 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

Rutherford used α particles to cause nuclear reactions.

The first tool used was the result 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 one, while an α particle has a charge of two. Rutherford hypothesized that the nitrogen had been artificially transmuted by the α particles. The unknown results of the transmutation can be written ${}^{A}_{Z}X$, and the nuclear reaction can be written

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

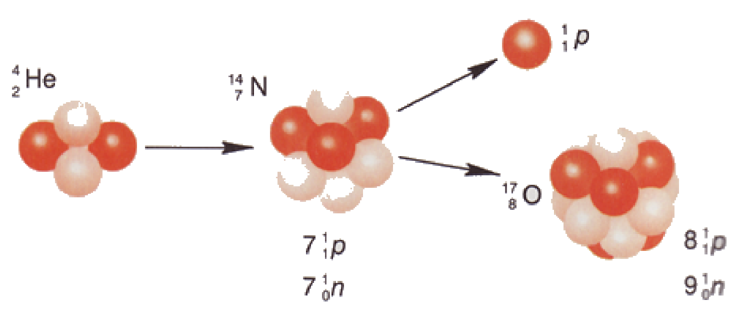
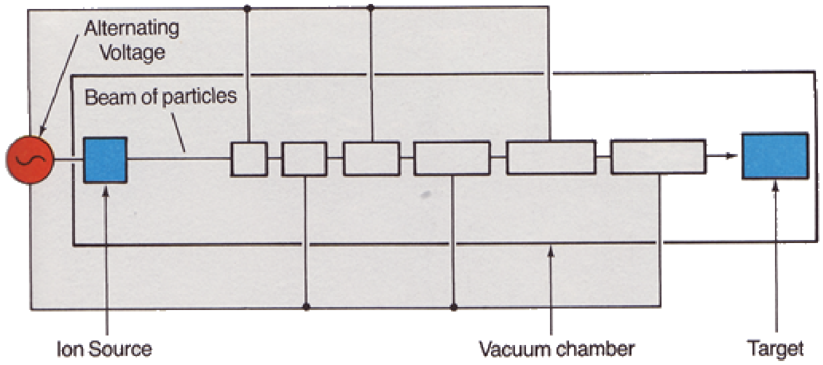


FIGURE 30–6. Production of oxygen-17 from the artificial transmutation of nitrogen.



b

a

FIGURE 30–7. The linear accelerator at Stanford University is 3.3 km long (a). A proton is accelerated in a linear accelerator by changing the charges on the tubes as the proton moves (b). Not drawn to scale.

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 Appendix Table D–5, the isotope must be $^{17}_{8}O$, Figure 30–6. The identity of the $^{17}_{8}O$ isotope was confirmed with a mass spectrometer several years later.

Bombarding $^{9}_{4}Be$ with α particles produced a radiation more penetrating than any previously discovered. In 1932, Irene 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 beryllium were uncharged, but had approximately the same mass as protons. That is, the beryllium emitted the particle Rutherford had theorized must be in the nucleus, the neutron. The reaction can be written using the symbol for the neutron, $^{1}_{0}n$.

Free neutrons can be produced in a nuclear reaction.

$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

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

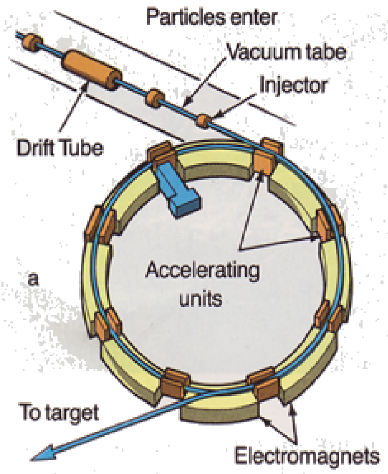
Alpha particles are useful in producing nuclear reactions. Alphas from radioactive materials, however, have fixed energies. In addition, sources that emit a large number of particles per second are difficult to produce. Thus methods of artificially accelerating particles to high energies are needed.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

Accelerators give more flexibility in producing nuclear reactions.

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, 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 proton moves 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 poten-

Alternating voltages accelerate charged particles along a straight line in a linear accelerator.



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).

tial of the second tube is negative with respect 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 proton rides 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.

Linear accelerators can be used with both electrons and protons. The largest linear accelerator is at Stanford University in California. It is 3.3 km long and accelerates electrons to energies of 20 GeV (2.0×10^{10} eV).

F. Y. I.

We dance round in a ring and suppose, but the secret sits in the middle and knows.

Robert Frost

The Synchrotron

A synchrotron uses magnetic fields to bend charged particles into circular paths.

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. 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, Figure 30–8. Protons there reach energies of 1 TeV (1.0×10^{12} eV). The Superconducting Super Collider (SSC), presently under construction near Dallas, Texas, is a synchrotron with two particle beams traveling around an 88-km ring in opposite directions. The beams will collide in several interaction regions and the results studied.

Particle Detectors

Particles that ionize matter can be detected by several means.

Photographic films become "fogged," or exposed, when α particles, β particles, or γ rays strike them. 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 when exposed to certain types of radiation. Thus, fluorescent substances can be used to detect radiation.

In the **Geiger-Mueller tube**, particles ionize gas atoms, Figure 30–9. 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 centre 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 new 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 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 contains an area supersaturated with water vapour or ethanol vapour. When charged particles travel through the chamber, leaving a trail of ions in their paths, the vapour tends to condense into small droplets on the ions. In this way, visible trails of droplets, or fog, are formed. The **bubble chamber** was similar, except that trails of small vapour droplets formed in a liquid held just above the boiling point.

Modern experiments use **spark chambers** that are like giant Geiger-Mueller tubes. Plates several metres in size are separated by a few centimetres. The gap is filled with a low-pressure gas. A discharge is pro-

POCKET LAB

FOLLOW THE TRACKS

Prepare the 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 radiations. Predict what might happen when you place a small neodymium magnet in the bottom of the centre of the chamber. Explain. Try it. Describe the results.

In a cloud chamber, particles create tracks of condensed vapour.

In a bubble chamber, trails of bubbles show paths of particles.

A spark chamber uses computers to analyse the trail of ions left by the particles.

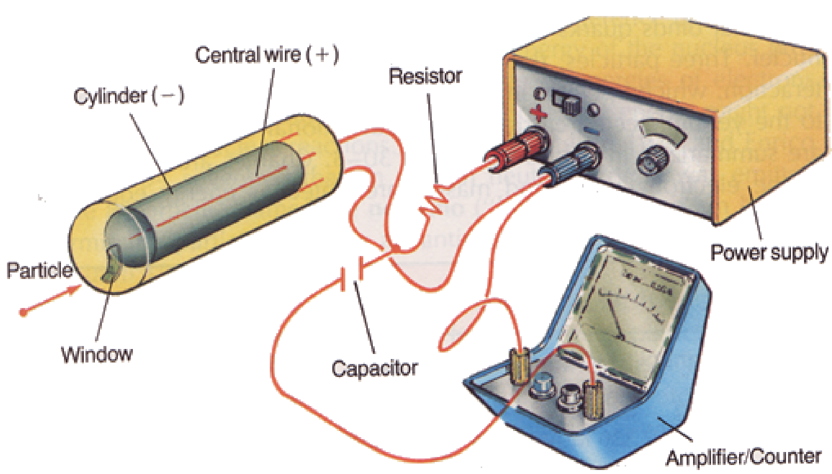
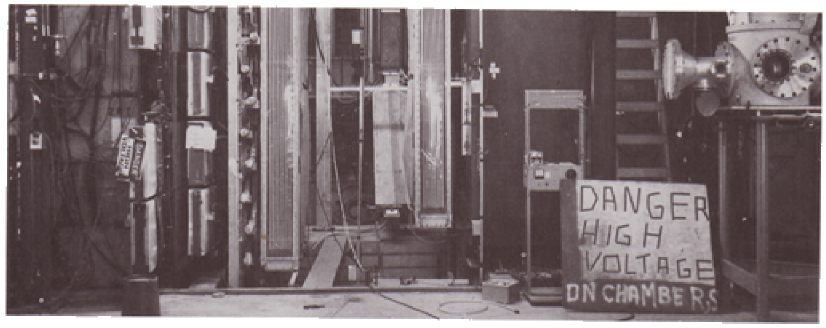


FIGURE 30–9. Gamma rays from a radioactive source ionize the low pressure gas in the tube, allowing a pulse of current to flow between the central wire and the copper tube.

FIGURE 30–10. The spark chamber used at Lawrence Livermore Laboratory.



duced 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 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 that in Figure 30–10, can be many metres in size, with a mass of 9 Mt or more, and cost tens of millions of dollars.

Neutral particles cannot be detected directly. The laws of conservation of momentum and energy are used to find their paths.

F.Y.I.

The atom is still the smallest amount of an element that retains the properties of that element.

The Fundamental Particles

The atom was once thought to be the smallest particle into which matter could be divided. Then Rutherford found that the atom had a nucleus surrounded by electrons. After the proton was discovered, it was also thought to be indivisible. Experiments have been done that bombard protons with other protons or electrons accelerated by accelerators to very high energies. The results of these experiments show that the proton is composed of yet smaller bodies. The neutron also appears to be composed of smaller bodies.

Physicists now believe that the particles out of which all matter is made are grouped into two families, quarks and leptons. **Quarks** make up protons and neutrons. **Leptons** are particles, like the electron and neutrino. In addition to quarks and leptons, there are also particles that carry, or transmit, forces between particles. The photon is the carrier of the electromagnetic force. Eight particles, called **gluons**, carry the strong force that binds quarks into protons and the protons and neutrons into nuclei. Three particles, the **weak bosons**, are involved in the weak interaction, which operates in beta decay. The **graviton** is the name given to the yet-undetected carrier of the gravitational force. These particles are summarized in Tables 30–2 and 30–3. Charges are given in units of the electron charge and masses are stated as energy equivalents.

Other particles like the photon carry, or transmit, forces.

All matter is composed of quarks and leptons.

Table 30–2

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

Table 30–3

Force carriers				
Force	Name	Symbol	Mass	Charge
Electromagnetic	photon	γ	0	0
Weak	weak boson	W^+	80.6 GeV	+e
		W^-	80.6 GeV	−e
		Z^0	91.2 GeV	0
Strong	gluon (8)	g	0	0
Gravitational	graviton (?)	G	0	0

LITERATURE CONNECTION

In 1964, an American physicist, Murray Gell-Mann, suggested that particles with a charge equal to 1/3e or 2/3e might exist. He named these particles "quarks"–the word comes from James Joyce's novel *Finnegan's Wake*. Quarks are now being looked for in cosmic-ray and bubble-chamber experiments.

given by Einstein's famous formula, $E = mc^2$. The energy unit, the electron volt, was defined in Chapter 27. The energy equivalent of these particles is much larger, and so are shown in MeV (mega-electron volts, or 10^6 eV) and GeV (giga-electron volts, or 10^9 eV).

Each quark and each lepton also has its **antiparticle.** The antiparticles are identical with the particles except they 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, Figure 30–11. The total number of quarks and the total number of leptons in the universe are constant. That is, quarks and leptons are created or destroyed only in particle-antiparticle pairs. The number of charge carriers is not conserved; the total charge, however, is conserved. Gravitons, photons, gluons, and weak bosons can be created or destroyed if there is enough energy. After exploring the production and annihilation of antiparticles, we will return to the quark and lepton theory of matter.

Quarks and leptons cannot be created or destroyed individually, only in particle-antiparticle pairs.

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 $^{234}_{90}Th$ 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 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 (actually an antineutrino) was not directly observed until 1956.

A neutron decay is accompanied by emission of an antineutrino.

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

$$^1_0n \rightarrow {}^1_1p + {}^{0}_{-1}e + {}^0_0\bar{\nu}.$$

FIGURE 30–11. The collision of a positron and an electron results in gamma ray production.

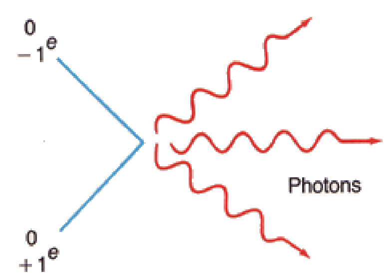
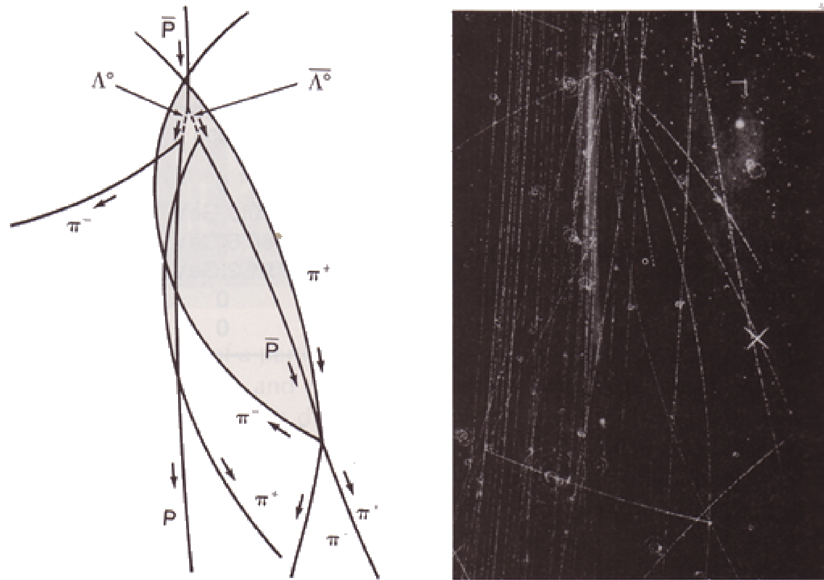


FIGURE 30–12. Scientists identify the particles produced in high-energy collisions by the tracks they produce.



When an isotope decays by emission of a **positron** (antielectron), a process like β decay occurs. A proton within the nucleus changes into a neutron with the emission of a positron ($^{0}_{1}e$) and a neutrino ($^{0}_{0}\nu$). The decay reaction is written

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

The decay of neutrons into protons and protons into neutrons cannot be explained by the strong force. The existence of β decay indicates there must be another force or interaction, called the weak interaction, acting in the nucleus.

When an electron and positron annihilate, gamma rays are produced with total energy equal to the rest energy of the two particles.

The positron is an example of an antiparticle, or a particle of antimatter. When a positron and an electron collide, the two can annihilate each other, resulting in energy in the form of γ rays. Matter is converted directly into energy. The amount of energy 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 is

$$\begin{aligned} E &= 2(9.11 \times 10^{-31}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2 \\ &= (1.64 \times 10^{-13}\ \text{J})(1\ \text{eV}/1.60 \times 10^{-19}\ \text{J}) \\ &= 1.02 \times 10^{6}\ \text{eV or } 1.02\ \text{MeV}. \end{aligned}$$

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.

The inverse of annihilation can also 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. This is called **pair production.** Reactions like $\gamma \rightarrow e^-$ or $\gamma \rightarrow e^+$, however, cannot occur because such an event would violate the law of conservation of charge. Matter and antimatter particles must always be produced in pairs.

F.Y.I.

The electromagnetic attraction of an electron and a positron is 42×10^{41} times stronger than their gravitational attraction.

—Isaac Asimov's *Book of Facts*

The production of a positron-electron pair is shown in the chapter-opening bubble chamber photograph. 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 1.02 MeV.

Phantom Tracks

Antiprotons can also 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. 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.

Gamma rays of sufficient energy can produce particle-antiparticle pairs.

Practice Problem

13. 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.

The Quark Model of Nucleons

The quark model describes 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 (charge $+2/3$ e) and one down quark (charge $-1/3$ e). A proton is described as $p = (uud)$. The charge on the proton is the sum of the charges of the three quarks, $(2/3 + 2/3 + -1/3)e = +e$. 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.

The weak interaction involves three force carriers: W^+, W^-, and Z^0 bosons. The weak interaction 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 occurs in two steps. First, one d quark in a neutron changes to a u quark with the emission of a W^- boson,

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

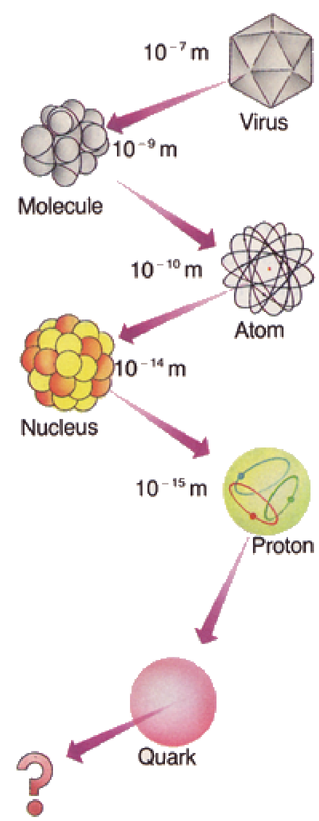
Then the W^- boson decays into an electron and an antineutrino,

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

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

FIGURE 30–13. Characteristic sizes of the structures of matter, given in metres, from the smallest "living" thing, a virus. It is not yet known whether quarks are measurable and have some internal structure, or whether they are really point-like objects.



KEY TERMS

proton
atomic mass unit
atomic number
neutron
mass number
isotope
nuclide
radioactive
radioactive decay
α decay
β decay
γ decay
transmutation
nuclear reaction
half-life
activity
linear accelerator
synchrotron
Geiger-Mueller tube
Wilson cloud chamber
bubble chamber
spark chamber
quark
lepton
gluon
weak boson
graviton
antiparticle
neutrino
positron
pair production
meson
baryon

REVIEWING CONCEPTS

1. What is the symbol for the atomic mass unit?
2. Define the term *transmutation* as used in nuclear physics and give an example.
3. What are the common names for an α particle, β particle, and γ radiation?
4. What happens to the atomic number and mass number of a nucleus that emits an alpha particle?
5. What happens to the atomic number and mass number of a nucleus that emits a beta particle?
6. What two quantities must always be conserved in any nuclear equation?
7. Why would a linear accelerator not work with a neutron?
8. Explain how a scintillation counter detects gamma rays and high-speed charged particles.
9. In which of the four interactions (strong, weak, electromagnetic, gravitational) does the following particle take part?
   a. electron **b.** proton **c.** neutrino
10. What happens to the atomic number and mass number of a nucleus that emits a positron?
11. Give the symbol, mass, and charge of the following particles.
    a. proton **c.** positron **e.** α particle
    b. neutron **d.** electron

APPLYING CONCEPTS

1. Which are generally more unstable, small or large nuclei?
2. Which isotope has the greater number of neutrons, uranium-235 or uranium-238?
3. Which is usually larger, *A* or *Z*? Explain.
4. Which is most like an X ray, alpha particles, beta particles, or gamma radiation?
5. Could a deuteron, ${}^{2}_{1}H$, decay via alpha decay? Explain.
6. Which will give a higher reading on a radiation detector: equal amounts of a radioactive substance that has a short half-life or a radioactive substance that has a long half-life?
7. Why is carbon dating useful in establishing the age of campfires but not the age of a set of knight's armor?
8. What would happen if a meteorite made of antiprotons, antineutrons, and positrons landed on Earth?

PROBLEMS

30.1 Radioactivity

1. 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?
2. 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?
3. List the number of neutrons in an atom of each of these isotopes.
   a. ${}^{112}_{48}Cd$ **c.** ${}^{208}_{83}Bi$ **e.** ${}^{1}_{1}H$
   b. ${}^{209}_{83}Bi$ **d.** ${}^{80}_{35}Br$ **f.** ${}^{40}_{18}Ar$
4. Find the symbol for the elements that are shown by the following symbols, where X replaces the symbol for the element.
   a. ${}^{18}_{9}X$ **b.** ${}^{241}_{95}X$ **c.** ${}^{21}_{10}X$ **d.** ${}^{7}_{3}X$
5. A radioactive bismuth isotope, ${}^{214}_{83}Bi$, emits a β particle. Write the complete nuclear equation, showing the element formed.
6. A radioactive polonium isotope, ${}^{210}_{84}Po$, emits an α particle. Write the complete nuclear equation, showing the element formed.
7. An unstable chromium isotope, ${}^{56}_{24}Cr$, emits a β particle. Write a complete equation, showing the element formed.

Objectives

- recognize the role and nature of the strong nuclear force; define the binding energy.
- relate the energy released in a nuclear reaction to change in binding energy before and after the reaction.

31.1 HOLDING THE NUCLEUS TOGETHER

The negatively-charged electrons that surround the positively-charged nucleus of an atom are held in place by the attractive electric force. The nucleus consists of positively-charged protons and neutral neutrons. The repulsive electric force between the protons might be expected to cause them to fly apart. This does not happen because an even stronger attractive force exists within the nucleus.

The Strong Nuclear Force

The strong force acts the same between neutrons and protons or between protons and protons or neutrons and neutrons.

The force that overcomes the mutual repulsion of the charged protons is called the **strong nuclear force**. The strong force acts between protons and neutrons that are very close together, as they are in a nucleus. The range of the strong force is very short, only about the radius of a proton, 1.3×10^{-15} m. It is attractive and is of the same strength between protons and protons, protons and neutrons, and neutrons and neutrons. As a result of this equivalence, both neutrons and protons are called **nucleons**.

The strong 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. Thus, the binding energy is negative.

Binding Energy of the Nucleus

The binding energy of a nucleus is proportional to the difference between the mass of the nucleus and the masses of the nucleons from which it is assembled.

Binding energy can be expressed in the form of an equivalent amount of mass, according to the equation $E = mc^2$. The unit of mass used in nuclear physics is the atomic mass unit, u. One atomic mass unit is 1/12 the mass of the ${}^{12}_{6}C$ nucleus.

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 2 protons and 2 neutrons. The mass of a proton is 1.007825 u. The mass of a neutron is 1.008665 u. The mass of the nucleons that make up the helium nucleus is equal to the sum of the masses of the two protons and the two neutrons. Thus, if it weren't for the binding energy, the mass of the nucleus would be 4.032980 u. Careful measurement, however, shows the mass of a helium nucleus is only 4.002603 u. The mass of the helium nucleus is less than the mass of its constituent parts by 0.0030377 u. The difference, 0.0030377 u is called the **mass defect.** The binding energy can be calculated from the experimentally-determined mass defect by using $E = mc^2$ to compute the energy equivalent of the missing mass.

F.Y.I.

Science is inherently neither a potential for good nor for evil. It is a potential to be harnessed by man to do his bidding.

Glenn T. Seaborg
1951 Nobel Laureate

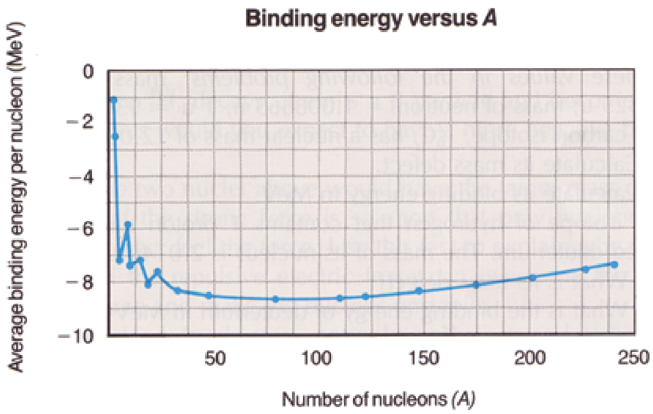


FIGURE 31–1. A graph of the binding energy per nucleon.

Masses are normally measured in atomic mass units. It will be useful, then, to determine the energy equivalent of 1 u (1.6605×10^{-27} kg). The most convenient unit of energy to use is the electron volt. To five significant digits,

$$\begin{aligned} E &= mc^2 \\ &= (1.6605 \times 10^{-27}\ \text{kg})(2.9979 \times 10^{8}\ \text{m/s})^2 \\ &= (14.923 \times 10^{-11}\ \text{J})(1\ \text{eV}/1.6022 \times 10^{-19}\ \text{J}) \\ &= 9.3149 \times 10^{8}\ \text{eV} \\ E &= 931.49\ \text{MeV}. \end{aligned}$$

A useful relationship is shown by the graph of binding energy per nucleon in Figure 31–1.

The energy equivalent of one atomic mass unit is 931.5 MeV.

Example Problem

Calculating Mass Defect and Nuclear Binding Energy

The mass of a proton is 1.007825 u. The mass of a neutron is 1.008665 u. The mass of the nucleus of the radioactive hydrogen isotope tritium, ${}^{3}_{1}H$, is 3.016049 u. **a.** What is the nuclear mass defect of this isotope? **b.** What is the binding energy of tritium?

Solution:

a. As indicated by the superscript and subscript in the symbol for tritium, its nucleus contains 1 proton and 2 neutrons.

$$\begin{aligned} \text{mass of 1 proton} &= 1.007825\ \text{u} \\ \text{mass of 2 neutrons} = (2)(1.008665\ \text{u}) &= \underline{2.017330\ \text{u}} \\ \text{total mass of nucleons} &= \underline{3.025155\ \text{u}} \\ \text{mass of tritium nucleus} &= 3.016049\ \text{u} \\ \text{less total mass of nucleons} &\ \underline{-3.025155\ \text{u}} \\ \text{mass defect} &= -0.009106\ \text{u} \end{aligned}$$

b. Since 1 u is equivalent to 931.49 MeV, the binding energy of the tritium nucleus can be calculated.

binding energy of ${}^{3}_{1}H$ nucleus,

$$\begin{aligned} E &= (-0.009106\ \text{u})(931.49\ \text{MeV/u}) \\ &= -8.482\ \text{MeV} \end{aligned}$$

POCKET LAB

BINDING ENERGY

Particles within the nucleus are strongly bonded. Place two disk magnets together to represent a proton and neutron within a nucleus. Slowly pull them apart. Feel how the force changes with separation. Describe how this analogy could be extended for a nucleus that contains several protons and neutrons.

F.Y.I.

Idealists maintain that all nations should share the atomic bomb. Pessimists maintain they will.

—Punch

Practice Problems

Use these values in the following problems: mass of proton = 1.007825 u; mass of neutron = 1.008665 u; 1 u = 931.49 MeV.

1. The carbon isotope, ${}^{12}_{6}C$, has a nuclear mass of 12.0000 u.

a. Calculate its mass defect.

b. Calculate its binding energy in MeV.

2. The isotope of hydrogen that contains 1 proton and 1 neutron is called deuterium. The mass of its nucleus is 2.0140 u.

a. What is its mass defect?

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

3. A nitrogen isotope, ${}^{15}_{7}N$, has 7 protons and 8 neutrons. Its nucleus has a mass of 15.00011 u.

a. Calculate the mass defect of this nucleus.

b. Calculate the binding energy of the nucleus.

▶ **4.** An oxygen isotope, ${}^{16}_{8}O$, has a nuclear mass of 15.99491 u.

a. What is the mass defect of this isotope?

b. What is the binding energy of its nucleus?

Iron-56 has the most negative binding energy per nucleon.

When you worked the Practice Problems you found that the heavier nuclei were bound more strongly than lighter nuclei. Except for a few nuclei, the binding energy per nucleon becomes more negative as A increases to a value of 56, iron, Fe. ${}^{56}_{26}Fe$ is the most tightly bound nucleus. Nuclei larger than iron are less strongly bound.

A nuclear reaction will occur naturally if energy is released by the reaction. Energy will be released if the nucleus that results from the reaction is more tightly bound than the original nucleus. When a heavy nucleus, such as ${}^{238}_{92}U$, decays by releasing an alpha particle, the binding energy per nucleon of the resulting ${}^{234}_{90}Th$ is larger than that of the uranium. The excess energy of the ${}^{238}_{92}U$ nucleus is transferred into the kinetic energy of the alpha particle. At low atomic numbers, reactions that add nucleons to a nucleus make the binding energy of the nucleus more negative. Thus the energy of the larger nucleus is less than the sum of the energies of the two smaller ones. Energy is released when the reaction occurs. In the sun and other stars, the production of heavier nuclei like helium and carbon from hydrogen releases energy that eventually becomes the electromagnetic radiation by which we see the stars.

FIGURE 31–2. The strawberries in the two cartons are identical except that those in the carton on the left have been treated with gamma radiation to destroy the bacteria causing spoilage.

CONCEPT REVIEW

1.1 When tritium, ^3_1H, decays, it emits a β particle and becomes ^3_2He. Which nucleus would you expect to have a more negative binding energy?

1.2 Which of the two nuclei above would have the larger mass defect?

1.3 The range of the strong force is so short that only nucleons that touch each other feel the force. Use this fact to explain why in very large nuclei the repulsive electric force can overcome the strong attractive force and make the nucleus unstable.

1.4 **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 would be the atomic number of the heaviest nucleus that could be formed this way? Explain.

31.2 USING NUCLEAR ENERGY

Objectives

- define artificially produced radioactive isotopes; describe their medical uses; solve nuclear equations involving the formation and decay of radioactive isotopes.
- define nuclear fission and a chain reaction; understand the source of energy in fission.
- describe the operation of one or more types of nuclear reactors; understand the formation of plutonium in a reactor.
- describe the fusion process and the formation of helium in the sun.
- describe two approaches to controlled nuclear fusion.

In no other area 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 tested for medical applications less than one year after being invented. In the case of nuclear fission, the military application was under development before the basic physics was even known. Peaceful applications followed in less than 10 years. The question of the uses of nuclear science in our society is an important one for all citizens today.

Artificial Radioactivity

Marie and Pierre Curie had noted as early as 1899 that substances placed close to radioactive uranium became radioactive themselves. In 1934, Irene Joliot-Curie and Frederic Joliot bombarded aluminum with alpha particles, producing neutrons by the reaction

$$^4_2He + ^{27}_{13}Al \rightarrow ^{30}_{15}P + ^1_0n.$$

In addition to neutrons, the Curies found another particle coming from the aluminum, a positively-charged electron, or positron. The positron, a particle with the same mass as the electron but with a positive charge, had been discovered two years earlier by American Carl Anderson. The most interesting result of the Curies' experiment was that positrons continued to be emitted after the alpha bombardment stopped. The positrons were found to come from the phosphorus isotope $^{30}_{15}P$. The Curies had produced a radioactive isotope not previously known.

Radioactive isotopes not found in nature can be produced by bombarding nuclei.

Radioactive isotopes can be formed from stable isotopes by bombardment with alpha particles, protons, neutrons, electrons, or gamma rays. The resulting unstable nuclei emit radiation until they are transmuted into stable isotopes. The radioactive nuclei may emit alpha, beta, and gamma radiation as well as positrons.

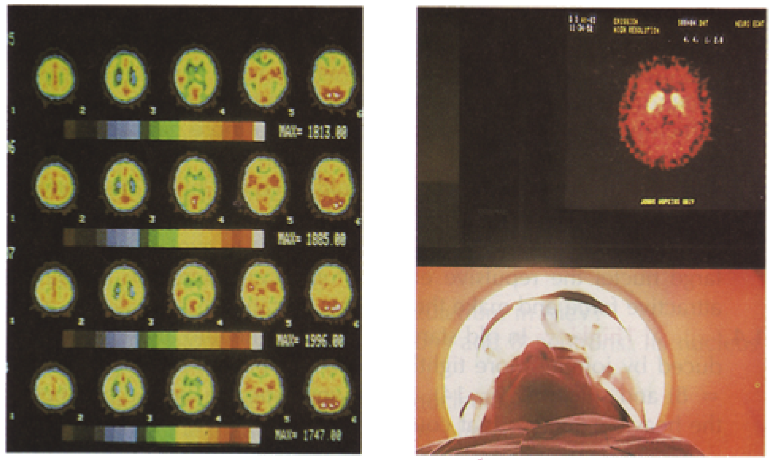


FIGURE 31–3. PET scanner results.

Tracer isotopes allow doctors to follow the path of molecules through the body.

Artificially produced radioactive isotopes have many uses, especially in medicine. In many medical applications, patients are given radioactive isotopes that are absorbed by specific parts of the body. The detection of the decay products of these isotopes allows doctors to trace the movement of the isotopes, and of the molecules to which they are attached, through the body. For that reason, these isotopes are called tracer isotopes. Iodine, for example, is primarily used in the thyroid gland. A patient is given an iodine compound containing radioactive $^{131}_{53}I$. The iodine concentrates in the thyroid gland. A physician uses a Geiger-Mueller counter to monitor the activity of $^{131}_{53}I$ in the region of the thyroid. The amount of iodine taken up by this gland is a measure of its ability to function.

MEDICINE CONNECTION

A new instrument, the Positron Emission Tomography Scanner, or PET scanner, Figure 31–3, uses isotopes that emit positrons. Such an isotope is included in a solution injected into the patient's body. In the body, the isotope decays, releasing a positron. The positron annihilates an electron, emitting two gamma rays. The PET scanner detects the gammas and pinpoints the location of the positron-emitting isotope. A computer is then used to make a three-dimensional map of the isotope distribution. By this means, details such as the use of nutrients in particular regions of the brain can be traced. For example, if a person in a PET scanner were solving a physics problem, more nutrients would flow to the part of the brain being used to solve the problem. The decay of the positrons in this part of the brain would increase, and the PET scanner could map this area.

A PET scanner makes a three-dimensional map of the distribution of decaying nuclei in the body.

Another use of radioactivity in medicine is the destruction of cells. Often gamma rays from the isotope $^{60}_{27}Co$ are used to treat cancer patients. The ionizing radiation produced by radioactive iodine can be used to destroy cells in a diseased thyroid gland, with minimal harm to the rest of the body. Another method of reducing damage to healthy cells is to use unstable particles produced by particle accelerators like the synchrotron. These unstable particles pass through body tissue without doing damage. When they decay, however, the emitted particles destroy cells. The physician adjusts the accelerator so the particles decay only in the cancerous tissue.

Ionizing radiation can destroy cells.

Practice Problems

5. Use Table D–5 of the Appendix to complete the following nuclear equations.
   a. $^{14}_{6}C \rightarrow ? + {}^{0}_{-1}e$
   b. $^{55}_{24}Cr \rightarrow ? + {}^{0}_{-1}e$
6. Write the nuclear equation for the transmutation of a uranium isotope, $^{238}_{92}U$, into a thorium isotope, $^{234}_{90}Th$, by emission of an alpha particle.
7. A radioactive polonium isotope, $^{214}_{84}Po$, undergoes alpha decay and becomes lead. Write the nuclear equation.
8. Write the nuclear equations for the beta decay of these isotopes.
   a. $^{210}_{82}Pb$ **b.** $^{210}_{83}Bi$ **c.** $^{234}_{90}Th$ **d.** $^{239}_{93}Np$

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Whatever nature has in store for mankind, unpleasant as it may be, men must accept, for ignorance is never better than knowledge.

—Enrico Fermi

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. They believed they had formed new elements with atomic numbers larger than 92, that of uranium.

German chemists Otto Hahn and Fritz Strassmann made careful chemical studies of the results of bombardment of uranium by neutrons. In 1939, their analyses showed that the resulting atoms acted chemically like barium. The two chemists could not understand how barium, with an atomic number of 56, could be produced from uranium. One week later, Lise Meitner and Otto Frisch proposed that the neutrons had

Fission is the splitting of a nucleus into two or more fragments of roughly equal size. It is accompanied by the release of a large amount of energy.

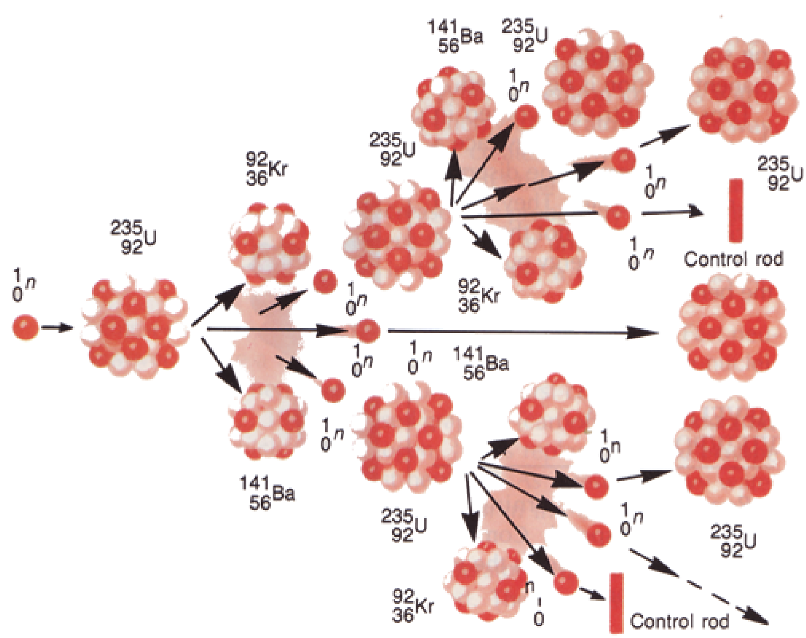


FIGURE 31–4. The nuclear fission chain reaction of uranium-235 takes place in the core of a nuclear reactor.

Physics and society

NUCLEAR WASTE DISPOSAL

Uranium fuel rods used to power nuclear reactors are useful for about 18 months before they must be replaced. In addition, some experts believe that entire nuclear facilities must be dismantled or sealed up after about 30 years due to high levels of radioactivity and resulting structural damage.

Although radiation has many useful applications, such as the treatment of cancer, it must be carefully monitored. Exposure to too much radiation can result in the destruction of body cells and eventual death. Unfortunately, all the materials in nuclear waste are still extremely radioactive and cannot be discarded using conventional waste disposal methods.

In Canada, approximately 1800 t of used fuel are produced every year. By 1989, about 14 000 t of used fuel had been accumulated in Canada — enough to fill an Olympic-sized swimming pool. This sounds like a lot of waste material, but it is quite small compared to the large amount of energy derived from it. (One 25-kg bundle of fuel can produce as much energy as 400 t of coal.)

So far, there is only one way to deal with nuclear waste. Used fuel is stored at nuclear reactor storage facilities (resembling large swimming pools). Liquid radioactive waste can be "vitrified" or turned into glass, resulting in a solid that minimizes the chance of releasing radioactivity into the environment. The safety of these solids is now being tested. If proven safe, they would be stored underground in giant vaults. As you might expect, however, governments at all levels are hesitant to compete for the seemingly lucrative right to become nuclear waste disposal sites because of health and environmental concerns.

The original concept for nuclear power was that scientists would be able to devise a way to reprocess spent fuel, chemically separating it into uranium, plutonium, and waste fission products, with the uranium going back into the fuel cycle. It was also assumed that modern technology would soon devise ways to dispose of the small amount of spent fuel that could not be reprocessed.

Fuel reprocessing technology, however, has not kept up with nuclear waste production, and countries around the world are faced with the problem of storing spent fuel until a more permanent solution is developed.

Those countries involved in the use of nuclear energy face a difficult problem in the disposal of nuclear waste. They must decide whether or not the problems of nuclear energy outweigh the benefits.

DEVELOPING A VIEWPOINT

Read further concerning nuclear waste disposal. Come to class prepared to discuss the following questions.

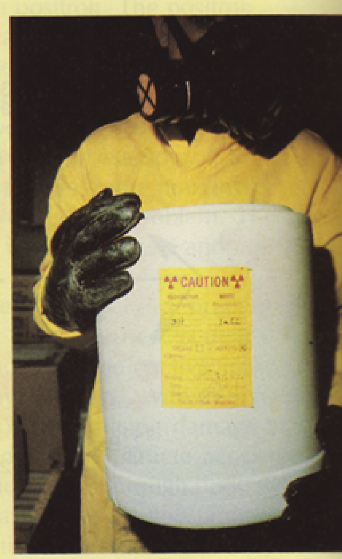
1. If ice cubes can be melted, vaporized, condensed, and refrozen into ice cubes, why can't we simply find a way to turn nuclear waste back into the raw material from which it was processed?
2. What are the pros and cons of sending nuclear waste into space?

SUGGESTED READINGS

Wolf, Häfele, "Energy from Nuclear Power," *Scientific American*, September 1990, p. 144.

George E. Brown, Jr. "U.S. Nuclear Waste Policy: Flawed but Feasible," *Environment*, Vol 29 (No. 8) October 1987, pp. 6–7.

Atomic Energy of Canada Limited, Managing Canada's Nuclear Fuel Wastes, 1989.



caused a division of the uranium into two smaller nuclei, with a large release of energy. 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 an explosive weapon, was immediately realized by many scientists.

The uranium isotope $^{235}_{92}U$ undergoes fission when bombarded with neutrons. The elements barium and krypton are typical results of fission, Figure 31–4. The reaction is

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

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 200 MeV. This energy is transferred to the kinetic energy of the products of the fission.

Once the fission process is started, the neutron needed to cause the fission of additional $^{235}_{92}U$ nuclei can be one of the three neutrons produced by an earlier fission. If one or more of the neutrons causes a fission, that fission releases three more neutrons, each of which can cause more fission. This process is called a **chain reaction.**

POCKET LAB

POWER PLANT

Call your local electric company and ask the following questions: 1. Where is the nearest nuclear power plant? 2. What fraction (or percentage) of electrical power is supplied by nuclear power in your area?

In a chain reaction, neutrons released by one fission induce other fissions.

Nuclear Reactors

Most of the neutrons released by the fission of $^{235}_{92}U$ atoms are moving at high speed and are unable to cause the fission of another $^{235}_{92}U$ atom. In addition, naturally occurring uranium consists of less than 1% $^{235}_{92}U$ and more than 99% $^{238}_{92}U$. 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.

A slow neutron is more effective in causing fission than is a fast neutron.

Fermi suggested that a chain reaction would occur if the uranium were broken up into small pieces and placed in 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** creates many slow neutrons, which are more likely to be absorbed by $^{235}_{92}U$ than by $^{238}_{92}U$. The larger number of slow neutrons greatly increases the probability that a neutron released by a fissioning $^{235}_{92}U$ 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.

The lightest atom, hydrogen, would be an ideal moderator. Fast neutrons, however, cause a nuclear reaction with normal hydrogen nuclei, $^{1}_{1}H$. For this reason, when Fermi produced the first controlled chain reaction on December 2, 1942, he used graphite (carbon) as a moderator.

Heavy water, in which the hydrogen, $^{1}_{1}H$, is replaced by the isotope deuterium, $^{2}_{1}H$, does not absorb fast neutrons. As a result, heavy water is used as a moderator with natural uranium in the Canadian CANDU reactors.

Ordinary water can be used as a moderator if the number of $^{235}_{92}U$ nuclei in the uranium sample is increased. The process that increases the number of fissionable nuclei is called enrichment. Enrichment of

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The CANDU reactor gets its name from **CAN**ada (its place of design), **D**euterium oxide (heavy water), and **U**ranium (the fuel).

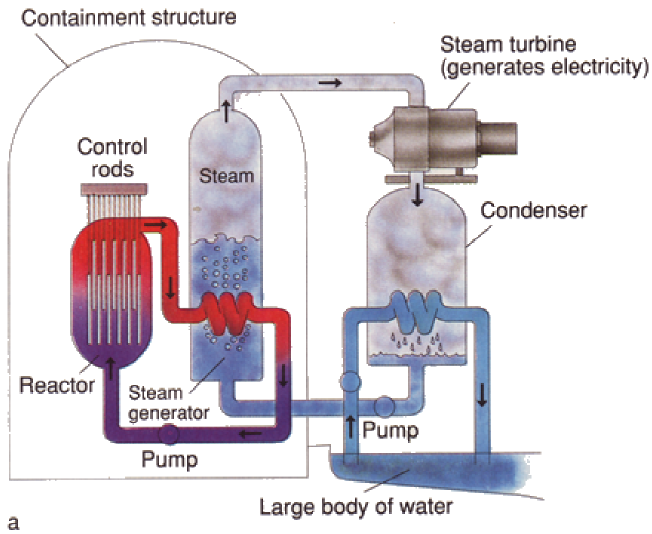


FIGURE 31–5. In a nuclear power plant, the thermal energy released in nuclear reactions is converted to electric energy. The nuclear reactor shown here is a pressurized water reactor. The Canadian-made CANDU reactor differs mainly in the use of heavy water as the moderator and coolant, and natural uranium (as opposed to enriched uranium).

uranium is difficult and requires large, expensive equipment. The United States produces enriched uranium for most of the nuclear reactors in the western world.

A common type of nuclear reactor used around the world, the pressurized water reactor, contains about 200 t of uranium sealed in hundreds of metal rods. The rods are immersed in water. Water not only is the moderator, but also transfers thermal energy away from the fissioning uranium. Between the uranium rods are placed rods of cadmium metal. Cadmium absorbs neutrons easily. 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 neutrons to prevent the chain reaction. As they are removed from the reactor, the rate of energy release increases.

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 temperature. As shown in Figure 31–5, 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.

Shock Waves

Some of the fission energy goes into kinetic energy of electrons and neutrons, giving them speeds near the speed of light in vacuum. When these particles enter the water, they exceed the speed of light in the water. As a result, a blue glow is emitted when fuel rods are placed in water. The glow is called the Cerenkov effect. It is not the result of radioactivity in the water; radioactive objects do not emit a blue glow.

Fission of $^{235}_{92}U$ nuclei produces Kr, Ba, and other atoms in the fuel rod. Most of these atoms are radioactive. About one every 18 months, some of the uranium fuel rods must be replaced. The old rods can no longer be used in the reactor, but they are still extremely radioactive and must be stored in safe locations. Research is now being done on methods of safe, permanent storage of these radioactive waste products. Among the products of fission is an isotope of plutonium, $^{239}_{94}Pu$. This isotope is fissionable when it absorbs neutrons and can also be used in nuclear weapons. It is also very toxic. As a result, plutonium-containing materials are all stored in safe, temporary locations, never in "waste dumps." There is hope that in the future this fissionable isotope might be removed from radioactive waste and recycled to fuel other reactors.

The world's supply of uranium is limited. If nuclear reactors are used to supply a large fraction of the world's energy, uranium will become scarce. Even though the plutonium produced by normal reactors might be recovered to fuel other reactors, there is still a net loss of fuel. In order to extend the supply of uranium, **breeder reactors** have been developed. When a reactor contains both plutonium and $^{238}_{92}U$, the plutonium will undergo fission just as $^{235}_{92}U$ does. Many of the free nuetrons from the fission are absorbed by the $^{238}_{92}U$ to produce additional $^{239}_{94}Pu$. For every two plutonium atoms that undergo fission, three new ones are formed. More fissionable fuel can be recovered from this reactor than was originally present. Breeder reactors are operating only in France, but research is underway elsewhere.

HELP WANTED

RADIOLOGIC TECHNOLOGIST

Do you have a community college degree and professional certification in radiological technology? We are looking for a person who is compassionate, conscientious, and cooperative. You must have a penchant for perfection when it comes to safety regulations and procedures. A large hospital offers excellent opportunity for advancement with increased training. For information contact:
Canadian Association of Medical Radiation Technologists,
280 Metcalfe Street, Suite 410,
Ottawa, Ontario, K2P 1R7

Nuclear Fusion

In nuclear **fusion**, nuclei with small masses combine to form a nucleus with a larger mass, Figure 31–6. In the process energy is released. The larger nucleus is more tightly bound, Figure 31–1, so its mass is less than the sum of the masses of the smaller nuclei. A typical 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 is transferred to the kinetic energy of the resultant particles. The energy released by the fusion of one helium nucleus is 25 MeV. In comparison, the energy released when one dynamite molecule reacts chemically is about 20 eV, almost one million times smaller.

Fusion is the union of small nuclei to form larger ones. It is accompanied by the release of a large amount of energy.

Fusion in the sun is believed to occur in steps. The most important process is expected to be the proton-proton chain.

$$^1_1H + ^1_1H \rightarrow ^2_1H + ^{0}_{+1}e + ^0_0\nu$$
$$^1_1H + ^2_1H \rightarrow ^3_2He$$
$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H$$

Fusion in the sun converts four protons to one helium nucleus.

The first two reactions must occur twice in order to produce the two ^3_2He particles needed for the final reaction. The net result is that four protons produce one ^4_2He, two positrons, and two neutrinos.

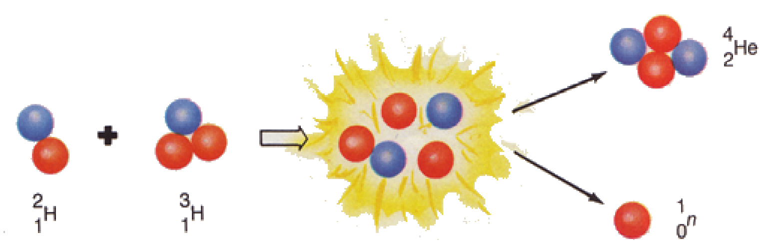


FIGURE 31–6. The fusion of deuterium and tritium produces helium. Protons are blue and neutrons are red in the figure.

PHYSICS LAB: Hot Stuff

Purpose

To measure the local power output from the nearest continuous running fusion reaction.

Materials

- photocell
- voltmeter
- ammeter
- electrical leads
- ruler

Procedure

1. With no load attached, measure the voltage output of a solar cell when the cell is outdoors and directly facing the sun.
2. Measure the current from the solar cell when the cell is outdoors and directly facing the sun.
3. Measure the length and width of the solar cell and determine its surface area.
4. Remeasure the voltage and current when the sunlight passes through a window.

Observations and Data

1. Record your voltage and current readings for outdoor and indoor readings.

Analysis

1. Calculate the power, IV, for the solar cell outdoors and indoors. What percentage of power did the window stop?
2. Calculate the amount of power that could be produced by a cell that had an area of 1.0 m^2.
3. The sun supplies about 1000 W of power per square metre to the earth. Calculate the efficiency of your solar cell.

Applications

1. Suppose that you installed 15 m^2 of solar cells on your roof. How much power could they produce?

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. For this reason, fusion reactions are often called **thermonuclear reactions.** The proton-proton chain requires temperatures of about 2×10^7 K, temperatures found in the centre 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, or "atomic," bomb.

Controlled Fusion

Could the huge energy available from fusion be used safely on Earth? Safe energy requires control of the fusion reaction. One reaction that might produce **controlled fusion** is

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6 \text{ MeV}.$$

Deuterium, $^{2}_{1}H$, is available in large quantities in seawater, and tritium, $^{3}_{1}H$, is easily produced from deuterium. Therefore, controlled fusion would give the world an almost limitless source of energy. In order to control fusion, however, some very difficult problems must be solved.

Fusion reactions require that the atoms be raised to temperatures of millions of degrees. No material we now have can withstand temperatures even as high as 5000 K. In addition, the atoms would be cooled if they touched confining material. Magnetic fields, however, can confine charged particles. Energy is added to the atoms, stripping away electrons and forming separated plasmas of electrons and ions. A sudden increase in the magnetic field will compress the plasma, raising its temperature. Electromagnetic fields and fast moving neutral atoms can also increase the energy of the plasma. Using this technique, hydrogen nuclei have been fused into helium. The energy released by the reaction becomes the kinetic energy of the neutron and helium ion. This energy would be used to heat some other material, possibly liquified lithium. The lithium, in turn, would boil water, producing steam to turn electric generators.

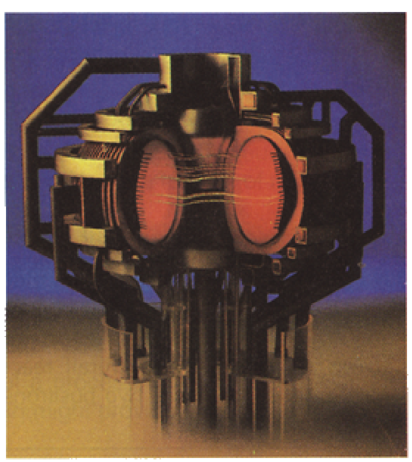
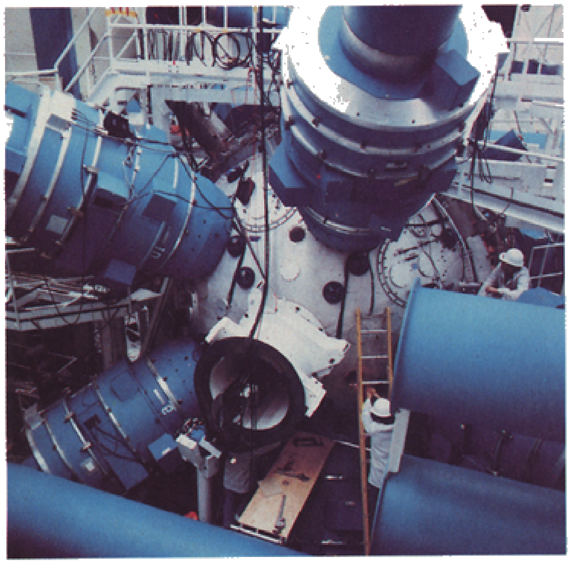
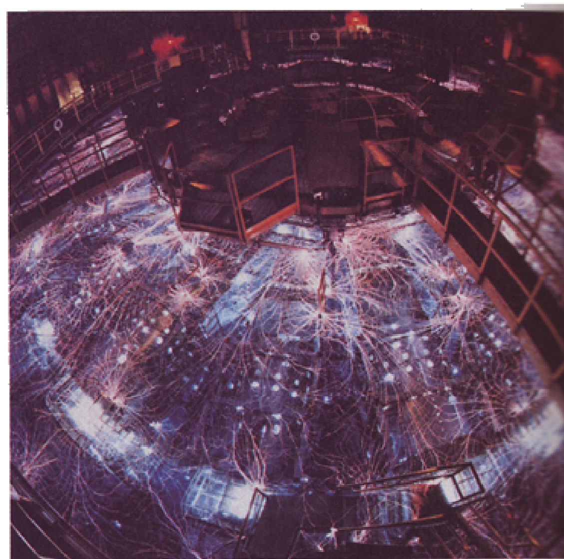


FIGURE 31–7. The Tokamak is an experimental controlled fusion reactor.



a



b

FIGURE 31–8. In laser confinement, pellets containing deuterium and tritium are imploded by many giant lasers, producing helium and large amounts of thermal energy (a). Electrical discharges are visible on the surface of the water covering the Particle Beam Fusion Accelerator II when a pulse of ions is fired (b).

Laser beams are used to implode tiny glass spheres containing liquified deuterium and tritium. The compression creates temperatures high enough to produce fusion.

A useful reactor must produce more energy than it consumes. So far, the energy produced by fusion has been only a tiny fraction of the energy required to create and hold the plasma. The confinement of plasma is a very difficult problem because instabilities in the magnetic field allow the plasma to escape. One of the most promising fusion reactors under development is the Tokamak reactor, Figure 31–7. The Tokamak provides a doughnut-shaped magnetic field in which the plasma is confined. Research has led to the confinement of larger amounts of plasma for longer periods of time. The next large Tokamak built should produce as much energy as it consumes.

A second approach to controlled fusion is called **inertial confinement fusion**. Deuterium and tritium are liquified under high pressure and confined in tiny glass spheres. Multiple laser beams, Figure 31–8a, are directed at the spheres. The energy deposited by the lasers causes forces that make the pellets implode, squeezing their contents. The tremendous compression of the hydrogen that results raises the temperature to levels needed for fusion.

Practice Problems

9. a. Calculate the mass defect for the deuterium-tritium fusion reaction used in the Tokamak, ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$.

b. Find the energy equivalent of the mass defect.

▶ **10.** Calculate the energy released for the overall reaction in the sun where four protons produce one ${}^{4}_{2}He$, two positrons, and two neutrinos.

7. What role does a moderator play in a fission reactor?
8. The reactor at the Chernobyl power station that exploded and burned used blocks of graphite. What was the purpose of the graphite blocks?
9. Breeder reactors generate more fuel than they consume. Is this a violation of the law of conservation of energy? Explain.
10. Scientists think Jupiter might have become a star, but temperatures inside the planet are too low. Why must stars have a very high internal temperature?
11. Fission and fusion are opposite processes. How can each release energy?
12. What two processes are being studied to control the fusion process?

APPLYING CONCEPTS

1. What is the relationship between the average binding energy per nucleon and the degree of stability of a nucleus?
2. Use the graph of binding energy per nucleon to determine if the reaction ${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He$ is energetically possible.
3. Give an example of a naturally and an artifically produced radioactive isotope. Explain the difference.
4. 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?
5. The fission of a uranium nucleus and the fusion of four hydrogen nuclei both produce energy.
   - **a.** Which produces more energy?
   - **b.** Does the fission of 1 kg of uranium nuclei or the fusion of 1 kg of deuterium produce more energy?
   - **c.** Why are your answers to parts **a** and **b** different?
6. Explain how it might be possible for some fission reactors to produce more fissionable fuel than they consume. What are such reactors called?
7. What is the difference between the fission process in an atomic bomb and in a reactor?
8. Why might a fusion reactor be safer than a fission reactor?

PROBLEMS

31.1 Holding the Nucleus Together

1. A carbon isotope, ${}^{13}_{6}C$, has a nuclear mass of 13.00335 u.
   - **a.** What is the mass defect of this isotope?
   - **b.** What is the binding energy of its nucleus?
2. A nitrogen isotope, ${}^{14}_{7}N$, has a nuclear mass of approximately 14.00307 u.
   - **a.** What is the mass defect of the nucleus?
   - **b.** What is the binding energy of this nucleus?
   - **c.** What is the binding energy per nucleon?
3. 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? Refer to the previous problem.
4. 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.
5. ▶ A ${}^{232}_{92}U$ nucleus, mass = 232.0372 u, decays to ${}^{228}_{90}Th$, 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?
6. ▶ The binding energy for ${}^{4}_{2}He$ is 28.3 MeV. Calculate the mass of a helium nucleus in atomic mass units.

31.2 Using Nuclear Energy

7. The radioactive nucleus indicated in each equation disintegrates by emitting a positron. Complete each nuclear equation.
   - **a.** ${}^{21}_{11}Na \rightarrow ?\ {}^{0}_{1}e + ?$
   - **b.** ${}^{49}_{24}Cr \rightarrow ?\ {}^{0}_{1}e + ?$
8. Complete the nuclear equations for these transmutations.
   - **a.** ${}^{30}_{15}P \rightarrow ? + {}^{0}_{1}e + ?$
   - **b.** ${}^{205}_{82}Pb \rightarrow ? + {}^{0}_{1}e + ?$
9. A mercury isotope, ${}^{200}_{80}Hg$, is bombarded with deuterons, ${}^{2}_{1}H$. The mercury nucleus absorbs the deuteron and then emits an α particle.