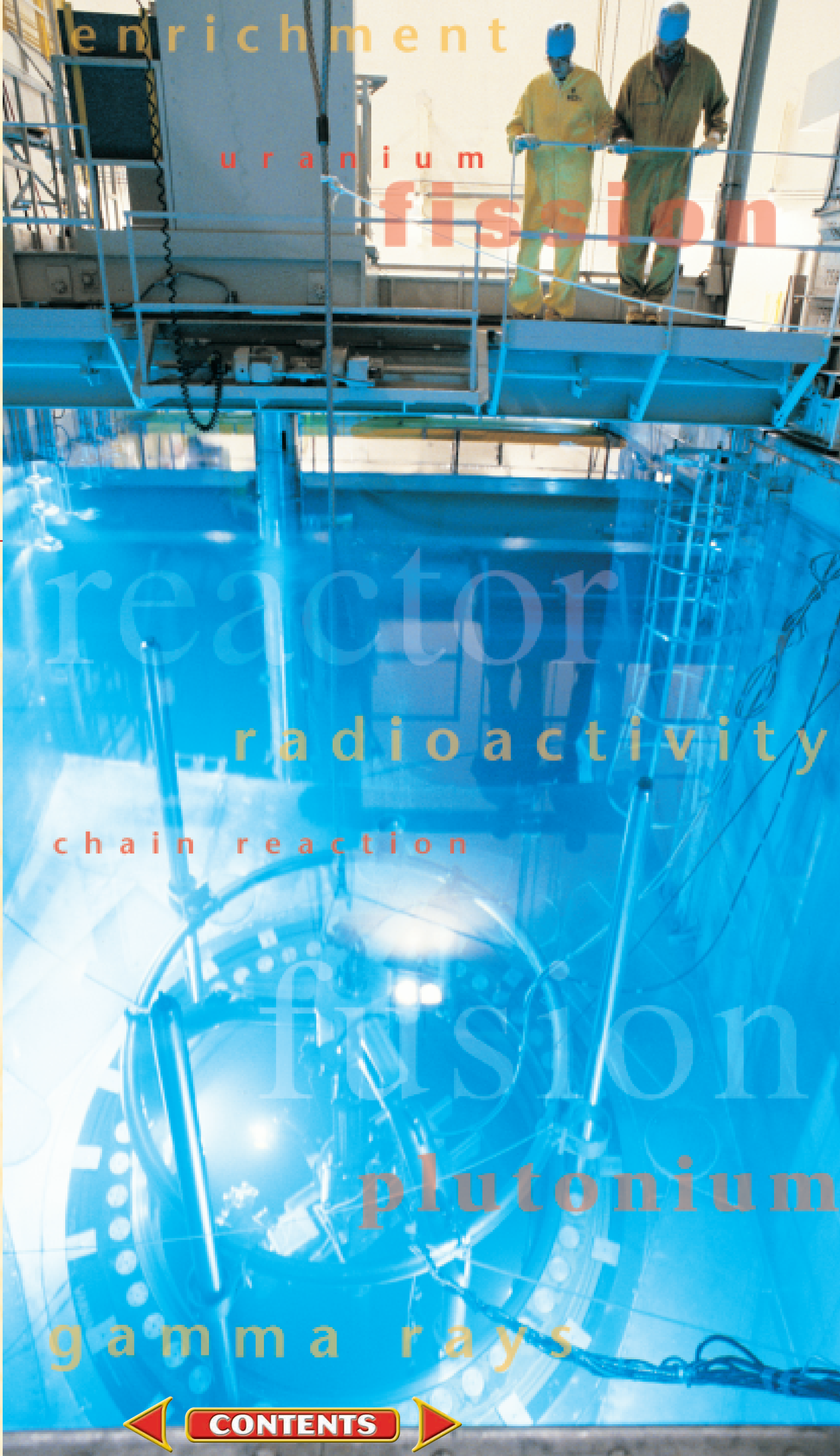
Shock Waves

The photo of a bundle of uranium-filled fuel rods in water may be familiar to you. What causes the blue glow surrounding the assembly?

Look at the text on page 728 for the answer.



CHAPTER

31 Nuclear Applications

No area of physics has evoked more controversy than nuclear physics. We've been able to apply the principles of electricity, magnetism, and mechanics to situations within our lives without much fanfare. However, because the nuclear force of the atom has been employed as a weapon, it is feared as a potent force for destruction.

Despite its potential for being used for destruction, nuclear physics is an area with great potential for developments for helping people. The applications of nuclear physics to disciplines such as health, safety, and power generation offer tremendous potential benefits. In medicine, the promise of nuclear physics includes tools to diagnose and treat an array of diseases. Harnessing nuclear power provides an array of possibilities. For example, large nuclear reactors can produce electric energy without the pollution associated with burning of fossil fuels, while tiny nuclear power cells drive the pacemakers that regulate the beating of a human heart. Even in your home, the nuclear physics at the heart of smoke detectors can warn you and your family in case of fire.

In many ways, today's modern existence would not be possible without nuclear physics. An informed citizen can weigh the risks and benefits associated with this potent technology. If we can develop ways in which nuclear applications can improve the quality of our lives, then surely we can develop the methods to ensure that the applications pose the lowest possible risk. A truly informed citizen will recognize his or her responsibility to understand some of the science and technology associated with nuclear power to fully evaluate its impact on society.

WHAT YOU'LL LEARN

- You will calculate the energy released in nuclear reactions.
- You will examine how radioactive isotopes are produced and used.
- You will examine how fission and fusion occur.
- You will study how nuclear reactors work.

WHY IT'S IMPORTANT

- Fission reactors are controversial methods of producing electric power, and a knowledge of how they work makes a person better equipped to discuss their strengths and weaknesses.

PHYSICS Online

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

CLICK HERE

31.1 Holding the Nucleus Together

OBJECTIVES

- **Define** binding energy of the nucleus.
- **Relate** the energy released in a nuclear reaction to the change in binding energy during the reaction.

What holds the nucleus together? The negatively charged electrons that surround the positively charged nucleus of an atom are held in place by the attractive electromagnetic force. But the nucleus consists of positively charged protons and neutral neutrons. The repulsive electromagnetic 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

You learned in Chapter 30 that 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 close together, as they are in a nucleus. This force is more than 100 times as intense as the electromagnetic force. The range of the strong force is 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. Because the assembled nucleus has less energy, the binding energy is identified as a negative value.

Binding Energy of the Nucleus

The binding energy comes from the nucleus converting some of its mass to hold the nucleons together, and it 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 two protons and two neutrons. The mass of a proton is 1.007825 u. The mass of a neutron is 1.008665 u. If the mass of the helium nucleus were equal to the sum of the masses of the two protons and the two neutrons, you would expect that the mass of the nucleus would be 4.032980 u. Careful measurement, however, shows that the mass of a helium nucleus is only 4.002603 u. The actual mass of the helium nucleus is less than

> **F.Y.I.**
>
> In the 1950s, Ford Motors designed the Ford Nucleon, which was to be powered by a small atomic reactor core located under a circular cover at the rear of the car. It was to be recharged with nuclear fuel. The car was never built.

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the mass of its constituent parts by 0.0030377 u. The difference between the sum of the masses of the individual nucleons and the actual mass is called the **mass defect.** The energy equivalent of the missing mass is the binding energy, the energy that holds the nucleus together. The binding energy can be calculated from the experimentally determined mass defect by using $E = mc^2$.

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). To determine the energy, you must multiply the mass by the square of the speed of light in air (2.9979×10^8 m/s). This is expressed to five significant digits.

Binding Energy $E = mc^2$

$$= (1.6605 \times 10^{-27}\ \text{kg})(2.9979 \times 10^8\ \text{m/s})^2$$

$$= 14.924 \times 10^{-11}\ \text{kg}\cdot\text{m}^2/\text{s}^2 = 14.924 \times 10^{-11}\ \text{J}$$

Remember that 1 $\text{kg}\cdot\text{m}^2/\text{s}^2$ equals 1 joule. The most convenient unit of energy to use is the electron volt. To express the energy in electron volts, you must convert from joules to electron volts.

$$E = (14.923 \times 10^{-11}\ \text{J})(1\ \text{eV}/1.6022 \times 10^{-19}\ \text{J})$$

$$= 9.3149 \times 10^8\ \text{eV}$$

$$= 931.49\ \text{MeV}$$

Hence, 1 u of nuclear mass is equivalent to 931.49 MeV of binding energy. **Figure 31–1** shows how the binding energy per nucleon depends on the size of the nucleus. Heavier nuclei are bound more strongly than lighter nuclei. Except for a few nuclei, the binding energy per nucleon becomes more negative as the mass number, A, increases to a value of 56, that of iron, Fe. $^{56}_{26}$Fe is the most tightly bound nucleus; thus, nuclei become more stable as their mass numbers approach that of iron. Nuclei whose mass numbers are larger than that of iron are less strongly bound and are therefore less stable.

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.

Analyze and Conclude Describe how this analogy could be extended for a nucleus that contains several protons and neutrons.

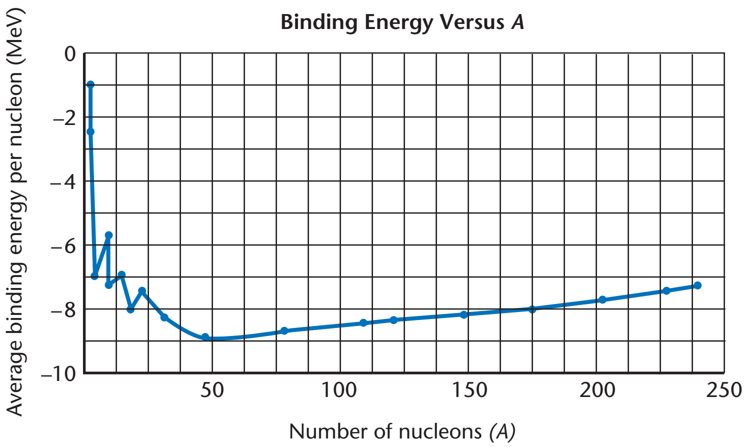

FIGURE 31–1 A graph of the binding energy per nucleon is shown.

Example Problem

Calculating Mass Defect and Nuclear Binding Energy

Find the nuclear mass defect and binding energy of tritium, ${}^3_1H$. The mass of tritium is 3.016049 u, the mass of a proton is 1.007825 u, and the mass of a neutron is 1.008665 u.

Calculate Your Answer

Known:

mass of 1 proton = 1.007825 u
mass of 2 neutrons = 2.017330 u
mass of tritium = 3.016049 u
binding energy of 1 u = 931.49 MeV

Unknown:

total mass of nucleons = ?
mass defect = ?

Strategy:

Add the masses of the nucleons.
The mass defect is equal to the actual mass of tritium less the mass of the one proton and two neutrons that comprise it.

Calculations:

Mass of 1 proton	1.007825 u
Plus mass of 2 neutrons	+2.017330 u
Total mass of nucleons	3.025155 u

Mass of tritium	3.016049 u
Less mass of nucleons	−3.025155 u
Mass defect	−0.009106 u

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

Binding energy: 1 u = 931.49 MeV,
so $E = (-0.009106 \text{ u})(931.49 \text{ MeV/u})$
$= -8.482 \text{ MeV}$

Check Your Answer

- Are the units correct? Mass is measured in u, and energy is measured in MeV.
- Does the sign make sense? Binding energy should be negative.
- Is the magnitude realistic? According to **Figure 31–1,** binding energies per nucleon are between −1 MeV and −2 MeV, so the answer for three nucleons is reasonable.

Practice Problems

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

1. The carbon isotope, ${}^{12}_6C$, 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 one proton and one neutron is called deuterium. The mass of its nucleus is 2.014102 u.

a. What is its mass defect?
b. What is the binding energy of deuterium in MeV?

3. A nitrogen isotope, $^{15}_{7}\text{N}$, has seven protons and eight 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, $^{16}_{8}\text{O}$, 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?

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 $^{238}_{92}\text{U}$, decays by releasing an alpha particle, the binding energy per nucleon of the resulting $^{234}_{90}\text{Th}$ has a more negative value than that of the uranium. This means that the excess energy of the $^{238}_{92}\text{U}$ nucleus is transferred into the kinetic energy of the alpha particle and that the thorium nucleus is more stable than the uranium nucleus. At low atomic numbers, those below $Z = 26$, reactions that add nucleons to a nucleus make the binding energy of the nucleus more negative and increase the stability of the nucleus. Thus, the binding energy of the larger nucleus is less than the sum of the energies of the two smaller ones.

Energy is released when a spontaneous nuclear reaction occurs. In the sun and other stars, the production of heavier nuclei such as helium and carbon from hydrogen releases energy that will become the electromagnetic radiation that you see as visible light from the stars.

HELP WANTED

RADIOLOGIC TECHNOLOGIST

Do you have an associate degree and professional certification in radiological technology? We are looking for a person with both of the above 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 an excellent opportunity for advancement with increased training.
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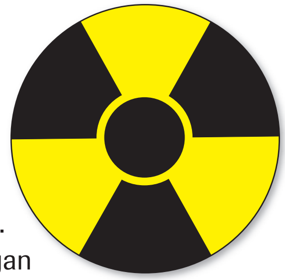
American Society of Radiologic Technologists
15000 Central Avenue, S.E.
Albuquerque, NM 87123

31.1 Section Review

1. When tritium, $^{3}_{1}\text{H}$, decays, it emits a beta particle and becomes $^{3}_{2}\text{He}$. Which nucleus would you expect to have a more negative binding energy?
2. Which of those two nuclei in question 1 would have the larger mass defect?
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 large nuclei, the repulsive electromagnetic force can overcome the strong attractive force and make the nucleus unstable.
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 in this way? Explain.

31.2 Using Nuclear Energy



OBJECTIVES

- **Define** how radioactive isotopes can be artificially produced and used.
- **Solve** nuclear equations.
- **Define** *nuclear fission* and *chain reaction.*
- **Describe** the operation of one or more types of nuclear reactors.
- **Describe** the fusion process.

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 ten years. Questions surrounding the uses of nuclear science in our society are important for all citizens today.

Artificial Radioactivity

Marie and Pierre Curie 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, which produced phosphorus atoms and neutrons by the following reaction (alpha particles can be represented by ${}^{4}_{2}\mathrm{He}$).

$$ {}^{4}_{2}\mathrm{He} + {}^{27}_{13}\mathrm{Al} \rightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n} $$

In addition to neutrons, the Joliot-Curies found another particle coming from the reaction, a positively charged electron, or positron. Remember from Chapter 30 that the positron is a particle with the same mass as the electron but with a positive charge. The most interesting result of the Joliot-Curies' experiment was that positrons continued to be emitted after the alpha bombardment stopped. The positrons were found to come from the phosphorus isotope ${}^{30}_{15}\mathrm{P}$. The Joliot-Curies had produced a radioactive isotope not previously known. The decay of the new isotope occurs via the following reaction.

$$ {}^{30}_{15}\mathrm{P} \rightarrow {}^{0}_{+1}\mathrm{e} + {}^{30}_{14}\mathrm{Si} \qquad ({}^{0}_{+1}\mathrm{e} \text{ is a positron}) $$

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 converted into stable isotopes. Recall from Chapter 30 that this process is known as transmutation. The ${}^{30}_{14}\mathrm{Si}$ isotope of silicon from the reaction above is stable. The radioactive nuclei may emit alpha, beta, and gamma radiation as well as positrons. **Figure 31–2** shows an example of a use of gamma radiation for food preservation.

Artificially produced radioactive isotopes have many other 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. Iodine, for example, is primarily used in the

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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 organisms that cause spoilage. The berries do not absorb the radiation and are not radioactive.

thyroid gland. The thyroid gland uses iodine obtained from food and water to produce thyroid hormone, which controls metabolism. When a gland produces too much hormone, the condition is called hyperthyroidism. When the patient is given radioactive iodine, ${}^{131}_{53}I$, it is concentrated in the thyroid gland. Excess energy in the nucleus of radioactive iodine slows the production of the thyroid hormone. A physician uses a radiation detector 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. **Figure 31–3** shows an image of a healthy thyroid gland superimposed on the area of the throat where it is found.

BIOLOGY CONNECTION

The Positron Emission Tomography Scanner, or PET scanner, is another medical application of isotopes. A positron-emitting isotope is included in a solution injected into a patient's body. In the body, the isotope decays, releasing a positron. The positron annihilates an electron, and two gamma rays are emitted. The PET scanner detects the gamma rays and pinpoints the location of the positron-emitting isotope. A computer is then used to make a three-dimensional map of the isotope distribution, which is affected by the density of the surrounding tissues. This information can then be used to determine the location of tumors and other anomalies. Details such as the use of nutrients in particular regions of the brain also 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.

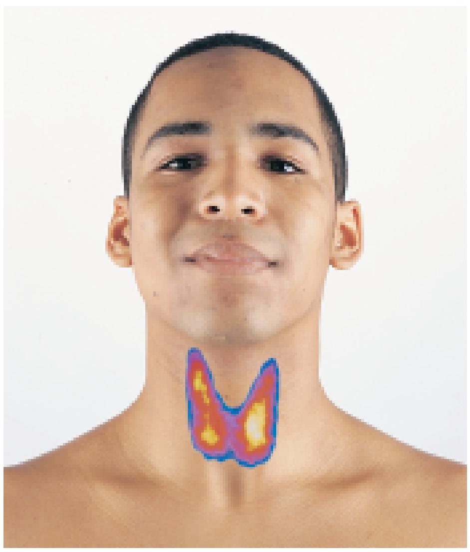
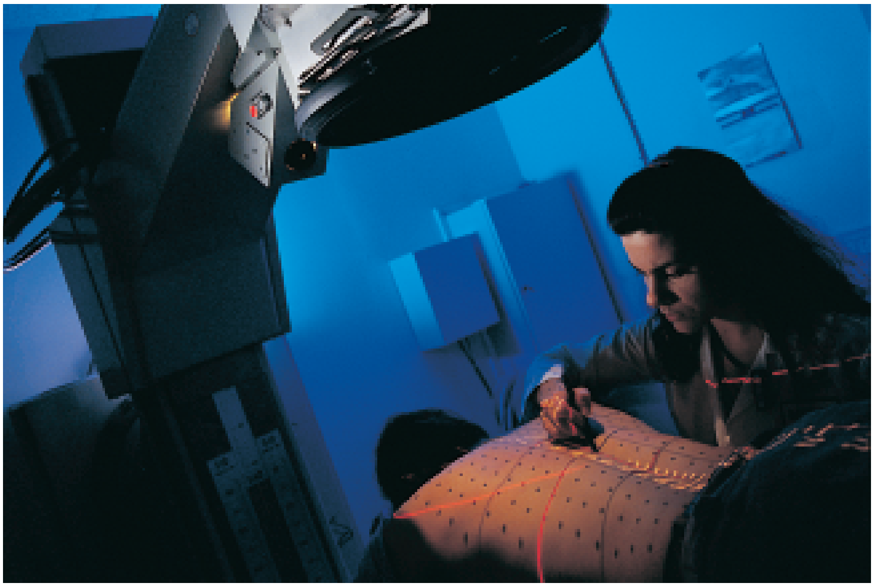


FIGURE 31–3 The photo shows an image of a normal thyroid gland obtained by using radioactive iodine-131. This image is superimposed on the area of the throat where it is found.

FIGURE 31–4 Radiation produced by cobalt-60 is carefully aimed at tumor cells. These cells are more sensitive to the damaging effects of radiation because they will divide more often than normal cells.



F.Y.I.

Gamma rays destroy both cancerous and healthy cells; thus, the beams of radiation must be directed only to the cancerous cells.

Another use of radioactivity in medicine is the destruction of cancerous cells. Often, gamma rays from the isotope $^{60}_{27}Co$ are used to treat cancer patients as is shown in **Figure 31–4.** The ionizing radiation produced by radioactive iodine can be localized and 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 particles such as pions produced by particle accelerators such as the synchrotron. The physician adjusts the accelerator so that the particles decay only in the cancerous tissue. These unstable particles pass through body tissue without doing damage and are trapped in cancerous tissues. When they decay, however, the emitted particles destroy cells.

Practice Problems

5. Use **Table F–6** 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 the 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. $^{210}_{80}Pb$ **b.** $^{210}_{83}Bi$ **c.** $^{234}_{90}Th$ **d.** $^{239}_{93}Np$

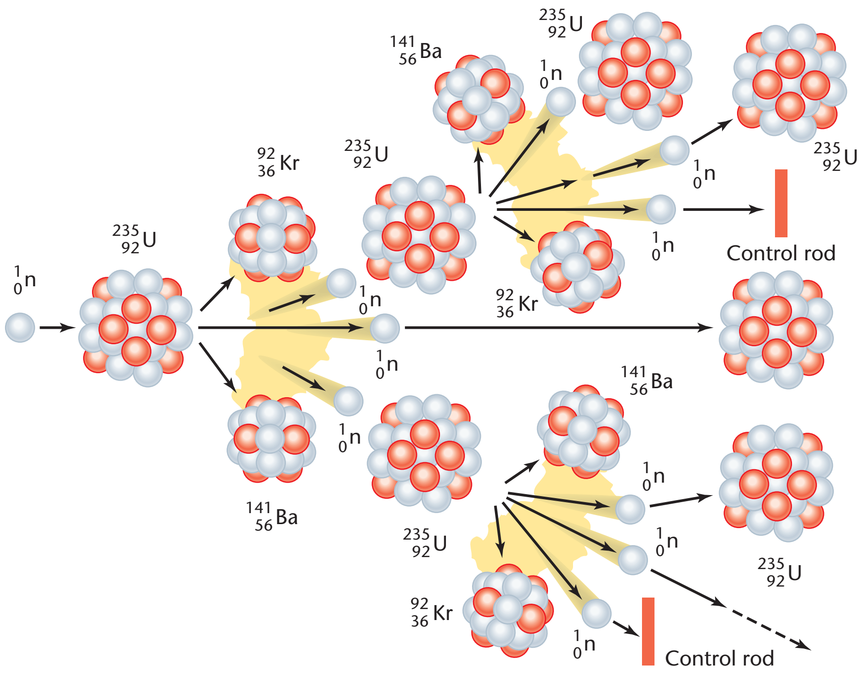


FIGURE 31–5 The nuclear fission chain reaction of uranium-235 takes place in the core of a nuclear reactor.

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 Segre produced many new radioactive isotopes by bombarding uranium with neutrons. They believed that they had formed new elements with atomic numbers larger than 92, the atomic number of uranium.

German chemists Otto Hahn and Fritz Strassmann made careful chemical studies of the results of bombarding uranium with 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 caused a division of the uranium into two smaller nuclei, resulting in a large release of energy. Such a division of a nucleus into two or more fragments is called **fission.** The possibility that fission could be not only a source of energy, but also an explosive weapon, was immediately realized by many scientists.

The uranium isotope, $^{235}_{92}$U, undergoes fission when it is bombarded with neutrons. The elements barium and krypton are typical results of fission, as shown in **Figure 31–5.** The reaction is defined by the following equation.

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

F.Y.I.

A 1000-MW nuclear power plant uses 25 metric tons of fuel per year and produces 25 metric tons of waste. An equivalent coal-burning power plant uses 2.5 million metric tons of coal per year and produces more than 15 million metric tons of waste.

The energy released by each fission can be found by calculating the masses of the atoms on each side of the equation. In the uranium-235 reaction, the total mass on the right side of the equation is 0.215 u smaller than that on the left. The energy equivalent of this mass is 3.21×10^{-11} J, or 2.00×10^{2} MeV. This energy 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 continual process of repeated fission reactions caused by the release of neutrons from previous fission reactions is called a **chain reaction.**

Nuclear Reactors

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

Fermi suggested that a chain reaction would occur if the uranium were broken up into small pieces and placed in a **moderator,** a material that can slow down, or moderate, the fast neutrons. When a neutron collides with a light atom, such as carbon, 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 the fission of a $^{235}_{92}U$ nucleus will cause another $^{235}_{92}U$ nucleus to fission. If there is enough $^{235}_{92}U$ in the sample, a chain reaction can occur.

A neutron loses the most energy when it strikes a hydrogen nucleus. Thus, hydrogen is 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 react with fast neutrons. Thus, the problem of the unwanted nuclear reaction with hydrogen is avoided. As a result, heavy water is used as a moderator with natural uranium in the Canadian CANDU reactors.

The process that increases the number of fissionable nuclei is called **enrichment.** Enrichment of uranium is difficult and requires large, expensive equipment. The U.S. government operates the plants that produce enriched uranium for most of the world.

Solar Power

Problem

How can you measure the local power output from the nearest continuous running fusion reactor, the sun?

Materials

solar cell
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.

Data and Observations			
Voltage indoor	Voltage outdoor	Current indoor	Current outdoor

Analyze and Conclude

1. **Calculating Results** Calculate the power, *IV*, for the solar cell outdoors and indoors. What percentage of power did the window stop?
2. **Calculating Results** Calculate the amount of power that could be produced by a cell that has an area of 1.0 square meter.
3. **Calculating Efficiency** The sun supplies about 1000 W of power per square meter to Earth. Calculate the efficiency of your solar cell.

Apply

1. You are planning to install 15 square meters of solar cells on your roof. How much power will you expect them to produce?
2. Solar panels are used to power satellites in orbit. These panels are generally more efficient than those used on Earth. Why, then, do the satellites still carry batteries?

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 electricity is supplied by nuclear power in your area?

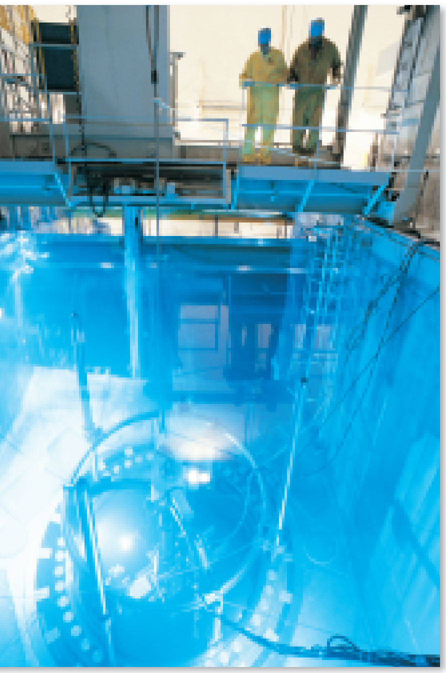
Analyze and Conclude How much electrical energy in your neighborhood is provided by nuclear power and how much is provided by other sources?

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

Energy released by the fission heats the water surrounding the uranium rods. The water itself doesn't boil because it is under high pressure, which increases its boiling point. As shown in **Figure 31–6,** 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

Answers question from page 716.



Some of the fission energy goes to increase the kinetic energy of electrons, giving these particles speeds near the speed of light in a vacuum. You learned in Chapter 14 that when light enters a medium of greater density, the speed of the light in that medium is reduced. In a

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. To extend the supply of uranium, **breeder reactors** have been developed.

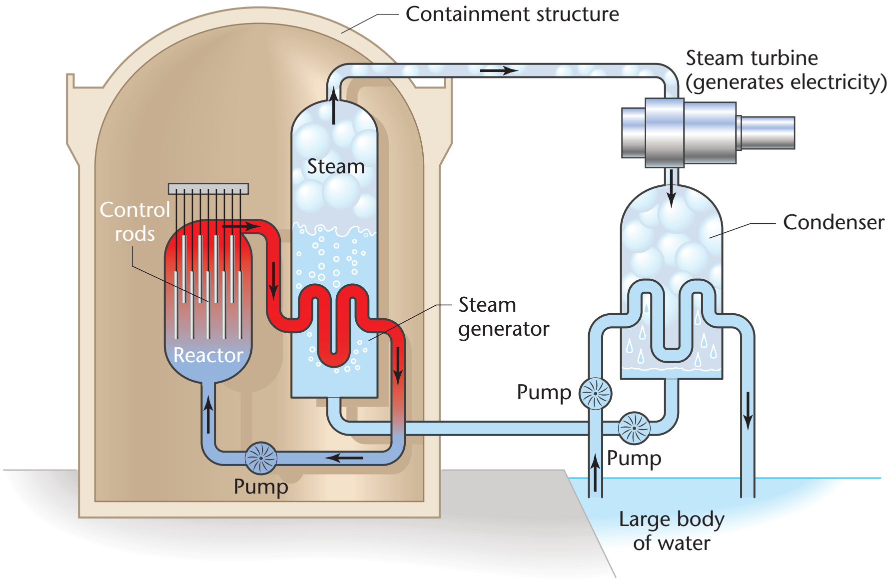


FIGURE 31–6 In a nuclear power plant, the thermal energy released in nuclear reactions is converted to electric energy.

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 neutrons 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 a breeder reactor than was originally present.

Nuclear Fusion

In nuclear **fusion,** nuclei with small masses combine to form a nucleus with a larger mass, shown in **Figure 31–7.** In the process, energy is released. You learned earlier in this chapter that the larger nucleus is more tightly bound, so its mass is less than the sum of the masses of the smaller nuclei. 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 1 million times smaller.

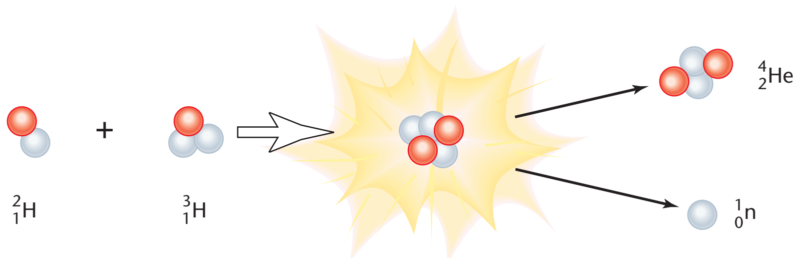


FIGURE 31–7 The fusion of deuterium and tritium produces helium. Protons are red and neutrons are gray in the figure.

F.Y.I.

The sun is a giant nuclear fusion reactor that supplies Earth with energy from more than 150 million km away.

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

$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{1}\mathrm{H} + ^{0}_{+1}\mathrm{e} + ^{0}_{0}\nu$$

$$^{1}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + \gamma$$

$$^{3}_{2}\mathrm{He} + ^{3}_{2}\mathrm{He} \rightarrow ^{4}_{2}\mathrm{He} + 2\ ^{1}_{1}\mathrm{H}$$

The first two reactions must occur twice in order to produce the two $^{3}_{2}\mathrm{He}$ particles needed for the final reaction. The net result is that four protons produce one $^{4}_{2}\mathrm{He}$, two positrons, and two neutrinos.

The repulsive force between the charged nuclei requires the fusing nuclei to have high energies. Thus, fusion reactions take place only when the nuclei have large amounts of thermal energy. For this reason, fusion reactions are often called **thermonuclear reactions.**

The proton-proton chain requires a temperature of about 2×10^7 K, such as that found in the center of the sun. Fusion reactions also occur in a hydrogen, or thermonuclear, bomb. In this device, the high temperature necessary to produce the fusion reaction is produced by exploding a uranium fission, or atomic, bomb.

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 the following.

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

Here, one deuterium atom fuses with one tritium atom to form a helium atom with a resulting release of a neutron and 17.6 million electron volts of energy.

Deuterium, $^{2}_{1}\mathrm{H}$, is available in large quantities in seawater, and tritium, $^{3}_{1}\mathrm{H}$, is easily produced from deuterium. Therefore, controlled fusion would give the world an almost limitless source of energy without the formation of radioactive wastes. In order to control fusion, however, some difficult problems must be solved.

Fusion reactions require that the atoms be raised to temperatures of millions of degrees. No material now in existence 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

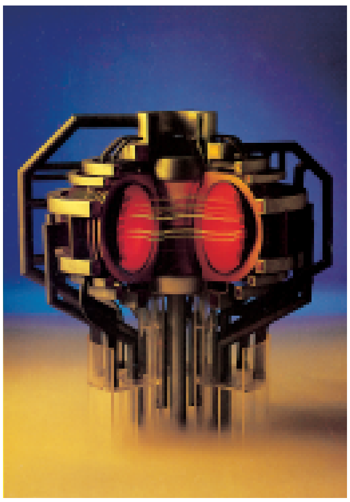
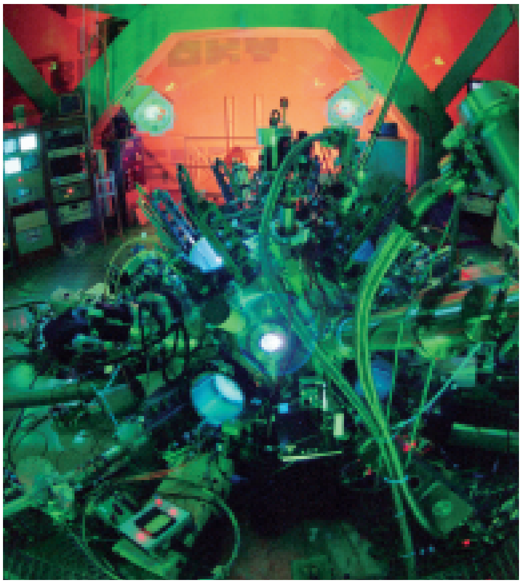


FIGURE 31–8 The Tokamak is an experimental controlled fusion reactor.



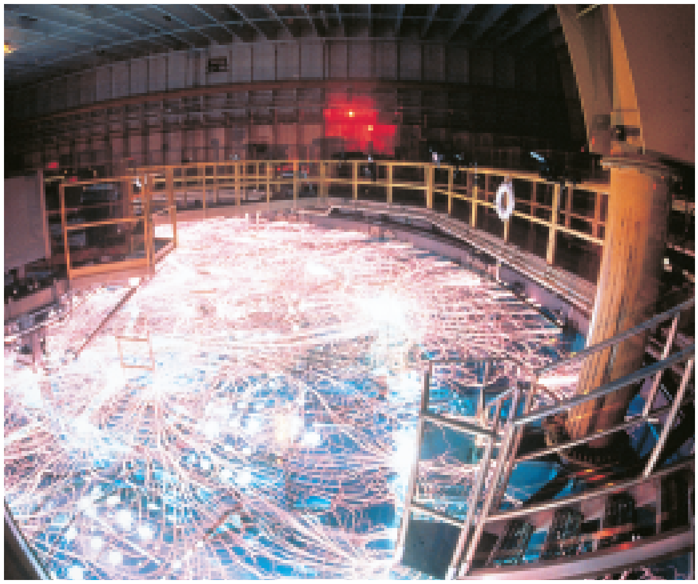


FIGURE 31–9 In laser confinement, pellets containing deuterium and tritium are imploded by many giant lasers, producing helium and large amounts of thermal energy. Electrical discharges are visible on the surface of the water covering the Particle Beam Fusion Accelerator II when a pulse of ions is fired.

liquefied lithium. The lithium, in turn, would boil water, producing steam to turn electric generators.

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 difficult problem because instabilities in the magnetic field allow the plasma to escape. The Tokamak reactor, shown in **Figure 31–8,** provides a doughnut-shaped magnetic field in which the plasma is confined.

A second approach to controlled fusion is called **inertial confinement fusion.** Deuterium and tritium are liquefied under high pressure and confined in tiny glass spheres. Multiple laser beams are directed at the spheres, as shown in **Figure 31–9.** The energy deposited by the lasers results in 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. Calculate the mass defect and the energy released for the deuterium-tritium fusion reaction used in the Tokamak, defined by the following reaction.

$$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

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

Physics & Technology

Radioactive Tracers

Radioactive isotopes are extremely useful in many scientific and industrial applications. Ecologists use radioactive tracers to follow the movement of pesticides or pollutants through ecosystems. For example, many pesticides contain sulfur (S). Replacing some of the S with radioactive sulfur-35 makes it possible to follow the pesticide as it moves through soil and into lakes, streams, or groundwater. Biologists can tag insects, bats, and other small animals with tiny amounts of a radioisotope such as cobalt-60. This enables the researchers to follow the animals' movements at night or in areas not accessible to humans.

Geologists and petrochemical engineers use radiation to learn about underground rock formations. Radioisotopes are lowered into a test well. The characteristics of the radiation that is reflected back from underground rocks and fluids reveal details about the density and composition of the rock. These characteristics also can be used to tell whether water, hydrocarbon deposits, or salt beds are present.

Testing the strength of a material without destroying it is important in industry. Carbon-containing engine parts can be exposed to radiation that turns some of the carbon (C) to carbon-14. After the treated part is installed in the engine and used, lubricating fluid from the engine is tested for carbon-14 content. Extremely small amounts of wear can be measured this way, enabling engineers to determine the rate of wear and predict how long a part can be expected to last.

Phosphorus (P) is a mineral important to plant growth. Plants grown in soil tagged with the radioisotope phosphorus-32 reveal how much of the mineral is absorbed and where it is located in the plant. The amount and location of the radiation emitted by the plant is detected by placing the plant next to a sheet of photographic film.

Thinking Critically Suppose you conducted an experiment with phosphorus-32 tagged soil. After developing the photographic film, what would you expect to see? Explain your reasoning.

31.2 Section Review

1. What happens to the energy released in a fusion reaction in the sun?
2. One fusion reaction involves two deuterium nuclei. A deuterium molecule contains two deuterium atoms. Why doesn't this molecule undergo fusion?
3. Research and evaluate the impact of fission and fusion research on the environment.
4. How does a breeder reactor differ from a normal reactor?
5. **Critical Thinking** Fusion powers the sun. The temperatures are hottest, and the number of fusion reactions greatest, in the center of the sun. What contains the fusion reaction?

CHAPTER 31 REVIEW

Key Terms

31.1
- nucleon
- binding energy
- mass defect

31.2
- fission
- chain reaction
- fast neutron
- moderator
- slow neutron
- enrichment
- control rod
- breeder reactor
- fusion
- thermonuclear reaction
- controlled fusion
- inertial confinement fusion

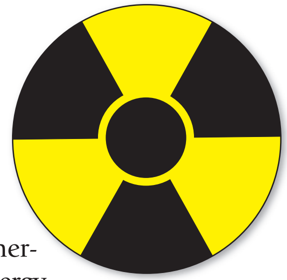
Summary

31.1 Holding the Nucleus Together

- The strong force binds the nucleus together.
- The energy released in a nuclear reaction can be calculated by finding the mass defect, the difference in mass of the particles before and after the reaction.
- The binding energy is the energy equivalent of the mass defect.

31.2 Using Nuclear Energy

- Bombardment can produce radioactive isotopes not found in nature. These are called artificial radioactive nuclei and are often used in medicine.
- In nuclear fission, the uranium nucleus is split into two smaller nuclei with a release of neutrons and energy.
- Nuclear reactors use the energy released in fission to generate electrical energy.



- The fusion of hydrogen nuclei into a helium nucleus releases the energy that causes stars to shine.
- Development of a process for controlling fusion for use on Earth might provide large amounts of energy safely.

Key Equation

31.1

$$E = mc^2$$

Reviewing Concepts

Section 31.1

1. What force inside a nucleus acts to push the nucleus apart? What force inside the nucleus acts in a way to hold the nucleus together?
2. Define the mass defect of a nucleus. To what is it related?

Section 31.2

3. List three medical uses of radioactivity.
4. What sequence of events must occur for a chain reaction to take place?
5. In a fission reaction, binding energy is converted into thermal energy. Objects with thermal energy have random kinetic energy. What objects have kinetic energy after fission?
6. A newspaper claims that scientists have been able to cause iron nuclei to undergo fission. Is the claim likely to be true? Explain.
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 that Jupiter might have become a star if the temperatures inside the planet had not been so low. Review scientific explanations in this chapter and analyze and critique this claim. Why must stars have a 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

13. What is the relationship between the average binding energy per nucleon and the degree of stability of a nucleus?

14. Use the graph of binding energy per nucleon in **Figure 31–1** to determine whether the reaction $^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He$ is energetically possible.
15. Give an example of a naturally and an artificially produced radioactive isotope. Explain the difference.
16. 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?
17. 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 a kilogram of uranium nuclei or the fusion of a kilogram of deuterium produce more energy?
    c. Why are your answers to parts **a** and **b** different?
18. Explain how it might be possible for some fission reactors to produce more fissionable fuel than they consume. What are such reactors called?
19. What is the difference between the fission process in an atomic bomb and in a reactor?
20. Why might a fusion reactor be safer than a fission reactor?

Problems

Section 31.1

21. 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?
22. A nitrogen isotope, $^{12}_{7}N$, has a nuclear mass of 12.0188 u.
    a. What is the binding energy per nucleon?
    b. Does it require more energy to separate a nucleon from a $^{14}_{7}N$ nucleus or from a $^{12}_{7}N$ nucleus? $^{14}_{7}N$ has a mass of 14.00307 u.
23. 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.
24. 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?
25. The binding energy for $^{4}_{2}He$ is 28.3 MeV. Calculate the mass of a helium nucleus in atomic mass units.

Section 31.2

26. The radioactive nucleus indicated in each of the following equations disintegrates by emitting a positron. Complete each nuclear equation.
    a. $^{21}_{11}Na \rightarrow ? + ^{0}_{+1}e + ?$
    b. $^{49}_{24}Cr \rightarrow ? + ^{0}_{+1}e + ?$
27. A mercury isotope, $^{200}_{80}Hg$, is bombarded with deuterons, $^{2}_{1}H$. The mercury nucleus absorbs the deuterons and then emits an α particle.
    a. What element is formed by this reaction?
    b. Write the nuclear equation for the reaction.
28. When bombarded by protons, a lithium isotope, $^{7}_{3}Li$, absorbs a proton and then ejects two α particles. Write the nuclear equation for this reaction.
29. Each of the following nuclei can absorb an α particle, assuming that no secondary particles are emitted by the nucleus. Complete each equation.
    a. $^{14}_{7}N + ^{4}_{2}He \rightarrow ?$
    b. $^{27}_{13}Al + ^{4}_{2}He \rightarrow ?$
30. When a boron isotope, $^{10}_{5}B$, is bombarded with neutrons, it absorbs a neutron and then emits an α particle.
    a. What element is also formed?
    b. Write the nuclear equation for this reaction.
31. When a boron isotope, $^{11}_{5}B$, is bombarded with protons, it absorbs a proton and emits a neutron.
    a. What element is formed?
    b. Write the nuclear equation for this reaction.
    c. The isotope formed is radioactive and decays by emitting a positron. Write the complete nuclear equation for this reaction.
32. The isotope most commonly used in PET scanners is $^{18}_{9}F$.
    a. What element is formed by the positron emission of this element?

b. Write the equation for this reaction.

c. The half-life of $^{18}_{9}F$ is 110 min. A solution containing 10.0 mg of this isotope is injected into a patient at 8:00 A.M. How much remains in the patient's body at 3:30 P.M.?

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

34. Complete the following fission reaction.

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ? + 3\,^{1}_{0}n$$

35. Complete the following fission reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ? + 3\,^{1}_{0}n$$

36. Complete each of the following fusion reactions.

a. $^{2}_{1}H + ^{2}_{1}H \rightarrow ? + ^{1}_{0}n$

b. $^{2}_{1}H + ^{2}_{1}H \rightarrow ? + ^{1}_{1}H$

c. $^{2}_{1}H + ^{3}_{1}H \rightarrow ? + ^{1}_{0}n$

37. One fusion reaction is $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He$.

a. What energy is released in this reaction?

b. Deuterium exists as a diatomic, two-atom molecule. One mole of deuterium contains 6.022×10^{23} molecules. Find the amount of energy released, in joules, in the fusion of one mole of deuterium molecules.

c. When one mole of deuterium burns, it releases 2.9×10^{6} J. How many moles of deuterium molecules would have to burn to release just the energy released by the fusion of one mole of deuterium molecules?

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

Critical Thinking Problems

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

39. The mass of the sun is 2×10^{30} kg. If 90 percent of the sun's mass is hydrogen, find the number of hydrogen nuclei in the sun. From the number of fusion reactions each second that you calculated in problem 38, estimate the number of years the sun could continue to "burn" its hydrogen.

40. If a uranium nucleus were to split into three pieces of approximately the same size instead of two, would more or less energy be released?

Going Further

Data Analysis An isotope undergoing radioactive decay is monitored by a radiation detector. The number of counts in each five-minute interval is recorded. The results are shown in **Table 31–1.** The sample is then removed and the radiation detector records 20 counts resulting from cosmic rays in five minutes. Find the half-life of the isotope. Note that you should first subtract the 20-count background reading from each result. Then plot the counts as a function of time. From your graph, determine the half-life.

TABLE 31–1
Radioactive Decay Measurements

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

Careers Interpret the role of frequency and wavelength in medical treatments such as radiation. Describe the connection between radioactivity and future careers.