CHAPTER 18

The Nucleus and Its Applications

18.1 THE PROBLEM OF NUCLEAR STRUCTURE

The discoveries of radioactivity and isotopes were extraordinary advances. And as usual, they also raised new questions about the structure of atoms, questions that involved the atomic nucleus. We saw in Chapter 17 that the transformation rules of radioactivity could be understood in terms of the Rutherford–Bohr model of the atom. But that model said nothing about the nucleus other than that it is small, has charge and mass, and may emit an α or a β particle. This implies that the nucleus has a structure that changes when a radioactive process occurs. The question arose: Can a theory or model of the atomic nucleus be developed that will explain the facts of radioactivity and the existence of isotopes?

The answer to this question makes up much of *nuclear physics*. The problem of nuclear structure can be broken down into two questions:

(1) What are the building blocks of which the nucleus is made?
(2) How are the nuclear building blocks put together?

The attempt to solve the problem of nuclear structure, although still a frontier activity in physics today, has already led to many basic discoveries and to large-scale practical applications. It has also had important social and political consequences, stretching far beyond physics into the life of society in general, as this text has frequently noted in its earlier chapters.

18.2 THE PROTON–ELECTRON HYPOTHESIS

The emission of α and β particles by radioactive nuclei suggested that a model of the nucleus might be constructed by starting with α and β particles as building blocks. Such a model would make it easy to see, for example, how a number of α particles could be emitted, in succession, in a radioactive series. But not all nuclei are radioactive, nor do all nuclei have masses that are multiples of the α-particle mass. For example, the nucleus of an atom of the lightest element, hydrogen, with an atomic mass of one unit (two units in the case of the heavy isotope), is too light to contain an α particle; so is the light isotope of helium, ${}^3_2\mathrm{He}$.

A positively charged particle with mass of one unit would seem to be more satisfactory as a nuclear building block. Such a particle does indeed exist: the nucleus of the common isotope of hydrogen, ${}^1_1\mathrm{H}$. This particle has been named the *proton*, from the Greek word *protos* for "first." Following the Rutherford–Bohr theory of atomic structure, the hydrogen atom thus consists of a proton with a single electron revolving around it.

In the preceding chapter we discussed the experimental result that the atomic masses of the nuclides are very close to whole numbers; hence, the nuclides are written in symbols with whole-number values for A. This result, together with the properties of the proton (e.g., its single positive charge) made it appear possible that all atomic nuclei are made up of protons. Could a nucleus of mass number A consist of A protons? If this were the case, the charge of the nucleus would be A units, but, except for hydrogen, the nuclear charge Z is found to be always less than A, usually less than $\frac{1}{2}A$. To get around this difficulty, it was assumed early that in addition to the protons, atomic nuclei contain just enough electrons to cancel the positive charge of the extra protons; that is, they were supposed to contain $A - Z$ electrons. After all, nuclei emitted electrons in β decay, so, it appeared, electrons must exist within the nucleus. These electrons would contribute only a small amount to the mass of the nucleus, but together with the protons they would make the net charge equal to $+Z$ units, as required.

It seemed plausible to consider the atom as consisting of a nucleus made up of A protons and $A - Z$ electrons, with Z additional electrons outside the nucleus to make the entire atom electrically neutral. For example, an atom of $^{16}_{8}O$ would have a nucleus with 16 protons and 8 electrons, with 8 additional electrons outside the nucleus. This model of the nucleus is known as the *proton–electron hypothesis* of nuclear composition.

The proton–electron hypothesis seemed to be consistent with the emission of α and β particles by atoms of radioactive substances. Since it was assumed that the nucleus contained electrons, explanation of β decay was no problem. When the nucleus is in an appropriate state, it may simply eject one of its electrons. It also seemed reasonable that an α particle could be formed, in the nucleus, by the combination of four protons and two electrons. (An α particle might exist, already formed in the nucleus, or it might be formed at the instant of emission.)

The proton–electron hypothesis is similar to an earlier idea suggested by the English physician William Prout in 1815. On the basis of the small number of atomic masses then known, Prout proposed that all atomic masses are multiples of the atomic mass of hydrogen and that therefore all the elements might be built up of hydrogen. Prout's hypothesis was discarded when, later in the nineteenth century, the atomic masses of some elements were found to be fractional, in particular, those of chlorine (35.46 units) and copper (63.54 units). With the discovery of isotopes, however, it was realized that the fractional atomic masses of chlorine and copper, like that of neon, arise because these elements are *mixtures* of isotopes, with each separate isotope having an atomic mass close to a whole number.

Although the proton–electron hypothesis was satisfactory in some respects, it led to serious difficulties and had to be given up. One of the most serious difficulties arose from Heisenberg's uncertainty principle in quantum mechanics. As we noted (Section 15.6), the confinement of an electron to a space as small as the nucleus would result in the circumstance that at times the electron's speed would be greater than the speed of light, which is not possible according to special relativity theory.

How could scientists account for the circumstance that electrons cannot be confined within the nucleus, yet they emerge from the nucleus in β decay. As he recalled later, Heisenberg and his assistants were contemplating this problem one day while sitting in a café across from a building housing a swimming pool. Heisenberg suggested a possible approach to the problem. "You see people going into the building fully dressed," he said. "And you see them coming out fully dressed. But does that mean that they also swim fully dressed?" In short, you see electrons coming out of the nucleus, and occasionally being captured by the nucleus, but that does not mean that they remain electrons while in the nucleus. Perhaps the electrons are created in the process of emission from the nucleus.

18.3 THE DISCOVERY OF ARTIFICIAL TRANSMUTATION

A path that led to a better understanding of nuclear composition was opened, almost by accident, in 1919. In that year, Rutherford found that when nitrogen gas was bombarded with α particles from bismuth-214, swift particles were produced that could travel farther in the gas than did the α particles themselves. When these particles struck a scintillation screen, they produced flashes of light fainter than those produced by α particles, about the intensity that would be expected for positive hydrogen ions (protons). Measurements of the effect of a magnetic field on the paths of the particles suggested that they were indeed protons. With the skepticism characterizing all good scientific research, Rutherford ruled out, by means of careful experiments, the possibility that the protons came from hydrogen present as an impurity in the nitrogen.

Since the nitrogen atoms in the gas were the only possible source of protons, Rutherford concluded that an α particle, in colliding with a nitrogen nucleus, can occasionally knock a small particle (a proton) out of the nitrogen nucleus. In other words, Rutherford deduced that an α particle can cause the *artificial disintegration* of a nitrogen nucleus, with one of the products of the disintegration being a proton. But this process does not happen easily. The experimental results showed that only one proton was produced for about one million α particles passing through the gas.

Between 1921 and 1924, Rutherford and his coworker James Chadwick extended the work on nitrogen to other elements and found evidence for the artificial disintegration of all the light elements, from boron to potassium, with the exception of carbon and oxygen. (These elements were later shown also to undergo artificial disintegration.)

The next step was to determine the nature of the nuclear process leading to the emission of the proton. Two hypotheses were suggested for this process:

(a) The nucleus of the bombarded atom loses a proton, "chipped off" as the result of a collision with a swift α particle.

(b) The α particle is *captured* by the nucleus of the atom it hits, forming a new nucleus that, a moment later, emits a proton.

It was possible to distinguish experimentally between these two possible cases by using a device called a "cloud chamber," which reveals the path or track of an individual charged particle. The cloud chamber was invented by C.T.R. Wilson and perfected by him over a period of years. In 1911, it became an important scientific instrument for studying the behavior of subatomic particles (see Figure 18.1). If hypothesis (a) holds, the chipped-off proton should create four tracks in a photograph of a disintegration event: the track of an α particle before the collision, the track of the same α particle after collision, and the tracks of both the proton and the recoiling nucleus after collision.

In case (b), on the other hand, the α particle should disappear in the collision, and only three tracks would be seen: that of the α particle before collision and those of the proton and recoil nucleus after the collision.

The choice between the two possibilities was settled in 1925 when P.M.S. Blackett studied the tracks produced when particles passed through nitrogen gas in a cloud chamber. He found, as shown in the photograph in Figure 18.2, that the only tracks in which artificial disintegration could be seen were those of the incident α particle, a proton, and the recoil nucleus. The absence of a track corresponding to the presence of an α particle after the collision proved that the α particle disappeared completely and that case (b) is the correct interpretation of artificial disintegration: *The α particle is captured by the nucleus of the atom it hits, forming a new nucleus which thereupon emits a proton.*

The process in which an α particle is absorbed by a nitrogen nucleus and a proton is emitted may be represented by an "equation" that is analogous to the representation used in Chapter 17 to describe radioactive

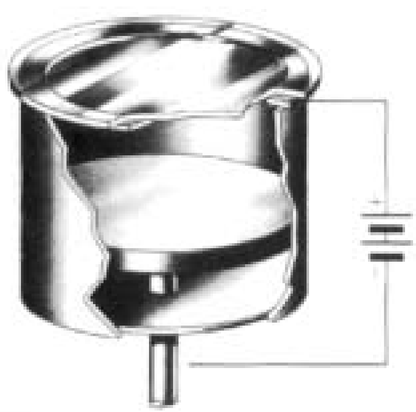


FIGURE 18.1 Cutaway drawing of the Wilson cloud chamber. When the piston is moved down rapidly, the gas in the cylinder cools and becomes supersaturated with water vapor. The water vapor will condense on the ions created along the path of a high-energy charged particle, thereby making the track. For his invention of the cloud chamber, C.T.R. Wilson (1869–1959) of Scotland shared the 1927 Nobel Prize in physics with Arthur H. Compton.

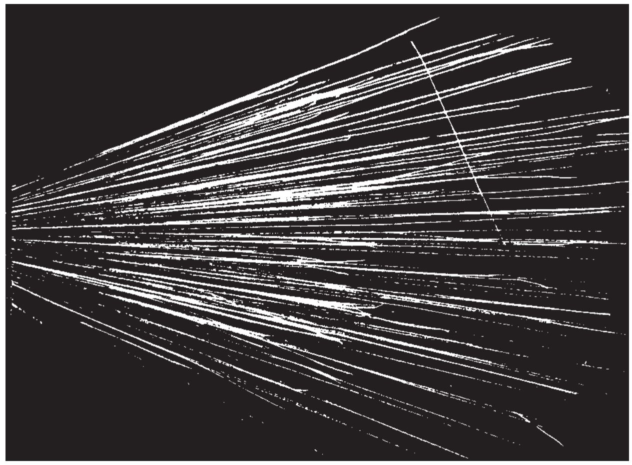


FIGURE 18.2 Alpha-particle tracks from a source at left, in a cloud chamber filled with nitrogen gas. At the right, one alpha particle has hit a nitrogen nucleus; a proton is deflected upward towards the left, and the resulting oxygen nucleus recoils downward to the right.

decay. The equation expresses the fact that the total mass number is the same before and after the collision (i.e., there is conservation of mass number) and the fact that the total charge is the same before and after the collision (there is conservation of charge). The atomic number, the mass number, and the nuclear charge are known for the target nucleus $^{14}_{7}N$, for the incident α particle $^{4}_{2}He$, and for the proton $^{1}_{1}H$. The product nucleus will therefore have the atomic number $7 + 2 - 1 = 8$, which is the atomic number for oxygen, and will have the mass number $14 + 4 - 1 = 17$. Therefore, the product nucleus must be $^{17}_{8}O$, an isotope of oxygen. The disintegration process may therefore be represented by the nuclear reaction

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H.$$

This reaction shows that a transmutation of an atom of one chemical element into an atom of another chemical element has taken place. The transmutation did not occur spontaneously, as it does in the case of natural radioactivity; it was produced by exposing target atoms (nuclei) to projectiles emitted from a radioactive nuclide. It was an *artificial transmutation*. In the paper in which he reported this first artificially produced nuclear reaction, Rutherford said:

> The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nuclear structure of many of the lighter atoms.

(This call for greater energies of "projectiles" was soon answered by the construction of accelerators, see Section 18.7.)

The further study of reactions involving light nuclei led (as you will see in the next section) to the discovery of a new particle, and to a better theory of the constitution of the nucleus. Many types of reactions have been observed with nuclei of all masses, from the lightest to the heaviest, and the possibilities indicated by Rutherford have been realized to an extent far beyond what he could have imagined in 1919.

18.4 THE DISCOVERY OF THE NEUTRON

In 1920, Rutherford suggested that a proton inside the nucleus might have an electron tied to it so closely as to form a neutral particle. Rutherford even suggested the name *neutron* for this hypothetical particle (since it would be neutral in charge). Physicists looked for neutrons, but the search presented at least two difficulties:

(1) They could find no naturally occurring neutron-emitting materials.
(2) The methods used for detecting atomic particles all depended on effects of the electric charge of the particles and so could not be applied directly to neutral particles. Until 1932, the search for neutrons was unsuccessful.

The proof of the existence of neutrons came in 1932 as the climax of a series of experiments on nuclear reactions made by physicists in different countries. The discovery of the neutron is a good example of how physicists operate, how they think about problems, and arrive at solutions. It is an excellent "case history" in experimental science. Working in Germany in 1930, W.G. Bothe and H. Becker found that when samples of boron or of beryllium were bombarded with α particles, they emitted radiations that appeared to be of the same kind as γ rays, at least insofar as the rays had no electric charge. Beryllium gave a particularly marked effect of this kind.

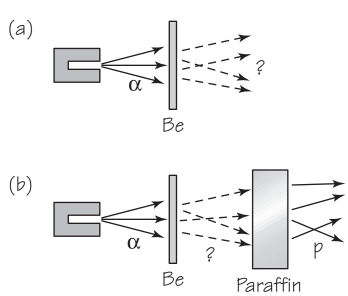


FIGURE 18.3 (a) Alpha particles hitting beryllium with the emission of unknown neutral rays. (b) When paraffin is placed behind the beryllium, protons are ejected.

Observations by physicists in Germany, France, and Great Britain showed that the induced radiation from the beryllium penetrated farther (through lead, for example) than any γ radiation found up to that time. Its interactions with matter showed that it carried energies of about 10 MeV, "MeV" standing for "million electron-volts." (This electron-volt as a unit of energy is discussed in Section 10.6.) The radiation was thus much more energetic than the γ rays (i.e., high-energy photons) previously observed and, as a result, aroused much interest.

Among those who investigated this radiation were the French physicists Frédéric Joliot and his wife Irène Curie, a daughter of the discoverers of radium. They studied the absorption of the radiation in paraffin, a material rich in hydrogen. In the course of their experiments, Joliot and Curie found that the radiation from beryllium, when it fell on paraffin, ejected large numbers of hydrogen nuclei (protons) from the paraffin. The energies of these protons were found to be about 5 MeV. Using the principles of conservation of momentum and energy, they calculated the energy a γ ray would need if it were to transfer 5 MeV to a proton in a collision. The result was about 50 MeV, a value much greater than the 10 MeV that had been measured for the radiation. In addition, the number of protons

FIGURE 18.4 Irène Curie and Frédéric Joliot in their laboratory. Curie and Joliot were married in 1926 and shared the Nobel Prize for chemistry in 1935.

produced was found to be much greater than that predicted on the assumption that the radiation consisted of γ rays.

These discrepancies (between the results of two sets of experiments and between theory and experiment) left physicists in a dilemma. Either they could conclude that the conservation principles of momentum and of energy did not apply to the collisions between the radiation and the protons in the paraffin, or they could seek another hypothesis about the nature of the radiation. Now, if there is any one thing physicists do not want to do it is to give up the principles of conservation of momentum and of energy. These principles are so basic to scientific thought and have proven so useful for so long and in a vast range of different cases that physicists tried very hard to find an alternative to giving them up.

The English physicist James Chadwick found similarly perplexing results for recoiling nuclei from several other light elements, including helium, lithium, carbon, nitrogen, and argon. In 1932, Chadwick proposed a successful alternative hypothesis about the nature of the radiation. Chadwick's first published report of his hypothesis is reproduced in the *Student Guide*. In a later, more complex paper, "The Existence of a Neutron," he wrote:

> If we suppose that the radiation is not a quantum radiation [γ ray], but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfers to different masses. In order to explain the great penetrating power of the radiation, we must further assume that the particle has no net charge. We must suppose it to consist of a proton and electron in close combination, the "neutron" discussed by Rutherford [as a speculation] in his Bakerian Lecture of 1920.

Thus, according to Chadwick's hypothesis, when an element such as beryllium is bombarded with α particles, a nuclear reaction can take place that produces neutrons

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

Here, the symbol $^{1}_{0}n$ represents the neutron postulated by Chadwick, with zero charge and mass number equal to 1. Such neutrons, because they have no electric charge, could penetrate bricks of a material as dense as lead without giving up their energy. When neutrons go through paraffin, there would occasionally be head-on collisions with hydrogen nuclei (protons). The recoiling protons could then be observed because of the ionization they produce. Thus, Chadwick's chargeless particle hypothesis could

FIGURE 18.5 James Chadwick (1891–1974) received the Nobel Prize in physics in 1935 for his discovery of the neutron.

account in a qualitative way for the observed effects of the mysteriously penetrating radiation.

Chadwick's estimate that the particle's mass must be nearly equal to the mass of a proton was made by applying the laws of conservation of momentum and energy to the case of perfectly elastic collisions, that is, simply applying the laws that worked well for the case of interacting billiard balls and other objects treated in "classical" physics. In a perfectly elastic head-on collision between two bodies, as you saw in Chapter 5, almost all of the kinetic energy of the initially moving body will be transferred to the initially stationary body only if the bodies have approximately equal masses. In collisions that are more glancing, i.e., not precisely head-on, less kinetic energy will be transferred. Therefore, on *average*, a kinetic energy of about 5 MeV for the recoiling protons would be about right for collisions produced by neutrons with energies about 10 MeV, if the neutron and proton masses were approximately equal.

Chadwick was able to make a more precise calculation of the neutron's mass by applying the conservation laws to data on collisions with nuclei of different masses; the details of the derivation are shown in the *Student Guide*.

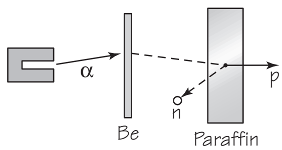


FIGURE 18.6 Experimental setup for alpha particle/beryllium collision producing neutrons that collide with protons in paraffin (compare with Figure 18.3).

Chadwick found the mass of the neutron to be 1.16 u. (The best methods now available for determining the neutron mass give 1.008665 u, based on a scale where ^{12}C is defined to have a mass of 12 u exactly). The difficulties of measuring the kinetic energies of the recoiling nuclei made this only an approximate value, but it was good enough to show that the neutron has a mass very close to that of the proton; thus, Chadwick's hypothesis did indeed offer a satisfactory solution to the problem of the "radiation" emitted when beryllium or boron was bombarded with particles.

Much research has been done since on the properties of neutrons and on the interactions between neutrons and atoms. An entire branch of study called *neutron physics* has arisen. Neutron physics deals with the production of neutrons, their detection, and their interaction with atomic nuclei and with matter in bulk. This research has led, among other things, to the discovery of nuclear fission, to be discussed below.

18.5 THE PROTON–NEUTRON MODEL

The discovery of the neutron, with an atomic mass close to one unit and with no electric charge, confirmed Rutherford's suggestion that the atomic nucleus is made up of protons and neutrons. This hypothesis was soon used as the basis of a detailed theory of the nucleus by Heisenberg in 1932. His work represented another triumph of quantum mechanics.

According to the *proton–neutron model* that arose from the new theory, the nucleus of an atom having atomic number Z and mass number A consists of Z protons and A–Z neutrons. The nuclei of the isotopes of a given element differ only in the number of neutrons they contain. Thus, the nucleus of the hydrogen isotope of mass number 1 contains one proton; the nucleus of the hydrogen isotope of mass number 2 contains one proton and one neutron. (That nucleus is called a deuteron.) The nucleus of the neon isotope ^{20}Ne contains 10 protons and 10 neutrons, while that of ^{22}Ne contains 10 protons and 12 neutrons. The atomic number Z identified with the charge on the nucleus, is the number of protons in the nucleus. The mass number A is the total number of protons and neutrons. The term

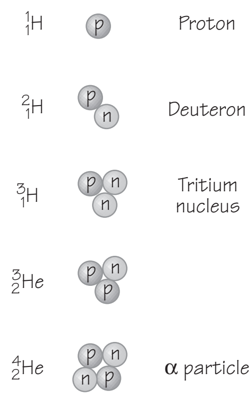


FIGURE 18.7 Neutron-proton models of isotopes of hydrogen and helium.

nucleons refers to both kinds of nuclear particles. *So atomic mass number A turns out to be simply the number of nucleons in the nucleus!*

According to the proton–neutron model, one proton alone forms the common isotope of hydrogen, $^1_1$H. One proton and one neutron yield $^2_1$H, called a deuteron, and the resulting atom is called deuterium. When two deuterium atoms combine with oxygen, they form "heavy water." The atom formed from the rare isotope $^3_1$H is called tritium, a radioactive substance.

Is the proton–neutron hypothesis for the structure of nuclei fully consistent with the facts of radioactivity, such as α and β emission and the transformation rules? If two protons and two neutrons could combine, the resulting particle would have $Z = 2$ and $A = 4$, just the properties of the α particle. The emission of two protons and two neutrons (in the combined form of an α particle) would be consistent with the first transformation rule of radioactivity. (The α particle might exist as such in the nucleus, or it might be formed at the instant of emission; the latter possibility is now considered more likely.)

The neutron–proton hypothesis raised a new question: if the nucleus consists of protons and neutrons, where could a β particle come from in β decay? This question is more difficult to answer than that of the origin of an α particle. The second transformation rule of radioactivity provides a clue: When a nucleus emits a β particle, its charge Z increases by one unit while its mass number A remains unchanged. This would happen if a neutron were to change into a proton and a β particle.

This idea was not a return to the proton–electron hypothesis discussed earlier. Physicists had already come to the conclusion that electrons are not present in the nucleus, so β decay was not considered to be a simple separation of a proton and electron; it would have to be a *transformation* of a neutron that *created* a proton and electron. However, there were additional experimental data that raised difficulties for such a simple transformation idea.

18.6 THE NEUTRINO

The description of β decay in terms of the transformation of a neutron in the nucleus is part of one of the most fascinating stories in modern physics: the prediction and eventual discovery of the particles called the *neutrino* and the *antineutrino*.

Quantitative studies of the energy relations in β decay during the 1920s and 1930s raised a difficult and serious question. Methods were devised for determining the energy change in a nucleus during β decay. According to the principle of conservation of energy, the energy lost by the nucleus should be equal to the energy carried off by the β particle; but the measured kinetic energies of the β particles had a whole range of measured values, all smaller than the amount of energy lost by the nucleus. Some of the energy lost by the nucleus seemed to have disappeared. Measurements made on a large number of β emitters indicated that on the average about two-thirds of the energy lost by the β-decaying nuclei seemed to disappear. Attempts to find the missing energy failed. For example, some physicists thought that the missing energy might be carried off by γ rays; but no such γ rays could be detected experimentally. The principle of conservation of energy seemed to be violated in β decay. Similar discrepancies were found in measurements of the momentum of the emitted electron and the recoiling nucleus.

As in the case of the experiments that led to the discovery of the neutron, physicists tried very hard to find an alternative to accepting a failure of the principles of conservation of energy and momentum. These and related considerations led the Austrian physicist Wolfgang Pauli to suggest that another, hitherto unnoticed, particle is emitted in β decay along with the electron, and that this particle carries off the missing energy and momentum. This hypothetical particle could have no electric charge, because the positive charge of the proton and the negative charge of the β particle together are equal to the zero charge of the original neutron. The mass–energy balance in the decay of the neutron indicated that the rest mass of the hypothetical particle should be very small, much smaller than the mass of an electron and possibly even zero. The combination of zero electric charge and zero or nearly zero mass would make the particle extremely hard to detect.

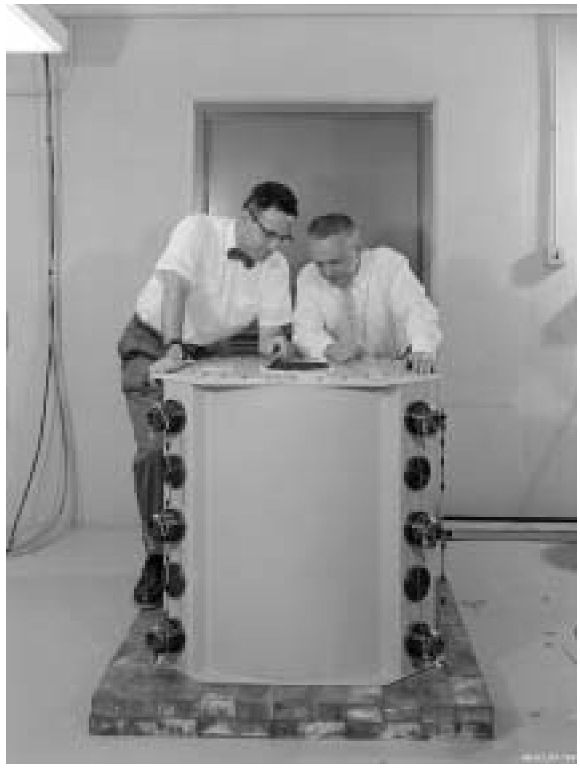


FIGURE 18.8 Neutrinos were first detected in this tank. Reactions provoked by neutrinos from a nuclear reactor cause flashes of light in the liquid with which the tank is filled. The flashes are detected by the photoelectric tubes that stud the tank wall. This work was done by two American physicists, Clyde Cowan and Frederick Reines (pictured here at a nuclear power plant in South Carolina).

The Italian physicist Enrico Fermi called the suggested particle the *neutrino* ("little neutral one" in Italian). Fermi constructed a theory of β decay based on Pauli's suggestion, in which a neutron decays into a proton, an electron, and a neutrino, here represented by the Greek letter nu (ν):

$$^1_0n + {}^1_1p \rightarrow {}^0_1e + \nu.$$

This theory has been successful in describing the known facts of β decay. From 1934 on, while the difficult hunt for its experimental verification was still in progress, the neutrino was accepted as a "real" particle for two reasons, both theoretical: It saved the principle of conservation of energy in β decay, and it could be used successfully both to describe the result of experiments in β decay and to predict the results of new experiments.

It is now known that a *free* neutron, that is, a neutron separated from an atom, sooner or later decays into a proton, an electron, and a neutrino. (The half-life of a beam of free neutrons has been measured to be 12 min.)

Many unsuccessful attempts were made to detect neutrinos over a period of 25 years. Finally, in 1956, neutrinos were detected in an experiment using the

There is one more complication. It is now known that there are several kinds of neutrinos. The one involved in β decay (as discussed so far) is now referred to as an *antineutrino* and is denoted by the symbol $\bar{\nu}$. The transformation of a neutron during β emission is now written

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

extremely large flow of neutrinos that comes out of a nuclear reactor. The detection of neutrinos is an indirect process that involves detecting the products of a reaction *provoked* by a neutrino. The reaction used was a reverse β decay, the production of a proton from a neutron. Because the proper meeting of a proton, an electron, and a neutrino at the same place and same time is an exceedingly unlikely event—neutrinos can go right through the entire Earth without change—and the resulting neutron difficult to detect, "catching" the neutrinos required a very elaborate and sensitive trap. Again, the faith of physicists in the principle of conservation of energy was justified.

18.7 THE NEED FOR PARTICLE ACCELERATORS

Up to 1932, the study of nuclear reactions was limited by the kind of projectile that could be used to bombard nuclei. Only α particles from the naturally radioactive nuclides could bring about reactions. Progress was limited because α particles could be obtained only in beams of low intensity and with fairly low kinetic energies. These relatively low-energy particles could produce transmutations only in light elements. When heavier elements are bombarded with α particles, the repulsive electric force exerted by the greater charge of the heavy nucleus on an α particle makes it difficult for the α particle to reach the nucleus. The probability of a nuclear reaction taking place becomes very small or zero. Because the interest in nuclear reactions was great, physicists in many countries sought methods of increasing the energy of charged particles to be used as projectiles.

There were advantages to be gained in working with particles like the proton or the deuteron (the nucleus of the deuterium or heavy hydrogen atom) that have only one positive charge. Having only a single charge, these particles would experience smaller repulsive electric forces than would α particles in the neighborhood of a nucleus, and thus would be more successful in getting close enough to produce transmutations, even of heavy (and therefore high-charge) target nuclei. Protons or deuterons could be obtained from positive-ray tubes, but their energies were rather low. Some device was needed to accelerate these particles to higher energies, as Rutherford was among the first to say. Such devices might also offer other advantages. The speed (and energy) of the bombarding particles could be controlled by the experimenter, and very intense projectile beams might be obtained. It would then be possible to find how nuclear reactions depend on the energy of the bombarding particles.

Since 1930 scientists and engineers have invented and developed many devices for accelerating charged particles. In each case, the particles used (electrons, protons, deuterons, α particles, or heavy ions) are accelerated by an electric field. In some cases, a magnetic field is used to control the path of particles, that is, to steer them. The simplest type has a single high-voltage step of about ten million volts, thus increasing electron or proton energies to 10 MeV.

Another type of accelerator has a long series of low-voltage steps applied as the particle travels in a straight line. Some of these machines produce electron energies up to 20 GeV (1 GeV = 10^9 eV, GeV standing for "giga electron-volts"). A third general type uses magnetic fields to hold the particles in a circular path, returning them over and over to the same low-voltage accelerating fields. The first machine of this type was the cyclotron (see Figure 18.9). Some of these accelerators produce 7 GeV electrons or

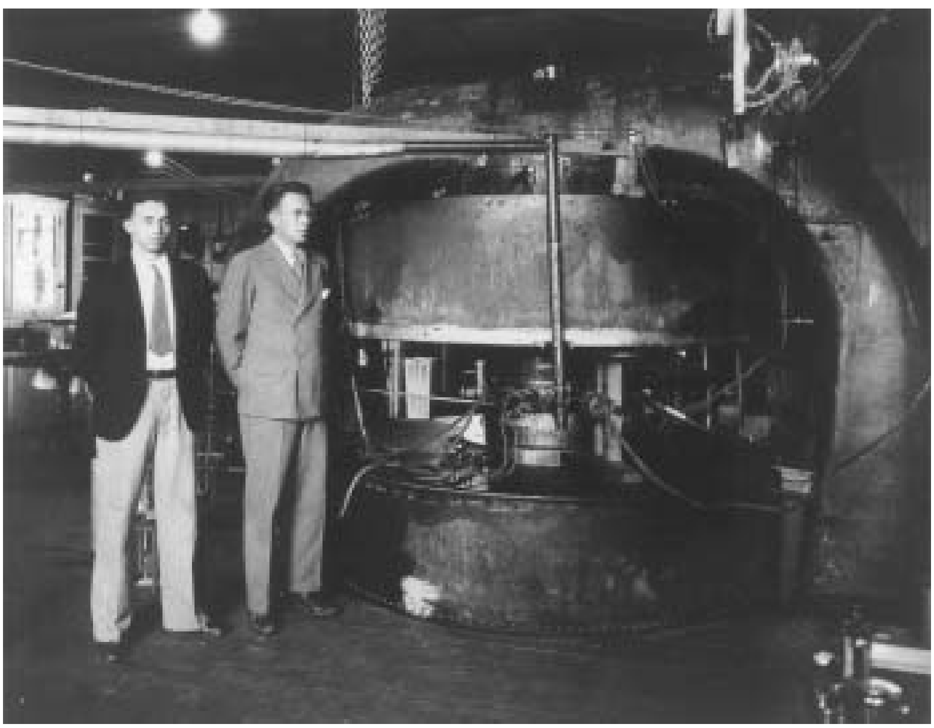
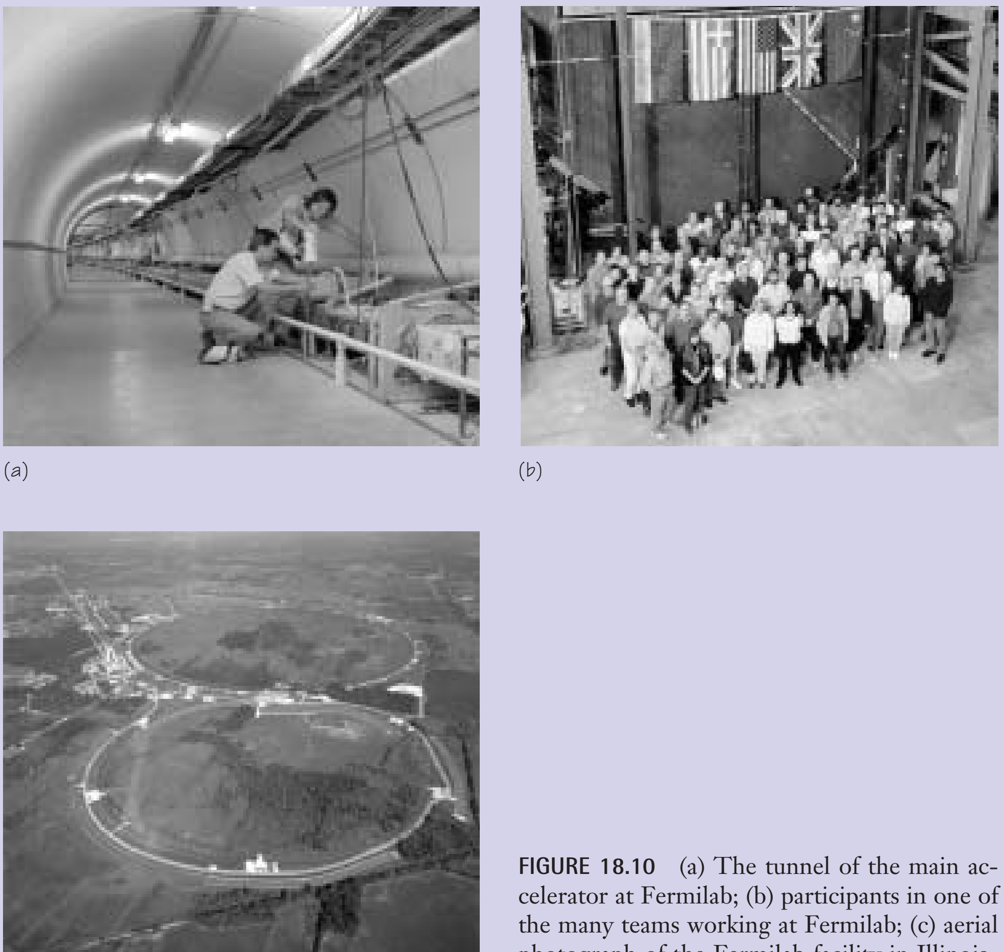


FIGURE 18.9 M.S. Livingston (left) and Ernest O. Lawrence (right) are shown standing beside the magnet for one of the earliest cyclotrons. Lawrence and Livingston invented the cyclotron in 1931, thereby initiating the development of high-energy physics in the United States.

ACCELERATORS

Research into the nature of matter has disclosed the structure of the atom and the atomic nucleus. Much current research is focused on the particles that make up the nucleus. Matter responds to four different types of force: (1) the strong force, (2) the electromagnetic force, (3) the weak force, and (4) the gravitational force. By observing how particles react when influenced by some of these forces, scientists have discovered the existence of many new and seemingly bizarre particles, using particle accelerators of increasingly higher energy. Probing the nature of matter is an international endeavor. For example, at Fermilab (Illinois) during 2001, there were over 2500 users of the accelerators, including 1368 foreign nationals from 25 countries.



(*a*) (*b*) (*c*)

FIGURE 18.10 (a) The tunnel of the main accelerator at Fermilab; (b) participants in one of the many teams working at Fermilab; (c) aerial photograph of the Fermilab facility in Illinois.

500 GeV protons. Accelerators producing in excess of 2000 GeV (2 TeV) are being planned at CERN, the European accelerator near Geneva, Switzerland. Accelerators have become basic tools for research in nuclear and high-energy physics. Accelerators are also used in the production of radioactive isotopes and as radiation sources, both for medical and for industrial purposes.

One of the most powerful accelerators currently in use is a 1000 TeV particle accelerator now in operation at the National Accelerator Laboratory (Fermilab) in Batavia, Illinois. Such "machines" are among the most complex and grandiose structures ever built. Indeed, they are monuments to human imagination and ingenuity, the ability to reason and to collaborate in groups—some as many as 500 persons—on peaceful projects that further the understanding of nature. Basically, the "machines" are tools to help physicists find out as much as they can about the structure of nuclear particles and the forces holding them together.

With the discovery of the neutron in 1932, it was then believed that three "elementary" particles act as the building blocks of matter: the proton, the neutron, and the electron. The existence of new particles found later, such as neutrinos and antineutrinos, has been mentioned. As high-energy accelerators became available, additional "elementary" particles were discovered, one after another. These particles are grouped into "families" according to their properties. Most of these particles exist only briefly; typical lifetimes are of the order of 10^{-8} s or less. A whole new field, high-energy physics, has evolved, and the aim of the high-energy physicist of today is to discern the order and structure behind the large number of "elementary" particles that have been discovered.

How do physicists detect these particles? A number of methods by which physicists can observe and measure radioactive emissions have already been mentioned. They include the electroscope and the electrometer employed since the early days of radioactivity, the Geiger counter, and the Wilson cloud chamber. In addition, various types of ionization chambers, scintillation counters, photographic emulsions, semiconductor devices, spark chambers, and bubble chambers are also in use.

18.8 THE ENERGY OF NUCLEAR BINDING

The concepts of atomic and nuclear structure—than an atom consists of a nucleus surrounded by electrons and that the nucleus is made up of protons and neutrons—led to a fundamental question: *Is the mass of a neutral atom equal to the sum of the masses of the protons, neutrons, and electrons that make up the neutral atom?*

This question can be answered precisely because the masses of the proton, the neutron, and the electron are known, as are the masses of nearly all the atomic species. A survey of the known atomic masses has shown that, for each kind of atom, the atomic mass is always *less* than the sum of the masses of the constituent particles when measured in their free states. The simplest atom containing at least one proton, one neutron, and one electron is deuterium, ${}^{2}{}_{1}$H. In this case, the masses (in atomic mass units, or u) of the constituents of a deuterium nucleus, called a deuteron, are

$$\begin{aligned}
\text{rest mass of one proton} &= 1.007276 \text{ u},\\
\text{rest mass of one neutron} &= \underline{1.008665} \text{ u},\\
\text{total rest mass of particles in free state} &\quad 2.01594 \text{ u},\\
\text{rest mass of deuteron} &= 2.01355 \text{ u},\\
\text{difference } (\Delta m) &= 0.00239 \text{ u}.
\end{aligned}$$

Although the difference in rest mass, Δm, may appear small, it corresponds to a significant energy difference, because of the factor c^2 in the relation $E = mc^2$, where c is the speed of light (about 3×10^8 m/s). The difference, Δm, in mass, which is called the *mass defect*, corresponds to a difference in the amount of energy ΔE before and after the formation of the nucleus according to the relationship from relativity theory: $\Delta E = \Delta mc^2$. A convenient conversion factor from atomic mass (expressed in atomic mass units) to energy (expressed in million electron volts) is 1 u = 931 MeV. If therefore we consider the formation of a deuterium nucleus from the combination of a proton and a neutron, then an amount of mass 0.00239 u will be "lost" in the process. This mass defect means that an amount of energy equal to (0.00239 u) × (931 MeV/u) = 2.23 MeV has to be radiated away from this system of combining particles before they settle down as a deuterium nucleus. (In addition, a tiny bit more of energy must also be lost, as a photon, when an electron is bound to an orbital path around this nucleus in forming a deuterium atom.)

The energy equivalent of 1 atomic mass unit:

$$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg},$$

$$\begin{aligned}
\Delta E &= \Delta mc^2\\
&= (1.66 \times 10^{-27} \text{ kg}) \times (3 \times 10^8 \text{ m/s})\\
&= 14.9 \times 10^{-11} \text{ J}.
\end{aligned}$$

But 1 MeV = 1.60×10^{-12} J:

$$\begin{aligned}
\Delta E &= \frac{14.9 \times 10^{-11} \text{ J}}{1.6 \times 10^{-13} \text{ J/MeV}}\\
&= 931 \text{ MeV}.
\end{aligned}$$

The expected energy loss calculated from the difference in rest mass can be compared with the result of a direct experiment. When hydrogen is bombarded with neutrons, a neutron can be captured in the reaction

$$ {}^{1}_{0}n + {}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + \gamma. $$

This reaction produces no particle fragments having large kinetic energy, so the mass of 0.00239 u by which ${}^2_1$H is lighter than ${}^1_0n + {}^1_1$H must be carried away by the γ ray. The energy of the γ ray has been determined experimentally and found to be 2.23 MeV, just as predicted! This confirms that on forming a nucleus, the constituents give up energy, generally as a gamma ray, corresponding to the amount of mass difference.

The inverse reaction, in which a deuteron is bombarded with γ rays, has also been studied

$$\gamma + {}^2_1\text{H} \rightarrow {}^1_1\text{H} + {}^1_0n.$$

When the energy of the γ rays is less than 2.23 MeV, this reaction cannot occur. But if γ rays of energy 2.23 MeV or greater are used, the reaction can occur; some photons are absorbed, and separate protons and neutrons can be detected.

To summarize: Following the "capture" of a neutron by the nucleus ${}^1_1$H, energy is liberated in the form of a γ ray. This energy (2.23 MeV) is called the *binding energy* of the deuteron. It can be thought of as the energy released when a proton and neutron bind together to form a nucleus. To get the inverse reaction (when ${}^2_1$H is bombarded with γ rays), energy must be absorbed. So you can think of the binding energy as also the amount of energy *needed* to break the nucleus up into its constituent nuclear particles.

The concept and observation of binding energy apply, of course, not only to the example just given but to all situations in which simple parts are bound together by some force to form a complex system. For example, the Earth is held in orbit around the Sun and would need to be given a certain additional amount of kinetic energy to escape from the Sun, to which it is now bound by their mutual gravitational attraction. In a hydrogen atom, the electron needs 13 eV before it can escape from the nucleus that

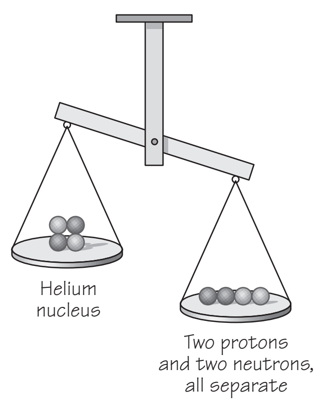


FIGURE 18.11 A case where the whole seems not to be equal to the sum of its parts. Two protons and two neutrons, measured separately, are distinctly more massive than a helium nucleus, which consists of the same particles that are bound together. The particles lose some energy (mass) in binding together to form a nucleus.

binds it by an electric attraction. Conversely, when a bare $^1_1$H nucleus captures an electron and becomes a stable, ordinary neutral atom of hydrogen, the system must give up an amount of energy equal to 13.6 eV by radiation, exactly the observed energy of the photon emitted in this process of electron capture. However, only the nuclear binding energies are relatively large enough to represent measurable mass differences.

18.9 NUCLEAR BINDING ENERGY AND STABILITY

The calculation of the nuclear binding energy made for the deuteron can be extended to all other nuclear species, and such calculations have been performed. Figure 18.12 shows in graphic form how the total nuclear bind-

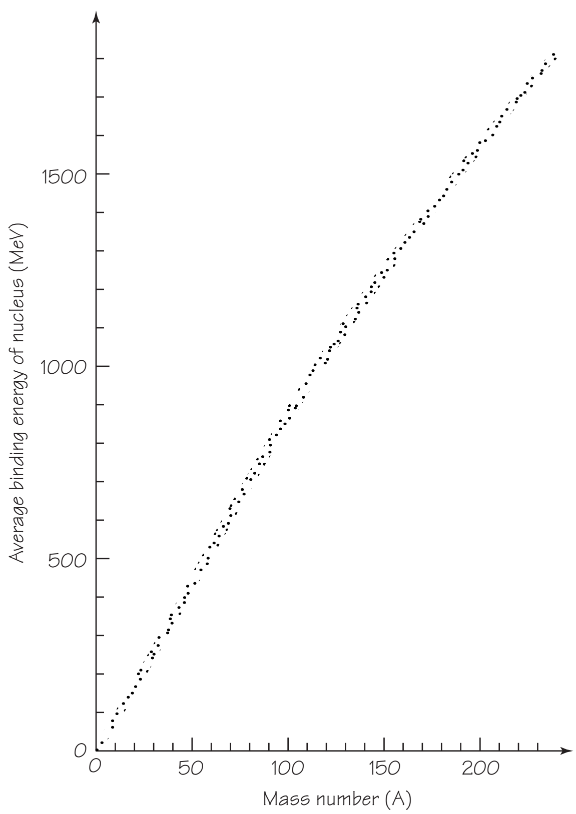


FIGURE 18.12 Nuclear binding energy as a function of the mass number—i.e., the number of particles in the nucleus.

ing energy for stable nuclides increases with increasing atomic mass, as more particles are added to form the nucleus. The term *nucleons* refers to both protons and neutrons; therefore, the binding energy of the nucleus increases with the number of nucleons. But, as you see, the result is not a straight line. Such experimental data have important implications.

The implications can be seen more clearly if the *average binding energy per nucleon* is calculated. In the case of the carbon-12 example, the total binding energy is 92.1 MeV. Since there are 12 nucleons inside the nucleus (six protons and six neutrons), the average binding energy per nucleon is 92.1 MeV/12, or 7.68 MeV. In the graph in Figure 18.13, the experimentally obtained values of the average binding energy per nucleon (in MeV) are plotted against the number of nucleons in the nucleus (mass number, *A*). Notice the unusually high position (above the curve) of the data point near 7.1 MeV, compared to its neighbors in the periodic table. The point is for ^{4}He. The relatively high value of the binding energy of this nucleus indicates its unusually great stability.

The significance of the graph lies in its striking shape. The binding energy per nucleon starts with a low value for the deuterium nucleus (the first point) and then increases rapidly. Some nuclei in the early part of the curve, for example, ^{4}He, ^{12}C, and ^{16}O, have exceptionally high values as compared with their neighbors. This indicates that more energy would have to be supplied to remove a nucleon from one of these nuclei than from one of

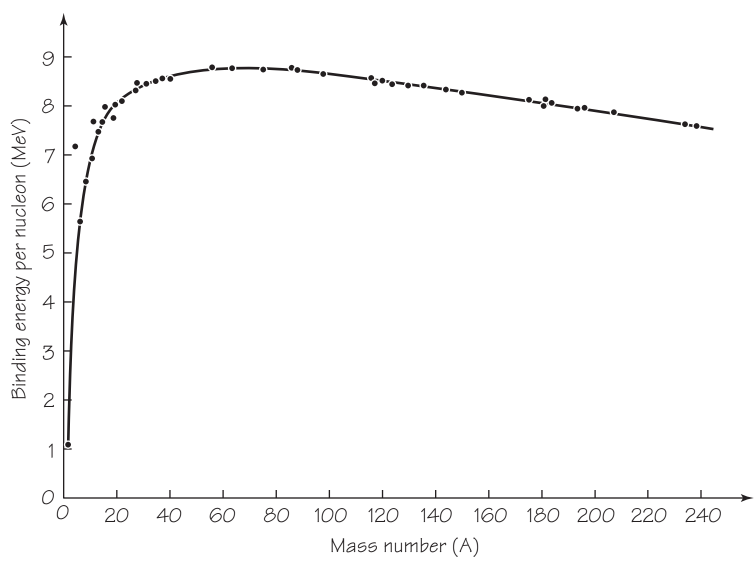


FIGURE 18.13 The average binding energy per nucleon for stable nuclei as a function of the number of particles in the nucleus.

their neighbors. (*Remember*: High binding energy per nucleon means a great deal of energy is needed to take the nucleus apart into its constituent nucleons. In a sense "binding energy" might have been better called "unbinding energy.")

The high binding energy per nucleon of ^{4}He compared with deuterium would mean that if two deuterium nuclei were joined together to form a ^{4}He nucleus, there would be a large amount of excess energy available, which would be emitted to the environment. This excess energy is the source of the enormous energies made available in *fusion*, or *thermonuclear*, reactions, discussed below.

Since they do have such high binding energies, you would expect ^{4}He, ^{12}C, and ^{16}O to be exceptionally stable. There is evidence in favor of this conclusion, for example, the fact that the four particles making up the ^{4}He nucleus are emitted as a single unit, the α particle, in radioactivity.

The experimentally obtained curve of binding energy per nucleon has a broad maximum, extending from approximately $A = 50$ to $A = 90$. Then it drops off for the heavy elements. Thus, $^{63}_{29}$Cu near the maximum is found to have a binding energy per nucleon of about 8.75 MeV, while $^{235}_{92}$U, near the high-A end of the curve, has a value of 7.61 MeV. This indicates that as more nucleons are added to the heavier nuclei, the binding energy per nucleon decreases. It follows that the nuclei in the neighborhood of the maximum of the curve, like those of copper, should be more difficult to break up than heavier nuclei, such as radium and uranium. It also follows that when uranium and other high-A nuclei somehow are made to break up, their fragments are smaller nuclei which possess higher binding energy per nucleon. In such a case there is again excess energy due to the difference in energy between the starting nucleus and its fragments, which is emitted to the environment in the form of kinetic energy of the fragments and gamma radiation. This historically significant process, which involves the splitting of the heaviest nuclei into lighter nuclei, is known as *nuclear fission*. The excess energies available during fission are the source of the enormous energies released in nuclear fission reactions.

The shape of the average binding energy curve, which drops off at both ends, indicates, therefore, that there are two general reaction processes by which one can hope to release energy from nuclei:

(1) combining light nuclei into a more massive nucleus, known as nuclear fusion; or
(2) splitting up heavy nuclei into nuclei of medium mass, which is called nuclear fission.

In either process, the resulting products would have greater average binding energy per nucleon, so energy would be released in the process. Both fusion and fission have been shown to occur, and the technology of fission has been simplified and exploited in many countries. Fission reactions can be made to take place slowly (as in a nuclear power plant) or very rapidly (as in a nuclear explosion).

The idea of binding energy should now make it clear why atomic masses, when precisely measured, are not exactly whole-number multiples of the mass of a hydrogen atom, even though nuclei are just collections of identical protons and neutrons. When those particles combined to make a nucleus, their total rest mass was reduced by an amount corresponding to the binding energy, and the average binding energy varies from nuclide to nuclide, as shown in Figure 18.13.

We now take a closer look at fission and fusion.

18.10 NUCLEAR FISSION: DISCOVERY

The discovery of nuclear fission is an example of an unexpected result with great practical and social implications, yet originally it was obtained during the course of research carried on for reasons having nothing to do with the possible uses society would make of the discovery. It is also an excellent example of the combined use of physical and chemical methods in nuclear research, and of the effectiveness of teamwork.

When Joliot and Curie showed that some products of neutron-induced nuclear reactions are radioactive, Fermi and his colleagues in Rome, Italy, undertook a systematic study of nuclear reactions induced by neutrons. One of the purposes of this research was to produce new nuclides. As a result, many new radioactive nuclides were made and their half-lives determined. One nuclear reaction used successfully in this study was the capture of a neutron followed at once by the emission of a γ ray. For example, when aluminum is bombarded with neutrons, the following reaction occurs:

$$^{1}_{0}n + ^{27}_{13}\mathrm{Al} \rightarrow ^{28}_{13}\mathrm{Al} + \gamma.$$

Aluminum-28 is radioactive, with a half-life of 2.3 min, decaying by β emission into silicon

$$^{28}_{13}\mathrm{Al} \rightarrow ^{28}_{14}\mathrm{Si} + ^{0}_{-1}e + \bar{\nu}.$$

As a result of these two reactions, a nuclide ($^{28}_{14}\mathrm{Si}$) is produced with values of Z and A each greater by one unit than those of the initial nucleus. Fermi thought that if neutrons bombarded uranium, the atomic species having the largest value of Z then known, an entirely *new* element might be formed by the β decay of the heavier uranium isotope

$$ {}^{1}_{0}n + {}^{238}_{92}\mathrm{U} \rightarrow {}^{239}_{92}\mathrm{U} + \gamma. $$

$$ {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}(?) + {}^{\;\,0}_{-1}e + \bar{\nu}, $$

He also speculated that the new nuclide denoted by ${}^{239}_{93}(?)$ in turn might also undergo β decay, producing a second element beyond uranium

$$ {}^{239}_{93}(?) \rightarrow {}^{239}_{94}(??) + \bar{\nu}. $$

In this way, two new elements might be produced, one with $Z = 93$, one with $Z = 94$. If these reactions could really be made to occur, the result would be the artificial production of an element, or elements, not previously known to exist: *transuranium elements*.

Fermi found in 1934 that the bombardment of uranium with neutrons actually produced new radioactive elements in the target, as shown by the emission of rays and a decay activity that revealed new, relatively short half-lives. The new elements were at first assumed to be the hypothesized transuranium elements.

Fermi's results aroused much interest, and in the next 5 years a number of workers experimented with the neutron bombardment of uranium. Many

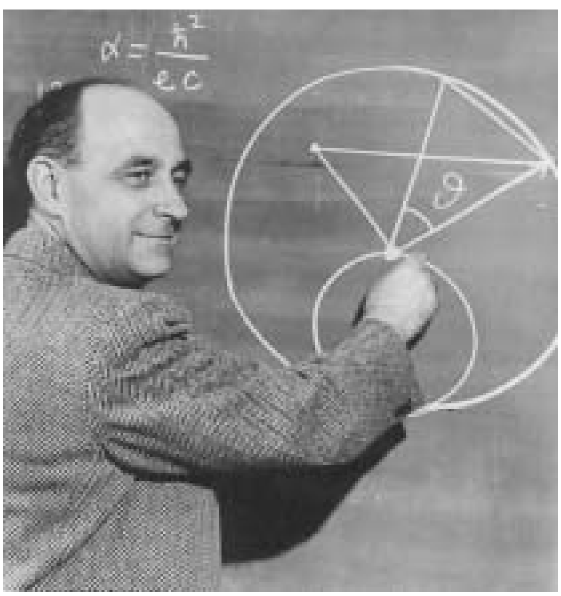


FIGURE 18.14 Enrico Fermi (1901–1955). Born in Rome, Italy, Fermi received the Nobel Prize for Physics in 1938 for his work on bombarding nuclei with the neutrons. Fermi fled Italy in 1938 and moved to the United States, where he continued work on nuclear structure and participated in the Manhattan Project. The equation Fermi wrote is incorrect. It is reported that after Fermi wrote the equation he turned to the audience to acknowledge the error when this picture was taken. He then erased it.

different radioactive half-lives were found for the radiation from the target, but attempts to identify these half-lives with particular elements led to great confusion. The methods used were similar to those used in the study of the natural radioactive elements (Section 17.7). But the difficulty of identification was even greater because a radioactive nuclide formed in a nuclear reaction is usually present in the target area only in an extremely small amount, possibly as little as 10^{-12} g; special techniques to separate these small quantities had to be developed.

The reason for the confusion was found late in 1938 when Otto Hahn and Fritz Strassmann, two German chemists, showed definitely that one of the supposed transuranium elements had the chemical properties of an isotope of *barium* ($^{139}_{56}$Ba), with a half-life of 86 min. Another nuclide resulting from the neutron bombardment of uranium was identified as lanthanum ($^{140}_{57}$La), with a half-life of 40 hr.

The production of the nuclides $^{139}_{56}$Ba and $^{140}_{57}$La from uranium, a nuclide with the atomic number 92 and an atomic mass of nearly 240, required an unknown kind of nuclear reaction, one in which the heavy nucleus is split almost in half. Nothing like it had been known to exist before. However, these two nuclides could not be the two halves, since the sum of their atomic numbers and masses exceeded those of uranium. Perhaps barium and lan-

FIGURE 18.15 Lise Meitner and Otto Hahn. Meitner, born in Austria, joined Hahn in 1908 in a research collaboration that lasted 30 years. In 1938, Meitner was forced to leave Germany by the Nazi regime. She was in Sweden when she published (along with her nephew, Otto Frisch) the first report recognizing and describing the existence of nuclear fission.

thanum were each only one of the two products of two different splittings of uranium. If such splitting processes really occurred, it should also be possible to find "the other half" of each splitting, that is, to find two other nuclides with masses between 90 and 100 and atomic numbers of about 35. Indeed, Hahn and Strassmann were able to find in the target material a radioactive isotope of strontium ($Z = 38$) and one of yttrium ($Z = 39$) which fulfilled these conditions, as well as isotopes of krypton ($Z = 36$) and xenon ($Z = 54$). It was clear from the chemical evidence that the uranium nucleus, when bombarded with neutrons, can indeed split into two nuclei of intermediate atomic mass.

Although Hahn and Strassmann showed that isotopes of intermediate mass did appear, they hesitated to state the conclusion that the uranium nucleus could indeed be split, since such an idea was so startingly new. In their historic report, dated January 9, 1939, they said:

> On the basis of these briefly presented experiments, we must, as chemists, really rename the previously offered scheme and set the symbols Ba, La, Ce in place of Ra, Ac, Th. As nuclear chemists with close ties to physics, we cannot decide to make a step so contrary to all existing experience of nuclear physics. After all, a series of strange coincidences may, perhaps, have led to these results.

The step which Hahn and Strassmann, as chemists, could not bring themselves to take was understood to be necessary by two Austrian physicists, Lise Meitner and her nephew, Otto R. Frisch, on January 16, 1939, both then in Sweden as forced exiles from Germany. They suggested that the incident neutron provoked a disintegration of the uranium nucleus into "two nuclei of roughly equal size," a process they called *nuclear fission* by analogy to the biological division, or fission, of a living cell into two parts.

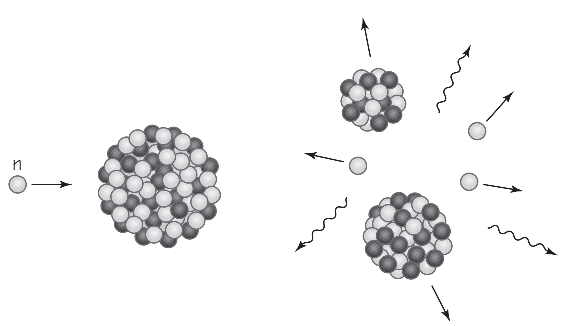


FIGURE 18.16 Schematic diagram representing uranium fission.

FIGURE 18.17 Otto R. Frisch (1904–1979).

On the basis of comparing the low average binding energy per nucleon of uranium with the higher average binding energy per nucleon of the products, they predicted that the fragments would have high kinetic energy resulting from the excess energy emitted in the fission process. This was soon verified experimentally.

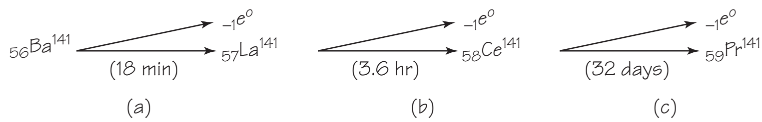
Shortly afterward, it was found that transuranium elements may, after all, *also* be formed when uranium is bombarded with neutrons. In other words, the capture of a neutron by uranium sometimes leads to fission and sometimes leads to β decay. The β decay results in the formation of isotopes of elements of atomic number 93 and 94, later named *neptunium* and *plutonium* (after the two planets in the solar system beyond Uranus). The presence of both types of reaction, fission and neutron capture followed by β decay, had been responsible for the earlier difficulty and confusion in the analysis of the effects of neutrons on the uranium target. Now, the interpretation of the experiments opened two new fields of scientific endeavor: the physics and chemistry of the transuranium elements, and the study of nuclear fission.

The discovery of nuclear fission caused research on it all over the world, and much new information was obtained within a short time. It was found that the uranium nucleus, after capturing a neutron, can split in fact into any one of more than 40 different pairs of fragments. Radiochemical analysis showed that nuclides resulting from fission have atomic numbers between 30 and 63 and mass numbers between 72 and 158.

Yet nuclides of medium mass are not the only fission products. In a finding that turned out to have extraordinary importance, neutrons also were discovered to result from fission; the average number of neutrons emitted is usually between two and three per fissioned nucleus. The following reaction indicates only one of the many ways in which a uranium nucleus can split.

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

$^{141}_{56}$Ba and $^{92}_{36}$Kr are not "natural" nuclides and are not stable; they are radioactive and decay by β emission. For example, $^{141}_{56}$Ba can decay into $^{141}_{59}$Pr by successive emission of three β particles, as shown by the following scheme (the numbers in parentheses in are the half-lives):



Similarly, $^{92}_{36}$Kr is transformed into $^{92}_{40}$Zr by four successive β decays.

It has been found that only certain nuclides can undergo fission. For those that can, the probability that a nucleus will split when bombarded depends on the energy of the neutrons used in the bombardment. The nuclides $^{235}_{92}$U and $^{239}_{94}$Pu can undergo fission when bombarded with neutrons of *any* energy, even 0.01 eV or less. On the other hand, ^{238}U and ^{232}Th undergo fission only when bombarded with neutrons having kinetic energies of 1 MeV or more. (As noted previously, ^{239}Pu, which is highly fissionable, is produced by the capture of a neutron by ^{238}U and the subsequent emission of two β particles.)

The energy released in the fission of a heavy nucleus is about 200 MeV. This value can be calculated either by comparing atomic rest masses of reactants and products or from the average binding energy curve of the graph in the previous section. The energy release in fission per atom is more than a million times larger than in chemical reactions, and more than 20 times larger than in the more common nuclear reactions, where it is usually less than 10 MeV.

There was one more important result that became obvious to researchers everywhere: Under appropriate conditions the neutrons released in fission can, in turn, cause fission in neighboring uranium atoms, and thereby a process known as a *chain reaction* can develop in a sample of uranium. The combination of the large energy release in fission and the possibility of a chain reaction is the basis of the large-scale use of nuclear energy.

18.11 CONTROLLING CHAIN REACTIONS

For a chain reaction in a sample of uranium to continue at an even rate, there must be a favorable balance between the net *production* of neutrons by fissions and the *loss* of neutrons due to the following three processes:

1. capture of neutrons by uranium without fission resulting;
2. capture of neutrons by other materials in the sample (such as rods of boron or cadmium) or in the structure containing the sample;
3. escape of neutrons from the sample without being captured.

If too *many* neutrons escape from or are absorbed in the structure or assembly (called a *reactor*), there will not be enough to sustain the chain reaction. If too *few* neutrons escape or are absorbed, the reaction will continue to build up more and more. The design of nuclear reactors as energy sources involves finding proper sizes, shapes, and materials to maintain or control a balance between neutron production and neutron loss.

Since the nucleus occupies only a tiny fraction of an atom's volume, the chance of a neutron colliding with a uranium nucleus is small, and a neutron can go past the nuclei of billions of uranium (or other) atoms while moving a few centimeters. If the reactor assembly is small, a significant percentage of the fission neutrons can escape from the assembly without caus-

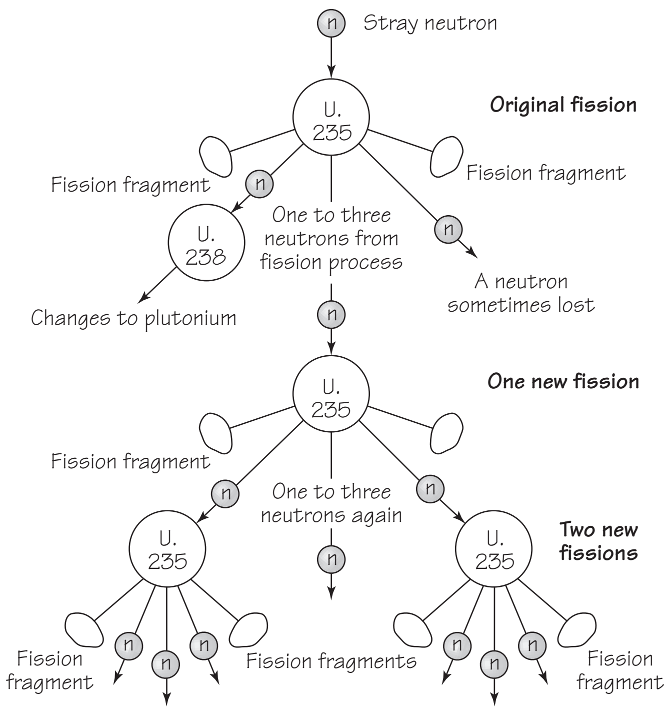


FIGURE 18.18 This diagram indicates what happens in a chain reaction resulting from the fission of uranium-235 atoms (not shown are other emissions, such as alpha, beta, and gamma rays).

ing further fissions. The "leakage" of neutrons can be so large that a chain reaction cannot be sustained. The number of neutrons produced is proportional to the *volume*, but the number of neutrons that escape is proportional to the *surface area*. As the linear size *L* of the assembly is increased, the volume and area increase in proportion to L^3 and L^2, respectively, so that neutron production increases with size more rapidly than neutron escape does.

For a given combination of materials (uranium and other structural materials that may be needed), there is a size of the reactor, called the *critical* size, for which the net production of neutrons by fission is just equal to the loss of neutrons by nonfission capture and escape. If the size of the reactor assembly is smaller than this critical size, a chain reaction cannot be sustained. The design of a reactor of reasonable dimensions, with given materials, which will correspond to critical size, is an important part of research in the field of *nuclear engineering*.

Another important consideration in the design of nuclear reactors is the fact that the fission is much more probable when ^{235}U is bombarded with *slow* neutrons than when it is bombarded with fast neutrons. The neutrons released in fission generally come out at very high speeds, having kinetic energies from about 0.01 MeV to nearly 20 MeV, with an average kinetic energy of about 2 MeV. The fast neutrons can be slowed down in the reactor by the addition of material (called "moderator") to which the neutrons can lose energy in collisions. The material should be relatively low in atomic mass so that the neutrons will transfer a significant fraction of their energy in collisions; but the material should not also capture and absorb many neutrons, thus taking them out of the reaction. Pure carbon in the form of graphite and also water and beryllium meet these requirements. As moderators, they slow down, or moderate, the newly produced neutrons to lower speeds at which the probability of causing additional fission is high. Although nuclear reactors can be built in which the fissions are induced by fast neutrons, it has been easier to build reactors with materials in which the fissions are induced by slow neutrons.

Although nuclear reactors can be built in which the fissions are induced by fast neutrons, it has been easier to build reactors with materials in which the fissions are induced by slow neutrons.

Hydrogen atoms in water are very effective in slowing down neutrons because the mass of a hydrogen nucleus (a single proton) is nearly the same as that of a neutron and because the number of hydrogen atoms per unit volume is high. A neutron can lose a large fraction of its energy in a collision with a hydrogen nucleus. Only about 20 collisions are needed, on average, to slow down the fast neutron to energies under 1 eV. However, neutrons can also be captured by the hydrogen nucleus in the reaction

$${}^1_0n + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + \gamma.$$

FIGURE 18.19 Lise Meitner (1878–1968).

The probability of this reaction occurring instead of an elastic collision is high enough so that it has been found impossible to achieve a chain reaction with natural uranium and ordinary water. But the absorption of a neutron by a deuterium nucleus ($^{2}_{1}H$), such as the nucleus of the heavy isotope of hydrogen, found in so-called *heavy water*, has an extremely small probability. Neutrons do not lose as much energy per collision with ^{2}H nuclei, but this disadvantage is compensated for by the much lower absorption rate. Therefore, a chain reaction can be achieved easily with natural uranium and heavy water. Reactors, with natural uranium as the fuel and heavy water as the moderator, have been built in the United States, Canada, France, Sweden, Norway, and other countries, and were attempted to be built by German scientists during World War II.

The contrast between the nuclear properties of hydrogen $^{1}_{1}H$ and deuterium ($^{2}_{1}H$ or $^{2}_{1}D$) has important implications for the development of nuclear reactors. Heavy water is expensive to produce, but when it is used with natural uranium (mostly ^{238}U), a chain reaction can be achieved efficiently. Although the uranium isotope ^{238}U normally absorbs neutrons rather than fissioning, the heavy water slows the neutrons below the energy at which they will be captured by the plentiful ^{238}U nuclei. A slow neutron will simply bounce off the ^{238}U nuclei it encounters until it is eventually absorbed by a rare ^{235}U nucleus, causing the nucleus to fission.

Ordinary water can be used as moderator in a uranium reactor *if* uranium enriched in the isotope ^{235}U is used instead of natural uranium. Many reactors "fueled" with enriched uranium and moderated with ordinary water have been built in the United States. Such reactors are called *light-water reactors*. In fact, this general reactor type is the preferred design for the commercial production of energy (electricity), since it is less expensive

FIGURE 18.20 The Chicago pile No. 1 used by Enrico Fermi and his associates when they first achieved a self-sustaining nuclear reaction on December 2, 1942. Alternate layers of graphite, containing uranium metal and/or uranium oxide, were separated by layers of pure solid graphite blocks. Graphite was used as a moderator to slow down neutrons in order to increase the likelihood of fission. Courtesy of Argonne National Laboratory.

to build and less likely to yield as by-products fissionable materials that could be used for nuclear weapons.

Carbon in the form of ultra-pure graphite has been used as a moderator in many reactors, including the earliest ones. Its atoms being more massive, it is not as good at slowing down fast neutrons as are light water and heavy water; about 120 collisions with carbon atoms are needed to slow down a fast neutron with an initial energy of 2 MeV to the desired energy of about 0.025 eV; in heavy water only about 25 collisions are needed. But although carbon in the form of pure graphite is not the best moderator and absorbs some neutrons, it does permit a chain reaction to occur when lumps of natural uranium (cylindrical rods containing uranium pellets, for example) are arranged in a large mass of graphite. The determination of just how this could be done was one of the main problems that had to be solved before the world's first chain reaction was achieved in December 1942 by a team working under Enrico Fermi at the University of Chicago. (It was a crucial experiment because until its success it was by no means certain that a chain reaction was really possible in practice.) Many graphite-moderated reactors are now in operation throughout the world. Their chief purpose will be discussed in the next section.

The control of a nuclear reactor is relatively simple. Lest fission is occurring too frequently, a few *control rods* are inserted into the reactor. The rods consist of a material (such as cadmium or boron) that absorbs slow neutrons, thereby reducing the number of neutrons in the reactor. Removal of the control rods will allow the rate of fission in the reactor to increase. The sketch (Figure 18.21) illustrates the basic reactions that occur in a nuclear reactor in which uranium is the fissionable material.

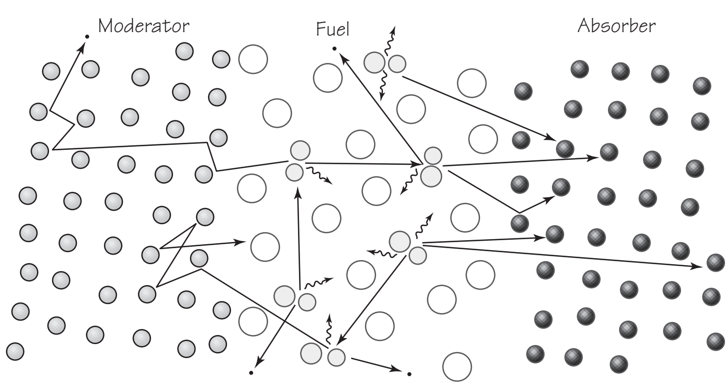


FIGURE 18.21 Schematic diagram of three types of functions fulfilled by parts of a nuclear reactor.

18.12 NUCLEAR POWER PLANTS

Nuclear reactors are useful for energy production because of the large amount of kinetic energy that the moderator in a reactor obtains from the fission neutrons in inelastic collisions. The fission neutrons are slowed by the moderator and return to the uranium to find more ^{235}U nuclei in which to induce fission. The kinetic energy lost by the fission neutrons as they are slowed by the moderator is gained by the molecules of the moderator and appears as heat. The heat generated can—and must—be pumped away from the reactor core by cool water which is thereby made to boil. The resulting steam can then be used to turn a turbine connected to the coils of an electric generator, thus producing electricity.

The main difference between a nuclear power plant and a fossil-fuel power plant is that heat produced by nuclear fission replaces heat produced by chemical reactions in the burning of fossil fuel. In both instances the heat is used to generate steam, as in steam-engine technology, to perform the useful work needed. In both instances the work is used, not to drive an engine directly, but to generate electricity.

The advantages of nuclear-powered production of electricity in a well-shielded and well-run reactor are obvious. The reaction produces no greenhouse gas emissions or other polluting gases. A nuclear reactor does not require the burning of fossil fuels, which are approaching depletion, and

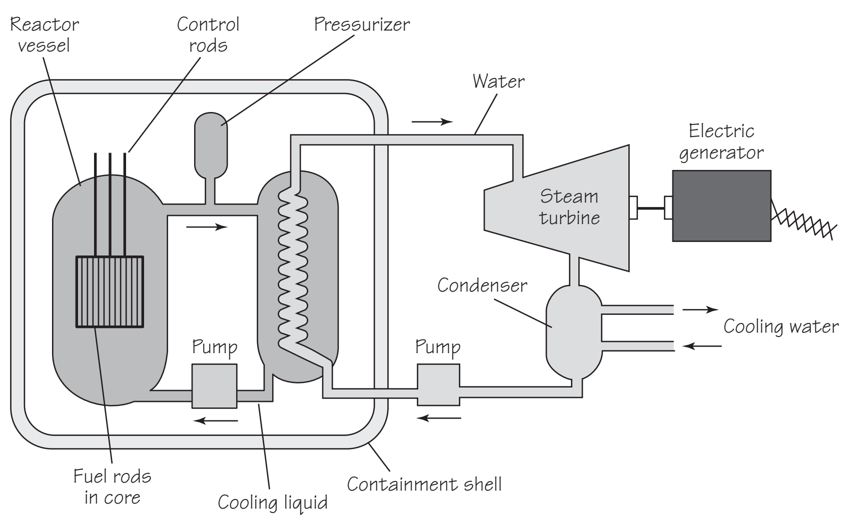


FIGURE 18.22 Schematic diagram of nuclear power plant. Heat from nuclear fission is used to boil water. The steam is used to turn a turbine which rotates coils in a magnetic field to generate electricity.

the dependence on the importation of expensive foreign fuel reserves is diminished. Nevertheless, the world supply of uranium is not unlimited, and reactors do require the disposal of long-lived radioactive waste, as well as the safe disposal of the heated water and all equipment and clothing exposed to radiation.

The ever-increasing use of electrical energy is an important aspect of modern life. As discussed in Chapter 11, every possible source of energy that might be used to meet the increasing demand for electricity is at present problematic.

The development of nuclear power in the United States was slower to develop than was expected at the end of World War II. But during the 1960s nuclear electric power became economically competitive with hydroelectricity and electricity from fossil fuels. By the beginning of 1978, 65 nuclear reactors were operating with over 47 million kilowatts capacity, about 9% of the nation's total electric power production.

However, the picture changed dramatically during the 1980s as the result of the public's increasing concern for safety, especially in the wake of the accidents at Three Mile Island and Chernobyl. More recently, the pos-

FIGURE 18.23 Reactor Number One at Great Britain's first nuclear power station at Calder Hall (opened in 1956). The large towers are cooling towers. The reactor is in the large building.

sibility that terrorists might crash an airplane into a nuclear reactor, with potentially devastating consequences, has underscored public concern about reactor safety. Plants under construction near densely populated areas where rapid evacuation is impossible, have been discontinued. At the same time, the Nuclear Regulatory Commission imposed stricter safety provisions during the 1990s on the operation of the plants and the disposal of radioactive waste. With the drop in the price of imported oil at the time, the operation of a nuclear power plant was no longer economically competitive with a power plant using imported fossil fuel. As a result, no new nuclear power plants have been built in the United States since the 1980s, and those still in operation may well be phased out in the years ahead.

Fusion energy, which has been the subject of intense, sophisticated research, is nevertheless still not a technical reality, but probably remains the main hope for an eventual large-scale solution to our rapidly increasing energy needs.

18.13 NUCLEAR WEAPONS

The large-scale use of nuclear energy in chain reactions was accomplished in the United States between 1939 and 1945. The work was done under the pressure of World War II, as a result of the cooperative efforts in which government agencies brought together large numbers of scientists and engineers. The workers in the United States included Americans, Britons, and European refugees from fascist-controlled countries. They hoped to obtain a nuclear weapon—if one could be made—before the Germans, who were known to be working on one, and in fact had started earlier. Many of the scientists hoped that the very existence of such a weapon would make future wars unlikely. A number of others petitioned that the Government would not use such a weapon on civilian targets, but only as a demonstration on uninhabited areas.

In a so-called *atomic bomb* (more properly a nuclear fission bomb), an extensive chain reaction occurs throughout the material in a few millionths of a second, thereby resulting in the explosive release of an enormous amount of energy. This reaction differs from the controlled nuclear reactor, in which the operating conditions are so arranged that the energy from fission is released at a much slower and essentially constant rate. In the controlled reactor, the fissionable material is mixed with other materials in such a way that, on average, only *one* of the neutrons emitted in fission causes the fission of another nucleus. In this way, the chain reaction just sustains itself. In a nuclear bomb, on the other hand, the fissionable material is not

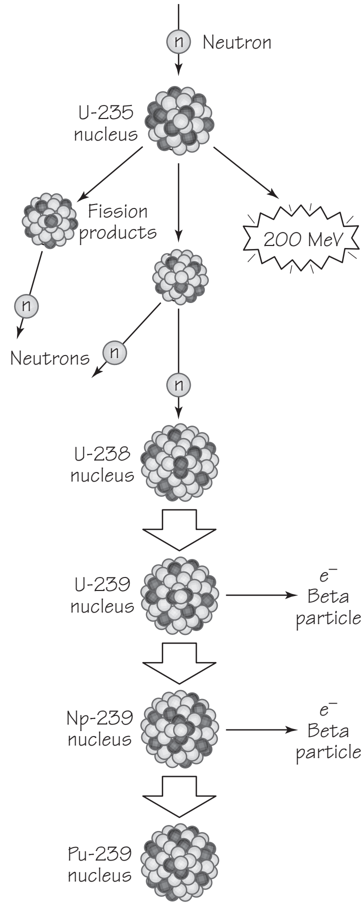


FIGURE 18.24 The “pile reactions” to produce plutonium-239.

mixed with a moderator, and the device is designed so that nearly all of the neutrons emitted in each fission can cause fissions in other nuclei.

Nuclear reactors were first used during World War II in the United States to produce raw materials for one kind of nuclear bomb, namely to manufacture highly fissionable plutonium, $^{239}_{94}Pu$, from the uranium isotope ^{238}U through β decay. Such reactors are called *breeder reactors*. These reactors are designed in such a way that some of the neutrons from the fission of ^{235}U are slowed down sufficiently *not* to cause fission in ^{238}U atoms. (In natural uranium, only about 0.75% of the atoms are ^{235}U.) Instead, the neutrons are absorbed by ^{238}U nuclei to form ^{239}Pu through the sequence of β-decay reactions described in Section 18.10. Some “nonnuclear” nations using nuclear reactors for generating electricity may have obtained weapons-grade plutonium from their reactors in this way. The United

States and other nations have been negotiating with these nations to provide more up-to-date light-water reactors containing less ^{238}U, along with other economic aid, in exchange for dismantling their old heavy-water reactors that can produce plutonium.

^{239}Pu behaves in many ways like ^{235}U. Both materials can sustain a rapid, uncontrolled chain reaction. Both isotopes were used to power the first nuclear weapons used in August 1945 in order to end World War II at President Truman's decision—a war, unleashed against the Allies, and that had already cost many millions of lives and devastated much of Europe and Japan. A single nuclear bomb, using pure ^{235}U, was dropped to destroy the city of Hiroshima, Japan, on August 6, 1945. Another bomb, using ^{239}Pu, destroyed the city of Nagasaki 3 days later. The war ended officially on September 2, 1945.

Since the end of World War II in 1945, other countries besides the United States have made nuclear weapons, including the United Kingdom, Russia (the former Soviet Union), France, India, Pakistan, and China. The enormous death-dealing capability of these weapons, and the ever-larger numbers of nuclear bombs of many varieties that have been accumulating

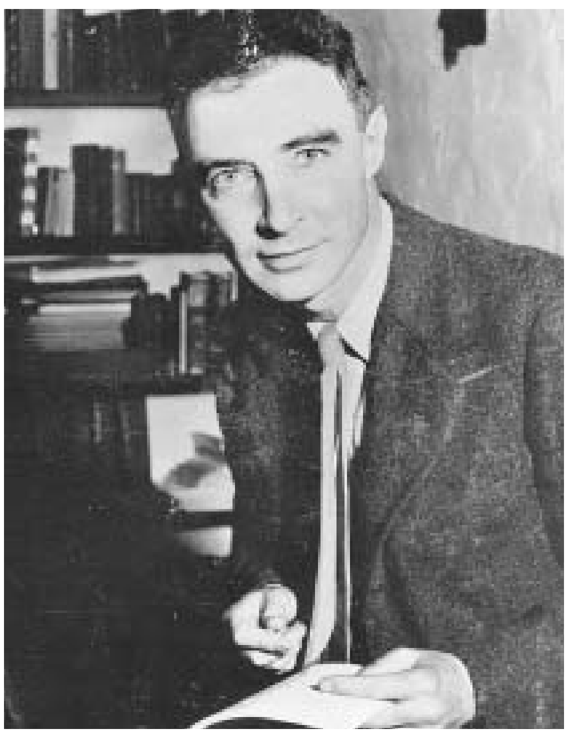


FIGURE 18.25 Robert Oppenheimer (1904–1967).

FIGURE 18.26 Maj. Gen. Leslie R. Groves (r), Chief of the Manhattan Engineering District where the first nuclear bomb was developed, and J. Robert Oppenheimer, Director of Los Alamos Atomic Bomb Project and Physicist at California Technological Institute, view the base of the steel tower on which the first atomic bomb hung when tested near Alamogordo, New Mexico in July, 1945. The intense heat of the bomb melted the tower and seared the surrounding sands into jade green, glass-like cinders.

all over the globe, have made more dangerous the tensions existing throughout the world, and have emphasized critically the need for the peaceful settlement of international disputes.

Tensions between Western nations and the Soviet Union and its allies reached a frightening level during the depths of the so-called Cold War, especially during the 1950s and early 1960s. As nuclear weapons became ever more powerful, the potential for destruction became ever more immediate with the development of intercontinental ballistic missiles (ICBMs). By the late 1950s, an ICBM launched by one nation and carrying a nuclear bomb could in principle reach any point on the globe in less than an hour. There was no defense against such an attack. Even defending missiles sent to intercept an attacking missile that was moving at thousands of kilometers per hour could be overwhelmed by “multiple reentry warheads” and by decoys, emitted by the single attacking missile.

Without the possibility of defense, the United States prepared the population for possible nuclear war, and both sides instituted a policy known appropriately by the acronym MAD, for “mutually assured destruction.” Any nuclear attack by one side in the Cold War would result in “massive retaliation” by the other side—the launching of every available nuclear weapon against the attacking nation, resulting in the likely total destruction of both sides, perhaps even most of the population of the entire world. The prospects for such a scenario became frighteningly more likely during the Missile Crisis in 1962, when the Soviet Union placed long-ranged nuclear-armed missiles in Cuba. When the United States blockaded ("quarantined") Cuba from Soviet ships, traditionally an act of war, the world held its breath as Soviet ships carrying more nuclear weapons approached Cuba. Finally, the ships turned back, averting a possible nuclear war, and the world breathed a sigh of relief.

Since then the world's nuclear powers became more realistic in their search for a way to control nuclear weapons. But the fears of the public remained, as reflected in such classic films as *Dr. Strangelove* and *Fail-Safe*. However, efforts to attempt a defense against incoming nuclear missiles have continued. One such attempt, originating during the 1980s, has involved the design of high-powered lasers, controlled by fast computers, which would target and destroy an incoming enemy missile. This technology, officially called the Strategic Defense Initiative (SDI) but popularly known as "star wars" (after the well-known films of the same name) and its more recent successors, have so far proved unsuccessful. Moreover, weapons of mass destruction could well be deployed by ships or trucks, therefore not vulnerable to a defense relying only upon missiles.

From the very beginning, scientists have been prominently involved in activities to alert their government and fellow citizens to the moral and practical problems raised by the nuclear arms race. One of their earliest successes involved international limits on nuclear testing. In order to develop ever more powerful and efficient weapons, test explosions are often

FIGURE 18.27 Energy released from nuclear fission: the first underwater test of an atomic bomb at Bikini Atoll in the Pacific Ocean in July 1946.

required, and most of these were performed above ground in remote areas during the 1950s. As noted previously, in the explosion of a nuclear bomb, large amounts of radioactive fission products are scattered. These materials can be blown by winds from one part of the world to another and carried down from the atmosphere by rain or snow. This is known as *fallout*.

Partly as the result of public petitions and protests organized by scientists—spearheaded by the chemist Linus Pauling, who received the Nobel Peace Prize for his efforts—the United States, Soviet Union, and most other nations agreed in 1963 to a moratorium on further aboveground testing. This greatly reduced the amount of radioactive pollution in the atmosphere. Testing continued, however, below ground. Further international treaties have placed further curbs on nuclear testing, but they have not yet eliminated all testing, despite the end of the Cold War. The United States and other nations rely increasingly on computer simulations to maintain their arsenals, but some nations have insisted on the right to continue underground testing.

Since the end of the Cold War and the breakup of the Soviet Union, tensions have diminished, but the dangers of the use of nuclear weapons remain high. There are fears that some of the weapons in the large arsenal of nuclear weapons stored in the former Soviet Union may find their way into the hands of bellicose nations or terrorist organizations. Developing nations are slowly obtaining the ability to produce nuclear weapons, and nations such as India and Pakistan, which have been long-time enemies, have both tested nuclear weapons and long-range missiles capable of delivering them.

Finally, the Cold-War weapons production has left the enormous problems and high costs of radioactive waste cleanup at weapons production facilities and the disposal of huge amounts of weapons-grade plutonium. Plutonium is extremely poisonous, and it is relatively long-lived, having a half-life of 24,000 years. Although most advanced nuclear weapons are now powered by fusion reactions involving hydrogen (see below), they are triggered by plutonium-based fission reactions. Disposing of the many tons of highly fissionable, long-lived plutonium, while keeping it out of the hands of terrorists and nonnuclear nations, is a major challenge for both sides of the former Cold War.

As in the past, the decisions by politicians and industrial leaders that will be necessary in the future development and uses of controlled and uncontrolled nuclear energy cannot be made on the basis of physics alone. Scientists can help to illuminate alternatives on which essentially political decisions can be based, and there are several dozen organizations founded by scientists in the U.S.A. alone that have been and are continuing to educate and advise. But science should not be used by itself to choose among the alternatives. Responsible scientific opinion should be supplemented by political insight and a broad humanistic view of society.

18.14 NUCLEAR FUSION

A fusion reaction involves the joining together of two light nuclei into a heavier nucleus. The reaction results in higher binding energies per nucleon when light nuclei are combined. As a consequence, a large amount of energy is released.

Fusion reactions have been produced in the laboratory by bombarding appropriate light target materials with, for example, high-energy deuterons from a particle accelerator. In these reactions, nuclei result that are heavier than the nuclei of either the "projectiles" or the targets; there are usually also additional particles released, as well as energy. Some typical examples of fusion reactions, together with the energy liberated in each reaction, are

$$^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_1\text{H} + {}^1_1\text{H} + 4\ \text{MeV},$$

$$^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + {}^1_0n + 3.2\ \text{MeV},$$

$$^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0n + 17.6\ \text{MeV},$$

$$^2_1\text{H} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + {}^1_1\text{H} + 18.3\ \text{MeV}.$$

In the first of the above equations, the heavier product nucleus is an isotope of hydrogen, called *tritium*, with mass number $A = 3$. It has been found in small traces in nature, is radioactive with a half-life of about 12 years, and decays by β emission into ^3_2He, an isotope of helium. When a target containing tritium is bombarded with deuterons, ^4_2He can be formed, as in the third equation above, liberating 17.6 MeV of energy. Of this energy, 14.1 MeV appears as kinetic energy of the neutron and 3.5 MeV as kinetic energy of the product nucleus.

Although the energy liberated in a single fusion is less than that in a single fission, the energy released *per unit mass* is much greater. The mass of about 50 helium atoms is approximately equal to the mass of one uranium atom; 50×17.6 MeV $= 1040$ MeV, compared to 200 MeV for a typical fission.

The fusion of tritium and deuterium offers the possibility of providing large sources of energy, for example, in electric power plants. Deuterium occurs in water with an abundance of about one part in seven thousand hydrogen atoms and can be separated from the lighter isotope. Four liters of water contain about 0.13 g of deuterium, which can now be separated at a cost of about 8 cents. If this small amount of deuterium could be made to react under appropriate conditions with tritium (perhaps produced by the reaction discussed above), the energy output would be equivalent to that from about 1140 l of gasoline. The total amount of deuterium in the oceans is estimated to be about 10^{17} kg, and its energy content would be about 10^{20} kW-yr. If deuterium and tritium could be used to produce energy, they would provide an enormous source of energy.

There are, of course, some difficult problems to be solved before fusion reactions are likely to be useful as steady sources of energy. The nuclei which react in the fusion processes are positively charged and repel one an-

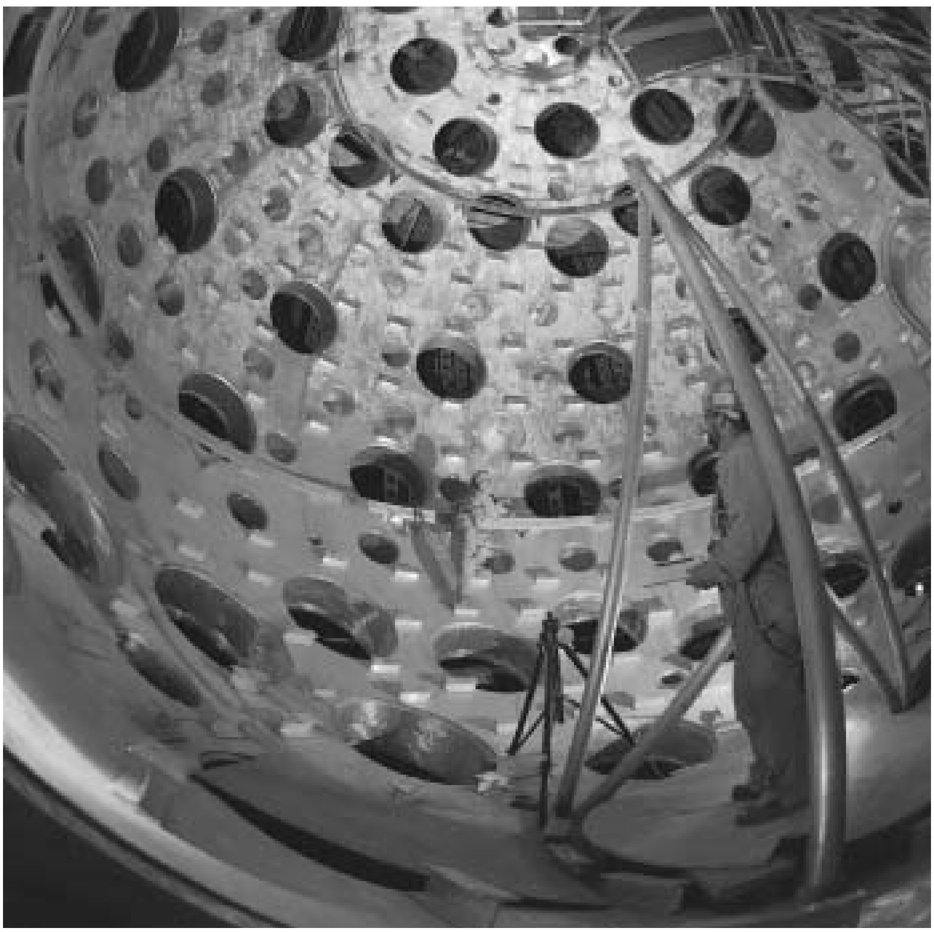


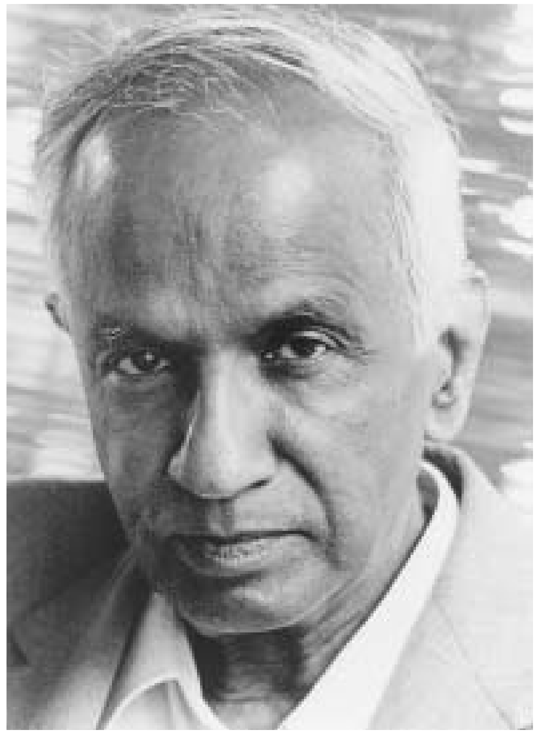
FIGURE 18.28 National Ignition facility. Lawrence Livermore National Laboratory, California.

FIGURE 18.29 Maintenance workers inside the vacuum chamber of the Tokamak Fusion Test Reactor, Princeton.

other because of the repulsive electric force. The nuclei must, therefore, be made to collide with a high relative speed to overcome the repulsive force tending to keep them apart. The nuclear force, which holds neutrons and protons together in the nucleus, is much stronger than the electric force—and it is often called the *strong force*—but it has a very short range. Its effect extends only about 10^{-14} m, about the size of a nucleus. The fusing nuclei must therefore approach within this range in order for the attractive nuclear force to overcome electric repulsion. The nuclei must also be confined in a region where they can undergo many collisions without escaping, or being absorbed by the walls bounding the region, or losing energy by collisions with too many "cooler" (less energetic) molecules. There must be enough collisions per unit time so that fusion can occur at a rate that will yield more energy than that needed to cause the collisions. The combination of these requirements means that the nuclei must be contained at a temperature of the order of 100 million degrees.

At the temperature required for fusion, the atoms have been stripped of their electrons, and the resulting nuclei and separated electrons are said to form a *plasma*. A *plasma* is an ionized gas in which positively and negatively charged particles move about freely. No wall made of ordinary material can

FIGURE 18.30 Subramanyan Chandrasekhar (1910–1995) made major contributions to fields ranging from magnetohydrodynamics to relativity to black hole theory. For his theoretical work on the physical processes of importance to the structure and evolution of stars he was awarded the Nobel Prize for physics in 1983.



contain a hot plasma at 10^8K (the wall would be vaporized instantly!). But the charged particles of a plasma can, in theory, be contained in an appropriately designed magnetic field. The first problem to be solved, therefore, is to contain the plasma of deuterium and tritium nuclei in a magnetic field, while accelerating the nuclei by means of an electric field to the required kinetic energy (or temperature). The behavior of the charged particles in a plasma is complicated; there are many kinds of instabilities that make the plasma difficult to contain properly and long enough. These problems of the release of energy to form a *controlled* and sustained fusion reaction have not yet been solved on a practical scale, but research on them is being carried on in many countries. Significant advances have been made during the last few years in containment of the plasma and in reaching high temperatures using intense, focused laser beams. There are still difficult technological problems to be overcome, and it may be a generation before electric power will be produced by fusion at costs that will compete with electricity from fossil fuels. Although the effort and expenses are great, the possible payoff in terms of future power resources is enormous. Fusion-supplied energy, without the dangerous by-products of fission, and in principle inexhaustible and cheap, can herald a vast change in human civilization, worldwide.

Fusion Reactions in Stars

Fusion reactions are actually quite common in nature, although not on Earth. They are the source of power generated by the Sun and all the many billions of stars throughout the Universe. In a sense, one can say that fusion energy is nature's primary energy source. On the scale of stars, confinement of the plasma is accomplished by gravitational attraction.

One of the most fascinating aspects of nuclear physics is the study of fusion reactions in different types of stars. The Sun is an example. In the Sun, the fusion process results in the production of a helium nucleus from four protons. The net results of the reactions can be written as

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{+1}e + 26\ \mathrm{MeV},$$

where ${}^{0}_{+1}e$ is an "anti-electron," also known as a positron. The reaction does not take place in a single step but can proceed through different sets of reactions whose net results are summarized in the above equation. In each case, the overall amount of energy released is 26 MeV.

The fusion of four protons into a helium nucleus is the main source of the energy of the Sun. Chemical reactions cannot provide energy at large enough rates (or for long enough duration!) to account for energy pro-

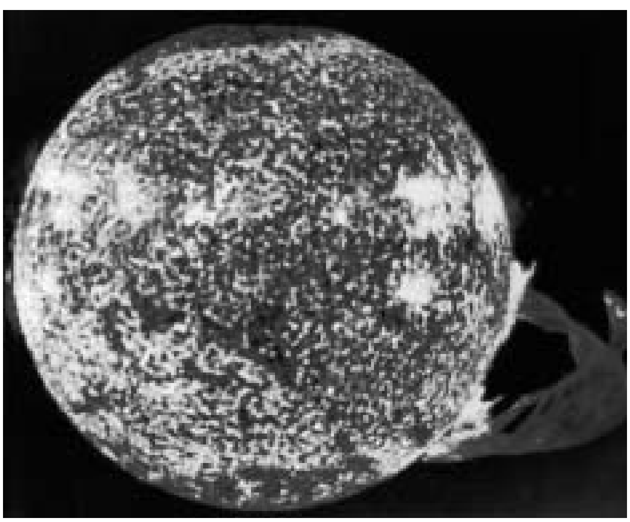


FIGURE 18.31 An X-ray photograph of the Sun. Nuclear fusion is the source of energy in our Sun and powers billions of stars throughout the Universe.

FIGURE 18.32 Cecilia Payne-Gaposchkin (1900–1979), the first person to receive a PhD in astronomy from Harvard University, discovered that stars are primarily made of hydrogen and have varying temperatures.

duction in the Sun, but nuclear fusion reactions can. Hydrogen and helium together make up about 99% of the Sun's mass, with approximately twice as much H as He. Fortunately, there is enough hydrogen to supply the Sun's energy for several billion years to come.

By which of the several possible sets of reactions does the transformation of hydrogen into helium take place? The direct process of four protons colliding to form a helium nucleus has been ruled out because the probability for such a reaction under solar conditions is too low. It may happen, but not often enough for the amount of energy released. A more likely set of reactions is as follows: When the temperature is about 10^7 K, the kinetic energies are large enough to overcome the electric repulsion between protons, and fusion of two protons ($^1_1$H) takes place. The nuclear reaction results in a deuteron ($^2_1$H), a positron ($^{\ 0}_{+1}e$), and a neutrino. As soon as the deuteron is formed, it reacts with another proton, resulting in helium-3 ($^3_2$He) and a γ ray. The helium-3 nuclei fuse with each other, forming α particles and two protons. In each of these reactions, energy is released, resulting in 26 MeV for the complete cycle of four protons forming a helium nucleus.

The rates of the reaction depend on the number of nuclei per unit volume and on the temperature. The higher the temperature, the faster the

FIGURE18.33 *View of Les Saintes-Maries-de-la-Mer* by Vincent Van Gogh. Courtesy of Oskar Reinhart Collection "Am Römerholz," Winterthur, Switzerland.

thermal motion of the particles and the more frequent and energetic the collisions. At the temperature of the Sun's interior, which has been estimated to be 10 million to 20 million degrees, the kinetic energies resulting from the thermal motion are in the neighborhood of 1 keV.

Fusion reactions are nature's primary source of energy for the Universe as a whole. It is reasonable to hope that in the future they will be ours as well.

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SOME NEW IDEAS AND CONCEPTS

artificial transmutation
binding energy
breeder reactor
chain reaction
control rods
critical mass
fission
fusion
heavy water
hydrogen bomb
light-water reactor
moderator
neutrino
neutron
nuclear bomb
nuclear proliferation
nucleon
nuclide
positron
proton
proton–electron hypothesis
proton–neutron model
reactor
strong force
transuranium elements

STUDY GUIDE QUESTIONS

18.1 The Problem of Nuclear Structure

1. What was one of the main questions raised about the nucleus?
2. What are the two main areas in which research has been pursued?

18.2 The Proton–Electron Hypothesis

1. Alpha and gamma rays are emitted by some radioactive nuclei. Why couldn't they be used as building blocks of the nucleus?
2. Why was the idea of hydrogen atoms being a basic building block of all atoms given up in the nineteenth century?
3. How could protons and electrons be used to build up the nuclei of atoms?

4. On the basis of the proton–electron hypothesis, what would a nucleus of ${}^{12}_{6}C$ contain?
5. Does the proton–electron hypothesis work out for, say, ${}^{4}_{2}He$?
6. Why did this model ultimately fail?

18.3 The Discovery of Artificial Transmutation

1. What evidence showed that the bombarding α particle was temporarily absorbed by the nitrogen nucleus rather than simply broken up and bounced off?
2. Why was the reaction called "artificial transmutation"?

18.4 The Discovery of the Neutron

1. What was Rutherford's hypothesis about protons and electrons in the nucleus?
2. Why could the neutral penetrating radiation from bombarded beryllium not be considered γ rays?
3. Why did the mass of a neutron have to be found by measurements on protons ejected by the neutrons in collision?
4. How could the principles of conservation be used to find the mass of the neutron?

18.5 The Proton–Neutron Model

1. Briefly describe the proton–neutron model of the nucleus.
2. According to the proton–neutron model, what is contained in the nucleus of ${}^{14}_{7}N$?
3. How does this model account for the existence of isotopes?
4. Describe an ordinary helium atom in terms of the three elementary particles: protons, neutrons, and electrons.
5. If nuclei do not contain β particles, how can β emission be explained?
6. What happens inside the nucleus in β emission? As a result, what happens to every isotope that emits a β ray?

18.6 The Neutrino

1. Why was an almost undetectable particle invented to patch up the theory of β decay?
2. What is the almost undetectable particle? Has it been detected?
3. ${}^{214}_{82}Pb$ undergoes β decay with a half-life of 26.8 min. From the information given on β decay, what would be the daughter nucleus? Write the nuclear equation for the β decay of ${}^{214}_{82}Pb$.

18.7 The Need for Particle Accelerators

1. Why can low-energy α particles cause transmutations only in nuclei of relatively small atomic number?
2. Why are protons more effective projectiles for producing nuclear reactions than are α particles or heavy ions?

3. What are some of the devices for producing high-energy particles to be used as projectiles?
4. What are some devices for detecting nuclear reactions induced by such projectiles?

18.8 The Energy of Nuclear Binding

1. When energy is "liberated" during a nuclear reaction, what becomes of it?
2. What is the definition of binding energy for the case of the deuteron nucleus?
3. Which would have more mass:
   (a) a deuteron, ^2_1H?
   (b) a proton and a neutron moving freely and independently of each other?
4. Explain the difference in mass between 3(a) and 3(b).

18.9 Nuclear Binding Energy and Stability

1. Which would be more stable, a nuclide with a high *total binding energy* or a nuclide with a high *average binding energy per nucleon*?
2. Where on the periodic table are elements for which (a) fission and (b) fusion processes can take place?
3. Using the graph of binding energy per nucleon, explain why energy is emitted in fission reactions and in fusion reactions.

18.10 Nuclear Fission: Discovery

1. What happens in nuclear fission?
2. Why was Fermi bombarding uranium with neutrons?
3. How did he make use of β decay in his research?
4. What two successive reactions can result in the appearance of a transuranium element?
5. Describe in your own words the sequence of events that leads to the element plutonium.
6. Why couldn't the observed lanthanum and barium be the products of the fissioning of a single uranium nucleus?
7. How did the physicists Meitner and Frisch explain the appearance of lanthanum and barium in the samples obtained by the chemists Hahn and Strassmann?
8. What product of the fission process makes a chain reaction possible?

18.11 Controlling Chain Reactions

1. A low-speed neutron is fired at a group of uranium isotopes. Describe what can happen if:
   (a) the neutron hits a ^{238}U isotope;
   (b) the neutron hits a ^{235}U isotope.
2. What is a moderator? Why is it needed?
3. What is an advantage and a disadvantage of using regular water as a moderator in nuclear reactors?
4. How can the rate of reaction be controlled in a reactor?
5. What is the difference between a light-water reactor and a heavy-water reactor?

6. Why are light-water reactors usually chosen for delivery to other nations?
7. Describe in your own words how a nuclear reactor works.

18.12 Nuclear Power Plants

1. How is a nuclear reactor used to produce electricity?
2. How does the operation of a nuclear power plant compare with the operation of a fossil-fuel electric-power plant?
3. What are the advantages and disadvantages of nuclear and fossil-fuel power plants?
4. Why did scientists in the U.S. during World War II agree to develop atomic weapons?

18.13 Nuclear Weapons

1. What are breeder reactors? What do they breed and why?
2. With the Cold War over, is the world now safe from the use of nuclear weapons? Explain.
3. Where do the decisions ultimately lie regarding the uses of nuclear energy?

18.14 Nuclear Fusion

1. Why are very high temperatures required to cause fusion reactions?
2. How could extremely hot gases be kept from contacting the wall of a container?
3. In what way has fusion energy been used by humankind?
4. How does the Sun make use of fusion energy?
5. Is the ratio of the amount of hydrogen to the amount of helium in the Sun increasing or decreasing?

DISCOVERY QUESTIONS

(Consult the periodic table as needed.)

1. When ordinary chemical reactions take place, such as the fusion of hydrogen and oxygen to form water, why do we not observe a loss of mass similar to the loss of mass when neutrons and protons fuse together to form a nucleus?
2. Complete the following nuclear equations:
   (a) ${}^{6}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + (\quad);$
   (b) ${}^{9}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + (\quad);$
   (c) ${}^{9}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow (\quad) + {}^{2}_{1}\mathrm{H};$
   (d) ${}^{11}_{5}\mathrm{B} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{14}_{7}\mathrm{N} + (\quad).$
3. Complete the following nuclear equations, then describe in words what is happening in each case:
   (a) ${}^{4}_{2}\mathrm{He}^{4} + {}^{10}_{5}\mathrm{B} + \rightarrow (\quad) + {}^{1}_{1}\mathrm{H};$
   (b) ${}^{1}_{1}\mathrm{H} + {}^{9}_{4}\mathrm{Be} \rightarrow (\quad) + {}^{2}_{1}\mathrm{H};$
   (c) ${}^{4}_{2}\mathrm{He} + (\quad) \rightarrow {}^{35}_{17}\mathrm{Cl} + {}^{1}_{1}\mathrm{H};$
   (d) ${}^{2}_{1}\mathrm{H} + {}^{27}\mathrm{Al} \rightarrow (\quad) + {}^{4}_{2}\mathrm{He};$
   (e) ${}^{1}_{0}n + {}^{27}\mathrm{Al} \rightarrow {}^{28}\mathrm{Al} + (\quad).$

4. How many electrons are there in a neutral atom of:
   (a) platinum-196;
   (b) gold-198;
   (c) mercury-198;
   (d) mercury-199.
5. Why would it be difficult to explain the nucleus of ${}^{235}_{92}U$ as a mixture of α particles and electrons?
6. Describe the following nuclear reactions in words:
   ${}^{1}_{0}n + {}^{27}_{13}Al \rightarrow {}^{27}_{12}Mg + {}^{1}_{1}H,$
   ${}^{27}_{12}Mg^{7} \rightarrow {}^{27}_{13}Al + {}^{0}_{-1}e + \nu' + \gamma \quad (T_{1/2} = 9.5\ \text{min}).$
7. How may the discovery of artificially radioactive nuclides have helped the development of theories of nuclear structure?
8. Complete the following table:

	A	Z	*Number of protons*	*Number of neutrons*	*Number of electrons in atom*
^{1}H					
^{2}H					
^{3}H					
^{4}He					
^{7}Li					
^{13}C					
^{238}U					
^{234}Th					
^{230}Th					
^{214}Pb					
^{206}Pb					

9. Write a set of equations that describe the decay of the fission product ${}^{92}_{36}Kr$ into ${}^{92}_{40}Z$.
10. Why are the high temperatures produced by the explosion of a fission bomb necessary to initiate fusion in a thermonuclear device?
11. It is generally agreed that stars are formed when vast clouds of hydrogen gas collapse under the mutual gravitational attraction of their particles. How might this process lead to fusion reactions beginning in such stars? (*Hint:* The cloud has gravitational potential energy.)
12. A team of scientists announces that it has discovered a possibly new source of cheap, nonpolluting, renewable energy that will solve all of our energy problems. They caution that further research will be required to determine if it is indeed feasible, and much work will be needed to render it commercially viable. However, there is one problem: the possibility exists that this new source of energy might also be turned into a new military weapon of enormous destructive power. The scientists declare that they are very eager to solve the world's energy problems, but they are worried that if it does prove feasible,

this source might also lead to a new weapon of mass destruction. They have turned to the public for advice.

(a) As an informed member of the public, what do you recommend?
(b) Assume you are a member of the scientific team. What are your thoughts on the issue?
(c) Set up a debate in your class or group on these issues.

13. Write an essay on one of the following topics:
    (a) The various ways an informed citizen can help assure that technological innovations will be made and used in a manner benefitting society as a whole.
    (b) The differences between technology and basic science.
    (c) The responsibilities of scientists to society.
    (d) The responsibilities of society to further science.
    (e) The fields of physics or related sciences in which you may want to do further study.
14. In studying this Part Two of the text, you have followed some of the immense transformation of humankind's culture, from the pre-scientific period to current research questions. After thoughtful reflection on this experience, write a page or two summarizing the stages in this adventure of the creative mind.

Quantitative

1. Compare the mass of a helium nucleus with the sum of the masses of two hydrogen nuclei, two neutrons. What conclusions do you draw from your result?
2. Suppose that a nucleus of $^{13}_{6}C$ is formed by adding a neutron to a $^{12}_{6}C$ atom. Neglecting any kinetic energy the neutron may have, calculate the energy that becomes available to the nucleus because of the absorption of that neutron to make $^{13}_{6}C$. The atomic masses of ^{12}C and ^{13}C (in an unexcited state) are, respectively, 12.000000 u (by definition, an international convention), and 13.003354 u.
3. The atomic mass of ^{4}He is 4.00260 u; what is the average binding energy per nucleon?
4. Use the graph on page 784 to find the binding energies for ^{235}U, ^{141}Ba, and ^{92}Kr. Use these values to show that the energy released in the fission of ^{235}U is approximately 200 MeV.
5. Fusion reactions in the Sun convert a vast amount of hydrogen into radiant energy each second. Knowing that the energy output of the Sun is 3.90×10^{26} J/s, calculate the rate at which the Sun is losing mass.