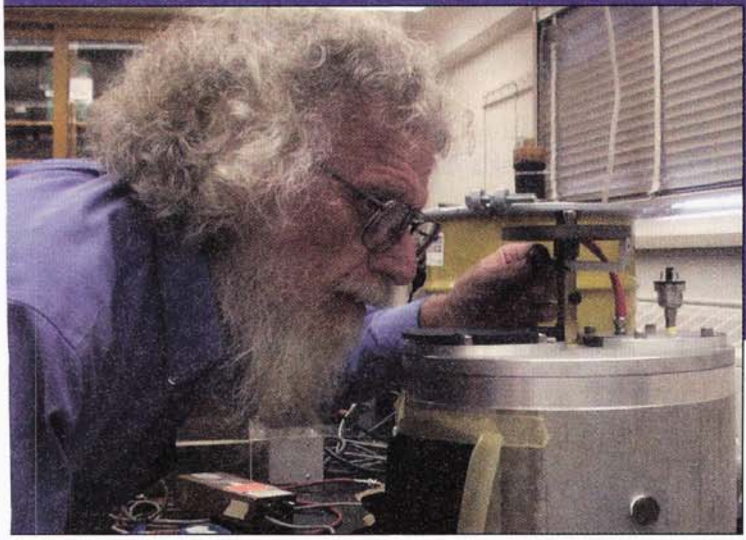

Nuclear Fission and Fusion

Dean Zollman investigates nuclear properties with a modern version of Rutherford's scattering experiment.

THE Physics Place
Nuclear Physics

In December 1938, two German scientists, Otto Hahn and Fritz Strassmann, made an accidental discovery that was to change the world. While bombarding a sample of uranium with neutrons in the hope of creating new heavier elements, they were astonished to find chemical evidence for the production of barium, an element about half the mass of uranium. They were reluctant to believe their own results. Hahn sent news of this discovery to his former colleague Lise Meitner, a refugee from Nazism working in Sweden. Over the Christmas holidays, she discussed it with her nephew Otto Frisch, also a German refugee, who was visiting her from Denmark, where he worked with Niels Bohr. Together, they came up with the explanation: The uranium nucleus, activated by neutron bombardment, had split in two. Meitner and Frisch named the process *fission*, after the similar process of cell division in biology.[1]

Nuclear Fission

THE Physics Place
Nuclear Fission

Nuclear fission involves a delicate balance within the nucleus between nuclear attraction and the electrical repulsion between protons. In all known nuclei, the nuclear forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape (Figure 34.1), the electrical forces may push it into an even more elongated shape. If the elongation passes a critical point, nuclear forces yield to electrical ones, and the nucleus separates. This is fission.[2] The absorption of a neutron by a uranium nucleus

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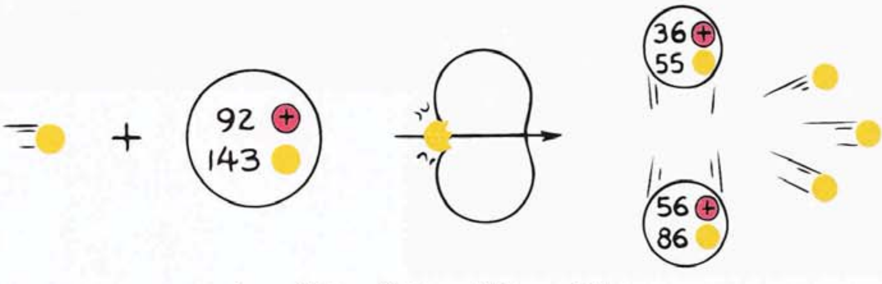
[1] Similarly, Ernest Rutherford used a biological term when he chose the word *nucleus* for the center of an atom.

[2] Fission resulting from neutron absorption is called *induced fission*. In rare instances nuclei can also undergo *spontaneous fission* without initial neutron absorption. There is evidence that at least one such major spontaneous fission event occurred in Africa almost two billion years ago when the percentage of U-235 in uranium deposits was greater (see *Scientific American*, July 1976). Interestingly, when U-235 absorbs a neutron it momentarily becomes U-236, which splits in half almost instantaneously. So, strictly speaking, it is U-236, not U-235, that undergoes fission. It's common, however, to speak of the fission of U-235.

supplies enough energy to cause such an elongation. The resultant fission process may produce many different combinations of smaller nuclei. A typical example is



$${}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{91}_{36}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba} + 3({}^{1}_{0}n)$$

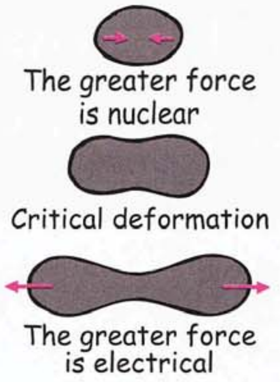


FIGURE 34.1
Nuclear deformation may result when repulsive electrical forces overcome attractive nuclear forces, in which case fission occurs.

In this reaction, note that one neutron starts the fission of the uranium nucleus and that the fission produces three neutrons (yellow).[3] Because neutrons have no charge and are not repelled by atomic nuclei, they make good "nuclear bullets" and can cause the fissioning of three other uranium atoms, releasing a total of nine more neutrons. If each of these neutrons succeeds in splitting a uranium atom, the next step in the reaction can produce 27 neutrons, and so on. Such a sequence is called a **chain reaction** (Figure 34.2).

A typical fission reaction releases energy of about 200,000,000 electron volts.[4] (By comparison, the explosion of a TNT molecule releases only 30 electron volts.) The combined mass of the fission fragments and neutrons produced in fission is less than the mass of the original uranium nucleus. The tiny amount of missing mass converted to this awesome amount of energy is in accord with Einstein's equation $E = mc^2$. Quite remarkably, the energy of fission is mainly in the form of kinetic energy of the fission fragments that fly apart from one another and of the ejected neutrons. Interestingly, a smaller amount of energy is that of gamma radiation.

$E = mc^2$ says that mass is congealed energy. Mass and energy are two sides of the same coin.

Insights

The scientific world was jolted by the news of nuclear fission—not only because of the enormous energy release but also because of the extra neutrons liberated in the process. A typical fission reaction releases an average of about two or three neutrons. These new neutrons can, in turn, cause the fissioning of two or three other atomic nuclei, releasing more energy and a total of from four to nine more neutrons. If each of these neutrons splits just one nucleus, the next step in the reaction will produce between 8 and 27 neutrons, and so on. Thus, a whole chain reaction can proceed at an exponential rate.

Why doesn't a chain reaction start in naturally occurring uranium deposits? Chain reactions don't ordinarily happen because fission occurs mainly for the rare isotope U-235, which makes up only 0.7% of the uranium in the Earth. Fissionable U-235 is very dilute in natural uranium deposits. The prevalent isotope U-238 absorbs neutrons, but it does not ordinarily undergo fission, so a chain reaction can be quickly snuffed out by the neutron-absorbing U-238 nuclei. The prevalence

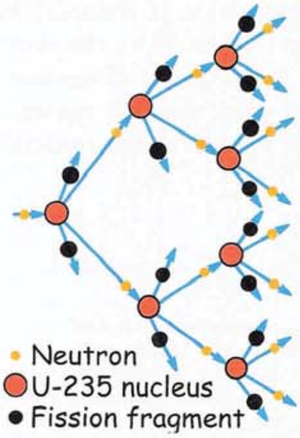


FIGURE 34.2
A chain reaction.

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[3] In this reaction, three neutrons are ejected when fission occurs. In some other reactions, two neutrons may be ejected—or, occasionally, one or four. On average, fission produces 2.5 neutrons per reaction.

[4] The electron volt (eV) is defined as the amount of kinetic energy an electron acquires in accelerating through a potential difference of 1 V.

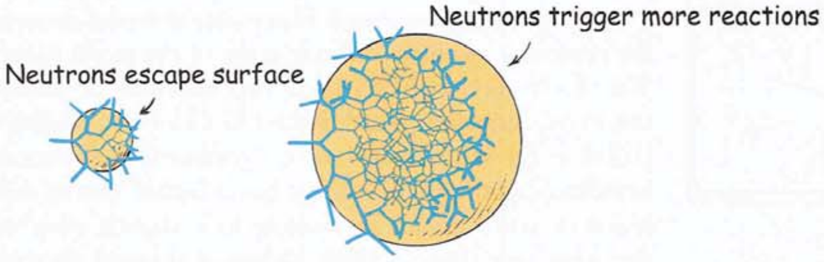

FIGURE 34.3
A chain reaction in a small piece of pure U-235 dies out because neutrons leak from the surface too readily. The small piece has a lot of surface area relative to its mass. In a larger piece, more uranium atoms and less surface area are presented to the neutrons.

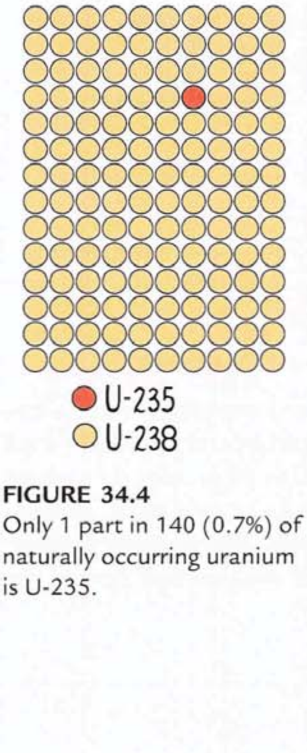

FIGURE 34.4
Only 1 part in 140 (0.7%) of naturally occurring uranium is U-235.

of U-238 lessens the chances of fission. With rare exceptions, naturally occurring uranium is too "impure" to undergo a chain reaction spontaneously.

If a chain reaction occurred in a baseball-size chunk of pure U-235, an enormous explosion would likely result. If the chain reaction were started in a smaller chunk of pure U-235, however, no explosion would occur. This is because a neutron ejected by a fission event travels a certain average distance through the material before it encounters another uranium nucleus and triggers another fission event. If the piece of uranium is too small, a neutron is likely to escape through the surface before it "finds" another nucleus. On the average, fewer than one neutron per fission will be available to trigger more fission, and the chain reaction will die out. In a bigger piece, a neutron can move farther through the material before reaching a surface. Then more than one neutron from each fission event, on the average, will be available to trigger more fission. The chain reaction will build up to enormous energy. We can also understand this geometrically. Recall the concept of scaling in Chapter 12. Small pieces of material have more surface relative to volume than larger pieces (there is more skin on 1 kilogram of small potatoes than on a single 1-kilogram large potato). The larger the piece of fission fuel, the less surface area it has relative to its volume.

The **critical mass** is the amount of mass for which each fission event produces, on the average, one additional fission event. It is just enough to "hold even." A *subcritical* mass is one in which the chain reaction dies out. A *supercritical* mass is one in which the chain reaction builds up explosively.

Consider a quantity of pure U-235 divided into two units, each having subcritical mass. Neutrons readily reach a surface and escape before a sizable chain reaction builds up. But, if one piece is suddenly driven into the other to form a single piece, the average distance a neutron can move within the material is increased, and fewer neutrons escape through the surface. The total surface area decreases. If the timing is right and the combined mass is greater than critical, a violent explosion takes place. This device is a nuclear fission bomb of the "gun type." Figure 34.5 shows such an idealized uranium fission bomb. Other designs are somewhat more complex.

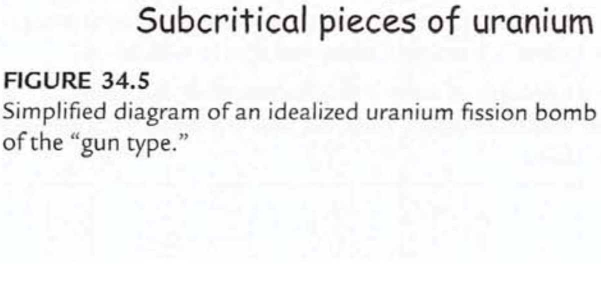

FIGURE 34.5
Simplified diagram of an idealized uranium fission bomb of the "gun type."

A chunk of U-235 probably a little larger than a softball was used in the historic Hiroshima blast in

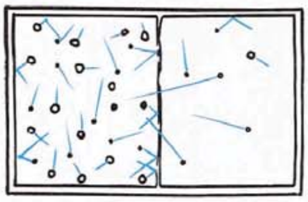

FIGURE 34.6
Lighter molecules move faster than heavier ones at the same temperature and diffuse more readily through a thin membrane.

1945. Separating this much fissionable material from natural uranium was one of the principal and most difficult tasks of the secret Manhattan Project during World War II. Project scientists used two methods of isotope separation. One method employed diffusion, where lighter U-235 has a slightly greater average speed than U-238 at the same temperature. Combined with fluorine to make the gas uranium hexafluoride, the faster isotope has a higher rate of diffusion through a thin membrane or small opening, resulting in a slightly enriched gas containing U-235 on the other side (Figure 34.6). Diffusion through thousands of chambers ultimately produced a sufficiently enriched sample of U-235. The other method, used only for partial enrichment, employed magnetic separation of uranium ions shot into a magnetic field. The smaller-mass U-235 ions were deflected more by the magnetic field than the U-238 ions and were collected atom by atom through a slit positioned to catch them (look ahead to Figure 34.14). After a couple of years, the two methods together netted a few tens of kilograms of U-235.

CHECK YOURSELF

1. A 10-kilogram ball of U-235 is supercritical, but the same ball broken up into small chunks isn't. Explain.
2. Why will molecules of uranium hexafluoride gas made with U-235 move slightly faster at the same temperature than molecules of uranium hexafluoride gas made with U-238?

Uranium-isotope separation today is more easily accomplished with a gas centrifuge. Uranium hexafluoride gas is whirled in a drum at tremendously high rim speeds (on the order of 1500 kilometers per hour). Gas molecules containing the heavier U-238 gravitate to the outside like milk in a dairy separator, and gas containing the lighter U-235 is extracted from the center. Engineering difficulties, overcome only in recent years, prevented the use of this method during the Manhattan Project.

Nuclear Fission Reactors

A chain reaction cannot ordinarily take place in *pure* natural uranium, since it is mostly U-238. The neutrons released by fissioning U-235 atoms are fast neutrons, readily captured by U-238 atoms, which do not fission. A crucial experimental fact is that *slow* neutrons are far more likely to be captured by U-235

CHECK YOUR ANSWERS

1. In smaller pieces, neutrons exit the material before sustaining a chain reaction that won't die out. Put another way, geometrically, the small chunks of U-235 have more combined surface area than the ball from which they came (just as the combined surface area of gravel is greater than the surface area of a boulder of the same mass). Neutrons escape via the surface before a sustained chain reaction can build up.
2. At the same temperature, the molecules of both compounds have the same kinetic energy ($1/2mv^2$). So the molecule made with the less massive U-235 must have a correspondingly higher speed.

Enrico Fermi. It was said jokingly that, when Fermi left Stockholm to return to his native Italy after receiving the Nobel Prize in December, 1938, he got lost and ended up in New York. In fact, he and his Jewish wife Laura carefully planned this escape from Fascist Italy. Fermi became an American citizen in 1945.

FIGURE 34.7
An artist's depiction of the setting in the squash court beneath the stands at the University of Chicago's Stagg Field, where Enrico Fermi and his colleagues constructed the first nuclear reactor.

than by U-238.[5] If neutrons can be slowed down, there is an increased chance that a neutron released by fission will cause fission in another U-235 atom, even amid the more plentiful and otherwise neutron-absorbing U-238 atoms. This increase may be enough to allow a chain reaction to take place.

FIGURE 34.8
The bronze plaque at Chicago's Stagg Field commemorates Enrico Fermi's historic fission chain reaction.

Within less than a year after the discovery of fission, scientists realized that a chain reaction with ordinary uranium metal might be possible if the uranium were broken up into small lumps and separated by a material that would slow down the neutrons released by nuclear fission. Enrico Fermi, who came to America from Italy at the beginning of 1939, led the construction of the first nuclear reactor—or *atomic pile,* as it was called—in a squash court underneath the grandstands of the University of Chicago's Stagg Field. He and his group used graphite, a common form of carbon, to slow the neutrons. They achieved the first self-sustaining controlled release of nuclear energy on December 2, 1942.

Three fates are possible for a neutron in ordinary uranium metal. It may (1) cause fission of a U-235 atom, (2) escape from the metal into nonfissionable surroundings, or (3) be absorbed by U-238 without causing fission. Graphite was used to make the first fate more probable. Uranium was divided into discrete parcels and buried at regular intervals in nearly 400 tons of graphite. A simple analogy clarifies the function of the graphite: If a golf ball rebounds from a massive wall, it loses hardly any speed; but, if it rebounds from a baseball, it loses considerable speed. The case of the neutron is similar. If a neutron rebounds from a heavy nucleus, it loses hardly any speed; but, if it rebounds

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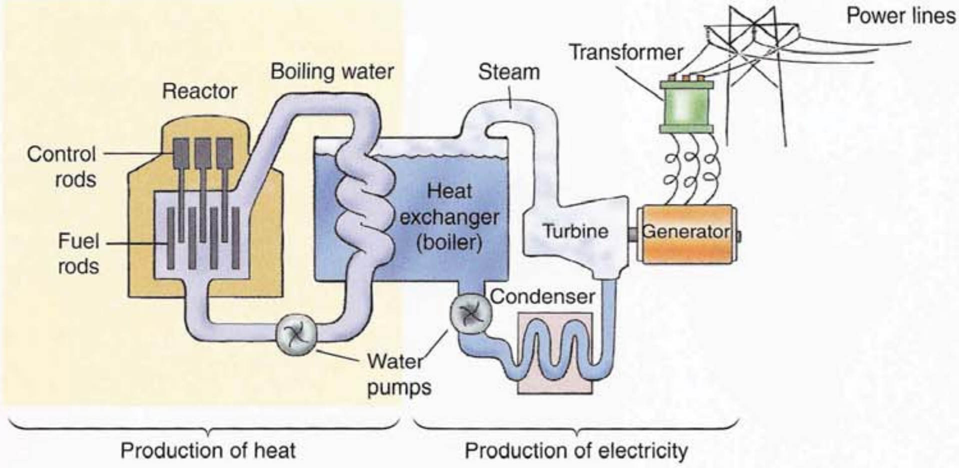
[5] This is similar to the selective absorption of various frequencies of light. Just as atoms of various elements absorb light differently, various isotopes of the same element, though chemically almost identical, can have quite different nuclear properties and absorb neutrons differently.

FIGURE 34.9
Diagram of a nuclear fission power plant.



from a lighter carbon nucleus, it loses considerable speed. The graphite was said to "moderate" the neutrons.[6] The whole apparatus is called a *reactor*.

Today's fission reactors contain three components: nuclear fuel, control rods, and a fluid (usually water) to extract heat from the reactor. The nuclear fuel is primarily U-238 plus about 3% U-235. Because the U-235 is so highly diluted with U-238, an explosion like that of a nuclear bomb is not possible.[7] The reaction rate, which depends on the number of neutrons available to initiate fission of other U-235 nuclei, is controlled by rods inserted into the reactor. The control rods are made of a neutron-absorbing material, usually cadmium or boron. Water surrounding the nuclear fuel is kept under high pressure to keep it at a high temperature without boiling. Heated by fission, this water then transfers heat to a second, lower-pressure water system, which operates a turbine and electric generator. Two separate water systems are used so that no radioactivity reaches the turbine.

CHECK YOURSELF

What is the function of a *moderator* in a nuclear reactor? Of *control rods*?

CHECK YOUR ANSWERS

A moderator slows down neutrons that are normally too fast to be absorbed readily by fissionable isotopes, such as U-235. Control rods absorb more neutrons when they are pushed into the reactor and fewer neutrons when they are pulled out of the reactor. They thereby control the number of neutrons that participate in the chain reaction.

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[6] *Heavy water*, which contains the heavy hydrogen isotope deuterium, is an even more effective moderator. This is because, in an elastic collision, a neutron transfers a greater portion of its energy to the deuterium nucleus than it would to the heavier carbon nucleus, and a deuteron never absorbs a neutron, as a carbon nucleus occasionally does.

[7] In a worst-case accident, however, heat sufficient to melt the reactor core is possible—and, if the reactor building is not strong enough, to scatter radioactivity into the environment. One such accident occurred at the Chernobyl reactor in 1986 in Ukraine, which was then a constituent republic of the Soviet Union.

Plutonium

THE Physics Place

Plutonium

When a U-238 nucleus absorbs a neutron, no fission occurs. The nucleus that is created, U-239, is radioactive. With a half-life of 24 minutes, it emits a beta particle and becomes an isotope of the first synthetic element beyond uranium—the transuranic element called *neptunium* (Np, named after the first planet discovered via Newton's law of gravitation). This isotope of Neptunium, Np-239, is also radioactive, with a half-life of 2.3 days. It soon emits a beta particle and becomes an isotope of *plutonium* (Pu, named after Pluto, the second planet to be discovered via Newton's law of gravitation). The half-life of this isotope, Pu-239, is about 24,000 years. Like U-235, Pu-239 will undergo fission when it captures a neutron. Interestingly, Pu-239 is even more fissionable than U-235.

Even before Fermi's atomic pile went critical, physicists realized that reactors could be used to make plutonium, and they set about designing large reactors for that purpose. The reactors constructed at Hanford, Washington, for plutonium production during World War II were 200 million times more powerful than Fermi's atomic pile. By mid-1945, they had manufactured kilograms of this element, which was not found in nature and unknown a few years earlier. Since plutonium is an element distinct from uranium, it can be separated from uranium by ordinary chemical methods when "fuel slugs" are removed from the reactor for processing. Consequently, the reactor provides a process for making fissionable material more easily than by separating the U-235 from natural uranium. The atomic bombs tested in New Mexico and detonated over Nagasaki were plutonium bombs.

Although the process of separating plutonium from uranium is simple in theory, it is very difficult in practice. This is because large quantities of radioactive fission products are formed in addition to plutonium. All chemical processing must be done by remote control to protect the staff against radiation. Also, the element plutonium is chemically toxic in the same sense that lead and arsenic are toxic. It attacks the nervous system and can cause paralysis; death can follow if the dose is sufficiently large. Fortunately, plutonium doesn't remain in its elemental form for long but rapidly combines with oxygen to form three compounds, PuO, PuO_2, and Pu_2O_3, all of which are chemically inert. They will not dissolve in water or in biological systems. These plutonium compounds do not attack the nervous system and have been found to be biologically inert.

Plutonium in any form, however, is radioactively toxic to humans and to other animals. It is more toxic than uranium, although less toxic than radium. Pu-239 emits high-energy alpha particles, which kill cells rather than simply disrupting them. Because damaged cells rather than dead cells produce

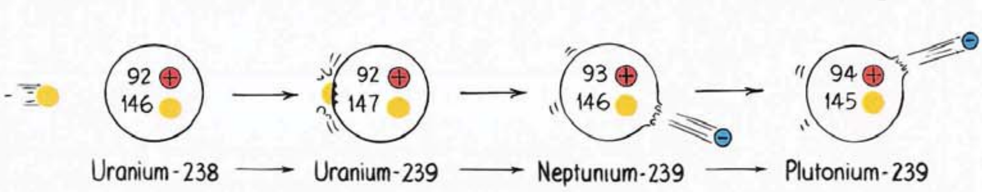

FIGURE 34.10 Interactive Figure

When a nucleus of U-238 absorbs a neutron, it becomes a nucleus of U-239. Within about half an hour, this nucleus emits a beta particle, resulting in a nucleus of about the same mass but with one more unit of charge. This is no longer uranium; it's a new element—*neptunium*. After the neptunium, in turn, emits a beta particle, it becomes plutonium. (In both events, an antineutrino, not shown, is also emitted.)

mutations and lead to cancer, plutonium ranks relatively low as a carcinogen. The greatest danger that plutonium presents to humans is its use in nuclear fission bombs. Its greatest potential benefit is in breeder reactors.

CHECK YOURSELF

Why does plutonium not occur in appreciable amounts in natural ore deposits?

The Breeder Reactor

A remarkable feature of fission power is the *breeding* of plutonium from nonfissionable U-238. Breeding occurs when small amounts of fissionable U-235 are mixed with U-238 in a reactor. Fissioning liberates neutrons that convert the relatively abundant nonfissionable U-238 to U-239, which beta-decays to become Np-239, which, in turn, beta-decays to fissionable plutonium—Pu-239. So, in addition to the abundant energy produced, fission fuel is bred from relatively abundant U-238 in the process.

Some breeding occurs in all fission reactors, but a **breeder reactor** is specifically designed to breed more fissionable fuel than is put into it. Using a breeder reactor is analogous to filling your car's gas tank with water, adding some gasoline, then driving the car and having more gasoline at the end of the trip than at the beginning! The basic principle of the breeder reactor is very attractive: After a few years of operation, a breeder-reactor power plant can produce vast amounts of power while breeding twice as much fuel as it had in the beginning.

The downside of breeder reactors is the enormous complexity of successful and safe operation. The United States gave up on breeders in the 1980s, and only France, Germany, India, and China are still investing in them. Officials in these countries point out that supplies of naturally occurring U-235 are limited. At present rates of consumption, all natural sources of U-235 may be depleted within a century. Countries then deciding to use breeder reactors may well find themselves digging up radioactive wastes they once buried.[8]

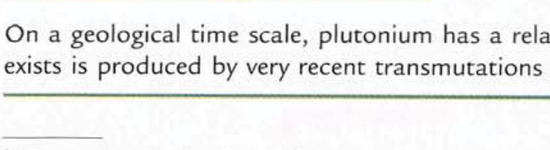

FIGURE 34.11 Interactive Figure

Pu-239 or U-233, like U-235, undergoes fission when it captures a neutron.

CHECK YOUR ANSWER

On a geological time scale, plutonium has a relatively short half-life, so any that exists is produced by very recent transmutations of uranium isotopes.

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[8] Many nuclear scientists do not think that deep burial is a desirable solution to the problem of nuclear waste. Devices are presently being studied that could, in principle, convert long-lived radioactive atoms of spent reactor fuel into short-lived or nonradioactive atoms. (See "Will New Technology Solve the Nuclear Waste Problem?" in *The Physics Teacher,* Vol. 35, Feb. 1997.) Nuclear wastes may not plague future generations indefinitely, as has been commonly thought.

CHECK YOURSELF

Complete these reactions, which occur in a breeder reactor:

$^{239}_{92}\text{U} \rightarrow$ ______ $+ ^{0}_{-1}e$

$^{239}_{93}\text{Np} \rightarrow$ ______ $+ ^{0}_{-1}e$

Fission Power

Energy available from nuclear fission was introduced to the world in the form of nuclear bombs. This violent image still impacts our thinking about nuclear power. Add to this the fearsome 1986 Chernobyl disaster in the Soviet Union, and we find many people viewing nuclear power as evil technology. Nevertheless, about 20% of electric energy in the United States is generated by nuclear-fission reactors. These reactors, sometimes called *nukes,* are simply nuclear furnaces. Like fossil-fuel furnaces, they do nothing more elegant than boil water to produce steam for a turbine. The greatest practical difference is the amount of fuel involved. One kilogram of uranium fuel, a chunk smaller than a baseball, yields more energy than 30 freightcar loads of coal.

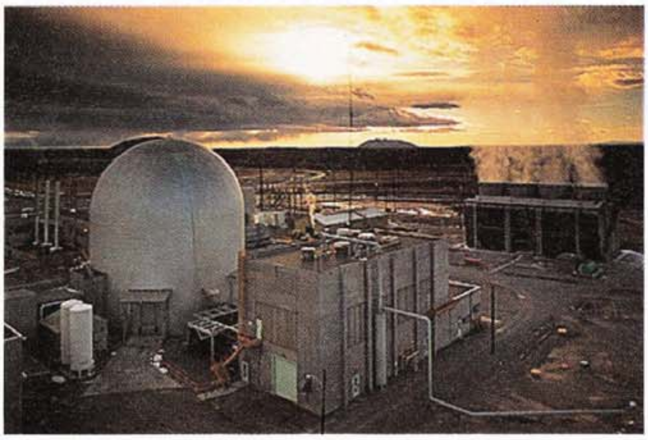

FIGURE 34.12
A typical nuclear fission power plant.

One disadvantage of fission power is the generation of radioactive waste products. Light atomic nuclei are most stable when composed of equal numbers of protons and neutrons, and it is mainly heavy nuclei that need more neutrons than protons for stability. For example, there are 143 neutrons but only 92 protons in U-235. When uranium fissions into two medium-weight elements, the extra neutrons in their nuclei make them unstable. These fragments are therefore radioactive, and most of them have very short half-lives. Some of them, however, have half-lives of thousands of years. Safely disposing of these waste products as well as materials made radioactive in the production of nuclear fuels requires special storage casks and procedures. Although fission power goes back a half century, the technology of radioactive waste disposal remains in the developmental stage.

The energy value of radioactive materials released in coal-burning power plants is some 1.5 times more than the energy provided by coal itself.

Insights

The benefits of fission power are (1) plentiful electricity; (2) the conservation of the many billions of tons of coal, oil, and natural gas that every year are literally turned to heat and smoke and that in the long run may be far more precious as sources of organic molecules than as sources of heat; and (3) the elimination of the megatons of sulfur oxides and other poisons, as well as the greenhouse gas carbon dioxide, that are put into the air each year by the burning of these fuels.

CHECK YOUR ANSWERS

$^{239}_{93}\text{Np}$; $^{239}_{94}\text{Pu}$. (Antineutrinos are also emitted in these beta-decay processes, and they escape unobserved.)

The drawbacks include (1) the problem of storing radioactive wastes; (2) the production of plutonium and the danger of nuclear weapons proliferation; (3) the low-level release of radioactive materials into the air and groundwater; and, most importantly, (4) the risk of an accidental release of large amounts of radioactivity.

Reasoned judgment requires not only that we examine the benefits and drawbacks of fission power but also that we compare its benefits and drawbacks with those of other power sources. For a variety of reasons, public opinion in the United States and much of Europe is now against fission power plants. Although there are growing signs of fission power acceptance, for the most part fission power is currently on the decline, and fossil-fuel power is on the upswing.[9]

CHECK YOURSELF

Coal contains tiny quantities of radioactive materials, enough so there is more environmental radiation surrounding a typical coal-fired power plant than surrounds a fission power plant. What does this indicate about the shielding typically surrounding the two types of power plants?

Mass–Energy Equivalence

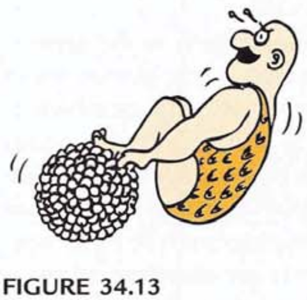

FIGURE 34.13
Work is required to pull a nucleon from an atomic nucleus. This work goes into mass energy.

From Einstein's mass–energy equivalence, $E = mc^2$, mass can be thought of as congealed energy. Mass is like a super storage battery. It stores energy—vast quantities of energy—which can be released if and when the mass decreases. If you were to stack up 238 bricks, the mass of the stack would be equal to the sum of the masses of the individual bricks. At the nuclear level, things are different. The mass of a nucleus is not simply the masses of the individual nucleons that compose it. Consider the work that would be required to separate nucleons from an atomic nucleus.

Recall that work, which is a way of transferring energy, is equal to the product of force and distance. Imagine that you could reach into a U-238 nucleus and, pulling with a force even greater than the attractive nuclear force, remove one nucleon. That would require a lot of work. Then keep repeating the process until you end up with 238 nucleons, stationary and well separated. What

CHECK YOUR ANSWER

Coal-fired power plants are, seemingly, as American as apple pie, with no required (and expensive) shielding to restrict the emissions of radioactive particles. Fission power plants, on the other hand, are required to have shielding to ensure strictly low levels of radioactive emissions.

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[9] Public outcry against electricity was common in the nineteenth century. Those with the loudest voices likely knew the least about electricity. Today there is public outcry against nuclear power—"No Nukes!" The position of this book, in contrast, is "Know Nukes!"—first know something about the promises of, as well as the drawbacks to, nuclear power before saying *yes* or *no* to nukes.

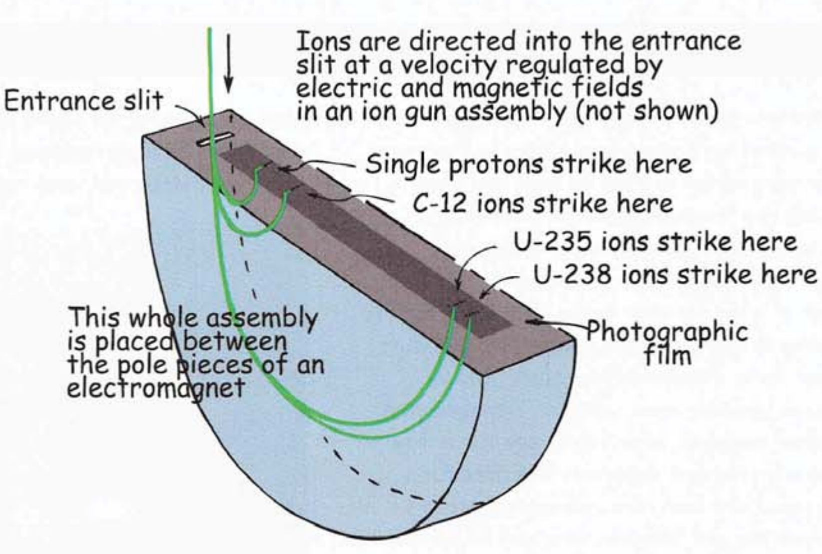


FIGURE 34.14
The mass spectrometer. Ions of a fixed speed are directed into the semicircular "drum," where they are swept into semicircular paths by a strong magnetic field. Because of different inertia, heavier ions are swept into curves of larger radii and lighter ions are swept into curves of smaller radii. The radius of the curve is directly proportional to the mass of the ion. Using C-12 as a standard, the masses of the isotopes of all the elements are easily determined.

happened to all the work that you have done? You started with one stationary nucleus containing 238 particles and ended with 238 stationary particles. The work that you did has to show up somewhere as additional energy. It shows up as *mass* energy. The separated nucleons have a total mass greater than the mass of the original nucleus, and the extra mass, multiplied by the square of the speed of light, is exactly equal to your energy input: $\Delta E = \Delta mc^2$.

One way to interpret this mass change is to say that an average nucleon inside a nucleus has less mass than a nucleon outside the nucleus. How much less depends on which nucleus. The mass difference is related to the "binding energy" of the nucleus. For uranium, the mass difference is about 0.7%, or 7 parts in a thousand. The 0.7% reduction in the nucleon mass in a uranium atom indicates the binding energy of the nucleus—how much work would be required to disassemble the nucleus.

The experimental verification of this conclusion is one of the triumphs of modern physics. The masses of nucleons and the isotopes of the various elements can be measured with an accuracy of 1 part per million or better. One means of doing this is with a *mass spectrometer* (Figure 34.14).

In a mass spectrometer, charged ions are directed into a magnetic field, where they deflect into circular arcs. The greater the inertia of the ion, the more it resists deflection and the greater the radius of its curved path. All the ions entering this device have the same speed. The magnetic force sweeps the heavier ions into larger arcs and the lighter ions into smaller arcs. The ions pass through exit slits, where they may be collected, or they strike a detector, such as photographic film. An isotope is chosen as a standard, and its position on the film of the mass spectrometer is used as a reference point. The standard is the common isotope of carbon, C-12. The mass of the C-12 nucleus is assigned the value of 12.00000 atomic mass units. As mentioned earlier, the atomic mass unit (amu) is defined to be precisely one-twelfth the mass of the common carbon-12 nucleus. With this reference, the amu values of the other atomic nuclei are measured. The masses of the proton and neutron are found to be greater when they are isolated than when they are in a nucleus. They are 1.00728 and 1.00867 amu, respectively.

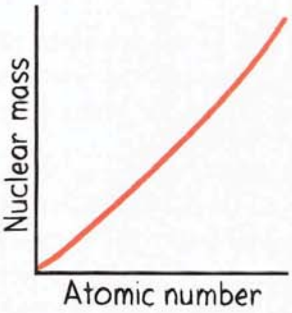
PHYSICS AT AIRPORT SECURITY

A version of the mass spectrometer shown in Figure 34.14 is employed in airport security. Ion mobility rather than electromagnetic separation is used to sniff out certain molecules, mainly the few nitrogen-rich ones characteristic of explosives. Security personnel swab your luggage or other belongings with a small disk of paper, which they place in a device that heats it to expel vapors from it. Molecules in the vapor are ionized by exposure to beta radiation from a radioactive source. Most molecules become positive ions, whereas nitrogen-rich molecules become negative, which drift against a flow of air to a positively charged detector. The time for a negative ion to reach the detector indicates the ion's mass—the heavier the ion, the slower it will be to reach the detector.

The same process occurs in body scans, in which a person stands momentarily in an enclosed region the size of a telephone booth where upward puffs of air impinge on the body. The air is then "sniffed" by the same technique, searching for some forty types of explosives and sixty types of drug residues. Presto, green light means none were detected, and red light means—uh-oh!

CHECK YOURSELF

Wait a minute! If isolated protons and neutrons have masses greater than 1.0000 amu, why don't 12 of them in a carbon nucleus have a combined mass greater than 12.0000 amu?



A graph of nuclear mass as a function of atomic number is shown in Figure 34.15. The graph slopes upward with increasing atomic number, as expected, telling us that elements are more massive as atomic number increases. (The slope curves because there are proportionally more neutrons in the more massive atoms.)

A more important graph results from a plot of average mass *per nucleon* for the elements hydrogen through uranium (Figure 34.16). This is perhaps the most important graph in this book, for it is the key to understanding the energy associated with nuclear processes—fission as well as fusion. To obtain the average mass per nucleon, you divide the total mass of a nucleus by the number of nucleons in the nucleus. (Similarly, if you divide the total mass of a roomful of people by the number of people in the room, you get the average mass per

CHECK YOUR ANSWER

When you pull a nucleon from the nucleus, you do work on it and it gains energy. When that nucleon falls back into the nucleus, it does work on its surroundings and *loses* energy. Losing energy means losing mass. It's as if each nucleon, on average, slims down to a mass of exactly 1.0000 amu when it joins with 11 other nucleons to form C-12. If you pull them back out, you'll get back the original mass. Indeed, $E = mc^2$.

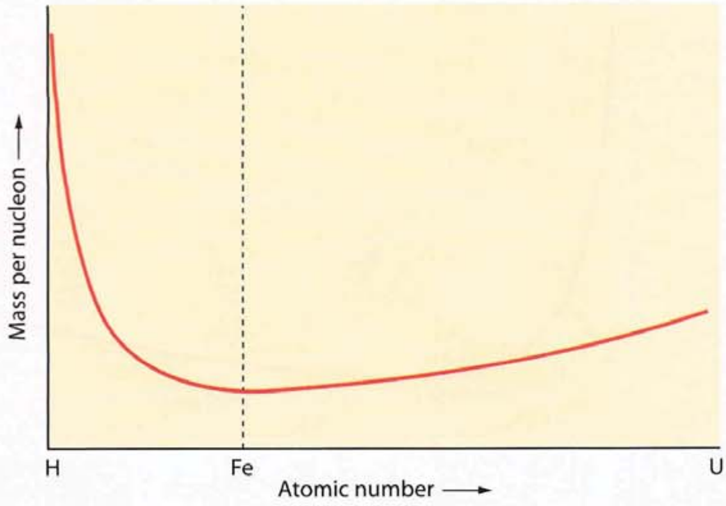


FIGURE 34.16
Interactive Figure

The graph shows that the mass of a nucleon depends on which nucleus it is in. Individual nucleons have the most mass in the lightest (hydrogen) nuclei, the least mass in iron nuclei, and intermediate mass in the heaviest (uranium) nuclei. (The vertical scale is exaggerated.)

person.) The major fact we learn from Figure 34.16 is that the average mass per nucleon varies from one nucleus to another.

The greatest mass per nucleon occurs for a proton when it occurs alone as a hydrogen nucleus because then it has no binding energy to pull its mass down. As we progress to elements beyond hydrogen, Figure 34.16 tells us that the mass per nucleon decreases and is least for a nucleon in an iron nucleus. Iron holds its nucleons more tightly than any other nucleus does. Beyond iron, the trend reverses itself as protons (and neutrons) have progressively more and more mass in atoms of increasing atomic number. This continues all the way through the list of elements.

From this graph, we can see why energy is released when a uranium nucleus is split into two nuclei of lower atomic number. When the uranium nucleus splits, the masses of the two fission fragments lie about halfway between the masses of uranium and hydrogen on the horizontal scale of the graph. It is most important to note that the mass per nucleon in the fission fragments is *less than* the mass per nucleon when the same set of nucleons are combined in the uranium nucleus.

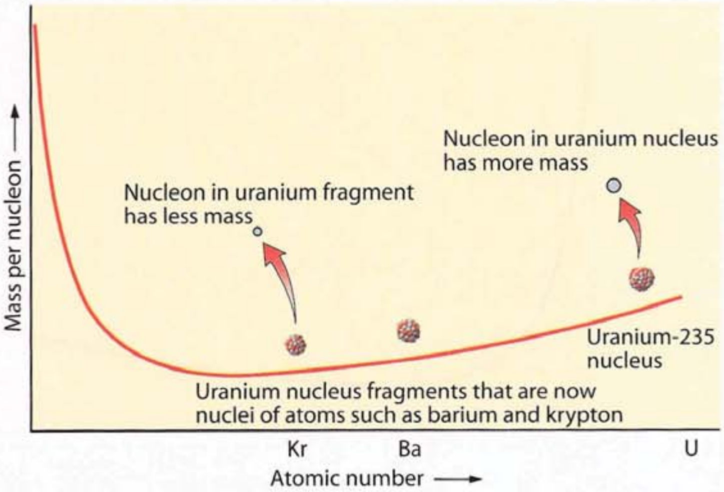
The graph of Figure 34.16 reveals the energy of the atomic nucleus, likely the primary source of energy in the universe—which is why it can be considered the most important graph in this book.

Insights

TABLE 34.1
Relative Masses and Masses/Nucleon of Some Isotopes

Isotope	*Symbol*	*Mass (amu)*	*Mass/Nucleon (amu)*
Neutron	n	1.008665	1.008665
Hydrogen	$^{1}_{1}\text{H}$	1.007825	1.007825
Deuterium	$^{2}_{1}\text{H}$	2.01410	1.00705
Tritium	$^{3}_{1}\text{H}$	3.01605	1.00535
Helium-4	$^{4}_{2}\text{He}$	4.00260	1.00065
Carbon-12	$^{12}_{6}\text{C}$	12.00000	1.000000
Iron-58	$^{58}_{26}\text{Fe}$	57.93328	0.99885
Copper-63	$^{63}_{29}\text{Cu}$	62.92960	0.99888
Krypton-90	$^{90}_{36}\text{Kr}$	89.91959	0.99911
Barium-143	$^{143}_{56}\text{Ba}$	142.92054	0.99944
Uranium-235	$^{235}_{92}\text{U}$	235.04395	1.00019

FIGURE 34.17
The mass of each nucleon in a uranium nucleus is greater than the mass of each nucleon in any one of its nuclear-fission fragments. This decrease in mass is mass that has been transformed into energy. Hence, nuclear fission is an energy-releasing process.



When this decrease in mass is multiplied by the speed of light squared, it equals 200,000,000 electron volts, the energy yielded by each uranium nucleus that undergoes fission. As mentioned earlier, most of this enormous energy is the kinetic energy of the fission fragments.

We can think of the mass-per-nucleon curve as an energy valley that starts at the highest point (hydrogen), slopes steeply down to the lowest point (iron), and then slopes more gradually up to uranium. Iron, which is at the bottom of the energy valley, has the most stable nucleus. It also has the most tightly bound nucleus: More energy per nucleon is required to separate nucleons from its nucleus than from any other nucleus. Any nuclear transformation that moves lighter nuclei toward iron by combining them or moves heavier nuclei toward iron by dividing them releases energy.

So the decrease in mass is detectable in the form of energy—much energy—when heavy nuclei undergo fission. As mentioned, a drawback to this process involves the radioactive fission fragments. A more promising long-range source of energy is to be found on the left side of the energy valley.

CHECK YOURSELF

1. Consider a graph like those of Figures 34.16 and 34.17—not for microscopic nucleons, but for a house or other structures made of regular bricks. Would the graph dip, or would it be a straight horizontal line?
2. Correct the following incorrect statement: When a heavy element, such as uranium, undergoes fission, there are fewer nucleons after the reaction than before.

TABLE 34.2
Energy Gain from Fission of Uranium

Reaction:	$^{235}\text{U} + n \rightarrow {}^{143}\text{Ba} + {}^{90}\text{Kr} + 3n + \Delta m$
Mass balance:	$235.04395 + 1.008665 = 142.92054 + 89.91959 + 3(1.008665) + \Delta m$
Mass defect:	$\Delta m = 0.186$ amu
Energy gain:	$\Delta E = \Delta mc^2 = 0.186 \times 931$ MeV $= 173.6$ MeV
Energy gain/nucleon:	$\Delta E/236 = 173.6$ MeV$/236 = 0.74$ MeV/nucleon

(When m is expressed in amu, c^2 is equivalent to 931 MeV.)

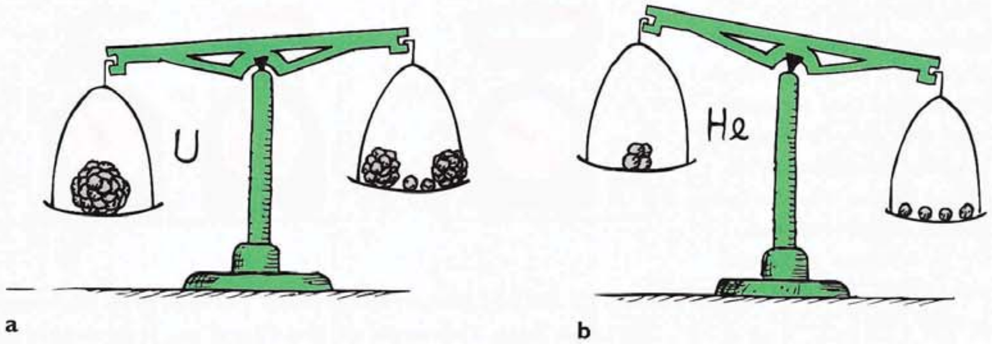


FIGURE 34.18 Interactive Figure

The mass of a nucleus is *not* equal to the sum of the masses of its parts. (a) The fission fragments of a heavy nucleus like uranium are less massive than the uranium nucleus. (b) Two protons and two neutrons are more massive in their free states than when they are combined to form a helium nucleus.

Nuclear Fusion

Inspection of the mass-per-nucleon versus atomic-number graph will show that the steepest part of the energy hill is from hydrogen to iron. Energy is gained as light nuclei *fuse* (which means that they combine). This process is **nuclear fusion**—the opposite of nuclear fission. We can see from Figure 34.19 that, as we move along the list of elements from hydrogen to iron (the left side of the

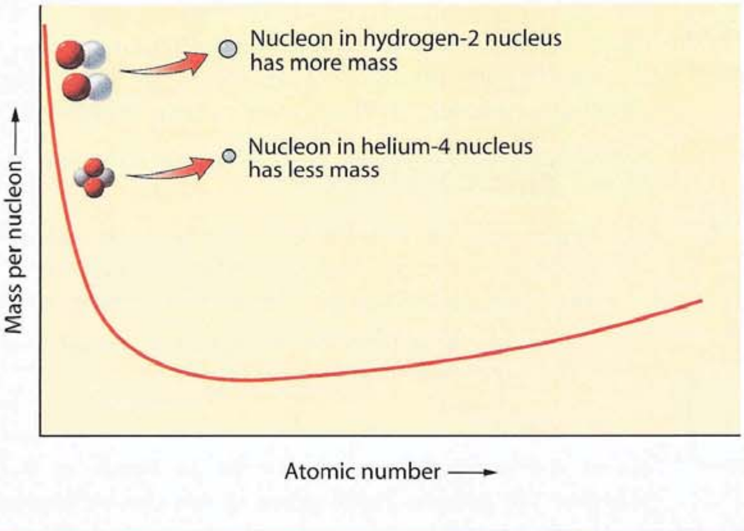


FIGURE 34.19
The average mass of a nucleon in hydrogen is greater than its average mass when fused with another to become helium. The decreased mass is mass that is converted to energy, which is why nuclear fusion of light elements is an energy-releasing process.

CHECK YOUR ANSWERS

1. It would be a straight horizontal line. The mass per brick would be the same for every structure. (Theoretically, however, it would not be *exactly* a straight horizontal line because, even for bricks, binding energy has some effect on mass, although the effect would be far too small to measure.)
2. When a heavy element, such as uranium, undergoes fission, there aren't fewer nucleons after the reaction. Instead, there's *less mass* in the same number of nucleons.

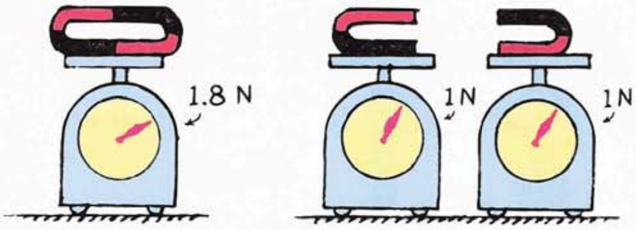


FIGURE 34.20
Fictitious example: The "hydrogen magnets" weigh more when they are apart than they do when they are together. (Adapted from Albert V. Baez, *The New College Physics: A Spiral Approach*. W. H. Freeman and Company, 1967. An oldie but a goodie.)

energy valley), the average mass per nucleon decreases. Thus, if two small nuclei were to fuse, the mass of the fused nucleus would be less than the mass of the two single nuclei before fusion. Energy is gained as light nuclei fuse.

Consider hydrogen fusion. For a fusion reaction to occur, the nuclei must collide at a very high speed in order to overcome their mutual electric repulsion. The required speeds correspond to the extremely high temperatures found in the Sun and other stars. Fusion brought about by high temperatures is called **thermonuclear fusion.** In the high temperatures of the Sun, approximately 657 million tons of hydrogen are fused to 653 million tons of helium each second. The "missing" 4 million tons of mass convert to energy. Such reactions are, quite literally, nuclear burning.

Interestingly, most of the energy of nuclear fusion is in the kinetic energy of fragments, mainly neutrons. When the neutrons are stopped and captured, the energy of fusion turns into heat. In fusion reactions of the future, part of this heat will be transformed to electricity.

Thermonuclear fusion is analogous to ordinary chemical combustion. In both chemical and nuclear burning, a high temperature starts the reaction; the release of energy by the reaction maintains a sufficient temperature to spread the fire. The net result of the chemical reaction is a combination of atoms into more tightly bound molecules. In nuclear reactions, the net result is nuclei that are more tightly bound. In both cases, mass decreases as energy is released. The difference between chemical and nuclear burning is essentially one of scale.

In a sense, nucleons in the heavy elements wish to lose mass and be like nucleons in iron. And nucleons in the light elements also wish to lose mass and become more like those in iron.

Insights

CHECK YOURSELF

1. First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction? How can energy be released by opposite processes?
2. To obtain energy from the element iron, should iron nuclei be fissioned or fused?

Know nukes before you say "No nukes"!

Insights

In fission reactions, the amount of matter that is converted to energy is about 0.1%; in fusion, it can be as much as 0.7%. These numbers apply whether the process takes place in bombs, in reactors, or in stars.

Some typical fusion reactions are shown in Figure 34.21. Note that all reactions produce at least a pair of particles—for example, a pair of deuterium nuclei that fuse produce a tritium nucleus and a neutron rather than a lone helium nucleus. Either reaction is okay as far as adding the nucleons and charges is concerned, but the lone-nucleus case is not okay with conservation of momentum and energy. If a lone helium nucleus flies away after the reaction, it adds momentum that wasn't there initially. Or if it remains motionless, there's no mechanism for energy release. So, because a single product particle

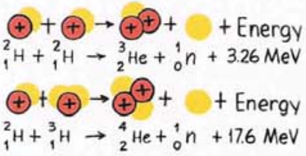


FIGURE 34.21
Two of many fusion reactions.

TABLE 34.3
Energy Gain from Fusion of Hydrogen

Reaction:	${}^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{H} + n + \Delta m$
Mass balance:	$2.01410 + 3.01605 = 4.00260 + 1.008665 + \Delta m$
Mass defect:	$\Delta m = 0.01888$ amu
Energy gain:	$\Delta E = \Delta mc^2 = 0.018888 \times 931$ MeV $= 17.6$ MeV
Energy gain/nucleon:	$\Delta E/5 = 17.6$ MeV$/5 = 3.5$ MeV/nucleon

can't move and it can't sit still, it isn't formed. Fusion normally requires the creation of at least two particles to share the released energy.[10]

Table 34.3 shows the energy gain from the fusion of hydrogen isotopes deuterium and tritium. This is the reaction proposed for plasma fusion power plants of the future. The high-energy neutrons, according to plan, will escape from the plasma in the reactor vessel and heat a surrounding blanket of material to provide useful energy. The helium nuclei remaining behind will help to keep the plasma hot.

Elements somewhat heavier than hydrogen release energy when fused. But they release much less energy per fusion reaction than hydrogen. The fusion of still heavier elements occurs in the advanced stages of a star's evolution. The energy released per gram during the various fusion stages from helium to iron amounts only to about one-fifth of the energy released in the fusion of hydrogen to helium. Hydrogen, most notably in the form of deuterium, is the choicest fuel for fusion.

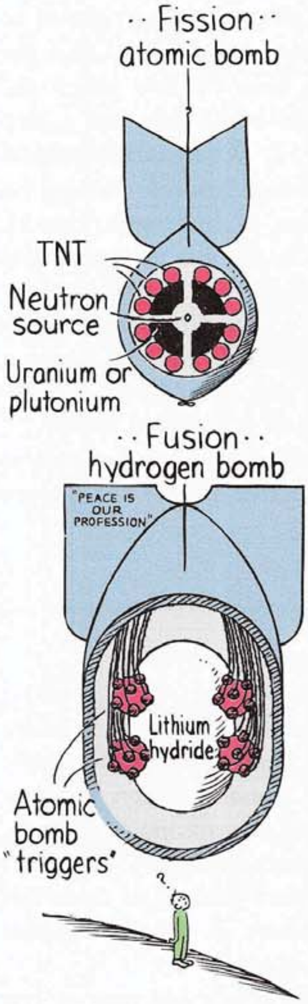


FIGURE 34.22
Fission and fusion bombs.

CHECK YOUR ANSWERS

1. Energy is released in any nuclear reaction in which the mass of the nuclei after the reaction is less than the mass of the nuclei before. When light nuclei, such as those of hydrogen, fuse to form heavier nuclei, total nuclear mass decreases. The fusion of light nuclei therefore releases energy. When heavy nuclei, such as those of uranium, split to become lighter nuclei, total nuclear mass also decreases. The splitting of heavy nuclei, therefore, releases energy. For energy release, "decrease mass" is the name of the game—any game, chemical or nuclear.
2. Neither, because iron is at the very bottom of the curve (energy valley). If you fuse two iron nuclei, the product lies somewhere on the upper right of iron on the curve, which means the product has a higher mass per nucleon. If you split an iron nucleus, the products lie on the upper left of iron on the curve, which again means a higher mass per nucleon. Because no mass decrease occurs in either reaction, no energy is ever released.

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[10] One of the reactions in the Sun's proton–proton fusion cycle does have a one-particle final state. It is proton + deuteron → He-3. This happens because the density in the center of the Sun is great enough that "spectator" particles share in the energy release. So, even in this case, the energy released goes to two or more particles. Fusion in the Sun involves more complicated (and slower!) reactions in which a small part of the energy also appears in the form of gamma rays and neutrinos. The neutrinos escape unhindered from the center of the Sun and bathe the solar system. Interestingly, the fusion of nuclei in the Sun is an occasional process, for the mean spacing between nuclei is vast, even at the high pressures in its center. That's why it takes some 10 billion years for the Sun to consume its hydrogen fuel.

Prior to the development of the atomic bomb, the temperatures required to initiate nuclear fusion on Earth were unattainable. When it was found that the temperatures inside an exploding atomic bomb are four to five times the temperature at the center of the Sun, the thermonuclear bomb was but a step away. This first hydrogen bomb was detonated in 1952. Whereas the critical mass of fissionable material limits the size of a fission bomb (atomic bomb), no such limit is imposed on a fusion bomb (thermonuclear, or hydrogen, bomb). Just as there is no limit to the size of an oil-storage depot, there is no theoretical limit to the size of a fusion bomb. Like the oil in a storage depot, any amount of fusion fuel can be stored with safety until it is ignited. Although a mere match can ignite an oil depot, nothing less energetic than a fission bomb can ignite a thermonuclear bomb. We can see that there is no such thing as a "baby" hydrogen bomb. It cannot be less energetic than its fuse, which is a fission bomb.

The hydrogen bomb is another example of a discovery applied to destructive rather than constructive purposes. The potential constructive side of the picture is the controlled release of vast amounts of clean energy.

Controlling Fusion

The world's oceans contain deuterium with the potential to release vastly more energy than all the world's fossil fuels, and much more than the world's supply of uranium. Therefore, fusion has to be considered as a possible source of long-term energy needs. Fusion reactions require temperatures of millions of degrees. There are a variety of techniques for attaining high temperatures. No matter how the temperature is produced, a technological problem is that all materials melt and vaporize at the temperatures required for fusion. A solution to this problem is to confine the reaction in a *nonmaterial container*.

The energy released in fusing a pair of hydrogen nuclei is less than that of fissioning a uranium nucleus. But because there are more atoms in a gram of hydrogen than in a gram of uranium, gram for gram, fusion releases several times as much energy as uranium.

Insights

One type of nonmaterial container is a magnetic field, which can exist at any temperature and can exert powerful forces on charged particles in motion. "Magnetic walls" provide a kind of magnetic straightjacket for hot plasmas. Magnetic compression further heats the plasma to fusion temperatures. At about a million degrees, some nuclei are moving fast enough to overcome electrical repulsion and to slam together and fuse. The energy output, however, is small relative to the energy used to heat the plasma. Even at 100 million degrees, more energy must be put into the plasma than is given off by fusion. At about 350 million degrees, the fusion reactions produce enough energy to be self-sustaining. At this ignition temperature, all that is needed to produce continuous power is a steady feed of nuclei. This is the sought-after condition called *break-even*.

Although break-even has nearly been achieved for very short times in several fusion devices, instabilities in the plasma have thus far prevented a sustained reaction. A big problem has been devising a field system that can hold the plasma in a stable and sustained position while an ample number of nuclei fuse. A variety of magnetic confinement devices are the subject of much present-day research.

THE Physics Place
Controlling Nuclear Fusion

Another approach uses high-energy lasers. One proposed technique is to aim an array of laser beams at a common point and drop pellets of frozen hydrogen isotopes through the synchronous crossfire (Figure 34.23). The energy of the multiple beams should crush the pellets to densities 20 times that of lead

Watch for the forthcoming International Thermonuclear Experimental Reactor (ITER), a joint fusion project by the European Union, Japan, and the United States.

Insights

and heat them to the required temperatures. Such laser-induced fusion could produce several hundred times more energy than is delivered by the laser beams that compress and ignite the pellets. Like the succession of fuel/air explosions in an automobile engine's cylinders that convert into a smooth flow of mechanical power, the successive ignition of pellets in a fusion power plant may similarly produce a steady stream of electric power.[11] The success of this technique requires precise timing, for the necessary compression must occur before a shock wave causes the pellets to disperse. High-power lasers that work reliably are yet to be developed. Break-even has not yet been achieved with laser fusion.

Still other approaches involve the bombardment of fuel pellets not by laser light but by beams of electrons and ions. Whatever the method, we are still looking forward to the great day in this twenty-first century when fusion power becomes a reality.

Fusion power, if it can be achieved, will be nearly ideal. Fusion reactors cannot become "supercritical" and go out of control because fusion requires no critical mass. Furthermore, there is no air pollution because the only product of the thermonuclear combustion is helium (good for children's balloons). Except for some radioactivity in the inner chamber of the fusion device because of high-energy neutrons, the by-products of fusion are not radioactive. Disposal of radioactive waste is not a major problem. Furthermore, there is no air pollution because there is no combustion. The problem of thermal pollution, characteristic of conventional steam-turbine plants, can be avoided by direct generation of electricity with MHD generators or by similar techniques using charged-particle fuel cycles that employ a direct energy conversion.

The fuel for nuclear fusion is hydrogen, the most plentiful element in the universe. The reaction that works best at "moderate" temperature is the fusion of the hydrogen isotopes deuterium ($^{2}_{1}$H) and tritium ($^{3}_{1}$H). Deuterium is found in ordinary water and tritium can be produced by the fusion reactor. Thirty

FIGURE 34.23
How laser fusion might work. Pellets of frozen deuterium are rhythmically dropped into synchronized laser crossfire. The resulting heat is carried off by molten lithium to produce steam.

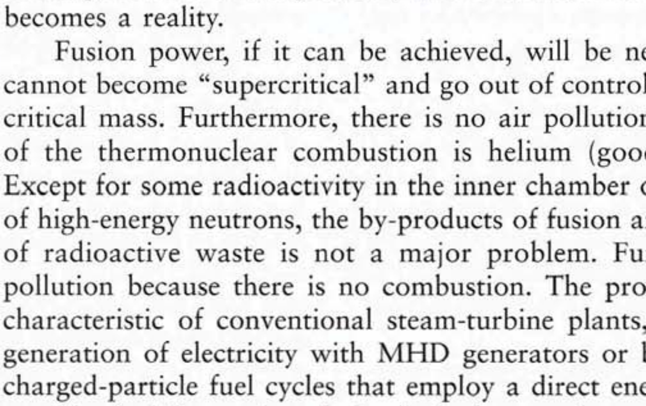

FIGURE 34.24
Pellet chamber at Lawrence Livermore National Laboratory. The laser source is Nova, one of the most powerful lasers in the world, which directs 10 beams into the target region.

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[11] The rate of pellet fusion is 5 per second at the National Ignition Facility at Lawrence Livermore National Laboratory. (For comparison, approximately 20 explosions per second occur in each automobile engine cylinder in a car that travels at highway speed.) Such a plant could produce some 1000 MW of electric power, enough to supply a city of about 600,000 people. Five fusion burns per second will provide about the same power as 60 L of fuel oil or 70 kg of coal per second from conventional power plants.

liters of seawater contain 1 gram of deuterium, which, when fused, release as much energy as 10,000 liters of gasoline or 80 tons of TNT. Natural tritium is much scarcer, but, given enough to get started, a controlled thermonuclear reactor will breed it from deuterium in ample quantities.

The development of fusion power has been slow and difficult, already extending over fifty years. It is one of the biggest scientific and engineering challenges that we face. Yet there is justified hope to believe that it will be achieved and will be a primary energy source for future generations.

FUSION TORCH AND RECYCLING

A fascinating application for the abundant energy that fusion of whatever kind may provide is the *fusion torch,* a star-hot flame or high-temperature plasma into which all waste materials—whether liquid sewage or solid industrial refuse—could be dumped. In the high-temperature region, the materials would be reduced to their constituent ionized atoms and separated by a mass-spectrometer-type device into various bins ranging from hydrogen to uranium. In this way, a single fusion plant could, in principle, not only dispose of thousands of tons of solid wastes daily but also provide a continuous supply of fresh raw material—thereby closing the cycle from use to reuse.

This would be a major turning point in materials economy (Figure 34.25). Our present concern for recycling materials would reach a grand fruition with this or a comparable achievement, for it would be recycling with a capital *R*! Rather than gut our planet further for raw materials, we'd be able to recycle existing stock over and over again, adding new material only to replace the relatively small amounts that are lost.

Fusion power holds the potential to produce abundant electrical power, to desalinate water, to help to cleanse our world of pollution and wastes, to recycle our materials, and, in so doing, to provide the setting for a better world—not necessarily in the far-off future but perhaps in this century. If and when fusion power plants become a reality, they are likely to have an even more profound impact upon almost every aspect of human society than did the harnessing of electromagnetic energy at the end of the nineteenth century.

When we think of our continuing evolution, we can see that the universe is well suited to those who will live in the distant future. If people are one day to dart about the universe in the same way we are able to jet about the world today, their supply of fuel is assured. The fuel for fusion is found in every part of the universe—not only in the stars but also in the space between them. About 91% of the atoms in the universe are estimated to be hydrogen. For people of this imagined future, the supply of raw materials is also assured; all the elements known to exist result from the fusing of more and more hydrogen nuclei. Simply put, if you fuse 8 deuterium nuclei, you have oxygen; if you fuse 26, you have iron; and so forth. Future humans might synthesize their own elements and produce energy in the process, just as the stars have always done. Humans may one day travel to the stars in ships fueled by the same energy that makes the stars shine.

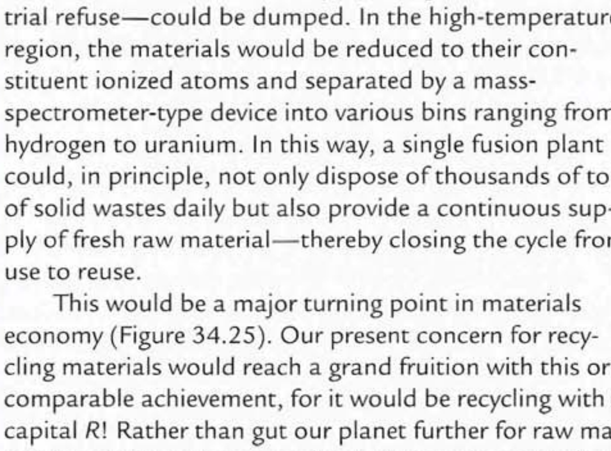

FIGURE 34.25

A closed materials economy could be achieved with the aid of the fusion torch. In contrast to present systems, (a) which are based on inherently wasteful linear material economies, a stationary-state system (b) would be able to recycle the limited supply of material resources, thus alleviating most of the environmental pollution associated with present methods of energy utilization. (Redrawn from "The Prospects of Fusion Power," by William C. Gough and Bernard J. Eastlund. *Scientific American,* Feb. 1971.) This idea remains as visionary and as enticing as it was more than thirty years ago.

Cannot it be said that humanity is in a great time of transition—that this is a great time to be young?

Insights

CHECK YOURSELF

1. One last time: Fission and fusion are opposite processes, yet each releases energy. Isn't this contradictory?
2. Would you expect the temperature of the core of a star to increase or decrease as a result of the fusion of intermediate elements to manufacture elements heavier than iron?

CHECK YOUR ANSWERS

1. No, no, no! This is contradictory only if the same element is said to release energy by both the processes of fission and fusion. Only the fusion of light elements and the fission of heavy elements result in a decrease in nucleon mass and a release of energy.
2. Energy is absorbed, not released, when heavier elements fuse, so the star core tends to cool at this late stage of its evolution. Interestingly, however, this allows the star to collapse, which produces an even greater temperature. Nuclear cooling is then more than offset by gravitational heating.

Summary of Terms

Nuclear fission The splitting of the nucleus of a heavy atom, such as uranium-235, into two smaller atoms, accompanied by the release of much energy.

Chain reaction A self-sustaining reaction in which the products of one reaction event stimulate further reaction events.

Critical mass The minimum mass of fissionable material in a reactor or nuclear bomb that will sustain a chain reaction.

Breeder reactor A fission reactor that is designed to breed more fissionable fuel than is put into it by converting nonfissionable isotopes to fissionable isotopes.

Nuclear fusion The combination of light atomic nuclei to form heavier nuclei, with the release of much energy.

Thermonuclear fusion Nuclear fusion produced by high temperature.

Suggested Reading

Bodanis, David. *$E = mc^2$: A Biography of the World's Most Famous Equation*. New York: Berkley Publishing Group, 2002. Insightful reading that includes some of the adventure in the early quest for nuclear power.

Review Questions

Nuclear Fission

1. What is the role of electrical forces in nuclear fission?
2. When a nucleus undergoes fission, what role can the ejected neutrons play?
3. Why does a chain reaction not occur in uranium mines?
4. Why is a chain reaction more likely in a big piece of uranium than it is in a small piece?
5. What is meant by the idea of a critical mass?
6. Which will leak more neutrons, two separate pieces of uranium or the same pieces stuck together?
7. What were the two methods used to separate U-235 from U-238 in the Manhattan Project during World War II?

Nuclear Fission Reactors

8. What was the function of graphite in the first atomic reactor?
9. What are the three possible fates of neutrons in uranium metal?
10. What are the three main components of a fission reactor?
11. Why can a reactor not explode like a fission bomb?

Plutonium

12. What isotope is produced when U-238 absorbs a neutron?
13. What isotope is produced when U-239 emits a beta particle?
14. What isotope is produced when Np-239 emits a beta particle?

15. What do U-235 and Pu-239 have in common?

16. Why is plutonium more easily separated from uranium metal than particular isotopes of uranium? What makes it difficult?

17. When is plutonium chemically toxic and when is it not?

The Breeder Reactor

18. What is the effect of placing small amounts of fissionable isotopes with large amounts of U-238?

19. Name three isotopes that undergo nuclear fission.

20. How does a breeder reactor breed nuclear fuel?

Fission Power

21. How is a nuclear reactor similar to a conventional fossil-fuel plant? How is it different?

22. Why are the fragments of fission radioactive?

23. What is the main advantage of fission power? What is the main drawback?

Mass–Energy Equivalence

24. What celebrated equation shows the equivalence of mass and energy?

25. Is work required to pull a nucleon out of an atomic nucleus? Does the nucleon, once outside, then have more energy than it did when it was inside the nucleus? In what form is this energy?

26. Which ions are least deflected in a mass spectrometer?

27. What is the basic difference between the graphs of Figure 34.15 and Figure 34.16?

28. In which atomic nucleus do nucleons have the greatest mass? In which nucleus do they have the least mass?

29. What becomes of the missing mass when a uranium nucleus undergoes fission?

30. If the graph in Figure 34.16 is seen as an energy valley, what can be said about the energy of nuclear transformations that progress toward iron?

Nuclear Fusion

31. When two hydrogen nuclei are fused, is the mass of the product nucleus more or less than the sum of the masses of the two hydrogen nuclei?

32. For helium to release energy, should it be fissioned or fused?

Controlling Fusion

33. What kind of containers are used to contain multimillion-degree plasmas?

34. In what form is energy initially released in nuclear fusion?

Project

Write a letter to Grandpa discussing nuclear power. Cite both the ups and downs of it, and explain how the comparison affects your personal view of nuclear power. Also explain to him how nuclear fission and nuclear fusion differ.

Exercises

1. Why doesn't uranium ore spontaneously undergo a chain reaction?

2. Do today's nuclear power plants use fission, fusion, or both?

3. Some heavy nuclei, containing even more protons than the uranium nucleus, undergo "spontaneous fission," splitting apart without absorbing a neutron. Why is spontaneous fission observed only in the heaviest nuclei?

4. Why will nuclear fission probably not be used directly for powering automobiles? How could it be used indirectly to power automobiles?

5. Why does a neutron make a better nuclear bullet than a proton or an electron?

6. Why will the escape of neutrons be proportionally less in a large piece of fissionable material than in a smaller piece?

7. Which shape is likely to need more material for a critical mass, a cube or a sphere? Explain.

8. A 56-kg sphere of U-235 constitutes a critical mass. If the sphere were flattened into a pancake shape, would it still be critical? Explain.

9. Does the average distance that a neutron travels through fissionable material before escaping increase or decrease when two pieces of fissionable material are assembled into one piece? Does this assembly increase or decrease the probability of an explosion?

10. U-235 releases an average of 2.5 neutrons per fission, while Pu-239 releases an average of 2.7 neutrons per fission. Which of these elements might you therefore expect to have the smaller critical mass?

11. Uranium and thorium occur abundantly in various ore deposits. However, plutonium could occur only in exceedingly tiny amounts in such deposits. What is your explanation?

12. Why, after a uranium fuel rod reaches the end of its fuel cycle (typically 3 years), does most of its energy come from the fissioning of plutonium?

13. If a nucleus of $^{232}_{90}\text{Th}$ absorbs a neutron and the resulting nucleus undergoes two successive beta decays (emitting electrons), what nucleus results?

14. The water that passes through a reactor core does not pass into the turbine. Instead, heat is transferred to a separate water cycle that is entirely outside the reactor. Why is this done?

15. Why is carbon better than lead as a moderator in nuclear reactors?

16. Is the mass of an atomic nucleus greater or less than the sum of the masses of the nucleons composing it? Why don't the nucleon masses add up to the total nuclear mass?

17. The energy release of nuclear fission is tied to the fact that the heaviest nuclei have about 0.1% more mass per nucleon than nuclei near the middle of the periodic table of the elements. What would be the effect on energy release if the 0.1% figure were instead 1%?

18. In what way are fission and fusion reactions similar? What are the main differences in these reactions?

19. How is chemical burning similar to nuclear fusion?

20. To predict the approximate energy release of either a fission reaction or a fusion reaction, explain how a physicist makes use of the curve of Figure 34.16 or a table of nuclear masses and the equation $E = mc^2$.

21. What nuclei will result if a U-235 nucleus, after absorbing a neutron and becoming U-236, splits into two identical fragments?

22. If U-238 splits into two even pieces, and each piece emits an alpha particle, what elements are produced?

23. Fermi's original reactor was just "barely" critical because the natural uranium that he used contained less than 1% of the fissionable isotope U-235 (half-life 713 million years). What if, in 1942, the Earth had been 9 billion years old instead of 4.5 billion years old? Would Fermi have been able to make a reactor go critical with natural uranium?

24. The energy of fission is the kinetic energy of its products. What becomes of this energy in a commercial power reactor?

25. U-235 has a half-life of about 700 million years. What does this say about the likelihood of fission power on the Earth 1 billion years from now?

26. Heavy nuclei can be made to fuse—for instance, by firing one gold nucleus at another one. Does such a process yield energy or cost energy? Explain.

27. Light nuclei can be split. For example, a deuteron, which is a proton–neutron combination, can split into a separate proton and separate neutron. Does such a process yield energy or cost energy? Explain.

28. Which process would release energy from gold, fission or fusion? Which would release energy from carbon? From iron?

29. If uranium were to split into three segments of equal size instead of two, would more energy or less energy be released? Defend your answer in terms of Figure 34.16.

30. Mixing copper and zinc atoms produces the alloy brass. What would be produced with the fusion of copper and zinc nuclei?

31. Oxygen and hydrogen atoms combine to form water. If the nuclei in a water molecule were fused, what element would be produced?

32. If a pair of carbon atoms were fused, and the product were to emit a beta particle, what element would be produced?

33. Suppose the curve of Figure 34.16 for mass per nucleon versus atomic number had the shape of the curve shown in Figure 34.15. Then would nuclear fission reactions produce energy? Would nuclear fusion reactions produce energy? Defend your answers.

34. The "hydrogen magnets" in Figure 34.20 weigh more when apart than when combined. What would be the basic difference if the fictitious example instead consisted of "nuclear magnets" half as heavy as uranium?

35. In a nuclear fission reaction, which has more mass, the initial uranium or its products?

36. In a nuclear fusion reaction, which has more mass, the initial hydrogen isotopes or the fusion products?

37. Which produces more energy, the fissioning of a single uranium nucleus or the fusing of a pair of deuterium nuclei? The fissioning of a gram of uranium or the fusing of a gram of deuterium? (Why do your answers differ?)

38. Why is there, unlike fission fuel, no limit to the amount of fusion fuel that can be safely stored in one locality?

39. If a fusion reaction produces no appreciable radioactive isotopes, why does a hydrogen bomb produce significant radioactive fallout?

40. List at least two major potential advantages of power production by fusion rather than by fission.

41. Sustained nuclear fusion has yet to be achieved and remains a hope for abundant future energy. Yet the energy that has always sustained us has been the energy of nuclear fusion. Explain.

42. Explain how radioactive decay has always warmed the Earth from the inside and how nuclear fusion has always warmed the Earth from the outside.

43. What effect on the mining industry can you foresee in the disposal of urban waste by means of a fusion torch coupled with a mass spectrometer?

44. The world has never been the same since the discovery of electromagnetic induction and its applications to electric motors and generators. Speculate and list some of the worldwide changes that are likely to follow the advent of successful fusion reactors.

45. Discuss, and make a comparison of, pollution by conventional fossil-fuel power plants and nuclear-fission power plants. Consider thermal pollution, chemical pollution, and radioactive pollution.

46. Ordinary hydrogen is sometimes called a perfect fuel, both because of its almost unlimited supply on Earth and because, when it burns, harmless water is the product of the combustion. So why don't we abandon fission energy and fusion energy, not to mention fossil-fuel energy, and just use hydrogen?

47. In reference to the fusion torch, if a star-hot flame is positioned between a pair of large, electrically charged plates, one positive and the other negative, and materials dumped into the flame are dissociated into bare nuclei and electrons, in which direction will the nuclei move? In which direction will the electrons move?

48. Suppose that the negative plate of a fusion torch has a hole in it so that atomic nuclei that move toward it and pass through it constitute a beam. Further suppose that the beam is then directed between the pole pieces of a powerful electromagnet. Will the beam of charged nuclei continue in a straight line or will the beam be deflected?

49. Supposing that the beam in the preceding exercise is deflected, will all nuclei, both light and heavy, be deflected by the same amount? How is this device similar to a mass spectrometer?

50. In a bucketful of seawater are minute amounts of gold. You can't separate them from the water with an ordinary magnet, but, if the bucket were dumped into the fusion torch speculated about in the chapter, a magnet could indeed separate them. If hydrogen atoms were collected in bin #1 and uranium atoms were collected in bin #92, what would be the bin number for gold?

Problems

1. The kiloton, which is used to measure the energy released in an atomic explosion, is equal to 4.2×10^{12} J (approximately the energy released in the explosion of 1000 tons of TNT). Recalling that 1 kilocalorie of energy raises the temperature of 1 kg of water by 1°C and that 4,184 joules is equal to 1 kilocalorie, calculate how many kilograms of water can be heated through 50°C by a 20-kiloton atomic bomb.

2. The isotope of lithium used in a hydrogen bomb is Li-6, whose nucleus contains 3 protons and 3 neutrons. When a Li-6 nucleus absorbs a neutron, a nucleus of the heaviest hydrogen isotope, tritium, is produced. What is the other product of this reaction? Which of these two products fuels the explosive reaction?

3. An important fusion reaction in both hydrogen bombs and controlled-fusion reactors is the "DT reaction," in which a deuteron and a triton (nuclei of heavy hydrogen isotopes) combine to form an alpha particle and a neutron with the release of much energy. Use momentum conservation to explain why the neutron resulting from this reaction receives about 80% of the energy, while the alpha particle gets only about 20%.