Thus,

$$0.92 = e^{-\lambda t}. \tag{22.59}$$

Taking the natural logarithm of both sides of the equation yields

$$\ln\ 0.92 = -\lambda t \tag{22.60}$$

so that

$$-0.0834 = -\lambda t. \tag{22.61}$$

Rearranging to isolate t gives

$$t = \frac{0.0834}{\lambda}. \tag{22.62}$$

Now, the equation $\lambda = \frac{0.693}{t_{1/2}}$ can be used to find λ for ^{14}C. Solving for λ and substituting the known half-life gives

$$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{5{,}730\text{ years}} = 1.21 \times 10^{-4}\text{y}^{-1}. \tag{22.63}$$

We enter that value into the previous equation to find t.

$$t = \frac{0.0834}{1.21 \times 10^{-4}} = 690\text{ years}. \tag{22.64}$$

Discussion

This dates the material in the shroud to 1988–690 = 1300. Our calculation is only accurate to two digits, so that the year is rounded to 1300. The values obtained at the three independent laboratories gave a weighted average date of 1320 ± 60. That uncertainty is typical of carbon-14 dating and is due to the small amount of 14 C in living tissues, the amount of material available, and experimental uncertainties (reduced by having three independent measurements). That said, is it notable that the carbon-14 date is consistent with the first record of the shroud's existence and certainly inconsistent with the period in which Jesus lived.

There are other noncarbon forms of radioactive dating. Rocks, for example, can sometimes be dated based on the decay of ^{238}U. The decay series for ^{238}U ends with ^{206}Pb, so the ratio of those nuclides in a rock can be used an indication of how long it has been since the rock solidified. Knowledge of the ^{238}U half-life has shown, for example, that the oldest rocks on Earth solidified about 3.5×10^9 years ago.

Virtual Physics

Radioactive Dating Game

Click to view content (https://www.openstax.org/l/02radioactive_dating_game)

Learn about different types of radiometric dating, such as carbon dating. Understand how decay and half-life work to enable radiometric dating to work. Play a game that tests your ability to match the percentage of the dating element that remains to the age of the object.

22.4 Nuclear Fission and Fusion

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain nuclear fission
- Explain nuclear fusion
- Describe how the processes of fission and fusion work in nuclear weapons and in generating nuclear power

Section Key Terms

chain reaction	critical mass	liquid drop model
nuclear fission	nuclear fusion	proton-proton cycle

The previous section dealt with naturally occurring nuclear decay. Without human intervention, some nuclei will change composition in order to achieve a stable equilibrium. This section delves into a less-natural process. Knowing that energy can be emitted in various forms of nuclear change, is it possible to create a nuclear reaction through our own intervention? The answer to this question is yes. Through two distinct methods, humankind has discovered multiple ways of manipulating the atom to release its internal energy.

Nuclear Fission

In simplest terms, **nuclear fission** is the splitting of an atomic bond. Given that it requires great energy separate two nucleons, it may come as a surprise to learn that splitting a nucleus can *release* vast potential energy. And although it is true that huge amounts of energy can be released, considerable effort is needed to do so in practice.

An unstable atom will naturally decay, but it may take millions of years to do so. As a result, a physical catalyst is necessary to produce useful energy through nuclear fission. The catalyst typically occurs in the form of a free neutron, projected directly at the nucleus of a high-mass atom.

As shown in Figure 22.26, a neutron strike can cause the nucleus to elongate, much like a drop of liquid water. This is why the model is known as the **liquid drop model**. As the nucleus elongates, nucleons are no longer so tightly packed, and the repulsive electromagnetic force can overcome the short-range strong nuclear force. The imbalance of forces can result in the two ends of the drop flying apart, with some of the nuclear binding energy released to the surroundings.

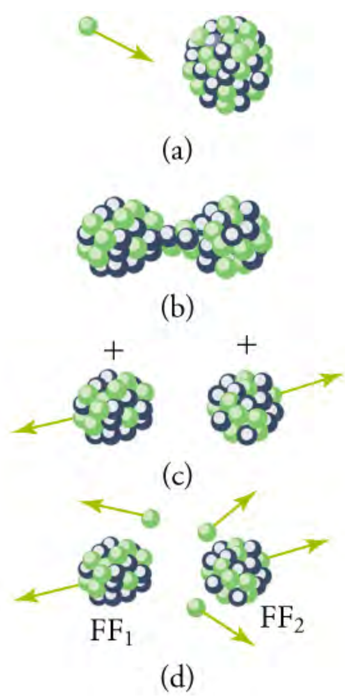

Figure 22.26 Neutron-induced fission is shown. First, energy is put into a large nucleus when it absorbs a neutron. Acting like a struck liquid drop, the nucleus deforms and begins to narrow in the middle. Since fewer nucleons are in contact, the repulsive Coulomb force is able to break the nucleus into two parts with some neutrons also flying away.

As you can imagine, the consequences of the nuclei splitting are substantial. When a nucleus is split, it is not only energy that is released, but a small number of neutrons as well. Those neutrons have the potential to cause further fission in other nuclei, especially if they are directed back toward the other nuclei by a dense shield or neutron reflector (see part (d) of Figure 22.26).

However, not every neutron produced by fission induces further fission. Some neutrons escape the fissionable material, while others interact with a nucleus without making it split. We can enhance the number of fissions produced by neutrons by having a large amount of fissionable material as well as a neutron reflector. The minimum amount necessary for self-sustained fission of a given nuclide is called its **critical mass**. Some nuclides, such as ^{239}Pu, produce more neutrons per fission than others, such as ^{235}U. Additionally, some nuclides are easier to make fission than others. In particular, ^{235}U and ^{239}Pu are easier to fission than the much more abundant ^{238}U. Both factors affect critical mass, which is smallest for ^{239}Pu. The self-sustained fission of nuclei is commonly referred to as a **chain reaction**, as shown in Figure 22.27.

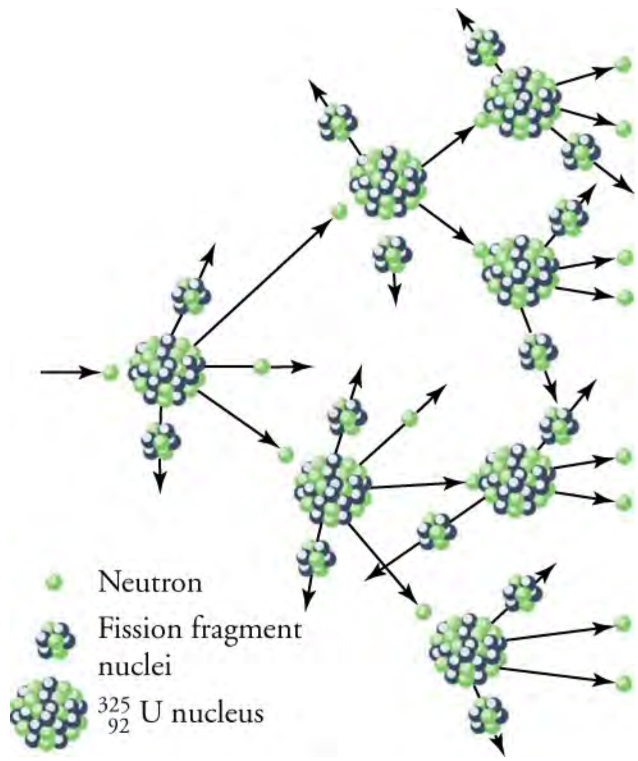

Figure 22.27 A chain reaction can produce self-sustained fission if each fission produces enough neutrons to induce at least one more fission. This depends on several factors, including how many neutrons are produced in an average fission and how easy it is to make a particular type of nuclide fission.

A chain reaction can have runaway results. If each atomic split results in two nuclei producing a new fission, the number of nuclear reactions will increase exponentially. One fission will produce two atoms, the next round of fission will create four atoms, the third round eight atoms, and so on. Of course, each time fission occurs, more energy will be emitted, further increasing the power of the atomic reaction. And that is just if two neutrons create fission reactions each round. Perhaps you can now see why so many people consider atomic energy to be an exciting energy source!

To make a self-sustained nuclear fission reactor with ^{235}U, it is necessary to slow down the neutrons. Water is very effective at this, since neutrons collide with protons in water molecules and lose energy. Figure 22.28 shows a schematic of a reactor design called the *pressurized water reactor*.

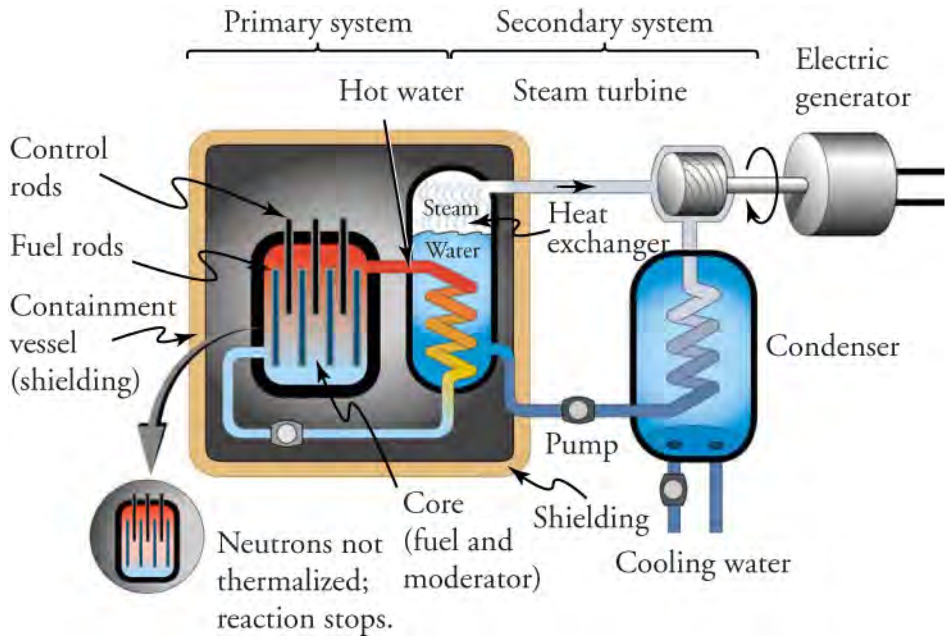

Figure 22.28 A pressurized water reactor is cleverly designed to control the fission of large amounts of ^{235}U, while using the heat produced in the fission reaction to create steam for generating electrical energy. Control rods adjust neutron flux so that it is self-sustaining. In case the reactor overheats and boils the water away, the chain reaction terminates, because water is needed to slow down the neutrons. This inherent safety feature can be overwhelmed in extreme circumstances.

Control rods containing nuclides that very strongly absorb neutrons are used to adjust neutron flux. To produce large amounts of power, reactors contain hundreds to thousands of critical masses, and the chain reaction easily becomes self-sustaining. Neutron flux must be carefully regulated to avoid an out-of-control exponential increase in the rate of fission.

Control rods help prevent overheating, perhaps even a meltdown or explosive disassembly. The water that is used to slow down neutrons, necessary to get them to induce fission in ^{235}U, and achieve criticality, provides a negative feedback for temperature increase. In case the reactor overheats and boils the water to steam or is breached, the absence of water kills the chain reaction. Considerable heat, however, can still be generated by the reactor's radioactive fission products. Other safety features, thus, need to be incorporated in the event of a loss of coolant accident, including auxiliary cooling water and pumps.

Energies in Nuclear Fission

The following are two interesting facts to consider:

- The average fission reaction produces 200 MeV of energy.
- If you were to measure the mass of the products of a nuclear reaction, you would find that their mass was slightly less than the mass of the original nucleus.

How are those things possible? Doesn't the fission reaction's production of energy violate the conservation of energy? Furthermore, doesn't the loss in mass in the reaction violate the conservation of mass? Those are important questions, and they can both be answered with one of the most famous equations in scientific history.

$$E = mc^2 \tag{22.65}$$

Recall that, according to Einstein's theory, energy and mass are essentially the same thing. In the case of fission, the mass of the products is less than that of the reactants because the missing mass appears in the form of the energy released in the reaction, with a constant value of c^2 Joules of energy converted for each kilogram of material. The value of c^2 is substantial—from Einstein's equation, the amount of energy in just 1 gram of mass would be enough to support the average U.S. citizen for more than 270 years! The example below will show you how a mass-energy transformation of this type takes place.

WORKED EXAMPLE

Calculating Energy from a Kilogram of Fissionable Fuel

Calculate the amount of energy produced by the fission of 1.00 kg of $^{235}\mathrm{U}$, given the average fission reaction of

$$^{235}\mathrm{U}\text{ produces }200\text{ MeV}. \tag{22.66}$$

Strategy

The total energy produced is the number of $^{235}\mathrm{U}$ atoms times the given energy per $^{235}\mathrm{U}$ fission. We should therefore find the number of $^{235}\mathrm{U}$ atoms in 1.00 kg.

Solution

The number of $^{235}\mathrm{U}$ atoms in 1.00 kg is Avogadro's number times the number of moles. One mole of $^{235}\mathrm{U}$ has a mass of 235.04 g; thus, there are $(1{,}000\text{ g})\,/\,(235.04.00\text{ g/mol}) = 4.25\text{ mol}$. The number of $^{235}\mathrm{U}$ atoms is therefore

$$(4.25\text{ mol})\left(6.02\ \times\ 10^{23}\,\mathrm{U/mol}\right) = 2.56\ \times\ 10^{24}\,\mathrm{atomsof235U}.$$

So the total energy released is

$$E = \left(2.56\ \times\ 10^{24}\right)\left(\frac{200\text{ MeV}}{^{235}\mathrm{U}}\right)\left(\frac{1.60\ \times\ 10^{-13}\,\mathrm{J}}{\mathrm{MeV}}\right) = 8.21 \times 10^{13}\,\mathrm{J}. \tag{22.67}$$

Discussion

The result is another impressively large amount of energy, equivalent to about 14,000 barrels of crude oil or 600,000 gallons of gasoline. But, it is only one fourth the energy produced by the fusion of a kilogram of a mixture of deuterium and tritium. Even though each fission reaction yields about ten times the energy of a fusion reaction, the energy per kilogram of fission fuel is less, because there are far fewer moles per kilogram of the heavy nuclides. Fission fuel is also much scarcer than fusion fuel, and less than 1 percent of uranium (the 235 U) is readily usable.

Virtual Physics

Nuclear Fission

Click to view content (https://www.openstax.org/l/16fission)

Start a chain reaction, or introduce nonradioactive isotopes to prevent one. Use the applet to control energy production in a nuclear reactor!

Nuclear Fusion

Nuclear fusion is defined as the combining, or fusing, of two nuclei and, the combining of nuclei also results in an emission of energy. For many, the concept is counterintuitive. After all, if energy is released when a nucleus is split, how can it also be released when nucleons are combined together? The difference between fission and fusion, which results from the size of the nuclei involved, will be addressed next.

Remember that the structure of a nucleus is based on the interplay of the compressive nuclear strong force and the repulsive electromagnetic force. For nuclei that are less massive than iron, the nuclear force is actually stronger than that of the Coulomb force. As a result, when a low-mass nucleus absorbs nucleons, the added neutrons and protons bind the nucleus more tightly. The increased nuclear strong force does work on the nucleus, and energy is released.

Once the size of the created nucleus exceeds that of iron, the short-ranging nuclear force does not have the ability to bind a nucleus more tightly, and the emission of energy ceases. In fact, for fusion to occur for elements of greater mass than iron, energy must be added to the system! Figure 22.29 shows an energy-mass curve commonly used to describe nuclear reactions. Notice the location of iron (Fe) on the graph. All low-mass nuclei to the left of iron release energy through fusion, while all high-mass particles to the right of iron produce energy through fission.

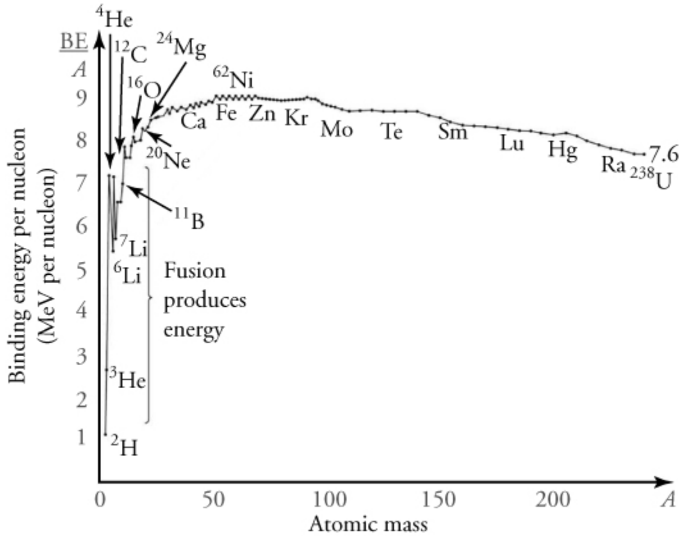

Figure 22.29 Fusion of light nuclei to form medium-mass nuclei converts mass to energy, because binding energy per nucleon (BE/A) is greater for the product nuclei. The larger BE/A is, the less mass per nucleon, and so mass is converted to energy and released in such fusion reactions.

TIPS FOR SUCCESS

Just as it is not possible for the elements to the left of iron in the figure to naturally fission, it is not possible for elements to the right of iron to naturally undergo fusion, as that process would require the addition of energy to occur. Furthermore, notice that elements commonly discussed in fission and fusion are elements that can provide the greatest change in binding energy, such as uranium and hydrogen.

Iron's location on the energy-mass curve is important, and explains a number of its characteristics, including its role as an elemental endpoint in fusion reactions in stars.

The major obstruction to fusion is the Coulomb repulsion force between nuclei. Since the attractive nuclear force that can fuse nuclei together is short ranged, the repulsion of like positive charges must be overcome in order to get nuclei close enough to induce fusion. Figure 22.30 shows an approximate graph of the potential energy between two nuclei as a function of the distance between their centers. The graph resembles a hill with a well in its center. A ball rolled to the left must have enough kinetic energy to get over the hump before it falls into the deeper well with a net gain in energy. So it is with fusion. If the nuclei are given enough kinetic energy to overcome the electric potential energy due to repulsion, then they can combine, release energy, and fall into a deep well. One way to accomplish that end is to heat fusion fuel to high temperatures so that the kinetic energy of thermal motion is sufficient to get the nuclei together.

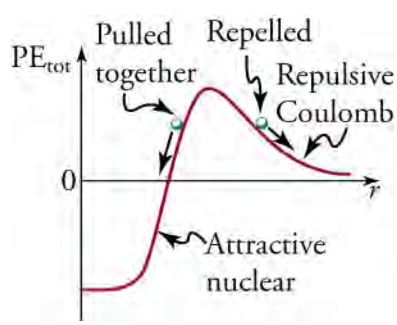

Figure 22.30 Potential energy between two light nuclei graphed as a function of distance between them. If the nuclei have enough kinetic energy to get over the Coulomb repulsion hump, they combine, release energy, and drop into a deep attractive well.

You might think that, in our Sun, nuclei are constantly coming into contact and fusing. However, this is only partially true. Only at the Sun's core are the particles close enough and the temperature high enough for fusion to occur!

In the series of reactions below, the Sun produces energy by fusing protons, or hydrogen nuclei ($^1\mathrm{H}$, by far the Sun's most abundant nuclide) into helium nuclei ${}^4\text{He}$. The principal sequence of fusion reactions forms what is called the **proton-proton cycle**

$$\begin{array}{ll} {}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + e^+ + v_e & (0.42\ \text{MeV}) \\ {}^1\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + \gamma & (5.49\ \text{MeV}) \\ {}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H} & (12.86\ \text{MeV}), \end{array} \tag{22.68}$$

where e^+ stands for a positron and v_e is an electron neutrino. The energy in parentheses is *released* by the reaction. Note that the first two reactions must occur twice for the third to be possible, so the cycle consumes six protons (${}^1\text{H}$) but gives back two. Furthermore, the two positrons produced will find two electrons and annihilate to form four more γ rays, for a total of six. The overall cycle is thus

$$2e - +4^1\text{H} \rightarrow 4\ \text{He} + 2v_e + 6\gamma \quad (26.7\ \text{MeV}),$$

where the 26.7 MeV includes the annihilation energy of the positrons and electrons and is distributed among all the reaction products. The solar interior is dense, and the reactions occur deep in the Sun where temperatures are highest. It takes about 32,000 years for the energy to diffuse to the surface and radiate away. However, the neutrinos can carry their energy out of the Sun in less than two seconds, because they interact so weakly with other matter. Negative feedback in the Sun acts as a thermostat to regulate the overall energy output. For instance, if the interior of the Sun becomes hotter than normal, the reaction rate increases, producing energy that expands the interior. The expansion cools it and lowers the reaction rate. Conversely, if the interior becomes too cool, it contracts, increasing the temperature and therefore the reaction rate (see Figure 22.31). Stars like the Sun are stable for billions of years, until a significant fraction of their hydrogen has been depleted.

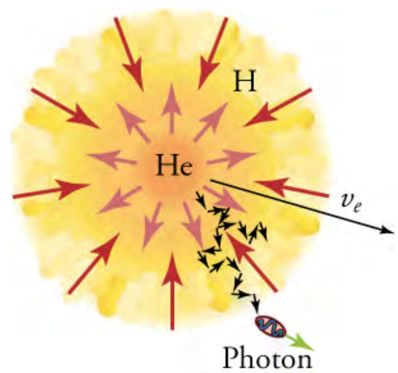

Figure 22.31 Nuclear fusion in the Sun converts hydrogen nuclei into helium; fusion occurs primarily at the boundary of the helium core, where the temperature is highest and sufficient hydrogen remains. Energy released diffuses slowly to the surface, with the exception of neutrinos, which escape immediately. Energy production remains stable because of negative-feedback effects.

Nuclear Weapons and Nuclear Power

The world was in political turmoil when fission was discovered in 1938. Compounding the troubles, the possibility of a self-sustained chain reaction was immediately recognized by leading scientists the world over. The enormous energy known to be in nuclei, but considered inaccessible, now seemed to be available on a large scale.

Within months after the announcement of the discovery of fission, Adolf Hitler banned the export of uranium from newly occupied Czechoslovakia. It seemed that the possible military value of uranium had been recognized in Nazi Germany, and that a serious effort to build a nuclear bomb had begun.

Alarmed scientists, many of whom fled Nazi Germany, decided to take action. None was more famous or revered than Einstein. It was felt that his help was needed to get the American government to make a serious effort at constructing nuclear weapons as a matter of survival. Leo Szilard, a Hungarian physicist who had emigrated to America, took a draft of a letter to Einstein, who, although a pacifist, signed the final version. The letter was for President Franklin Roosevelt, warning of the German potential to build extremely powerful bombs of a new type. It was sent in August of 1939, just before the German invasion of Poland that marked the start of World War II.

It was not until December 6, 1941, the day before the Japanese attack on Pearl Harbor, that the United States made a massive commitment to building a nuclear bomb. The top secret Manhattan Project was a crash program aimed at beating the Germans.

It was carried out in remote locations, such as Los Alamos, New Mexico, whenever possible, and eventually came to cost billions of dollars and employ the efforts of more than 100,000 people. J. Robert Oppenheimer (1904–1967), a talented physicist, was chosen to head the project. The first major step was made by Enrico Fermi and his group in December 1942, when they completed the first self-sustaining nuclear reactor. This first *atomic pile*, built in a squash court at the University of Chicago, proved that a fission chain reaction was possible.

Plutonium was recognized as easier to fission with neutrons and, hence, a superior fission material very early in the Manhattan Project. Plutonium availability was uncertain, and so a uranium bomb was developed simultaneously. Figure 22.32 shows a gun-type bomb, which takes two subcritical uranium masses and shoots them together. To get an appreciable yield, the critical mass must be held together by the explosive charges inside the cannon barrel for a few microseconds. Since the buildup of the uranium chain reaction is relatively slow, the device to bring the critical mass together can be relatively simple. Owing to the fact that the rate of spontaneous fission is low, a neutron source is at the center the assembled critical mass.

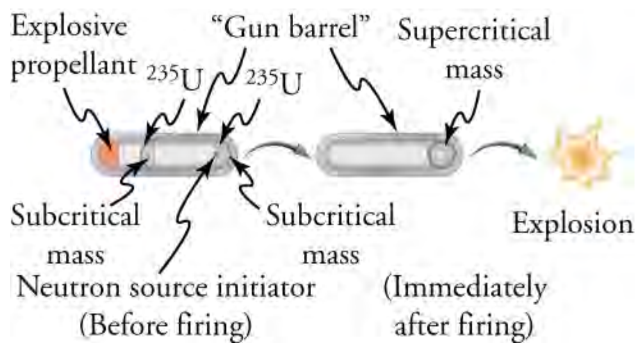

Figure 22.32 A gun-type fission bomb for ^{235}U utilizes two subcritical masses forced together by explosive charges inside a cannon barrel. The energy yield depends on the amount of uranium and the time it can be held together before it disassembles itself.

Plutonium's special properties necessitated a more sophisticated critical mass assembly, shown schematically in Figure 22.33. A spherical mass of plutonium is surrounded by shaped charges (high explosives that focus their blast) that implode the plutonium, crushing it into a smaller volume to form a critical mass. The implosion technique is faster and more effective, because it compresses three-dimensionally rather than one-dimensionally as in the gun-type bomb. Again, a neutron source is included to initiate the chain reaction.

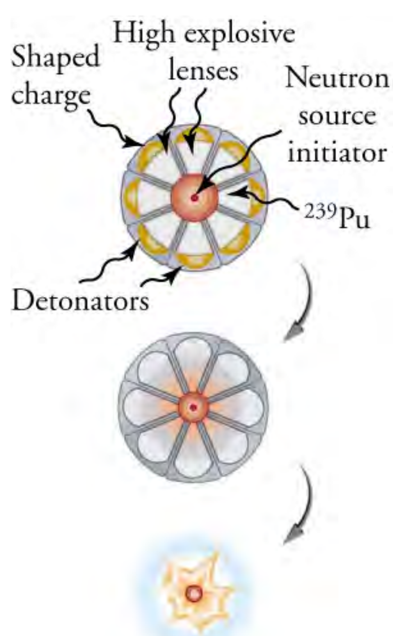

Figure 22.33 An implosion created by high explosives compresses a sphere of ^{239}Pu into a critical mass. The superior fissionability of plutonium has made it the preferred bomb material.

Owing to its complexity, the plutonium bomb needed to be tested before there could be any attempt to use it. On July 16, 1945, the test named Trinity was conducted in the isolated Alamogordo Desert in New Mexico, about 200 miles south of Los Alamos (see Figure 22.34). A new age had begun. The yield of the Trinity device was about 10 kilotons (kT), the equivalent of 5,000 of the largest conventional bombs.

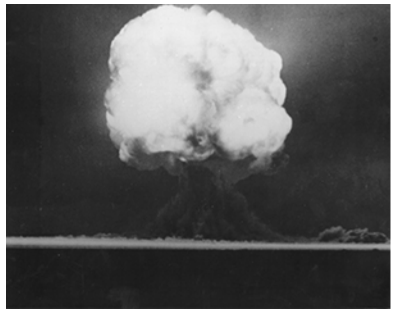

Figure 22.34 Trinity test (1945), the first nuclear bomb (credit: U.S. Department of Energy)

Although Germany surrendered on May 7, 1945, Japan had been steadfastly refusing to surrender for many months, resulting large numbers of civilian and military casualties. Invasion plans by the Allies estimated a million casualties of their own and untold losses of Japanese lives. The bomb was viewed as a way to end the war. The first bomb used was a gun-type uranium bomb dropped on Hiroshima on August 6 by the United States. Its yield of about 15 kT destroyed the city and killed an estimated 80,000 people, with 100,000 more being seriously injured. The second bomb was an implosion-type plutonium bomb dropped on Nagasaki only three days later. Its 20-kT yield killed at least 50,000 people, something less than Hiroshima because of the hilly terrain and the fact that it was a few kilometers off target. The Japanese were told that one bomb a week would be dropped until they surrendered unconditionally, which they did on August 14. In actuality, the United States had only enough plutonium for one more bomb, as yet unassembled.

Knowing that fusion produces several times more energy per kilogram of fuel than fission, some scientists pursued the idea of constructing a fusion bomb. The first such bomb was detonated by the United States several years after the first fission bombs, on October 31, 1952, at Eniwetok Atoll in the Pacific Ocean. It had a yield of 10 megatons (MT), about 670 times that of the fission bomb that destroyed Hiroshima. The Soviet Union followed with a fusion device of its own in August 1953, and a weapons race, beyond the aim of this text to discuss, continued until the end of the Cold War.

Figure 22.35 shows a simple diagram of how a thermonuclear bomb is constructed. A fission bomb is exploded next to fusion fuel in the solid form of lithium deuteride. Before the shock wave blows it apart, γ rays heat and compress the fuel, and neutrons create tritium through the reaction $n + {}^{6}\text{Li} \rightarrow {}^{3}\text{H} + {}^{4}\text{He}$. Additional fusion and fission fuels are enclosed in a dense shell of ${}^{238}\text{U}$. At the same time that the uranium shell reflects the neutrons back into the fuel to enhance its fusion, the fast-moving neutrons cause the plentiful and inexpensive ${}^{238}\text{U}$ to fission, part of what allows thermonuclear bombs to be so large.

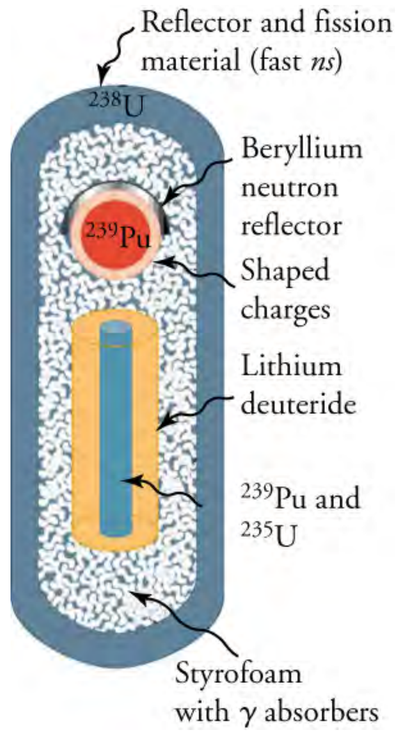

Figure 22.35 This schematic of a fusion bomb (H-bomb) gives some idea of how the ^{239}Pu fission trigger is used to ignite fusion fuel. Neutrons and γ rays transmit energy to the fusion fuel, create tritium from deuterium, and heat and compress the fusion fuel. The outer shell of ^{238}U serves to reflect some neutrons back into the fuel, causing more fusion, and it boosts the energy output by fissioning itself when neutron energies become high enough.

Of course, not all applications of nuclear physics are as destructive as the weapons described above. Hundreds of nuclear fission power plants around the world attest to the fact that controlled fission is both practical and economical. Given growing concerns over global warming, nuclear power is often seen as a viable alternative to energy derived from fossil fuels.

BOUNDLESS PHYSICS

Fusion Reactors

For decades, fusion reactors have been deemed the *energy of the future*. A safer, cleaner, and more abundant potential source of energy than its fission counterpart, images of the fusion reactor have been conjured up each time the need for a renewable, environmentally friendly resource is discussed. Now, after more than half a century of speculating, some scientists believe that fusion reactors are nearly here.

In creating energy by combining atomic nuclei, the fusion reaction holds many advantages over fission. First, fusion reactions are more efficient, releasing 3 to 4 times more energy than fission per gram of fuel. Furthermore, unlike fission reactions that require *heavy* elements like uranium that are difficult to obtain, fusion requires *light* elements that are abundant in nature. The greatest advantage of the fusion reaction, however, is in its ability to be controlled. While traditional nuclear reactors create worries about meltdowns and radioactive waste, neither is a substantial concern with the fusion reaction. Consider that fusion reactions require a large amount of energy to overcome the repulsive Coulomb force and that the byproducts of a fusion reaction are largely limited to helium nuclei.

In order for fusion to occur, hydrogen isotopes of deuterium and tritium must be acquired. While deuterium can easily be gathered from ocean water, tritium is slightly more difficult to come by, though it can be manufactured from Earth's abundant lithium. Once acquired, the hydrogen isotopes are injected into an empty vessel and subjected to temperature and pressure great enough to mimic the conditions at the core of our Sun. Using carefully controlled high-frequency radio waves, the hydrogen isotopes are broken into plasma and further controlled through an electromagnetic field. As the electromagnetic field continues to exert pressure on the hydrogen plasma, enough energy is supplied to cause the hydrogen plasma to fuse into helium.

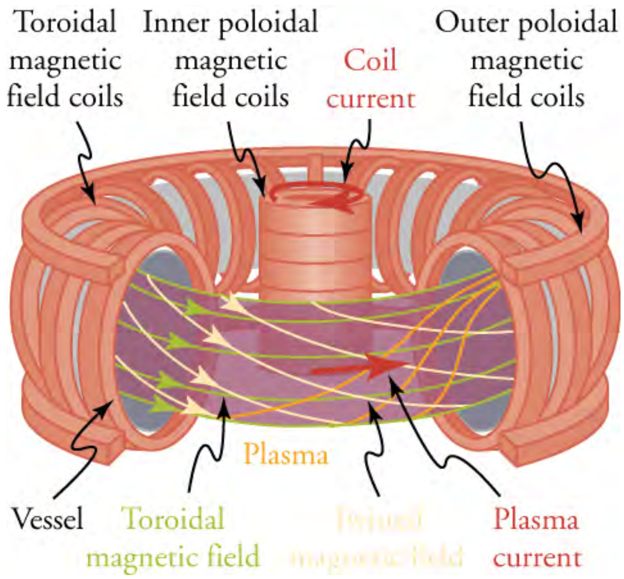

Figure 22.36 Tokamak confinement of nuclear fusion plasma. The magnetic field lines are used to confine the high-temperature plasma (purple). Research is currently being done to increase the efficiency of the tokamak confinement model.

Once the plasma fuses, high-velocity neutrons are ejected from the newly formed helium atoms. Those high velocity neutrons, carrying the excess energy stored within bonds of the original hydrogen, are able to travel unaffected by the applied magnetic field. In doing so, they strike a barrier around the nuclear reactor, transforming their excess energy to heat. The heat is then harvested to make steam that drives turbines. Hydrogen's tremendous power is now usable!

The historical concern with nuclear fusion reactors is that the energy required to control the electromagnetic field is greater than the energy harvested from the hydrogen atoms. However, recent research by both Lockheed Martin engineers and scientists at the Lawrence Livermore National Laboratory has yielded exciting theoretical improvements in efficiency. At the time of this writing, a test facility called ITER (International Thermonuclear Experimental Reactor) is being constructed in southern France. A joint venture of the European Union, the United States, Japan, Russia, China, South Korea, and India, ITER is designed for further study into the future of nuclear fusion energy production.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe how nuclear imaging works (e.g., radioisotope imaging, PET)
- Describe the ionizing effects of radiation and how they can be used for medical treatment

Section Key Terms

Anger camera	rad	radiopharmaceutical	therapeutic ratio
relative biological effectiveness (RBE)	roentgen equivalent man (rem)	tagged	

Medical Applications of Nuclear Physics

Applications of nuclear physics have become an integral part of modern life. From the bone scan that detects one cancer to the radioiodine treatment that cures another, nuclear radiation has diagnostic and therapeutic effects on medicine.

Medical Imaging

A host of medical imaging techniques employ nuclear radiation. What makes nuclear radiation so useful? First, γ radiation can