SECTION D

Nuclear Energy: Benefits and Burdens

In the 1930s, a bombardment reaction involving uranium unlocked a new energy source and led to the development of both nuclear power and nuclear weapons. This event marked the start of the nuclear age. How did scientists first unleash the enormous energy of the atom, and how have nuclear engineers harnessed atomic energy for both useful and destructive purposes?

D.1 UNLEASHING NUCLEAR FORCES

Shortly before the start of World War II, German scientists Otto Hahn and Fritz Strassman bombarded uranium with neutrons in the hope of creating a more massive nucleus and, thus, a new element. Much to their surprise, they found that one reaction product was atoms of barium, with only about half the atomic mass of the original target uranium atoms.

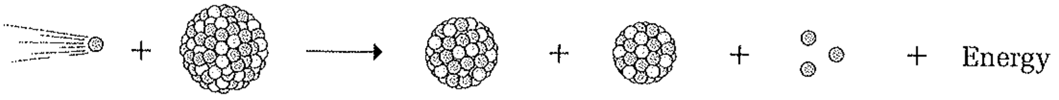
Figure 6.55 *Lise Meitner was first to suggest that nuclei might split due to neutron bombardment.*

The first to understand what had happened was the Austrian physicist Lise Meitner (Figure 6.55), then living in Sweden, who had previously worked with Strassman and Hahn. Meitner and her nephew Otto Frisch suggested that neutron bombardment had split the uranium atom into two parts of nearly equal mass. Other scientists quickly verified Meitner's explanation.

Lise Meitner fled to Sweden when Nazis assumed control of Germany and Austria.

Hahn and Strassman had actually triggered an array of related reactions. One of the reactions that produced barium is:

$$\underset{\text{Neutron}}{{}^{1}_{0}n} + \underset{\text{Uranium-235}}{{}^{235}_{92}\text{U}} \longrightarrow \underset{\text{Barium-140}}{{}^{140}_{56}\text{Ba}} + \underset{\text{Krypton-93}}{{}^{93}_{36}\text{Kr}} + \underset{\text{Neutrons}}{3\,{}^{1}_{0}n} + \text{Energy}$$



Splitting an atom into two smaller atoms is called **nuclear fission.** Scientists soon found that the uranium-235 nucleus can fission (split) into numerous pairs of smaller nuclei. The uranium usually did not split into two equal halves, but into one element accounting for about 60% of uranium's mass (such as barium) and another element equivalent to about 40% of uranium's mass (such as krypton). Here is another example of a nuclear fission reaction involving uranium-235:

$$\underset{\text{Neutron}}{{}^{1}_{0}n} + \underset{\text{Uranium-235}}{{}^{235}_{92}\mathrm{U}} \longrightarrow \underset{\text{Xenon-143}}{{}^{143}_{54}\mathrm{Xe}} + \underset{\text{Strontium-90}}{{}^{90}_{38}\mathrm{Sr}} + \underset{\text{Neutrons}}{3\,{}^{1}_{0}n} + \text{Energy}$$

Fission of U-235 produces many other pairs of nuclei, such as Te-137 and Zr-97.

The nuclear fission of heavy atoms such as uranium releases a huge quantity of energy. Gram for gram, the released energy is at least a *million* times more than the energy of any chemical reaction. This is what makes nuclear explosions so devastating and nuclear energy so powerful.

Not all nuclei are fissionable. U-235 is the only naturally occurring isotope that undergoes fission with lower-energy (thermal) neutrons. However, many synthetic nuclei (e.g., U-233, Pu-239, and Cf-262) also fission under neutron bombardment.

Why does a nuclear reaction release much more energy than does a chemical reaction? Recall what you know about chemical reactions, such as burning petroleum. Chemical reactions involve breaking chemical bonds in reactants and making new chemical bonds in products. When bonds are stronger in products than in reactants, energy is released, often as thermal energy (heat). Thus, chemical energy is converted into thermal energy. There is no overall energy loss or gain. Similarly, mass is conserved in a chemical reaction. The nucleus of each atom, and thus its identity, remains intact in all chemical reactions. As a result, the number of atoms of each element remains unchanged; the atoms simply become rearranged. Balanced chemical equations illustrate this conservation of atoms and mass.

Nuclear reactions are also based on conserving energy and mass. However, during nuclear fission, very small quantities of mass are converted into appreciable energy. Where does this energy originate?

The origin of nuclear energy lies in the force that holds protons and neutrons together in the nucleus. This force, called the **strong force,** is fundamentally different from, and a thousand times stronger than, the electrical forces that hold atoms and ions together in chemical bonds. The strong force operates over very short distances, extending only across an atom's nucleus.

The forces holding nuclear particles together in the two atomic nuclei produced during U-235 fission are stronger than those in the nucleus of the uranium atom that was split. A small loss of mass results from forming two new nuclei and is converted into a large quantity of released energy.

If one kilogram of U-235 fissions, a mass of about one gram would be converted into energy.

How much mass and energy are involved? The mass loss is very small, often less than 0.1% of the total mass of the fissioning atom. Even so, the conversion of these small quantities of mass into energy accounts for the vast power of nuclear reactions.

Albert Einstein's famous equation relates mass and energy: $E = mc^2$. This equation indicates that the energy released (E) equals the mass lost (m) multiplied by the speed of light (a very large number) squared (c^2). If one gram of matter were fully converted to energy, the energy released would equal that produced by burning 700 000 gal of high-octane gasoline!

One gram of mass loss (1×10^{-3} kg) times the speed of light (3×10^8 m/s) squared equals 9×10^{13} J of energy.

Such nuclear energy release has been harnessed by engineers to generate electricity (see Figure 6.56) and to create atomic weapons. However, the fission of one nucleus does not produce enough energy for practical use. How are fission reactions sustained to involve much larger quantities of nuclei?

Note from the equations on page 541–542 that another product of nuclear fission is the release of neutrons. These emitted neutrons can sustain the fission reaction by serving as reactants to split additional fissionable nuclei, which produce additional neutrons, which can split additional fissionable nuclei, and so on. The result is a **chain reaction** (see Figure 6.57).

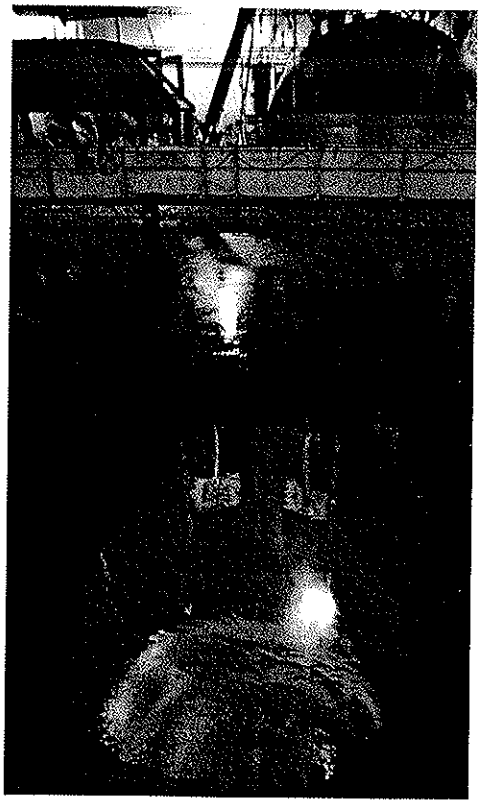


Figure 6.56 *The core of a fission reactor, based on a nuclear chain reaction, emits visible light due to ionizing radiation released.*

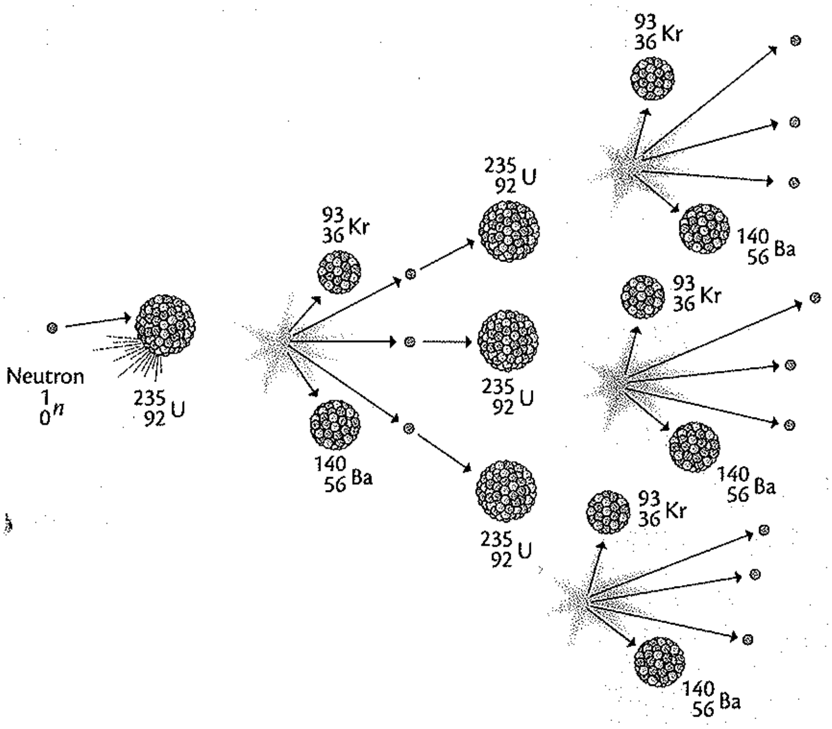


Figure 6.57 *A nuclear chain reaction. A neutron colliding with a uranium-235 nucleus initiates the reaction (left). The reaction continues and grows, as emitted neutrons encounter and split the nuclei of other fissionable atoms.*

Recall, however, that most of an atom is empty space. The probability that a neutron from a fission reaction will hit and split another fissionable nucleus depends on how much fissionable material is available. Unless a certain **critical mass** (minimum quantity) of fissionable material is present, the neutrons are not likely to encounter enough fissionable nuclei to sustain the reaction. However, if a critical mass of fissionable material is present, a chain reaction can occur, as depicted in Figure 6.57, page 543. Shortly after the first fission reactions were explained in 1939, scientists recognized that they could employ large-scale nuclear reactions in military weapons. Germany and the United States soon initiated projects to build atomic bombs during World War II. In 1945, U.S. planes dropped two such bombs onto Hiroshima and Nagasaki in Japan, which led rapidly to the end of the war.

More recently, nuclear engineers have used the energy produced by nuclear fission chain reactions to generate electricity. They carefully monitor and control the rate of fission for such uses. Nuclear power plants harness the enormous energy produced by nuclear fission reactions, while also minimizing the risks of an uncontrolled chain reaction. You will soon learn more about these design features.

Modeling Matter

D.2 THE TUMBLING DOMINO EFFECT

Chain reactions sustain nuclear fission reactions in applications such as electrical power generation and atomic weapons. In this activity, dominoes will model some aspects of a chain reaction.

Each domino that falls represents a nucleus that has been split through fission. Figure 6.58 shows one way that you could set up the dominoes so that making one domino fall causes other dominoes also to fall. Because you will model a specific fission reaction, your models will not match the one depicted in Figure 6.58.

The uranium-235 nucleus can fission into over 100 different pairs of nuclei. One way, for example, produces tellurium-137 and zirconium-97:

$$^{1}_{0}n + {}^{235}_{92}\text{U} \longrightarrow {}^{137}_{52}\text{Te} + {}^{97}_{40}\text{Zr} + 2\,^{1}_{0}n + \text{Energy}$$

1. As this equation shows, splitting *one* U-235 nucleus releases *two* neutrons.
   a. Set up all the dominoes you receive from your teacher so that each falling domino will make two more erect dominoes fall.
   b. Sketch your setup.
   c. Push over the first domino and record what happens.
   d. Explain how this models the release of neutrons during the fission of U-235 as in the equation above.
   e. What aspects of the U-235 fission reaction are not modeled by the behavior of your domino setup?