10.2: Fission and Fusion

Learning Outcomes

- Define fission.
- Describe a nuclear chain reaction and how it is applied in both a fission bomb and in a nuclear power plant.
- Define fusion.

Nuclear Fission

The most stable nuclei are of intermediate mass. To become more stable, the heaviest nuclei are capable of splitting into smaller fragments. **Nuclear fission** *is a process in which a very heavy nucleus (mass > 200) splits into smaller nuclei of intermediate mass*. Because the smaller nuclei are more stable, the fission process releases tremendous amounts of energy. Nuclear fission may occur spontaneously or may occur as a result of bombardment. When uranium-235 is hit with a slow-moving neutron, it absorbs it and temporarily becomes the very unstable uranium-236. This nucleus splits into two medium-mass nuclei while also emitting more neutrons. The mass of the products is less than the mass of the reactants, with the lost mass being converted to energy.

Nuclear Chain Reactions

Because the fission process produces more neutrons, a chain reaction can result. A **chain reaction** *is a reaction in which the material that starts the reaction is also one of the products and can start another reaction*. Illustrated below is a nuclear chain reaction for the fission of uranium-235.

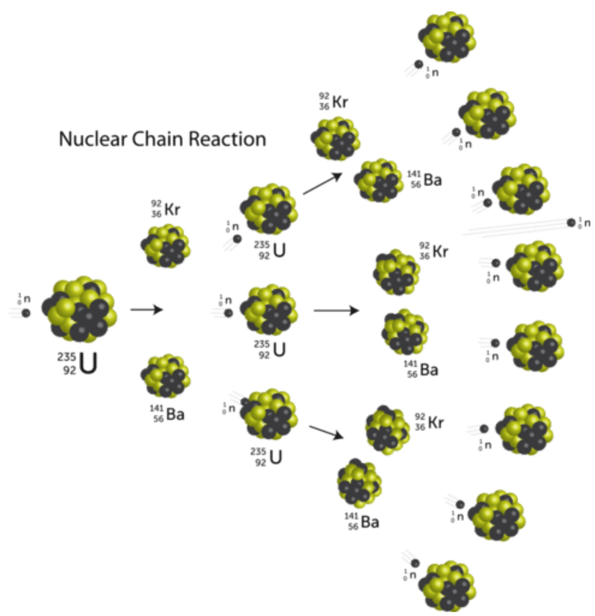

Figure 10.2.1: The nuclear chain reaction is a series of fission processes that sustains itself due to the continuous production of neutrons in each reaction.

The original uranium-235 nucleus absorbs a neutron, splits into a krypton-92 nucleus and a barium-141 nucleus, and releases three more neutrons upon splitting.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3^{1}_{0}\text{n} \tag{10.2.1}$$

Those three neutrons are then able to cause the fission of three more uranium-235 nuclei, each of which release more neutrons, and so on. The chain reaction continues until all of the uranium-235 nuclei have been split, or until the released neutrons escape the sample without striking any more nuclei. If the size of the original sample of uranium-235 is sufficiently small, too many neutrons escape without striking other nuclei, and the chain reaction quickly ceases. The **critical mass** *is the minimum amount of fissionable material needed to sustain a chain reaction*. Atomic bombs and nuclear reactors are two ways to harness the large energy released during nuclear fission.

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Atomic Bombs - Uncontrolled Nuclear Reactions

In an atomic bomb, or fission bomb, the nuclear chain reaction is designed to be uncontrolled, releasing huge amounts of energy in a short amount of time. A critical mass of fissionable plutonium is contained within the bomb, but not at a sufficient density. Conventional explosives are used to compress the plutonium, causing it to go critical and trigger a nuclear explosion.

Nuclear Power Plants- Controlled Nuclear Reactions

A nuclear power plant (see figure below) uses a controlled fission reaction to produce large amounts of heat. The heat is then used to generate electrical energy.

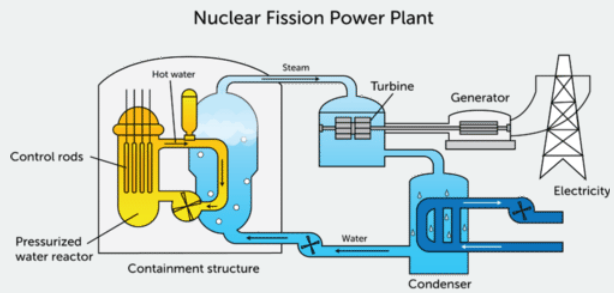

Figure 10.2.2: A nuclear reactor harnesses the energy of nuclear fission to generate electricity.

Uranium-235, the usual fissionable material in a nuclear reactor, is first packaged into fuel rods. In order to keep the chain reaction from processing unchecked, moveable control rods are placed in between the fuel rods. **Control rods** *limit the amount of available neutrons by absorbing some of them and preventing the reaction from proceeding too rapidly*. Common control rod materials include alloys with various amounts of silver, indium, cadmium, or boron. A **moderator** *is a material that slows down high-speed neutrons*. This is beneficial because slow-moving neutrons are more efficient at splitting nuclei. Water is often used as a moderator. The heat released by the fission reaction is absorbed by constantly circulating coolant water. The coolant water releases its heat to a steam generator, which turns a turbine and generates electricity. The core of the reactor is surrounded by a containment structure that absorbs radiation.

Nuclear Fusion

The lightest nuclei are also not as stable as nuclei of intermediate mass. **Nuclear fusion** *is a process in which light-mass nuclei combine to form a heavier and more stable nucleus*. Fusion produces even more energy than fission. In the sun and other stars, four hydrogen nuclei combine at extremely high temperatures and pressures to produce a helium nucleus. The concurrent loss of mass is converted into extraordinary amounts of energy (see figure below).

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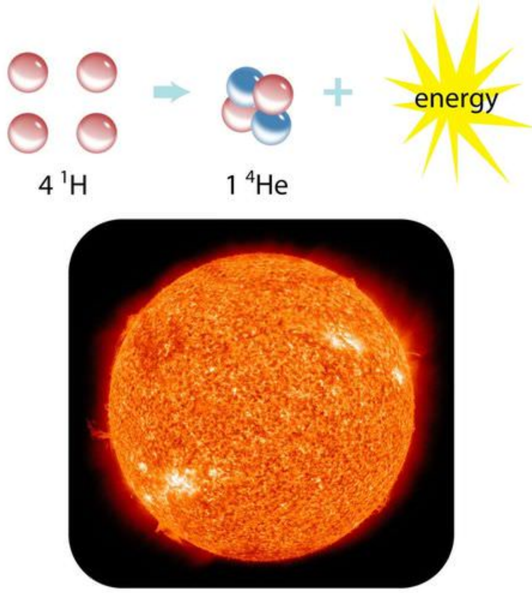

Figure 10.2.3: Nuclear fusion takes place when small nuclei combine to make larger ones. The enormous amounts of energy produced by fusion powers our sun and other stars.

Fusion is even more appealing than fission as an energy source because no radioactive waste is produced and the only reactant needed is hydrogen. However, fusion reactions only occur at very high temperatures - in excess of $40,000,000^{o}\text{C}$. No known materials can withstand such temperatures, so there is currently no feasible way to harness nuclear fusion for energy production, although research is ongoing.

Uses of Radiation

As we saw earlier, different types of radiation vary in their abilities to penetrate through matter. Alpha particles have very low penetrating ability and are stopped by skin and clothing. Beta particles have a penetrating ability that is about 100 times that of alpha particles. Gamma rays have very high penetrating ability, and great care must be taken to avoid overexposure to gamma rays.

Exposure and Detection

Radiation emitted by radioisotopes is called ionizing radiation. **Ionizing radiation** *is radiation that has enough energy to knock electrons off the atoms of a bombarded substance and produce ions*. The **roentgen** *is a unit that measures nuclear radiation and is equal to the amount of radiation that produces* 2×10^9 *ion pairs when it passes through* 1 cm^3 *of air.* The primary concern is that ionizing radiation can do damage to living tissues. Radiation damage is measured in rems, which stands for roentgen equivalent man . A **rem** *is the amount of ionizing radiation that does as much damage to human tissue as is done by 1 roentgen of high-voltage x-rays*. Tissue damage from ionizing radiation can cause genetic mutations due to interactions between the radiation and DNA, which can lead to cancer.

You are constantly being bombarded with background radiation from space and from geologic sources that vary depending on where you live. Average exposure is estimated to be about 0.1 rem per year. The maximum permissible does of radiation exposure for people in the general population is 0.5 rem per year. Some people are naturally at higher risk because of their occupations, so reliable instruments to detect radiation exposure have been developed. A **Geiger counter** *is a device that uses a gas-filled metal tube to detect radiation* (see figure below). When the gas is exposed to ionizing radiation, it conducts a current, and the Geiger counter registers this as audible clicks. The frequency of the clicks corresponds to the intensity of the radiation.

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Figure 10.2.4: A Geiger counter is used to detect radiation.

A **scintillation counter** *is a device that uses a phosphor-coated surface to detect radiation by the emission of bright bursts of light*. Workers who are at risk of exposure to radiation wear small portable film badges. A **film badge** *consists of several layers of photographic film that can measure the amount of radiation to which the wearer has been exposed*. Film badges are removed and analyzed at periodic intervals to ensure that the person does not become overexposed to radiation on a cumulative bases.

Medicine and Agriculture

Radioactive nuclides, such as cobalt-60, are frequently used in medicine to treat certain types of cancers. The faster growing cancer cells are exposed to the radiation and are more susceptible to damage than healthy cells. Thus, the cells in the cancerous area are killed by the exposure to high-energy radiation. Radiation treatment is risky because some healthy cells are also killed, and cells at the center of a cancerous tumor can become resistant to the radiation.

Radioactive tracers *are radioactive atoms that are incorporated into substances so that the movement of these substances can be tracked by a radiation detector*. Tracers are used in the diagnosis of cancer and other diseases. For example, iodine-131 is used to detect problems with a person's thyroid. A patient first ingests a small amount of iodine-131. About two hours later, the iodine uptake by the thyroid is determined by a radiation scan of the patient's throat. In a similar way, technetium-99 is used to detect brain tumors and liver disorders, and phosphorus-32 is used to detect skin cancer.

Radioactive tracers can be used in agriculture to test the effectiveness of various fertilizers. The fertilizer is enriched with a radioisotope, and the uptake of the fertilizer by the plant can be monitored by measuring the emitted radiation levels. Nuclear radiation is also used to prolong the shelf life of produce by killing bacteria and insects that would otherwise cause the food to spoil faster.

Contributors and Attributions

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- Allison Soult, Ph.D. (Department of Chemistry, University of Kentucky)

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