

**FIGURE 13.5** Schematic diagram of a nuclear reactor based on thermal neutron fission.

**PHYSICS**

A simplified online simulation of a nuclear reactor  
<http://esa21.kennesaw.edu/activities/nukeenergy/nuke.htm>

fission. It contains the fuel elements in suitably fabricated form. The fuel may be say enriched uranium (i.e., one that has greater abundance of  $^{235}_{92}\text{U}$  than naturally occurring uranium). The core contains a moderator to slow down the neutrons. The core is surrounded by a *reflector* to reduce leakage. The energy (heat) released in fission is continuously removed by a suitable *coolant*. A containment vessel prevents the escape of radioactive fission products. The whole assembly is shielded to check harmful radiation from coming out. The reactor can be shut down by means of rods (made of, for example, cadmium) that have high absorption of neutrons. The coolant transfers heat to a working fluid which in turn may produce steam. The steam drives turbines and generates electricity.

Like any power reactor, nuclear reactors generate considerable waste products. But nuclear wastes need special care for treatment since they are radioactive and hazardous. Elaborate safety measures, both for reactor operation as well as handling and reprocessing the spent fuel, are required. These safety measures are a distinguishing feature of the Indian Atomic Energy programme. An appropriate plan is being evolved to study the possibility of converting radioactive waste into less active and short-lived material.

### 13.7.3 Nuclear fusion – energy generation in stars

When two light nuclei fuse to form a larger nucleus, energy is released, since the larger nucleus is more tightly bound, as seen from the binding energy curve in Fig. 13.1. Some examples of such energy liberating nuclear fusion reactions are :



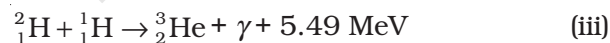
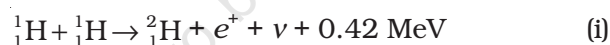
In the first reaction, two protons combine to form a deuteron and a positron with a release of 0.42 MeV energy. In reaction [13.29(b)], two deuterons combine to form the light isotope of helium. In reaction (13.29c), two deuterons combine to form a triton and a proton. For fusion to take place, the two nuclei must come close enough so that attractive short-range nuclear force is able to affect them. However, since they are both positively charged particles, they experience coulomb repulsion. They, therefore, must have enough energy to overcome this coulomb barrier. The height of the barrier depends on the charges and radii of the two interacting nuclei. It can be shown, for example, that the barrier height for two protons is  $\sim 400$  keV, and is higher for nuclei with higher charges. We can estimate the temperature at which two protons in a proton gas would (averagely) have enough energy to overcome the coulomb barrier:

$$(3/2)kT = K \simeq 400 \text{ keV, which gives } T \sim 3 \times 10^9 \text{ K.}$$

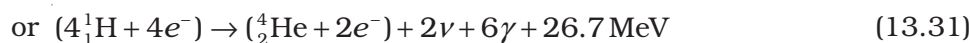
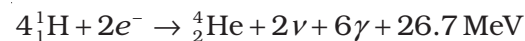
When fusion is achieved by raising the temperature of the system so that particles have enough kinetic energy to overcome the coulomb repulsive behaviour, it is called *thermonuclear fusion*.

Thermonuclear fusion is the source of energy output in the interior of stars. The interior of the sun has a temperature of  $1.5 \times 10^7$  K, which is considerably less than the estimated temperature required for fusion of particles of average energy. Clearly, fusion in the sun involves protons whose energies are much above the average energy.

The fusion reaction in the sun is a multi-step process in which the hydrogen is burned into helium. Thus, the fuel in the sun is the hydrogen in its core. The *proton-proton (p, p) cycle* by which this occurs is represented by the following sets of reactions:



For the fourth reaction to occur, the first three reactions must occur twice, in which case two light helium nuclei unite to form ordinary helium nucleus. If we consider the combination  $2(\text{i}) + 2(\text{ii}) + 2(\text{iii}) + (\text{iv})$ , the net effect is



Thus, four hydrogen atoms combine to form an  ${}^4_2\text{He}$  atom with a release of 26.7 MeV of energy.

Helium is not the only element that can be synthesized in the interior of a star. As the hydrogen in the core gets depleted and becomes helium, the core starts to cool. The star begins to collapse under its own gravity

which increases the temperature of the core. If this temperature increases to about  $10^8$  K, fusion takes place again, this time of helium nuclei into carbon. This kind of process can generate through fusion higher and higher mass number elements. But elements more massive than those near the peak of the binding energy curve in Fig. 13.1 cannot be so produced.

The age of the sun is about  $5 \times 10^9$  y and it is estimated that there is enough hydrogen in the sun to keep it going for another 5 billion years. After that, the hydrogen burning will stop and the sun will begin to cool and will start to collapse under gravity, which will raise the core temperature. The outer envelope of the sun will expand, turning it into the so called *red giant*.

### NUCLEAR HOLOCAUST

In a single uranium fission about  $0.9 \times 235$  MeV ( $\approx 200$  MeV) of energy is liberated. If each nucleus of about 50 kg of  $^{235}\text{U}$  undergoes fission the amount of energy involved is about  $4 \times 10^{15}$  J. This energy is equivalent to about 20,000 tons of TNT, enough for a superexplosion. Uncontrolled release of large nuclear energy is called an atomic explosion. On August 6, 1945 an atomic device was used in warfare for the first time. The US dropped an atom bomb on Hiroshima, Japan. The explosion was equivalent to 20,000 tons of TNT. Instantly the radioactive products devastated 10 sq km of the city which had 3,43,000 inhabitants. Of this number 66,000 were killed and 69,000 were injured; more than 67% of the city's structures were destroyed.

High temperature conditions for fusion reactions can be created by exploding a fission bomb. Super-explosions equivalent to 10 megatons of explosive power of TNT were tested in 1954. Such bombs which involve fusion of isotopes of hydrogen, deuterium and tritium are called hydrogen bombs. It is estimated that a nuclear arsenal sufficient to destroy every form of life on this planet several times over is in position to be triggered by the press of a button. Such a nuclear holocaust will not only destroy the life that exists now but its radioactive fallout will make this planet unfit for life for all times. Scenarios based on theoretical calculations predict a long *nuclear winter*, as the radioactive waste will hang like a cloud in the earth's atmosphere and will absorb the sun's radiation.

#### 13.7.4 Controlled thermonuclear fusion

The natural thermonuclear fusion process in a star is replicated in a thermonuclear fusion device. In controlled fusion reactors, the aim is to generate steady power by heating the nuclear fuel to a temperature in the range of  $10^8$  K. At these temperatures, the fuel is a mixture of positive ions and electrons (plasma). The challenge is to confine this plasma, since no container can stand such a high temperature. Several countries around the world including India are developing techniques in this connection. If successful, fusion reactors will hopefully supply almost unlimited power to humanity.