nucleus by high speed α-particles gives $^{37}_{17}Cl$, 14 protons and 16 neutrons.

$$^{63}_{29}Cu + ^{4}_{2}He \longrightarrow ^{37}_{17}Cl + 14\,^{1}_{1}H + 16\,^{1}_{0}n$$

2. Classification based on the nature of the bombarding particle. This classification gives the following types of nuclear reactions.

(i) Nuclear reactions induced by alpha particles ($^{4}_{2}He$)

(a) (α, p) reactions. These reactions are common with the elements of low atomic number.

$$^{10}_{5}B + ^{4}_{2}He \longrightarrow ^{13}_{6}C + ^{1}_{1}H \;;\; ^{23}_{11}Na + ^{4}_{2}He \longrightarrow ^{26}_{12}Mg + ^{1}_{1}H$$

(b) (α,n) reactions. These reactions are obtained by using more energetic α-particles.

$$^{7}_{3}Li + ^{4}_{2}He \longrightarrow ^{10}_{5}B + ^{1}_{0}n \;;\; ^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

(c) (α,γ) reactions. A typical example of this type of reaction is given below:

$$^{7}_{3}Li + ^{4}_{2}He \longrightarrow ^{11}_{5}B + ^{0}_{0}\gamma$$

(ii) Nuclear reactions induced by protons ($^{1}_{1}H$)

(a) (p, α) reactions: $^{9}_{4}Be + ^{1}_{1}H \longrightarrow ^{6}_{3}Li + ^{4}_{2}He$

$$^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{11}_{6}C + ^{4}_{2}He$$

(b) (p, n) reactions: $^{23}_{11}Na + ^{1}_{1}H \longrightarrow ^{23}_{12}Mg + ^{1}_{0}n$

$$^{18}_{8}O + ^{1}_{1}H \longrightarrow ^{18}_{9}F + ^{1}_{0}n$$

(c) (p, γ) reactions. With proton as the projectile, radioactive capture processes of (p, γ) type have been observed for a number of lighter elements.

$$^{7}_{3}Li + ^{1}_{1}H \longrightarrow ^{8}_{4}Be + \gamma \;;\; ^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N + \gamma$$

(d) (p , d) reactions. $^{9}_{4}Be + ^{1}_{1}H \longrightarrow ^{8}_{4}Be + ^{2}_{1}H$ or D

(iii) Nuclear reactions induced by duetrons ($^{2}_{1}H$ or d)

(a) (d, α) reactions. $^{6}_{3}Li + ^{2}_{1}H \longrightarrow ^{4}_{2}He + ^{4}_{2}He \;;\; ^{16}_{8}O + ^{2}_{1}H \longrightarrow ^{14}_{7}N + ^{4}_{2}He$

(b) (d, p) reactions. $^{23}_{11}Na + ^{2}_{1}H \longrightarrow ^{24}_{11}Na + ^{1}_{1}H$

(c) (d, n) reactions. $^{27}_{13}Al + ^{2}_{1}H \longrightarrow ^{28}_{14}Si + ^{1}_{0}n$

$$^{12}_{6}C + ^{2}_{1}H \longrightarrow ^{13}_{7}N + ^{1}_{0}n$$

(iv) Nuclear reactions induced by neutrons ($^{1}_{0}n$). In these reactions the neutrons are captured resulting in the emission of any following (a) γ-rays (b) α-particle (c) proton (d) neutron.

(a) (n , γ) radiation: $^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{60}_{27}Co + \gamma \;;\; ^{27}_{13}Al + ^{1}_{0}n \longrightarrow ^{28}_{13}Al + \gamma$

(b) (n , α) reactions: $^{16}_{8}O + ^{1}_{0}n \longrightarrow ^{13}_{6}C + ^{4}_{2}He \;;\; ^{27}_{13}Al + ^{1}_{0}n \longrightarrow ^{24}_{11}Na + ^{4}_{2}He$

(c) (n , p) reactions: In these reactions, the final product is a new element whose atomic number is one unit less than the target nucleus and atomic mass is the same.

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}He$$

$$\underline{^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}e \quad \text{(decay reactions)}}$$

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{7}N + ^{1}_{1}H + ^{0}_{-1}e$$

Thus we find that the final product is the same as the target nucleus and hence the overall effect is that the bombarding neutron splits up into a proton and an electron.

(d) (n, 2n) reactions. When the kinetic energy of the bombarding neutron is about 10 MeV, it is able to eject two neutrons from nucleus. For higher energies more than two neutrons may be ejected.

$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{237}_{92}U + 2\,^{1}_{0}n$; $^{12}_{6}C + ^{1}_{0}n \longrightarrow ^{11}_{6}C + 2\,^{1}_{0}n$; $^{39}_{19}K + ^{1}_{0}n \longrightarrow ^{38}_{19}K + 2\,^{1}_{0}n$

In these cases the product nucleus invariably decays with the emission of positron. For example;

$$^{38}_{19}K \longrightarrow ^{38}_{18}Ar + ^{0}_{+1}e$$

(v) Nuclear reactions induced by tritons ($^{3}_{1}H$ or $^{3}_{1}T$).

(a) (t, p) reactions: $^{59}_{27}Co + ^{3}_{1}H \longrightarrow ^{61}_{27}Co + ^{1}_{1}H$

(b) (t, n) reactions: $^{6}_{3}Li + ^{3}_{1}H \longrightarrow ^{7}_{3}Li + ^{2}_{1}H$

(c) (t, n) reactions: $^{32}_{16}S + ^{3}_{1}H \longrightarrow ^{34}_{17}Cl + ^{1}_{0}n$

(d) (t, α) reactions: $^{7}_{3}Li + ^{3}_{1}H \longrightarrow ^{6}_{2}He + ^{4}_{2}He$

(vi) Nuclear reactions induced by photons or γ-rays

The nuclear reactions induced by photons are called **photo-disintegration.** The type of nuclear reaction induced by photons depends on the energy of the incident photons. Various types of reactions produced by photons are given below:

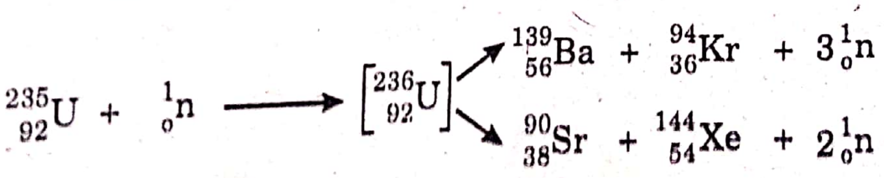
(a) (γ , n) reactions: $^{31}_{15}P + ^{0}_{0}\gamma \longrightarrow ^{30}_{15}P + ^{1}_{0}n$; $^{2}_{1}H + ^{0}_{0}\gamma \longrightarrow ^{1}_{1}H + ^{1}_{0}n$

(b) (γ , p) reactions: $^{25}_{12}Mg + ^{0}_{0}\gamma \longrightarrow ^{24}_{11}Na + ^{1}_{1}H$

(c) (γ, 2p , n) reactions: $^{27}_{13}Al + ^{0}_{0}\gamma \longrightarrow ^{24}_{11}Na + 2\,^{1}_{1}H + ^{1}_{0}n$

8. 12 Nuclear Fission

The splitting of a heavy nucleus into two nuclei of intermediate mass is termed ***nuclear fission.*** This is accompanied by liberation of some neutrons and enormous energy. Of the natural nuclides, only ^{235}U undergoes fission when struck by a slow, or thermal, neutron. The ^{235}U nucleus absorbs the neutron, which supplies sufficient energy to pass the activation energy barrier and produce the fission reaction. The highly activated intermediate ^{236}U can cleave in several ways, depending on its energy level.



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow \left[^{236}_{92}U\right] \begin{cases} \nearrow\ ^{139}_{56}Ba + ^{94}_{36}Kr + 3\,^{1}_{0}n \\ \searrow\ ^{90}_{38}Sr + ^{144}_{54}Xe + 2\,^{1}_{0}n \end{cases}$$

In the formation of smaller nuclides from the ^{235}U the products are more stable than the nucleus undergoing fission, that is, the binding energies are greater and the reaction is exothermic by 1.737×10^{13} J mol^{-1}, or 1.737×10^{10} kJ mol^{-1}, which is greater by a factor of about 10^{6} than the energy released in highly exothermic processes. In these fission reaction, the mass of the product is less than the mass of the reactants due to the mass defect. A loss of mass about 0.2 amu per uranium atom occurs which corresponds to a loss of 0.2 g mol^{-1}, or 2.0×10^{-4} kg mol^{-1} which is released as energy. On the average, however, approximately 200 Me V of energy and 2.5 neutrons are released in the fission of $^{235}_{92}U$.

The fission of each uranium atom produces two to three neutrons if each of these neutrons is captured by other fissionable nuclei (other ^{235}U nuclei), the process continues, and the result is **a chain reaction** in which the sudden fission of many nuclei and the resulting production of huge quantities of energy produce a **nuclear explosion.** In the atomic bomb a certain quantity, *the critical mass*, of a fissionable nuclide is suddenly assembled by the bomb mechanism. If the mass is less than the critical mass, too many neutrons escape and the chain cannot be sustained. One way of triggering a bomb is to use a chemical explosion to blow two separate subcritical masses of fissionable material at each other, so that the critical mass is suddenly exceeded. Both uranium-235 and plutonium-239 have been used in nuclear weapons. Plutonium-239 is made by bombarding uranium-238 with neutrons. The synthetic nuclide $^{239}_{94}Pu$ is also fissionable.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U$$

$^{239}_{92}U$ then decays in two steps to form $^{239}_{94}Pu$

$$^{239}_{92}U \longrightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

$$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

Since the neutron bombardment of the nonfissionable but relatively abundant ^{238}U produces ^{239}Pu in good quantity and with reasonable case, and hence this nuclide is used extensively for fission reactions. A third fissionable nuclide is ^{233}U, formed from $^{232}_{90}Th$, also rather abundant.

$$^{232}_{90}Th + ^{1}_{0}n \longrightarrow ^{233}_{90}Th$$

$$^{233}_{90}Th \longrightarrow ^{233}_{91}Pa + ^{0}_{-1}e$$

$$^{233}_{91}Pa \longrightarrow ^{233}_{92}U + ^{0}_{-1}e$$

A fission reaction where the neutrons from a previous step continue to propagate and repeat the reaction is called **nuclear chain reaction.**

The minimum amount of fissionable material required to sustain the chain reaction is called the **critical mass.** Masses below critical mass are said to be **subcritical,** and masses larger than critical mass are said to be **supercritical.** The energy released by the fission of nuclei is called **nuclear fission energy** or **nuclear energy.**

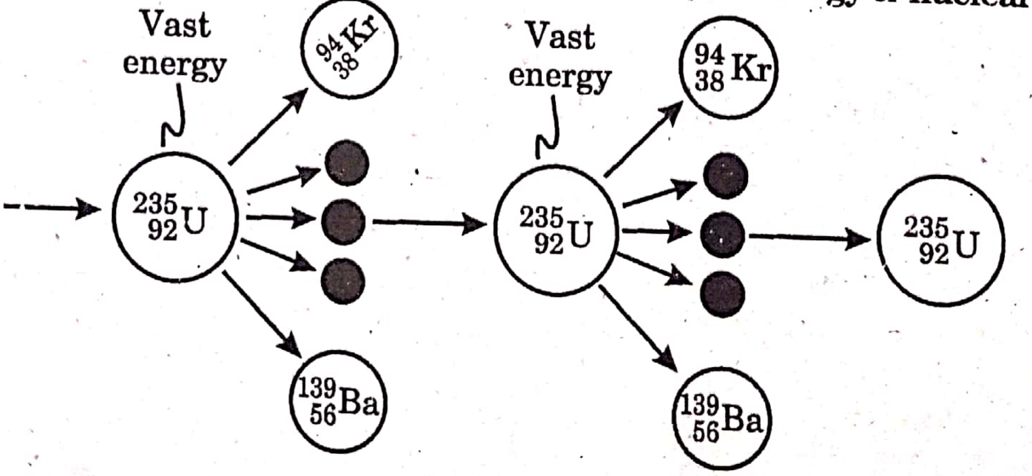


Fig. 8.8 Chain reactions of U-235 producing energy.

For a chain reaction to occur, the sample of the fissionable material should be large enough to capture the neutrons internally. If the sample is too small, most neutrons will escape from its surface, thereby breaking the chain. A certain quantity, the critical mass, of a fissionable nuclide is required to sustain a chain reaction. The uncontrolled fission of a supercritical mass of a fissionable nuclide results in an explosion and is used in nuclear weapons. Controlled fission is used in the nuclear reactors as an energy source to power ships and generate electricity.

8.13. NUCLEAR REACTOR

Nuclear reactor is a device to obtain the nuclear energy in a controlled nuclear fission reactions, usually used to generate power. In other words, **Nuclear Reactor** is an equipment for carrying out controlled nuclear fission reactions, usually used to generate power. In a nuclear reactor, no more than one of the neutrons emitted when a nucleus undergoes fission is allowed to be captured by another fissionable nucleus. In this way the reaction is kept under control. The basic parts (components) of a nuclear reactor are :

(i) **The Fuel.** In a conventional nuclear reactor used for power generation, the fuel is uranium oxides which have been enriched to contain approximately 3 percent ^{235}U. The enrichment is necessary, since the natural abundance of the fissionable ^{235}U is only 0.7 percent of the heavier ^{238}U, which is not fissionable. The fission of ^{235}U , produces heat energy and neutrons that start the chain reaction.

(ii) **Moderator.** *A material that has the ability to slow down neutrons quickly and which, at the same time, has little tendency to absorb neutrons is called a* **moderator.** The most commonly used moderator is water which serves to moderate the energy of the fast neutrons emitted by the fission process, and convert them to slow (neutrons) which are more effective in inducing fission of ^{235}U. Graphite rods are sometimes used. The most efficient moderator is helium which slows neutrons but does not absorb them all. Neutrons slow down by losing energy due to collisions with atoms / molecules of the moderator.

(iii) **The Coolant.** The heat generated in the core of the reactor is removed by a "*Coolant*". Water used in the reactor serves both as moderator and coolant. Since water absorbs neutrons, it is not satisfactory for coolant purpose. Liquid sodium, liquid alloy of Na and K are recommended as coolants for use at high temperatures. Various other coolants such as air, CO_2, CH_4, He and benzene are also used.

(iv) **Control Rods (The Control System).** The reactor is kept under control by trusting the positions of control rods which are inserted among the nuclear fuel element in the reactor. These control rods are usually made out of cadmium or boron, which are highly efficient for a neutron absorption.

(v) **The Radiation Shield.** Since the reactor is highly radioactive, it has to be shielded to prevent escape of radiations. The reactor is housed in a thick concrete (about 8 feet thick) which acts as the shield. There is also an internal shield usually consisting of a steel lining, which is used in high power reactors to protect the walls of the reactor vessel from radiation damage.

Light - Water Nuclear Power Plant

Most commercial power plants today are 'light water reactor'. In this type of reactor, ^{235}U fuel rods are submerged in water. Here water acts as coolant and moderator. 'The control rods of B–10 are inserted or removed automatically from spaces in between the fuel rods.

The heat emitted by fission ^{235}U in the fuel core is absorbed by the coolant. The heated coolant (water at 300°C) then goes to the *exchanger*. Here the coolant transfer heat to sea water which is converted into steam. The steam then turns the turbine, generating electricity. A reactor once started can continue to function and supply power of generation.

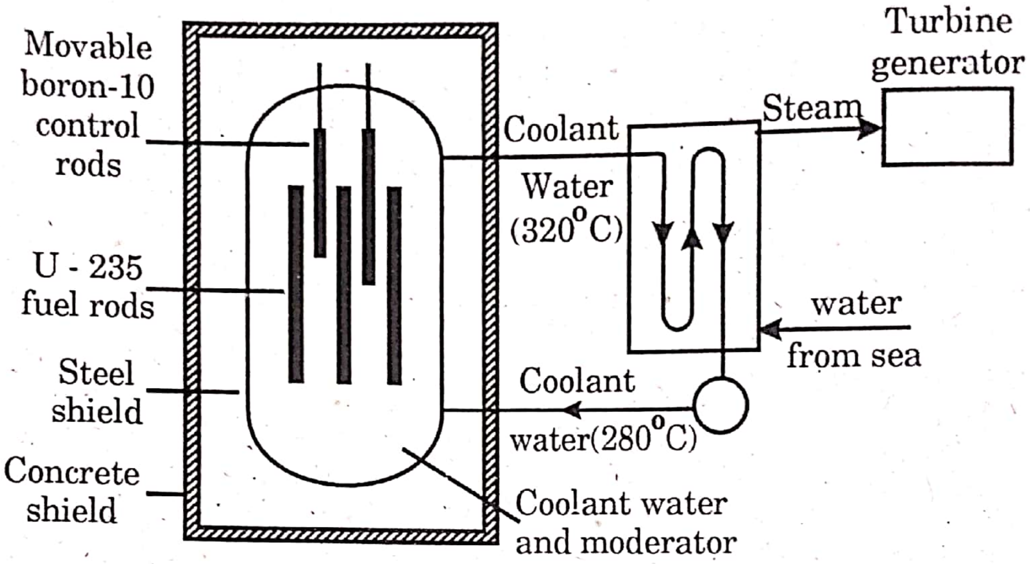


Fig. 8.9A light water reactor producing electricity.

8.14 NUCLEAR FUSION

A *nuclear process in which two lighter nuclei merge or fuse to form a single heavier nucleus with release of energy is called* **nuclear fusion.** Nuclear fusion reactions are also called **thermonuclear reactions** as these reactions occur at ultrahigh temperatures about 10^8 °C. Such very high temperatures are reached in stars where fusion reactions of light nuclei are source of the radiant energy, and in nuclear fission explosions used to trigger nuclear fusion bombs. The source of energy in the Sun is a series of reactions, the net result of which is the fusion of four protons to form a single $^{4}_{2}He$ nucleus. The reaction undoubtedly takes place in steps.

$$^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{2}_{1}H + ^{0}_{1}e$$

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He$$

$$^{3}_{2}He + ^{1}_{1}H \longrightarrow ^{4}_{2}He + ^{0}_{1}e$$

$$\text{Net:} \quad 4\,^{1}_{1}H \longrightarrow ^{4}_{2}He + 2\,^{0}_{1}e \text{ (positrons)}$$