Module 5 : MODERN PHYSICS
Lecture 27 : Nuclear Energy

Objectives

In this course you will learn the following

- Mass energy equivalence.
- Nuclear binding energy.
- Nature of nuclear forces.
- Energy released in nuclear fission.
- Controlled chain reaction and principle of a nuclear reactor.
- Nuclear fusion.

Nuclear Energy

Energy is one of the main requirement of sustaining human civilization. Conventional sources of energy, which account for over 85% of the total energy consumed by the mankind, are fossil fuels. Fossil fuels were formed over millions of years from remains of plants and animals by action of pressure and heat and are now found beneath the earth's surface. When such fuels are burnt, they release chemical energy trapped in them. Fossil fuels consist of coal, petroleum and natural gases. Coal is a solid hydrocarbon with nearly 75% of the world's deposit being found in China, USA and the Russian Federation. Though most abundant and the lesat expensive of the three, burning coal causes a lot of environmental problems as it releases harmful chemical SO_2, which can cause *acid rain.* In addition, release of large amount of carbon dioxide is responsible for global warming. Oil and natural gas deposits are limited and they are being depleted at a very fast rate. Though the nature makes them, fossil fuels are *non-renewable* sources of energy as it takes nature millions of years to make them while humans consume them at a fast rate. Nuclear energy is produced from practically unlimited amount of energy trapped in all matter. Production of nuclear energy does not produce particulate impurities like NO_2, SO_2 etc. and also does not release CO_2. In this sense, nuclear energy is a clean fuel. However, there are several issues connected with disposal of radioactive nuclear waste and decommissioning of old nuclear power plants, which makes the production of nuclear energy a contentious subject. In addition, the technology that produces nuclear power can also be used to produce nuclear bombs, which makes transfer of nuclear technology a delicate issue. Nuclear energy is made available by **fission** and by **fusion** . In the following, we will discuss the principle behind production of nuclear energy.

Mass - Energy Equivalence

According to Einstein's special theory of relativity, a particle of mass m has equivalently an amount of energy given by the relation

$$E = mc^2$$

where c is the speed of light in vacuum which has a numerical value (approximately) 3×10^8 m/s ^{2}. The theory of relativity introduces the concept of *rest mass* , which is the mass an object has when it is at rest relative to an inertial frame. If the mass of an object in such a frame is m_0, the object has an equivalent energy given by . In addition to the rest energy, the object may have a kinetic energy K

$$E_0 = m_0 c^2$$

because of motion that it has with respect to the inertial frame. The total energy of the object may be written as

$$E = m_0 c^2 + K$$

Since the product of mass and the square of the velocity of light has the dimensions of energy, it is possible to express K as a product of some mass δm times c^2, so that the energy of the object may be written as $E = mc^2$, where $m = m_0 + \delta m$. In this expression m is the relativistic mass of the body, which depends both on the rest mass of the body and the state of motion of the body. According to the special theory of relativity, for a body moving with a speed v with respect to an inertial frame,

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Atomic Mass Unit

Nuclear mass is usually expressed in terms of an unit known as the *atomic mass unit* , denoted by the letter *u* .One atomic mass unit is defined as one twelfth the mass of an atom of the most abundant isotope of Carbon , viz., $_{12}$C

$$1\ \mathrm{u} = \frac{1}{12} \times \text{mass of one atom of } {}^{12}\mathrm{C}$$

$$= 1.6604 \times 10^{-27}\ \mathrm{kg}$$

$$= 931.5\ \mathrm{Mev/c^2}$$

In high energy physics, it is common to use mass and energy interchangeably and frequently one expresses mass in terms of MeV, which actually stands for the corresponding energy equivalent. In terms of the above units, the masses of a neutron and a proton are as follows : Mass of a neutron = m_n =1.008 665 u $\approx$

939.57 MeV/c ^{2} Mass of a proton = m_p = 1.007 825 u $\approx$ 938.28 MeV/c ^{2}

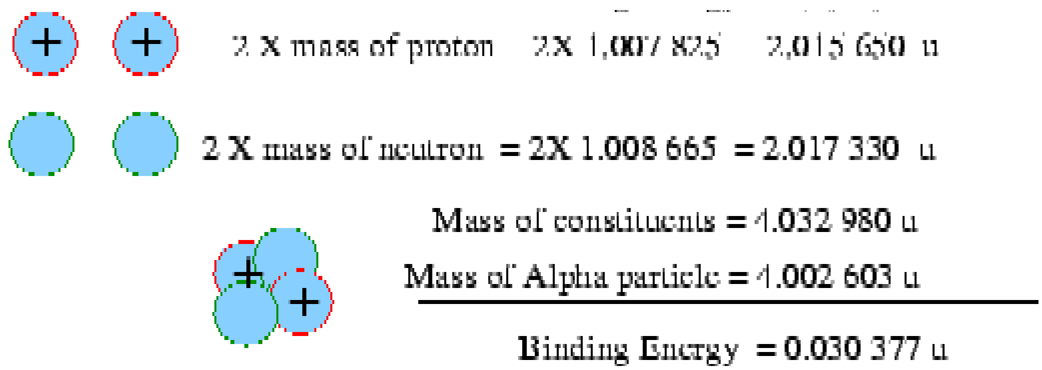
Nuclear Binding Energy :

The constituents of a nucleus are neutrons and protons, collectively known as **neucleons** . Mass of a nucleus is always less than the sum of the masses of its constituent nucleons, the difference between the two is called **the mass defect** and the equivalent energy the **binding energy** of the nucleus. Binding energy of a nucleus is the amount of energy required to separate the nucleus into its constituent nucleons.

Example 19

The Helium nucleus $^4_2$He (also called the **alpha particle**) has a mass of 4.001 506 u. Determine its binding energy in terms of the atomic mass units and in MeV.

Solution :



Alpha particle has two protons and two neutrons. Binding energy calculation in atomic mass unit is shown alongside. In terms of MeV, the binding energy is $0.030377 \times 931.5 = 28.296$ MeV, i.e. 7.074 MeV per nucleon.

Exercise 1

An isotope of Uranium $^{235}_{92}$U has a nuclear mass of 235.043930 u. Calculate the binding energy per nucleon in MeV.

(Ans. 7.59 MeV)

Exercise 2

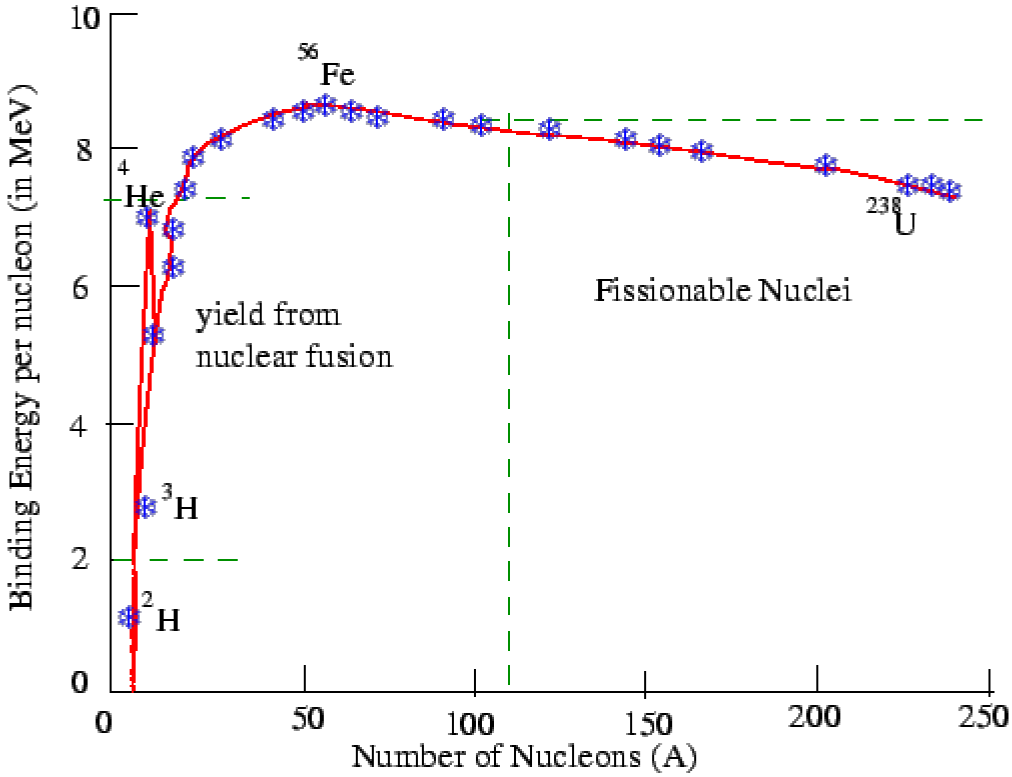
The most abundant isotope of Uranium $^{238}_{92}$U has a nuclear mass of 235.050788 u. Calculate the binding energy per nucleon in Mev.

(Ans. 7.57 MeV)

For a nucleus $^{A}_{Z}$X of mass M with atomic number Z and mass number A, the binding energy is given by

$$E_B = [Zm_p + (A - Z)m_n - M]\, c^2$$

The adjoining figure gives a plot of the binding energy per nucleon of the elements. It may be noted that the nucleus ^{56}Fe is the most tightly bound nucleus with a binding energy of about 8.8 MeV per nucleon. This is the reason why the iron group of nuclei are the most stable of the nuclei.



[See the animation]

Nuclear Force

The large binding energy suggests that the nucleons in an nucleus are very tightly bound. As a nucleus consists of protons which, being positively charged, would repel each other by Coulomb force, and neutrons which are charge neutral, the nucleons in a nucleus obviously cannot be glued together by electromagnetic forces which would actually make them fly apart. What binds the nucleons together is a new type of force, called **the strong force** . The characteristics of the strong force are

- the force is extremely short ranged - the force exists when the distance between nucleons becomes of the order of nuclear dimensions ($\sim$ 1 Fermi = 10^{-15} m).
- it is charge independent - the force is the same whether it is between a pair of protons or a pair of neutrons or between a proton and a neutron.
- It is strong and **attractive** , relative to electrmagnetic forces it is about a hundred times stronger.

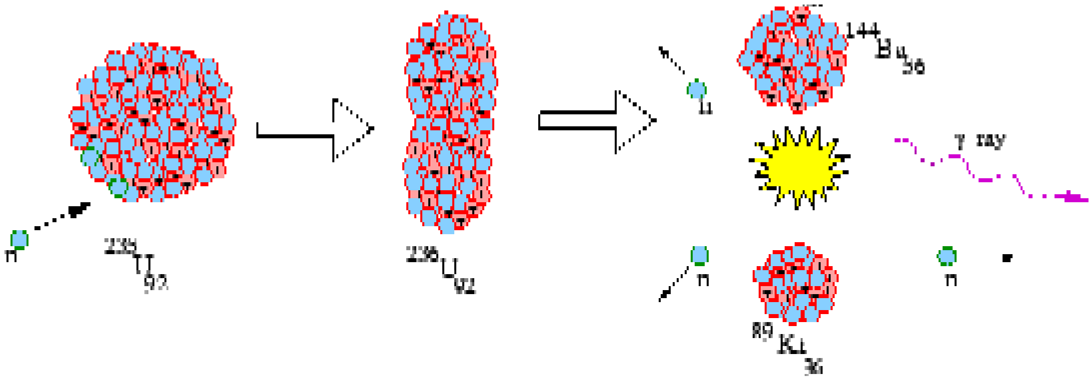
Inside a nucleus there is a competition between the repulsive Coulomb force and the attractive strong force. In most nuclei the strong force dominates. However, for heavier nuclei, there is a delicate balance between the two which can be easily disturbed leading to a fission of such nuclei. Spontaneous fission is of rare occurrence as the half life for fission is very high. The way to effect fission in a nucleus is to excite the nucleus - the energy required to initiate fission being between 5 to 6 MeV.

Fission :

Nuclear energy has been harnessed for power production, primarily through fission of Uranium, Thorium and Plutonium, with Uranium being the most common fissile material today. Looking at the binding energy curve, one can see that lighter nuclei have less binding energy than the heavier ones. Thus if a heavy nucleus breaks up into fragments, the sum of energies of the fragments would be less than the energy of the initial nucleus. This is the principle behind release of energy through fission. As the released energy is in MeV, fission released a million times more energy than chemical processes like burning of coal or oil which release energy of the order of electron volts.

Fission of $^{235}_{92}$U :

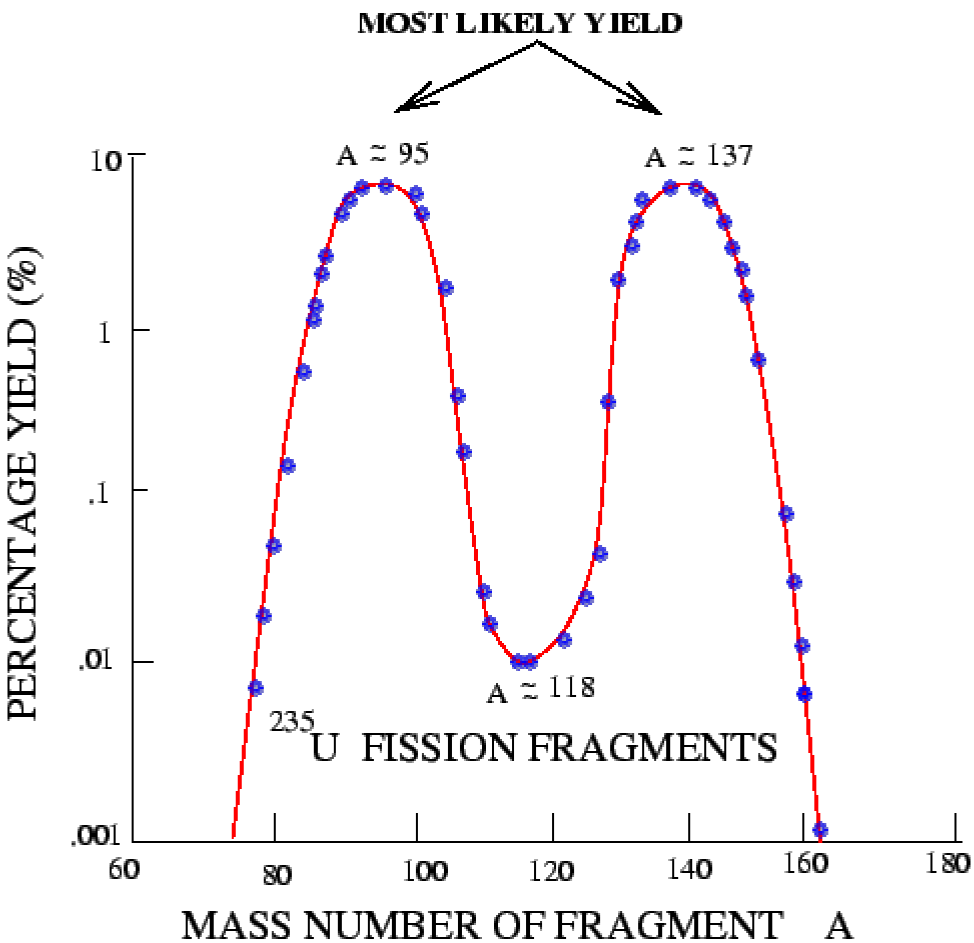
Natural uranium consists of 98.275% of ^{238}U, 0.72% of ^{235}U and 0.005% of ^{234}U. Most of the nuclear energy produced in the world today is produced by fission of ^{235}U. (An isotope of uranium ^{233}U is also fissionable though it does not naturally occur but is produced by exposing thorium to neutrons.) The process of fission is initiated by capture of a slow neutron, called **thermal neutron** as the kinetic energy of such a neutron is of the order of thermal energy of air molecules, by uranium nucleus. Upon capuring a neutron, the uranium nucleus gets into an excited state and the delicate force balance inside the nucleus gets disturbed. The excited nucleus breaks up into two fragments of nearly comparable size.



[See the animation]

Various fragments that are produced by fission of ^{235}U are distributed as shown in the adjoining figure. Some of the possible reactions that take place are as follows :

$$^{235}_{92}U + n \longrightarrow {}^{93}_{37}Rb + ^{141}_{55}Cs + 2n$$
$$^{235}_{92}U + n \longrightarrow {}^{92}_{36}Kr + ^{142}_{56}Ba + 2n$$
$$^{235}_{92}U + n \longrightarrow {}^{89}_{36}Kr + ^{144}_{56}Ba + 3n$$
$$^{235}_{92}U + n \longrightarrow {}^{90}_{38}Sr + ^{144}_{54}Xe + 2n$$

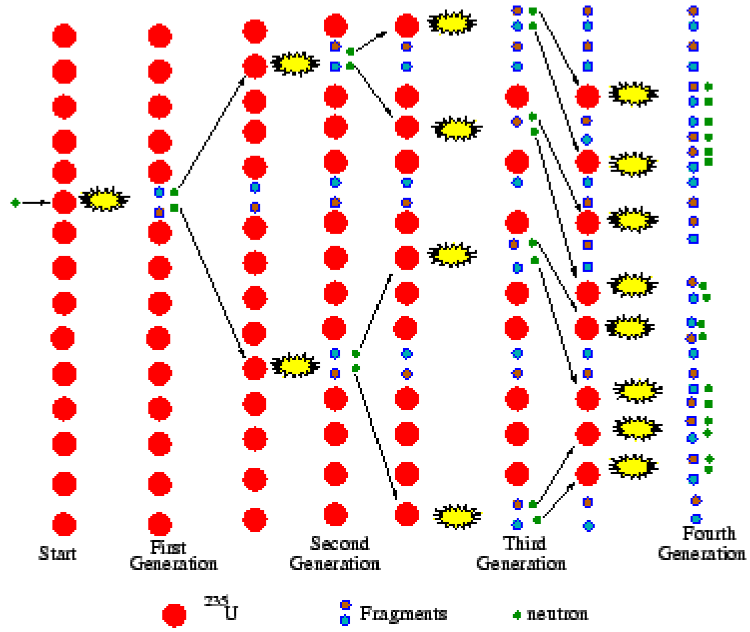


[See the animation]

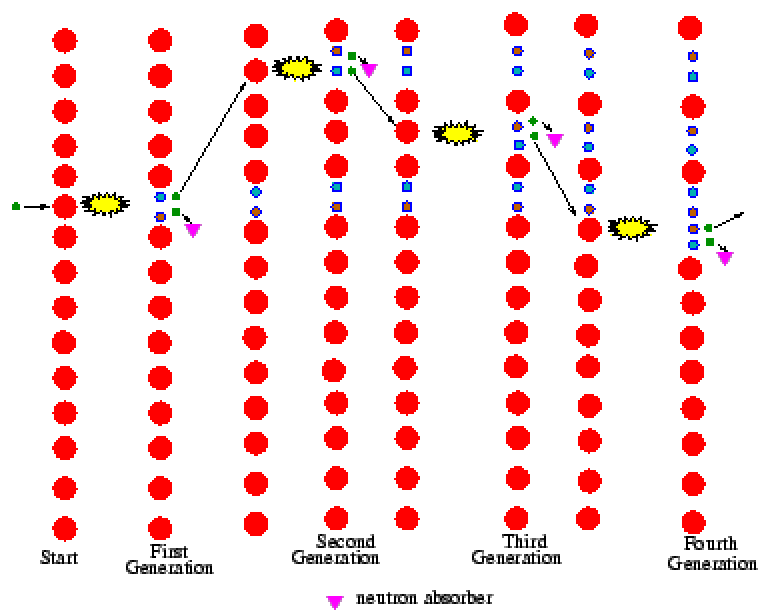
Chain Reaction

Notice that in each of the reactions neutrons are produced. The average number of neutrons produced in fission reactions is 2.5. Thse neutrons can then be used to produce **Chain Reaction.**

Consider reactions where 2 neutrons are produced. The first neutron causes one uranium nucleus to split into two fragments producing 2 neutrons, which in turn can cause two more uranium to fission, producing four fragments and four new neutrons. The chain reaction will continue till all the ^{235}U fuel is spent. This is roughly what happens in an atom bomb. The run away chain reaction needs to be controlled, if one is to use it for power generation. This is done by removing excess neutrons so that the chain reaction can proceed at a slow pace till all the fuel is burnt. Removing excess neutrons is achieved by inserting control rods which contain neutron absorbing material. Cadmium and boron rods are usually used for such purpose.



Fission :



Nuclear Power Reactor

When fission reaction occurs tremendous amount of energy is liberated. While some energy appears as radiation, most of the energy is in the form of kinetic energy of the fragments. The fragments dissipates most of their kinetic energy as heat, which can be used to boil water and the resulting steam can be used to turn turbines to generate electricity. The following are the stages in the working of a power reactor.

Enrichment

The percentage of ^{235}U in the naturally occurring uranium is only about 0.7%. In a nuclear reactor, the percentage of U-235 is increased by a process called *enrichment* . This is usually achieved either by gaseous diffusion or by a centrifuge. In the diffusion process, natural uranium, which is first converted to gaseous uranium hexafluorid (UF_6) is passed through a series of semi-porus membranes which permit passage of the gas that contains the lighter U-235 but not the component containing the heavier isotope U-238. The technique is somewhat inefficient and it requires several stages of diffusion barriers to achieve the desired concentration of about 4 to 5% of U-235. In the centrifuge technique the natural UF_6 is spun at high speed which separates the heavier and the lighter components as they are subjected to different centrifugal forces. Newer techniques of enrichment using lasers are now available.

Reactor Core

The core is the centre of the reactor which contains the fuel which is used in running the reactor. Control rods to absorb excess neutrons are introduced into the core. Usually a heavy steel vessel surrounds the core. A reactor which produces enough neutrons to sustain controlled chain reaction is called **critical** . Criticality not only depends on the nuclear reaction producing neutrons but also depends on availability of enough uranium which must absorb a released neutron. Enrichment of the fuel ensures this for a reactor. The mass of the fissile material required to sustain chain reaction is said to be **critical mass** . If a reactor cannot sustain chain reaction, it is called **sub-critical**. On the other hand if the chain reaction proceeds uncontrolled, as in an atom bomb, the reactor is called **supercritical** .

Moderators

A neutron produced in a nuclear reaction must be slowed down before it can be capured by another fuel element. Such *thermalization* of neutrons is performed by collision with substances which have light masses such as water, heavy water or graphite. These are known as moderators.

Neutron absorbers

We have seen that control rods of neutron absorbing materials like Cd are inserted to make sure that the reactor does not become supercritical. It is not possible to mechanically control the rate of insertion or withdrawal of control rods which are emitted the instant the nuclear reaction takes place. However, the radioactive decay of the fission fragments produce additional neutrons which are called **delayed neutrons**. For instance, in the first mentioned fission reaction above, U-236 fragments into $^{141}_{55}$Cs and $^{93}_{37}$Rb, in addition to releasing two **prompt neutrons**. These fission fragments themselves are unstable and undergo different types of radioactive decays. Delayed neutrons are associated with fragments which undergo beta decay. In case of $^{141}_{55}\mathrm{Cs}$, about 0.03% of the decay is through beta emission, half life against beta decay being 25 seconds

$$^{141}_{55}Cs \rightarrow ^{140}_{56} Ba + n$$

Similarly $^{93}_{37}$Rb undergoes beta decay to $^{92}_{38}$Sr in about 1.4% cases producing neutrons with a time lag of about six seconds. The delayed fraction allows mechanical control to be established for controlling both prompt and delayed neutrons.

Coolant

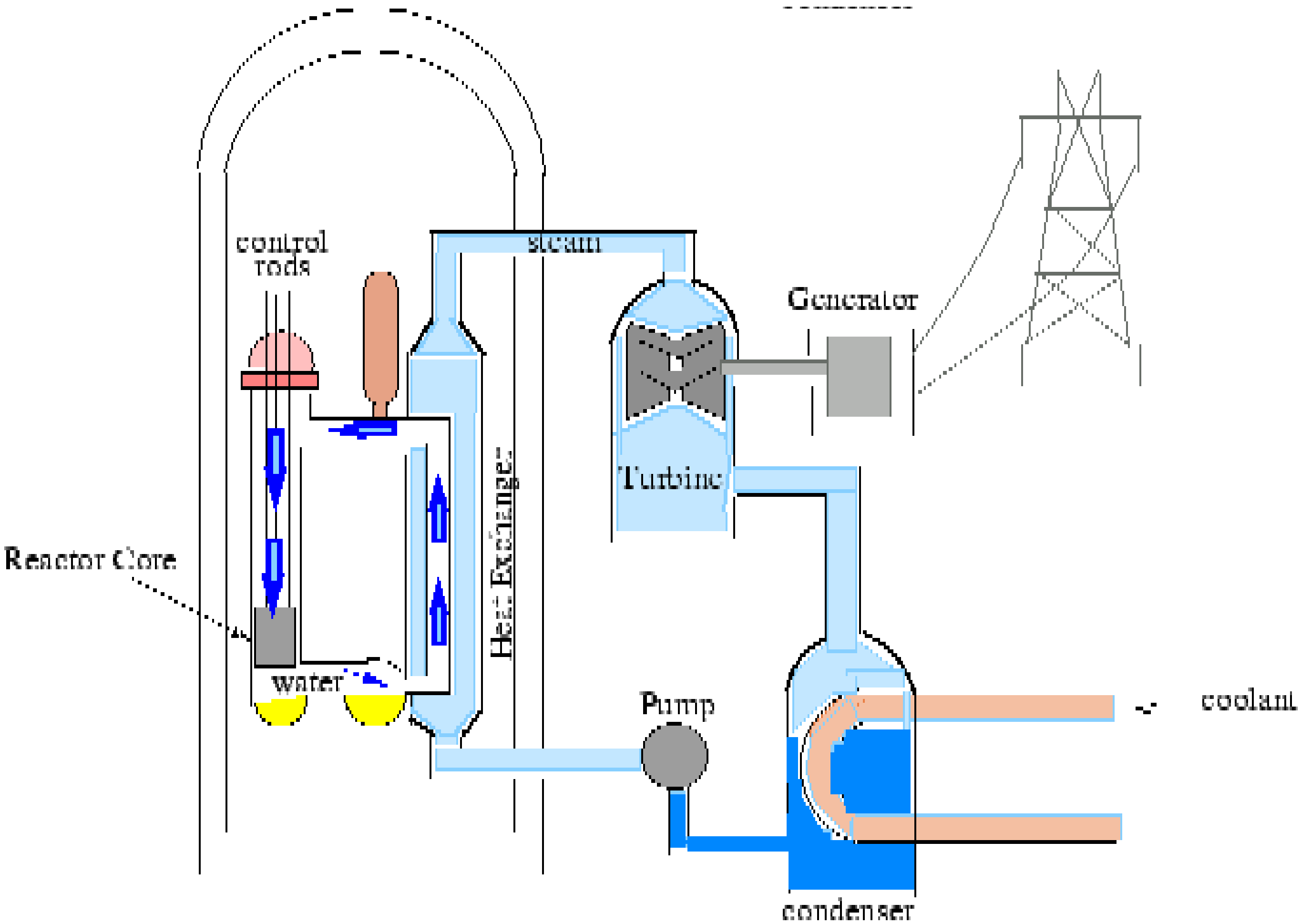
The heat generated in the core is to be removed for being used to heat water to generate steam and eventual generation of electricity. The thermal energy is removed by a liquid coolant that flows throgh pipes in the reactor core. Based on the method used for exatracting fission energy from the core of the reactor, there are two primary types of reactor. They are

Boiling - Water Reactor (BWR)

In a boiling water reactor, water in pipes circulates inside the core. The water gets heated, generates steam which is then used to drive turbines. As the water enters the core, there is a possibility of its becoming radioactive. Further, in case of a rapture of the pipe due to extreme heat, it could lead to accidents.

Pressurized - Water Reactor (PWR)

In these reactors water is extracted in two steps. The primary coolant, as in the case of BWR circulates inside the core. However, the water circulates under great pressure so that it does not become steam. The heat is transferred through a heat exchanger to a secondary coolant, which may be used to drive a turbine. As the secondary coolant does not enter the core, it does not become radioactive.



In addition to the above, liquid metal reactors in which the coolant used is a metal like liquid sodium are also in existence.

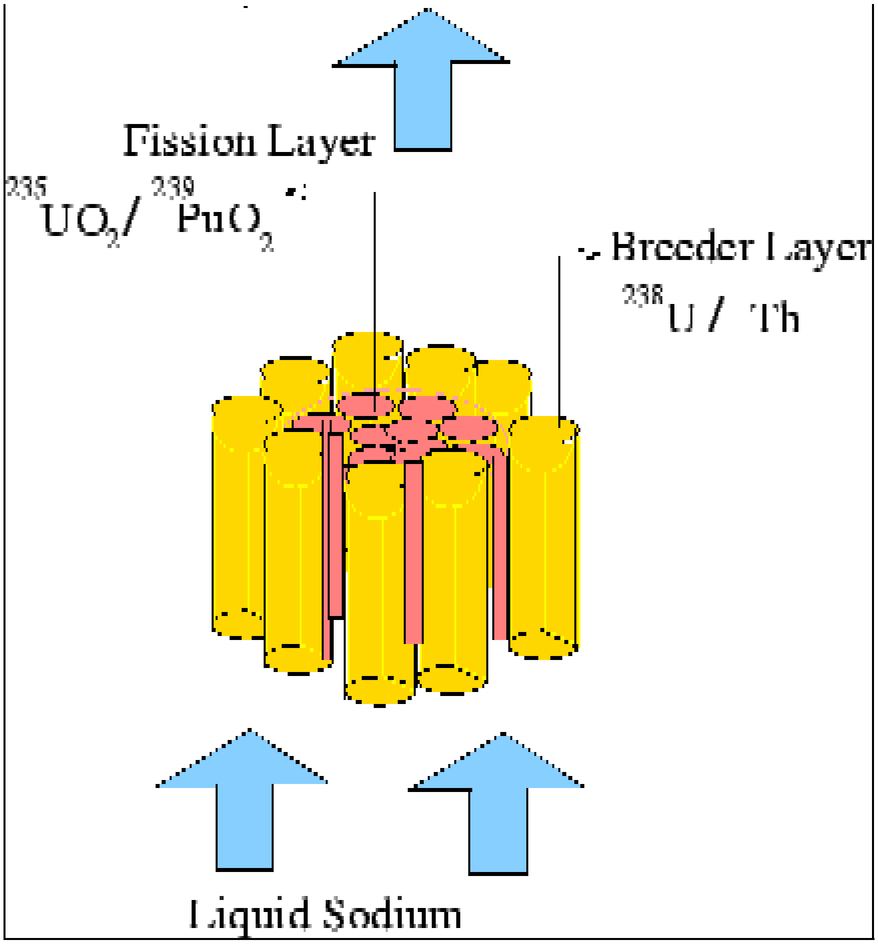
Fast Breeder Reactor

While fission of U-235 can yield substantial energy, the world's supply of U-235 is limited. However, it is possible to use the neutrons given out by fission reaction to *breed* fuel from non-fissionable isotopes like U-238. As U-238 is more plentiful than U-235, it is an attractive option. U-238 can absorb a *fast neutron* given out by a fission reaction to yield fissionable plutonium. A typical breeding reaction is as follows :

$$\begin{aligned} {}^{1}_{0}n + {}^{238}_{92}U &\longrightarrow {}^{239}_{92}U \\ &\xrightarrow{23.5\text{ min.}} {}^{239}_{93}\mathrm{Np} + \beta^- \\ &\xrightarrow{2.3\text{ days}} {}^{239}_{94}\mathrm{Pu} + \beta^- \end{aligned}$$

U-238 absorbs a fast neutron and undergoes two successive beta decay to give rise to plutonium. The core of a fast breeder reactor consists of an inner part which contains the fission fuel consisting of enriched ${}^{235}UO_2$ and ${}^{239}PuO_2$ and an outer part which consists of U-238, depleted uranium and ${}^{232}Th$ in some combination.

The fast neutrons that are produced during fission of the inner part is captured by the outer layer to breed fissionable plutonium and U-233. Thus the reactor breeds more fuel than it consumes, which accounts for the name. No moderators are used in the reactor as the neutrons should not be slowed down. This is also the reason why the primary coolant used is not water which could slow down neutrons. The usual coolant used in the primary loop is liquid sodium.



Example 20

Calculate the energy released in the fission reaction

$$^{235}_{92}U + n \longrightarrow ^{93}_{37}Rb + ^{141}_{55}Cs + 2n$$

Solution :

The masses of the reactants and the product (in units of u)are as follows :

Reactants :

mass of $^{235}_{92}U$	= 235.043929
mass of $^{1}_{0}n$	= 1.008665

Total mass of reactants	= 236.052594

Products :

mass of $^{93}_{37}Rb$	= 92.922042
mass of $^{141}_{55}Cs$	= 140.920046
mass of 2 $^{1}_{0}n$	= 2.017330

Total mass of product	= 235.859418

The products being lighter than the reactants by u. This

$$236.052594 - 235.859418 = 0.193176$$

amounts to $0.193176 \times 931.5 = 179.94$ MeV of energy.

Fission produces about 200 Mev of energy of which about 175 MeV is the kinetic energy of fission fragments, the reamaining energy is distributed as the kinetic energy of neutrons and energy associated with photons, neutrinos and other radioactive products.

Exercise 3

Calculate the energy released in the fission reaction

$$^{235}_{92}U + n \longrightarrow ^{89}_{36} Kr + ^{144}_{56} Ba + 3n$$

The masses of the product are as follows :
$^{89}_{36}$Kr = 88.917630 u and $^{144}_{56}$Ba = 143.922953 u.

(Ans. 173.27 MeV.)

Nuclear Fusion

Energy may also be produced by two light nuclei fusing to give a heavier nucleus. This would happen at the initial part of the binding energy curve where the rise in binding energy per nucleon with atomic number is sharp. For instance, if two deuterium (heavy hydrogen) nuclei fuse, we may get

$$^2_1H + ^2_1 H \rightarrow ^3_2 He + ^1 n_0$$

We can calculate the energy balance as follows

Reactants :

mass of two $^2_1$H $= 2 \times 2.014101 = 4.028202$

Products :

mass of $^3_2$He	=	3.016029
mass of $^1_0$n	=	1.008665

Total mass of product	=	4.024694

The mass deficit is $4.028202 - 4.024694 = 0.003508$ u, corresponding to 3.267 MeV. Though energy from fusion can be an enormous source of power because of abundance of deuterium in sea water, fusion of nuclei can be achieved only at extremely high temperatures (of the order of over a million degree !). At such temperatures, no solid container can be used to contain the material used for fusion (the reactants and products would be completely ionized - the mixture of the electrons and the nuclei being in a state of plasma). Controlled thermonuclear fusion has only been possible on a laboratory scale and *fusion reactor* remains a distant possibility. It may be mentioned that it is the energy released from fusion that keeps our sun (and other stars) hot and luminous. Fusion is possible in sun because of extremely high density of protons at the centre of the sun.

Exercise 4

Calculate the energy released in the fusion process (use mass data given above) $^2_1$H $+ ^3_1$H $\longrightarrow$ $^4_2$He + $^1_0$n

(Ans. 17.59 MeV)

Environmental Issues Connected With Nuclear Reactors :

Though nuclear energy can be plentiful in availability and, unlike fossil fuel, is a *clean* fuel as it does not give rise to particulate impurities, there are several issues which have been causes of concern. Some of the issues are as under :

- Nuclear waste (which consists of fission products) contains highly radioactive material. Though the level of

radioactivity for most components goes down fast, the nuclear waste have to be kept away from human contact as they could cause serious illnesses like cancer. Safe disposal of nuclear waste is a cause of major concern.

- Like any major power station, nuclear reactors are also likely to have accidents due to faulty design or things out of control. The worst recorded accident which led to several deaths and other fallouts from the released radioactivity occurred in Chernobyl, near Kiev (Ukraine). A faulty design led to a fire and explosion of the graphite core. The radioactivity spread over erstwhile USSR and also to parts of Europe, including Scandinavia. In 1979 one of the plants in Three Mile Island, near Harrisberg in USA, lost coolant leading to over heating and partial meltdown of the core which caused radioactive leak.
- Because of their high cost, nuclear power plants are designed to produce very high power. This leads to thermal emissions which can lead to local warming at a level much higher than that for conventional power stations. Though the nuclear power stations do not give out more heat to the surroundings than thermal power stations per kilowatt of power produced for electricity, the effect of local heating is more for large power stations.

Recap

In this course you have learnt the following

- Einstein's relation $E = mc^2$ obtained from the principle of relativity establishes the equivalence of mass and energy.
- Mass of a nucleus is less than the sum of the masses of constituent nuclei, the difference is the mass defect and the equivalent energy is known as the binding energy of the nucleus.
- Nucleus is held together by a force that is strong, short ranged and attractive.
- The nuclear binding energy is more for heavier nuclei than for lighter nuclei, as a result of which when a heavier nucleus splits into smaller fragments (fission), energy gets released.
- Fission is effected by a thermal neutron striking a heavy nucleus such as ^{235}U and disturbing the delicate balance of forces. Nucleus thereby fissions and in the process liberates more neutrons, which, in turn, can cause more fission. A nuclear reactor is based on the principle of controlling this chain reaction.
- When two light nuclei coalesce to form a heavier nucleus, the process is called fusion. Thermonuclear fusion can also be a source of great energy provided the process can be controlled.