Chapter = 19

The Atomic Nucleus

NUCLEAR STRUCTURE:

The nucleus consists of protons and neutrons. A proton is a positively charged particle having mass 1.6726 x 10^{-27}Kg and charge 1.60 x 10^{-19} coulombs. The charge of the proton is equal in magnitude of the charge of an electron but opposite to it in sign. A neutron has no charge. Its mass is 1.6750 x 10^{-27} Kg. The mass of proton is 1836 times the mass of an electron.

MASS NUMBER:

The sum of the number of protons and neutrons in a nucleus is called mass number. It is denoted by A. this number or charge number nucleus number.

ATOMIC NUMBER:

The number of protons in a nucleus is called atomic number of proton number or charge number it is denoted by Z.

NEUTRON NUMBER:

The difference between mass number and atomic number is called neutron number. It is denoted by N and is given by. $N = A - Z$

REPRESENTATION OF AN ELEMENT:

An element X having mass number A and atomic number Z is represented by the symbol. ${}_{Z}X^{A}$

Where X = chemical abbreviation for the particular element.

ISOTOPES:

The elements having same atomic number but different mass number or neutron number are called isotopes. For example hydrogen, deuterium and tritium.

Hydrogen A=1, Z=1, N=0
Deuterium A=2, Z=1, N=1
Tritium A=3, Z=1, N=2

ISOBARS:

The nuclei with the same number of nucleons but different number of neutrons and protons are called isobars.

RADIOACTIVITY:

Radio activity may be defined as the spontaneous disintegration of nucleus of atoms. It is a self disrupting activity exhibited by some naturally occurring elements.

HENRI BACQUERAL:

Discovered that uranium atoms (Z= 92 highly penetrating radiations. There radiations could penetrate not only paper but also glass and even thin sheets of aluminum. It has been found that the elements whose atomic number is greater than 83 are unstable. They emit certain radiations such substances (e.g uranium, radium, polonium) are called radioactivity substances and the radiations emitted form their nuclei are called radio active radiations and this phenomenon is known as radioactivity.

Separation of radiations:

Rutherford and his coworkers proved that the radiations emitted by a radioactive substance are of three different types. The radio active radiations can be separated by applying electric or magnetic field as shown in the figure 1 and 2. a small amount of radioactive substance is placed at the bottom of a cavity drilled in a block of lead. When the narrow beam of radioactive rays is allowed to pas through the space between two charged plates bends towards the positive plate and some rays bends towards the negative plate while others go undeflected by the influence of electric field between the plates. Similar effect is observed in the presence of magnetic field as shown in the figure 2.

The rays bending towards the negative plate indicate that they consist of positively charged particles while those bending towards the positive plate indicate negatively charged particles. The positively charged particles are called $\propto$ alpha particles and the negatively charged particles are called β beta particles. The rays which go undeflected indicate no charge and are therefore energetic photons or the γ gamma rays.

PROPERTIES OF ∝ PARTICLES:

1. The ∝ particles are helium nuclei. The charge of an ∝ particle is twice the charge of a proton and mass is four times that of a proton.
2. The speed of ∝ particles is one hundredth of the velocity of light.
3. They produce fluorescence and affect photographic plate.
4. They are not very penetrating but highly ionizing.
5. In ∝ decay a new element is produced.

PROPERTIES OF β PARTICLES:

1. The β particles are electrons with more energy as compared to ordinary electrons because their origin is nucleus and not the atomic orbits.
2. The sped of β particles is about one tenth of the velocity of light.
3. The produce fluorescence and affect photographic plate.
4. Their penetrating power is greater than the ∝ particles but is less ionizing.
5. In β decay a new element is produced.

PROPERTIES OF γ PARTICLES:

1. γ rays are energetic photons have o charge they are similar to X-rays but are more energetic.
2. They travel with the speed of light.
3. They produce fluorescence and affect photographic plate.
4. Their penetrating power is very high.

THE DISINTEGRATION OF RADIOACTIVE ELEMENTS:

A nuclear species corresponding to given values of A and Z is called a nuclide and is denoted by $_zX^A$ where X is the chemical symbol for the particular element. The main cause of radioactivity is the instability of nucleus of heavy elements.

Emission of ∝:

When a nucleus $_zX^A$ disintegrates by the emission of an ∝ particle its charge number decreases by 2 and mass number decreases by 4. This is given by the following equation.

$_zX^A \rightarrow$ ∝ particle + $(_{z-2}Y^{A-4})$

the original nuclide $_zX^A$ is called parent nucleus and the new nucleus $(_{z-2}Y^{A-4})$ is called daughter nucleus.

In this process the daughter nucleus may also remain unstable and undergo further disintegration till it attains stability.

Emission of β particles:

When a nucleus $_zX^A$ disintegrates by the emission of β particle its charge number decreases or increases by 1 while mass number remains same. This is given by the following equations.

$_zX^A \rightarrow (_{z-1}Y^A) + \beta^+$ (positron)

$_zX^A \rightarrow (_{z+1}Y^A) + \beta^-$ (electron)

β emits due to the disintegration of neutron or proton in the nucleus shown by the following equations.

$_0n^1 \rightarrow + \, _1p^1 + \beta^-$ (electron)

this shown that the disintegration of neutrons causes emission of electron while disintegration of proton causes emission of position.

Emission of γ:

Most frequently the ∝ or β emission leaves the daughter nuclide in an excited state and that one or more γ rays are emitted as it goes back to the ground or normal state (unexcited state). Since the gamma rays are massless photons γ emission will cause no change in either A or Z.

$(_{z-1}Y^A) \rightarrow \gamma + \, _{z-1}Y^A$ OR $(_{z+1}Y^A) \rightarrow \gamma + \, _{z+1}Y^A$

Excited nucleus — excited nucleus

RADIOACTIVE DECAY LAW:

According to this law"In a radio active process the rate of decay is directly proportional to the number of parent nuclides present in the unstable nuclides of a given species at that time. If ΔN be the number of nuclei disintegrated in time Δt and N be the number of nuclei present at time t then.

$$\frac{\Delta N}{\Delta t} \propto N$$

$$\frac{\Delta N}{\Delta t} = -\lambda N \text{ ----------------(1)}$$

Where λ = decay constant or disintegration constant. Its value depends upon the nature of the substances that decays and is independent of all external condition such as temperature, pressure etc. the negative sign shows that number of nuclei N decreases as time increases.

Equation(1) can be written as.

$$\Delta N = -\lambda N \Delta t \text{ --------------(2)}$$

Form equation (2) it can be seen that λ is large more nuclei will decay in the given time i.e the element decays rapidly. On the other hand if λ is small, the element will decay slowly.

ACTIVITY:

The number of nuclei decayed per second or The number of disintegration per second is called activity.
It is a positive quantity end is denoted by A. it is given by.

$$A = \frac{\Delta N}{\Delta t} = \lambda N$$

RELATIVE ACTIVITY:

The ration between the number of nuclei N present at any time t and the number of parent nuclie N_o present at time t=0 is called relative activity.

$$relative\ activity = \frac{N}{N_o}$$

GRAPH:

If a graph is plotted between activity and time or relative activity and time or number of nuclei and time it will be a exponential decreasing curve as shown in the figure. The graph shows that the number of radioactive atoms decreases rapidly in the beginning and then the decay slows down as the time passes. From this nature of decay it is found that:

$$\frac{N}{N_o} = e^{-\lambda t}$$

$$N = N_o e^{-\lambda t}$$

Where e = Natural Logarithm base = 2.718 , above equation is a form of the exponential law of radio active disintegrations.

THE HALF PERIOD OR HALF LIFE OF THE RADIO ACTIVE NUCLIDE:

Half life of a radioactive element is the time required for the radioactive element to decay to one half of its initial number N_o. It is denoted by $T_{1/2}$ and is given by.

$$T_{1/2} = \frac{0.693}{\lambda}$$

This shown that the half life of a radioactive element is inversely proportional to the decay constant.

NUCLEAR CHANGES AND THE CONSERVATION LAWS:

All types of radio actives decays obey some simple and basic rules which are based on conservation laws. The common conservation laws are as follows.

1. Conservation of nuclear number A
2. Conservation of charge number Z
3. Conservation of energy
4. Conservation of linear momentum
5. Conservation of angular momentum (including spin)

EXPLANATION:

The above rules can be explained by considering the example of disintegrating of $_{90}Th^{227}$ into $_{88}Ra^{223}$ and on alpha particles.

$$_{90}Th^{227} \rightarrow {}_{88}Ra^{223} + {}_{2}He^{4} \ (\propto \text{ particles})$$

1. By 1st rule total number of nucleons A on both sides is equal i.e 227
2. By 2nd rules total charge number Z on both sides is equal i.e 90
3. The mass of $_{90}Th^{227}$ = 227.027U the mass of $_{88}Ra^{223}$ = 223.018U and the mass of $_{2}He^{4}$ = 4.002U.

The difference in mass before and after the decay

= 22.7U –(223.018U + 4.002U)

= 227.027 – 227.020U = 0.007U

Where U is deified as one twelfth of the mass of an atom of $_{6}C^{12}$ = atomic mass unit = 931.5MeV.

This difference mass is converted into energy equal to 0.007 x 931.5 = 6.517MeV. out of this energy an energy of 6.04MeV is taken away by the $\propto$ particle. While remaining energy 0.11MeV is taken away by the radium nucleus as K.E.

Q- Value: All the radioactive decays or nuclear reaction involve the release of some energy which is commonly denoted by 'Q' and in the general terminology of nuclear physics it is referred to as the "Q-Value" of the reaction it may be positive or negative

Exothermic reaction:

The reaction in which energy is released is called "exothermic reaction" in this reaction value of 'Q' is positive

Exothermic Reaction:

The reaction in which energy is supplied is called "endothermic reaction" in this reaction value of 'Q' is negative

MASS DEFECT:

The mass of a nucleus is less than the total mass of its constituent's nucleon i.e.

"The difference between mass of constituent nucleon and the mass of nucleus is called mass defect". It is denoted by "Δm".

i.e. m = mass of nucleus in free state- mass of nucleus

BINDING ENERGY:

The difference in mass (Δm) of nucleus and its constituent's nucleus is converted into energy during the formation of the nucleus this energy is called "binding energy" it can be found by formula

Binding energy = E = Δm c2

Where c= speed of light = 3 x 10 m/s

If energy equal to binding energy is supplied to a nucleus it will break i.e. Fission will occur

PACKING FRACTION:

The binding energy per nucleon is called "packing fraction" i.e.

$$\text{Packing fraction} = \frac{BINDING\ ENERGY}{NUCLEON}$$

The packing fraction i.e. binding energy per nucleon of the elements in the middle region of periodic table i.e. iron, cobalt, nickle, is greatest as compared to the other elements.

NUCLEAR FISSION:

The process in which a heavy nucleus such as uranium nucleus is broken into two lighter nuclei of nearly equal masses is known as "nuclear fission"

In most of the nuclei of heavy elements fission can not be produced easily but if there nuclei are bombarded with high energy particles like neutron, fission, can take place in some elements

Hahn, Strassman and other scientists discovered that when an isotope of uranium ${}_{92}U^{235}$ is bombarded with slow neutrons fission take place during the process two intermediate nuclei three neutrons and some energy is released if barium and krypton are the intermediate nuclei produced in fission reaction then it can be represented by the following equation

${}_0n^1 + {}_{92}U^{235} \rightarrow ({}_{92}U^{236}) \rightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3{}_0n^1 + Q$

Where Q is the energy released in the reaction $({}_{92}U^{236})^*$ is excited compound nucleus.

General scheme of Fission:

Barium and Krypton are not only the intermediate nuclei which are obtained in the fission reaction but other intermediate nuclei are also produced thus the general scheme of the nuclear fission reaction is of the following form

${}_0n^1 + {}_{92}U^{235} \rightarrow ({}_{92}U^{236}) \rightarrow x + y + \text{neutrons} + \text{energy} \ (\gamma - \text{ray})$

Chain Reaction

The most important aspect in the fission reaction is the liberation of atleast one or more neutrons. This may further induce fission in the additional heavy nuclei in the form of a Chain reaction resulting in the sudden release of a huge amount of energy (a nuclear bomb). The energy release in the fission process is due to the conversion of mass defect between the mass of the heavy nucleus and the resulting fragments, into energy.

If two neutrons out of three are stopped or captured which can be done by cadmium or graphite rods in nuclear reactors than the chain reaction takes place at the uniform rate and a fixed amount of energy is obtained

Critical Mass and Critical Volume:

It is not possible to start chain reaction n any mass of uranium the mass of uranium required for producing smooth chain reaction is called CRITICAL MASS an the volume occupied by this mass is called CRITICAL VOLUME if the mass is less than the critical mass than fission chain reaction dies on the other hand if the mass of uranium is more than it its critical mass the chain reaction will be uncontrolled one and it will build up at a fast rate and in a few seconds an explosion will occur this is the mechanism which is used in ATOMIC BOMB

NEUTRINO: Neutrino is electrically neutral particle of very very small mass it mass is very small as compared to that of electron and can be neglected

NUCLEAR FUSSION:

A process in which two light nuclei combine (or fuse together) to form a heavy nucleus and energy is released is called NUCLEAR FUSSION the energy released is called "Thermo- nuclear fusion energy"

For example when light nuclei of hydrogen are combined to form a heavier nucleus of helium energy is liberated in fusion the final mass is smaller than the initial mass and the deficit of mass is comparatively greater than its fusion for this reason the energy librated in fusion process is far greater than that librated in the process of fission

It is very difficult to produce fusion reaction due to the fact that when two positively charged nuclei are brought closer and closer and then fused together work has to be done against the electrostatics force of repulsion this require a great deal of energy

Fusion in the laboratory: Control fusion reaction takes place in the laboratory in the following way

i) $_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1 + Q$ (=3.3Mev)
ii) $_1H^2 + {}_1H^2 \rightarrow {}_2H^3 + {}_1H^1 + Q$ (=4.0Mev)
iii) $_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1 + Q$ (=17.6Mev)

Fusion reaction (iii) can produce great amount of energy the raw material for the reaction is deuteron which is found in abundance in world oceans as heavy water

Fusion in Sun and Stars:

The fusion reaction is possible in sun and stars because of very high temperature the fusion reactions are also the basic source of energy in stars including the sun

Fusion in Sun:

In the sun reaction of fusion process is as follows:

$_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + \beta^+ + \upsilon$ (neutrino)
$_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + \gamma$(Gamma ray)
$_1H^1 + {}_2He^3 \rightarrow {}_2He^4 + \beta^+ + \upsilon$

This process is called PROTON – PROTON CYCLE in this fusion process the amount of energy is released is of the order of 25 Mev

Fusion in Stars:

Another fusion process is suggested by Bethe it is called CARBON – NITROGEN CYCLE or simply CARBON CYCLE this process is assumed to occur in stars hotter than sun in this process four protons are converted into an alpha particle with carbon acting as a catalyst in the reaction the sequence of reaction taking place in the carbon cycle are

$_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13} + \gamma$ (gamma ray)
$_7N^{13} \rightarrow {}_6C^{13} + \beta^+ + \upsilon$ (Neutrino)
$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} + \gamma$ (Gamma ray)
$_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15} + \gamma$ (Gamma ray)
$_8O^{15} \rightarrow {}_7N^{15} + \beta^+ + \upsilon$ (Neutrino)
$_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$ (alpha particle)

Carbon reappear i.e. it acts as a catalyst the energy released in complete cycle is more than 26.7 Mev

NUCLEAR REACTION:

A nuclear reactor is a device for utilizing a chain reaction for any of the several purpose to produce power to supply neutrns to induce nucleus reactions to prepare radioisotopes or to make fissionable material from certain "fertile" materials

Components of a Reactor:

Typical components of a reactor are
1) Nuclear fuel or fissionable fuel
2) Moderators
3) Control materials
4) Coolants
5) Shielding

1) Nuclear Fuel: A material consisting of the fissionable (or fissile) isotope is called "reactor fuel" the fuel that may be used in the reactor are uranium $_{92}U^{235}$ or $_{92}U^{239}$ or platinum $_{92}P^{239}$.

2) Moderators: In the nuclear fission process at least one or more energetic neutrons are produced per fission to reduce the energy of these neutrons some suitable materials are required which are known as "moderators" the good moderating materials possess usually low mass number and large slowing down power light water heavy water graphite beryllium and its oxide and certain organic compounds are used as moderators

3) Coolants:

As a result of fission a large amount of heat is generated in the reactor core to remove this heat materials are use which are called "coolants" these materials are usually circulated through the core in order to absorb heat and transfer it to the outside light water heavy water liquid material such as sodium, sodium potassium alloy mercury certain organic liquids and gases are used as coolants the choice of the coolants depends upon the type of the reactor

Properties of a Good Coolant:

Following are the properties of a good coolant

a) It should have a little effect on neutrons as possible i.e. it should not absorb nor moderate the neutrons

b) It should not induce any chemical effect with other material in contact with system

c) The coolant should not breakup under the effect of radiations

d) The coolant material should be capable of acquiring long lived radioactivity during its circulation through the reactor

e) It should have low vapour pressure at the operating temperature of the reactor

f) The material should be able to remove large quantities of heat for a small input of pumping power

Control Material:

In order to control the nucleus fission in a reactor suitable neutron absorbing materials required to be placed in the core region the control material should be such that it does not become radioactive by neutron capture CADMIUM is used as a control material at low temperature due to its low melting point for higher temperature an alloy of SILVER with 15% and 5% CANDIUM is used because of a higher melting point due to large neutron absorbing capability and very high melting point BORON is also use as a control material since times BORON is mixed with stainless steel alumunium or carbon

(5) Shielding: With the exception of reactors operating at very low powers all reactors are the sources of dangerous intense neutron and r- ray radiations to product the health of persons working in the reactor area shielding materials is used generally a layer of concrel about six to eight feet thick is used as a "Biological shield" to remove heat a few centimeters thick iron or steel very closed to the core is used as a "thermal shield"

BREEDER REACTOR:

A Nuclear Reactor that produces (Breeds) the some kind of fissile material as it burns is called breeder reactor. These reactors produce more fuel than what they consume. They generate electricity and build up fuel inventory. Breeder reactors while using plutonium as a fuel can produce more plutonium (${}_{94}Pu^{239}$) than it consumes, by converting ${}_{92}U^{238}$. A Breeder reactor which makes use of fast moving neutrons to bring about the nuclear chain reaction is called Fast Breeder Reactors.

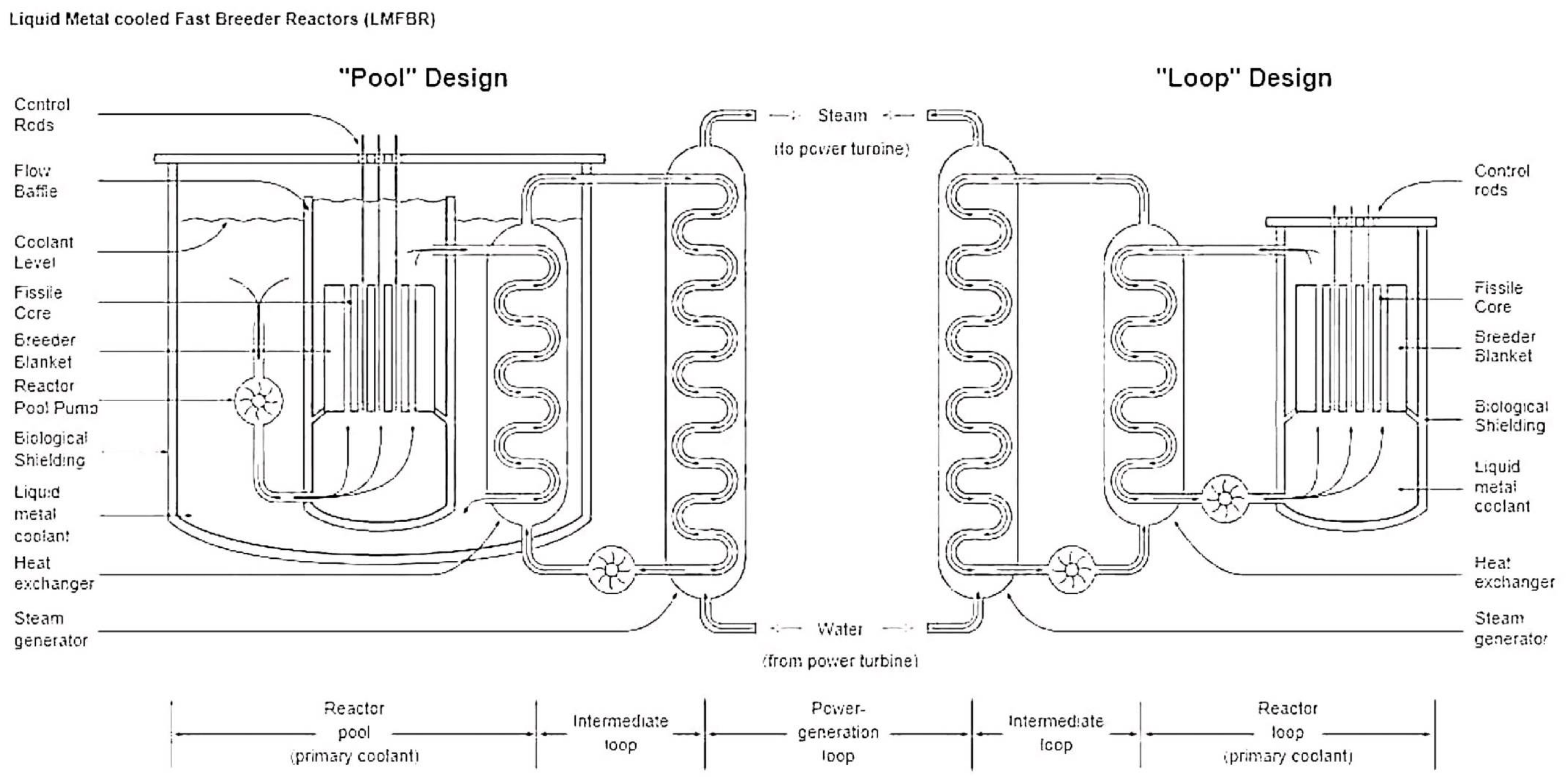
In the natural occurrence of uranium, the isotope ${}_{92}U^{235}$, makes up only 0.72% whereas the rest 99.28% is the other isotope ${}_{92}U^{238}$. The least abundant isotope ${}_{92}U^{235}$ is used as the fuel for conventional reactors. If somehow we could make use of ${}_{92}U^{238}$ as a fuel as a nuclear reactor, we could be better off in increasing the life span of the existing uranium fuel supplies of the world deposits of uranium ore. Due to this reason our interest in breeder type reactors has increased significantly. The far more available isotope, ${}_{92}U^{238}$ has been found more likely to undergo the following reaction:

$${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{93}Np^{239} + \beta^{-} + \upsilon^{-} (anti\ neutrino)$$

$${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{94}Pu^{239} + \beta^{-} + \upsilon^{-} (anti\ neutrino)$$

In this nuclear reaction ${}_{94}Pu^{239}$ is an alpha emitter with a half life of 2.4×10^4 years. It is responsive to undergo fission by slow neutrons. In a breeder reactor some of the neutrons from the fission of ${}_{92}U^{235}$ are used to transmute ${}_{92}U^{238}$ into ${}_{94}Pu^{239}$ as indicated in the above reaction. We see that the breeder reactor does not create material capable of undergoing fission, but it simply converts the unusable most abundant isotope ${}_{92}U^{238}$ into fissionable isotope ${}_{94}Pu^{239}$ with a very long half life of $2.44\times\ 10^4\ years.$ The isotope ${}_{94}Pu^{239}$ is also radioactive and can decay into ${}_{92}U^{235}$ with emission of alpha particle, but due to its long half life large quantities of ${}_{94}Pu^{239}$ can be collected and used for power reactors where it fissions under neutron bombardment with the release of huge amounts of energy through the following nuclear reaction:

$_0n^1 + {}_{94}Pu^{239} \rightarrow 2\ {}_0n^1 + X + Y + 200$ Mev
Where X and Y are the fission fragments.



Fast Breeder Reactor (FBR)
In a fast breeder reactor (FBR) more fissionable material is produced than consumed by the capture of fast neutrons from fertile materials in such reactors the energy of neutrons should not be lowered thus there is no need to use moderator in this reactor reaction in FBR shown in the figure

Liquid Metal Fast Breeder Reactor (LMFBR):
In liquid metal fast breeder rector (LMFBR) stead of using water as coolant sodium is as coolant the sodium melts at 98°C and boiling point is 892°C due to this property of sodium there is no need to pressurize the reactor keep the liquid sodium from vaporizing sodium as a high specific heat and is therefore a good liquid for heat transfer
A schematic diagram of LMFBR is shown in the figure the reactor core is made up of 15 to 30% 92U235 surrounded by a blanket of ${}_{92}U^{238}$ since fast neutrons are more efficient in converting ${}_{92}U^{238}$ to ${}_{94}Pu^{239}$ there is no need o use a moderator in this reactor to slow down the librated neutrons

Advantages of Breeder Reactor:
A few advantages of breeder rector are
1) There is no need of moderator
2) No need to pressurize he reactor to keep the liquid sodium from vaporizing
3) Major portion of available uranium can be used