THE ATOMIC NUCLEUS 19

19.1 RADIO ACTIVITY:

In 1896, a French scientist Henry Becquerel discovered that uranium and its compounds and several elements whose $Z > 82$ emit some mysterious type of radiations which effect photographic plate in dark and also produce ionization in the gases. Such elements are known as ***RADIO-ACTIVE ELEMENTS*** and the phenomena is known as ***RADIOACTIVITY.***

In the beginning it was thought that there were only one type of radiations, but Rutherford and his co-workers were able to prove that the radiations emitted by radioactive substances are of three different types. These are named as Alpha rays, Beta rays and Gamma rays.

19.2 ALPHA PARTICLES OR ALPHA RAYS:

ALPHA DECAY:

Alpha rays or particles possess charge to mass ratio equal to that of Helium nuclei. Hence their mass no. Is A = 4 and charge number is Z = 2, thus they possess +2e charge. When an alpha particle is shot out from a radioactive nucleus (parent nucleus), the mass number of resulting element (daughter nucleus) is decreased by four units and charge number of two units.

$$ {}_{Z}X^{A} \xrightarrow{\alpha\text{-decay}} {}_{Z-2}Y^{A-4} + {}_{2}He^{4} $$

Parent Nucleus — **Daughter Nucleus** — **Alpha Particle**

PROPERTIES OF ALPHA RAYS:

Alpha particles are low penetrating and can be absorbed by 0.1mm of aluminum foil completely. They however possess high ionization power. When alpha particles move in gases, they produce several thousands of ions and ultimately change into Helium atom by absorbing electrons. They travel with a speed one tenth to one hundredth of the light speed. Being the charged particles they deflect in magnetic and electric field and also cast shadow when an opaque object is placed in their paths, which shows their particles nature.

19.3 BETA PARTICLES OR BETA RAYS:

BETA DECAY:

Beta particles are those particles whose charge to mass ratio is equal to that of electron. During Nuclear disintegration, neutrons split up into protons and electron. Since electron cannot stay in the nucleus otherwise it would need energy of about 10^3 MeV, whereas the observed energies of the electrons are a few MeV only, therefore, they are shot out from nucleus spontaneously, thereby changing Neutrons into protons. Hence in Beta decay the charge number of resulting element (daughter nucleus) is increased by one unit whereas mass number remains constant. Beta activity lead to the following disintegration.

$$ {}_{Z}X^{A} \xrightarrow{\beta\text{-decay}} {}_{Z+1}Y^{A} + \beta^{-} $$

(Parent nucleus) — **(daughter nucleus)** — **(Electron)**

Since positron also possess the same charge to mass ratio as that of electron, therefore beta decay also takes place in the following way

$$ {}_{Z}X^{A} \xrightarrow{\beta\text{-decay}} {}_{Z+1}Y^{A} + \beta^{+} $$

(Parent nucleus) — **(daughter nucleus)** — **(Positron)**

PROPERTIES OF BETA RAYS:

The charge to mass ratio of beta particles is the same to that of the electrons and they travel with velocity equal to one-fifth of light speed. They are more penetrating than alpha particles and are absorbed completely by aluminum foil when its thickness is greater than 0.5cm. They can ionize gases but their ionization power is weaker than alpha particles. Being the charged particle they deflect in magnetic and electric field and cast shadow when an opaque abject is placed in their paths, which shows their particle nature.

19.4 GAMMA PARTICLES OR GAMMA RAYS:

GAMMA DECAY:

During Nuclear decay some mysterious radiations were also found which possess energy greater than X-rays. These radiations were called gamma rays ***"Thus gamma particles are the photons of very high energy".*** In gamma decay no change in either the mass number or charge number was observed in the parent nuclei.

$$_{Z}X^{A} \xrightarrow{\gamma\text{-decay}} {}_{Z}Y^{A} + \textbf{Photon } (\gamma\textbf{-rays})$$

PROPERTIES OF GAMMA RAYS:

Gamma rays are the most penetrating rays among the all three types of radiations but possess the least ionization power. They are in general electromagnetic waves, like x-rays but possess greater frequency and energy. They travel in space with light speed "c". Being the uncharged particles they remain unelected in magnetic and electric fields, but cast shadow when an opaque object is placed is their path, which shows their particle nature.

19.5 HALF LIFE:

The time required for one half of parent nuclei to decay into daughter nuclei is called Half Life of Radioactive elements.

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

Where "λ" is the constant depending upon the nature of radioactive element called as decay constant. Thus the Half life of a radioactive element is inversely proportional to the decay constant. S.I unit decay constant is sec^{-1}. The half life of various radioactive elements rangers from 10^{-11}sec to 1.5×10^{7} years.

19.6 LAW OF RADIOACTIVE DECAY:

In natural radioactivity either an Alpha particle or a Beta particle is emitted and gamma particle may accompany in their process. The number of radioactive nuclei in any sample of a radioactive substance decreases continuously as some of the nuclei disintegrate. The rate which the number of nuclei decrease various widely for different nuclei. Rutherford and his coworkers studied the rate of decrease of nuclei and started in a law as, which states that

"The decrease in the rate of parent nuclei is directly proportional to the number of nuclei available for disintegration."

If N is the number of nuclei available initially and ΔN is the number of nuclei that decayed in time Δt, then

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

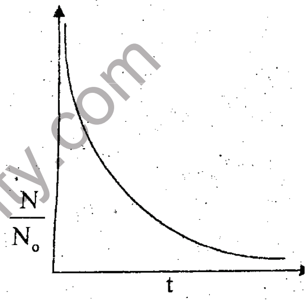
OR $$\frac{-\Delta N}{\Delta t} = \lambda N$$

Where λ is the decay constant, defined as ***"The number of parent nuclei disintegrated in unit time with respect to the nuclei present for decay."*** The negative sign indicates that N decreases with time. The product of decay constant and number of parent nuclei is called the ***Activity*** and is defined as, ***"The number of nuclei disintegration per second."***

$$\lambda N = A$$

Where A is the Activity. The activity of a radioactive element is a positive number which represents the decaying ability of substance subjected to extrinsic conditions.

IF N_0 is the number of parent nuclei available to decay at t = 0, then the graph between the relative activity N/N_0 and time is an exponential curve, which shows that the number of radioactive nuclei decrease rapidly in the beginning and the decays slowly as the time passes. This trend of radioactivity decay is mathematically expressed as:



$$\frac{N}{N_0} = e^{-\lambda t}$$

Where "e" is the base of natural logarithm.

$$N = N_0 e^{-\lambda t}$$

This shows that parent nuclei follow exponential decay with time.

19.7 MASS DEFECT:

Exact measurements of the atomic masses of radio isotopes showed that these masses were not exactly the whole numbers. When the nuclear masses were measured and compared with the masses of the constituent nucleons in free state, the nuclear mass were found less than the mass of the constituent nucleons. This difference in mass is called as the ***Mass Defect.***

Thus mass defect is defined as ***"The Difference of mass of Nucleons in free state and mass of nucleus".*** If A is the nuclear mass of radio isotope and M is the mass of nucleons in the free state then the mass defect Δm is given by

$$\Delta m = (M-A)$$

19.8 BINDING ENERGY:

During the study of nuclear masses it was found that the mass of nucleus (A) is slightly less then the mass of its constituents or nucleons in the free state (M). This difference in nuclear mass Δm = M-A turns into the energy according to the Einstein's Mass-energy relation. Thus $(\Delta m)\ C^2$ is the energy by which Nucleons are binded together. Therefore, an equivalent amount of energy is required to split up the nucleus into its constituents. The magnitude of this energy is called the ***Binding Energy*** of Nucleus. Thus ***"the energy required to assemble or to split up the nucleus into its constitutes is called the binding energy".*** Thus greater the binding energy of Nucleus, the greater is its stability, against splitting up into its constituents.

$$\textbf{B.E} = (\Delta m)\ C^2$$

$$\textbf{B.E} = (M-A)\ C^2$$

19.9 BINDING ENERGY PER NUCLEON OR BINDING FRACTION:

Binding energy of nucleus the measure of the stability of nucleus against splitting up into its constituent. If however, one requires to evaluate the absolute stability of nucleus against splitting up into all its constituents, the binding energy would be expected to increase with increasing A. This trend follow irrespective of the degree of stability of nucleus. Thus to measure the degree of stability of nucleus, we use the term binding fraction ***"Binding fraction of Nucleus is defined as the binding energy per nucleon."***

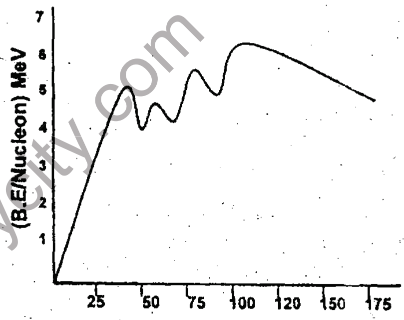
$$F = \frac{B.E}{A}$$

OR

$$F = \frac{(\Delta m)C^2}{A}$$

OR

$$F = \frac{(M - A)C^2}{A}$$



Where "F" is the binding fraction and B.E/A is the binding energy per nucleon. If we plot the binding energy nucleon (B.E/A) against the nucleon number (A) or the nuclear mass, the following trend is observed.

The binding energy per nucleon increases rapidly at first and then slowly decreases as the number of nucleons increases beyond about 60.

Apparently the nuclei with largest binding per nucleon and most tightly bounded are those in the middle region of the periodic table of elements. Their binding energy per nucleon is over 8MeV.

19.10 PACKING FRACTION:

Binding Fraction provides the degree of stability of nuclei Aston introduced another term for the same called the packing fraction. It is denoted by P.F, and is defined as ***"the mass defect of nucleus per nucleon."***

$$P.F = \frac{\Delta m}{A}$$

OR

$$P.F = \frac{M - A}{A}$$

Packing fraction has small value for those nuclei whose mass number lie between 20 and 80 and has minimum value close to A = 60. For value "A" less than 80 the stability of nuclei increase. Thus the nucleus has a very high stable condition. It seems that helium nucleus can act as a sun-unit in nuclear structure. That is why many lights elements, whose mass numbers are exact multiple of 4, lie on the side of stable curve.

19.11 FISSION PROCESS:

"Nuclear Fission is the process in which a heavy nucleus splits up into two smaller fragments with an evolution of huge amount of energy". Meinster and Frisch in 1939 observed by $_{92}u^{235}$ makes it sufficiently exited to split up into smaller fragments of approximately equal masses. A typical nuclear fission is the following

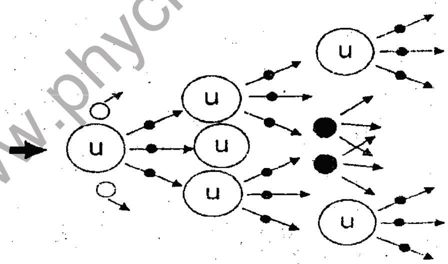
$$_0n^1 + {}_{92}U^{235} \longrightarrow ({}_{92}U^{236})^* \longrightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3{}_0n^1 + Q\ (\text{energy})$$

(Excited compound nucleus)

Where Q is the energy released in the reaction.

Each Fission Process takes place only in certain heavy nuclei. The fragments formed release neutrons and undergo β-decay which is accompanied by gamma decay. Huge amount of energy is released in the fission process itself and further in the decay of the fission fragments.

CHAIN REACTION:



Hahns and Strassman in their attempt found that the number of fresh neutrons produced per fission is on the average between one and three. Hence if the number of number of neutrons is allowed to increase, the process of fission becomes automatically faster and faster. This is called chain reaction.

A typical type of chain reaction takes place in the Atom bomb when a neutron enters in the nucleus of, $_{92}U^{235}$. Certain transmutation takes place and a huge amount of energy is released due to the conversion of mass defect between the mass of the heavy nucleus and the resulting fragments. If such a reaction is allowed to proceed, it would lead to a huge explosion because of the uncheck release of energy. Graphite and cadmium rods inserted in reaction chamber are used as a device called Moderator which keeps the chain reaction well below the self sustaining level.

19.12 FUSION PROCESS:

"The process in which two lights nuclei fused to form up a bigger nucleus with an evolution of large amount of energy is called Nuclear Fusion". When two positively charged nuclei are brought close to fuse together, a large amount of energy is required to bring them close against the electrostatic repulsion force between the nuclei. For this purpose a fission bomb is exploded inside the thermo nuclear explosive. The fusion reaction produce a large number of neutrons of fairly large energy, which can be used to produce fusion again.

$${}_1H^3 + {}_1H^1 \longrightarrow {}_2He^3 + {}_0n^1 + Q$$

$${}_2He^3 + {}_0n^1 \longrightarrow {}_2He^4 + Q$$

One of the promising fusion reaction is the hydrogen bomb. In hydrogen bomb two nuclei of Deuterium are fused to form a helium nucleus with the conversion of mass into energy. In order to start fusion, the explosive material must be heated at a high temperature (several millions of degree celcius), which overcomes the electrostatic repulsive force between two deuteron nuclei which then fused together and results one tritium nucleus and a proton and heat energy.

$${}_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + Q$$

The heat energy evolved now fuse helium isotope and neutron together to result an alpha particle. Thus finally a large amount of energy is obtained.

$${}_1H^3 + {}_1H^1 \longrightarrow {}_2He^4 + Q$$

Fusion reactions are also the basic source of energy in stars. In 1938 Bethe proposed a cycle of fusion reactions in the sun known as carbon cycle in which four protons are converted into an alpha particles with carbon acting as a catalyst. The sequence of reaction taking place in the carbon cycle are:

$${}_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13} + \gamma$$

(Proton) (Gamma ray)

$${}_7N^{13} \longrightarrow {}_6C^{13} + \beta^+ + \upsilon$$

(Neutrino)

$${}_6C^{13} + {}_1H^1 \longrightarrow {}_7N^{14} + \gamma$$

(Proton) (Gamma ray)

$${}_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15} + \gamma$$

(Proton) (Gamma ray)

$${}_8O^{15} \longrightarrow {}_7N^{15} + \beta^+ + \upsilon$$

(Neutrino)

$${}_7N^{15} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4$$

(Proton) (Alpha particle)

19.13 NUCLEAR REACTORS:

"*Nuclear Reactor is the device where Nuclear Fission is carried in a controlled manner for peaceful purpose*". The general features of Nuclear reactor are highlighted as:

1) NUCLEAR FUEL:

"***A material consisting of the fissionable isotope is called the Nuclear Fuel***". The conventional nuclear fuel is $_{92}U^{235}$.

2) MODERATORS:

"***Moderators are the devices used in Nuclear Reactor to control the energy of Neutrons Produced Per Fission***". Heavy water, graphite, Beryllium and certain organic compounds are used as moderators.

3) COOLANTS:

"***Materials such as heavy water, sodium, mercury etc. which are used in Nuclear reactor to remove a huge amount of heat energy generated as a result of Fission are called coolant***". The Properties of a good coolant are:

- **i)** It should not absorb nor moderate the Neutrons.
- **ii)** It should not induce any chemical effect neither in itself nor in other materials of reactor.
- **iii)** It should not break up under the effect of radiations.
- **iv)** It should have low vapor pressure.

4) CONTROL MATERIALS:

"***The devices which control the Nuclear Fission by absorbing Neutrons are called control materials***". Cadmium, an alloy of Silver-Indium-Cadmium, Boron etc. are the best control materials.

5) SHIELDING:

"Shielding is the process of preventing environment and life from the hazards of radiations of Nuclear Fission in the Nuclear Reactor". Protection of health of persons working in reactor is called "***Biological Shielding***". Where as protection from heat is called "***Thermal shielding***".

19.14 BREEDER REACTOR:

"The process in which a nonfissile abundant isotopes $_{92}U^{238}$ is converted into a fissile nucleus $_{94}Pu^{239}$ is called Breeding and the reactor conducting breading of uranium is called Breeder Reactor".

In the Natural occurrence of uranium, the isotope $_{92}U^{235}$ makes up only 0.7% which is used as a nuclear fuel and whose half life is only seven days. In a Breeder reactor some of the neutrons from the fission of $_{92}U^{235}$ are used to transmute $_{92}U^{238}$ in $_{94}Pu^{239}$ whose half life is 2.44 x 10^4 years.

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{94}Pu^{239} + 2\beta^- + \upsilon$$

The isotope $_{94}Pu^{239}$ is an alpha emitter which can decay into $_{92}U^{235}$.

$$_0n^1 + {}_{94}Pu^{239} \longrightarrow {}_{92}U^{235} + {}_2He^4 + {}_0n^1$$

Where neutron acts as a catalyst. Later on modifications of Breeder Reactor made it possible to produce more fissionable material by the capture of fast neutrons from fertile material. Breeder Reactor thus modified is called ***Fast Breeder Reactor (FBR)***. In some Breeder reactor sodium due to its low vapor pressure used as a coolant in liquid state, therefore such reactor is called ***Liquid Metal Fast Breeder Reactor (LMFBR).***

USES OF NUCLEAR REACTOR:

i) Nuclear reactors are the source of power generation.

ii) Nuclear reactors are the source of useful neutrons. Which acts as research tools in various sciences?

iii) Nuclear reactors are used in providing such isotopes which are used in the treatment of various ailments such as cancer.