ARTI VERMA

NUCLEAR PHYSICS

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P-II

Completed

UNIT - 1

NUCLEAR PHYSICS AND ELECTRON BALLISTICS

Lect 45

structure of atomic nuclei :-

atom contains -

(i) Three fundamental sub atomic particles electrons, protons, & neutrons.

(ii) A nucleus which comprises practically the whole mass of atom, consists of protons and neutrons and

(iii) Electrons moves in space surrounding the nucleus.

Each protons carries a unit +ve charge and charge in the nucleus is equal to the number of protons in it. A chemical element always has its atoms with same positive charge in the nucleus. A nuclear charge is fixed by number of protons and the number of protons in the nucleus distinguish the various atoms of different elements. The nuclear charge (number of positive change in the nucleus) of atom was determined by Moseley in 1914 by study of the wavelength of x-ray emitted from different elements.

Mathematically we have

Atomic number = Number of protons in the nucleus.

= Number of electrons outside the nucleus.

Nucleus contains another ~~charged~~ neutral particle called neutrons. These neutral particle possess a mass of 1.675×10^{-27} kg, which is 1.00866 a.m.u. The neutron particle has extremely high penetrating power much greater than alpha and beta particles. Like protons, neutrons also contribute to the mass of atoms. The mass of the atom on atomic weight scale is equal to sum of of protons and neutrons present therein. Recent researches on the nuclei of various elements have indicated that the atomic number is a fundamental property of the atom which determines the physical and chemical properties of the atoms.

Classification of Nuclei :—

Atoms of different elements are classified as follows:—

(i) **Isotopes** :— are nuclei with same atomic number Z but different mass numbers A. The isotopes of elements have identical chemical properties but different physical properties.

Eg :- $_8O^{15}$, $_8O^{16}$, $_8O^{17}$, $_8O^{18}$ are isotopes of oxygen.

(ii) **Isobars** :— are nuclei with same mass ~~atomic~~ number A. The Isobars are atoms of different elements and have different physical and chemical properties.

Eg:- $_8O^{16}$ and $_7N^{16}$ are isobars.

(iii) **Isotones**:— are nuclei with an equal number of neutrons (N)

Eg:- $_6C^{14}$, $_7N^{16}$ & $_8O^{16}$ in which

$N = A - Z = 8$

(iv) Mirror Nuclei :—
having same mass number A but with the proton and neutron number interchanged.

Eg:— $_4Be^7$ ($Z = 4$ and $N = 3$) and
$_3Li^7$ ($Z = 3$ and $N = 4$)

Lect 43

Properties of Nucleus :—

(i) Nuclear Size :—
Rutherford α- particle scattering experiment showed that the mean radius of an atomic nucleus is of the order of 10^{-14} to 10^{-15} m.
As the volume of a nucleus is directly proportional to number of nucleons (A)

$$\text{volume} \propto A$$

$$\frac{4}{3}\pi R^3 \propto A$$

where $R \Rightarrow$ nuclear radius.

Hence $R^3 \propto \frac{3}{4\pi} A$

$$R = C\left(\frac{3}{4\pi}\right)^{1/3} A^{1/3}$$

where C is proportionality constant

Let $C\left(\frac{3}{4\pi}\right)^{1/3} = R_0$ (say)

$$\boxed{R = R_0 A^{1/3}}$$

The value of R_0 is :

size of mass distribution $R_0 = 1.4$ fm

size of charge distribution $R_0 = 1.2$ fm

where $1 \text{ fm} = 10^{-15}$ m.

(ii) Nuclear mass :—

As we know that the nucleus consists of protons and neutrons

Hence

Assumed nuclear mass $= Zm_p + Nm_n$

where $m_p \rightarrow$ mass of proton

$m_n \rightarrow$ mass of neutrons

$N \rightarrow$ Neutron number.

Measurments by mass spectrometer however show that

$$\text{real nuclear mass} < Zm_p + Nm_n$$

The difference in masses

$$(Zm_p + Nm_n) - (\text{real nuclear mass}) = \Delta$$

This Δm is called mass defect.

(iii) Nuclear Density :—

The nuclear dencity ρ_N can be calulated from

$$\rho_N = \frac{\text{Nuclear mass}}{\text{Nuclear volume}}$$

$$= \frac{A \times (\text{mass of a nucleon})}{\frac{4}{3}\pi R^3}$$

$$= \frac{A \times M}{\frac{4}{3}\pi R_0^3 A} \quad \left\{ \because R = R_0 A^{1/3} \right.$$

$$\boxed{\rho_N = \frac{3M}{4\pi R_0^3}}$$

Therefore nuclear density is independent of mass number.

$$\therefore \quad \rho_N = \frac{3 \times 1.66 \times 10^{-27}}{4 \times 3.14 \times (1.4)^3} = 1.45 \times 10^{17}\ kg/m^3$$

(iv) Nuclear ~~size~~ :— charge :—

The charge of nucleus is due to the protons contained in it. Each protons has a positive charge of 1.6×10^{-19} C. The nuclear charge is (Ze) where Z is the atomic number of the nucleus.

(v) spin and magnetic moments :—
protons and neutrons like electrons are fermions with spin quantum numbers of $s = \frac{1}{2}$.
Therefore spin angular momentum
$$S = \sqrt{s(s+1)}\,\hbar = \sqrt{\frac{3}{2}}\,\hbar$$

✓

Magnetic moments are expressed in nuclear magnetons (μ_N)

$$\mu_N = \frac{e\hbar}{2m_p} = 5.051 \times 10^{-27}\ J/T$$

$$= 3.152\ eV/T$$

Where m_p is mass of proton. Since $m_p = 1836\, m_e$, the nuclear magneton is only $\frac{1}{1836}$ of a Bohr magneton $\left(\mu_B = \frac{eh}{4\pi m}\right)$. For nucleons, however, measurements give $\mu_p = 2.7925\ \mu_N$ and $\mu_n = -1.9128\ \mu_N$

Lect 44

Radioactive Decay :-

The spontaneous transformation occuring in the constitution of radioactive nuclei due to radioactive property is called radioactive decay or radioactive disintegration.

The transformation accompa by emission of α- rays is called α-decay and that accompained by emission of β-rays is called β-decay. The nucleus that undergoes radioactive decay is called the <u>parent</u>, the intermediate products are called <u>daughters</u> and the final stable radioactive nucleus is called the <u>end products</u>.

Properties of α-rays :—

(i) α-rays are heavily charged particles having two positive charges ie doubly ionized helium atom (He atom with both of its electron removed). The mass of α particle is 6.645×10^{-27} kg and charge is 3.2×10^{-19} coulomb. They are represented by $_2He^4$.

(ii) being charged particle α-rays are deflected by electric and magnetic fields. The direction of deflections shows that they consists of positively charged particles. Their deflection in fields indicated that they are ~~heavily~~ heavy particles having greater inertia.

(iii) The velocity of α particles, depends upon the nature o[f] the emitting ~~radiation~~ radioactive element. The velocit[y] ranging from $1/10$ to $1/100$ of the velocity of light.

(iv) They effect photographic pla[te]

(v) They produce heating effect when stopped and cause fatal burn on human body.

(vi) They produce fluorescence in substance like zinc sulphide, barium platinocyanide etc.

(vii) They produce intense ionization in gases through which they pass. The ionizing capacity of α particles is about 100 times that of β particles and about 1000 times γ- rays.

(viii) penetrating power of α- particle is less than β and γ- particle the penetrating power of α-particles is inversely proportional to ionizing power.

(ix) The range of α-particle is defined as the distance travelled through air at NTP before it loses its ionizing power. The range depends on nature of radioactive material giving α particle, nature of absorbing material and initial velocity of emission.

(x) As α-particles are positively charged, they are scattered while passing through thin sheet of mica and aluminium etc. The deflections are due to scattering of α-particle due to nucleus.

Properties of β- rays :—

(i) β- particles are fast moving electrons which are of nuclear origin without having orbital mo

(ii) They are deflected by electric and magnetic field. Their greater deflec in electric field indicates that β-particle is lighter than α- particle

(iii) β - particles emitted by nucleus have velocity which covers wide range

(iv) They effect photographic plate very much than α- particles.

(v) They produce fluorescence in barium platinocyanide, calcium tungstate etc.

(vi) β - particles produce ionization in air.

(vii) β - particles are more penetrating than α- particles and can pass through 1 mm of aluminium.

(viii) The range of β particle is much greater than that of α-particles. A β-particle with energy of 0.5 MeV has a range in air at NTP about a meter.

(ix) β-particles are readily scattered by matter due to their extremely small mass.

Properties of γ-rays:-

(i) γ-rays are not charged particles but they are electromagnetic waves of very short wavelength. They are identical with x-rays. The only difference in their origin. photons originating from nucleus are called γ-rays.

(ii) Since they are uncharged particles they are unaffected by electric and magnetic field.

(iii) γ- rays travel with velocity of light.

(iv) They affect the photograph plate more strongly than β-ra

(v) They produce fluorescence in certain crystals.

(vi) They produce feeble ionizat The ionization power is very low as compared to β- particles.

(vii) They produce a small heatin effect when absorbed in matter

(viii) They have high penetrating power. They can even pass throug an iron plate 30 cm thickness.

(ix) They are diffracted by crystal like x- rays.

(x) They eject β- rays from matter on which they fall.

(xi) These rays exhibits the phenomenon of pair production

$$h\nu \longrightarrow e^- + e^+$$
(γ photon) (electron) (position)

Lect 47

Nuclear Reactions:—

A change in the structure of nuclei can be brought about by bombarding them with fast moving particles. In this process characteristic or identity of incident particle undergoes a change which is called nuclear reaction.

Nuclear reaction are generally produced by exponsing the target nuclei with the help of fast moving nuclear projectile. The nuclear particles may be charged particles like protons etc, or uncharged particles like neutrons, γ-rays etc

Bohr's theory of Nuclear reactio

Bohr's on the basis of liquid drop model explained the process of nuclear reactions. According to Bohr, when a nuclear particle strikes the nucleus, it is captured by nucleus and compound nucleus is formed. The compound nucleus is of similar in heated up liquid drop. ~~model~~ Now projectile particle loses its identity and its all energy is distributed among all the particles of newly formed compound nucleus.

The compound nucleus is in excited state, of course no particle has sufficient energy to escape from the compound nucleus. After considerable gap of time one of the particle acquires sufficiently excess energy and escapes from the nucleus. The process of escaping is known as disintegration or transmutation.

Nuclear reaction may of the following two types:-

(i) particle disintegration process: the process in which outgoing particle is material particle

(ii) simple capture process:- In this process outgoing emission consists of γ-rays.

Conservation laws of Nuclear reaction :-

(1) Conservation of charges:- total charge of the reactants is conserved.

(2) Conservation of nucleons:- total number of nucleons before and after reaction remains constant as nucleons can neither be created nor be destroyed.

(3) Mass and energy:- In a nuclear reaction mass and energy are not separately conserved. However their total is always conserved.

(4) Conservation of linear momentum
It is fundamental law and is conserved in nuclear reaction

(5) Conservation of angular momentum
total angular momentum is composed of ~~an~~ orbital angular momentum and spin angular momentum, vector sum of the angular momentum is conserved in a nuclear reaction.

(6) Conservation of spin and statics
statics imposes a restriction in a nuclear reaction.

Natural and Artificial Radioactivity

Natural Radioactivity :— The phenomenon of spontaneous emission of powerful radiation exhibited by the heavier element found in nature is called natural radioactivity

Artificial Radioactivity :— The phenomenon of spontaneous emission of powerful radiation from the element much lighter than those occure in nature by modern techniques of artificial or induced radioactivity.

Radioactive disintegration:-

The spontaneous breaking up of the nucleus is known as radioactive disintegration.

when element disintegrated by emission of α-rays it is turned into a new element with chemical properties similar to those of an element two place earlier in periodic table.

Eg:- An element X of mass number A and atomic number Z while emitting an α-particle is converted into another element Y having mass number less by four and atomic number less by two.

$$_{Z}X^{A} \longrightarrow {}_{2}He^{4} + {}_{Z-2}Y^{A-4}$$

(α-particle

$$_{92}U^{238} \longrightarrow {}_{2}He^{4} + {}_{90}Th^{234}$$

Similarly element disintegrated emission of β- particle, it is turned into another new element with properties similar to those of an element one place later in periodic table

Eg:— An element X which emits β-rays is turned into another daughter element Y

$$_{Z}X^{A} \longrightarrow {}_{-1}e^{0} + {}_{Z+1}Y^{A} + \gamma \text{ ra}$$

(β-particle)

$$_{90}Th^{234} \longrightarrow {}_{-1}e^{0} + {}_{91}Pa^{234} + \gamma$$

(Thorium) (β-particle) (protactium)

Laws of radioactive dis integration

Rutherford and soddy discovered following laws of radioactive disintegration.

(1) Atoms of all radioactive elements undergo spontaneous disintegrations is accompained by emission of α, β, γ

(2) The disintegration is at random ie which atom will ~~disintegration~~ by disintegrate first is only a matter of chance.

(3) The number of atoms that disintegrate per second is directly proportional to No. of remaining unchanged radioactive atoms present at any instant. The disintegration is Independent of all physical and chemical conditions.

Let N be the number of atoms present in radioactive substance at any instance 't', and dN is number of atoms that disintegrate in short interval dt then the rate of decay of atom is $-(dN/dt)$. Now $-dN/dt$ is proportional to N ie

$$-\frac{dN}{dt} \propto N$$

$$-\frac{dN}{dt} = \lambda N \quad \text{——— (1)}$$

where λ is constant of proportionality and knowns as disintegration constant or radioactive constant.

$$\therefore \frac{dN}{N} = -\lambda dt$$

Integrating

$$\log_e N = -\lambda t + C \quad \text{--- (2)}$$

Where 'C' is disintegration const

Let at time $t = 0$, the number of atom present $N = N_0$ hence equati (2)

$$\log N_0 = C \quad \text{--- (3)}$$

Substituting the value of C in equation (2) we get

$$\log_e N = -\lambda t + \log_e N_0$$

$$\log_e N - \log_e N_0 = -\lambda t$$

$$\log_e \left(\frac{N}{N_0}\right) = -\lambda t$$

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

$$\boxed{N = N_0 e^{-\lambda t}} \quad \text{--- (4)}$$

Unit of radioactivity
1 curie = 3.7×10^{10} dis / sec
1 rd = 10^6 dis / sec.

Above equation shows that number of atoms of a given radioactive substance decreases exponentially with time.

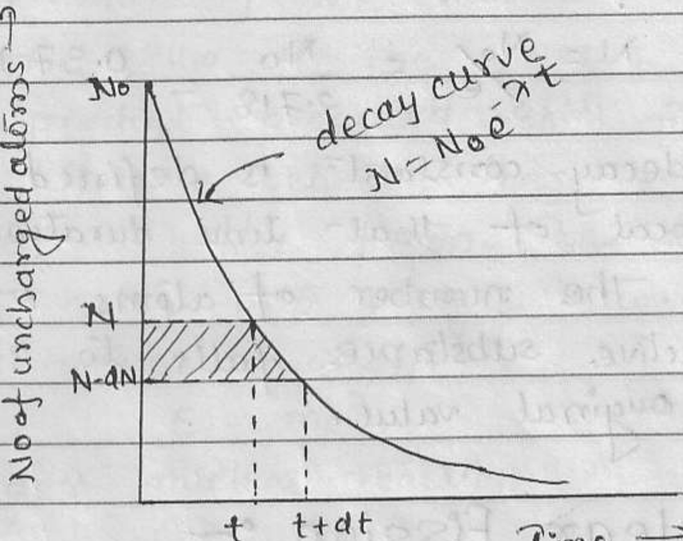

fig 1.1

From equation (4) we have

$$\lambda = \frac{-dN/dt}{N}$$

Hence decay constant is defined as the ratio of the amount of the substance disintegrated in unit time to the amount of substance present.

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

Let $t = 1/\lambda$

$$N = N_0 e^{-\lambda \times \frac{1}{\lambda}}$$

$$N = N_0 e^{-1}$$

$$N = N_0/e = \frac{N_0}{2.718} = 0.37 N_0$$

Thus decay constant is defined as the reciprocal of that time duration for which the number of atoms of radioactive substance falls to 37% of its original value.

Nuclear Fission :-

The process in which a heavy nucleus, after capturing a neutron splits up into two lighter nuclei of comparable masses, with the release of a large amount of energy is known as nuclear reaction.

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236*} \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1}$$

Energy released in fission :—

In the nuclear fission process a large amount of energy is released. This energy is produced because the original mass of the nucleus is greater than the sum of the masses of the product produced after fission. The difference between these masses before and after fission. ~~The~~ difference is converted into energy according to Einstein's equation.

$$E = mc^2$$

Consider nuclear reaction

$$_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236*} \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_0n^1 + Q$$

Estimate the actual ~~and~~ masses before and after the fission reaction.

Mass of $_{92}U^{235}$ = 235.045733 u
Mass of $_0n^1$ = 1.0086654

~~Total mass = 236.0543984 u~~

Mass of $_{56}Ba^{141}$ = 140.9177 u

Mass of $_{36}Kr^{92}$ = 91.8854 u

mass of 3 neutrons = 3.025995 u

Total final mass = 235.829095

mass decrease = 236.054398 − 235.8290
= 0.2253 u

This decrease in mass is converted into energy

Energy released = 0.2253 × 931
= 209.8 MeV

(∵ 1 u = 931 Me

Thus in the process of fission of one nucleus of uranium, about 200MeV energy is released.

<u>Energy Released by 1gm of Uranium</u>

Number of atoms in 1gm of uranium

$$= \frac{6.023 \times 10^{23}}{235}$$

Energy released in one fission = 200 MeV

Energy produced by 1 kg of uranium during fission

$$E = \frac{6.023 \times 10^{26}}{235} \times 200$$

$$= 5.128 \times 10^{26}\ \text{MeV}$$

$$E = (5.128 \times 10^{26}) \times (1.6 \times 10^{-13})\ J$$

$$(\because 1\ \text{MeV} = 1.6 \times 10^{-13}\ J)$$

$$= \frac{(5.128 \times 10^{26}) \times (1.6 \times 10^{-13})}{3.6 \times 10^{6}}\ \text{kwh}$$

$$(\because 1\ \text{kwh} = 3.6 \times 10^{6}\ J)$$

$$E = 2.26 \times 10^{7}\ \text{KWh}$$

Thus the energy released by fission of 1 kg of U^{235} is 2.26×10^{7} KWh. This is the reason why, nuclear energy is being used for generating electricity.

Chain Reaction :—

The chain reaction is a proce in which the nuclear fission of an atom induces nuclear fission another atom which again induces fission in another atom and so on.

During every fission proces neutrons are emitted which attack other atoms causing fission. The number of neutrons goes on multiply rapidly during fission process, till whole of the fissionable material is disintegrated.

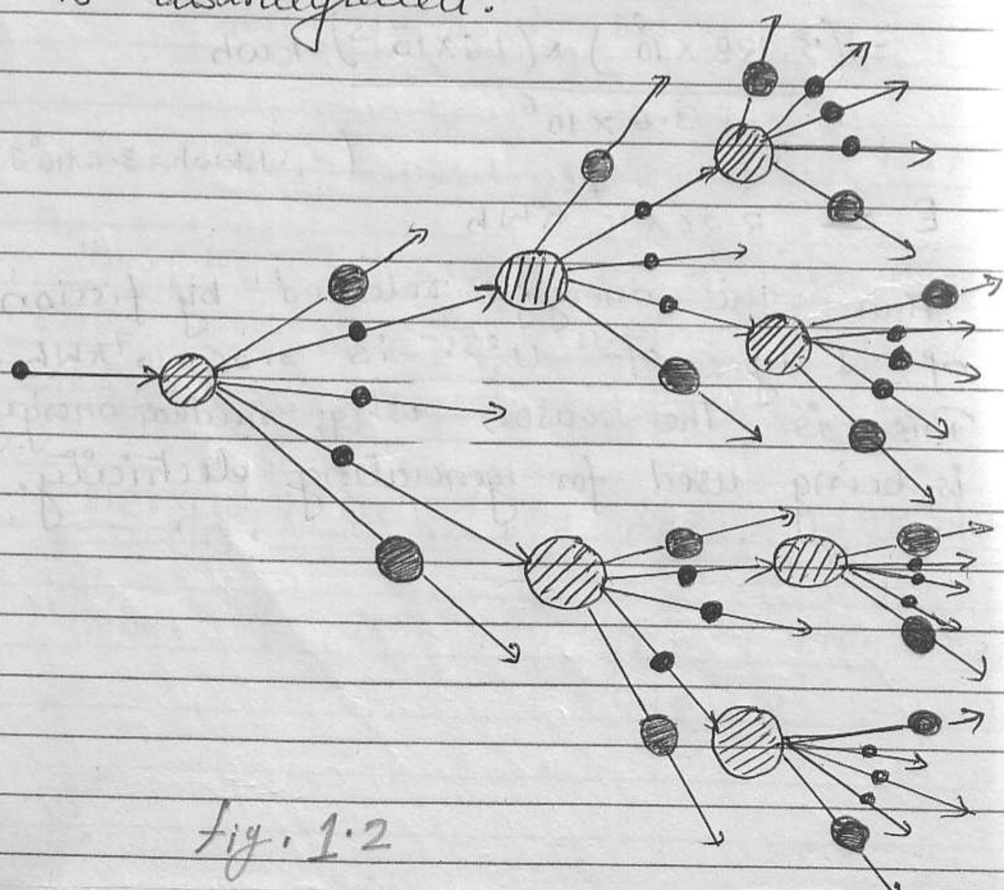

fig. 1.2

The chain reactions may be of two types :—

(1) **Uncontrolled chain Reaction :—**

In this type of chain reaction the number of neutrons is allowed to multiply indefinitely and entire energy is released all at once as a violent explosion.

Eg:- nuclear bomb.

(2) **Controlled chain Reaction :—**

In this type of chain reaction, the reaction is first accelerated so that neutrons are built up to certain level and thereafter number of fission producing neutrons is kept constant by some means. Such a controlled chain reaction is used in nuclear reactor.

Neutron multiplication factor:-

The ratio of secondary neutrons produced to the original neutrons is called "neutron multiplication factor". It is denoted by K

$$K = \frac{\text{(No of neutrons present in one generation)}}{\text{(No of neutrons present in previous generation)}}$$

If $K < 1$ the chain reaction will slow down and stop, this condition is termed as 'subcritical'.

If $K = 1$, the chain reaction will proceed at steady rate, condition is termed "a critical".
Eg:- nuclear reactor.

If $K > 1$ the chain reaction will grow to explosive rate, this condition is termed as "super critical".
Eg:- nuclear bomb.

Critical Size for maintenance of chain reaction.

In the fission of uranium nuclei, 2.5 neutron on an average emitted per fission. Some of them escape through the surface of the uranium while many are lost in non-fission process. The maintenance of the chain reaction depends upon a fovourable balance of neutrons among the three process given below:-

(1) The fission of uranium nuclei which produces more neutrons than the number of neutrons used for inducing fission.

(2) Non-fission processes, including the radiative capture of neutrons by the uranium and the parasitic capture, by the different substances in the system and by impurities.

(3) Escape or leakage of neutrons through the surface of the system.

If the loss of neutrons due to the last two causes is less than the surplus of neutr produced in the first, a chain reaction takes place. Otherwis it cannot take place.

Let us consider a uranium sphere of radius R. Let N_1 be the number of neutrons produced in a given tim interval, N_2 be number of neutrons lost in non-fission process and N_3 the number escaped through the surface in same time-interva N_1 and N_2 will be proportional the volume, while N_3 will be propo to the surface area of sphere.

Thus $N_1 \propto \frac{4}{3}\pi R^3 = c_1 R^3$

$$N_2 \propto \frac{4}{3}\pi R^3 = c_2 R^3$$

$$N_3 \propto 4\pi R^2 = c_3 R^2$$

where c_1, c_2, c_3 are proportionali constant.

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where C_1, C_2, C_3 are proportionality constant.

For $K > 1$, we must have

$$\Rightarrow N_1 > N_2 + N_3$$

$$\Rightarrow C_1 R^3 > C_2 R^3 + C_3 R^2$$

$$\Rightarrow C_1 R > C_2 R + C_3$$

$$\Rightarrow (C_1 - C_2) R > C_3$$

$$\Rightarrow \boxed{R > \frac{C_3}{C_1 - C_2} = C \text{ (say)}}$$

C is known as critical size of sample. Thus in order to achieve a self sustained chain reaction, the size (or mass) of sample must be greater than a critical value C. Below the critical size (or critical mass) the chain reaction would not occure.

Critical size of a system containing fissile material is defined as the minimum size for which for which the number of neutrons produced in the fission process just balance those lost by leakage and non-fission capture. The mass of fissionable material at this size is called critical mass.

If the size is less than critical size, a chain reaction is not possible.

Nuclear Reactors :—

A nuclear is a device in which a self-sustaining, controlled chain reaction is produced in a fissionable material. It is thus a source of controlled energy. The main part of a typical nuclear reactor are as follows:

(i) Fuel :— An important feature of nuclear reactor is that the fuel here is not highly enriched. The uranium fuel (U^{235} isotopes) is generally used in the form of rods about few cm in diameter.

(ii) <u>Moderator</u> :— fission of U^{235} is much more probable when it is bombarded with slow neutrons than when it is bombarded with fast neutrons. The slowing down of neutron is achieved by <u>moderators</u>. Thus fast neutrons are slow down by mixing suitable moderators with uranium fuel. Commonly used materials for moderators are heavy water, graphite and beryllium. In general moderator should have light weight and its chances for absorbing neutrons should be low as possible.

(iii) <u>Control Rods</u> :— The control of reaction in a reactor is achieved by <u>control</u> <u>rods</u>. These rods are generally of those material whose nuclei posses the property of readily capturing slow neutrons. Commonly used material for control rods are <u>cadmium</u> and <u>boron</u>. when the rods are pushed into the reactor, the fission rate decreases, and when they are pulled out, the fission grows.

(iv) **Sheild :—** due to neutron bombardment, some dangerous biological effects might arise. To avoid this the reactor is surrounded by concrete wall about 2 meter thick and containing high proportion of element like iron.

(v) **Coolant :—** the energy is released inside the reactor in the form of heat which is removed by means of ~~coolant~~ cooling agent, known as coolant. The carbon dioxide (CO_2) gas is main coolant in a reactor. It is circulated through the interior of reactor by a pumping system.

(vi) **Safety Device :—** Special set of control rods known as safety ~~rods~~ 'shut-off rods are designed for an emergency that might arise whenever the reactor

Nuclear Reactor

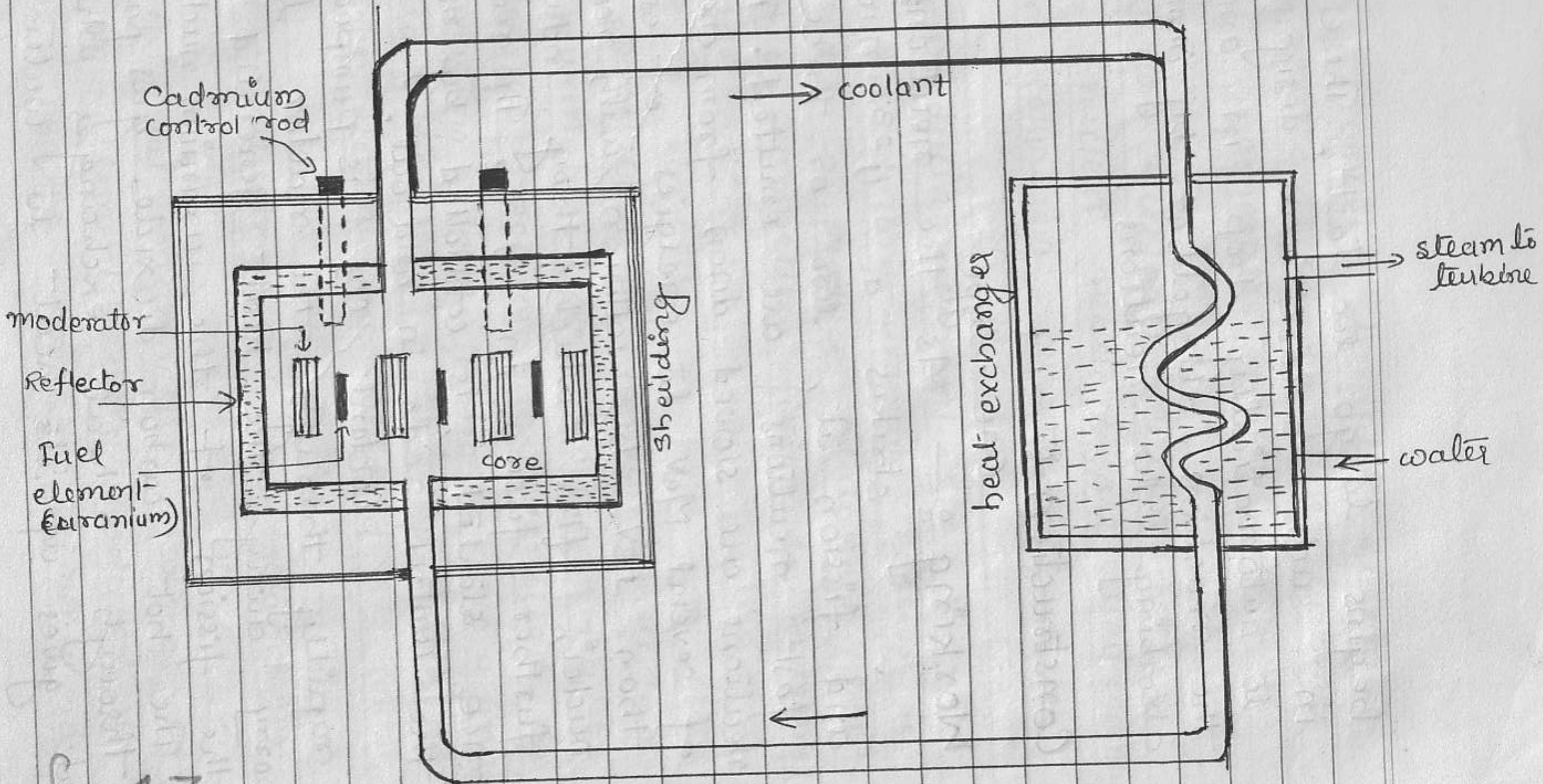


fig 1.3

begins to go too fast. These rods in such a case are designed to automatically drop in and stop the reaction altogether by immediately absorbing the neutrons.

Construction :—

~~One~~ type

Working :— As the neutrons strikes a U^{235} nucleus and fission it, two or three fast neutrons are emitted. These neutrons are slowed down from energies of several Mev to energies of less than 1ev by collision with ~~meductor~~ moderator nuclei, after which they induce further fission in U^{235}. The reaction, once started, is controlled by moving the control rods in and out.

Coolant CO_2 is pumped rapidly through the reactor to carry away the heat generated by the fission of the uranium nuclei. The hot carbon dioxide gas passes through a heat exchanges where it gives up its heat to water and converts it into steam. This steam drives the turbines and generates electric power.

Uses of nuclear Reactors :-

The nuclear reactors are used mainly for following purposes :-

(i) production of Pu^{239}:

The ordinary uranium reactor is used to produce plutonium (Pu^{239}) which is better fissionable material than U^{235}.

(ii) production of neutron beam :-

during fission process, fast moving neutrons are emitted. By converging these neutrons into a fine beam, artificial disintegration of other elements are studied.

(iii) production of radio-isotopes :-

Artificial radioactive isotopes of many elements are produced in the reactor. For this elements are placed in the reactor and bombarded with fast moving neutrons. These radio isotopes are utilised in medicines, biology, agriculture, industries and scientific discoveries.

(iv) production of energy :—
The energy produced in reactors is used to run electric generators. Thus nuclear energy is converted into electrical energy. This energy is used at power stations and can also be used as alternate source for driving the engines, for propulsions of ships, submarines and aircrafts.

Nuclear Fusion :—
when two or more light nuclei moving at very high speed are fused (combine) together to form a single heavy nucleus, then this process is known as nuclear fusion. ~~the mass~~ When four hydrogen nuclei are fused together, a helium

nucleus is formed. The mass of single nucleus formed is always less than the sum of the masses of individual nuclei. The difference in mass is converted into energy according to Einstein's equation.

$$E = mc^2$$

Consider a single helium nucleus formed by the fusion of two deuterium nuclei.

Mass of $_1H^2$ = 2.014102 unit

Mass of $_2He^4$ = 4.002604 unit

$$_1H^2 + _1H^2 \longrightarrow _2He^4$$

The initial mass of 2 deuterium atoms = 2 × 2.014102

= 4.028204 u

Mass of helium atom

= 4.002604 u

Decrease in mass = 4.028204 − 4.002604

= 0.025600 u.

Energy released in fusion

$$= 0.025600 \times 931.3 \text{ MeV}$$

$$= 23.84 \text{ MeV}.$$

Hence energy output in a fusion reaction is much less than the energy released in the fission of a U^{235} nucleus which is about 200MeV. But this does not mean that fusion is weaker energy source than fission. The number of deuterium in 1 gram of heavy hydrogen is much larger than the number of U^{235} nuclei in 1 gm of uranium. Therefore the energy output per unit mass of the material consumed is much greater in case of the fusion of the light nuclei than in case of the fission of heavy nuclei.

Nuclear Fusion in Stars :—

The sun is radiating energy at the rate of about 10^6 Joules/sec. Nuclear fusion is the source of stellar energy. It is presumed that the energy release occure by two possible process:

(i) **proton – proton cycle :–**

Bethe in 1939 suggested that the production of stellar energy is by thermonuclear reactions in which protons are continuously transformed into helium nuclei. In proton-proton cycle, the first step involves the fusion of two protons to form a deution nucleus releasing a positron and energy. The reaction is given by

$$ {}_1H^1 + {}_1H^1 \longrightarrow {}_1H^2 + {}_1e^0 + Q_1 $$

The deutron then combines with another proton and forms helium $({}_2He^3)$. The corresponding reaction is given by

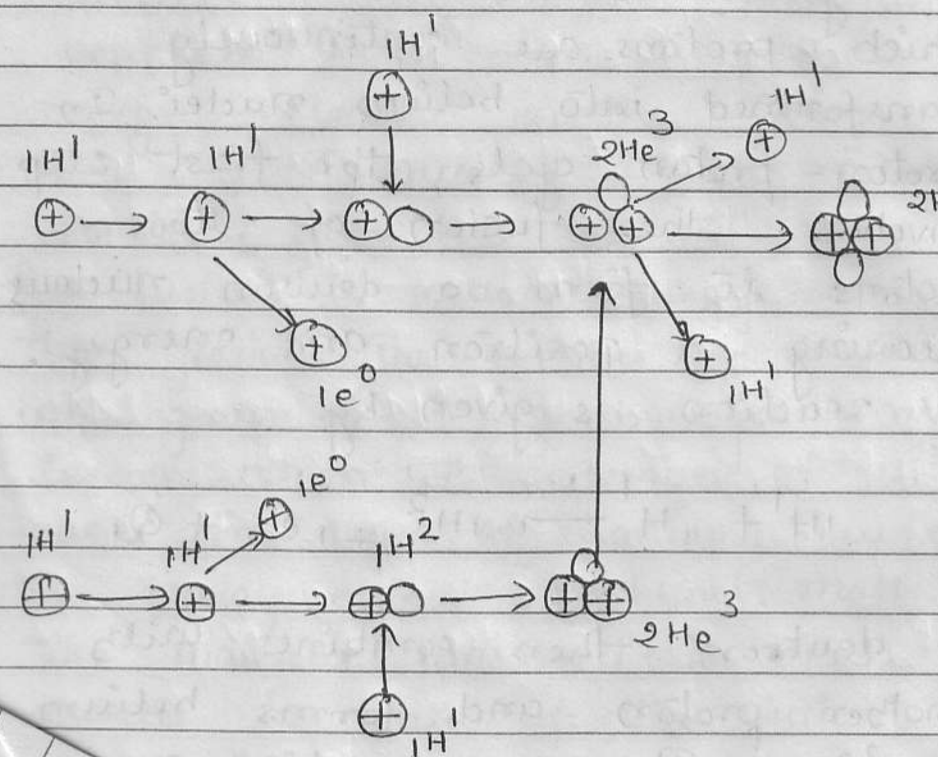
$$ {}_1H^2 + {}_1H^1 \longrightarrow {}_2He^3 + \gamma $$

The two helium 3 nuclei fuse to produce helium $({}_2He^4)$ nuclei.

$$ {}_2He^3 + {}_2He^3 \Rightarrow {}_2He^4 + 2\,{}_1H^1 + Q_2 $$

so that we have

$$4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0 + Q$$



(proton- proton cycle)

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i.e. nuclei.

$+ 2\,{}_1H^1 + Q_2$

(2) Carbon - nitrogen Cycle :—

In this cycle the synthesis of hydrogen nuclei with carbon (acting as nuclear catalyst) takes place. The carbon nuclei absorb the proton in succession and ultimately discharge a particle becoming carbon nuclei again. The reactions are given below:

$$_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13} + Q_1$$

where Q_1 is energy released.
The radioactive nitrogen 13 decays as

$$_7N^{13} \longrightarrow {}_6C^{13} + {}_{+1}e^0$$

Now stable $_6C^{13}$ nucleus react with another proton, thereby liberating more energy

$$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} + Q_2$$

where Q_2 is additional energy released during nuclear reaction.

The stable $_7N^{14}$ again combines with a proton to form oxygen ($_8O^{18}$) with release of more energy Q_3, thus

$$_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15} + Q_3$$

Now oxygen ($_8O^{15}$) decay

$$_8O^{15} \longrightarrow {}_7N^{15} + {}_{+1}e^0$$

Nitrogen ($_7N^{15}$) then again capture a proton to become ($_6C^{12}$) with the release of a particle ($_2He^4$)

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

...ll process may be written

$$\ldots {}_2He^4 + 2\,{}_{+1}e^0 + 27\,MeV$$

4.002604 u.

0.00

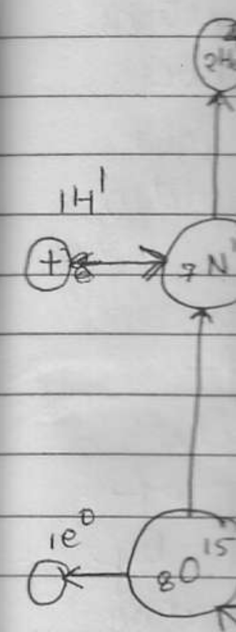
$_1H^1 + Q_2$

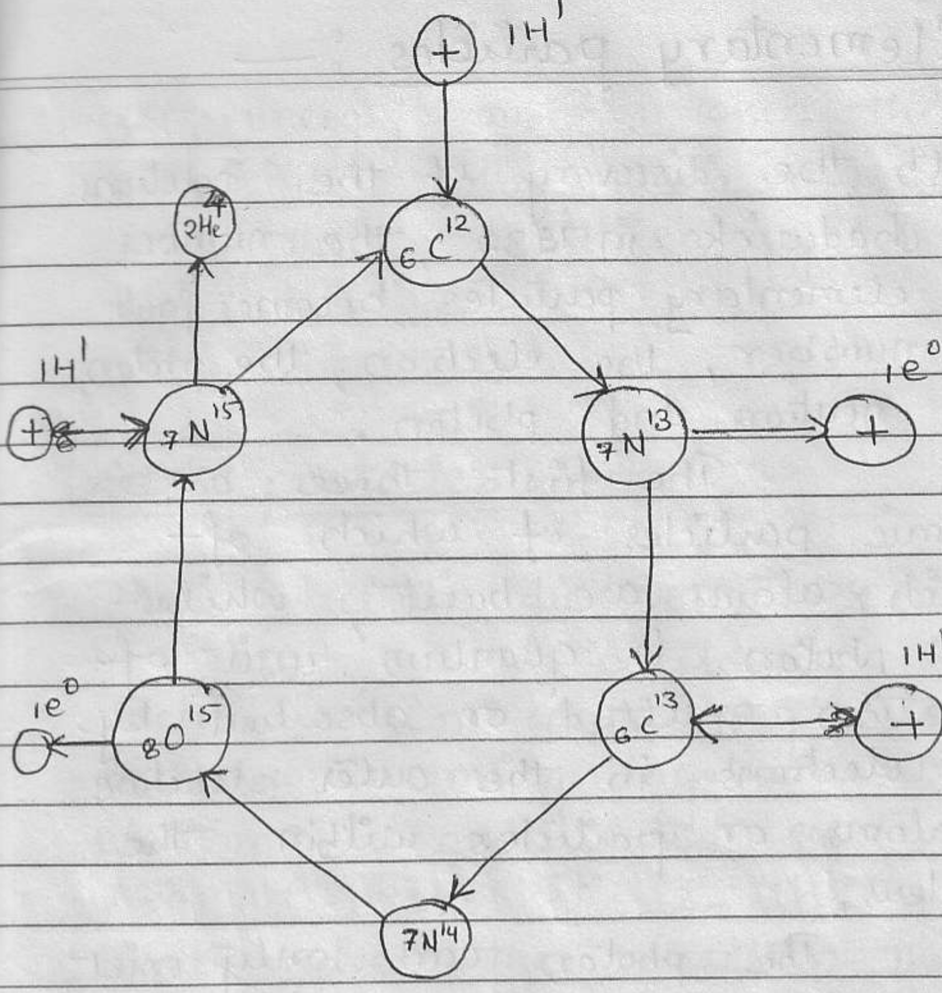
Si...

process

~~the~~ mas...

nuclei are ...





(carbon - nitrogen cycle)

fig 1.5

Elementary particles :—

With the discovery of the neutrons by Chadwick in 1932, the number of elementary particles becomes four in number, the electron, the proton, the neutron and photon.

The first three are atomic particles of which of which atoms are built, while the photon is quantum unit of radiation emitted or absorbed by the electrons in the outer structure of atoms or particles within the nucleus.

The photon can only exist ...velling with the speed ... because of its ... $h\nu$. By the ... $E = mc^2$, a ... $h\nu/c^2$. It ... virtue of its ...st it would ...nd no mass. ...ron, proton and ...ther hand, have ... mass m_0 and

Nu...
The ...
the ra...
Nuclear ...
stellar e...
that the e...

lg. nuclei.

$e^{+} + {}^{2}_{1}H + Q_2$

rest energy m_0c^2. when they are set into motion, their mass increases and their total energy is given by m_0c^2.

Anti particles :—

The positron discovered by Anderson in 1932, is a positively charged electron. In cosmic ray a free positron incoming together with an electron is annihilated and becomes two γ- rays. It is this property that gives the positron the name antiparticle — it destroy itself along with an electron and becomes another form energy.

when high - energy photon comes close to nucleus, meson may be produced. If a pair of meson is produced, one positive, one negative, one is antiparticle of other. These π mesons may react with other nuclei or they may decay into μ - mesons.

The muons in turn may decay into electrons and positions or they may be captured by some other nucleus.

The discovery of position, three pi mesons π^+, π^0, π^-, the two mu mesons μ^+ and μ^- alongwith the two neutrions ν^0 and $\bar{\nu}^0$ raised the number of ~~particle~~ elementary particles by 1950 to <u>twelve</u>.

<u>Classification of Elementary particles:-</u>

Elementary particles are classified on the basis of their half lives as:-

(i) Stable particles having half life $\geq 10^{-16}$ sec.

...ances having half-life $= 10^{-23}$ sec.

hicle may they

...ther classification of

neutr... alone. ...y particles are—

a

(II) Baryons :—

They can be further divided into the following groups:

(i) Nucleons

(ii) Hyperons or strange baryons.

Nucleons :—

(a) **protons** :— It has a positive charge and mass = 1.0072777 amu. proton repels each other. The charge on proton = 1.6×10^{-19} coloumbs.

(b) **Neutrons** :— It has no charge and its mass is equal to 1.008665 amu. It is unstable particle when it is free, but in combination with protons it forms a stable nucleus. Neutrons in the nucleus attract each other. A mesonic field exist between them.

(c) **Hyperons** :— These are the particles having mass mass more than the nucleons (protons and neutrons). Their name, symbols, mass and charge are given in the table.

particle	symbol	mass (amu)	charge (e)	life (sec)
(1) Lambda	λ^0	1.19	0	$\sim 10^{-10}$
(2) positive sigma	Σ^+	1.27	+1	$\sim 10^{-10}$
(3) Negative sigma	Σ^-	1.27	−1	$\sim 10^{-10}$
(4) Neutral sigma	Σ^0	1.27	0	$\sim 10^{-10}$
(5) Negative Xi	Ξ^-	1.41	−1	$\sim 10^{-10}$
(6) Neutral Xi	Ξ^0	1.41	0	$\sim 10^{-10}$

All these particle have their antipaiticles also.

(II) Leptons :—

These group contains electron, photon, nutrino and muon.

(a) **Electron :—** It is negative changed particle ($\bar{e}$). Its mass $= 5.48 \times 10^{-4}$ amu. An electrostatic field exists between two electrons.

It is a stable particle.

(b) <u>photon</u> (γ) :- It has no charge and no rest mass. It has energy given by plank's equation $E = h\nu$ and equivalent mass given by Einstein's equation $E = mc^2$. when electron (e^-) and position (e^+) annihilates each other photon is generated.

(c) <u>Neutrino</u> (ν) :- It has zero charge and zero mass.

(d) <u>Muon</u> or <u>Mu-meson</u> ~~(μ)~~ :
It has negative charge and mass = 207 × mass of electron. Its life is 10^{-6} sec.

~~(e)~~ (III) <u>Mesons</u> :-
This group contains positive pi meson, neutral pi^0 meson, chaged K meson, neutral K meson.

(a) <u>positive</u> <u>pi</u> <u>meson</u> (π^+)
It has mass equal to 273 times the mass of electron.

It is a positively charged particle and has a life of 10^{-8} second.

(1) (b) **Neutral pi mesons :— (π^0)**
It has no charge
(2) and mass its mass is equal to 264 times the mass of electron.

(3)

(c) **Charged K meson or Kaon (K^+) :-**

(4)

It has a mass = $966 m_e$
(5) and has a positive charge. It means it has a mass about
(6) one-half of a proton.

(d) **Neutral K meson (K^0) :**

It has mass 967 me and has no charge. Its life is of the order of 10^{-9} sec.

(IV) **Anti particles :—**
Some of the important antiparticles are given below:

(a) **Anti-proton :** It has negative charge and mass equal to mass of proton. Its mass = 1.0072 amu. when a proton and anti-proton meets they annihilates each other and their combined mass is converted into 1870 MeV of energy.

(b) **Anti neutron :** It has no charge and its mass = 1.0086 amu. It is unstable.

(c) **position (e^+) :**

This was discovered by Anderson in 1932. It is positively charged particle having the mass and charge equal to the electron. It is anti electron. Its mass $= 4.48 \times 10^{-4}$ amu.

(d) **Anti nutrino ($\bar{\nu}$) :**

It has zero charge and zero rest mass.

(e) **Anti mu-meson (μ^+) :**

It has positive charge

and its mass = 207 × mass of electron.

(f) **Anti-charged K meson (K^-)**
It has mass = $966 m_e$ and has a negative charge. Its life is of the order of 10^{-8} sec.

(V) Three types of new particles are given below:

(a) **Rho-meson: (T)** these have positive, neutral or negative charge.

(b) **Omega meson (neutral) (Ω^0):**
Its mass is about $1540\ m_e$ and is neutral. Its life is of the order of 10,20 sec. These particles have been found by observing thousands of π meson tracks.

(c) **Negative Omega meson (Ω^-)**
Its mass is about $1540\ m_e$ and ~~is neutral~~.

has negative charge.

Motion of charged particle (electron) in uniform electric field :-

Case I :-

Motion along the field :

Let A and B are two metal plates parallel to each other separated by distance 'd' and insulated from each other. The direction of electric field is from positive plate to negative plate.

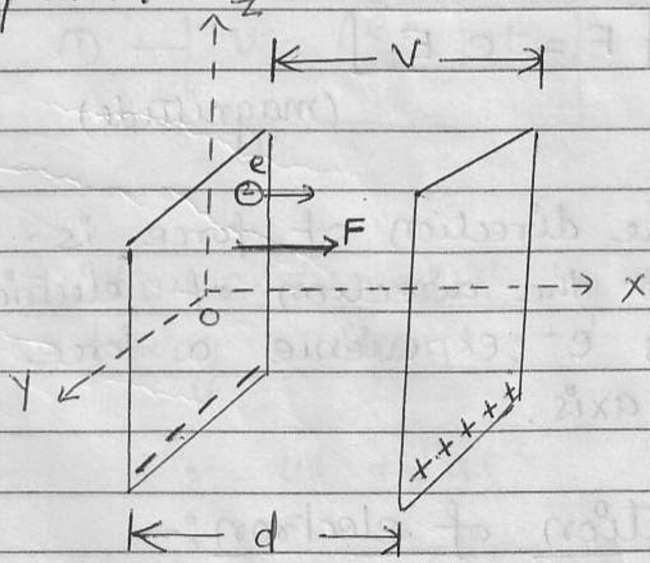


fig 1.6

Let 'V' is potential diff between two plates A & B. Then uniform electric field is set up between A and B and is given by

$$E = \frac{V}{d}$$

Let an electron of mass 'm' and charge 'e' is placed in uniform electric field. An electron experiences force due to electric field is given by

$$\boxed{F = eE} \quad \text{--- (1)}$$

(magnitude)

for e^- the direction of force is opposite to the direction of electric field. Thus e^- experience a force along x-axis.

(1) <u>Acceleration of electron:-</u>

According to Newton's 2nd law

$$F = ma$$

$$\boxed{a = \frac{F}{m} = \frac{eE}{m}} \quad \text{——— (2)}$$

Due to uniform electric field charge has constant acceleration along x-axis.

(2) <u>Velocity acquired by electron at any time t :</u>

$$v = u + at$$

$$v = 0 + \left(\frac{eE}{m}\right)t \qquad (\because \text{ initial velocity } u = 0)$$

$$\therefore \quad \boxed{v = \left(\frac{eE}{m}\right)t}$$

(3) <u>Distance travelled by electron during time t :</u>

$$x = ut + \frac{1}{2}at^2$$

$$x = 0 + \frac{1}{2}\left(\frac{eE}{m}\right)t^2$$

$$\boxed{x = \frac{1}{2}\left(\frac{eE}{m}\right)t^2}$$

(4) Velocity acquired by electron after travelling distance x:

is given by

$$v^2 = u^2 + 2ax$$

$$\boxed{v^2 = 2\frac{eE}{m}\,x}$$

when $x = d$

$$\boxed{v^2 = \frac{2eE}{m} \cdot d}$$

$$v^2 = \frac{2e}{m} \cdot \frac{V}{d} \cdot d \qquad \because E = \frac{V}{d}$$

$$v^2 = \frac{2eV}{m}$$

$$v = \left(\frac{2e}{m}\right)^{1/2} \sqrt{V}$$

$$v \propto \sqrt{V} \quad \text{since } \left(2e/m\right)^{1/2} = \text{const.}$$

Thus velocity (v) required by an electron moving through a uniform electric field is proportional to square root of potential difference (V) through which the electron are accelerated.

(5) **K.E of electron:**

after moving through a potential difference is given by

$$K.E = \frac{1}{2} m v^2$$

$$= \frac{1}{2} m \left(\frac{2eV}{m}\right)$$

$$\boxed{K.E = eV}$$

Thus energy gained by electron when it is accelerated by a potential (V) is 1 electron volt (eV).

Case II:

Motion perpendicular to the field:-

Let an electron of mass 'm' and charge 'e' be projected with speed u_x at right angle to uniform electric field E.

Inside the electric field, it will move along the curved path BA. On coming out of electric field, it will move along straight path AS, tangent to the curved path BA at 'A'. Then it strikes the fluroscent screen at S and produces a luminuous spot.

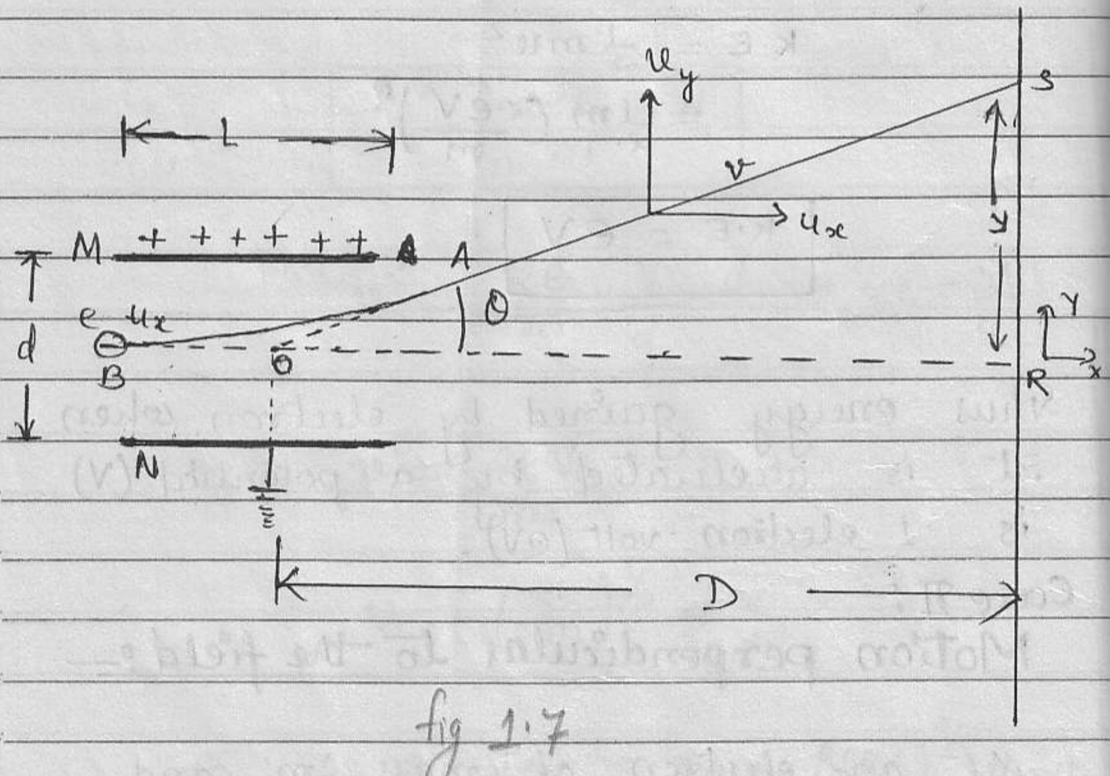


fig 1.7

Inside Electric field:- electron experiences a constant force in y- direction and hence a constant acceleration. In x-direction it does not experiences any force. Therefore it moves with uniform velocity along x- direction.

For uniform motion along x-axis

$$x = u_x t \quad \text{——— (1)}$$

For accelerated motion along y-axis: with initial velocity zero

$$y = 0 + \frac{1}{2} a_y t^2 \quad \text{——— (2)}$$

$a_y \rightarrow$ vertical acceleration.

$$a_y = \frac{F}{m} = \left(\frac{eE}{m}\right)$$

$$\therefore \; y = \frac{1}{2}\left(\frac{eE}{m}\right) t^2$$

$$\therefore \; \boxed{y = \frac{1}{2}\left(\frac{eE}{m}\right)\left(\frac{x}{u_x}\right)^2} \quad \text{— (3)} \quad \text{using (1)}$$

above equation is used to determine (e/m) of an electron if deflection 'y' is known.

Here $\frac{1}{2}\frac{eE}{m}\cdot\frac{1}{u_x} = \text{const.} = c$

$$\therefore \quad y \propto x^2 \quad \text{--- (4)}$$

Equation (4) is equation of parabola and hence inside the electric field, a charged particle moves along curve BA, which is parabolic in nature.

<u>Outside electric field</u>: the final velocity of electron is given by

$$v_y = 0 + a_y t$$

$$v_y = \frac{eE}{m}\cdot\frac{x}{u_x} \quad \text{--- (5)}$$

Here $x = L$ = length of plates
= horizontal distance travelled as it comes out of electric field.

$$\therefore \boxed{v_y = \frac{eE}{m} \frac{L}{u_x}}$$

This vertical velocity remains constant after the electron comes out of the field and it travels in a straight line. It's velocity is

$$v = \left[u_x^2 + v_y^2\right]^{1/2}$$

The straight line produced backwards will meet the x-axis at point O which is mid point of plates. The line makes an angle of θ with the x-axis. From fig.

$$\tan\theta = \frac{y}{D} \quad \text{—— (6)}$$

also $\tan\theta = \frac{v_y}{u_x}$

using (5) $\tan\theta = \frac{eE}{m} \frac{1}{u_x} \cdot \frac{L}{u_x}$ —— (7)

from (6) and (7)

$$\frac{y}{D} = \frac{eE}{m} \frac{L}{u_x^2}$$

$$y = \frac{eELD}{m u_x^2} \quad \text{—— (8)}$$

If before entering the field, the electron had been accelerated by a potential V_A then

$$\frac{1}{2} m u_x^2 = eV_A$$

$$u_x^2 = \frac{2eV_A}{m} \quad \text{—— (9)}$$

$$(8) \Rightarrow \quad y = \frac{eE}{m} \frac{LD}{2eV_A} \cdot m \quad \text{using (9)}$$

$$y = \frac{ELD}{2V_A}$$

where $E = \frac{V}{d}$

$$y = \frac{VLD}{2dV_A}$$

$V \rightarrow$ potential difference between plates.

Case III Motion of charged particles when velocity makes an angle θ with E.

The velocity u can be resolved into two components $u\cos\theta$ and $u\sin\theta$. The motion is just like that of projectile fired with velocity u at an angle θ with horizontal. As the electron moves, it covers distance along horizontal due to horizontal component $u\cos\theta$ & along vertical due to vertical component $u\sin\theta$.

Let the electron reaches point P (x, y) at any instant 't'.

<u>Motion along horizontal</u>: is uniform (zero acceleration)

using $s = ut + \frac{1}{2}at^2$ — ①

$$x = u\cos\theta \cdot t + 0$$

$$\therefore \boxed{x = u\cos\theta\, t} \quad —②$$

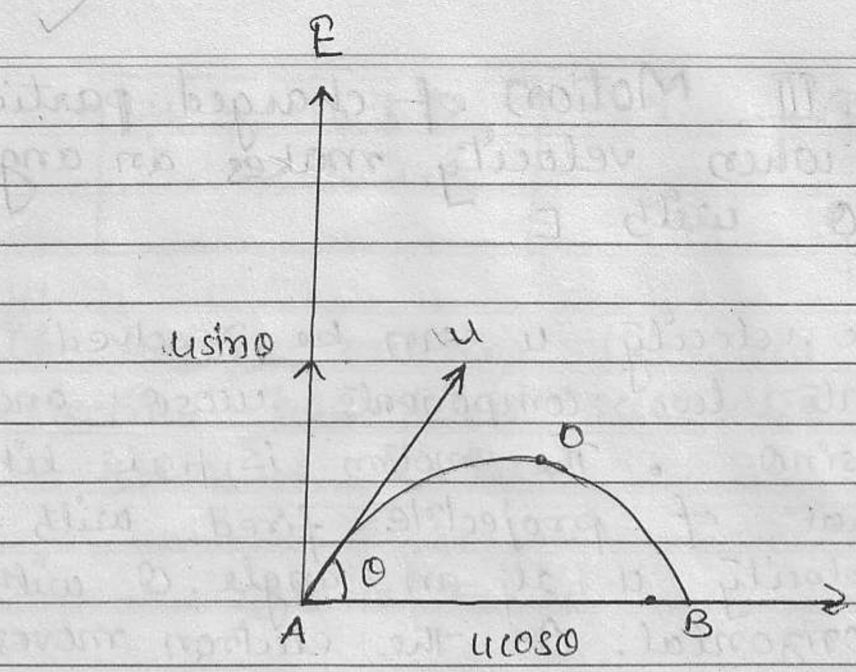


fig. 1.8

<u>Motion</u> along <u>vertical</u>: (Is deaccelerated)

$$\text{acceleration} = -a = -\frac{eE}{m}$$

using ① $y = u\sin\theta\, t - \frac{1}{2}\frac{eEt^2}{m}$ — ③

Time of flight (T) is the time taken by projectile to return to ground ie to travel from A to B

Time of travel from A to O = $T/2$

At O vertical component of velocity $(v_y) = 0$

Now velocity of projectile at any time 't' along y-axis is

$$v_y = u\sin\theta + \left(\frac{-eE}{m}\right)\frac{T}{2} \quad \{\because v = u + at\}$$

$$0 = u\sin\theta - \frac{eET}{2m}$$

$$\boxed{u\sin\theta = \frac{eET}{2m}} \quad \text{—— (4)}$$

Lect 57

Motion of charged particle (electron) in uniform magnetic field:

If a charge moving with velocity v enters into region of a uniform field of strength B it experience Lorentz forces, a Lorentz force, in direction perpendicular to v and B.

$$\vec{F} = e(\vec{v} \times \vec{B}) = evB\sin\theta \quad \text{— ①}$$

Thus $\vec{F}$ will be perpendicular to plane containing $(\vec{v} \times \vec{B})$

Conditions:—

① If $\theta = 90°$ ie $\vec{v}$ and $\vec{B}$ are perpendicular to each other then

$$F = evB \text{ (max.)}$$

Thus force experienced by a charged particle moving in a direction pendiculal to magnetic field is maximum.

(2) If $\theta = 0°$ ie electron moves parallel to magnetic field then

$$F = qvB\sin\theta = 0$$

It will not experience any force and continuously move with same velocity and same direction.

(3) when $v = 0$. ie charge is stationary.

$$F = evB\sin\theta = 0.$$

ie moving charge will not experience force in magnetic field.

Motion of charged particle when $\vec{v}$ is perpendicular to $\vec{B}$:

Consider a uniform magnetic field directed along z-axis and charge particle having charge 'q' and mass 'm' is moving in x-y plane. Suppose that at any instant charged particle is at point A and has velocity $\vec{v}$. Then Lorentz force on charged particle will be

$$\vec{F} = e(\vec{v} \times \vec{B})$$

The direction of force $\vec{F}$ on particle will be along AO ie perpendicular to both $\vec{v}$ and $\vec{B}$.

Since the force acts on the charged particle perpendicular to its velocity, the force does not do any work. Hence magnitude of its velocity remains const and only the direction of velocity of charged particle changes. In other words, the force $\vec{F}$ on the charged particle acts as the centripetal force and makes it move along circular path.

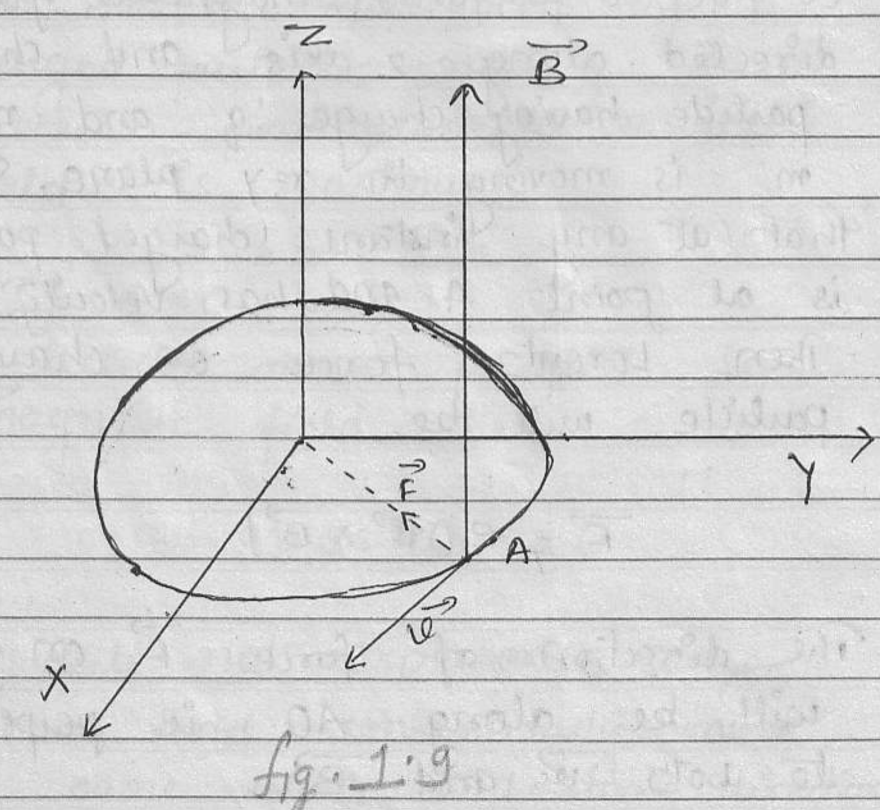


fig. 1.9

The centripetal force $\vec{F}$ can be expressed as

$$\vec{F} = \frac{mv^2}{R} \quad \text{——} \ (1)$$

where $R \rightarrow$ radius of circular path.

Also $\vec{F} = evB\sin\theta$

$$F = evB \quad \text{——} \ (2) \quad \because \theta = 90^\circ$$

Equating (1) and (2)

$$\frac{mv^2}{R} = evB$$

$$\boxed{R = \frac{mv}{eB}}$$

Above equation shows that –

(1) faster the particles moves (v large), the large is the radius of circular path. ie $R \propto v$

(2) heavier the charged particle (m large), the larger is the radius of circular path.

$$R \propto m$$

The angular frequency of particle is given by

$$\omega = \frac{v}{R} = \frac{v}{mv/Be}$$

$$\boxed{\omega = \frac{Be}{m}}$$

The time period of circular motion of charged particle is given by

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{Be/m}$$

$$\therefore \boxed{T = \frac{2\pi m}{Be}}$$

From above equation it follows that the angular frequency and period of circular motion of charge particle moving in a uniform magnetic field neither depends upon its velocity nor on radius of circular path. This fact is made use in cyclotron.

Motion of charged particle in a uniform magnetic field: when it makes an angle θ with direction of B:

Suppose that the charged particle is moving with velocity $\vec{v}$ inside a uniform magnetic field $\vec{B}$ making an angle θ with the direction of magnetic field.

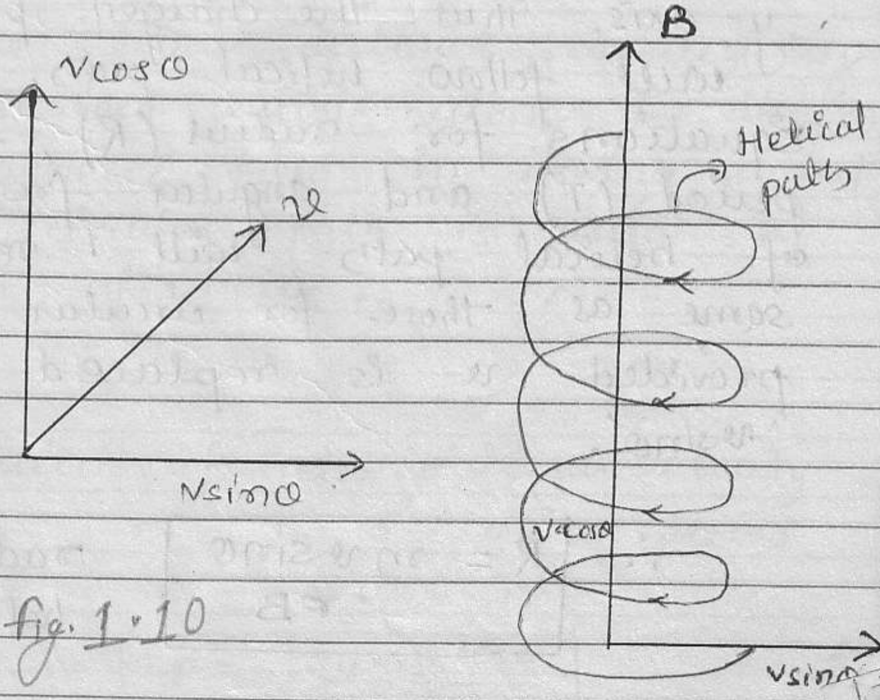


fig. 1.10

The velocity $\vec{v}$ of charged particle can be resolved into two components v_x and v_y such that

$$v = \sqrt{v_x^2 + v_y^2}$$

The charged particle moves along a circular path due to its component of velocity $v \sin\theta$ and at the same time moves along y-axis (linear path) due to it's component of velocity $v \cos\theta$ along y-axis. Thus the charged particle will follow helical path.

Equations for radius (R), time period (T) and angular frequency (ω) of helical path will remain same as those for circular path provided v is replaced by '$v \sin\theta$'.

$$\therefore \boxed{R = \frac{m v \sin\theta}{eB}} \quad \text{radius of helical path}$$

Time period $T = \frac{2\pi R}{v}$

i.e. $T = \frac{2\pi m v \sin\theta}{v \sin\theta \, eB}$

$$\boxed{T = \frac{2\pi m}{eB}}$$

and frequency

$$\boxed{f = \frac{eB}{2\pi m}}$$

<u>Pitch of Helix</u> :—

The linear distance travelled by the charged particle along the direction of magnetic field in moving around one circular path is called as <u>pitch of Helix</u>.

∴ pitch of helix = linear velocity × Time period

$$P = v\cos\theta \cdot T$$

$$\boxed{P = \frac{2\pi m v \cos\theta}{eB}}$$

Lect 52

ASTON MASS SPECTROGRAPH :-

Aston's mass spectrograph is an apparatus designed by Aston which enables the measurment of the mass of single atomic ions. and is useful for investigation of isotopes.

principle :- The positive rays emerging from perforated cathode are made into a fine pencil by using slits. They are then subjected to an electrostatic field with the help of electrically charged plates P_1 and P_2. The beam is not only deflected but also dispersed because the particles are having different velocities. The dispersed beam is then subjected to magnetic field whose direction is perpendicular to the direction of electric field. Thus magnetic field produce dispersion and deviation in an opposite direction but in same plane. If a photographic plate is held in the direction of deflected beam, line image are obtained. Each line corresponds to a particular value of q'/m'. The number of lines corresponds to the number of isotopes present in the element.

Theory :-

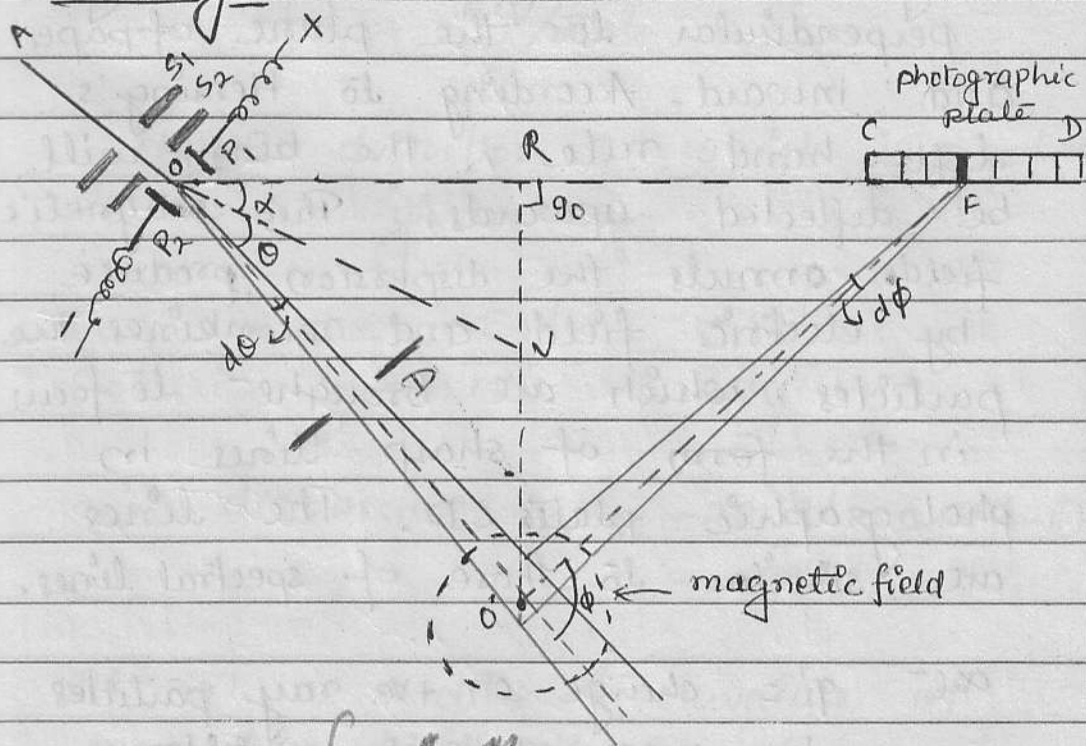


fig. 1.11

AO is direction of +ve rays before entering the electric field. S_1 and S_2 are slits which provide a fine pencil of positive rays. The electrostatic field is maintained by plates P_1 and P_2 and direction of field from P_1 to P_2

The beam is deflected and dispersed downward. Let θ and $d\theta$ be the angle of deviation and dispersion. Using a diaphram D some of the rays are selected and are allowed to pass between poles of an electro-magnets. The magnetic field being perpendicular to the plane of paper and inward. According to Fleming's left-hand rule, the beam will be deflected upwards. This magnetic fields annuls the dispersion produce by electric field and recombines the particles which are brought to focus in the form of sharp lines in photographic plates CD. The lines are similar to those of spectral lines.

Let q' = charge on +ve ray particles

m' = mass of each particles.

$E \rightarrow$ electric field

$B \rightarrow$ magnetic field

v = velocity of each particle.

ϕ = angle of deviation produced by magnetic field.

$d\phi \rightarrow$ angle of dispersion produced by magnetic field.

Considering the deflection in electrostatic field is small, the curve near the vertex may be considered as circular of radius r, we have.

$$Eq' = \frac{m'v^2}{r}$$

$$\frac{1}{r} = Eq'/m'v^2$$

Hence deflection θ, which is proportional to $1/r$ is given by

$$\theta = c\frac{Eq'}{m'v^2} = \frac{c_1 q'}{m'v^2}$$

$\therefore$ dispersion $$\frac{d\theta}{dv} = -2c_1\frac{q'}{m'v^2} = \frac{-2\theta}{v} \quad \text{—(1)}$$

If r' is radius of curvature in magnetic field then

$$Bq'v = \frac{m'v^2}{r'}$$

$$\text{or} \quad \frac{1}{r'} = \frac{Bq'}{m'v}$$

$$\therefore \quad \phi = c' \frac{Bq'}{m'v} = c_2 \frac{q'}{m'v} \quad (\because B = \text{const})$$

Again dispersion $\frac{d\phi}{dv} = -c_2 \frac{q'}{m'v^2} = -\frac{\phi}{v} \rightarrow (2)$

from equation (1) and (6) we have

$$\frac{d\theta}{\theta} = 2\frac{d\phi}{\phi} \quad \text{—— (3)}$$

Thus for a given deflection, the dispersion due to electric field is twice that due to magnetic field. The small changes $d\theta$ and $d\phi$ refers to the particles with identical mass and charge but possessing velocities differing by dv.

In absence of magnetic field, the dispersion produced in the beam for a distance $(a+b)$ is given by

$$= (a+b)\, d\theta. \quad \text{—— (4)}$$

a = dist. OO' and b = distance $O'F$

The magnetic field acts in the direction perpendicular to electric field and produces the same dispersion in a distance 'b' but in opposite direction.

Dispersion produced by magnetic field $= b\,d\phi$ — (5)

As all the ions are focussed on same position

$$(a+b)\,d\theta = b\,d\phi$$

and $$\frac{d\theta}{d\phi} = \frac{b}{(a+b)} \quad \text{— (6)}$$

From equation (3) $$\frac{d\theta}{\phi} = \frac{2\theta}{\phi}$$

$$\therefore \frac{b}{(a+b)} = \frac{2\theta}{\phi}$$

or $$\boxed{b\phi = (a+b)\,2\theta} \quad \text{— (7)}$$

This is the condition of focusing.

Let O'R be perpendicular to line CD produced and $\angle ROV = \alpha$. Then from $\Delta ROO'$, we have

$$RO' = OO' \sin(\alpha+\theta) = a \sin(\alpha+\theta)$$

In $\Delta RO'F$, $RO' = O'F \sin(RFO')$

$$= b \sin[180 - (\phi - \alpha - \theta)]$$

$$= b \sin(\phi - \alpha - \theta)$$

$$\therefore \quad a \sin(\alpha + \theta) = b \sin(\phi - \alpha - \theta)$$

For small angles, $a(\alpha + \theta) = b(\phi - \alpha - \theta)$ — (8)

Comparing (7) and (8), it is observed that two equations are same when $\alpha = \theta$. Thus focussing condition is that the photographic plate must be placed at an angle θ with the direction of the incident positive ray beam.

Thus we find that in Aston Apparatus:

(1) All particles of the same q/m are brought to focus irrespective of their velocities.

(2) particles of different masses are brought to different foci.

Lect 55

Bainbridge mass spectrograph:

A mass spectrograph is an instrument that measures the nuclear (atomic masses. There are different types of mass spectrograph that are based on different principle.

Principle:— The Bainbridge mass spectrograph is based on the principle that a uniform magnetic field acting normal to path of ions having the same velocity deflects the ions of different masses along circular paths of different raddii, the diameter of each semi-circular path being linearly related to the mass of ion describing the semi-circular path.

Construction:— It consists of

(i) A source of ion beam with collimating slits S_1 and S_2.

(ii) **Velocity selector:**— It consists of crossed electric and magnetic fields mutually perpendicular and also perpendicular to ion beams. The electric field strength $\vec{E}$ is produced by applying a potential difference between a pair of parallel plates P_1 and P_2. The magnetic field of strength $\vec{B}$ is produced by an electro-magnet shown by dotted circle.

(iii) An evacuated chamber D fitted with slit S_3 and a photographic plate F.

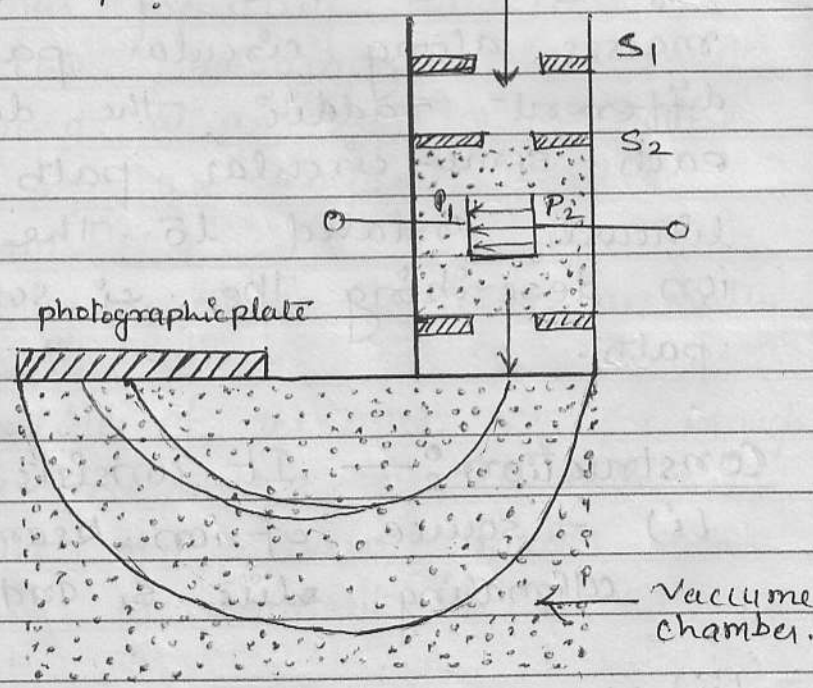


fig 1.12

Working :-

The ion produced by discharge tube or a spark is collimated by slits S_1 and S_2 and allowed to enter the velocity selector. The electric field strength E and magnetic field strength B are adjusted such that only ions of given velocity v pass undeflected experiencing equal and opposite electric ~~field~~ and magnetic ~~field~~ force

$$qE = qvB$$

$$v = \frac{E}{B}$$

Only the ions having velocity $\left(\frac{E}{B}\right)$ enter the evacuated chamber D through the slit S_3. The positive ions entering into D are subjected to strong uniform magnetic field of strength B' perpendicular to their path. The force acting on each ion is qvB' and transverse circular paths of radius r given by:

$$\frac{mv^2}{r} = qvB'$$

$$r = \frac{mv}{qB'}$$

That is ions of different masses 'm', but having same charge q, describe semicircles of different radii.

$$\frac{q}{m} = \frac{v}{rB'}$$

using value of $v = \frac{E}{B}$ we get

$$\frac{q}{m} = \frac{E}{rB \cdot B'}$$

As E, B, and B' are constants,

$$\left(\frac{q}{m}\right) \propto \left(\frac{1}{r}\right).$$

If 'q' is same for all ions then mass $\propto r$. The ions of different masses strike the photographic plate of different points and we obtain a typical mass spectrum on photographic plate, the mass scale being linear.

Lect. 55

THE CYCLOTRON :

The cyclotron was devised by Lawrence in 1932. It is used to accelerate positively charged particles like protons and deutrons to very higher energies so that these particles may produce disintegration.

Construction :— A cyclotron consists of a cylindrical cavity which is divided into two halves called Dees. It is placed in a uniform magnetic field parallel to its axis. The two cavity are insulated electrically from each other. An ion source, which is the chamber consisting of heated filament and a gas hydrogen or deuterium. S is placed near the mid point of gap between the dees. An alternating potential difference of the order 10^4 volts is applied between the dees.

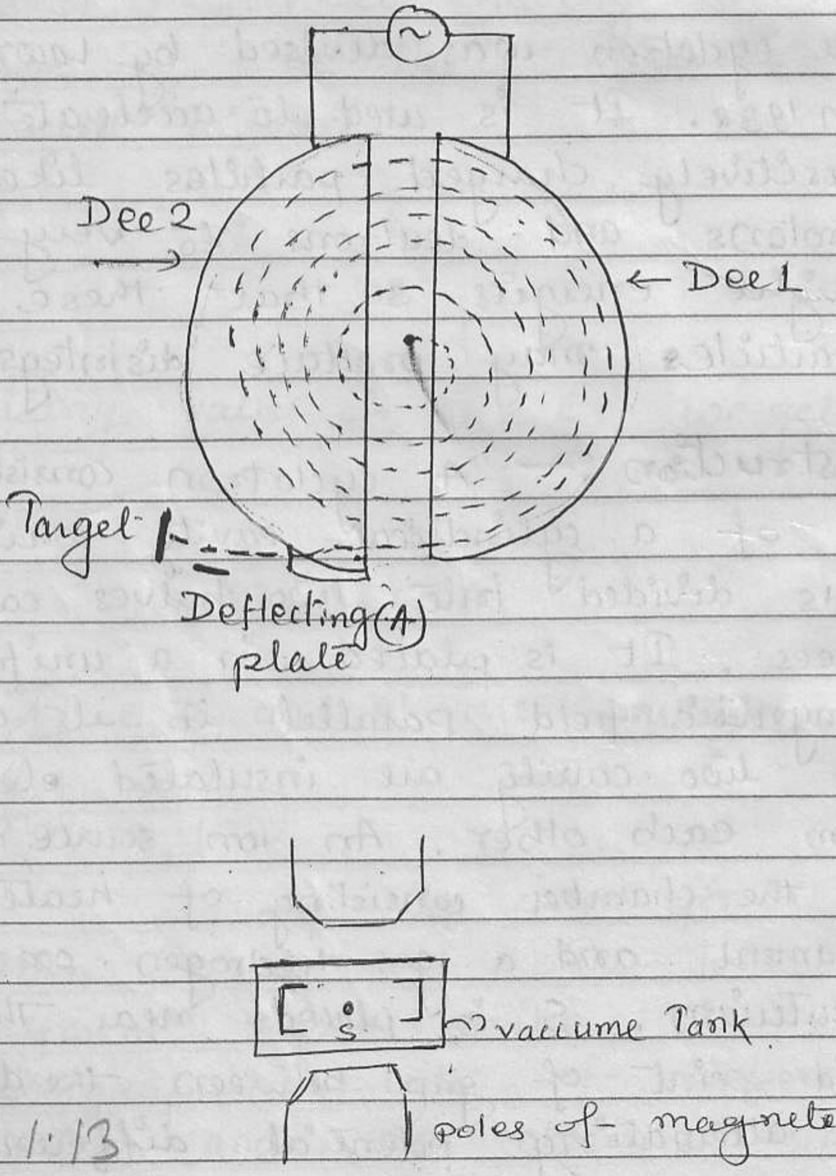


fig 1.13

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principle and working :—

when an ion of mass m and charge +q gets inside a dee (at negative potential), it experiences no electrical force because the electric field is zero inside a conductor. However, under the action of magnetic field, ions describes a circular orbit with a constant speed v and radius r given by

$$r = \frac{mv}{qB} \quad \text{— (1)}$$

where B → magnetic induction.

The angular velocity of ions in its circular path

$$= \omega = \frac{v}{r} = \frac{qB}{m} \quad \text{— (2)}$$

The time taken by circular ion to travel semicircular path

$$= t = \frac{\pi}{\omega} = \frac{\pi m}{Bq}. \quad \text{— (3)}$$

The potential difference between dees oscillates with frequency equal to ω. In this way, the potential difference between dees is in resonance with the circular motion of ions.

When the ions completes half revolution the parity of dees is reversed. Therefore the ions recieves again small acceleration while crossing gap between the two dees. Then the next half circle described by the ions has large radius but the same angular velocity 'ω' (v & r both increased). The process repeats itself several times, until the radius attains a maximum value r_{max} approximately equal to the radius 'R' of the dees. The ~~process~~ magnetic field at the edge of dees is decreased sharply so that the ions moves tangentially and escaping out through opening A.

Energy of ion :—

Let r_{max} be the radius of the outermost orbit described by the ions and v_{max} is the maximum velocity gained by the ions in its final orbit. Then the equation of motion of ion in a magnetic field is

$$Bqv_{max} = \frac{mv_{max}^2}{r_{max}}$$

$$v_{max} = \frac{Bqr_{max}}{m}$$

∴ The energy of the ion

$$E = \frac{1}{2}mv_{max}^2 = \frac{B^2 r_{max}^2}{2}\left(\frac{q^2}{m}\right)$$

The condition for acceleration of the ions in the inter dee gap is that: Half the time period of the time taken by ions to travel the semicircular path = oscillation of the applied high frequency voltage i.e $\frac{\pi m}{Bq} = \frac{T}{2}$

or $T = \frac{2\pi m}{Bq}$

∴ frequency of the oscillator

$$f = \frac{Bq}{2\pi m}$$

Hence energy of ion is given by

$$\boxed{E = 2\pi^2 r_{max}^2 f m}$$

The particles are emitted from cyclotron not continuously but as pulsed stream.

Limitations:— A cyclotron cannot accelerate the particles to velocities of the order of velocity of light 'c'. As the energy increases, the velocity of the particle also increases, resulting in change in mass according to relation

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

where $m_0 \rightarrow$ rest mass of the particle.

when energy is v. large, the change in mass is sufficient to change cyclotron frequency of particle. Therefore the orbit of the particle will not be in phase with oscillating potential and no further acceleration is produced.

As the mass of proton is small then proton or deutron, therefore for a given energy the velocity of electron is much greater than proton or deutron. Hence the relativistic mass increases is also greater for electron and their orbit cannot remains in phase with oscillating potential.

Q-value of a nuclear reaction :

Transmulation or disintegration is the process in which one atom is converted to another atom. Transmulation can represented in the form of an equation is called transmulation equation.

The energy absorbed or liberated during nuclear reaction is called nuclear energy Q-value. Consider the nuclear reaction

$$A + B \rightarrow C \rightarrow P + O$$

$$A + B \rightarrow P + O$$

Let $M_0 \rightarrow$ mass of target nucleus (A) assumed stationary

$M_1, E_1 \rightarrow$ mass & energy of projectile

$M_2, E_2 \rightarrow$ mass & energy of product

$M_3, E_3 \rightarrow$ mass and energy of outgoing particle.

Applying law of conservation of energy, we get

$$M_0 + (M_1 + E_1) = (M_2 + E_2) + (M_3 + E_3)$$

$$\Rightarrow (M_0 + M_1) - (M_2 + M_3) = (E_2 + E_3) - E_1 \quad \text{--- (1)}$$

$Q = (E_2 + E_3) - E_1$ = difference in energies of particle resulting from reaction and the energy of projectile particle.

also $Q = (M_0 + M_1) - (M_2 + M_3)$ --- (2)

= Diff. between masses of the particle taking part in reaction and the masses of the particles resulting from reaction.

Consider the following case!

(I) If $(M_0 + M_1) > (M_2 + M_3)$ then

Q-value will be positive and reaction is exothermic

Eg:- $_3Li^7 (p, \alpha) _2He^4$ reaction

Interacting particles	product particles
$_1H^1 = 1.00814$	$_2He^4 = 4.00387$
$_3Li^7 = 7.01822$	$_2He^4 = 4.00387$
Total $= 8.02636$	Total $= 8.00774$

Decrease in mass $= 8.02636 - 8.00774$

$= 0.01862$ amu

$= 0.01862 \times 931$

$= 17.3$ MeV

Hence increase in energy $= 17.3$ MeV

The reaction is expressed as

$$_1H^1 + {_3Li^7} \Rightarrow {_2He^4} + {_2He^4} + Q.$$

(II) <u>If $(M_0 + M_1) < (M_2 + M_3)$ then</u>

Q will be negative and reaction is endothermic.

Eg: $_7N^{14}(\alpha, P)\,{_8O^{17}}$ reaction.

Interacting particle	product particle
$_2He^4 = 4.00387$	$_8O^{17} = 17.00450$
$_7N^{14} = 14.00753$	$_1H^1 = 1.00814$
Total = 18.01140	Total = 18.01264

The increase in mass = 18.01264 − 18.01140
= 0.00124 amu.

∴ Decrease in energy = 0.00124 × 931
= 1.15 MeV

The reaction is expressed as

$$_2He^4 + {_7N^{14}} \Rightarrow {_8O^{17}} + {_1H^1} + Q.$$

(III) If $(M_0 + M_1) = (M_2 + M_3)$ then $Q = 0$, this is the case of 1st elastic collision.

Types of nuclear reaction:—

Depending upon nature of projectile particle and outgoing particle, the various nuclear reactions are classified as —

(1) **Transmutation by α-particle**

(α,p) (α, n)

Eg:- (α P)

(i) $_5B^{10} + {_2He^4} \rightarrow {_6C^{13}} + {_1H^1}$

(α-particle) (proton)

(ii) $_{11}Na^{23} + {_2He^4} \rightarrow {_{12}Mg^{26}} + {_1H^1}$

(α-particle) (proton)

Eg:- (α, n) reaction

(i) $_3Li^7 + {_2He^4} \rightarrow {_5B^{10}} + {_0n^1}$

(α-particle) (neutron)

(ii) $_{11}Na^{23} + {_2He^4} \rightarrow {_{13}Al^{26}} + {_0n^1}$

(α-particle) (neutron)

(2) Transmutation by protons:

(P, α) (P, n) (P, d) (P, γ)

Eg:- (P, α) reactions.

(i) ${}_{3}Li^{7} + {}_{1}H^{1} \rightarrow {}_{2}He^{4} + {}_{2}He^{4}$

(proton) (α particle)

(ii) ${}_{5}B^{11} + {}_{1}H^{1} \rightarrow {}_{4}Be^{8} + {}_{2}He^{4}$

$\rightarrow {}_{2}He^{4} + {}_{2}He^{4} + {}_{2}He^{4}$

(α-particle)

Eg:- (P, n) reactions:

(i) ${}_{8}O^{18} + {}_{1}H^{1} \rightarrow {}_{9}F^{18} + {}_{0}n^{1}$

(proton) (neutron)

(ii) ${}_{11}N^{23} + {}_{1}H^{1} \rightarrow {}_{12}Mg^{23} + {}_{0}n^{1}$

(proton) (neutron)

eg:- (P, d) reactions

(i) ${}_{4}Be^{9} + {}_{1}H^{1} \rightarrow {}_{6}C^{12} + {}_{1}H^{2}$

(proton) (deuterium)

(ii) ${}_{3}Li^{7} + {}_{1}H^{1} \rightarrow {}_{3}Li^{6} + {}_{1}H^{2}$

(proton) (deuterium)

(iv) (P, γ) reactions

(i) $_5B^{11} + {}_1H^1 \rightarrow {}_6C^{12} + \gamma$
(proton)

(ii) $_{13}Al^{27} + {}_1H^1 \rightarrow {}_7Na^{13} + \gamma$

(3) Transmutation reaction by neutrons:

(i) (n, α) reactions

$_3Li^6 + {}_0n^1 \rightarrow {}_1H^3 + {}_2He^4$

$_{11}Na^{23} + {}_0n^1 \rightarrow {}_9F^{20} + {}_2He^4$

(ii) (n, P) reactions

$_7N^{14} + {}_0n^1 \rightarrow {}_6C^{14} + {}_1H^1$

$_{12}Mg^{24} + {}_0n^1 \rightarrow {}_{11}Na^{24} + {}_1H^1$

(iii) (n, 2n) reaction

$_{92}U^{238} + {}_0n^1 \rightarrow {}_{92}U^{237} + 2\,{}_0n^1$

(iv) (n,

13 Al

92 U

(4) Tra

(i) (γ,

(ii) (

(5) Tr

(i) (

(iv) (n, γ) reaction

$$_{13}Al^{27} + {}_0n^1 \rightarrow {}_{13}Al^{24} + \gamma$$

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239} + \gamma$$

(4) <u>Transmutation reaction by photons</u>

(i) (γ, n) reactions

$$_1H^2 + \gamma \longrightarrow {}_1H^1 + {}_0n^1$$

$$_{15}P^{31} + \gamma \longrightarrow {}_{15}P^{30} + {}_0n^1$$

(ii) (γ, P) reactions

$$_{12}Mg^{25} + \gamma \rightarrow {}_{11}Na^{24} + {}_1H^1$$

$$_4Be^9 + \gamma \rightarrow {}_3Li^8 + {}_1H^1$$

(5) <u>Transmutations by deutrons</u>

(i) (d, α) reactions

$$_8O^{16} + {}_1H^2 \rightarrow {}_7N^{14} + {}_2He^4$$

$$_{20}Ca^{40} + {}_1H^2 \rightarrow {}_{19}K^{38} + {}_2He^4$$

(ii) (d, p) reactions

$_{3}Li^{7} + {}_{1}H^{2} \rightarrow {}_{3}Li^{8} + {}_{1}H^{1}$

$_{15}P^{31} + {}_{1}H^{2} \rightarrow {}_{15}P^{32} + {}_{1}H^{1}$

(iii) (d, n) reactions

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

$_{83}Bi^{209} + {}_{1}H^{2} \rightarrow {}_{84}Po^{210} + {}_{0}n^{1}$