Nuclear Physics Easy Notes

Notes

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typeset with LaTeX

MODULE-5

Nuclear Physics

MODULE-5

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Sub: Physics [NUCLEAR PHYSICS]

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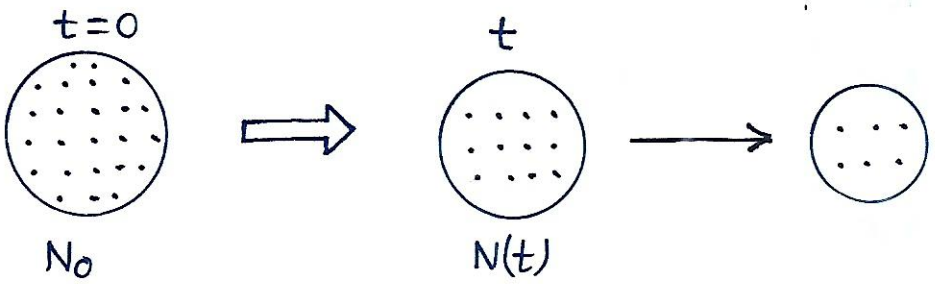
Radioactive Decay Law-

- Probabilistic Observed phenomena.



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

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

↳ Decay constant

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

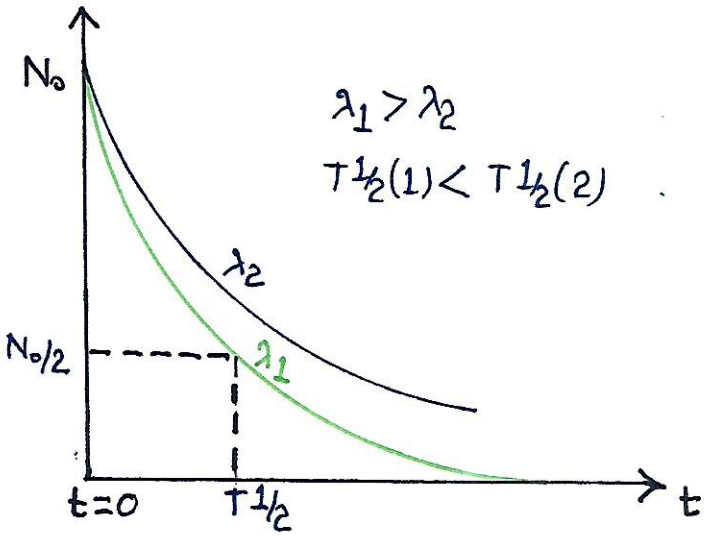
$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{t=0}^{t} dt$$

$$\ln \frac{N}{N_0} = -\lambda t$$

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

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

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



$\lambda_1 > \lambda_2$

$T_{1/2}(1) < T_{1/2}(2)$

$t \equiv T_{1/2}$

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

$$\frac{N_0}{2} = N_0 e^{-\lambda t} \qquad [\because t = T_{1/2}]$$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

$$e^{-\lambda T_{1/2}} = 2$$

$$\lambda T_{1/2} = \ln 2$$

$$\boxed{T_{1/2} = \frac{0.69}{\lambda}}$$

$$\text{Mean life} = \frac{\text{Total lifespan of all radioactive atoms}}{\text{Total numbers of atom}}$$

$$\text{Mean life} = \frac{\int_{t=0}^{\infty} t\, dN}{\int_{N_0}^{0} dN} = \frac{1}{\lambda}$$

$$\boxed{\tau = \frac{1}{\lambda}}$$

We know

$$T_{1/2} = \frac{0.69}{\lambda}$$

$$T_{1/2} = 0.69\tau$$

$$\boxed{\tau = 1.44\, T_{1/2}}$$

$\frac{dN}{dt} \equiv$ Activity

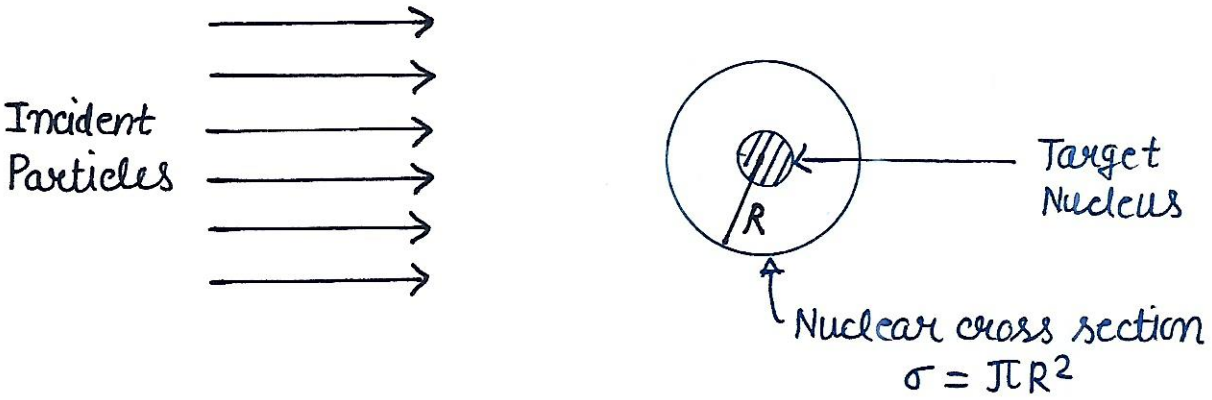
$R = \frac{dN}{dt}$ (Bequrel) = 1 disinitigration sec^{-1}
Bq

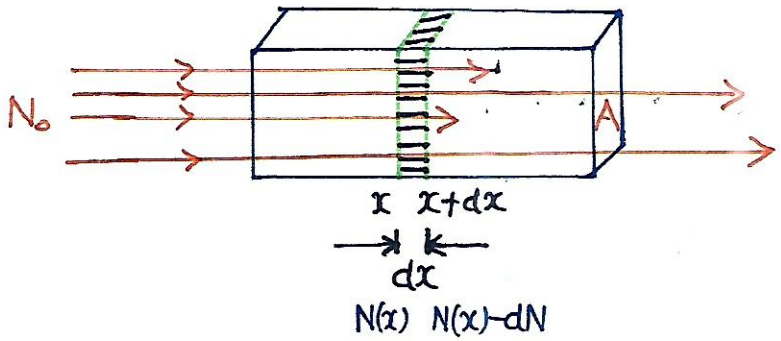
1 curie = 3.7×10^{10} disintigration sec^{-1}

$$R = \frac{dN}{dt} = -\lambda N = -\lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$

$$\boxed{R = R_0 e^{-\lambda t}}$$

#Nuclear Cross Section-





Nuclear cross section is that area around the nucleus facing the incident particles, within which the incident particle will lead to an interaction with the nucleus.

1 barn = 1b = $10^{-28} m^2$ = 100 fm

$n \equiv$ Number density

Number of target nucleus in dx $= n \times A \times dx = nAdx$

→ Cross section area = $nAdx\sigma$

$$\frac{\text{No. of Interaction}}{\text{Total no. of Incident particle}} = \frac{\text{Total (number) nuclear cross sec}^{n}}{\text{Area of cross section of material slab}}$$

$$\frac{dN}{N} = \frac{n\sigma A dx}{A}$$

$$\boxed{\frac{dN}{N} = n\sigma dx}$$

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_{x=0}^{x} n\sigma dx$$

$$[\ln]_{N_0}^{N} = -n\sigma \int_{x=0}^{x} dx$$

$$\ln \frac{N}{N_0} = -n\sigma x$$

$$\frac{N}{N_0} = e^{-n\sigma x}$$

$$\boxed{N(x) = N_0 e^{-n\sigma x}}$$

Rate of Nuclear Reaction $= \frac{\Delta N}{\Delta t}$

$$= \frac{N_0 - N}{\Delta t} = \frac{N_0 - N_0 e^{-n\sigma \Delta x}}{\Delta t}$$

$$= \frac{N_0}{\Delta t}(1 - e^{-n\sigma \Delta x})$$

Approximation

$$\Delta x <<< 1$$

$$\Rightarrow n\sigma\Delta x << 1$$

$$e^{-r} = 1 - r + \ldots\ldots$$

$$= 1 + n\sigma\Delta x$$

$$R = \frac{N_0}{\Delta t}(1 - 1 + n\sigma\Delta x)$$

$$\boxed{R = \frac{N_0 n\sigma\Delta x}{\Delta t}}$$

$$\phi = \frac{N_0}{A\Delta t}$$

Then

$$R = \left(\frac{N_0}{A\Delta t}\right) X A X n\sigma\Delta x$$

$$R = \phi \underbrace{(A n \Delta x)}_{n'} \sigma$$

$$\boxed{R = \phi n' \sigma}$$

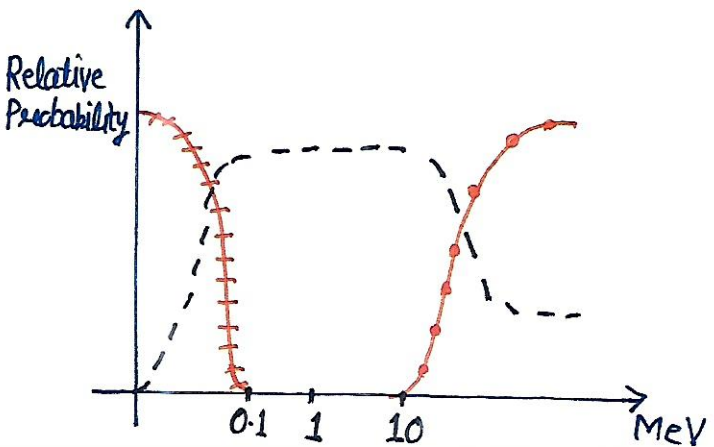
Interaction of Nuclear Radiation with matter-

Nuclear Particles

- γ radiation (PHOTONS)
- ELECTRONS
- α- PARTICLE

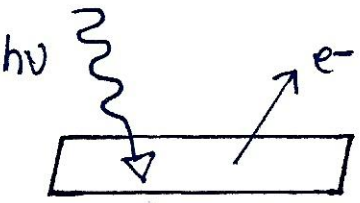
• PHOTON-

- Photoelectric Effect ++++
- Compton Effect ----
- Pair production -•-•-



1. Photoelectric Effect-

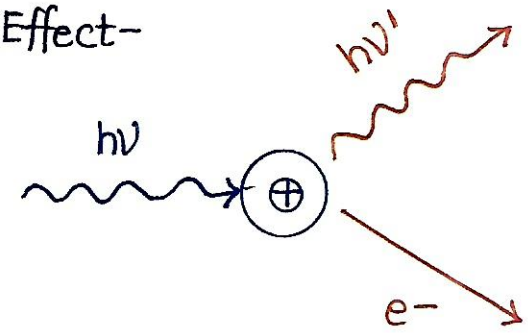
$E < 0.1$ MeV



$KE = h\nu - W$

2. Compton Effect-

$0.1 < E < 10$ MeV

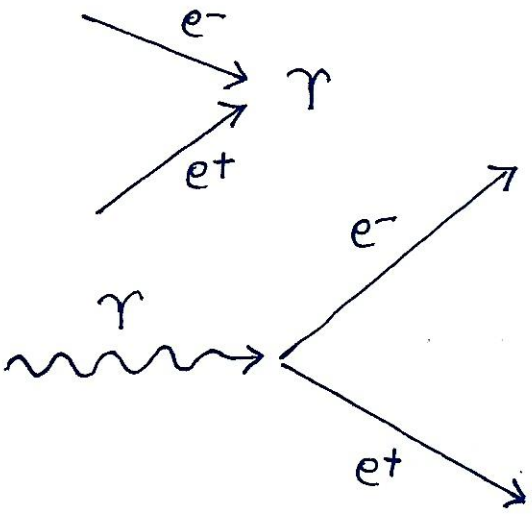


$KE = h\nu - h\nu' - W$

For free e^-

3. Pair Production-

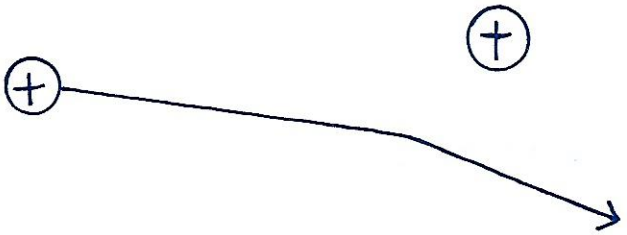
$E > 10$ MeV



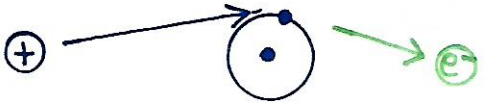
$h\nu > 2m_0c^2$

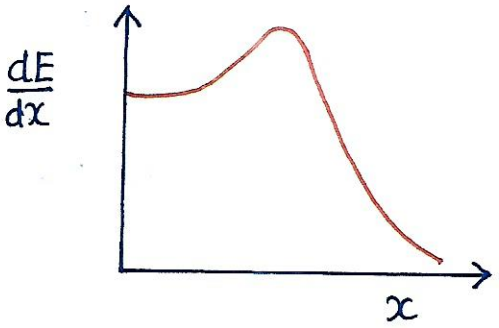
- Electron and α particle-
  - Columb scattering
  - Ionization & Excitation of e^-
  - Brumsstnahlung

1. Columb Scattering-

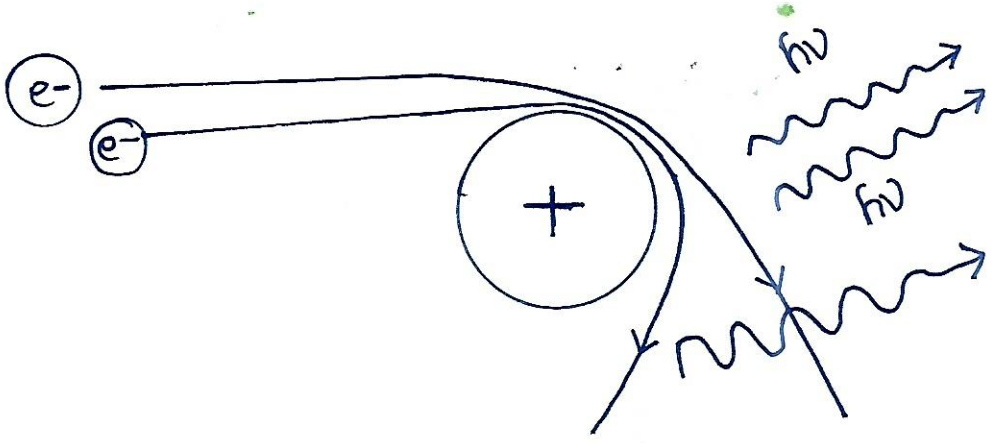


2. Ionization-





3. Brumsstnahlung -
   - Exclusively shown by e^-
   - Deaccelerated



#Cherenkov Radiation-

- Is this possible to travel in speed of light?

↓

C = 299,792,458 m/s

↓

- Nothing can travel faster than speed of light in vaccum.

↓

Air, water, Glass at much lower speed (travel)

↓

C/n → Refractive Index

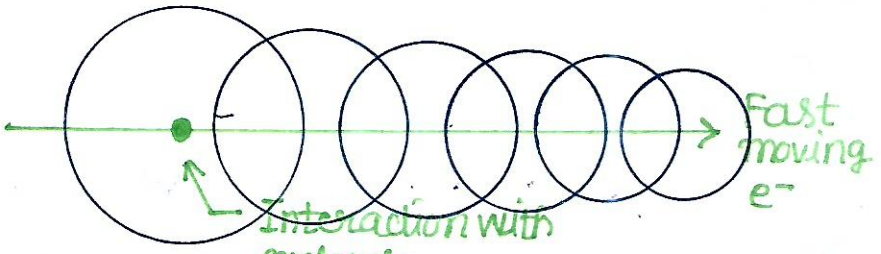
↓

YES

↓

Cherenkov Radiation

DIELECTRIC MEDIUM



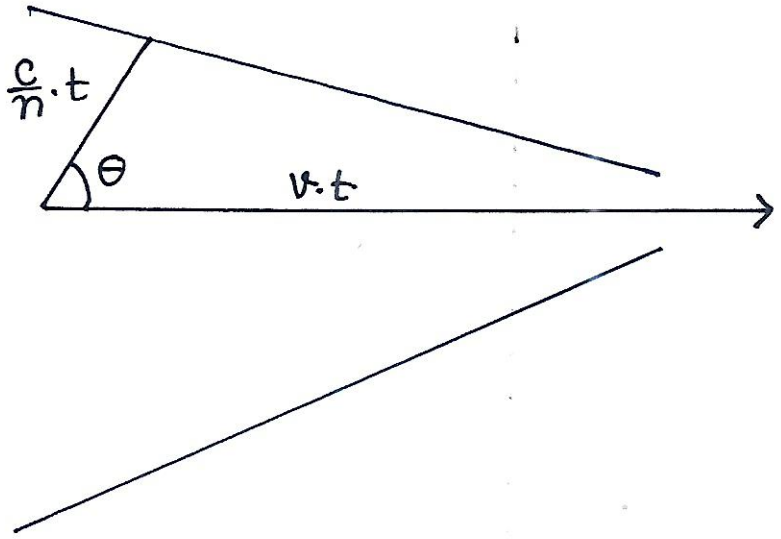
(Polarization and depolarization)

$v < c/n$

↓

$c/n < v < C$ → doppler shift

Example : Sonic boom

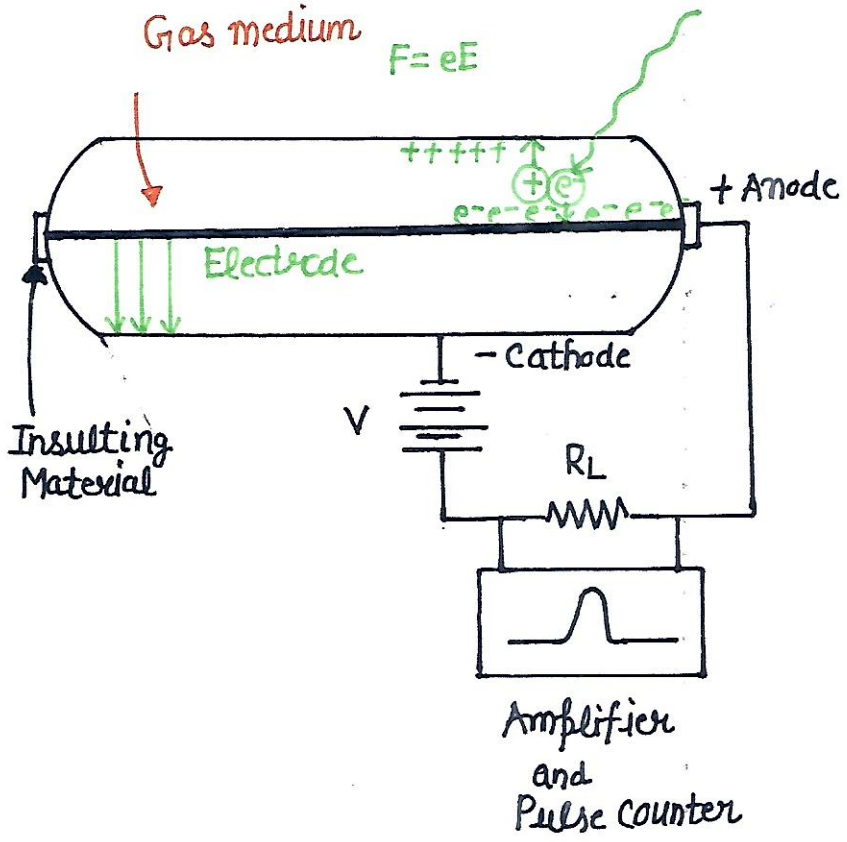


$$\cos\theta = \frac{c}{n}\not{t} \times \frac{1}{v\not{t}}$$

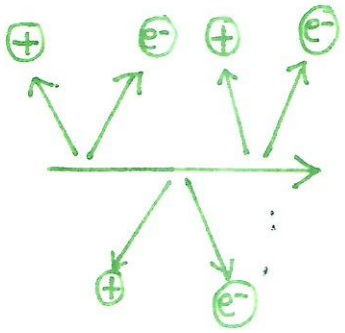
$$\boxed{\theta = \cos^{-1}\left(\frac{c}{nv}\right)}$$

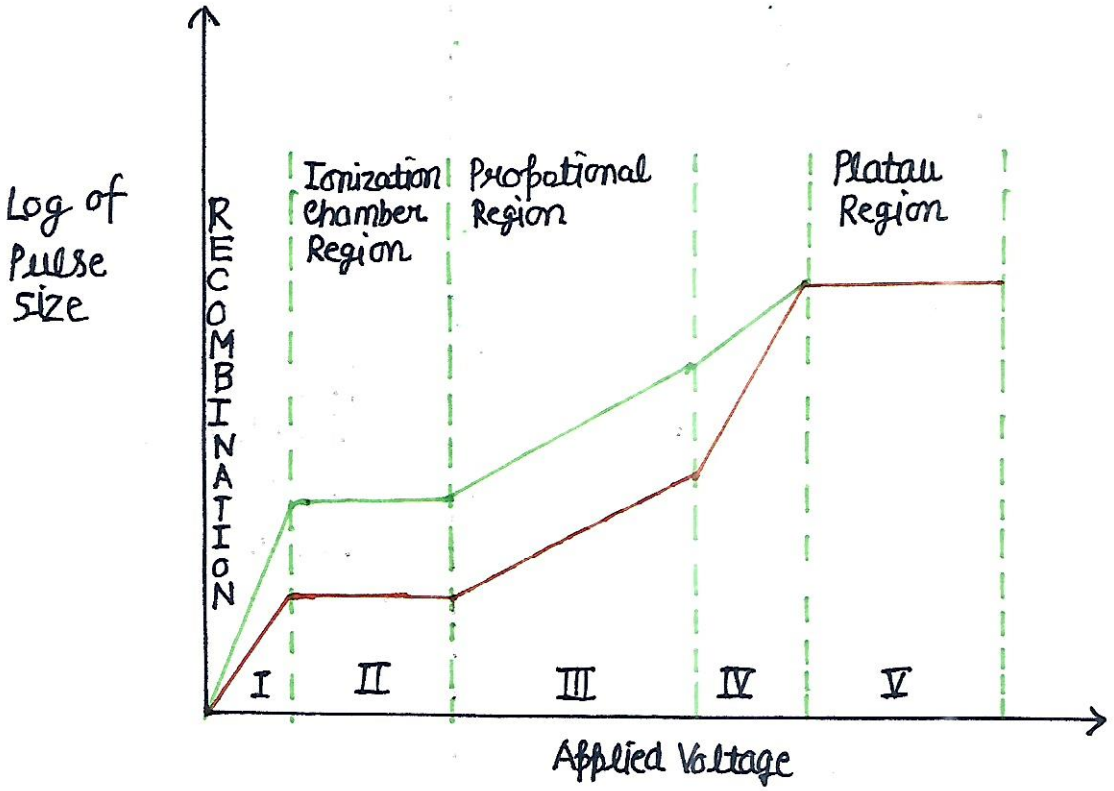
#NUCLEAR DETECTORS | IONIZATION CHAMBER & PROPORTIONAL COUNTER-

- Gas detectors-

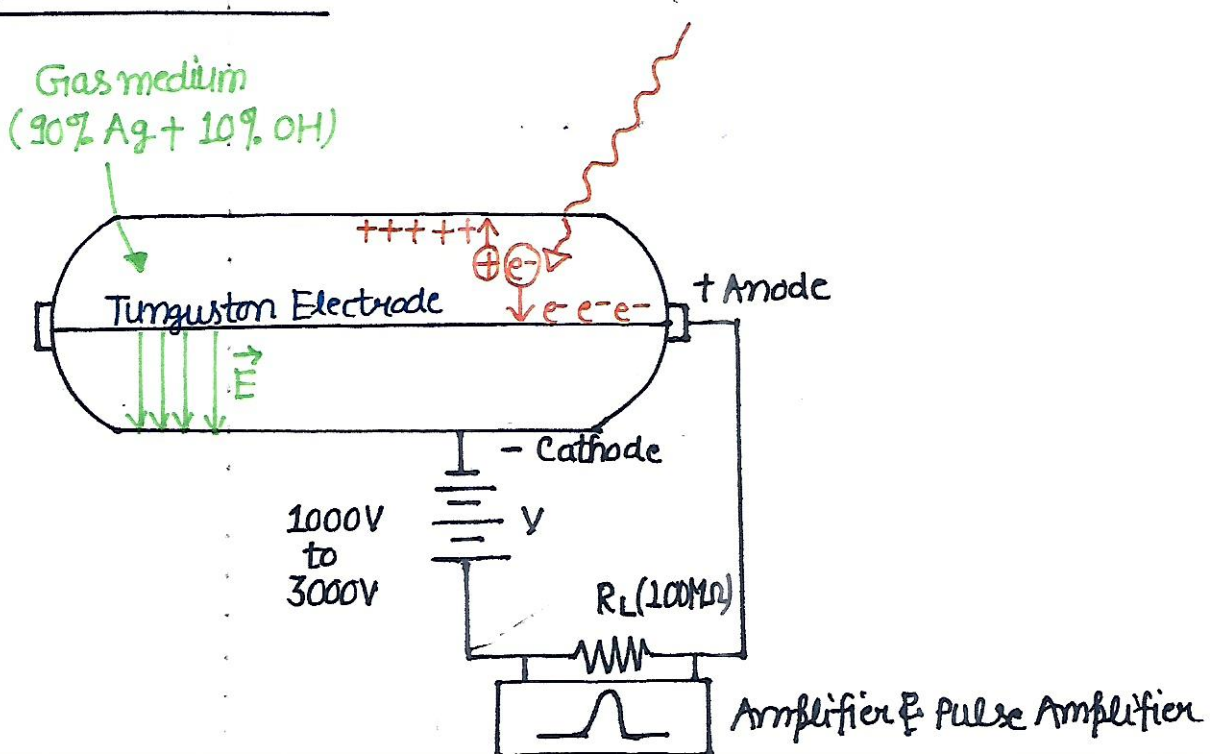


It is based on the principle of ionization. When a high energatic nuclear particle passes through a material medium, it ionizes the medium.

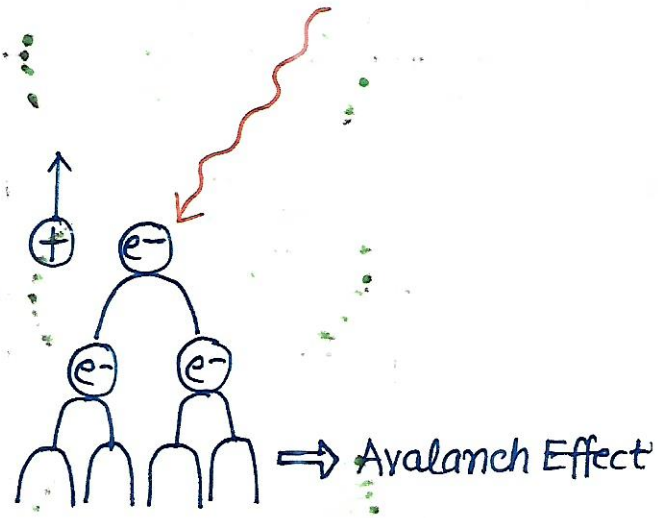




GEIGER MULLER COUNTER-



- It is a kind of nuclear detector.
- Detect α, β, γ, particle (neutron).
- Designed by Geiger Muller in 1928.
- Central electrode made of Tungston.



⇒ Avalanch Effect

1. Dead Time-
   - Inefficient detector.
   - Time 200 mSec.

2. Quenching-
   - Emission of photons while e⁻ recombine with + ion.

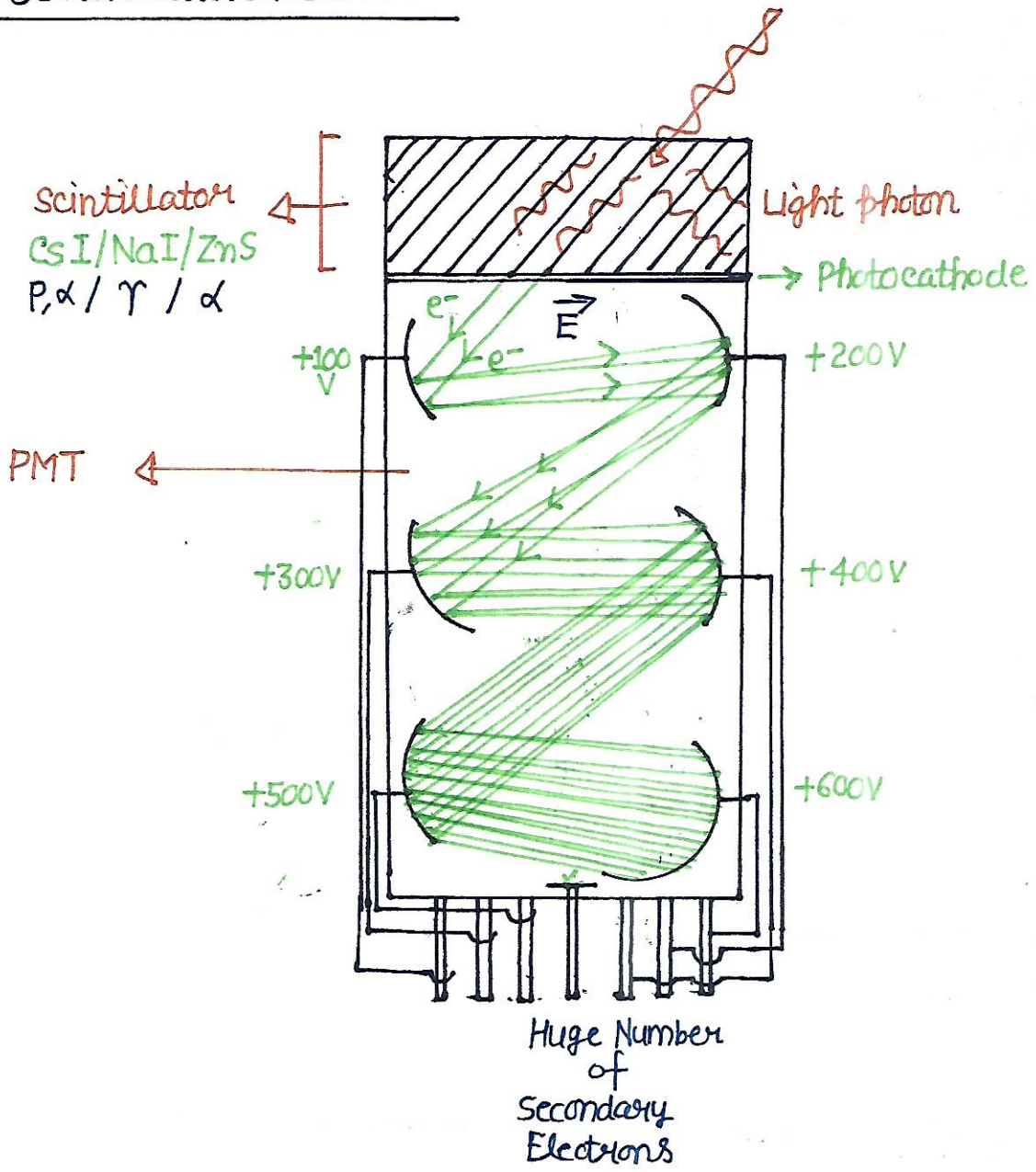
Chemical Quenching | External Quenching

- Advantages-
  - Simple to built.
- Disadvantages-
  - High dead time.
  - Used for low countings.
  - Can't distinguish b/w the energies.

↓

different Energies.

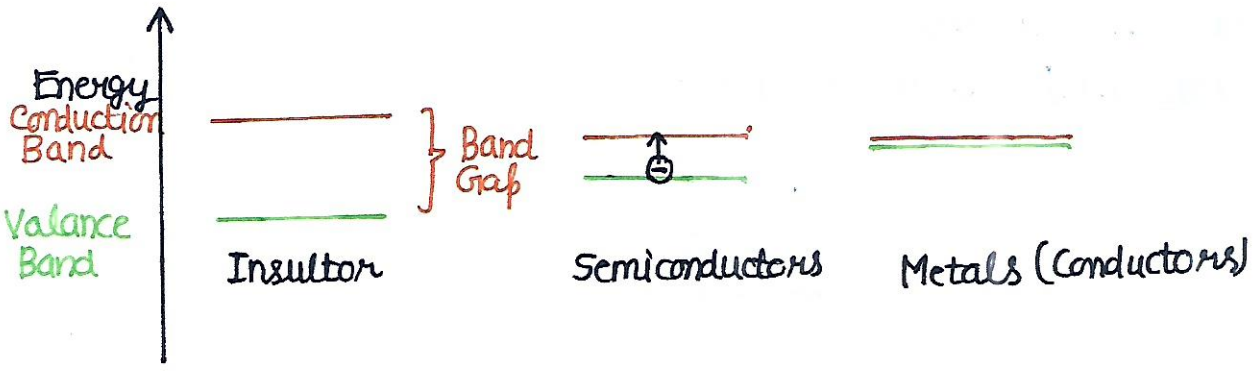
Scintillation Detector–

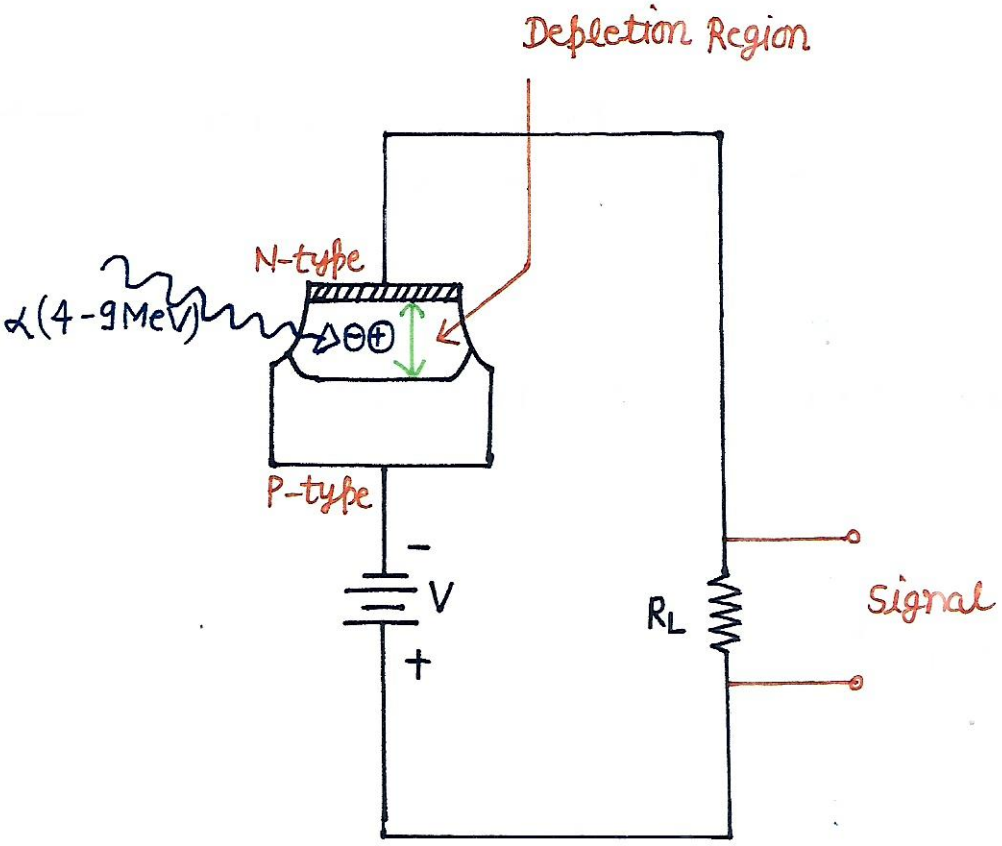


- Intensity of particle
- Energy of particle.

Semiconductor Detector–

- Material that can distinguish between insultor and conductors.





N type :
- Electrons (Charge carrier).

P type :
- Hole (charge carrier).

↓

Reverse bias

↓

Current is minimal flowing through circuit

↓

Depletion layer is large.

↓

Semiconductor detector has better pulse than gas detector

↓

Also work for low energetic particles.

↓

Small and combact in size

#Accelerators-

- Accelerators are instruments that helps scientists to gain information about the structure and properties of nucleus.

↓

Rutherford Scattering Experiment

↓

Alpha particle +
Nucleus +

↓

Repulsion

↓

Alpha particle 4-9 MeV
Columbic Repulsion 20-30 MeV

↓

Need more energy to break down the nucleus → Accelerators

Electrostatic Accelerator
- Van de Graff Accelerator

Electromagnetic Accelerator
- Cyclotron
- Synchroton
- Betatron
- Linear Accelerator

Low Energy
10 - 100 MeV

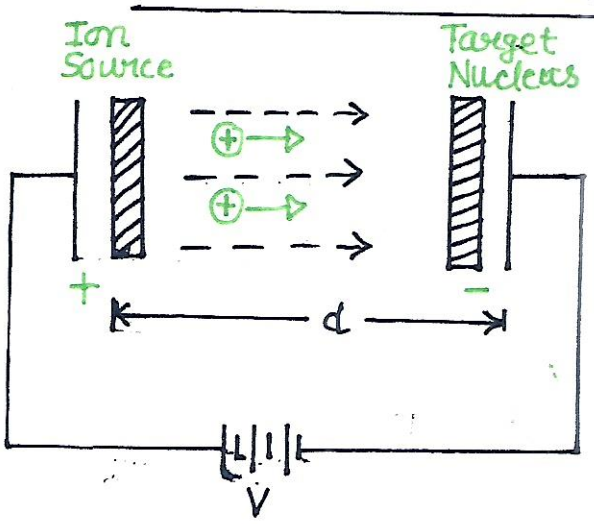
Medium Energy
100 - 1000 MeV

High Energy

Information-

- Scattering Experiment
- Electronic state of Nucleons
- Induce Nuclear reaction
- Study Fundamental particle

ELECTROSTATIC ACCELERATORS



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

$$F = ZeE = qE$$

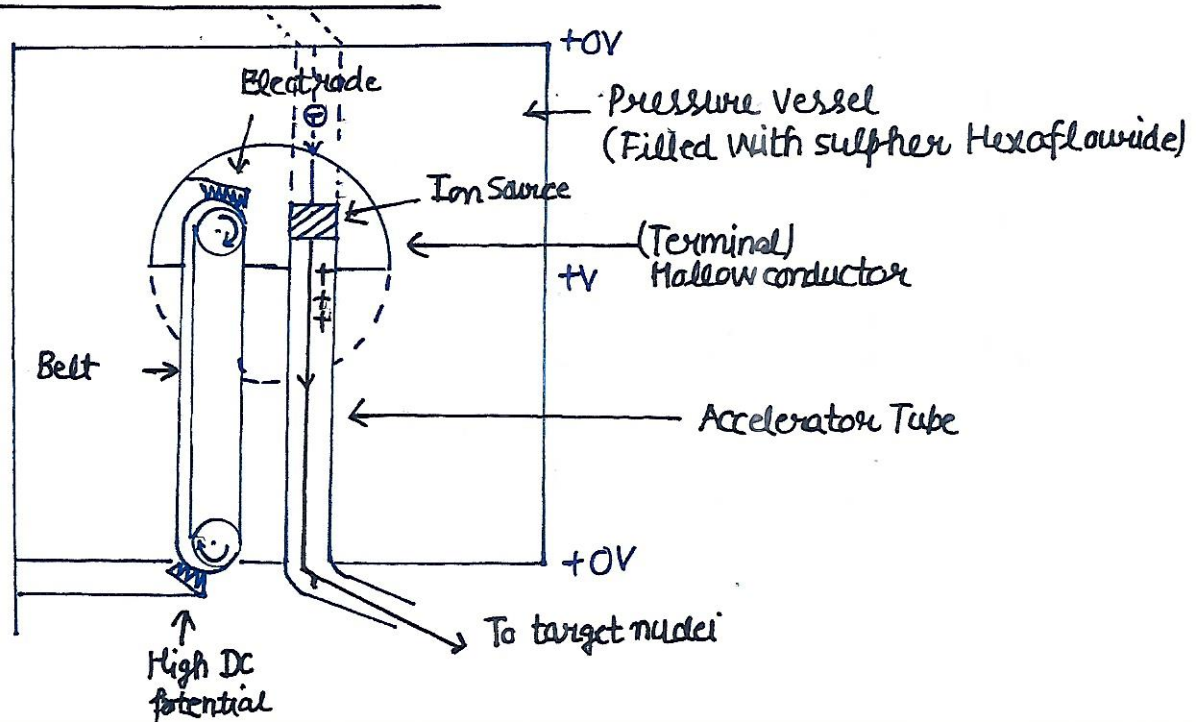
$$F = (Ze)\frac{V}{d}$$

$$W = Fd = Ze\frac{V}{d}d$$

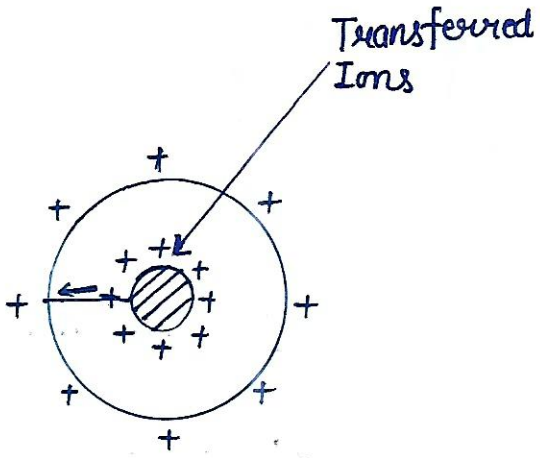
$$\boxed{W = ZeV} \text{ Joule}$$

$$\boxed{W = qV}$$

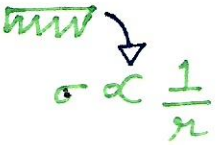
#VAN DE GRAFF GENERATOR-



- Tandom Accelerator
- Pelletron Accelerator
~ 5 MV Energy



- When a charged conductor is brought internally in contact with an external hollow metallic conductor, then all the charges can be transfered to the outside surface of a metallic conductor.



- Van de Graff generators are some of the earliest electrostatic accelerators to attain potential difference of the order of millions of Volts.
- We can increase the potential difference only upto that point where the rate of transfer of charges is equal to the rate of leakage of charges.
- We can use it only for +ve charges.

⇩

Modification for
-ve charges

⇩

$H^- \rightarrow H \rightarrow H^+$

$He^- \rightarrow He \rightarrow He^+ \rightarrow He^{2+}$

$O^- \rightarrow O \rightarrow O^+ \rightarrow O^{2+} \rightarrow O^{3+}$

→ ~ (1+n) V eV

→ Twice acceleration than van de Graff Generator

→ For -ve or stipper particles

- Pelletoon Accelerator

↓

Conveyor belt with small cylinders

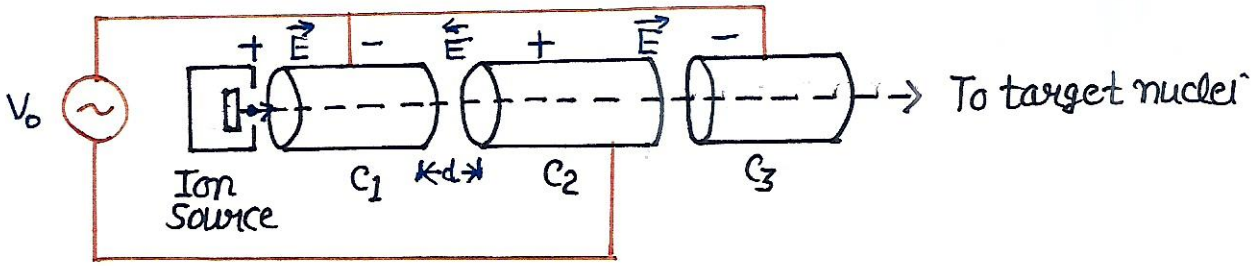
↓

- can charge quickly
- Better energy resolution

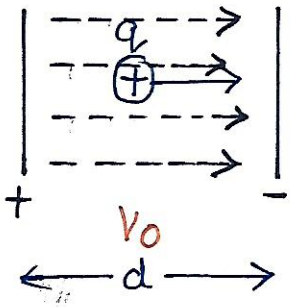
→ TIFR, IUAC

LINAC -

- Linear Charge Accelerator
- Charge particle is accelerated by a potential difference.
- Alternating charge Potential difference.



C_1, C_2, C_3 → Hollow cylinder Electrode



$W = qV_0$

$\Rightarrow F \times d = qV_0$

$ma \times d = qV_0$

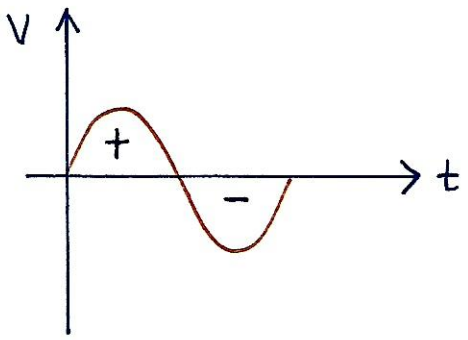
$$\boxed{a = \frac{qV_0}{md}}$$

Kinematics Eq^n -

$v_2^2 = v_1^2 + 2ad$

$v_2^2 = v_1^2 + 2\frac{qV_0}{md}d$

$$\boxed{v_2^2 = v_1^2 + 2\frac{qV_0}{m}}$$



$$\omega = \frac{2\pi}{T}$$

$$\frac{T}{2} = \frac{\pi}{\omega}$$

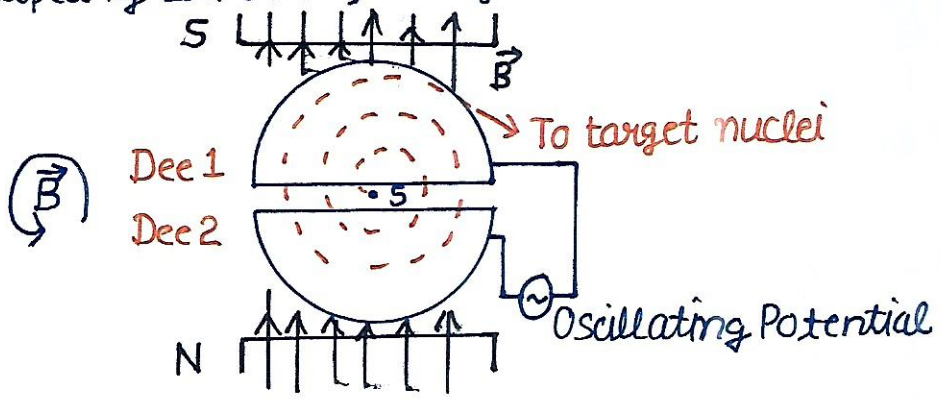
$$\boxed{t = \frac{\pi}{\omega}}$$

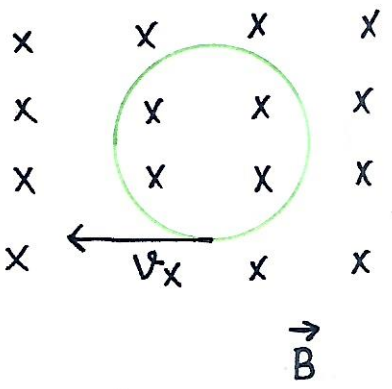
V_1	V_2	KE
0	$\sqrt{\frac{2qV_0}{m}}$	qV_0
$\sqrt{\frac{2qV_0}{m}}$	$\sqrt{\frac{4qV_0}{m}}$	$2qV_0$
$\sqrt{\frac{4qV_0}{m}}$	$\sqrt{\frac{6qV_0}{m}}$	$3qV_0$
$\sqrt{\frac{6qV_0}{m}}$	$\sqrt{\frac{8qV_0}{m}}$	$4q_0$

CIRCULAR
CHARGE
ACCELERATOR
USING
SAME
PRINCIPLE

#CYCLOTRON–

– developed by Lawrance & Livingston in 1929.





$$\vec{F} = q\vec{v} \times \vec{B} = qvB \sin 90^\circ = qvB$$

So

$$qvB = \frac{mv^2}{r} \Rightarrow \boxed{r = \frac{mv}{qB}}$$

Velocity

$$v = \frac{qBr}{m}$$

$$T = \frac{2\pi r}{v}$$

$$T = \frac{2\pi r}{\frac{qBr}{m}}$$

$$T = \frac{2\pi m}{qB} \Rightarrow f = \frac{1}{T}$$

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

$$qV = KE_2 - KE_1$$

$$qV = \frac{1}{2}m(v_2^2 - v_1^2)$$

$$\frac{2qV}{m} = v_2^2 - v_1^2$$

$$v_2^2 = v_1^2 + \frac{2qV}{m}$$

$$v_2 = \sqrt{v_1^2 + \frac{2qV}{m}}$$

$$f = \frac{qB}{2\pi m_0}\sqrt{1-\frac{v^2}{c^2}}$$

- It can't work with relativistic speed.

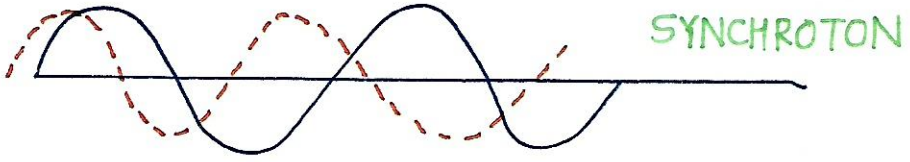
#Synchroton-

- Modified version of cyclotron.
- Work with and beyond relativistic speed.
- Placed perpendicular to $\vec{B}$ Field.

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

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

$$f = \frac{qB}{2\pi m_0}\sqrt{1-\frac{v^2}{c^2}}$$

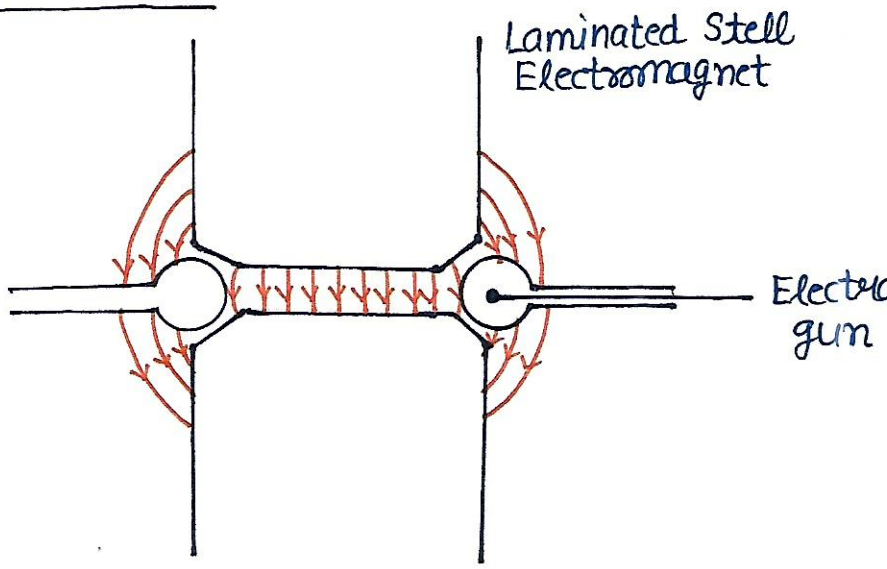


- Sometimes acceleration & sometimes deacceleration in cycloton.

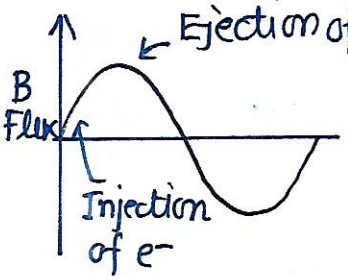
↓

Failed

#BETATRON-



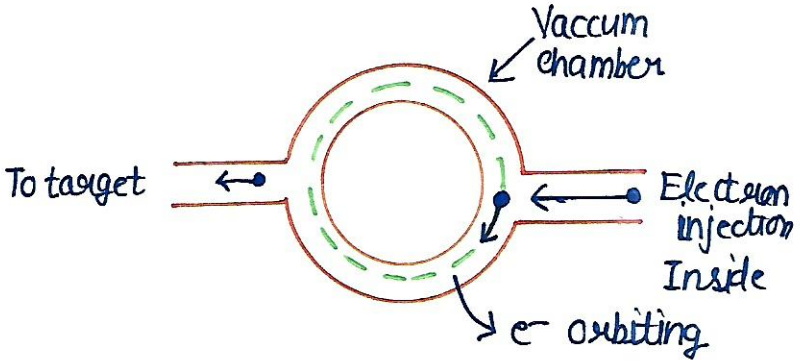
- Changing $\vec{B}$ Field
- AC current passing



changing magnetic field

- Electromagnetic Induction (Accelerate e⁻)
- Lorentz Force (e⁻ moves in circle).

- Accelerate Beta particles like e⁻



Betatron is based on the principle that a changing current in the electromagnet (leads to a changing magnetic field) induces an emf in the secondary coil associated with the e⁻ motion, thus accelerating the e⁻.

$$\mathcal{E} = \frac{d\phi}{dt}$$

Work done $W = qE = e\mathcal{E}$

$$W = SF_1 = 2\pi R F_1$$

So,

$$2\pi R F_1 = e\mathcal{E} = e\frac{d\phi}{dt}$$

$$\boxed{F_1 = \frac{e}{2\pi R}\frac{d\phi}{dt}}$$

$F_L = qvB$

$F_L = evB \qquad (\because \vec{v} \perp \vec{B})$

$\leftarrow F$

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

$$\boxed{mv = eBR}$$

$$\frac{d}{dt}(mv) = eR\frac{dB}{dt}$$

$$\frac{dp}{dt} = eR\frac{dB}{dt}$$

$$\boxed{F_2 = eR\frac{dB}{dt}}$$

$F_1 = F_2$

$$\frac{e}{2\pi R}\frac{d\phi}{dt} = eR\frac{dB}{dt}$$

$$\frac{d\phi}{dt} = 2\frac{d}{dt}(\pi R^2 B)$$

$$\boxed{\phi = \pi R^2 B_{av}}$$

$$\boxed{B_{av} = 2B}$$

- Betatron works at relativistic speed.
- Betatrons emit X rays.

Fission & Fusion-

- Nuclear Binding energy.

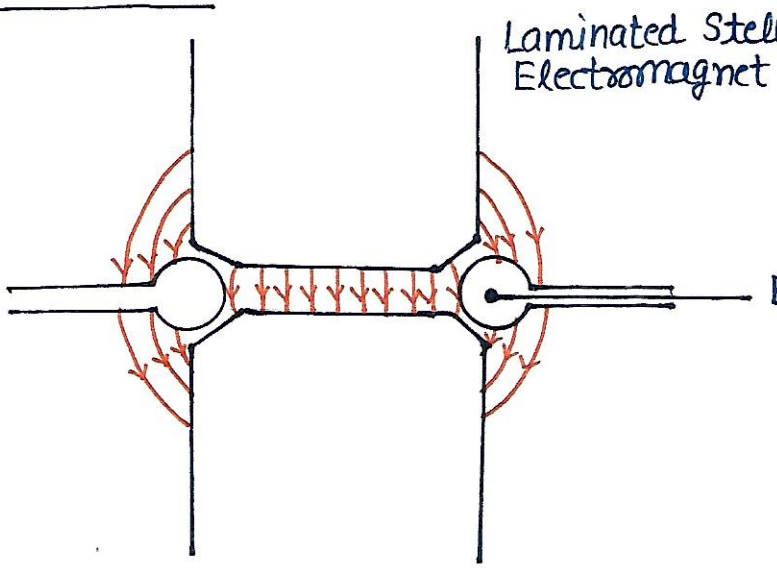
$\Sigma m = M$

$\Sigma m \neq M$ (mass defect)

$\Sigma m - M = \Delta m$

$BE = \Delta m c^2$

#BETATRON-



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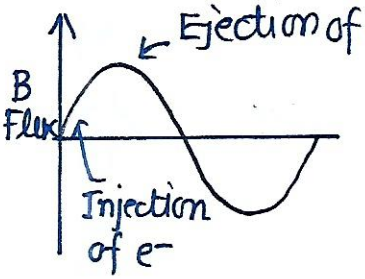

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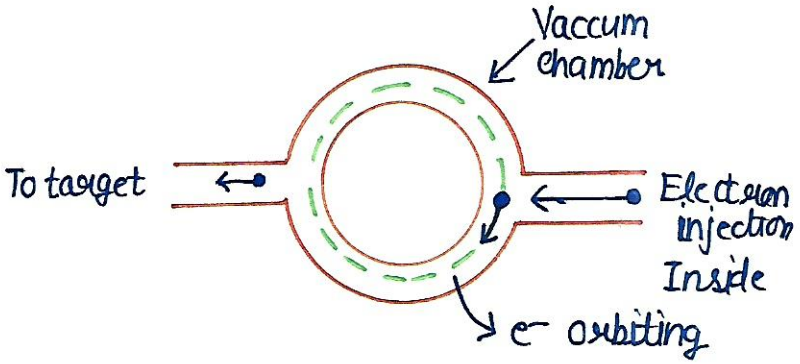

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Greater BE $\Rightarrow$ Higher Stability

$^{2}_{1}H \rightarrow BE = 2.2\ MeV\ ;\ \frac{BE}{A} = 1.1\ MeV$

$^{16}_{8}O \rightarrow BE = 127.6\ MeV\ ;\ \frac{BE}{A} = 7.9\ MeV$

$^{209}_{63}Bi \rightarrow BE = 1640\ MeV\ ;\ \frac{BE}{A} = 7.8\ MeV$

$A \Rightarrow B$

$A \Rightarrow B + Energy$

Low Stability — High Stability

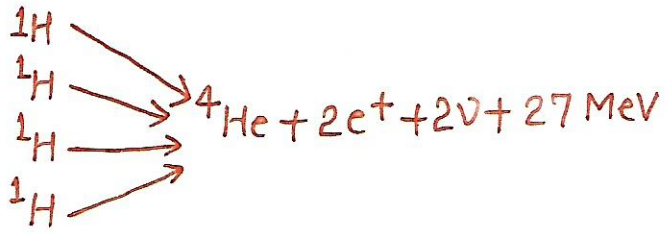


Nuclear Fission

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

Nuclear Bomb
Nuclear Reactor

Nuclear Fusion



Hydrogen Bomb

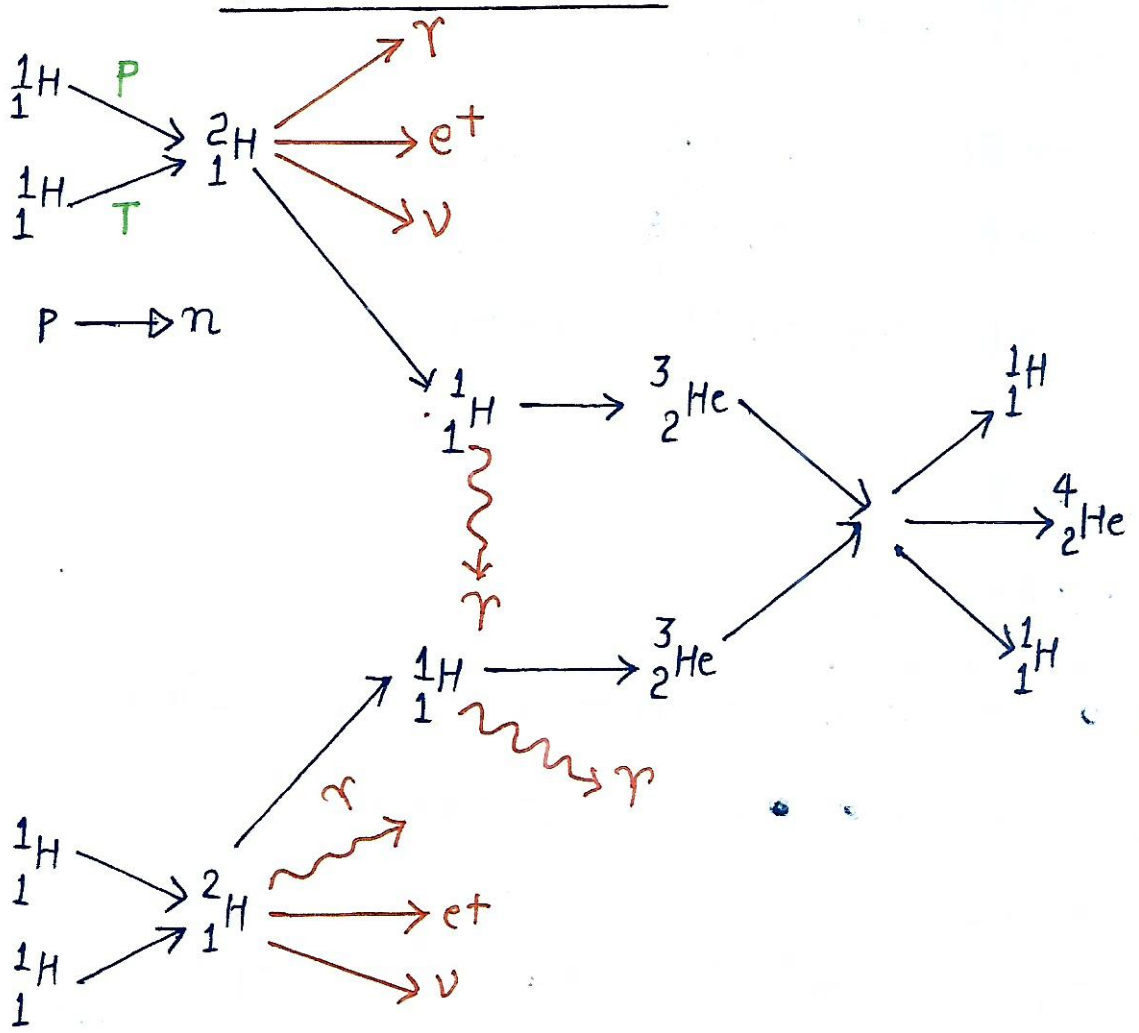
Proton Proton cycle & CNO cycle-

- Nuclear Fusion

In star cores

- Proton-Proton cycle $\Leftrightarrow$ common in small stars
- carbon-nytrogen-oxygen cycle $\Leftrightarrow$ common in bigger stars

Proton-Proton cycle

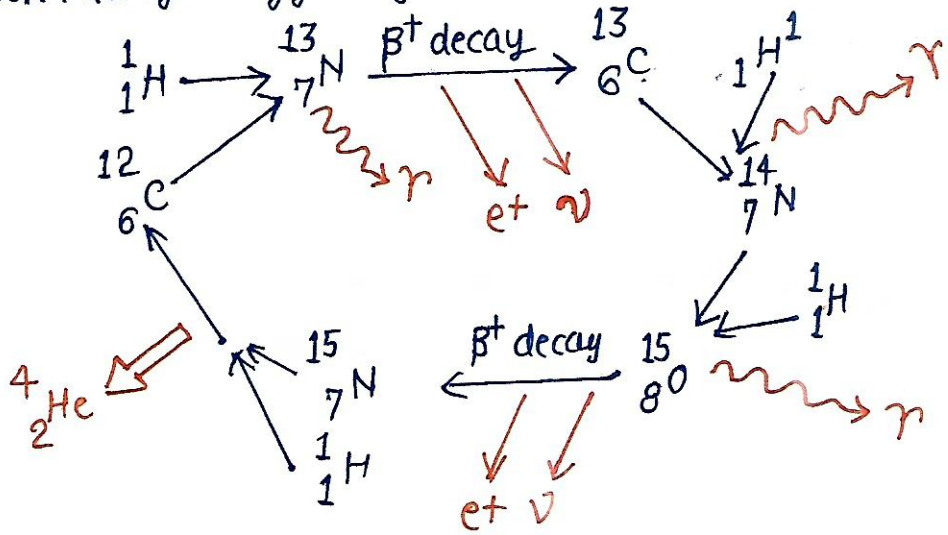


NET REACTION:

$$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2e^{+} + 2\nu + \text{Energy}$$

CNO cycle

- Carbon Nitrogen Oxygen cycle.



NET REACTION:

$$4\,{}_1^1H \longrightarrow {}_2^4He + 2e^+ + 2\nu + \text{Energy}$$

MESON THEORY OF NUCLEAR FORCE–

- Exchange of particle theory.

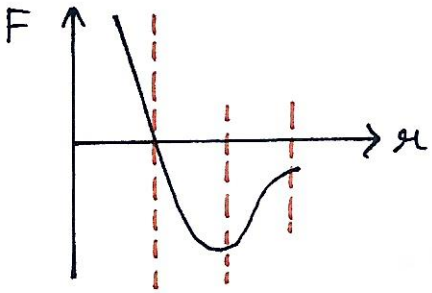




$$F_c = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

$$\boxed{F_c = 230\,N}$$

- Columbic Repulsion Force
- Dominating Nuclear Force
  - Repulsive
  - Attractive



< 0.8 fm ; Repulsive

0.8–2 fm ; Attractive

> 2 fm ; Negligible

⇩

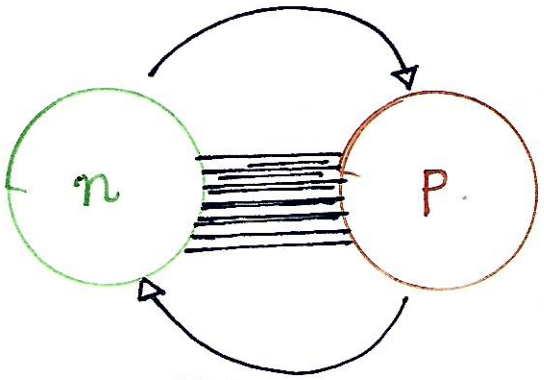
Theory

↓

Hideki Yukawa

↓

Yukawa or Meson theory of Nuclear Force



Exchange of particle

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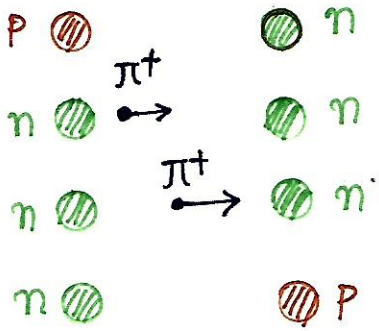
π-meson

π^+, π^-, π^0 (Pions)

$$P \longrightarrow \pi^+ + n$$

$$n + \pi^+ \longrightarrow P$$

- Estimation of mass of pion



- Heigenberg's Uncertainty principle

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

$r = 1.7$ fm

$v \sim c$

$$t = \frac{r}{c} = \frac{1.7}{c}$$

$$\Delta E \Delta t \approx \hbar$$

$$m_\pi c^2 \times \frac{1.7}{c} \approx \hbar$$

$$m_\pi \approx \frac{\hbar}{c} \times \frac{1}{1.7\,\text{fm}}$$

$$m_\pi \approx 2 \times 10^{-28}\ kg\ /\ 9.1 \times 10^{-31}\ kg$$

$$\boxed{m_\pi \approx 220 m_e}$$

- Experimentally proved later on.

$$m_{\pi^+} = 273\, m_e$$
$$m_{\pi^0} = 264\, m_e$$

-

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^0 \longrightarrow \gamma + \gamma$$