(AM)

lec 11 - NP (14th March, 2023)

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* Types of nuclear reactions:

1) Scattering — elastic / inelastic   ~~X,~~ X(a, a)X
   (a = incoming particle; a = outgoing particle)

2) Capture (incoming particle captured by nucleus, outgoing energy in form of γ)
   $X(a,\gamma)Y$

3) Transfer ⇒ $X(a,b)Y$

4) Decay ⇒ α, β, γ

5) Fission ⇒ 1 nucleus = 2 nuclei

6) Fusion ⇒ 2 nuclei = 1 nucleus

** $X(a,b)Y \Rightarrow X + a = Y + b$

(X, Y: nucleus; a, b: particle)

* Conservation laws followed in nuclear reactions

1) Nucleon number (A is conserved)

2) Charge

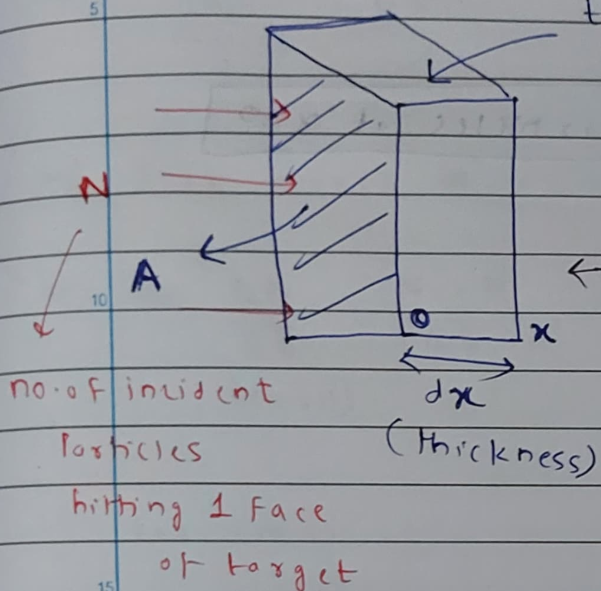
3) Momentum — linear / Angular (Spin & orbital angular momentum both need to be conserved)

4) Mass & Energy (including mass-energy equivalence)
   → Total amount of mass-energy conserved.

nucleus

$\boxed{\sigma \text{ depends on nature of incoming particle \& parent nucleus. It also depends on energy of incoming particle}}$

* Cross-section (σ) = measure of likelihood of a reaction written as an effective area.



target (with parent nuclei)

$$\boxed{\text{no. density } (n) = \frac{\text{no. of atoms}}{\text{Volume}}}$$

HOW DOES N BEHAVE AS FUNCTION OF x (distance moved through target)?

$\Rightarrow$ dN = no. of particles reacting after moving thru thickness dx of target.
= decrease in no. of incoming particles

$\Rightarrow$ if σ = effective area offered by 1 nucleus to incoming beam.

$\Rightarrow$ $nAdx$ = Total no. of nuclei in target.

$\Rightarrow$ aggregate σ = Total effective area of the target for incoming beam
$= \sigma n A dx$

no. of particles reacting

$$\Rightarrow \frac{dN}{N} = \frac{\sigma n A dx}{A} = \frac{\text{effective area}}{\text{Actual area}}$$

no. of incident particles

σ different for diff. materials

Writing as negative:

$$\Rightarrow \frac{dN}{N} = -\sigma n \, dx$$

$\boxed{N_0 \text{ is incident no. of particles at } x=0}$

$\Rightarrow$ Integrating both sides

$$\Rightarrow \int_{N_0}^{N} \frac{dN}{N} = -\int_0^x \sigma n \, dx$$

$$\int_{N_0}^{N} \frac{dN}{N} = -\sigma n \int_0^x dx$$

why it can be taken outside?

(uniform density target with same nuclei throughout, uniform incident beam with particular energy)
(same)

$$\Rightarrow \boxed{N = N_0 \underbrace{e^{-\sigma n x}}_{\text{Probability Factor}}}$$

distance moved by particles through the target

n = no. density of atoms or nuclei in target
N_0 = initial no. of incident particles
N = no. of incident particles after distance
σ = cross-section (area)
A = dist. through target

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→ how much of beam goes away in time interval Δt

REACTION RATE

n' = no. of atoms or nuclei in target

ϕ = flux = no. of incoming particles / area × time

$$\Rightarrow \underset{\text{(small)}}{\frac{\Delta N}{\Delta t}} = \frac{N_0 - N}{\Delta t}$$

⇒ Dist. moved is x in time Δt

$$\Rightarrow \underset{\text{(small)}}{\frac{\Delta N}{\Delta t}} = \frac{N_0 - N}{\Delta t} = \frac{N_0(1 - e^{-n\sigma x})}{\Delta t}$$

for small Δt, x is also small & $\boxed{n\sigma x \ll 1}$

$$\boxed{e^{-n\sigma x} = 1 - n\sigma x} + \underbrace{O(N^2)}_{\text{can be neglected}} - - - -$$

only this much is taken

can be neglected since $n\sigma x$ is small

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

$$\Rightarrow \frac{\Delta N}{\Delta t} = \frac{N_0(n\sigma x)}{\Delta t}$$

usually known (measured qty.)

$$\boxed{\text{Incoming flux of particles } (\phi) = \frac{N_0}{\text{Area} \times \text{time}}} = \frac{N_0}{A \cdot \Delta t}$$

$$\Rightarrow \left(\frac{N_0}{\Delta t} = A\phi\right)$$ {to remove Δt factor from above equation}

$$\Rightarrow \frac{\Delta N}{\Delta t} = A\sigma x n \phi$$

Camlin

KE_{CM} = centre of mass frame (KE in)

→ "n" is no. density

$$n = \frac{n'}{Ax}$$ ← no. of nuclei in target

to remove factor 'x' from previous page

⇒ $$\boxed{\frac{\Delta N}{\Delta t} = \sigma n' \phi}$$

"reaction rate"

RELATION B/W Q & K.E. OF INCOMING PARTICLE

* What KE_{lab} will make reaction happen?

* Q-value, if -ve, gives $K.E._{CM}$ required for reaction to happen

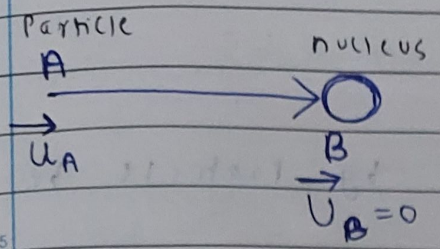
KE_{CM} has to be $\geq |Q|$

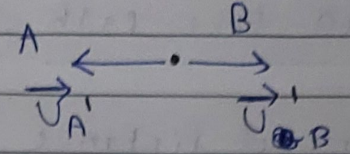
this much energy reqd. for reaction to happen.

σ is calculated in barns $= 10^{-28}\ m^2$
$= 100\ fm^2$

lab frame

C.O.M frame





$$\vec{U}_A' = \frac{m_B \vec{U}_B}{m_A + m_B} \qquad \vec{U}_B' = -\frac{m_A \vec{U}_A}{m_A + m_B}$$

$$KE_{lab} = \frac{1}{2} m_A v_A^2$$

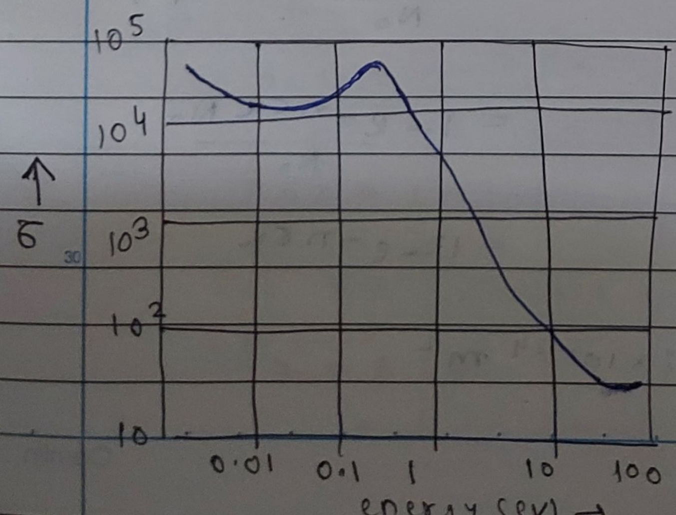
$$KE_{COM} = \frac{1}{2} m_A v_A'^2 + \frac{1}{2} m_B v_B'^2 = \frac{m_B}{m_A + m_B}\left(\frac{1}{2} m_A v_A^2\right)$$

$$\boxed{KE_{COM} = \frac{m_B}{m_A + m_B} \underline{KE_{lab}}}$$

energy that particle must carry if Q-value is < 0

---

* $^{113}_{46}Ca + n \longrightarrow {}^{114}_{48}Ca + \gamma$



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lec 12 - NP (17th March, 2023)

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* Mean free path (mfp)

Average distance moved by particle before reacting

$$\boxed{mfp = \frac{\int_0^\infty x e^{-n\sigma x} dx}{\int_0^\infty e^{-n\sigma x} dx} = \frac{1}{n\sigma}}$$

Q1) $^{113}Cd + n \longrightarrow {}^{114}Cd$ $\quad \sigma = 2\times10^4$ barns $(2\times10^4 b)$

mean atomic mass of natural Cd = 112u

density = 8.64 g/cm³

^{113}Cd is 12% of natural cadmium.

($1u = 1.66\times10^{-27}$ kg)

Find (i) Fraction of incident beam of n absorbed by 0.1 mm thick cadmium sample

Soln: No. of n absorbed $= N_0 - N$

Fraction of n absorbed $= \frac{N_0 - N}{N_0} = 1 - \frac{N}{N_0}$

$= 1 - \frac{e^{-n\sigma x} N_0}{N_0}$

$= 1 - e^{-n\sigma x}$

$\sigma = 2\times10^4$ b $= 2\times10^{-24}$ m²

$x = 10^{-4}$ m

Camlin

$\boxed{n}$ = no. density

$$= \boxed{\frac{\text{density}}{\text{mass of 1 atom}}} = \frac{8.64 \times 10^{3}\ kg/m^3}{112 \times 1.66 \times 10^{-27}\ kg}$$

"This is of every type of cadmium but we want only ^{113}Cd"

therefore

$$n_{actual} = \frac{12}{100} \times \left(\frac{8.64 \times 10^{3}\ kg/m^3}{112 \times 1.66 \times 10^{-27}\ kg} \right)$$

$$= 5.58 \times 10^{27} \text{ atoms}/m^3$$

$$n\sigma = 1.12 \times 10^{4}\ m^{-1}$$

$$\boxed{\text{Fraction}} = 1 - e^{-n\sigma x} = \boxed{0.67}$$

(ii) Thickness of Cadmium needed to absorb 99% of incident neutrons

Soln:

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

99% absorbed $\Rightarrow$ 1% left

$$N = 0.01 N_0$$

$$\frac{N}{N_0} = 0.01$$

$$0.01 = e^{-n\sigma x}$$

$$e^{n\sigma x} = 100$$

$$n\sigma x = \ln 100$$

Put value calculated previously

$$\boxed{\begin{aligned} x &= 4.1 \times 10^{-4} m \\ &= 0.41\ mm. \end{aligned}}$$

if we have around 0.5mm, then 100% may be absorbed

ΔN = no. of reactions happening in time Δt

(iii) mean free path

Soln: $\boxed{mfp} = \frac{1}{n\sigma} = \boxed{0.0893 \text{ mm}}$

Q2) Natural gold has only ^{197}Au

σ for: $^{197}Au + n \longrightarrow {}^{198}Au$ is 99 b

How long should a ~~to~~ 10 mg of gold foil be exposed to flux of 2×10^4 neutrons/$m^2 s$ in order for the sample to have 2.48×10^{12} ^{198}Au atoms?

Soln: $\Delta t = \frac{\Delta N}{\phi n' \sigma}$ $\quad \sigma = 99$ b

$\phi = 2 \times 10^4 \ m^{-2} s^{-1}$

$\boxed{n' = \frac{\text{mass of target in kg}}{\text{mass of 1 atom in kg}}}$ → 10 mg ; → $197 \times 1.66 \times 10^{-27}$ kg

$n' = 3.06 \times 10^{19}$ atoms

ΔN = no. of ^{198}Au after Δt time
= no. of reactions in Δt time
= 2.48×10^{12}

$\boxed{\Delta t = 6 \text{ min } 49 \text{ sec.}}$

β decay = Parity is not conserved

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* TO STUDY A REACTION FOR CONSERVATION OF ANGULAR MOMENTUM & PARITY

$(l_{rel})^{\mu_{rel}} = ?$ $(l_{rel})^{\mu_{rel}} = ?$ ⇒ these we need to find in this topic ↓

$$^{7}_{3}Li + ^{1}_{1}H \longrightarrow ^{4}_{2}He + ^{4}_{2}He$$

j^μ j^μ j^μ j^μ

$Q = 17.35$ MeV

"We want to know j & μ of individual nuclei"

	j^μ
$^{4}_{2}He$	$= (0)^+$
$^{4}_{2}He$	$= (0)^+$
$^{7}_{3}Li$ =	$(3/2)^-$
$^{1}_{1}H$ =	$(1/2)^+$

$\boxed{\text{even-even} \Rightarrow \mu = +1}$

$1p$ — $1p_{1/2}$, $1p_{3/2}$

$1s$ — $1s_{1/2}$

$P = 3$
$N = 4$

* $\boxed{\text{relative motion parity } (\mu_{rel}) = (-1)^{l_{rel}}}$

→ Parity is also conserved in this reaction

"Parity is conserved in some reactions only (will be given in exam)"

→ Parity is multiplicative

* We want to calculate $(l_{rel})^{\mu_{rel}}$ on both sides

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* RHS is 2 identical bosons → wavefunction has to be symmetric

+ve parity μ^{rel} (+1)

it means RHS ⇒ l_{rel} has to be even
⇒ l_{rel} can be 0, 2, 4 ---

$\boxed{RHS = (0, 2, 4 ---)^+}$ → $(l_{rel})^{\mu_{rel}}$

$\boxed{\text{Total } j^\mu = (0, 2, 4 ---)^+ \text{ on RHS}}$

* μ_{rel} on LHS = −ve (so as total becomes +ve)

$\mu_{rel} \times (-) \times (+)$

on LHS — For ^7_3Li — For ^1_1H

⇒ $\mu_{rel} = (-1)^{l_{rel}} = (-1)$ — 1, 3, 5 ---

⇒ l_{rel} can have odd values = $(1, 3, 5 ---)^-$

⇒ We choose 1^- on LHS since higher l_{rel} doesn't allow nuclei to come close enough to react

Reason.
if higher values, particles move faster past each other & do not [illegible]

Camlin

"Angular momentum is additive"

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Total j^H on LHS $= (\overset{\times}{0}, 1, 2, \overset{\times}{3} - -) +$ not allowed, since only 1 & 2 are on RHS & we need conservation

$$\left.\begin{array}{l} 1 + \frac{3}{2} - \frac{1}{2} \\ 1 - \frac{3}{2} + \frac{1}{2} \\ -1 + \frac{3}{2} + \frac{1}{2} \\ - - - - \end{array}\right\}$$

angular momentum is additive and since they can be parallel/antiparallel, can be added or subtracted.

(AM)

lec 13 – NP (21st March, 2023)

Nuclear reactions

(slow neutrons)
energy = few eV to < 1 MeV

Time reqd. for incident particle to be in target ~ 10^{-15} s

compound nucleus reactions

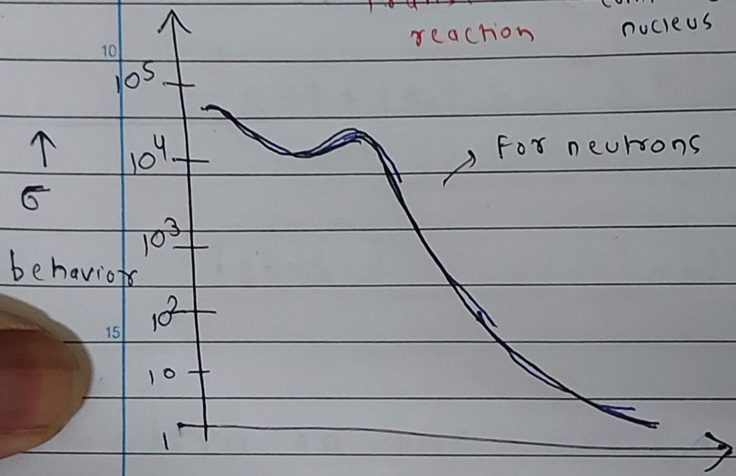
~~$^{107}Ag + n \rightarrow {}^{108}Ag^{*}$~~
~~$^{108}Ag^{*} \rightarrow {}^{108}Ag + \gamma$~~

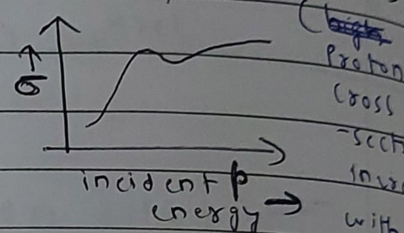
capture ~~reaction~~ reaction: $^{107}Ag + n \longrightarrow {}^{108}Ag + \gamma^{*}$

$\boxed{X + a \longrightarrow Y + b^{*} \qquad X + a \longrightarrow C^{*} \longrightarrow Y + b}$

Transfer reaction (for $X + a \longrightarrow Y + b^{*}$)

compound nucleus (for C^{*})





(~~high~~ Proton cross-section increases with increasing K.E. since proton repelled by nucleus & that much min. energy reqd to overcome repulsion

* Why decreasing? = because n has to spend some time in target for reaction to happen.

* ~~A~~ Why Peak? = More energetic (faster) n ~~*~~ pass thru in quickly for reaction to happen

⟶ Faster n is less likely to have the reaction

⟶ σ decreases with increasing n energy.

→ So High energy of proton required to reach the target.

* $^{107}Ag + n \longrightarrow {}^{108}Ag^*$ → compound nucleus

$^{108}Ag^* \longrightarrow {}^{108}Ag + \gamma$

* Compound nucleus loses memory of ~~formation~~ Formation.

formation channel

$X + a \longrightarrow C^*$

$C^* \longrightarrow Y + b$ decay channel

*
$$\left.\begin{array}{l} {}^{1}_{0}n + {}^{13}_{7}N \\ {}^{1}_{1}H + {}^{13}_{6}C \\ {}^{2}_{1}H + {}^{12}_{6}C \\ {}^{3}_{1}H + {}^{11}_{6}C \\ {}^{3}_{2}He + {}^{11}_{5}B \end{array}\right\} \longrightarrow {}^{14}_{7}N^* \longrightarrow \left\{\begin{array}{l} {}^{13}_{7}N + {}^{1}_{0}n \\ {}^{13}_{6}C + {}^{1}_{1}H \\ {}^{12}_{6}C + {}^{2}_{1}H \\ {}^{10}_{5}B + {}^{4}_{2}He \end{array}\right.$$

imp. Decay channel depends on excitation state of compound nucleus, not on formation channel

* C.S. for formation of compound nucleus

$$\cancel{\sigma = A / B}$$

$$\sigma_a = A \left[\frac{B}{(E - E_R)^2 + C} \right]$$

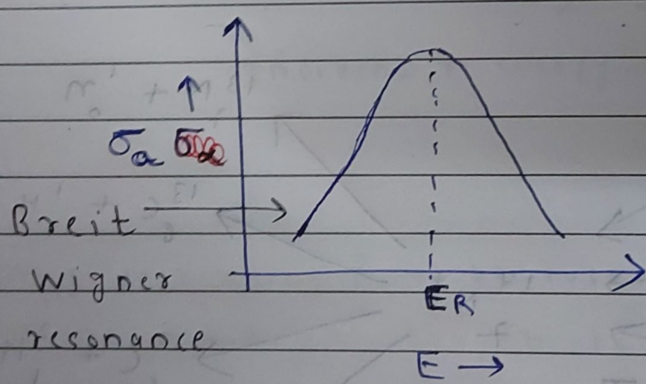
A, B, C → independent of energy

σ_a → cross section of formation channel

E → K.E. of incident particle

E_R → constant energy

⇓ graph



E_R = energy of compound nucleus (state)

* C.S. for reaction to happen is a function of function σ_a, some function of σ_a

$$\sigma_{ab} = F(\sigma_a)$$

σ_{ab} → cross section for reaction

10% to 15% are direct reactions

↑

* Direct reactions → Fast n react only with surface of nuclei within 10^{-21} s to directly give end particles.

~~[illegible]~~

$$X + a \longrightarrow Y + b$$

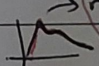
these reactions can also happen

* Slow n ~ few eV to < 1 MeV spend 10^{-15} s time

* Fast n > 1 MeV, spend 10^{-21} s time

Features of Direct reactions

1) ~~Mono~~ Monotonic dependence of σ on neutron energy

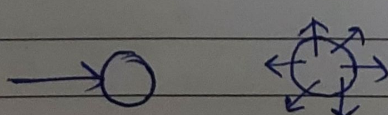
→ no peaks in graph →  → not allowed

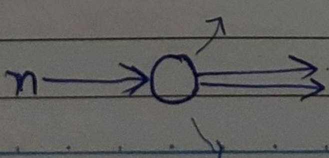
2) Highly energetic output Particles

→ due to ~~highly~~ energetic input particles

3) Forward peaking of output Particles spectrum.

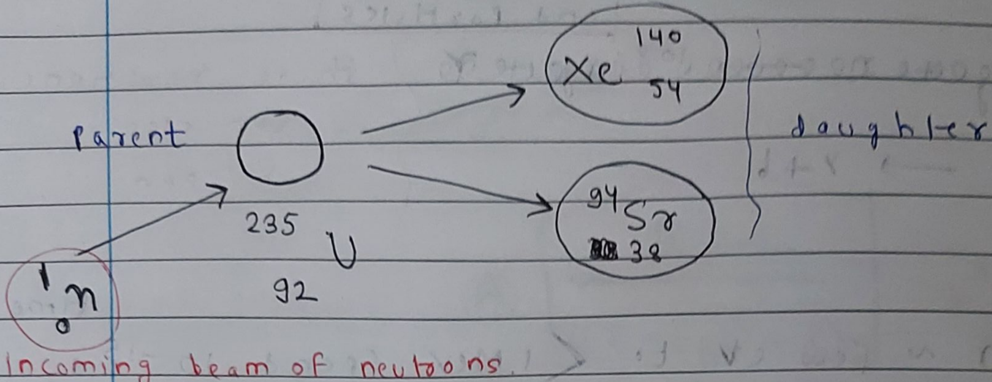
→ O/P particles tend to go in same direction as that of I/P particles.

C.N.R.  O/P Particles in all directions

D.R.  O/P Particles in same direction as I/P Particles

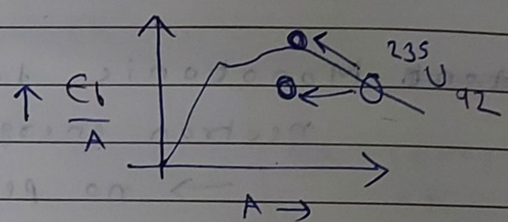
This also happen but mostly in same direction.

NUCLEAR FISSION



* exothermic / exergic reaction because E_b/A of parent is lower than of daughters.

* excess E_b/A of daughter is released.



* 99.9% = make it happen
0.1% = spontaneously

* nuclear weapons & artificial way of generating energy.

* releases 200 MeV of energy (Huge source of power)

* Fission is compound nucleus reaction

has to be sufficiently excited to vibrate ~~violently~~ violently break up

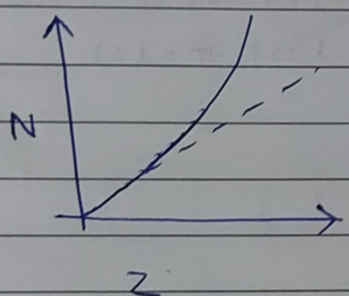
$2\left({}^{1}_{0}n\right)$

* $^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U^{*} \longrightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + \cancel{2n}$

2 neutrons released.

* no. of released ~~neutrons~~ n > no. of incident n

because $\left(\frac{N}{Z}\right)_{stable}$ ratio is higher for heavier nuclei



* $^{1}_{0}n + {}^{A+B+C}_{Y+Z}X \longrightarrow {}^{A+B+C+1}_{Y+Z}X^{*} \longrightarrow {}^{A}_{Y}X' + {}^{B}_{Z}X'' + (C+1)\,{}^{1}_{0}n$

"C+1" neutrons

"general expression for nuclear fission"

* artificially induced fission (99%)

* $^{A+B+C}_{Y+Z}X \longrightarrow {}^{A}_{Y}X' + {}^{B}_{Z}X'' + C\,{}^{1}_{0}n$

Spontaneous fission (rare)

(AM)

lec 14 – NP (24th March, 2023)

* **Nuclear fission** → fair probability of happening

$$ {}^{A+B+C}_{Y+Z}X + {}^{1}_{0}n \longrightarrow {}^{A+B+C+1}_{Y+Z}X^{*} \longrightarrow {}^{A}_{Y}X' + {}^{B}_{Z}X'' + (C+1)\,{}^{1}_{0}n $$

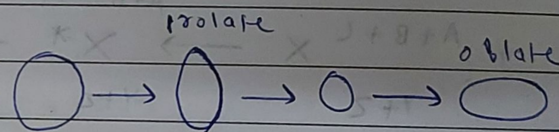
⇒ Needs energy but exothermic

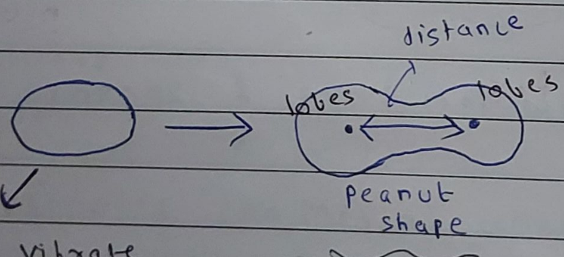
* Fission chain reaction
  ↳ makes ~~it~~ fission useful for us

* Fission as per Liquid drop model

* ${}^{235}U$ ~~and~~ vs. ${}^{238}U$

* **Liquid drop (LD)**

LD → excited Nucleus → 



if vibrate violently enough, then nuclei may become peanut shape

form 2 lobes separated by distance

* almost Impossible to create 8 MeV incoming neutrons

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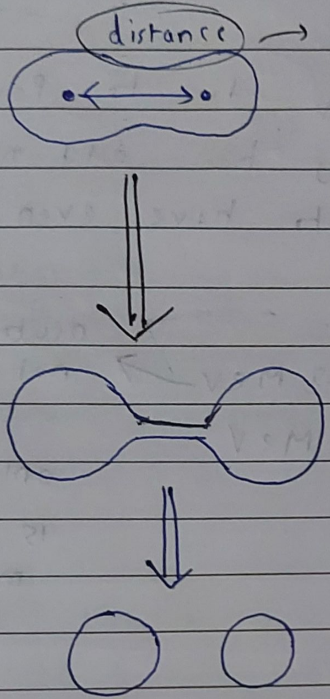
2 forces exist in nuclei:

* N-N short range attractive force
* Repulsive coulomb force



if > critical distance, attractive force loses its efficiency and only repulsive force acts.

"dumbell shape" (only repulsive force and no attractive force)

2 nuclei

$$KE_{\text{incoming neutrons}} + BE_{\text{incoming neutrons}}$$

* About 7-8 MeV energy is reqd. to form lobes.

* $BE_n = BE_{in}$ = BE incoming neutrons
higher means it wants another neutron.

* ^{235}U vs. ^{238}U

⇒ ^{235}U has higher B.E. ~~incoming neutrons~~ (in) &

^{238}U has lower BE_{in} due to Pauli's exclusion principle, ^{235}U has odd no. of neutrons and wants to have even no. of neutrons

⇒ BE_n for $^{235}U \simeq 7-8$ MeV → ∴ neutrons does not need to carry K.E. only its B.E. is enough to make fission happen

BE_n for $^{238}U \simeq 6$ MeV → neutrons need to have ~~K.E.~~ ~2 MeV K.E. to make fission happen

⇒ hard to make fission happen in ~~238U~~ ^{238}U

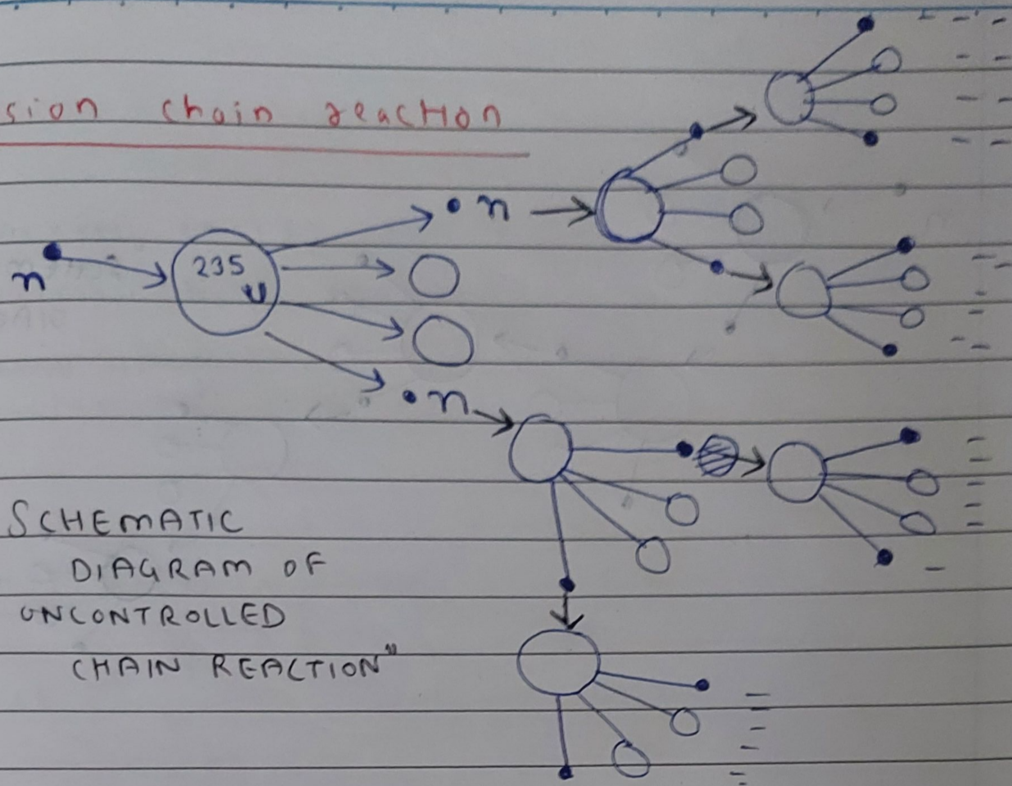
⇒ ^{238}U more likely to capture the incoming neutron (even of ~1 MeV).

⇒ $\boxed{\text{"Fissile nuclear fuel"}}$ ⇒ ^{235}U, fuel which makes fission easily happen

⇒ $\boxed{\text{"Fissionable"}}$ ⇒ ^{238}U

O = nuclei • = neutrons

* Fission chain reaction



" SCHEMATIC DIAGRAM OF UNCONTROLLED CHAIN REACTION"

Stage 1		stage 2		stage 3		stage 4		stage 5	
* 1	→	2	→	4	→	8	→	16	- - - -

exponentionally increasing fission reactions
if both neutrons used for fission in each stage

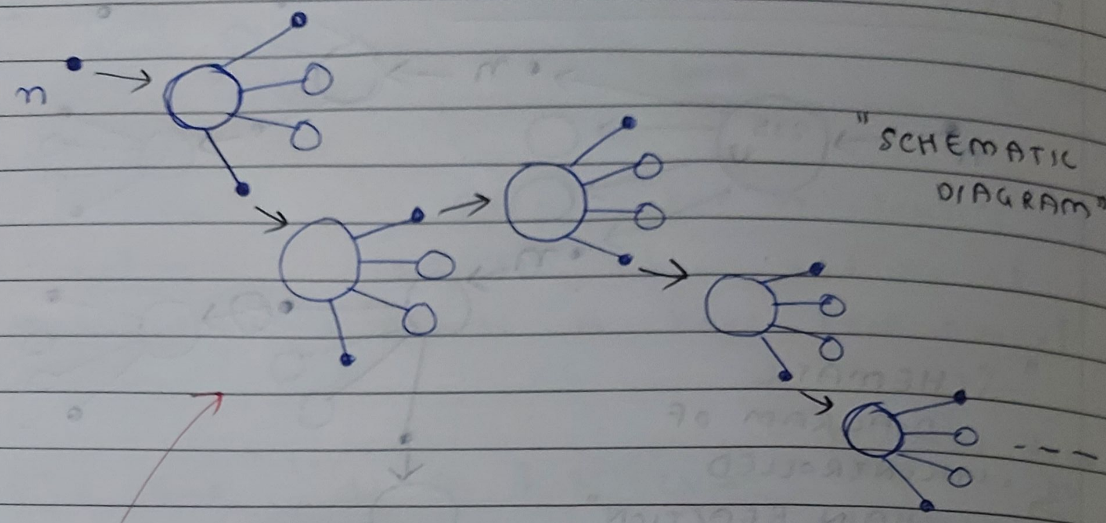
* "$\boxed{\text{Super critical or uncontrolled chain reaction}}$"

→ more than 1 neutron from one fission is used in the next fission

→ release uncontrolled amount of energy (explosion)

→ Used in nuclear weapon / bombs

*



* **Critical or controlled chain reaction**

- exactly 1 neutron from one fission is used in the next fission
- controlled release of energy
- ~~Nucle~~ used in nuclear reactors

* **Sub-critical chain reaction** ⟹ less than 1 neutron from 1 fission is used in the next fission

- chain reaction dies out with time
- not useful to us

Natural U ⇒ 99.3% ^{238}U
0.7% ^{235}U

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Nuclear reactors

⇒ Generate energy by controlled (critical) fission chain reaction.

⇒ Generally Reactor has a lifetime of a few years.

* Things reqd. in nuclear reactors

1) Fuel ⇒ uranium → we want ^{235}U ~~but Natural U has 99.3% ^{238}U & 0.7% ^{235}U so we~~ use processes such as diffusion etc. to get enriched U with 97% ^{238}U and 3% ^{235}U

→ Uses uranium oxide (UO_2)

2) ~~Control rods~~

3) ~~Coolant~~

4) ~~Moderator~~

2) Control rods

⇒ "Cd" rods with large σ of neutron capture, which is used to keep chain reaction in critical phase

Cadmium

⇒ can be pushed in and out of core of reactor which has fuel.

⇒ Have a sensor → if too much energy released, pushed in

→ if less energy released, pushed out

⇒ maintains the reaction in critical phase (controlled phase)

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o/p of nuclear reactor

3) Coolant

⇒ material (usually H_2O) which carries away the generated energy for its use, use can be like run turbine etc.

4) Moderator

⇒ slows down neutrons so that they don't get captured by ^{238}U and instead have fission with ^{235}U

to overcome problem of capture by ^{238}U

⇒ slows down neutrons to few eV

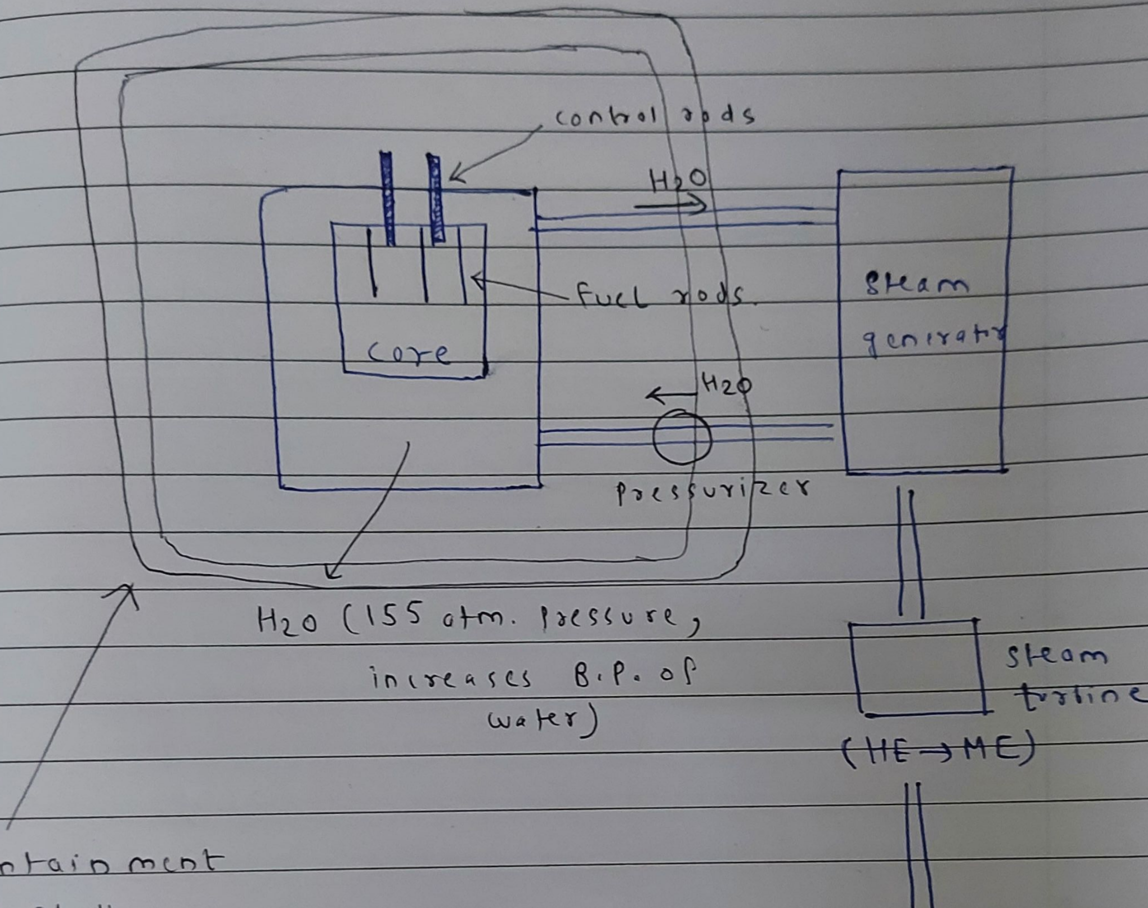
⇒ we want atoms that collide with neutrons & slow them

⇒ max. KE transfer happens if 2 particles are of same mass.

⇒ Hydrogen has same mass as neutrons, so H_2O is an efficient moderator.

HE = Heat energy
ME = mech. energy
EE = electrical energy.

* SCHEMATIC DIAGRAM OF NUCLEAR REACTOR



containment shell
(thick cement to prevent radioactivity / ~~rods~~ radioactive waste to leak)

electrical power plant
(ME → EE)

(AM)

lec 16-NP (11th April, 2023)

Nuclear fusion reactors → possible?
↳ experimentally not, theoretically yes

$$^2_1H + ^3_1H \longrightarrow ^4_2He + n + 17.6\,MeV$$

^2_1H ↙ from sea water

^3_1H ↳ from lithium

Requirements for fusion:

1) Temperature (plasma temp $\sim 10^7 - 10^8$ K)
→ to ensure high energy of nuclei to cross repulsion barrier

2) Plasma density (ions/m^3) ⇒ high to ensure frequency of collisions

3) Confinement time ⇒ for nuclei to stay together long enough

→ "confinement quality parameters"
($n\tau > 10^{20}$ s/m^3 for ignition)

1) Breakeven ⇒ input = output of energy
2) Ignition ⇒ fusion becomes self-sustaining

→ We want to achieve these in fusion reactors

$\boxed{\text{ITER}}$ = International thermonuclear experimental reaction (35 countries)

$\boxed{\text{tokamak}}$ = To confine plasma using magnetic field.

PARTICLE ACCELERATORS

→ to accelerate particles upto 10's of GeV
↳ to probe much more inside the nucleus (go to smallest particle)

→ energy $(E) = \frac{hc}{\lambda}$ ← de Broglie wavelength

nuclear size $\approx 10^{-15}$ m

$h = 4.135 \times 10^{-15}$ eVs

↳ putting these values, we get

$E = 1000$ MeV
$= 1$ GeV

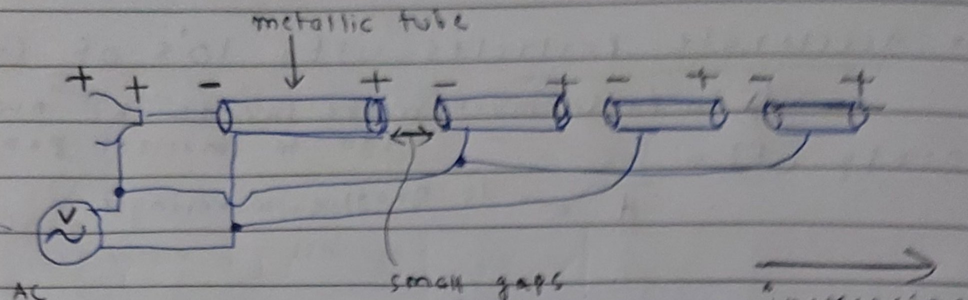
Accelerator

linear accelerator
→ uses electric field to accelerate charged particles

Cyclotron
uses electric & magnetic field to accelerate charged particles

AC voltage = V

* **Linear Accelerator (LINAC)**



* After constant intervals of time, gaps change polarities

* increasing velocity ⇒ requires increasing length of tubes to pass thru in the same time.

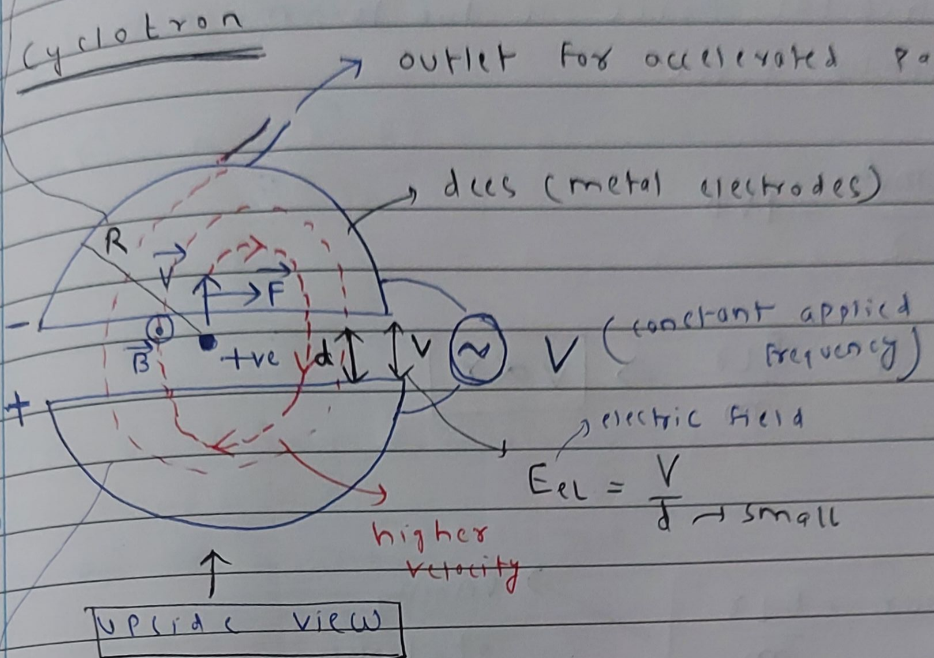
* SLAC ~ 3 kms long ~ tens of GeV

* Frequency of V has to match with frequency of particle reaching the gap

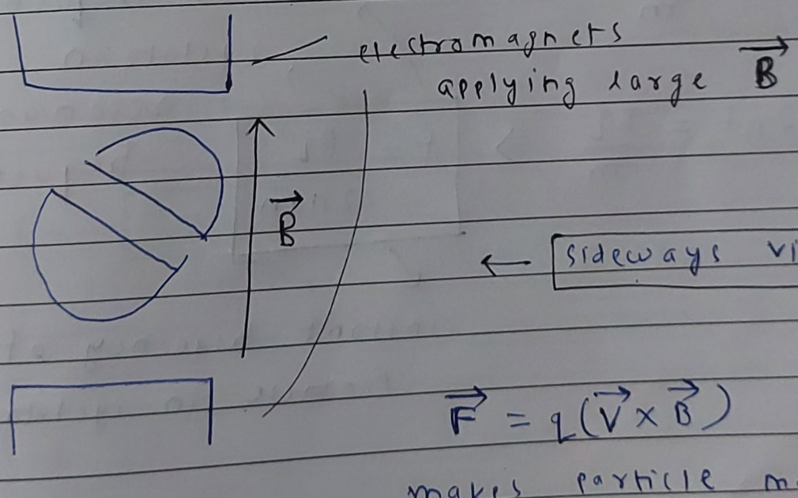
Problems
1) only electric field is used ⇒ high voltage required
2) long lengths of tube needed ⇒ many kms needed

radius of dees.

* Cyclotron



→ By the time, particle reaches this "dee", it changes its polarity to -ve



← sideways view

$$\vec{F} = q(\vec{V} \times \vec{B})$$

makes particle move in a semicircular path & come back to the gap.

* Spiral motion = radius increases with increasing velocity

* centripetal force is due to magnetic lorentz force

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

$$V = \frac{Bqr}{m} \Rightarrow \boxed{v \propto r}$$

* $\boxed{v = \omega r = \frac{Bqr}{m}}$ velocity of particle rotating in cyclotron

$$\Rightarrow \omega = \frac{Bq}{m}$$

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

natural frequency

cyclotron resonance frequency

constant frequency of particle in cyclotron

* f should be = applied AC voltage frequency for cyclotron to work

* $\boxed{V_{max} = \frac{BqR}{m}}$ velocity is max., when particle reaches boundary ($r = R$)

* $KE_{max} = \frac{1}{2} m v_{max}^2$

$$\boxed{KE_{max} = \frac{B^2 q^2 R^2}{2m}}$$

→ if mass less, KE more
⇒ electrons will have energy in cyclotron than protons

* if $v > 0.3c$ (relativistic velocity)

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

m_0 → rest mass

m → relativistic mass

* For relativistic particle :

$$\boxed{f = \frac{\sqrt{1 - v^2/c^2}\; Bq}{2\pi m_0}}$$

For cyclotron to work, f = applied AC voltage freq.

→ {This is varying, applied AC voltage} frequency is constant, then how will cyclotron work ?

To solve this

Cyclotron

fine tuning ← Synchrotron
(Freq. of applied AC voltage is constantly decreased to match with f at all times.)

Isochronous cyclotron
(B is varied to match f with applied voltage frequency)

B is increased at same rate as $\sqrt{1 - v^2/c^2}$ decreases to keep f constant

* Neutral particle acceleration

1) Neutron is already energetic when produced

2) Accelerate a charged particle then make it neutral

↳ accelerate p, add e^- when accelerated $\longrightarrow$ accelerated neutral particle of high energy