31/3/23

Breeder reactors (no moderator

$$^{238}_{92}U + n \longrightarrow {}^{239}_{92}U + \gamma$$ half life of few minutes

$$^{239}_{92}U \longrightarrow {}^{239}_{93}Np + e^- + \nu$$ half life of few hours

$$^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + e^- + \nu$$ unstable

Reactor is Breeder of Nuclear fuel $^{239}_{94}Pu$

Here one reactor cycle → 3 years

More ^{239}Pu generates than ^{235}U

1) ^{238}U is being used, no enriching required

2) No moderator

3) New fuel is generated ^{239}Pu

Problems

1) Operational costs are high since coolant is different from water (D_2O i.e. Heavy water) (So that there is no H to slow down neutrons)

2) ^{239}Pu is fuel for nuclear weapons since more fissile than ^{235}U. → security risk

Nucleor fusion

lighter nuclei join to form heavier nuclei releasing energy

1) energy in stars
2) Creation of elements

Fusion of hydrogen in case of stars

Requirements for fusion

1) High temperature $\sim 10^7$ K so that lighter nuclei have enough energy to approach close enough & overcome repulsion.
2) High Density → To ensure frequency of collisions
3) Large reacting mass ⇒ to give them enough time to have fusion.

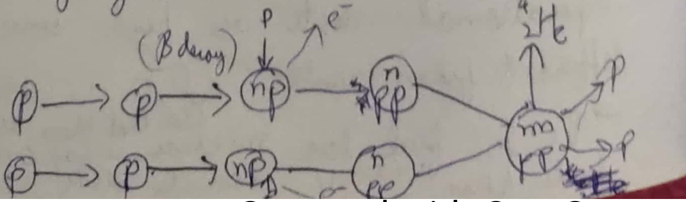
Hydrogen fusion ~ 10^7K temperature

Sun core temperature $\sim 1.5 \times 10^7$K

~~Hu~~ → Sun is an intermediate size, young/middle aged star (4.6 billion years)

~ 70% hydrogen, 28% helium, 2% other elements

1) p-p cycle



$2\times\left({}^{1}_{1}H + {}^{1}_{1}n \longrightarrow {}^{2}_{1}H + e^{+} + \nu\right)$

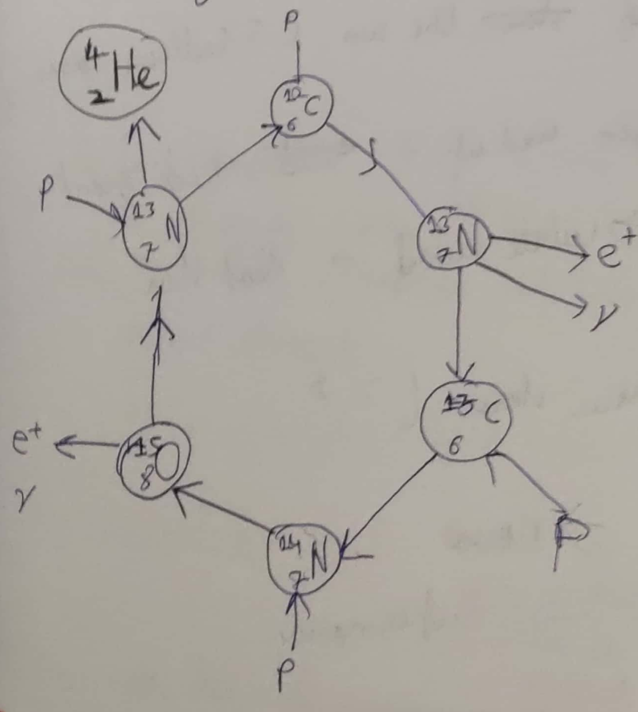
$2\times\left({}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He\right)$

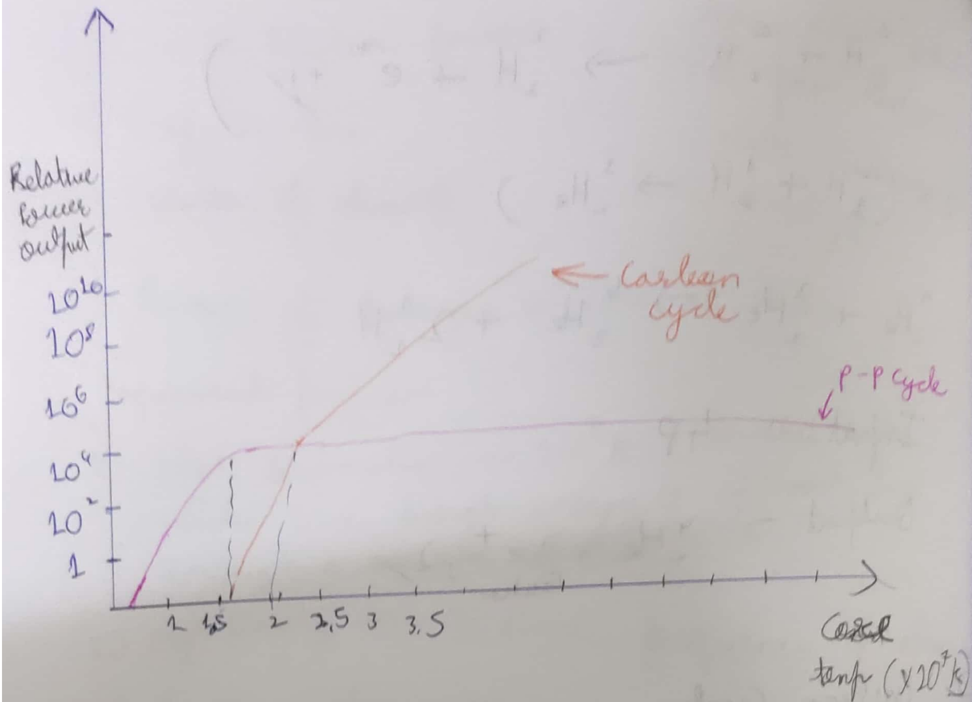
${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2\,{}^{1}_{1}H$

Input 4P

Output $\rightarrow$ ${}^{4}_{2}He$, $2e^{+}$, 2ν
Positron

2 Carbon Cycle





For stars of the size of ~~star~~ the sun (5 billion years)

hydrogen used up → ~~red~~ red giant

→ white dwarf → dead star

For massive stars (> 8

→ nova

→ Supernova

Formation of elements → higher core temperature $10^8 K$

Triple α reaction

$${}^{4}_{2}He + {}^{4}_{2}He \rightarrow {}^{8}_{4}Be$$

$${}^{4}_{2}He + {}^{8}_{4}Be \rightarrow {}^{12}_{6}C$$

Can happen in Sun

$${}^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O$$

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{24}_{12}Mg$$

$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$$

Stars $> 10 \times$ Sun's mass
temperature $\sim 10^8 K$

Fusion forms elements upto ${}^{56}_{26}Fe$

For $A > 56$, neutron capture (followed by β decay) ~~that~~ creates new elements

$56 \leq A \leq 209$ (Highest stable element)

$209 < A \leq 260$ Formed by n captures IN SUPERNOVA EXPLOSIONS
→ we are made up of stardust scattered from nova/Supernova explosions

(those with high n densities)

Nuclear fusion reactors — Possible? 11/4/23

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + n + 27.6\ MeV$$

${}^{2}_{1}H$ (from sea water)

${}^{3}_{1}H$ (from lithium)

Requirements

1) Temperature (plasma temperature → $10^7 - 10^8 K$)
{For above case D-T plasma deuterium-tritium }
⇓
To ensure high energy nuclei to cross repulsion barrier.

CONFINEMENT QUALITY PARAMETER $= n\tau$ (their product)

2) Plasma Density ($1000\ /m^3$) → high to ensure frequency of collisions $= n$

3) Confinement time :- for nuclei to stay together long enough $= \tau$

∴ $n\tau$ should be $> 10^{20}\ s/m^3$ for s

1) Breakeven :→ Input - output of energy
2) Ignition :→ Fusion becomes self-sustaining

In Practise

ITER: International Thermo nuclear Experimental Reactor (35 countries including India)

where there are large Toroidal magnets called
Tokamak :→ Confines plasma using magnetic field.

PARTICLE ACCELERATORS ~ 10's of GeV

energy $E = hc/\lambda$ → de-Broglie wavelength

For nuclear size i.e. $\sim 10^{-15}$ m

& putting in value of h & c

$\Rightarrow E \approx 1000$ MeV $= 1$ GeV

So To ~~?~~ observe small particles they should have high energy which require Particle accelerators.

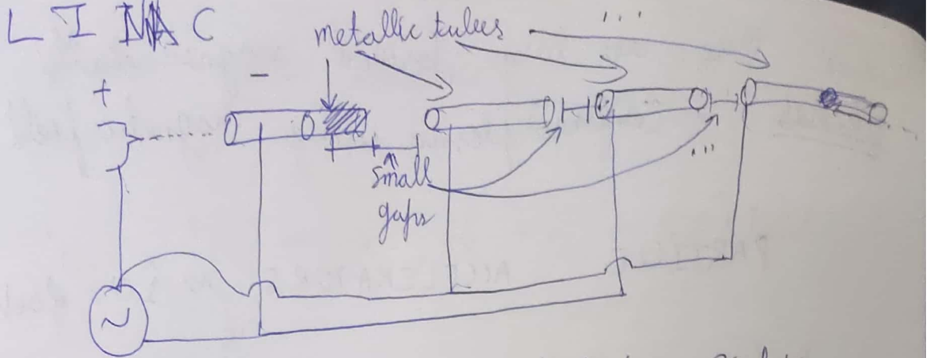
1) Linear Accelerator: using electric field to accelerate charged particles

2) Cyclotron: using electric & magnetic field to accelerate charged particles.

LINAC

(P.T.O. for illustration)

LINAC



* From Left to Right
Particle is Increasing velocity
→ requires increasing length of tubes to pass through in the same time.

NAC at Stanford : → ~~3~~ 3 Km long SLAC

Disadvantage

1) Frequency of AC voltage has to match frequency of particle traversing the gap

· Problem: 1) Only Electric field is used,
→ high voltage required.
2) Long length ~ many Kms needed.

Nuclear Reactions

Compound nuclear reactions

energy few ev to <1 MeV

$^{107}Ag + n \longrightarrow {}^{108}Ag + \gamma$

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

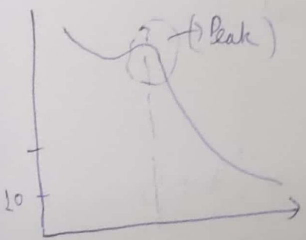
$X + n \longrightarrow Y + b$; $X + a \longrightarrow C \rightarrow Y + b$

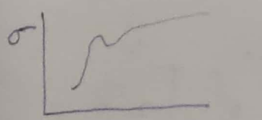
why decreasing ? → because n has to spend sometime in target for rx^n to happen

why is there a peak? → More energetic neutrons pass too quickly than required for rx^n to happen.

→ Faster n is less likely to have the reaction

→ σ decreases with increase in energy.





σ increases with increasing KE since p is repelled by nucleus & has to overcome it so higher energy of p is required to enter the target.

Reason for $X + a \rightarrow C^* \rightarrow Y + b$ → Compound nucleus

$^{108}Ag + n \rightarrow {}^{108}Ag^* \rightarrow$ Compound nucleus

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

Compound nucleus loses energy of formation.

$$\underbrace{X+a}_{a} \rightarrow C^* \quad \boxed{\text{Formation Channel}}$$

$$\underbrace{C^*}_{b} \rightarrow Y+b \quad \boxed{\text{Decay Channel}}$$

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

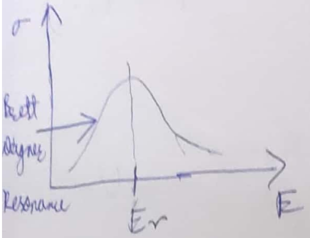
Decay channel depends on properties of excitation state of compound nucleus & not on the formation channel.

For formation of compound nucleus

$$\sigma_a = A\boxed{\frac{B}{(E - E_r)^2 + C}}$$

Constant value

independent of energy



For overall reaction to happen is a function of formation σ

$$\sigma_{ab} = \text{i.e } f(\sigma_a)$$

Direct Reactions

$$X + a \rightarrow Y + b$$

~~$^{207}Ag + n \rightarrow {}^{208}Ag + \gamma$~~

→ Fast neutrons react only with surface of nuclei within 10^{-22} s to directly give the end products

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

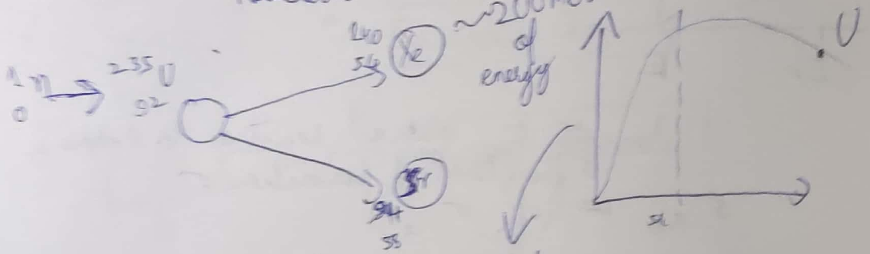
* Fast n ~ > 1 MeV spend 10^{-22} s time

1) Maximum dependance of σ on n energy

2) Highly energetic output particles (Since energetic input particle.)

3) Forward peaking of output particles spectrum (output particles roughly move in same direction as in incoming particles before int^n)

Nuclear Fission



exothermic/exoergic reaction

because Be/A of parent is lower ~~that~~ than that of daughter.

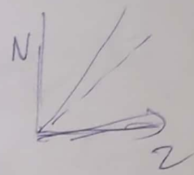
Excess Be/A of daughter is released
~200 MeV of energy

~~$^1_0 n \rightarrow$~~

$$^1_0 n + {}^{236}_{92}U \longrightarrow {}^{235}_{92}U^* \longrightarrow {}^{146}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^1_0 n$$

Excited

number of neutron released > number of incident neutron because $\left(\frac{N}{Z}\right)_{stable}$ ratio is higher for heavier nuclei.



Artificially Induced Fissions (about 99% of all fissions)

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

Spontaneous Fission

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

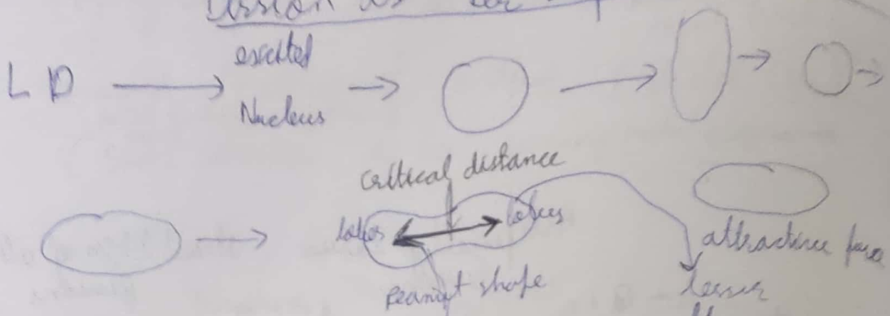
Recap

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

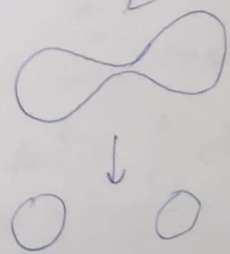
Needs energy but exothermic

Fission chain reaction makes it useful for us 24/3/..

Fission as per Liquid Drop Model



- N-N short range attractive force
- coulomb repulsive force



7-8 MeV required = $KE_n + BE_n$ (incoming neutron)

★ Among ^{235}U & ^{238}U

$^{235}_{92}U$ has higher BE_n as compared to $^{238}_{92}U$ which has lower BE_n

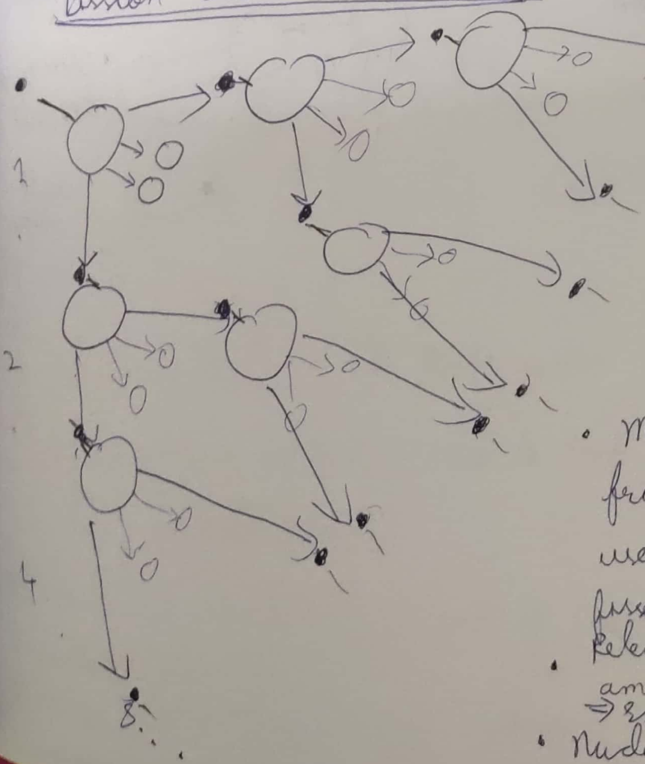
due to Pauli's exclusion principle ^{235}U ~~BE~~ which has odd number of neutrons & wants to have even number

Fissile ← ^{235}U = 7.8 MeV → n does not exist. easy KE.
reactor fuel

Fissionable ← ^{238}U = 6 MeV → n needs to have 2 MeV KE to make fission happen

So ^{238}U is more likely to capture the incoming n (of ~ 3 MeV)

Fission Chain Reaction

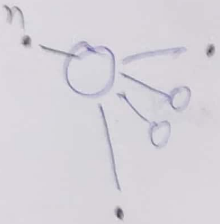


- Super critical or uncontrolled chain reaction.
- More than 1 neutron from each fission is used in the next fission.
- Release of uncontrolled amount of energy ⇒ explosion
- Nuclear weapons

Controlled or critical Chain Reaction

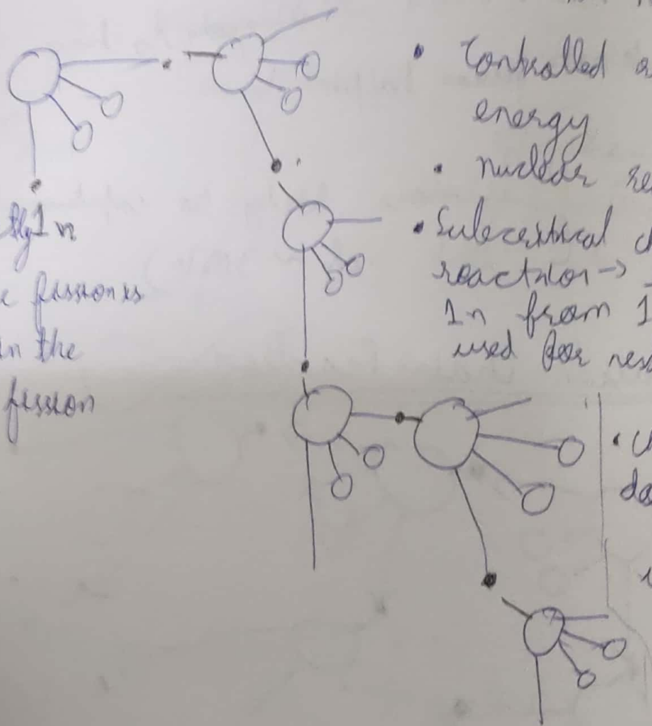
↳ exactly 1 n from one fission is used in next fission

- Controlled release of energy
- nuclear reactors
- Subcritical chain reaction → less than 1 n from 1 fission is used for next fission



* exactly 1 n from one fission is used in the next fission

- Chain reaction does not with time



Nuclear Reactors ~ have a lifetime of few years.

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

1) Fuel → Uranium: We want ^{235}U but natural U has 99.3% of ^{233}U & 0.7% ^{235}U.
2) Control rods
3) Coolant
4) Moderator

Through diffusion & some other Techniques we obtain U with 97% ^{238}U & 3% ^{235}U.

Control Rods: Cd rods with large σ (cross section) of neutron capture → used to keep chain reaction in critical phase.

* Can be pushed in & out of core of reactor which has fuel.
* These control rods have a sensor, if too much energy is released they are pushed in and if too less ~~then~~ then pushed out.

Coolant : Material (usually H_2O) which carries away generated energy for its use.

Moderator : Slows down n so that they don't get captured by ^{238}U & instead undergo fissions of ^{235}U (to continue chain reaction)

* Maximum KE transfer occurs if 2 particles are of the same mass.
* H has same mass as neutrons ⇒ so H_2O is an efficient & good moderator.

...ter can act as both coolant & moderator.