Fusion

~~universe~~ Sun initially ~~all~~ mostly hydrogen

Need neutrons to form heavier elem's

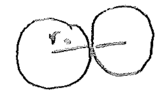
$$p + p \rightarrow D + e^+ + \nu_e \qquad D = (^2H)^+$$

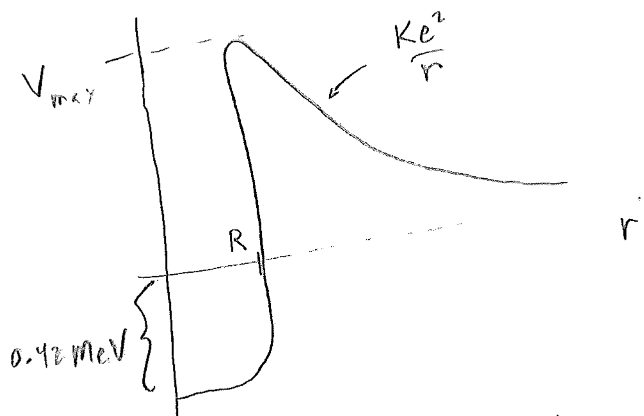
$$Q = 2[1u + \Delta(^1H) - m_e] - [2u + \Delta(^2H) - m_e] - m_e$$

$$= 2\Delta(^1H) - \Delta(^2H) - 2m_e$$

$$= 0.420 \text{ MeV} \qquad \Rightarrow E_\nu(max) = 0.42 \text{ MeV}$$

Reaction is allowed but Coulomb barrier





$$R \sim 2r_0 \sim 2.4 \text{ fm}$$

$$V_{max} = \frac{Ke^2}{R} = \frac{1.44 \text{ MeV fm}}{2.4 \text{ fm}} = 0.6 \text{ MeV}$$

If force of gravity can compress balls of hydrogen to high enough temps to allow protons to get close enough (despite EM repulsion)

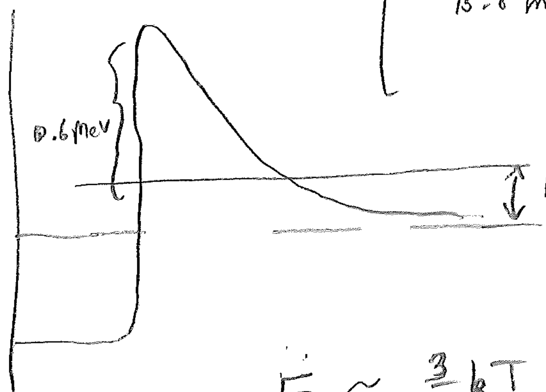
the weak force allows $p \rightarrow n + e^+ + \nu_e$

at which point the strong force binds p + n into d, releasing energy

[delicate interplay of all 4 forces allows us to exist]

[300 K = $\frac{1}{40}$ eV
6000 K = $\frac{1}{2}$ eV
15.8 million K = 1.3 keV
(1 MeV = 1.16E10 K)]

FU-2



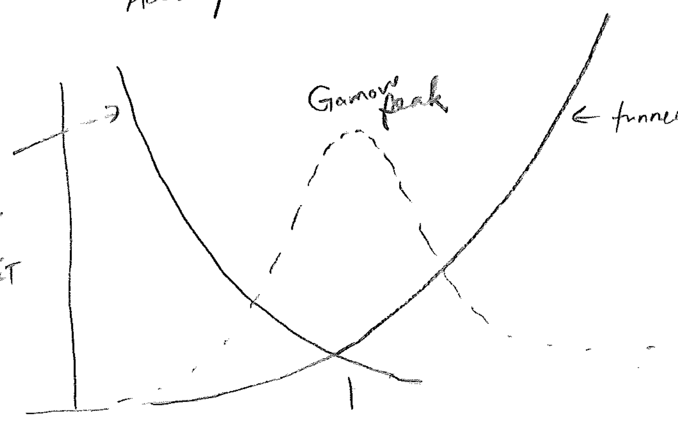
$\bar{E} \sim \frac{3}{2}kT$

T ~ 15.8 million K $\Rightarrow \frac{3}{2}\left(\frac{1.5E7}{3E2}\right)\frac{1}{40}$ eV = 2 keV

(would need T ~ 5×10^9 K to overcome barrier)

but protons have a Maxwellian distribution (tail)

Also protons can tunnel through barrier



E_G ~ 0.49 MeV
(Clayton, p. 192)
Pcl Astro

Even if proton tunnels through barrier prob. it weak interacts while ... is 10^{-20}.
usually elastic scattering (via strong force) of pp occurs

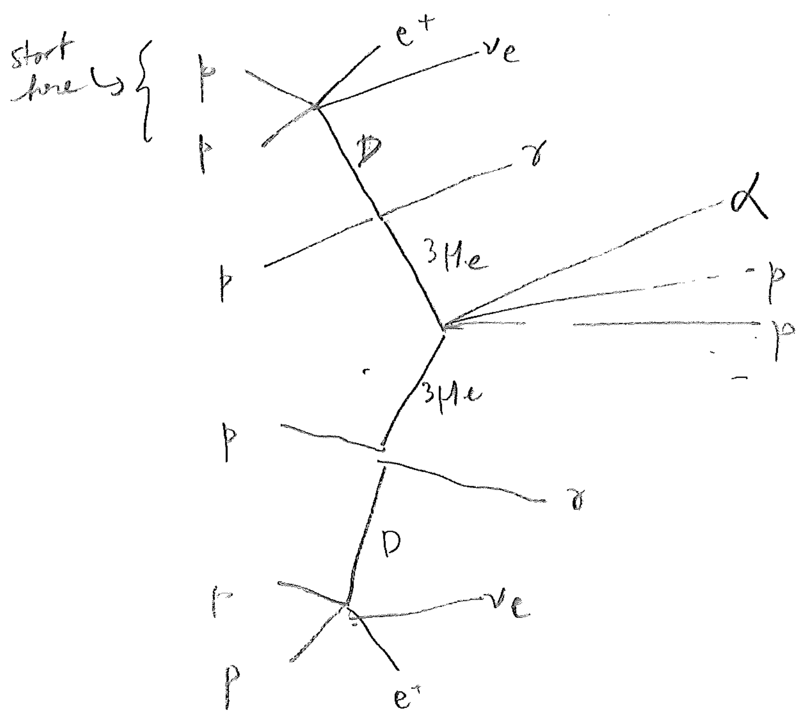
[Next steps]

$$p + D \rightarrow (^3He)^{++} + \gamma$$ ← nucleus

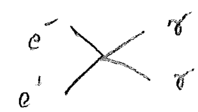
$$(^3He)^{++} + (^3He)^{++} \rightarrow \alpha + p + p$$

[85%
Carroll + Ostlie say 69%
p. 345]

Altogether



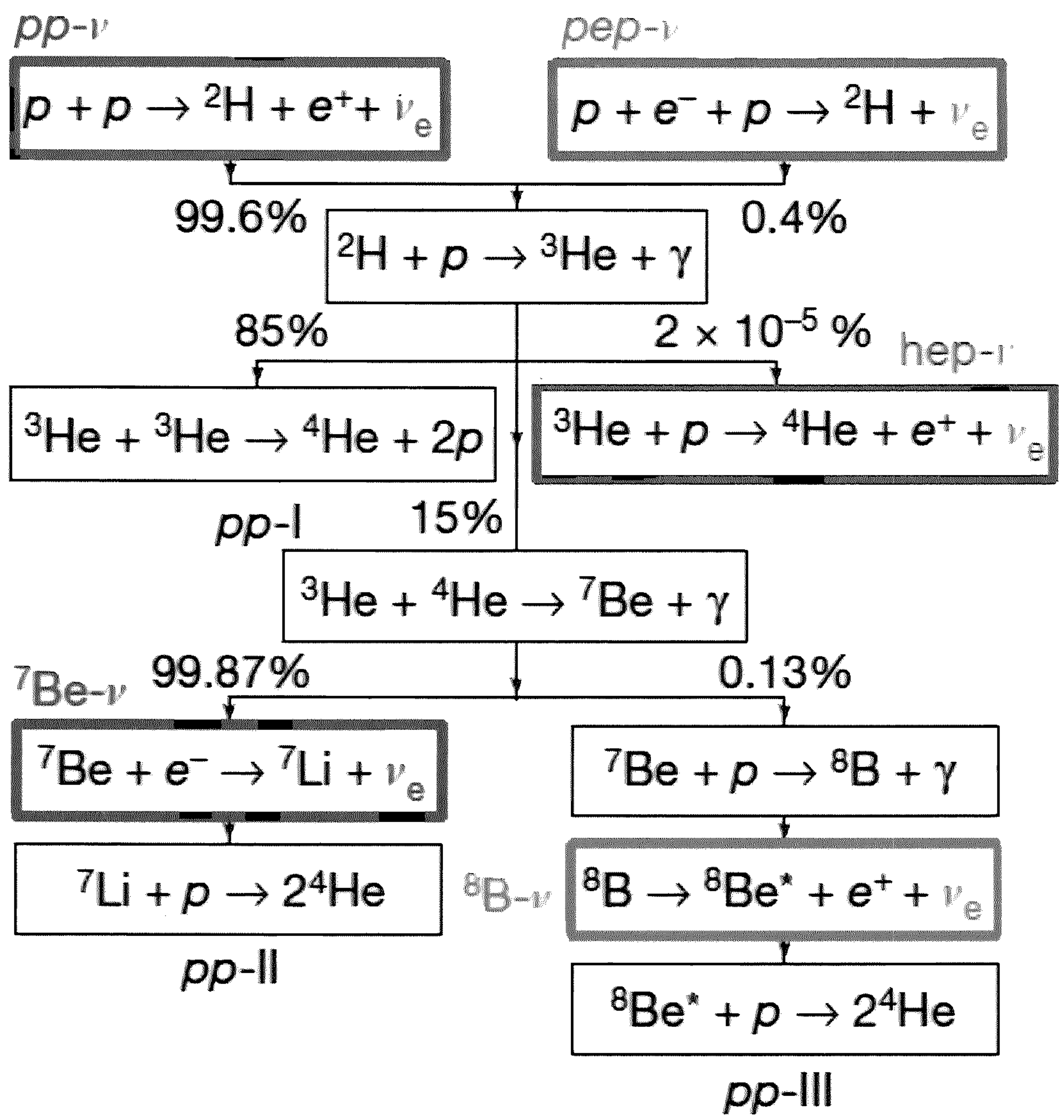
[Then add in two places:



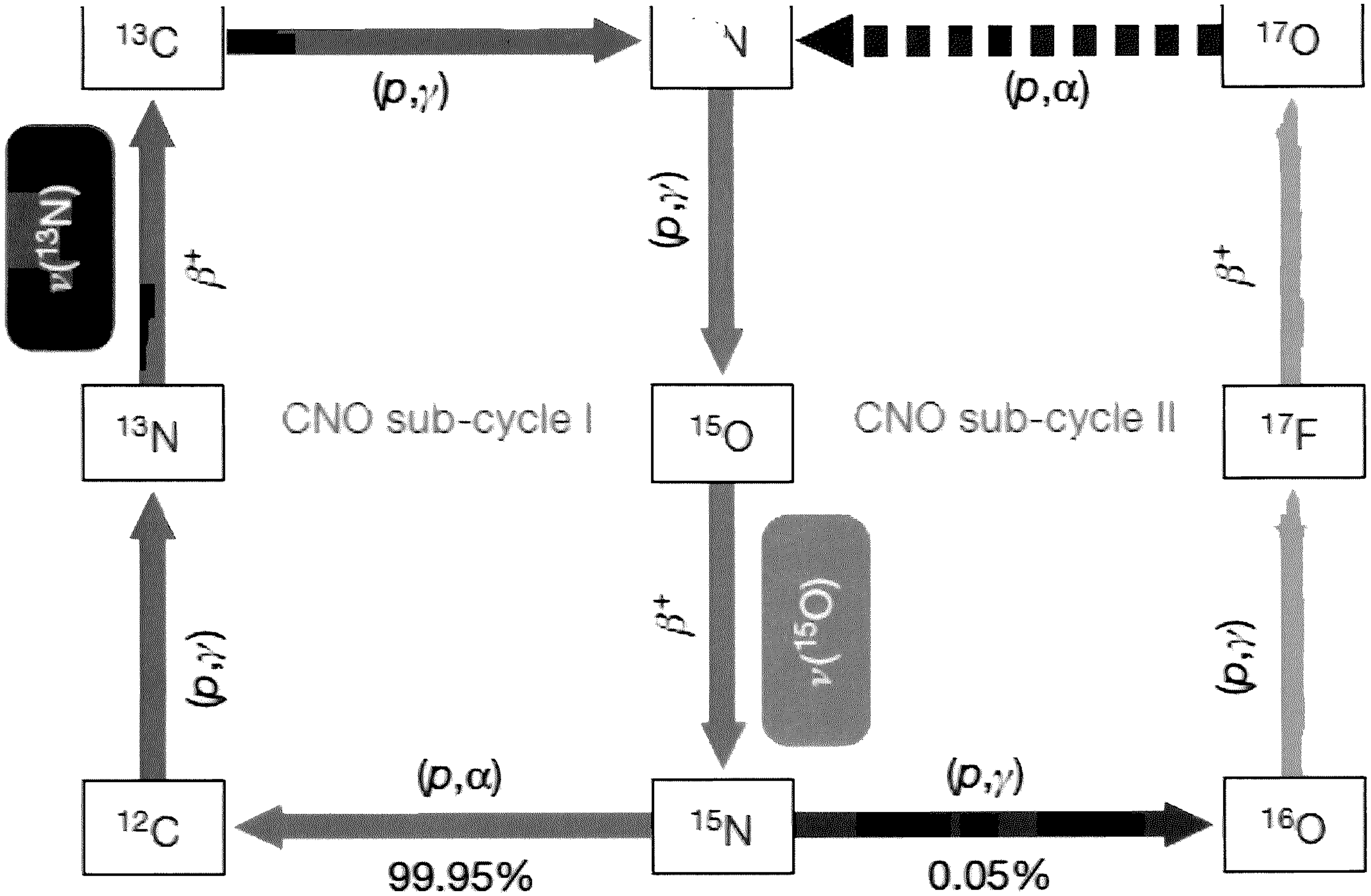
Total pp cycle: $6p + 2e^- \rightarrow \alpha + 2p + 6\gamma + 2\nu_e$

- How much energy does this release? [HW]
- Some goes into ν, which escapes [HW]
- The rest heats the sun & is eventually radiated away about 26.2 MeV per helium nucleus formed or 6.5 MeV per proton consumed.

(more efficient than fission on a mass basis ↳ ~ 0.7 MeV per nucleon) pp chain



why not $D + {}^3He \rightarrow {}^4He + p$?



13C
(p,γ)
17O
(p,α)
ν(13N)
β+
(p,γ)
β+
13N
CNO sub-cycle I
15O
CNO sub-cycle II
17F
β+
ν(15O)
(p,γ)
(p,γ)
(p,α)
(p,γ)
12C
15N
16O
99.95%
0.05%

BBN (Baumann)

$n,p \to D \to {}^3He, {}^3H \to {}^4He \to {}^7Li$

$n\,p \to D\,\gamma \qquad Q = 2.224\ MeV$

occurs at $T \approx 0.07\ MeV \quad (\approx 10^9\ K)$

$\left(\frac{N_n}{N_B} \approx \frac{1}{8}\right)$

$\Rightarrow \frac{{}^4He}{{}^1H} \approx \frac{1}{12}$ or $\frac{1}{3}$
↑ # ↑ mass

$D\,p \to {}^3He\,\gamma$

also:
$D\,D \to {}^3H\,p$
$D\,D \to {}^3He\,n$
$D\,n \to {}^3H\,\gamma$ [Perkins p.57] ← Weinberg's (p.165) γ processes are slower

${}^3He\,D \to {}^4He\,p$

also:
${}^3H\,p \to {}^3He\,n$
${}^3H\,D \to {}^4He\,n$
${}^3H\,p \to {}^4He\,\gamma$
${}^3He\,n \to {}^4He\,\gamma$ [Perkins]

${}^4He\,{}^3He \to {}^7Be\,\gamma$

${}^3H\,{}^4He \to {}^7Li\,\gamma$

$e^-\,{}^7Be \to {}^7Li\,\nu_e$ (at low temp)

${}^7Li\,p \to {}^4He\,{}^4He$