Fusion

universe initially all hydrogen

Need neutrons to form heavier elements

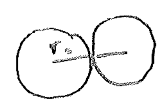
$$p + p \rightarrow d + e^+ + \nu_e$$

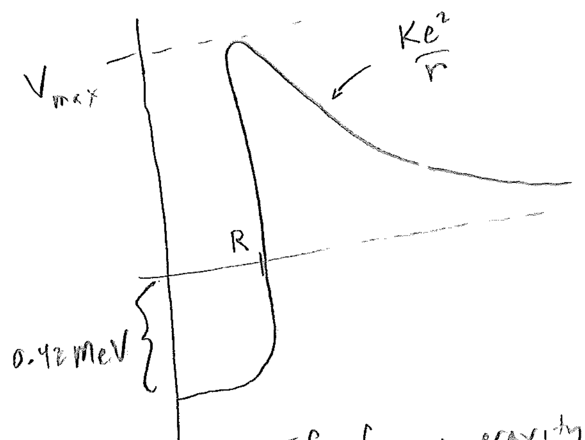
$$Q = 2\left[1u + \Delta(^1H) - m_e\right] - \left[2u + \Delta(^2H) - m_e\right] - m_e$$

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

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

Reaction is allowed but Coulomb barrier



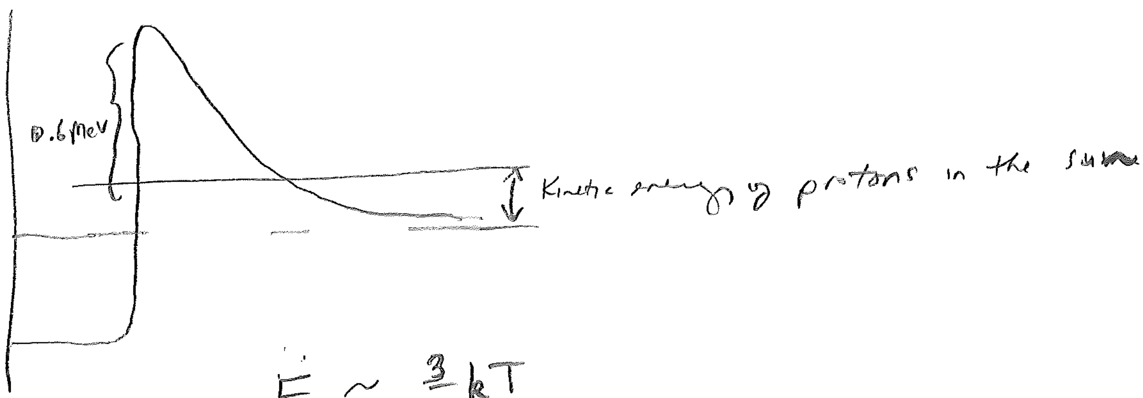


$$R \sim 2r_0 \sim 2.4 \text{ fm}$$

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

If force of <u>gravity</u> can compress balls of hydrogen to high enough temps to allow protons to get close enough (despite <u>EM</u> repulsion) the <u>weak</u> force allows $p \rightarrow n + e^+ + \nu_e$ at which point the <u>strong</u> force binds p + n into d, releasing energy!

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



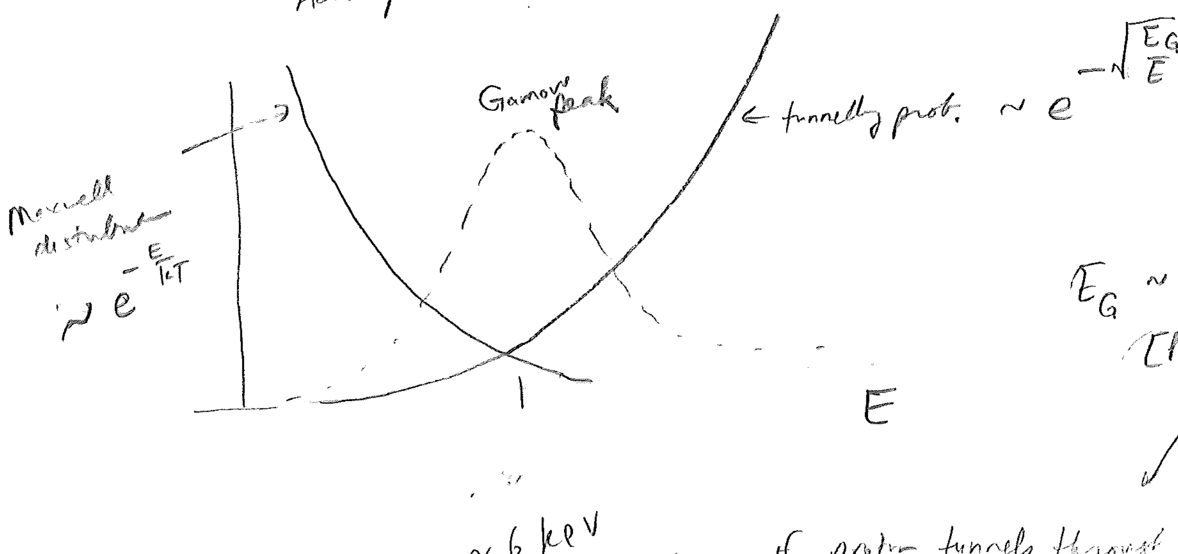
$\bar{E} \sim \frac{3}{2} kT$

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

(would need $T \sim 5\times10^{9}$ K to overcome barrier)

but protons have a Maxwellian distribution (tail)

Also protons can tunnel through barrier



$E_G \sim 0.49$ MeV

([illegible] p. [illegible] [illegible] Astro)

Even if proton tunnels through barrier prob that weak int. will occur is 10^{-20}. Usually elastic scattering (via strong force) of pp occurs

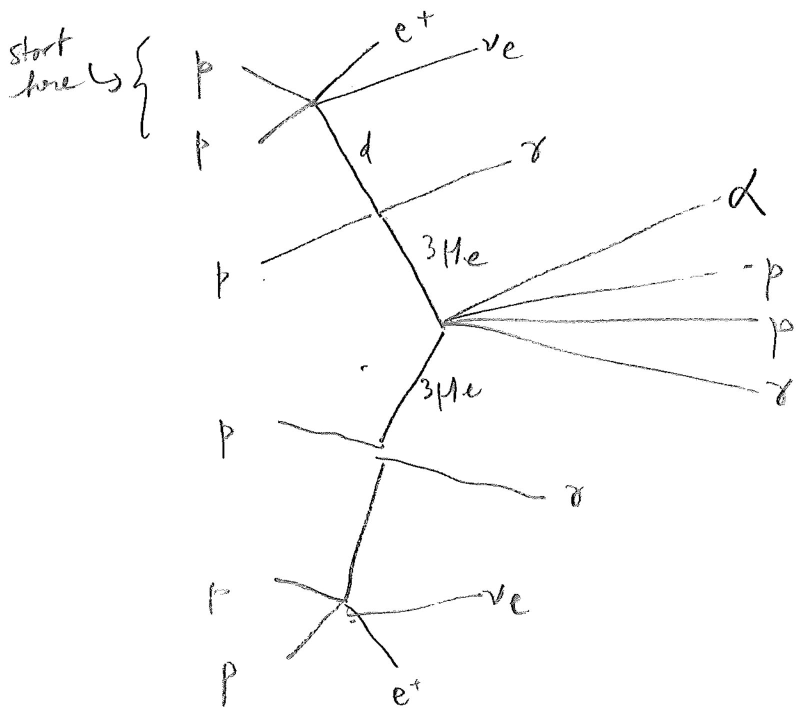
[Next steps]

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

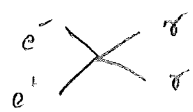
$${}^3He + {}^3He \rightarrow \alpha + p + p + \gamma$$

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

Altogether

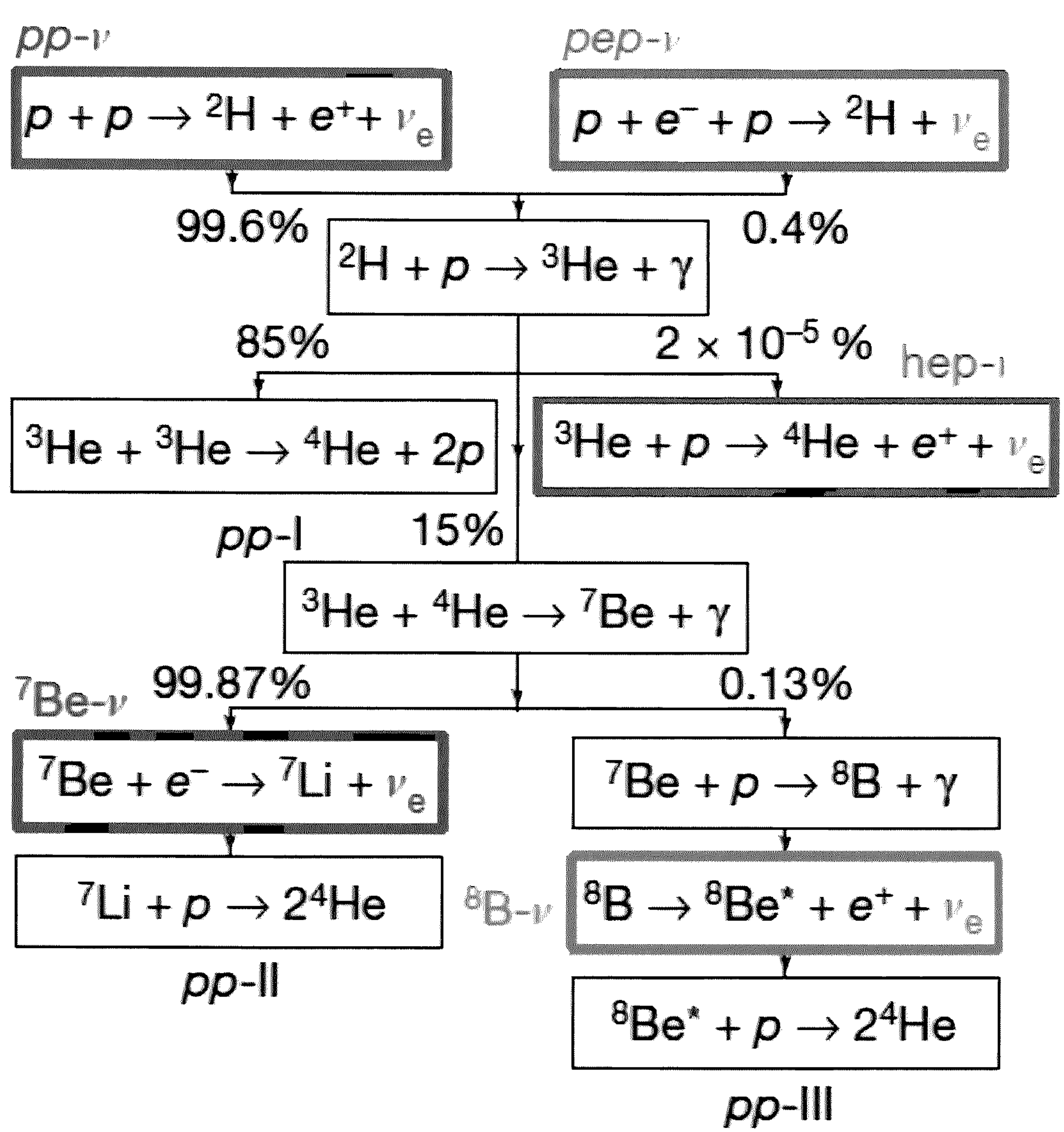


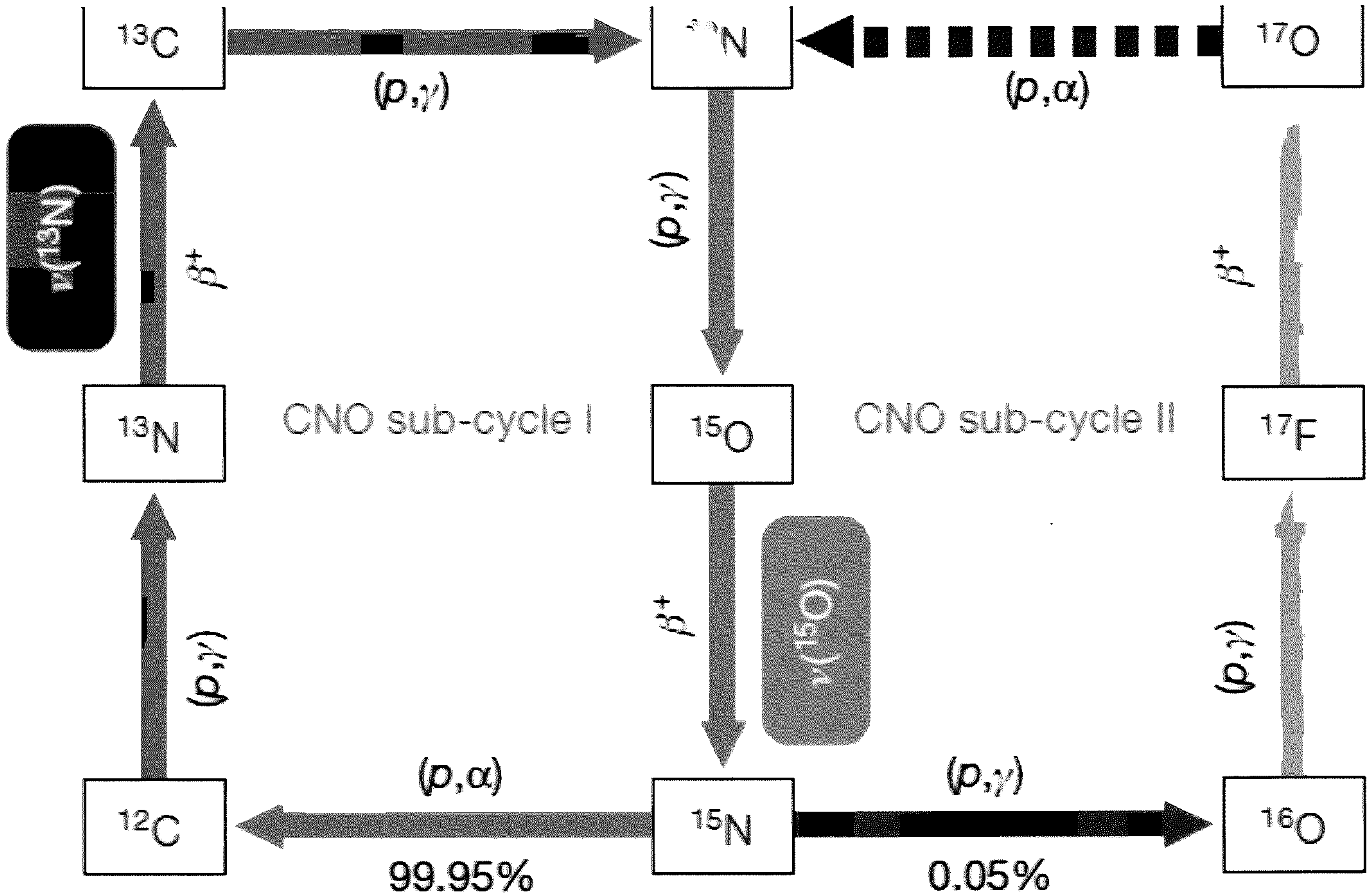
[Then add in two places:



Total pp cycle: $6p + 2e^- \rightarrow \alpha + 2p + 7\gamma + 2\nu_e$

- How much energy does this release? [HW]
- Some goes into ν, which escape [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-ν
$p + p \rightarrow {}^2H + e^+ + \nu_e$
pep-ν
$p + e^- + p \rightarrow {}^2H + \nu_e$
99.6%
0.4%
${}^2H + p \rightarrow {}^3He + \gamma$
85%
2×10^{-5} %
hep-ν
${}^3He + {}^3He \rightarrow {}^4He + 2p$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$
pp-I
15%
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
^{7}Be-ν
99.87%
0.13%
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^7Li + p \rightarrow 2\,{}^4He$
^{8}B-ν
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
pp-II
${}^8Be^* + p \rightarrow 2\,{}^4He$
pp-III



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