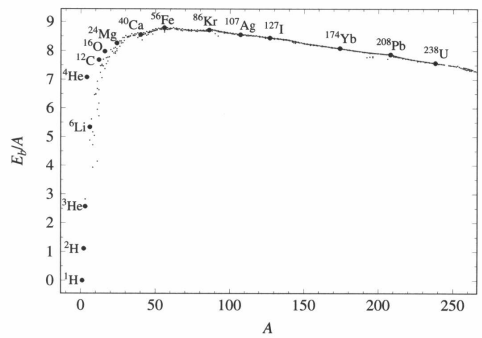
Lec #33: 9 November 2011 Chapter 6.1, .2, .5

Energy Generation Within Stars:

- ✓ Nuclear Physics Basics
- Fusion
- PP, CNO, and Triple-Alpha Processes
- Main Sequence Evolution

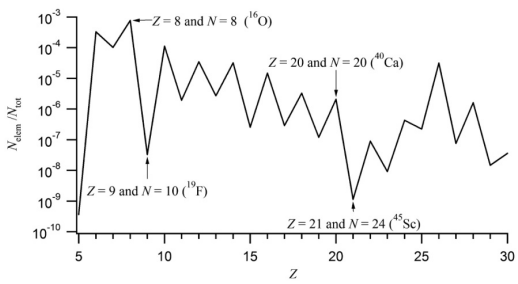
NEXT: Post Main-Sequence Evolution (6.6-6.8)

The "Curve of Binding Energy" (see John McFee)



<--FUSION | FISSION-->

Typical Cosmic Metal Abundance Pattern

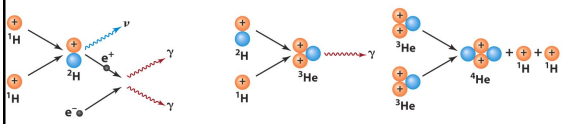


PROTON-PROTON CHAIN

Net effect: 4 H --> 1 He + energy

6 x 10^{11} kg/s mass -> energy

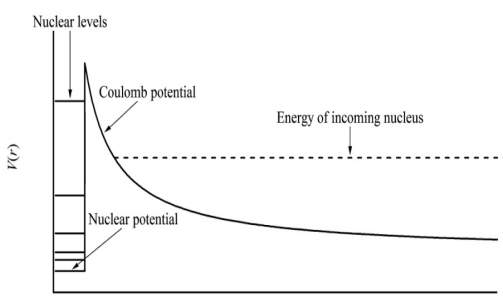
(1 earth mass in 300,000 y; 1500 earth's consumed so far)



(a) Step 1:
- Two protons (hydrogen nuclei, ^{1}H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^+).
- The proton and neutron form a hydrogen isotope (^{2}H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).

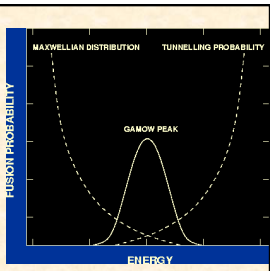
(b) Step 2:
- The ^{2}H nucleus from the first step collides with a third proton.
- A helium isotope (^{3}He) is formed and another gamma-ray photon is released.

(c) Step 3:
- Two ^{3}He nuclei collide.
- A different helium isotope with two protons and two neutrons (^{4}He) is formed and two protons are released.



The Gamow Peak

Fusion most likely to occur in the energy window defined as the "Gamow Peak".

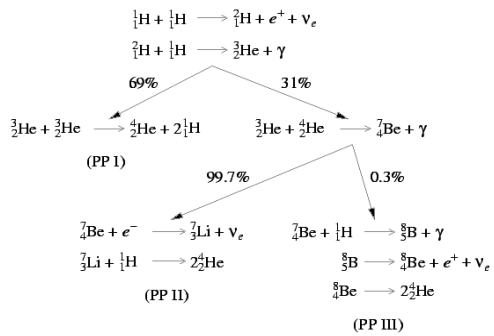


The Gamow peak is the product of the Maxwellian distribution and tunnelling probability. The area under the Gamow peak determines the reaction rate.

The higher the electric charges of the nuclei, the greater the repulsive force, hence the higher the E_{kin} and T before reactions occur.

Highly charged nuclei also more massive, so reactions between **light elements** occur at **lower *T*** than reactions between heavy elements.

Proton-Proton Chain



Which steps produce energy? Where does it go?

CNO Cycle

$$^{12}C + {}^1H \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$
$$^{13}C + {}^1H \rightarrow {}^{14}N + \gamma$$
$$^{14}N + {}^1H \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$
$$^{15}N + {}^1H \rightarrow {}^{12}C + {}^4He$$
$$^{15}N + {}^1H \rightarrow {}^{16}O + \gamma$$
$$^{16}O + {}^1H \rightarrow {}^{17}F + \gamma$$
$$^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$$
$$^{17}O + {}^1H \rightarrow {}^{14}N + {}^4He$$

C, N, O act as "catalysts"

very Temp. dependent

less important than PP in Sun

dominant in massive stars

Temperature Dependence of PP Chain and CNO Cycle

$$\varepsilon_{PP} = \varepsilon_0 \rho X_H^2 \left(\frac{T}{T_0}\right)^{4.6} \qquad \varepsilon_{CNO} = \varepsilon_0 \rho X_H X_{CNO} f_N \left(\frac{T}{25\times10^6}\right)^{16.7}$$

Equating the two gives the ***Temperature*** at which they produce the **same** rate of energy production:

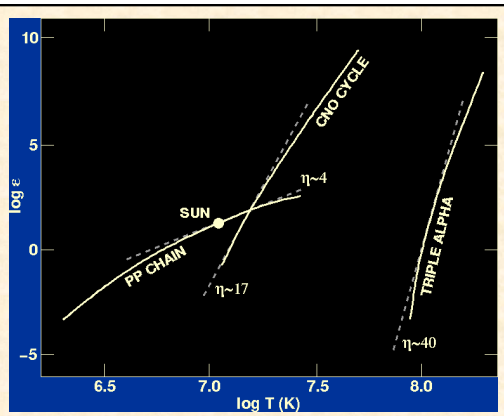
$$T \approx 1.7\times10^7 \left(\frac{X_H}{50 X_{CN}}\right)^{\frac{1}{12.1}} \text{K}$$

Below this temperature the PP chain is most important, and above it the CNO cycle dominates. This occurs in stars slightly more massive than the Sun e.g. 1.2-1.5$M_\odot$.

Triple-Alpha Process

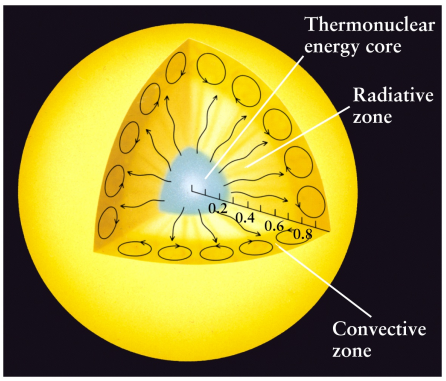
$$^4He + {}^4He \rightleftharpoons {}^8Be$$
$$^8Be + {}^4He \rightarrow {}^{12}C + \gamma$$

- X decreases, Y & Z increase, μ increases
- counterintuitive: as He builds up, PP goes down, but central pressure increases; 3-alpha more important
- C->O by alpha capture
- Abundance of C and O > N
- "Nucleosynthesis"
  - heavy elements made out of light elements
  - PP up to Boron
  - Triple Alpha up to Oxygen
  - B unstable; Li and Be consumed



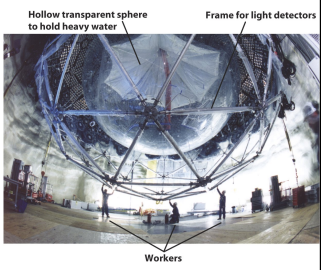
Major Nuclear Burning Processes

Nuclear Fuel	Process	$T_{threshold}$ 10^6 K	Products	Energy per nucleon (Mev)
H	PP	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C,O	0.61
C	C+C	600	O,Ne,Ma,Mg	0.54
O	O+O	1000	Mg,S,P,Si	~0.3
Si	Nuc eq.	3000	Co,Fe,Ni	<0.18



Solar Neutrino Problem

- Neutrinos have been detected, but only about 1/3 of prediction
- Recent neutrino experiments : "neutrino oscillations"



Helioseismology