Lectures in Nuclear Astrophysics

Jim Truran

Lecture I: Introduction and Overview

- Nuclear Physics in Stellar Evolution and Nucleosynthesis
  - evidence of nuclear physics behaviors
  - energy generation in stars

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Nuclear Astrophysics: Perspective

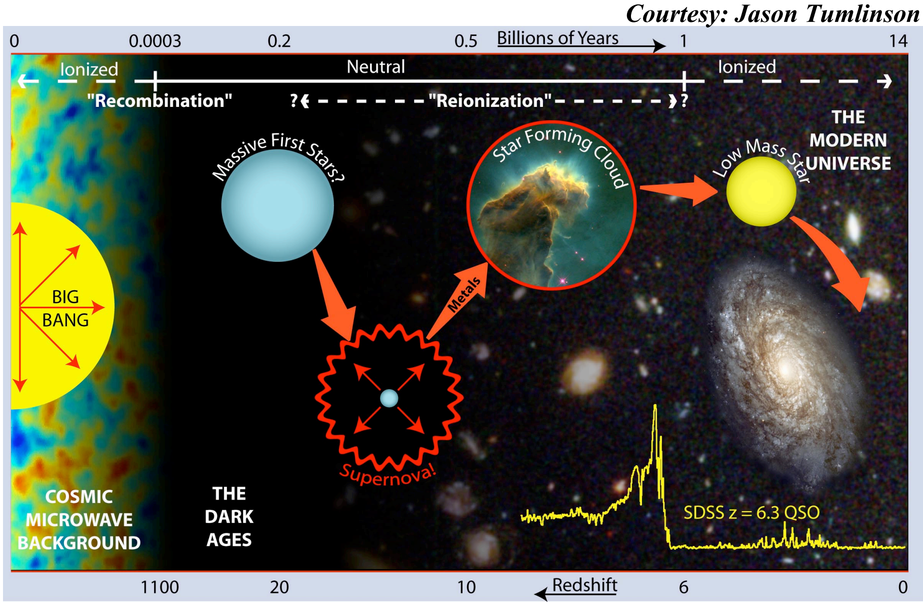
- **The Universe emerged from the first three minutes of the cosmological Big Bang with a composition consisting of ^{1}H, ^{2}D, ^{3}He, ^{4}He, and ^{7}Li, with only trace abundances of heavy elements.**

- **The synthesis of all elements heavier than ^{4}He is then understood to occur in stars and supernova explosions over the history of the Galaxy.**

- **Thermonuclear reactions proceeding in stellar cores serve both to power stars over their lifetimes of billions of years and to synthesize the common elements with which we are familiar - from carbon to the actinide nuclei thorium, uranium, plutonium, etc.**

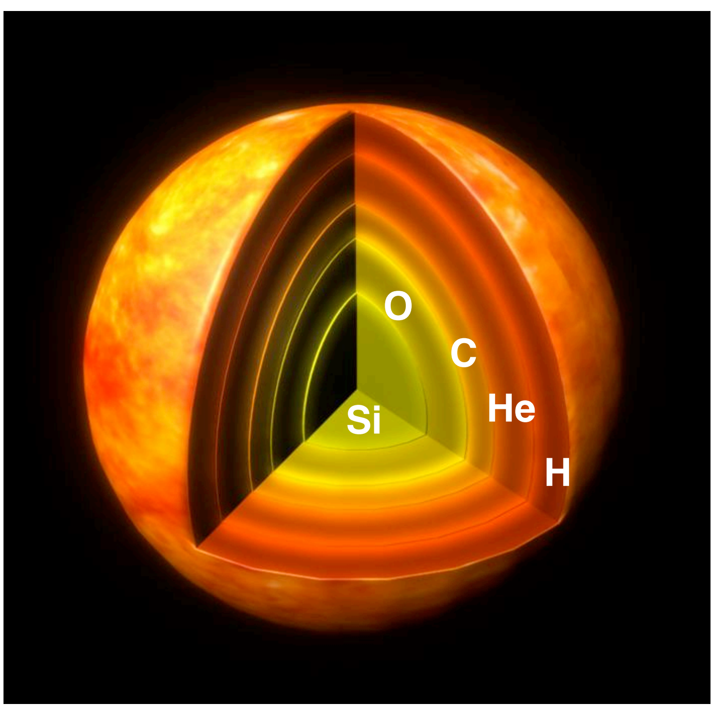
Nuclear Astrophysics: Perspective

Courtesy: Jason Tumlinson



History of the Universe?

Nuclear Astrophysics: Perspective



Onion-like structure of a <u>presupernova star</u> several million years after its birth:

mass: 10 ... 10^2 $M_\odot$
radius: 50 ... 10^3 $R_\odot$

- **shells of different composition are separated by active thermonuclear burning shells**
- **core Si-burning leads to formation of central <u>iron core</u>**

Nuclear Astrophysics: Perspective

- The need for nuclear energy to power stars was recognized not long after the earliest discoveries in nuclear physics in the last century.

- The gravitational energy available for the Sun is given by: $E_{grav} = 3GM_\odot^2/5R_\odot \approx 2.4\mathrm{x}10^{48}$ ergs

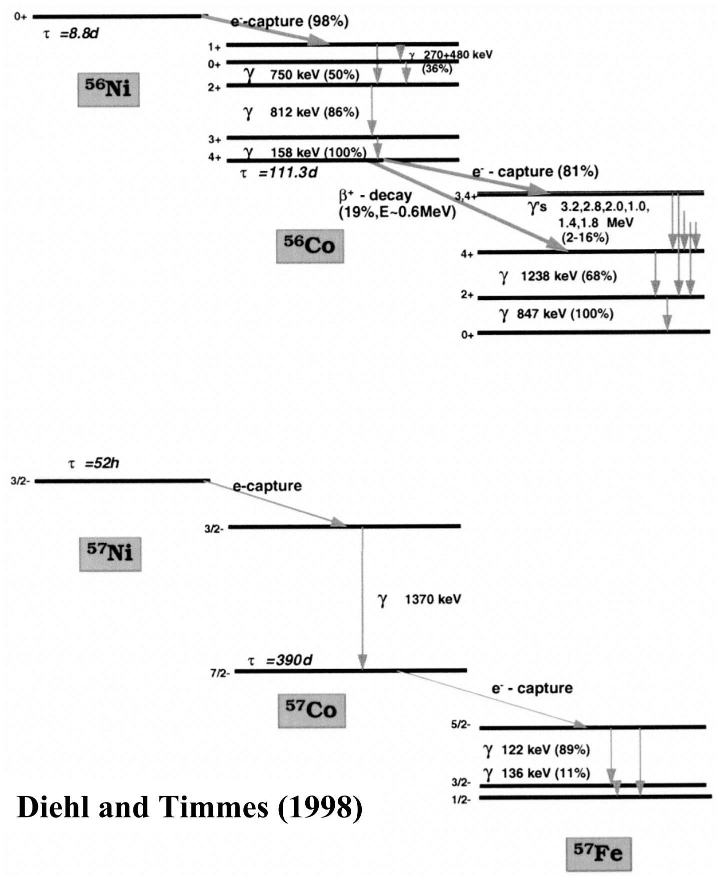
- Which yields a possible burning lifetime (for a constant luminosity Sun: $\tau_{grav} = E_{grav}/L_\odot \approx 20$ million years

- In contrast, thermonuclear burning of approximately 10% of the Sun's mass from hydrogen to helium (releasing ≈ 7 MeV/nucleon) yields approximately 10^{51} ergs and can thus provide the Sun's luminosity of 3.9×10^{33} erg s^{-1} for a lifetime exceeding ≈ 10^{10} years.

Nuclear Astrophysics: Perspective

- Supernova energetics are tied to nuclear processes:

- Type Ia are understood to be pure thermonuclear supernovae, powered by energy release in the incineration of a ^{12}C and ^{16}O degenerate core of mass 1.4 $M_\odot$
  - The energy release in the conversion of one solar mass of a 50/50 mix of ^{12}C and ^{16}O to pure ^{56}Ni is (with an increase in binding energy per nucleon of 0.8 MeV) approximately 1.6×10^{51} ergs.
  - This is sufficient both to unbind the white dwarf and to account for the observed kinetic energy of the ejecta.
  - The luminosity of a Type Ia supernova at maximum is then provided by the decay energy of the transition from Ni to Fe via $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$.



Diehl and Timmes (1998)

Radioactivity

- Isotopes of Ni and other elements
  - conversion of γ-rays and positrons into heat and optical photons

Type Ia Supernova : 1994D

Nuclear Astrophysics: Perspective

- Type II supernovae (or "core collapse" supernovae) are powered rather by the gravitational energy release in the formation of a neutron star.

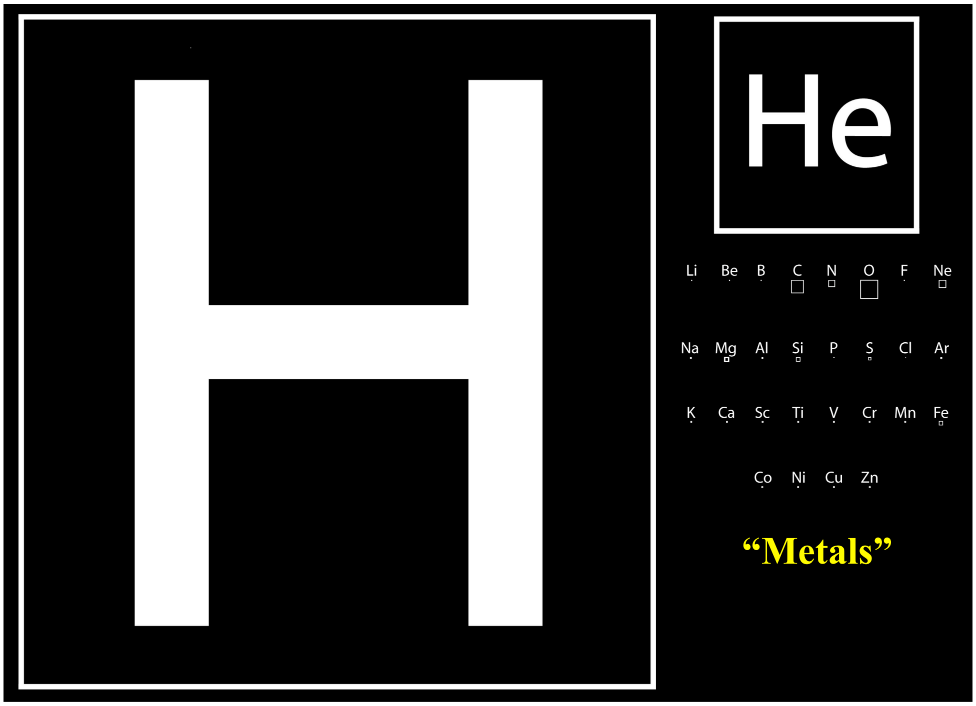
  - The formation of a 1.4 $M_\odot$ neutron star of radius 15 km releases: $E_{grav} = 3GM_{NS}^2/5R_{NS} \approx 2.1\times10^{53}$ ergs

  - Thermonuclear reactions here again play an important role in synthesizing nuclei from oxygen to zinc. Type II supernovae are indeed the main source of such nuclei in galaxies.

  - For the case of supernova 1987A, observations of gamma rays from ^{56}Co decay to ^{56}Fe confirmed the ejection of 0.07 $M_\odot$ of mass A=56 in the form of ^{56}Fe, powering the tail of the light curve.

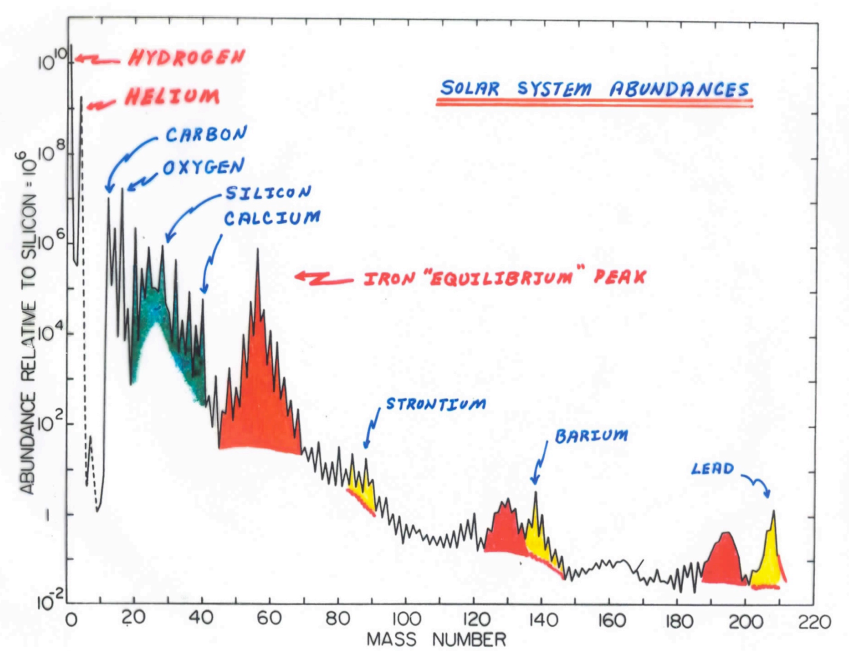
Type II Supernova: Crab (Nebular Remnant) 1054

The Astronomer's Periodic Table of the Elements



After Ben McCall (UIUC)

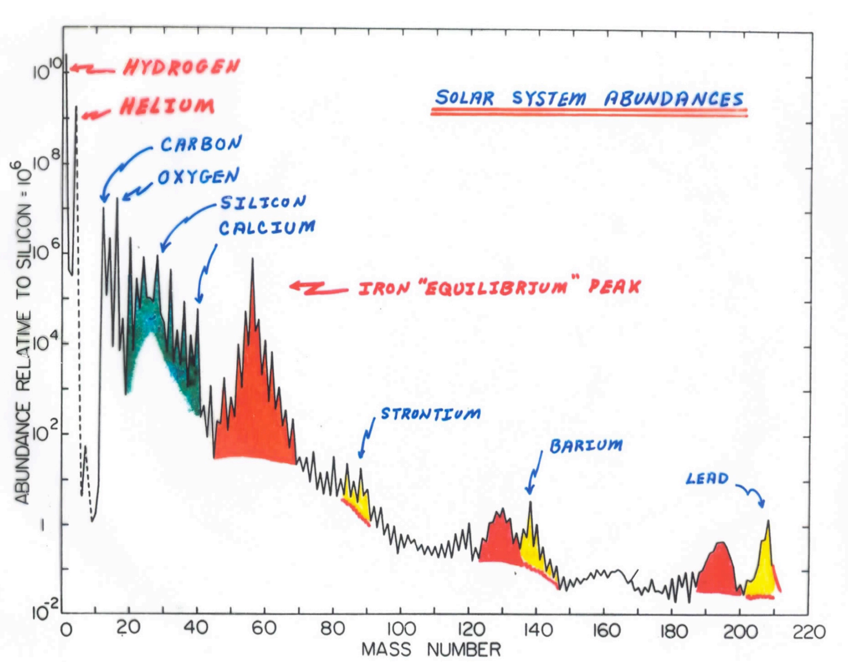
"Cosmic" Abundances of the Elements



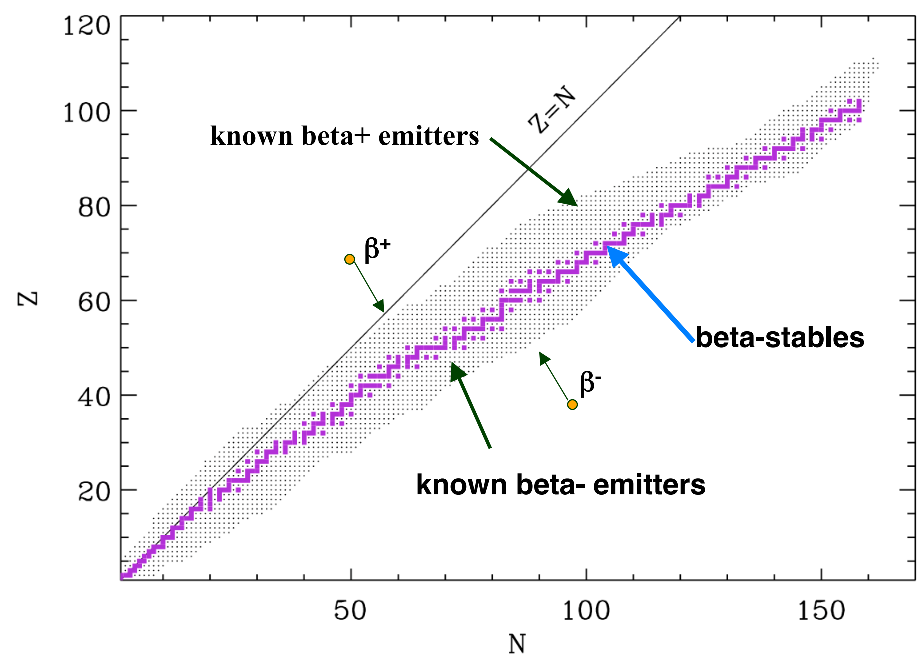
Nuclear Astrophysics: Perspective

- The "Cosmic" abundance patterns - which represent the integrated contributions from stars and supernovae in our Galaxy over some 14 billiion years - clearly reflect nuclear systematics, e.g.:
  - dominance of α-particle nuclei: ^{12}C through ^{40}Ca
  - dominance of unstable α-nuclei products ^{44}Ti, ^{48}Ti, ^{52}Fe, ^{56}Ni, ^{60}Zn, ^{64}Ge, ^{68}Se, ^{72}Kr seen in decay products
  - nuclear statistical equilibrium centered on A=56, first noted by Hoyle (1946)
  - strong signatures of neutron shell structure in the abundance peaks in the heavy element region at magic numbers N=50, 82, and 126
  - odd-even abundance trends
  - existence of 4 stable odd-odd nuclei: ^{2}D,^{6}Li, ^{10}B, ^{14}N

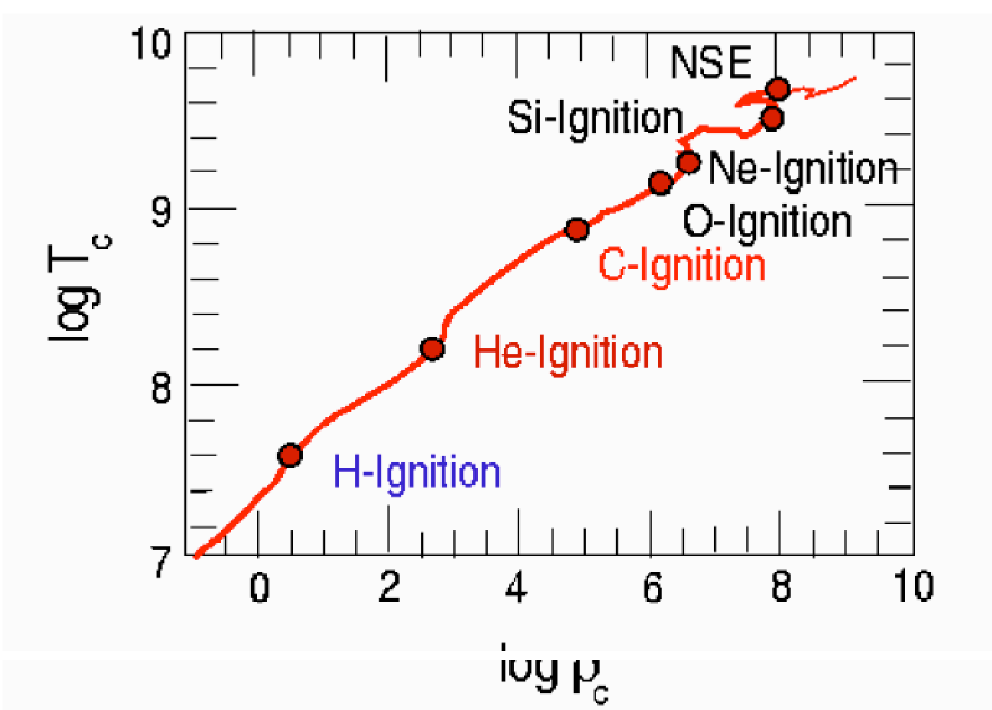
"Cosmic" Abundances of the Elements



Valley of Beta Stability



Core Temperature and Density Evolution in Stars



Nuclear Reactions and Energy Generation

- Thermonuclear reaction rates for hot stellar interiors are generally determined by averaging the product of the relative velocity of the two interacting particles times the cross section $<\sigma v>$ over a Maxwellian distribution of relative velocities.

- For a particle of number density n_p interacting with target particles n_T of cross section σ and moving with velocity v, the number of interactions per target nucleus per unit time is $n_p \sigma v$ and the collision lifetime per target nucleus is $\tau_C = (n_p \sigma v)^{-1}$ seconds.

- The number of collisions per unit volume per unit time is then $r = n_p(v)\, n_T(v)\, \sigma(v)\, v \;\; cm^{-3}\, s^{-1}$.

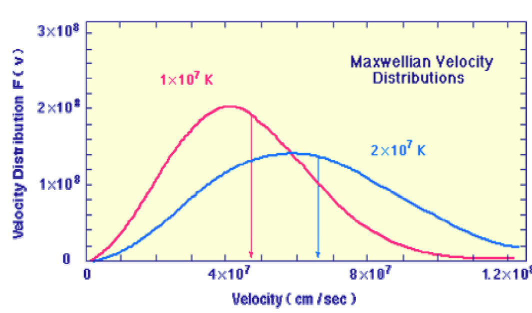
Nuclear Reactions and Energy Generation

- The appropriate rate when averaged over a Maxwellian distribution of relative velocities is then $r = n_p\, n_T <\sigma v>$, where the n_p and n_T are now the total number densities.

- The rate (where μ is the reduced mass and v the velocity of relative motion) is given more generally by:

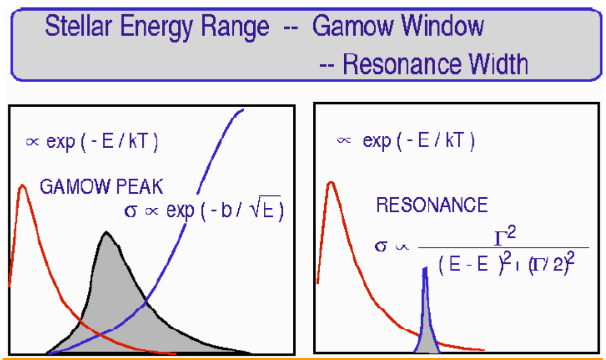
$$r = n_p\, n_T \int^{\infty} v\, \sigma(v)\, 4\pi\, (\mu/2\pi kT)^{3/2} \exp(-\, \mu v^2/2kT)\, v^2\, dv$$

- The Maxellian temperature dependence is as shown⇒



Nuclear Reactions and Energy Generation

- The Gamow 'window' identifies the energy range for which the cross section needs to be experimentally or theoretically known.



E_0

$$E_0 = \left(\frac{bkT}{2}\right)^{3/2} = 0.122 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3} \text{ MeV}$$

$$\Delta E = \frac{4}{\sqrt{3}}\sqrt{E_0 kT} = 0.2368 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/6} T_9^{5/6} \text{ MeV}$$

Nuclear Reactions and Energy Generation

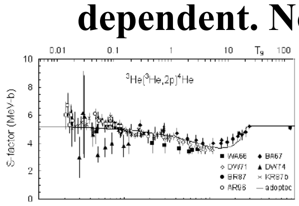
- It is common and useful in astrophysics to remove the dominant Coulomb barrier dependence and identify the astrophysical S factor.

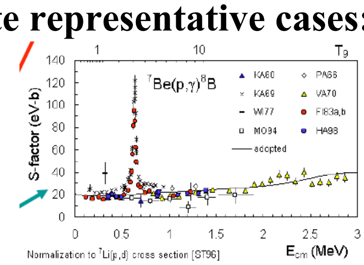
$$S(E) = \sigma \cdot e^{2\pi\cdot\eta}$$

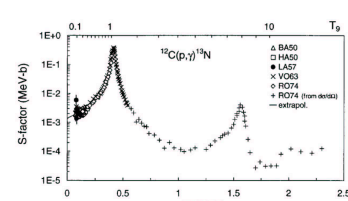
- Where:

$$2\pi\cdot\eta = \frac{2\pi \cdot Z_1^2 \cdot Z_2^2 \cdot e^2}{\hbar\sqrt{\frac{2\cdot E_{cm}}{\mu}}}$$

- With the Coulomb barrier dependence thus removed, the residual factor S(E) is significantly less energy dependent. Note representative cases:

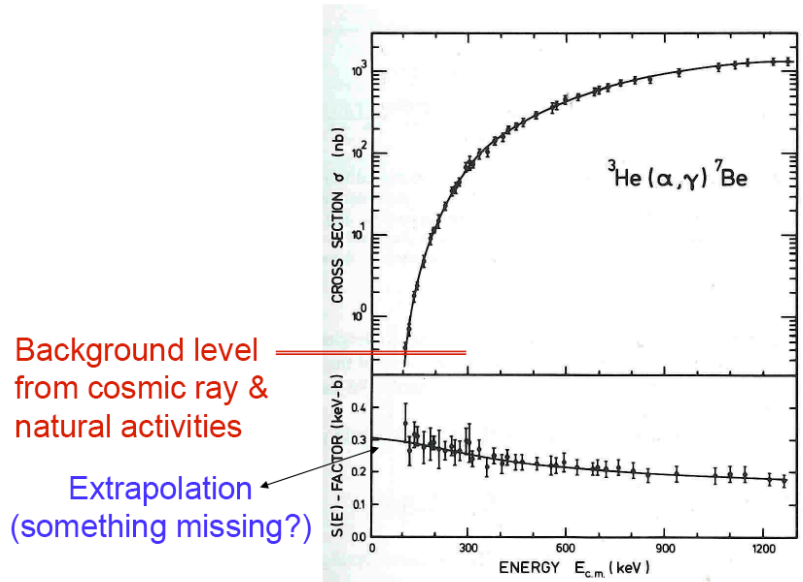






Nuclear Reactions and Energy Generation

Experimental difficulties!



Nuclear Reactions and Energy Generation

Nuclear Burning Stages

- **The choice of nuclear fuel as a stellar energy choice is dictated largely by two factors:**

  - **Charge: The Coulomb barrier energy is typically significantly higher than the thermal energy of the constituent particles.**

    $$B_C = 1.44\ Z_1Z_2/R\ \mathrm{MeV} \approx Z_1Z_2/A^{1/3}\ \mathrm{MeV}$$
    $$E_{thermal} = kT \approx 0.86\ \mathrm{MeV}\ (T/10^9\mathrm{K})$$

  - **Abundance: The earliest phases of energy generation involve hydrogen and helium, the dominant BBN products. The initial composition of the Sun involved less than 2% elements heavier than helium.**

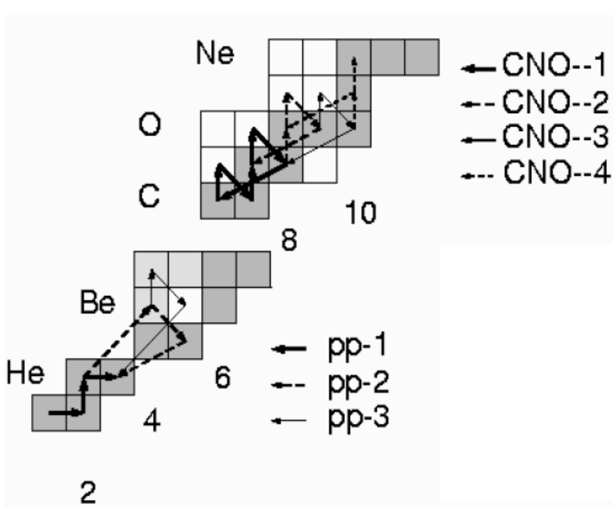
Nuclear Reactions and Energy Generation

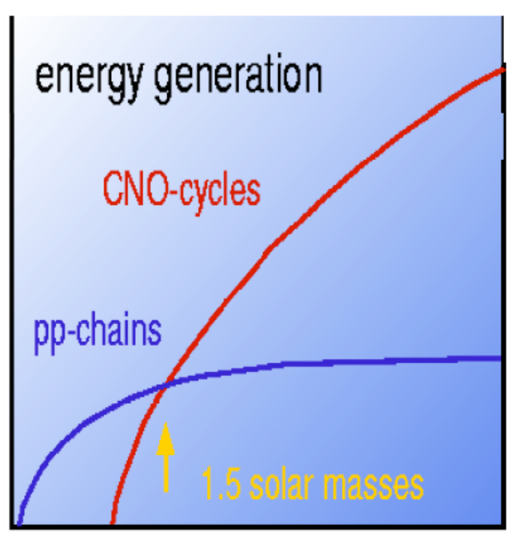
Representative Optimum Bombarding Energies

Reaction	B_C(MeV)	E_0(keV)	ΔE_0(keV)	T(K)
$^{2}D(p,\gamma)^{3}He$	0.83	5.7	4.3	10^7
p+p	0.95	5.7	4.3	10^7
$^{6}Li(p,\alpha)^{3}He$	1.9	12	6.2	10^7
$^{10}B(p,\alpha)^{7}Be$	2.7	17	7.3	10^7
$^{12}C(\alpha,\gamma)^{16}O$	4.8	300	180	$2\text{x}10^8$
$^{12}C + ^{12}C$	12.5	2.4 MeV	1 MeV	10^9

Nuclear Reactions and Energy Generation

Hydrogen Burning Phase of Stellar Evolution





Nuclear Reactions and Energy Generation

Proton-Proton Hydrogen Burning Reactions

The pp-chains

pp-1:	$^1H(p,e^+\nu)^2H$	
	$^2H(p,\gamma)^3He$	
	$^3He(^3He,2p)^4He$	84.7%
pp-2:	$^3He(\alpha,\gamma)^7Be$	13.8%
	$^7Be(e^-,\nu)^7Li$	13.78%
	$^7Li(p,\alpha)^4He$	
pp-3:	$^7Be(p,\gamma)^8B$	0.02%
	$^8B(\beta^+\nu)2^4He$	

fusion of $4\ ^1H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

Nuclear Reactions and Energy Generation

Network for the pp-chain I

$$\frac{d^1H}{dt} = -2\cdot\frac{1}{2}\cdot Y_{^1H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^1H(p,e^-\nu)} + 2\cdot\frac{1}{2}\cdot Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)}$$

$$\frac{d^2H}{dt} = -Y_{^2H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^2H(p,\gamma)} + \frac{1}{2}\cdot Y_{^1H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^1H(p,e^-\nu)}$$

$$\frac{d^3He}{dt} = -2\cdot\frac{1}{2}Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)} + Y_{^2H}\cdot Y_{^1H}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^2H(p,\gamma)}$$

$$\frac{d^4He}{dt} = \frac{1}{2}Y_{^3He}\cdot Y_{^3He}\cdot\rho\cdot N_A\langle\sigma\upsilon\rangle_{^3He(^3He,2p)}$$

Nuclear Reactions and Energy Generation

Reactions in the CNO cycles

CNO-1:
$^{12}C(p,\gamma)^{13}N$ $S_{12C(p,\gamma)}$=3 10^{-3} MeV-barn
$^{13}N(\beta+\nu)^{13}C$
$^{13}C(p,\gamma)^{14}N$
$^{14}N(p,\gamma)^{15}O$ $S_{14N(p,\gamma)}$=2 10^{-3} MeV-barn
$^{15}O(\beta+\nu)^{15}N$
$^{15}N(p,\alpha)^{12}C$ $S_{15N(p,\alpha)}$=1 10^{+2} MeV-barn

CNO-2:
$^{15}N(p,\gamma)^{16}O$ $S_{15N(p,\gamma)}$=5 10^{-2} MeV-barn
$^{16}O(p,\gamma)^{17}F$
$^{17}F(\beta^{+}\nu)^{17}O$
$^{17}O(p,\alpha)^{14}N$

CNO-3:
$^{17}O(p,\gamma)^{18}F$
$^{18}F(\beta^{+}\nu)^{18}O$
$^{18}O(p,\alpha)^{15}N$ $\Rightarrow$ CNO-4

Solar Neutrino Fluxes