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(1)

Ph203: L15

Nuclear Astrophysics:

Invented @ Caltech in Kellogg Lab

Prior to 1950's Observed Chem. elements thought to be primordial (initial Soup)

but ... BBFH PIC

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

→ B^2FH

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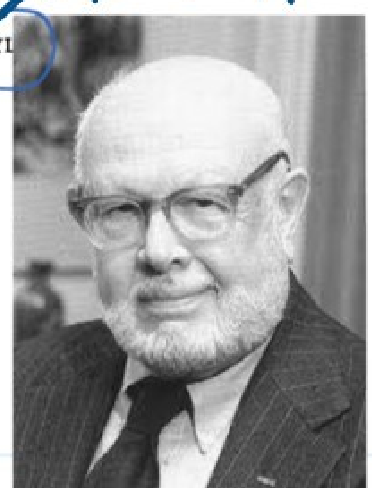
Kellogg Radiation Laboratory, California Institute of Technology, and *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*



'83 Nobel

> "It is the stars, The stars above us, govern our conditions";
> (*King Lear*, Act IV, Scene 3)
>
> but perhaps
>
> "The fault, dear Brutus, is not in our stars, But in ourselves,"
> (*Julius Caesar*, Act I, Scene 2)

Solar System abundances

Solar System abundances

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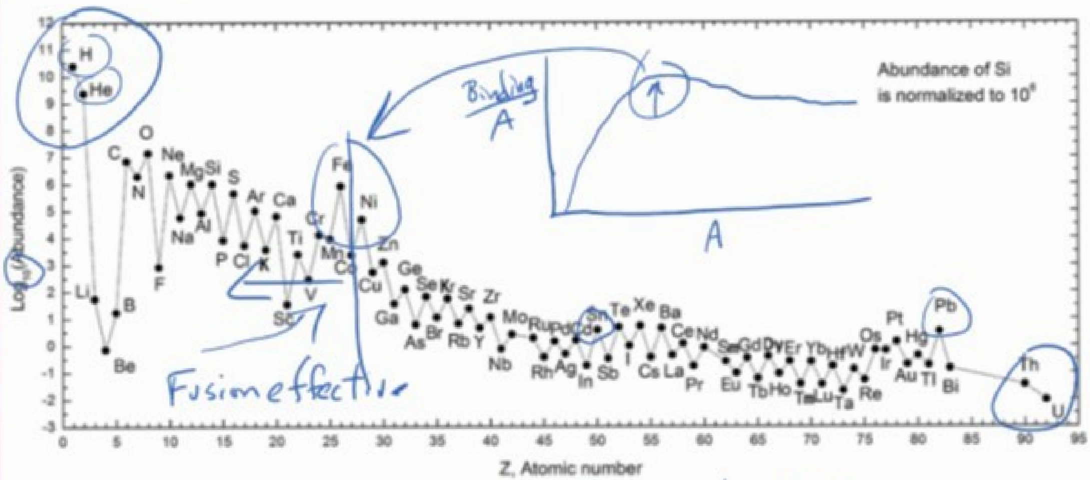

↳ even proton #'s are more abundant ⇒ pairing!

Also magic #'s are more abundant

<u>Key issues in Nucl. Astro.</u>

1. Stellar Energy Production (via Nucl. Fusion)
2. Element / Isotope production (Nucleosynthesis)
   a. BBN (Big Bang Nucleosyn.)
      ↳ developed in 80's & 90's
   b. Fusion Burning in Stars (Medium Mass)
   c. Heavy Element Production ⇒ Neutron Capture
3. Element Dissemination via Novae & Supernovae
4. Neutrino Production (Solar & Supernovae)
5. Neutron Star Formation & Structure

Start with

<u>Stellar Evolution & Nucleosyn.</u>

Evolution summarized via 2D scatterplot of star observables based on Black Body Radiation Laws:

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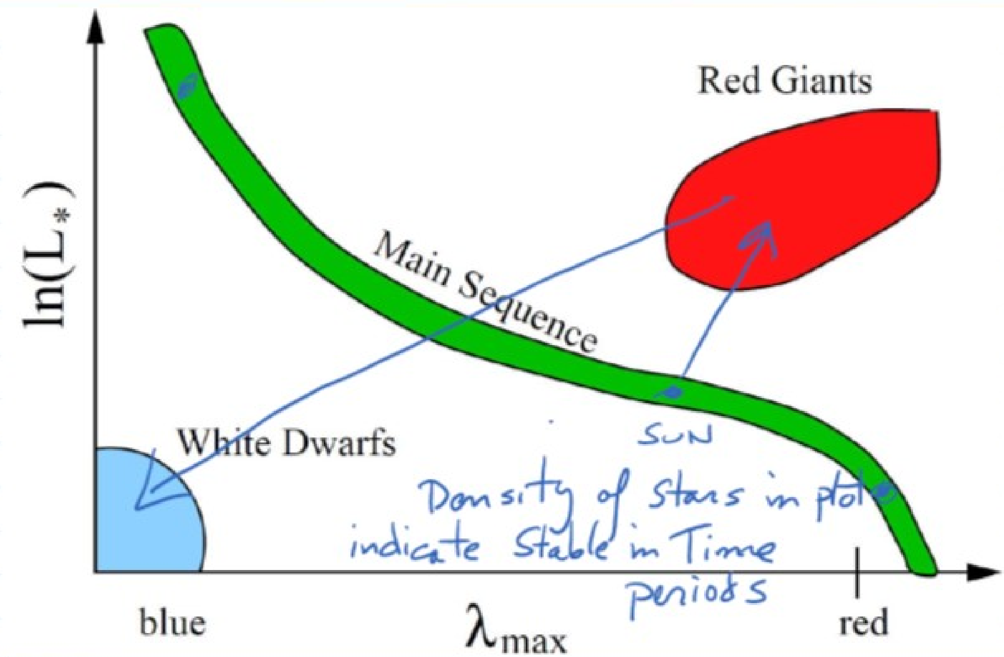
T_s = Surface Temp

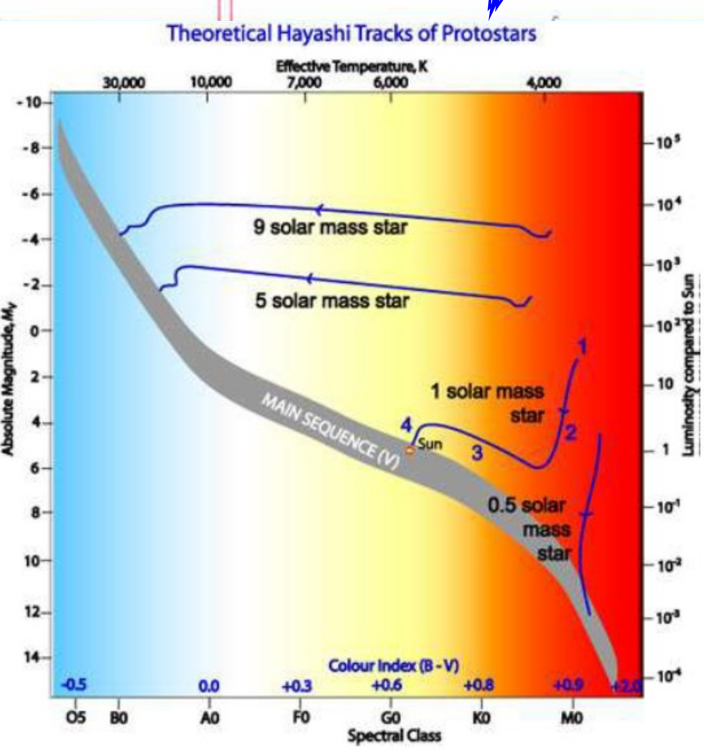
Y-axis
Stefan-Boltzmann Law
$$L_* = 4\pi R^2 \sigma T_s^4$$
"Brightness"/Magnitude (corrected for distance)

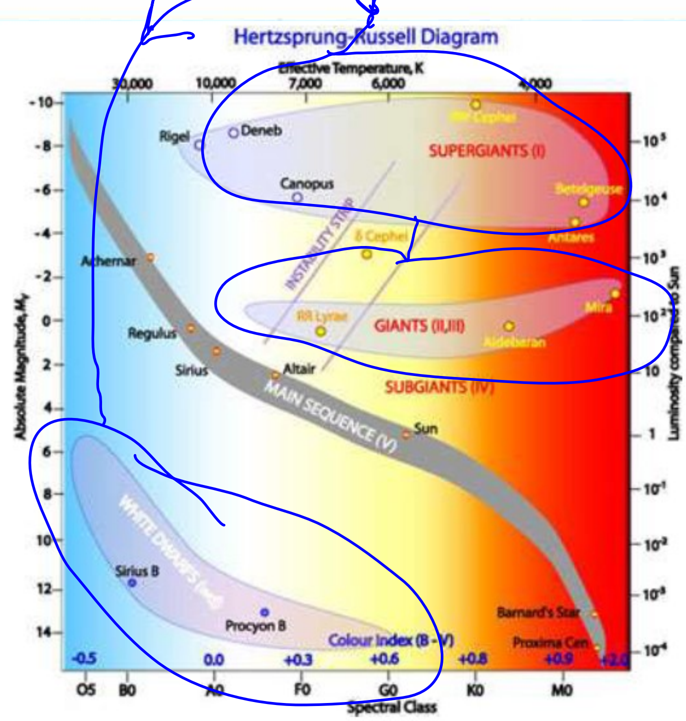


X-axis: Wien's Law: $\lambda_{max} \propto \frac{1}{T_s}$
"Color"

Start w Protostar — Evolution

"Baby" → Middle Age → "Old Geezer"
(Main Sequence)





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Example Evolve: $1 M_\odot$ Star aka SUN

Age $T_\odot$ ($\times 10^9$ yrs)

1. Perturbation (Supernova, passing star) causes contraction of Molecular Cloud = 75% H, 25% ^4He by mass
   ↳ from BBN
2. Contraction converts Gravity Energy to PdV work to increase T
3. Central Temp reaches $> 10^7 K$ ($\equiv T_6 = 10$)
   ↳ fusion begins

0.05 — 4. @ $T_6 = 15$ Hydrostatic Equil. achieved Gravity = Thermal rad. pressure
   ↳ called Zero-Age Main Sequence

10 — 5. Stable H-burning (see later) in core
   Sun @ $T_\odot = 4.5 \cdot 10^9$ yrs

6. Core H fuel exhausted (via $4p \to {}^4He$)
   Gravity contracts core $R_\odot \downarrow \therefore T_{core} \uparrow$
   Shell H burns & radiation press > Gravity $\therefore R_\odot \uparrow \times 50$ & $T_S \downarrow$
   $\therefore$ Red Giant

11 — 7. Core R ↓ until $T_6^{core} = 100 - 200$
   then He burns ($3He \to {}^{12}C$, $4He \to {}^{16}O$)

12 - 13 — 8. He depleted & $R_\odot \downarrow\downarrow$ $T_S \uparrow$ e^- degeneracy stops contraction
   ↳ White Dwarf

15 — Star cools to ~~Black~~ Brown Dwarf

Above combines Fluid Dynamics, Thermo/Stat. Mech, Radiative Transport (AMO) + Nuclear Reactions

Nuclear Reactions in a Thermal Environment

For astrophys., key reactions are:

1. Charged particle fusion reactions $\sigma(E)$
2. Neutron capture "

both @ "low" energy since for

$T_6 = 15$, $kT \simeq 1.3$ keV

$T_6 = 100$, $kT \simeq 9$ keV

Charged Part. Resonant vs. Non-Res.

Consider reaction $A + B \rightarrow X$:

Generally see 2 processes:

Compound Nucleus Reac.

$A + B \rightarrow C \rightarrow D + E$

(C ↑ short-lived intermediate state "metastable")

$\tau_c \gg v_A \times 2R_{(A+B)}$

Direct Reac.

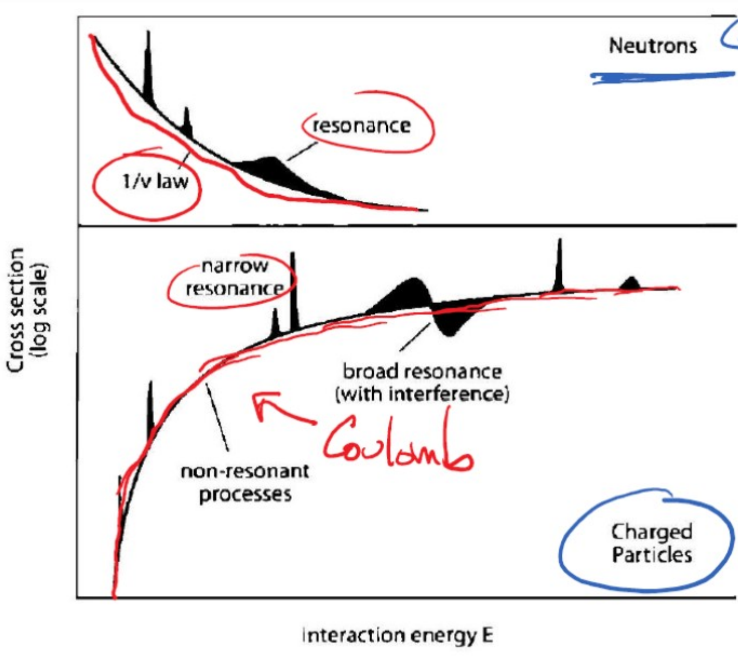
$(p/n) + (A) \rightarrow (A+n) + (p)$

$d + A \rightarrow p + (A+n)$

↳ e.g. stripping reac.

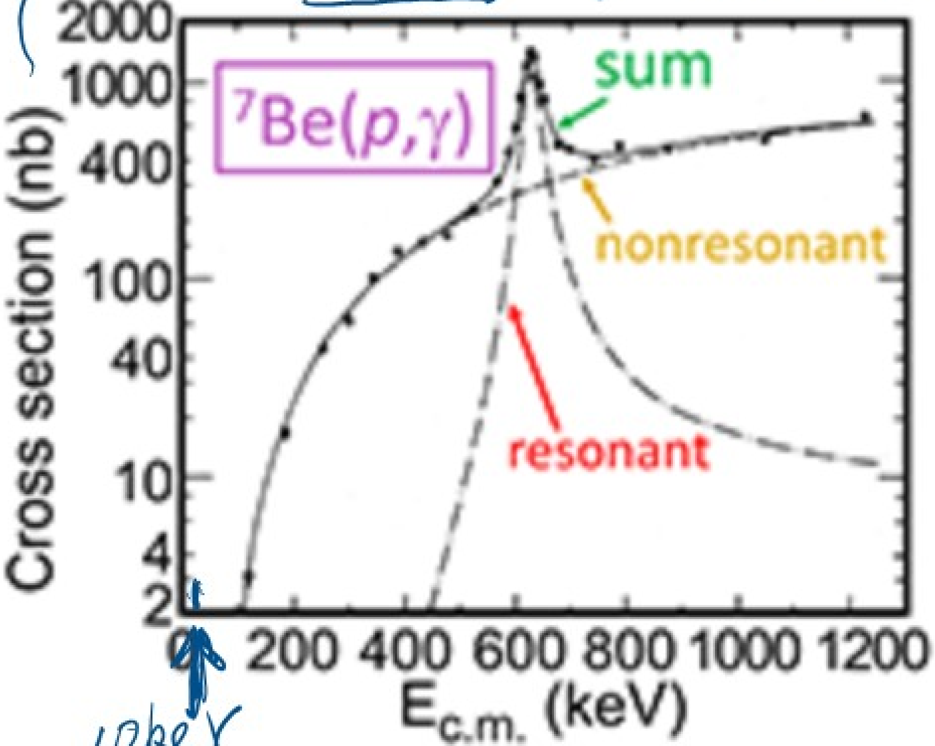
$\tau \simeq v_d \times 2R_A$

If $E_{cm}^{A+B} \simeq$ excited state in C then can have resonant $\sigma(E)$ if WF of C (& J^π) overlaps capture w/ $A+B$:



(6)

10^{-9} b ($n + A$ $\sigma \sim$ mb - b)



10 keV

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(6)

$\sigma_{Res}(E)$ is Breit-Wigner form:

$$\sigma(E) = \pi \lambda^2 \frac{\Gamma_\alpha \Gamma_\beta}{(E - E_R)^2 + \left(\frac{\Gamma_{tot}}{2}\right)^2}$$

reaction channels: $\alpha \Rightarrow A + B$, $\beta = D + E$

Γ_α = rate to produce C from A+B

Γ_β = " " " D+E " C

↳ if only 2 channels then $\Gamma_{tot} = \Gamma_\alpha + \Gamma_\beta$

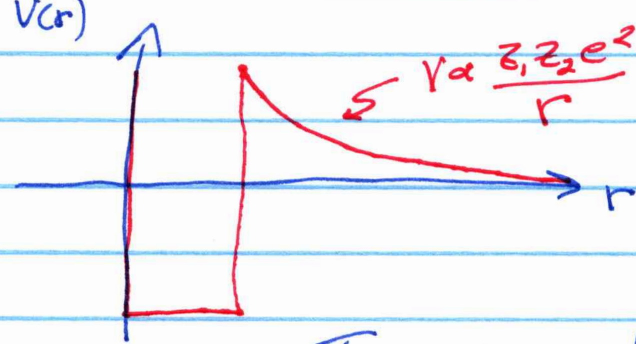
& $\sigma(E_R)$ is large if Γ_{tot} is small

also get σ_R for neutron capture

For non-res. $\sigma(E)$:

Charged Particle:

$\sigma(E)$ @ low E dominated by Coulomb Barrier:



Transmission thru barrier (WKB) gives

$$\sigma \propto T \propto e^{-(E_G/E_{cm})^{1/2}}$$

← see H.W. Bert. 12.10

$$E_G = (2\pi \alpha_{EM} Z_1 Z)^2 \frac{\mu c^2}{2}$$

μ = reduced mass of A + B $= \frac{m_A m_B}{m_A + m_B}$

Now including $\pi \lambda^2$ term ($\propto \frac{1}{E_{cm}}$)

$$\sigma_{NR}(E_{cm}) = \frac{S(E_{cm})}{E_{cm}} e^{-(E_G/E_{cm})^{1/2}}$$

w $S(E_{cm}) \simeq$ constant => see Pic

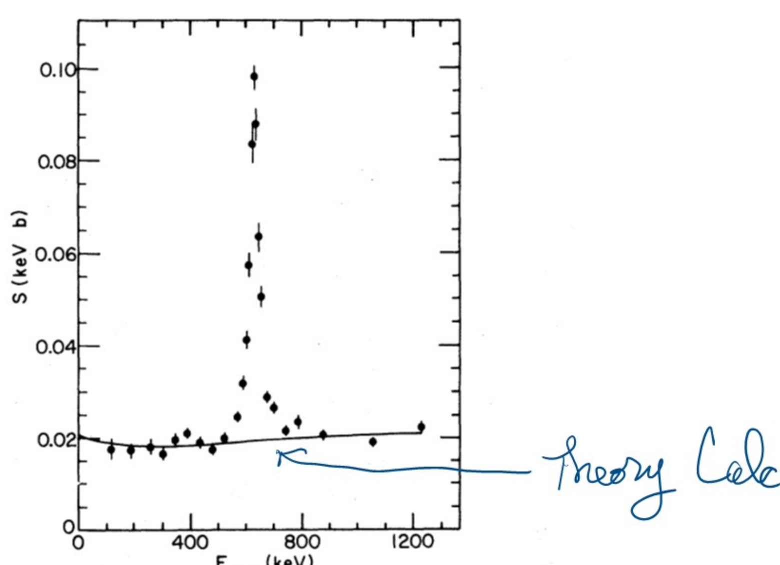


FIG. 8. $^7Be(p,\gamma)^8B$ S factor versus center of mass energy. The solid curve is a least-squares normalization of the calculation of Ref. 6 to the off-resonance data.

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Reactions (cont.)

Neutron Capture $\sigma(E)$

Recall Week 1 Scattering:

$$\sigma_{sc} = \frac{\pi}{k^2}\sum_l (2l+1)\,|1 - S_l|^2, \quad S_l = e^{2i\delta_l} \quad \leftarrow \text{S-Matrix}$$

consider low E ($l=0$) & δ = complex = $\delta_0 + i\epsilon_0$, $\epsilon_0 > 0$

then

S_l not unitary &

$$\sigma_{cap} = \frac{\pi}{k^2}\left(1 - |S_0|^2\right)$$

$$\text{w } |S_0|^2 = \left(e^{2i\delta_0}e^{-2\epsilon_0}\right)\left(e^{-2i\delta_0}e^{-2\epsilon_0}\right) = e^{-4\epsilon_0}$$

$$\therefore \sigma_{cap} = \frac{\pi}{k^2}\left(1 - e^{-4\epsilon_0}\right) \simeq \frac{4\pi\epsilon_0}{k^2} \text{ ; if } \epsilon_0 \ll 1$$

see pics of n-capture (next page) $\left[\sigma \propto \frac{1}{v} \text{ @ low E}\right]$ $\quad \frac{\epsilon_0}{k}$ = const. $\propto R_A$, $\epsilon_0 \lambda$ = const.

Thermal Env. of Stars:

Max-Boltz dist. ($v = |\vec{v}|$)

$$f(v)\,dv = \left(\frac{m_i}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{m_i v^2}{2kT}}\,dv$$

For Energy Prod. or Nucleosyn. need...

Reaction Rates:

$$\text{Reactions}/\text{cm}^3\text{-s} = R(v) = \frac{N_{targ}}{\text{cm}^3} \times \sigma(E) \times \left(\frac{\#\text{ incident part.}}{\text{cm}^2\text{-s}}\right)$$

($\#$ incident part./cm²-s $= n_i v$, $n_i \to$ density (N/cm^3))

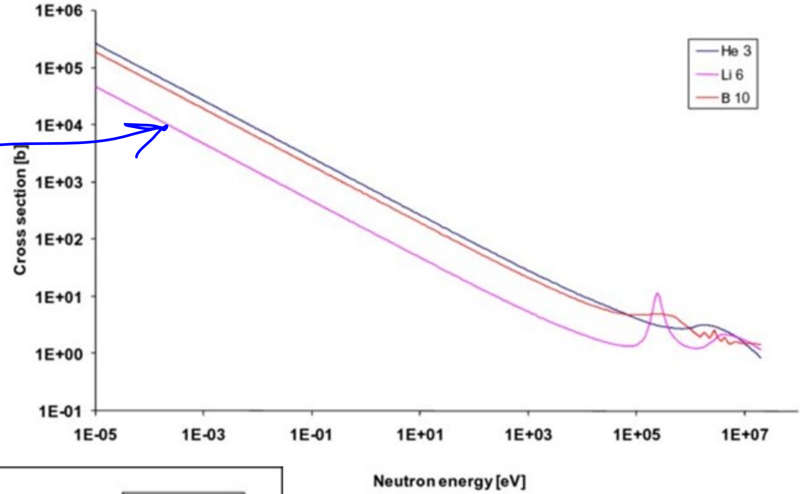
$$= n_i n_T \sigma(E) v$$

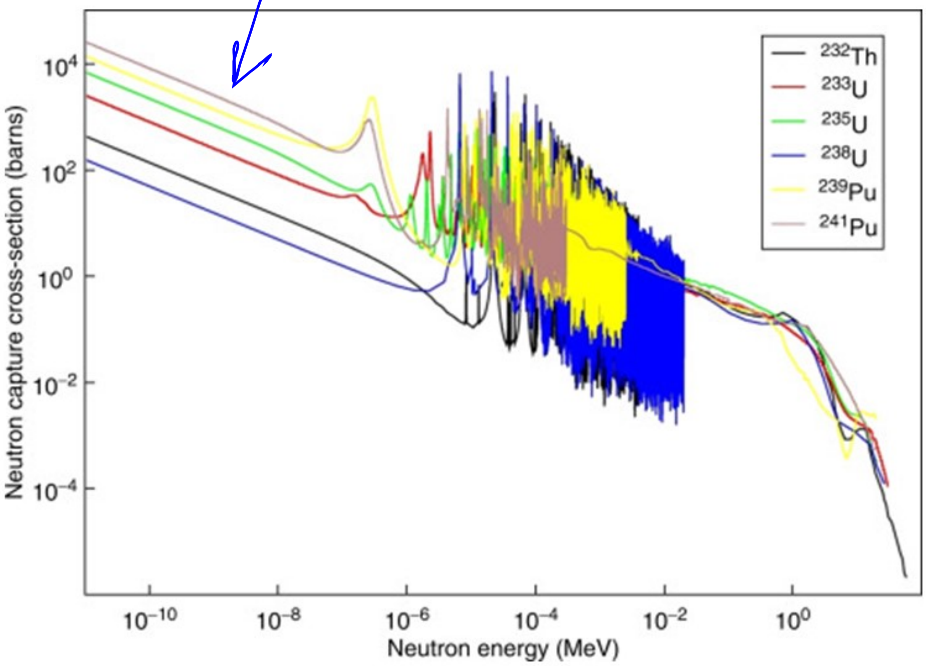
& Normalized Rate:

$$r = \frac{R}{n_T n_i} = \sigma(v)\,v$$

Neutron Capture Cross Section Examples

$\sigma \propto \frac{1}{v}$



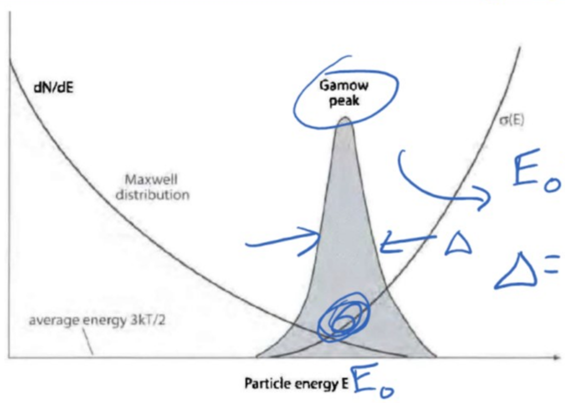


& average over MB: $\langle r \rangle = \langle \sigma(v) v \rangle_{\text{over } f(v)}$ ↗ most probable E_0

⇒ For non-res. charged particles get a peak in $\langle r \rangle$ due to balance of M.B. & Coulomb Penetrat.

Most Probable Reaction Energy – E_0

$$E_G = (2\pi \alpha Z_1 Z_2)^2 \frac{\mu c^2}{2}$$



$$E_0 = \left(\frac{\sqrt{E_G}\, kT}{2} \right)^{2/3}$$

$$\Delta = 4 \left(\frac{E_0\, kT}{3} \right)^{1/2}$$

Figure 12.4 The Gamow peak is a convolution of the energy distribution of the Maxwell-Boltzmann probability and the quantum mechanical Coulomb barrier transmission probability. The peak in the shaded region near energy E_0 is the Gamow peak that gives the highest probability for charged particle reactions to take place. Usually the Gamow peak is at a much higher energy than kT, and in the figure the ordinate scale (for the Gamow peak) is magnified with respect to those of the Maxwell-Boltzmann and barrier penetration factors.

E.g. for H burning:

$T_6 = 15$, $kT = 1.3\,\text{keV}$

$E_0 = 19\,\text{keV}$ $\Delta = 12\,\text{keV}$

for He burning:

$T_6 = 200$, $kT = 20\,\text{keV}$

$E_0 = 300\,\text{keV}$, $\Delta = 170\,\text{keV}$

& can calc. $\langle r \rangle$ using $S(E_0)$

⇒ For neutron capture (non-res)

$\sigma \propto \frac{1}{v}$ & $\langle \sigma(v) v \rangle \neq f(E)$

then many $\langle r \rangle_{ij}$ give reaction Network

to calc Energy/time or $\frac{N_i(t)}{\sum_i N_i}$ = abundances

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(4)

Reaction Network Examples:

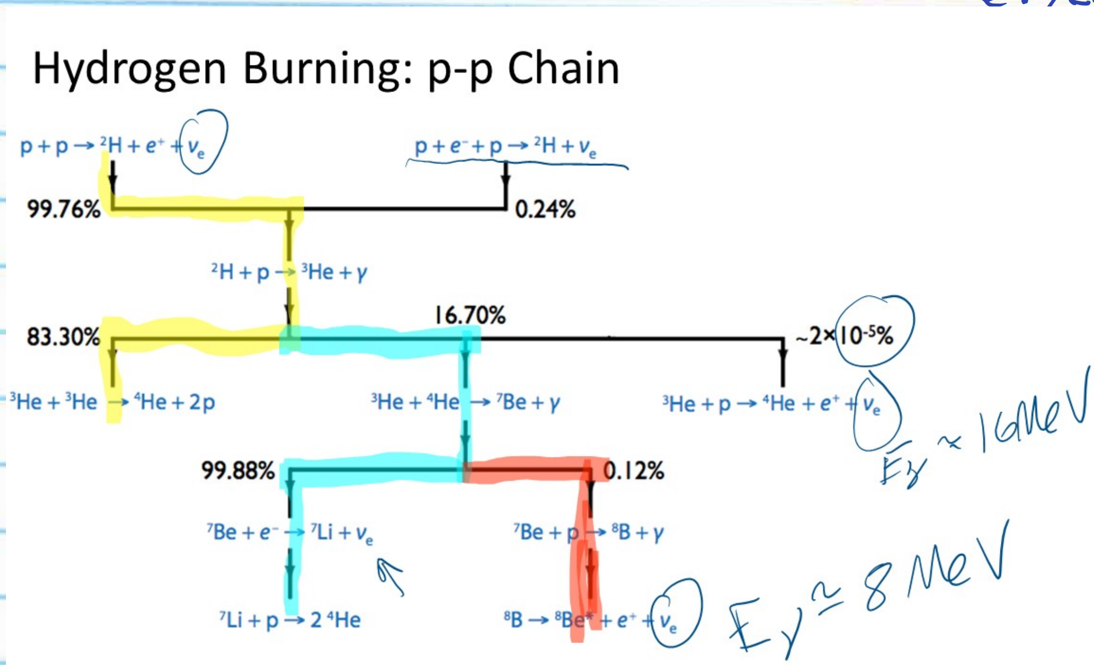
Solar H-burning : "pp chain" ($4p \to {}^4He$)

e.g. via $p + p \to d + e^+ + \nu_e$ (weak) ($\ll$ pb)

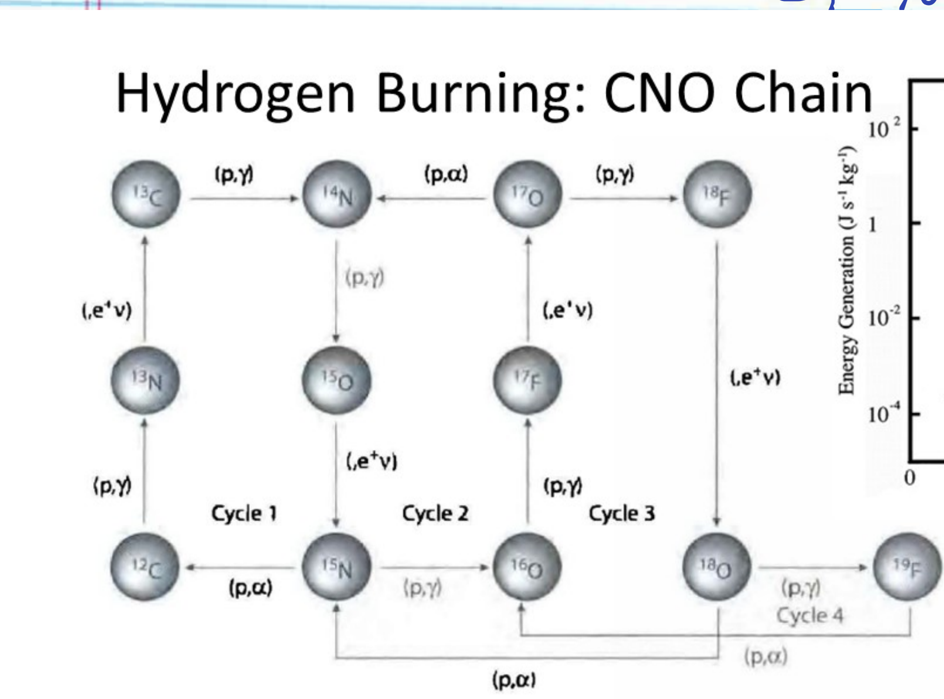
$p + d \to {}^3He + \gamma$ (EM) ($<$ nb)

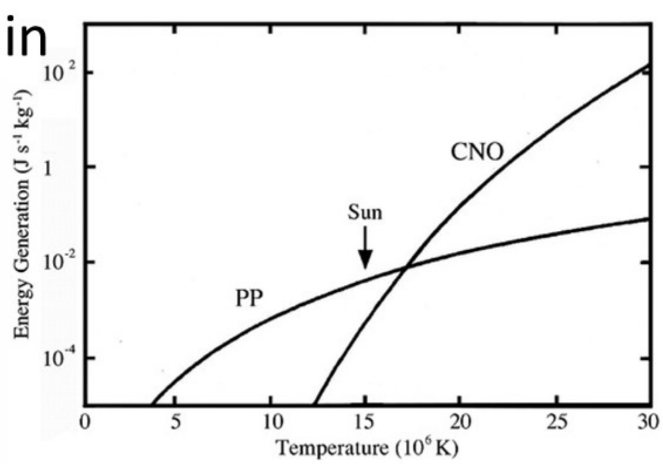
${}^3He + {}^3He \to {}^4He + 2p$ (strong) ($\sim$ mb)

$+ 26.2$ MeV/cycle



At slightly higher temp. can do $4p \to {}^4He$ w/ ${}^{12}C$, ${}^{14}N$ as catalyst





Helium Burning Network:

Complication: No stable isotopes of any element w $A = N + Z = 8$ or $A = 5$

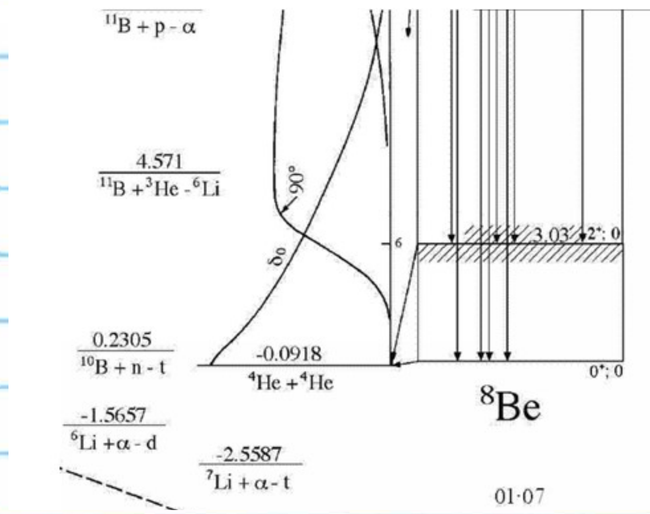
How to make ^{12}C?

Consider ^{8}Be gnd state $\Gamma \simeq 5.6\,eV$

$\tau \simeq 10^{-16} s$

@ $T_6 = 100$, $^4He + {}^4He$ transit time $\simeq 10^{-19} s$

Look @ Energy level ...



Does ^8Be live long enough to get $^4He + {}^8Be \to {}^{12}C + \gamma$??

@ $T_6 = 200$

$E_0 = 240\,keV$ w $\Delta = 170\,keV$

Can we produce enough ^{12}C to make us??

⇒ Fred Hoyle (1953):

Non-resonant "triple-alpha" process could not make enough ^{12}C "...and all life." 1960.

Only <u>resonant</u> reaction could work ∴

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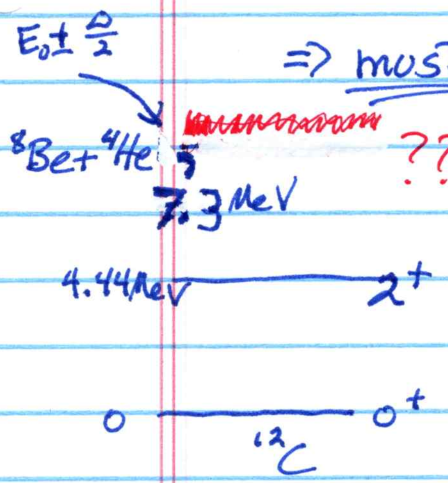
(7)



⇒ must be a excited state in ^{12}C

?? not $1^-, 2^+, \ldots$

"just right"

not too high E

" " low E

" " hi spin

not parity = (−)

Kellogg Lab Exp found it!

@ E = 7.68 MeV

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 195

The 7.68-Mev State in C^{12}

D. N. F. Dunbar,* R. E. Pixley, W. A. Wenzel, and W. Whaling

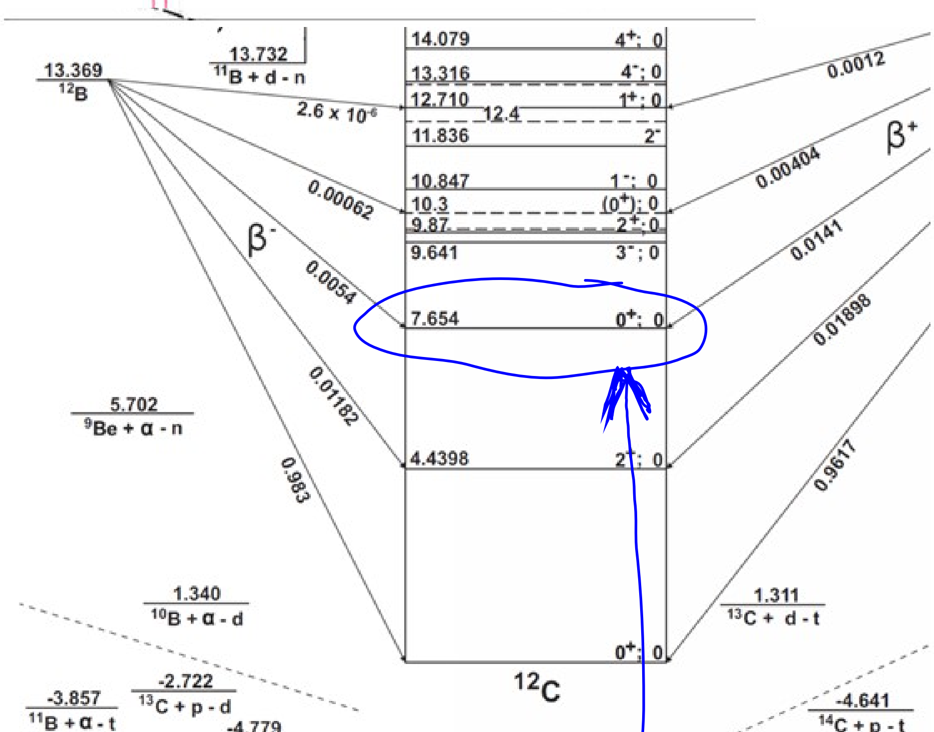
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68±0.03 Mev. At E_d=620 kev, θ_{lab}=90°, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from that this reaction should have a resonance at 0.31 Me or at 7.68 Mev in C^{12}.

An early measurement of the range of the alph particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} a 7.62 Mev.[4] However, a recent magnetic analysis o



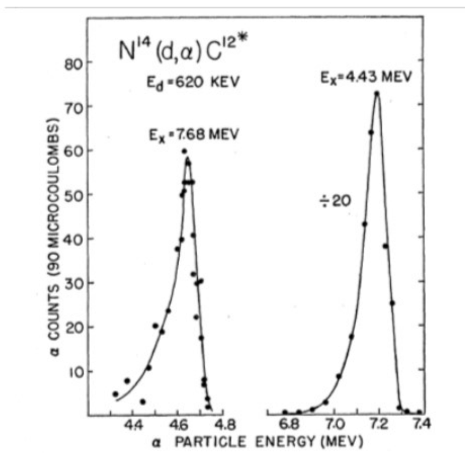


Fig. 1. Alpha spectrum from $N^{14}(d,\alpha)C^{12}$ obtained with a thick NH_3 target. No other groups were observed in the range E_α=3.7−7.4 Mev of magnitude 1 percent of the group to the 4.43-Mev state. The spectrometer was set at θ_{lab}=90°.

7.65 MeV state = "... secret of life"

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(8)

But what happens next?

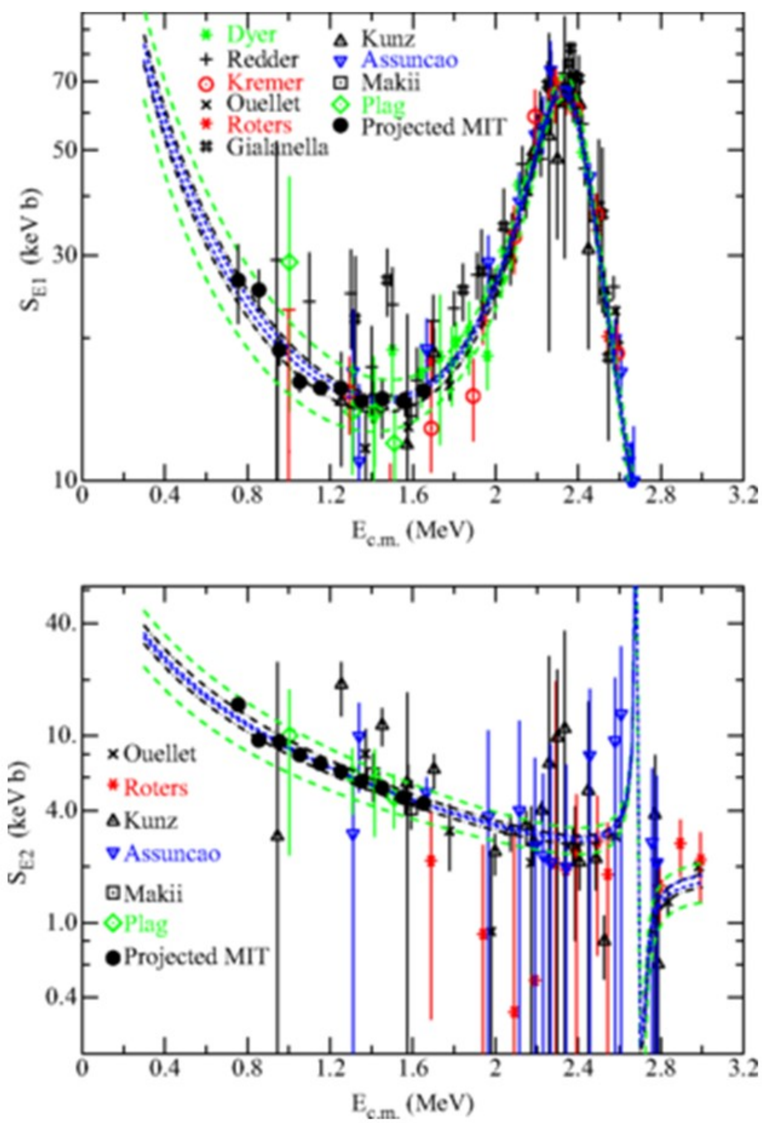
⟺ $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

If this is strongly resonant then all ^{12}C consumed. However...,

It is resonant but capture is surpressed since resonance is 1^- & ^{16}O is 0^+
→ E1 ←

⇒ Very hard to measure, but very important
(Nucleosyn. & GW)

$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ Reaction



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(9)

Next step: $^{16}O + \alpha \to {}^{20}Ne + \gamma$ is highly supressed due to ang. mom. mismatch

He-burning stops here (see Fig)

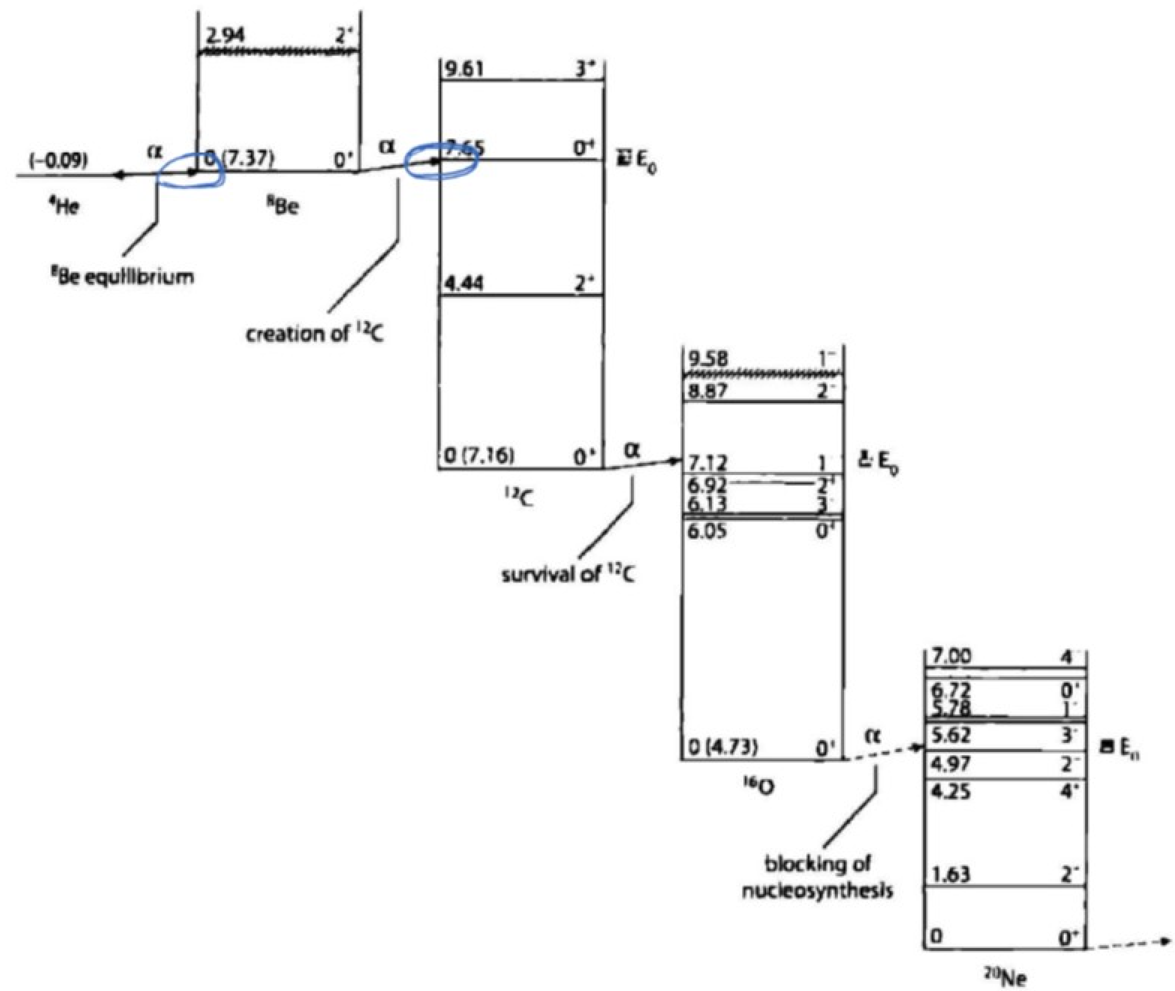

Figure 12.11 Energy levels of nuclei participating in thermonuclear reactions during the helium burning stage in red giant stars (adapted from [RR88]). The survival of both ^{12}C and ^{16}O in red giants, believed to be the source of terrestrial abundances depends upon fortuitous circumstances of nuclear level structures and other properties in these nuclei.

For $M_* \lesssim 5 M_\odot$ Core Fusion stops & Star goes to Red Giant ⇒ then to White Dwarf

But for $M_* \simeq 10 M_\odot$ more burning possible b/c large grav. energy gives higher T_{core} ⇒ $T_6 \sim 500$
this allows:

C-burning: $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$
$\rightarrow ^{23}Na + p$
then $\rightarrow ^{23}Mg + n$

O-burning: $^{16}O + ^{16}O \rightarrow ^{28}Si + \alpha$ $T_6 = 3000$
then $\rightarrow ^{32}S + \gamma$

Si-burning:
@ $T_6 \sim 5000$ BBR allows
$^{28}Si + \gamma \rightarrow ^{24}Mg + \alpha$ ⟺ new source of ^4He
∴
$^{28}Si + \alpha \rightarrow ^{32}S + \gamma$
$^{32}S + \alpha \rightarrow ^{36}Ar + \gamma$
$+\alpha$ ... ... Ca → Ti → $^{52}Fe \rightarrow ^{56}Ni$
then $^{56}Ni \xrightarrow{\beta} ^{56}Co \xrightarrow{\beta} ^{56}Fe$

Nuclear burning & Stellar Nucleosyn. stops @ ^{56}Fe since Fusion impossible beyond this

Next time: need to use <u>neutrons</u>