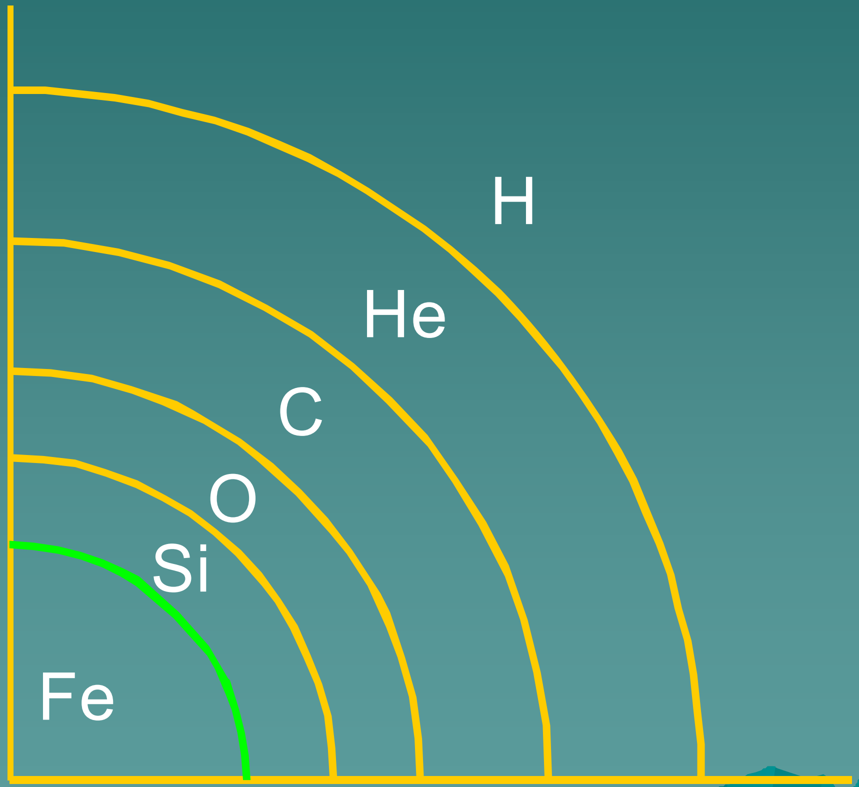
Advanced Burning

Building the Heavy Elements

Advanced Burning

- Advanced burning can be (is) very inhomogeneous
- The process is very important to the chemical history of the galaxy
- The problem is to not only explain the existence of heavy elements, but also their absolute and relative abundances.



Energy Generation Nucleosynthesis

- Energy generators build elements up to Z ~ 20 / 22 (maybe 26).
- The exact amount depends on the source
- Type II SN (10-100 $M_{\odot}$) put out lots of O which is generated during He burning
- Type I SN (<1.41 $M_{\odot}$) put out great quantities of Fe.

So What is Built During Energy Generation?

- He
  - He^4 – Result of H burning
  - He^3 – Incomplete pp chain
- Li, Be, B
  - These are not formed during pp or CNO – Their abundances present difficulties due to their sensitivity to destruction – best current source is spallation of C^{12} by cosmic rays
- C^{12}, O^{16}
  - Formed in 3α process (and immediate follow-on)
  - Also get some O^{18} and Ne^{22}

Proceeding

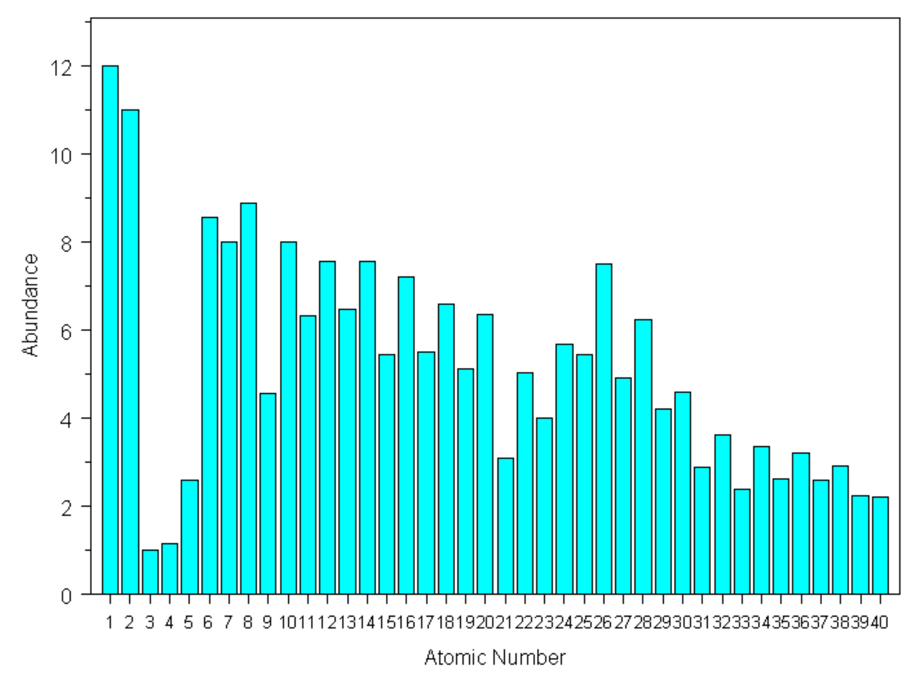
- N^{14}
  - Forms as a result of CNO processing during H burning.
- Ne^{20}, Na, Mg, Al, Si, (P, and S)
  - Result from C burning
  - The latter two come from O burning
- We are up to $Z = 16$ and A 32
  - Note that fluorine is missing ($Z = 9$)

Comparison

- The relative proportions produced by these burning processes agree rather well with the values seen in the solar neighborhood.
- The absolute quantities are governed by not only the mechanism but also by the "rate" or the yield per generation.
  - To get into stars this material must be recycled

Production of A ≥ 28

- We consider the range 28 ≤ A ≤ 60
- The high end of the range is the Fe peak a very strong perturbation in abundance versus Z.



What Burns Next?

- We have built: Ne^{20}, Na^{23}, and Mg^{24,25,26}
- We also have available: Al^{27}, Si^{28,29,30} as well as P^{31} and S^{32}.
- The next fuel should be the species that has the lowest Coulomb barrier: this will be either Ne^{20} or Na^{23} or maybe Mg. But there is less Mg than there is Si or S.
- Gamow Peak: T $\simeq$ 2 or 3 (10^9) K
  - Thermal rays can photodisintegrate S^{32} and perhaps (ultimately) Si^{28}

→ Normal Burning cannot proceed! ←

What Happens Next?

Normal Burning Cannot Proceed

- A quasi-equilibrium configuration is established involving photodisintegration and particle capture.
- Ultimate end is the production of the Fe- peak.
- Fe Peak elements are highly favored: the binding energy per nucleon is at or near maximum at Fe.
  - Binding Energy is defined as the energy it takes to separate the nucleus into individual particles.

The Binding Energy Curve

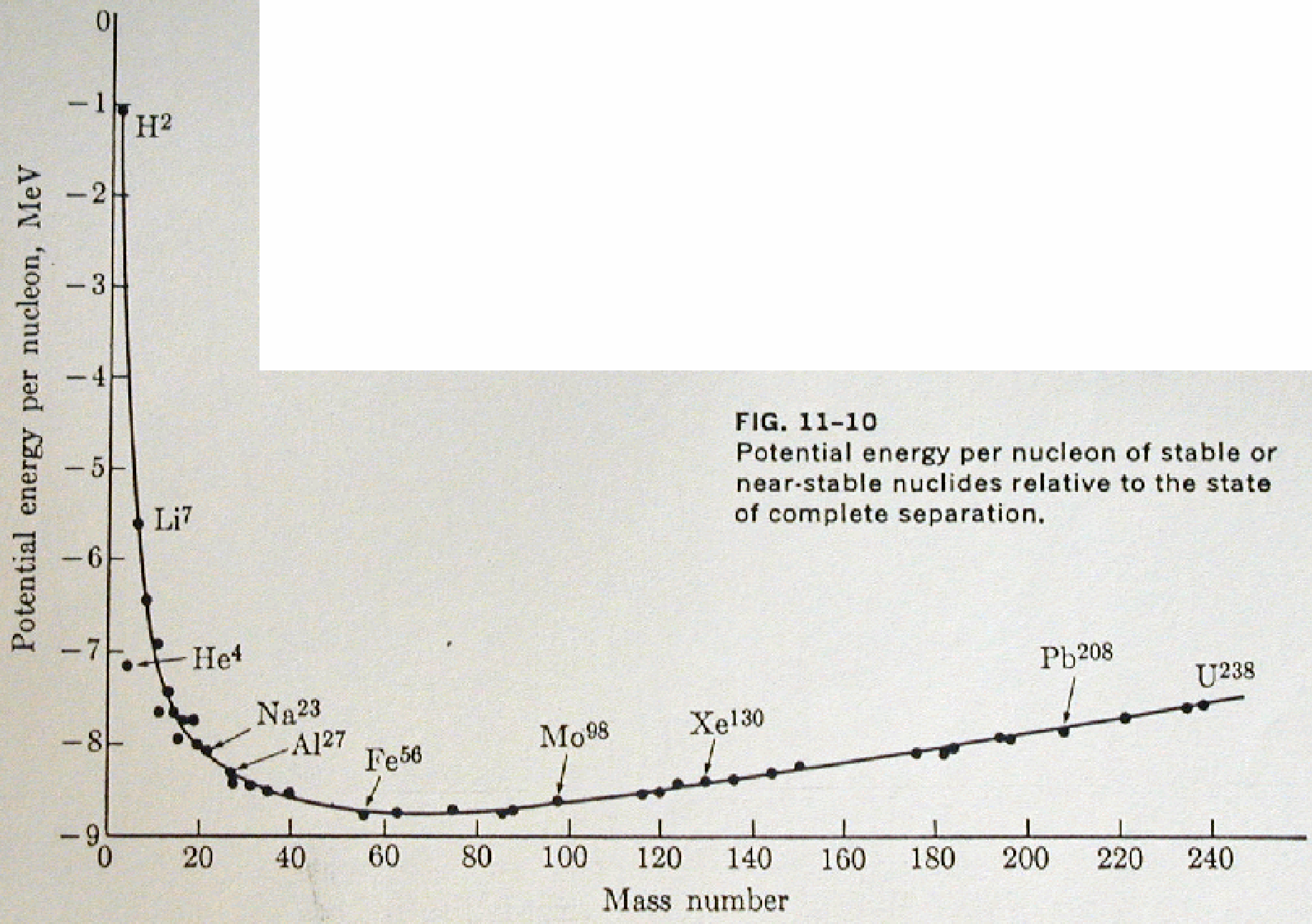


FIG. 11-10
Potential energy per nucleon of stable or near-stable nuclides relative to the state of complete separation.

Details of Si Burning

- At $2(10^9)$ K absorption of energetic photons by nuclei produces excited states which can eject p, n, α.
- Reaction Rates: $r_i \sim \exp(-Q_i/kT)\,\Gamma_{eff}$
  - Q_i is the binding energy of the ejected particle
  - Γ_{eff} = a rate factor (effective particle width) producing maximum rates near the Gamow peak.
- After O^{16} burns the dominant species are Si^{28} and S^{32}.
  - Other products of O^{16}/C^{12} burning do not affect energy generation but do affect element generation.

Si^{28} and S^{32}

- Si^{28} is more tightly bound that S^{32} so at $2.5*10^{9}$ K:
  $S^{32} + \gamma \rightarrow Si^{28} + \alpha$
  - Therefore, at $3(10^{9})$ K the core is mainly Si^{28}
- There follows two competing processes:
  - Disintegration of Si^{28}
    - $Si^{28} + \gamma \rightarrow Al^{27} + p$
    - $Si^{28} + \gamma \rightarrow Mg^{24} + \alpha$
    - $Si^{28} + \gamma \rightarrow Si^{27} + n$
    - Other processes also occur which (could) lead to a dominance of light elements in the core.
  - The photodisintegration takes place on a finite timescale so particle interactions can occur

Si Burning

- $\mathrm{Si}^{28} + \alpha \leftrightarrows \mathrm{S}^{32} + \gamma$
- $\mathrm{S}^{32} + \alpha \leftrightarrows \mathrm{Ar}^{36} + \gamma$
- �
- $\mathrm{Cr}^{52} + \alpha \leftrightarrows \mathrm{Ni}^{56} + \gamma$

Details, Details ...

The Net Process: 2 $Si^{28} \rightarrow Ni^{56}$

- These chains can also do n,p captures but the α chain is the more efficient
- The heavier species that are built persist as they have larger binding energies per nucleon.
- Each of the individual links is a quasi- equilibrium process.
- The light particles are used up in the formation of the heavier species. The primary source of the particles (mainly α) is $Si^{28} + \gamma$

More Details

- Si burning will not produce elements with A > 56.
- Fe^{56} has the largest binding energy per nucleon. To go heavier one must tap the thermal pool – ie, “exothermic” up to Fe^{56}, “endothermic” afterwards.
- Note that n,p reactions to increase Z are also possible. Along with the backward reactions these decide the isotopic content (yield) of Si burning. Note that many of the products are unstable and will begin to β decay.

Still More Details

- Note that we produce Ni^{56} and Fe^{54}.
- The dominant isotope of Fe is Fe^{56} (91.8%). Ni^{56} has a half-life of 6.1 days to electron capture. It becomes Co^{56} which has a half-life of 77 days to either electron capture or positron emission.
- Note the 77 day half-life – it is very important to understanding supernovae.

Energy Generation

- $\varepsilon = \varepsilon_0 X_{Si}^{1.143} (1-X_{Si})$-
  $0.143 T_9^{6.31} e^{-143/T9}$
  - T_9 = T in billions of degrees
  - ε_0 📬 $2.9(10^{27})$
- At $T_9 = 3$; $X_{Si} \sim 0.5$
  - $\varepsilon = 3(10^9)$ erg gm^{-1} s^{-1}
- Duration
  - For T < 3 T_9: 10^6s (11.6 days)
  - For T > 3 T_9: can be as little as 10s
- The nucleosynthetic yield depends on T

Yield From Si Burning	
T_9	Species
2	Fe^{56}
3	Fe^{54}
4.3	Ni^{56}
5.7	Fe^{54} + 2p
>6.5	He^4

Production of Elements with A > 56

- Coulomb barrier is essentially impenetrable at A > 56 to charged particles ➔ **Neutron capture** 🡐
- Consider the process: ${}_{Z}X^{A} + n \rightarrow {}_{Z}X^{A+1}$
- There are two possibilities ${}_{Z}X^{A+1}$ is either stable or unstable
  - Stable: go to the next step – add another n
  - Unstable:
    - It Decays
    - It has time to add another neutron before the decay
    - This obviously depends strongly on the cross sections and neutron velocities (that is, T)

The r and s process

- s-process: capture rate is slow compared to the decay rate (usually β)
  - Proceed along a chain of stable isotopes of an element until an unstable one is encountered
    - Then you decay to a new element and start over.
- r-process: capture rate is fast compared to the decay rate.
  - Proceed along a chain of stable isotopes of an element until an unstable one is encountered
    - And you just go right over it by another capture to another isotope of the same species.
    - You do this until you cannot proceed
      - Binding energy problem
      - A very fast decay/large decay cross section is encountered.
      - Now decay to a stable isotope
    - This builds neutron rich isotopes.

What do we build?

- s-process builds the more stable balanced (n -p) species – Valley of β stability
- r-process builds the neutron-rich isotopes
- The major problem is where do the neutrons come from?
  - Energy generators do not produce them
  - They must come from a subsidiary process

Consider the r-process

- $dN_A/dt = n_N\langle v\rangle(\sigma_{A-1}N_{A-1} - \sigma_A N_A)$
  - σ_A = neutron cross section
  - n_N = neutron # density
- To order of magnitude: $1/\tau = n_N\sigma\langle v\rangle$
  - σ is an average capture cross section 10^{-25} cm^2
  - At $T \sim 10^9$ K $\langle v\rangle \approx 3(10^8)$ cm / s
  - Typical β decay is $\sim 10^{-2}$ s so we require $\tau \ll 10^{-2}$
  - This means $n_N\langle v\rangle \gg 10^{27}$ cm^{-2}s^{-1}
  - Since $\langle v\rangle \approx 3(10^8)$ cm / s this means the neutron flux is about $3(10^{18})$

➔ An awful lot of neutrons! 🡐