Nuclear Reactions in Stars and the Build-up of the Heavy Elements

These notes list some representative examples of nuclear reactions possibly of importance in maintaining stars in equilibrium at various stages of their careers, and in manufacturing heavy elements which may be ejected from stars in their late, explosive, stages. The list is not complete, but is representative of most types of reaction which play an important rôle in stellar evolution and in the origin of the chemical elements.

NOTATION FOR NUCLEAR REACTIONS

<u>nuclei</u>: E^n ← number of nucleons (protons + neutrons) in nucleus

↑ chemical symbol of element whose atom might contain such a nucleus

e.g., C^{12}, Fe^{56}, etc.

<u>nucleons</u>: H^1 - proton

n - neutron

<u>Byproducts</u>: e^- - electron

e^+ - positively-charged electron (positron)

ν - neutrino

γ - γ-radiation (high-energy electromagnetic radiation)

1. HYDROGEN FUSION IN STARS

$$\left.\begin{aligned} &H^1 + H^1 \rightarrow H^2 + e^+ + \nu \\ &H^1 + H^2 \rightarrow He^3 + \gamma \\ &He^3 + He^3 \rightarrow He^4 + H^1 + H^1 \end{aligned}\right\} \quad \text{main proton-proton reaction chain}$$

↳ <u>favoured</u> because the <u>result</u> is particularly stable.

Possible alternative processes (occur occasionally) are:

$$He^3 + He^4 \rightarrow Be^7 + \gamma$$

$$\left.\begin{aligned} &Be^7 + e^- \rightarrow Li^7 + \nu \\ &Li^7 + H^1 \rightarrow He^4 + He^4 \end{aligned}\right\} \quad \text{or} \quad \left\{\begin{aligned} &Be^7 + H^1 \rightarrow B^8 + \gamma \\ &B^8 \rightarrow He^4 + He^4 + e^+ + \nu \end{aligned}\right.$$

In "late-model" stars with appreciable content of heavier elements, and at higher temperatures where electrical-repulsion barrier can be overcome:

$H^1 + C^{12} \rightarrow N^{13} + \gamma$

$N^{13} \rightarrow C^{13} + e^+ + \nu$

$C^{13} + H^1 \rightarrow N^{14} + \gamma$

$N^{14} + H^1 \rightarrow O^{15} + \gamma$

$O^{15} \rightarrow N^{15} + e^+ + \nu$

$N^{15} + H^1 \rightarrow C^{12} + He^4$

"carbon-nitrogen cycle"
Net effect is $4H^1 \rightarrow He^4 + 3\gamma + 2e^+ + 2\nu$

↑ regenerated (C^{12})

2. HELIUM FUSION IN STARS

$He^4 + He^4 \rightarrow Be^8 \rightarrow He^4 + He^4$ again

$He^4 + H^1 \rightarrow Li^5 \rightarrow He^4 + H^1$ again

↑ unstable

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

$C^{12} + He^4 \rightarrow O^{16} + \gamma$

$O^{16} + He^4 \rightarrow Ne^{20} + \gamma$

$Ne^{20} + He^4 \rightarrow Mg^{24} + \gamma$

These all fuse He^4 with stable products to make heavier stable products.

... etc., to Si^{28}, S^{32}, A^{36}, Ca^{40}

3. CARBON FUSION IN STARS

$C^{12} + C^{12} \rightarrow Ne^{20} + He^4$ - nothing "new" formed

$C^{12} + H^1 \rightarrow C^{13} + e^+ + \nu$ - rarer isotope of carbon

$C^{13} + H^1 \rightarrow N^{14} + \gamma$ - common isotope of nitrogen

$C^{13} + He^4 \rightarrow O^{16} + n$ - common isotope of oxygen and a neutron

Neutron-induced reactions (NO electrical repulsive barrier to be overcome):

$C^{13} + n \rightarrow C^{14} + \gamma$ - radioactive isotope of carbon

$N^{14} + n \rightarrow N^{15} + \gamma$ - rarer isotope of nitrogen

etc., etc., (many processes possible)

$O^{16} + H^{1} \rightarrow F^{17} + \gamma$

$F^{17} \rightarrow O^{17} + e^{-} + \nu$

$O^{17} + H^{1} \rightarrow N^{14} + He^{4}$

} more complex proton-induced reactions

4. EQUILIBRIUM NUCLEAR COOKERY

1. Reactions involving commonplace reactants (especially H^1, He^4) will be favoured.

2. Reactions with small electrical-repulsion barriers will be favoured.

3. Stable products will be formed easily and broken down only with difficulty.

Results: $3He^4 \rightarrow C^{12}$ bypasses Li, Be, B, which can only be formed by occasional "side-reactions". These have small abundances.

Nuclei which are multiples of He^4 are easily formed and hard to remove. These have large abundances.

Abundances of other nuclei depend on which processes lead to them, given (1) and (2) above - general decline in abundance with increasing mass because formation is less likely the more steps are needed.

"Piling up" at Fe^{56} because of (3)

-- indeed --

How does anything beyond Fe^{56} in mass ever get formed?

5. S-PROCESS

Slow neutron addition ($\sim$ 1 per year)

$Fe^{56} + n \rightarrow Fe^{57}$ (STABLE)

$Fe^{57} + n \rightarrow Fe^{58}$ (STABLE)

$Fe^{58} + n \rightarrow Fe^{59} \rightarrow Co^{59} + e^{-} + \overline{\nu}$ ($t_{\frac{1}{2}} \sim$ 45 days)

$Co^{59} + n \rightarrow Co^{60} \rightarrow Ni^{60} + e^{-} + \overline{\nu}$, etc.

Builds up nuclei that are stable against β-decay for few years or more.

Cannot explain all heavy nuclei though.

1) "Bismuth Barrier"

$Bi^{209} + n \rightarrow Bi^{210} \rightarrow Po^{210} + e^{-} + \overline{\nu}$

$Po^{210} \rightarrow Pb^{206} + He^{4}$

$Pb^{206} + n \rightarrow Pb^{207}$

$Pb^{207} + n \rightarrow Pb^{208}$

$Pb^{208} + n \rightarrow Pb^{209} \rightarrow Bi^{209} + e^{-} + \overline{\nu}$

This prevents formation of radioactive elements such as thorium, uranium.

2) Some neutron-rich isotopes cannot be reached because intermediate steps form nuclei with RAPID β-decays.

6. R-PROCESS

Rapid neutron addition (many per second)

Can bypass some unstable nuclei on way to forming more massive stable ones.

e.g., $Fe^{56} + n \rightarrow Fe^{57}$ (STABLE)

$Fe^{57} + n \rightarrow Fe^{58}$ (STABLE)

$Fe^{58} + n \rightarrow Fe^{59}$

$Fe^{59} + n$ (quickly) $\rightarrow Fe^{60}$ (STABLE)

Slow neutron addition could not get beyond Fe^{59} because Fe^{59} decays to Co^{59} with half-life of 45 days. Rapid neutron addition can make Fe^{60}.

Rapid neutron addition is needed to form any of the radioactive elements heavier than lead (e.g., thorium, uranium). Also need rapid removal of products from neutron supply, to prevent their destruction by neutron-induced fission.

Most likely to scenario for this is supernova explosion.