Genesis of the Elements

I. In the first few minutes, the following processes would take place:

"Big Bang"

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}H + {}^{0}_{-1}e + \bar{\nu}_e $$

$$ \bar{\nu} + {}^{1}_{1}H \rightarrow {}^{1}_{0}n + \bar{e} $$

$$ {}^{1}_{1}H + {}^{1}_{0}n \rightarrow {}^{1}_{1}H + {}^{1}_{0}n + \gamma $$

$$ e + \bar{e} \rightarrow \gamma + \gamma $$

$$ \gamma \rightarrow e + \bar{e} $$

equilibration at high temperature

where ${}^{1}_{1}H = p$ = proton of charge +1, mass = 1.007 amu

γ = gamma ray (high energy photon) with zero rest mass

${}^{0}_{-1}e = e^- =$ electron of charge -1, mass $\frac{1}{1823}$ amu
also known as a β particle

${}^{0}_{1}e = e^+ = \bar{e} =$ positron, charge +1, mass $\frac{1}{1823}$ amu

ν_e = neutrino with no charge & very small mass

$\bar{\nu}_e$ = antineutrino, no charge & very small mass

${}^{1}_{0}n$ = neutron with no charge, mass = 1.009 amu

amu $\equiv 1.660 \times 10^{-27}$ kg (or dalton)

convention: ${}^{\text{mass \#}}_{\text{atomic \#}}\text{symbol}$ $\qquad$ $Z+N=A$, ${}^{A}_{Z}\text{Symbol}$

mass # = #protons + #neutrons

atomic # = nuclear charge = #protons

II. In the high-density equilibrium distribution that existed for a short time before the system blew itself apart, T dropped to $\sim 10^9$ K as universe expanded, and He would be formed:

$$^1_1H + ^1_0n \rightarrow ^2_1H + \gamma$$

$$^2_1H + ^2_1H \rightarrow ^3_2He + ^1_0n$$

$$^2_1H + ^2_1H \rightarrow ^3_1H + ^1_1H$$

$$^3_2He + ^1_0n \rightarrow ^3_1H + ^1_1H$$

$$^3_1H + ^2_1H \rightarrow ^4_2He + ^1_0n$$

He formed to about 10%

90% essentially ^1_1H mostly from β-decay of n that formed themselves in free space after big bang

III. ^1_1H-burn

$$^1_1H + ^1_1H \rightarrow ^2_1H + \bar{e} + \nu + 0.42\ MeV$$

two ^1_1H fuse ($1eV = 1.602 \times 10^{-22}\ kJ$)

Now: $\frac{1eV}{mol} = 96.48 \frac{kJ}{mol} = 23.06 \frac{kcal}{mol}$

$\frac{MeV}{mol} \cong 9.7 \times 10^7 \frac{kJ}{mol} \cong 2.3 \times 10^7 \frac{kcal}{mol}$

IV. He is formed in a star cycle of rxns called the proton-proton cycle, consisting of the proceeding rxns followed by ^1_1H/^3_2He-burn

$$^1_1H + {}^1_1H \rightarrow {}^2_1H + {}^0_1e + \nu + 0{,}42\ MeV$$

$$^2_1H + {}^1_1H \rightarrow {}^3_2He + \gamma + 5{,}49\ MeV$$

$$^3_2He + {}^3_2He \rightarrow {}^4_2He + 2\,{}^1_1H + 12.86\ MeV$$

V He-burn ($\sim 10^8$ K)

$$^4_2He + {}^4_2He \rightarrow {}^8_4Be + \gamma - 0{,}094\ MeV$$

$$^4_2He + {}^8_4Be \rightarrow {}^{12}_6C + \gamma + 7{,}37\ MeV$$

$$^{12}_6C + {}^1_1H \rightarrow {}^{13}_7N \rightarrow {}^{13}_6C + {}^0_1e + \nu$$

Other rxns include:

$$^3_2He + {}^4_2He \rightarrow {}^7_4Be + \gamma$$

$$^7_4Be + {}^1_0n \rightarrow {}^7_3Li + {}^1_1H$$

VI Carbon cycle (C/N-burn)

$$^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + \gamma + 1.94\,MeV$$

$$^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{1}e + \nu + 1.20\,MeV$$

$$^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + \gamma + 7.55\,MeV$$

$$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma + 7.29\,MeV$$

$$^{15}_{8}O \rightarrow {}^{15}_{7}N + {}^{0}_{1}e + \nu + 1.73\,MeV$$

$$^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + {}^{12}_{6}C + 4.96\,MeV$$

$^{12}_{6}C$ is a "catalyst"

VII Heavier elements: successive captures of $^{4}_{2}He$ by $^{12}_{6}C$:

$$^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$$

$$^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{28}_{14}Si + {}^{4}_{2}He$$

$$^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{31}_{16}S + {}^{1}_{0}n$$

$$^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O$$

$$^{16}_{8}O + {}^{4}_{2}He \rightarrow {}^{20}_{10}Ne$$

$$^{20}_{10}Ne + {}^{4}_{2}He \rightarrow {}^{24}_{12}Mg$$

$$^{24}_{12}Mg + {}^{4}_{2}He \rightarrow {}^{28}_{14}Si$$

$$^{28}_{14}Si + {}^{4}_{2}He \rightarrow {}^{32}_{16}S$$

$$^{32}_{16}S + {}^{4}_{2}He \rightarrow {}^{36}_{18}Ar$$

⋮ ⋮

through $^{56}_{26}Fe$

Nuclei of odd A values can be formed, if even-A nuclei are forced by turbulence out of the stellar core into the surrounding cooler zone where $^{1}_{1}H/^{1}_{1}H$ cycle is occurring

$$^{20}_{10}Ne + {}^{1}_{1}H \rightarrow {}^{21}_{11}Na + \gamma$$

$$^{21}_{11}Na \rightarrow {}^{21}_{10}Ne + {}^{0}_{1}e + \nu$$

$^{21}_{10}Ne + {}^{4}_{2}He \rightarrow {}^{24}_{12}Mg + {}^{1}_{0}n$

process stops at $A \geq 60$, which is $^{56}_{26}Fe$, the most stable nucleus

to go past Fe requires extreme conditions

$$^{56}_{26}Fe + 13\,{}^{1}_{0}n \rightarrow {}^{69}_{26}Fe \rightarrow {}^{69}_{27}Co + {}^{0}_{-1}e$$

14-body collision
not common