CARBON BURNING

$T_8 = 5 .. 10$

PRACTICE: $\gtrsim 8$

$$^{12}C + {}^{12}C \rightarrow \begin{cases} {}^{24}Mg + \gamma , & Q = +13.931 \\ {}^{23}Mg + n , & -2.605 \\ {}^{23}Na + p , & +2.238 \\ {}^{20}Ne + \alpha , & +4.616 \\ {}^{16}O + 2\alpha & -0.114 \text{ MeV} \end{cases}$$

T- DEP. DISTRIBUTION

MOST LIKELY

$$\langle Q \rangle \simeq 13 \text{ MeV}$$

Q: HOW CAN THIS BE? POST REACTION RELEASE << 13 MeV! ?

Q: WHAT IS Δm PER NUCLEON

A: SECONDARY REACTIONS

$$^{16}O + \alpha \longrightarrow {}^{20}Ne + \gamma$$

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

$$^{24}Mg + \alpha \longrightarrow {}^{28}Si + \gamma$$

MAIN PRODUCTS:

^{16}O, $\underline{^{20}Ne}$, ^{24}Mg, ^{28}Si

! $n \longrightarrow$ S-PROCESS

(p,γ) e.g. $^{12}C\,(p,\gamma)\,{}^{13}N\,(\beta^+)\,{}^{13}C\,(\alpha,n)\,{}^{16}O$

$\hookrightarrow$ free n from p!

A DIFFERENT KIND OF REACTION:

Ne BURNING $T_9 \gtrsim 1.5$

$$^{20}Ne + \gamma \longrightarrow {}^{16}O + \alpha \quad , \quad Q = -4.73\,MeV$$

HIGH-E TAIL OF PLANCK SPECTRUM

WE HAVE ALREAD SEEN. SECONDARY REACTIONS!

$$^{20}Ne + \alpha \longrightarrow {}^{24}Mg + \gamma \qquad Q = +9.313\,Me$$

→ COMBINED:

$$2\ {}^{20}Ne + \gamma \longrightarrow {}^{16}O + {}^{24}Mg + \gamma$$

$$Q = +4.583\,Me$$

- TYPICALLY HAPPENS JUST BEFORE O BURNING
- VERY "FLASHY" → HIGH T-DEP
  NO DENSITY-DEP (FEEDBACK)
  FOR (γ, α) REACTION

OXYGEN BURNING

$T_9 \gtrsim 1.5 \ldots 2$

$$ {}^{16}O + {}^{16}O \longrightarrow {}^{32}S + \gamma \qquad Q = 16.541\ MeV$$

$$ {}^{31}P + p \qquad 7.677$$

$$ {}^{31}S + n \qquad \text{MAIN} \qquad 1.453$$

$$ {}^{28}Si + \alpha \qquad 9.593$$

$$ {}^{24}Mg + 2\alpha \qquad -0.393$$

$\langle Q \rangle \sim 16\ MeV$

AGAIN: DUE TO SECONDARY REACTIONS

MAIN PRODUCTS: ${}^{28}Si$, ${}^{32}S$

ALSO DURING O BURNING (MOSTLY AT BEGINNING)

(MAGNESIUM BURNING)

$$ {}^{24}Mg \longrightarrow \begin{array}{l} (\alpha,\gamma)\ {}^{28}Si \\ (\gamma,\alpha)\ {}^{20}Ne(\gamma,\alpha){}^{16}O \end{array}$$

SILICON BURNING

$T_9 \gtrsim 3 \ldots 3.5$

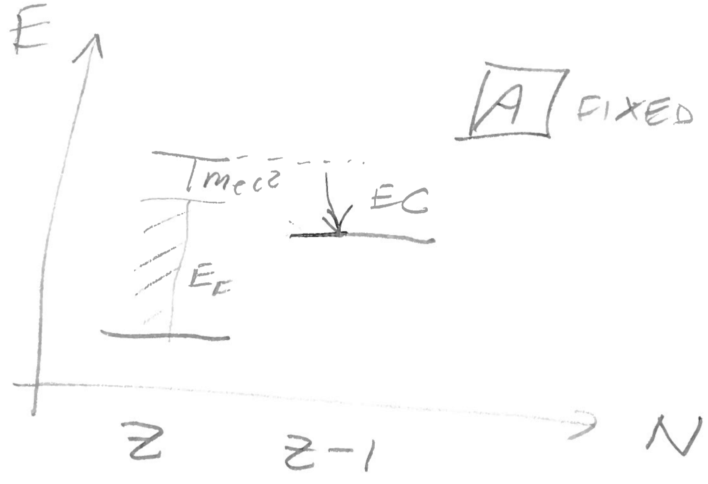
- SERIES of (γ,α) AND (α,γ) REACTIONS BUILD UP "IRON GROUP" ELEMENTS
- THERE ARE "WEAK" REACTIONS

$$p \rightarrow n + e^+ + \nu_e$$
$$p + e^- \longrightarrow n + \nu_e$$

(MOSTLY: NEUTRONIZATION)

Q: WHY?

A: HIGH DENSITY → HIGH E_F → EC



DEF. NEUTRON EXCESS: $\eta := \frac{N-Z}{N+Z} \simeq 1 - 2Y_e$

BEYOND Si BURNING

IRON CORE IN NUCLEAR STATISTICAL EQUILIBRIUM (NSE)

$\leftrightarrow$ NUCLEAR REACTIONS "FAST" COMPARED TO EVOLUTION TIME-SCALE OF STARS

$\leftrightarrow$ DISTRIBUTION of nuclei is given BY SAHA EQUATION

density $n \sim e^{-E/k_BT}$

BUT # RATIO OF neutrons/proton (η) only evolves slowly (weak reactions)

$\rightarrow$ DISTRIBUTION DEPENDS ON T, ρ, Y_e

URCA PROCESS

$$(Z, A) + e^- \rightarrow (Z-1, A) + \nu$$

$$(Z-1, A) \longrightarrow (Z, A) + e^- + \bar{\nu}$$

FINITE T : e^- BEYOND E_F

CONVECTION : changing E_F
FOR MASS ELEMENT