Helium Burning Reactions in Stars

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Helium burning reaction rates are calculated with newly acquired experimental information at temperatures in the ranges $1-2 \times 10^8 \text{oK}$ and $3-6 \times 10^8 \text{oK}$. A fresh supply of helium at higher range of temperatures may have come from certain heavy-ion reactions. At lower temperature range Ne$^{20}$ production rate is found to be too slow.

§ 1. Introduction

The helium burning phase starts in the core of the red giant stage of stellar evolution after the exhaustion of hydrogen as the energy producing material. The first reaction that takes place in a helium core at $T \approx 10^8 \text{oK}$ is the triple alpha collisions forming C$^{12}$ in its 7.66 Mev excited state. Then subsequent captures of helium by C$^{12}$ produce O$^{16}$, and so on. Hayakawa et al.$^1$ calculated the reaction rates leading to the formation of C$^{12}$, O$^{16}$ and Ne$^{20}$ under the condition at temperature $\sim 10^8 \text{oK}$. The rates of formation of C$^{12}$ and Ne$^{20}$ were found to be larger. Nakagawa et al.$^2$ made detailed calculations on the helium capturing reactions. Many other authors$^3$, $^4$, $^5$ studied the fusion of helium as a mode of element synthesis in stars. The helium burning processes were found to be responsible for the synthesis of C$^{12}$, O$^{16}$, Ne$^{20}$, and perhaps Mg$^{24}$.

Recent experimental investigations and results thereof warrant a reinvestigation of the reaction rates during the helium burning phase of stellar evolution. The rate of production of Ne$^{20}$ was expected to be due to the 4.97 Mev excited state of Ne$^{20}$ whose spin-parity were supposed to be $2+$ . The formation of Ne$^{20}$ through O$^{16}$($\alpha$, $\gamma$)Ne$^{20}$ requires that the level should have either odd-spin, odd-parity or even-spin, even-parity. Experiments,$^5$, $^6$ however, showed that this level has spin-parity $2-$, and hence might not be formed by alpha-capturing reaction in O$^{16}$. There are other two levels in Ne$^{20}$ in the relevant energy regions$^5$, $^6$ (5.64 and 5.80 Mev levels) having odd-spin and odd-parity. Thus it is expected that these two levels will contribute to the resonance formation of Ne$^{20}$ in stellar interiors. It was suggested$^7$ that hydrogen from the envelope might be mixed into the expanding helium core in a globular cluster star at the tip of the giant branch. Considerable amounts of carbon cycle products would then take part in helium burning reactions. Neutrons produced through C$^{18}$($\alpha$, $n$)O$^{16}$, which become operative even at slightly lower...
temperature \((\approx 8 \times 10^7 \text{K})\), will soon be depleted through \(^{14}\text{N}(n, p)\)\(^{14}\text{C}\) reaction and enough neutrons will not be available for heavy element synthesis. To facilitate heavy element formation it is required that \(^{14}\text{N}\) should be used up by \(^{14}\text{N}(\alpha, \gamma)\)\(^{18}\text{F}\)\((\beta^+, \nu)\)\(^{18}\text{O}\) reaction.  

\[\text{§ 2. Calculations}\]

\(\text{Ne}^{20}\) production rates through the two resonance levels are calculated by the usual procedures outlined in the literature. The quantity \(\omega \Gamma_\gamma \Gamma_\alpha / \Gamma\) for the 5.64 (3\(\text{–}\)) and 5.80 (1\(\text{–}\)) Mev levels are 0.003 ev\(^{10}\) and \(\lesssim 0.15\) ev\(^{9}\), respectively. For the \(^{14}\text{N}(\alpha, \gamma)\)\(^{18}\text{F}\) resonant reaction through 4.651 Mev state of \(^{18}\text{F}\), the different parameters are taken from the work of Cameron\(^{10}\). \(\Gamma_\alpha\) is calculated to be \(4.0 \times 10^{-11}\) ev with the help of Wigner and Eisenbud’s dispersion relation for nuclear reactions\(^{11}\). \(3\alpha \rightarrow \text{C}^{12}\) rates are calculated with a slightly modified value of \(\Gamma_\gamma\) due to Alburger\(^{12}\) for the 7.66 Mev second excited state of \(^{12}\text{C}\). \(\Gamma_\gamma\) is taken to be \(2.5 \times 10^{-8}\) ev. The nonresonant rates of formation of \(\text{Ne}^{20}\) and \(\text{Mg}^{26}\) through \((\alpha, \gamma)\) reaction are also calculated by the method outlined by Cameron\(^{13}\) assuming that \(\Gamma_\gamma \ll \Gamma_\alpha \approx \Gamma\), \(\langle \sigma \rangle / \langle \sigma \rangle(\alpha, \gamma) = \Gamma_\gamma / \Gamma_\alpha \approx 0.01\). These reaction rates are shown in Fig. 1.

\[\langle \sigma \rangle = \frac{2\pi^2}{K_\alpha} \left( \frac{\omega \Gamma_\alpha \Gamma_\gamma}{\Gamma D} \right) \times 10^{24} \text{ barns}, \quad (1)\]

![Fig. 1. Helium burning mean lifetimes vs. temperatures (t is in year and temperature is in \(10^8\) K unit, \(px_0 = 10^5 \text{ g/cc}\)). (1) and (2) against \(\text{O}^{18} \rightarrow \text{Ne}^{20}\) give the mean lifetimes of this reaction for the 5.64 and 5.80 Mev levels respectively.](image)
which after simplifications (like $\Gamma_a \ll \Gamma_{\gamma} \approx \Gamma$ and $\Gamma_a = 2K_a P_{\alpha}^2$) reads

$$\langle \sigma \rangle = \frac{12\pi^3}{K_a} P_0 \langle r^3/D \rangle \times 10^{24} \text{ barns}, \quad (2)$$

for $\langle \omega \rangle = 3$, where $P_0$ is the barrier penetrability for s-wave alpha-particles and $\langle r^3/D \rangle$ is taken to be equal to ten-percent of the black-nucleus value ($= 2 \times 10^{-14} \text{cm}$). Knowing $\langle \sigma \rangle$, the reaction rates are calculated with the nonresonant rate formula. Figure 2 shows the reaction rates at higher temperatures ($3-6 \times 10^8 \text{K}$) for $\rho x_a = 10^4 \text{ g/c.c.}$.

§ 3. Discussions and conclusions

The helium burning time-scale and temperature are supposed to be $\sim 10^7 \text{ years}$ and $1-2 \times 10^8 \text{K}$ respectively. During this period negligible amount of O is converted into Ne due to helium burning. Thus it is expected that Ne is not synthesized in considerable amount during the helium burning stages. At higher temperatures, supposed to be prevalent in the core of late giants or pre-supernova stage of a star, the rates of formation of Ne and Mg are faster. However, the reaction rate of Ne ($\alpha, \gamma$)Mg is definitely an over-estimate at lower temperatures. But as helium is exhausted at lower temperatures, further helium burning reactions do not proceed unless a fresh supply of helium is available. At this stage, heavy-ion reactions such as C ($\alpha, \gamma$)Ne may provide a helium source; but it takes place at temperature of $\sim 6 \times 10^8 \text{K}$. Otherwise, the helium burning reactions (Fig. 2) may be envisaged to be taking place at the supernova shell sources where the temperature is considerably higher. N ($\alpha, \gamma$) rate is found to be faster than that of $3\alpha \rightarrow C$ (Fig. 1). Therefore, it may be expected that this reaction would compete with $3\alpha$ reaction as a source of energy generation at the temperature and density under consideration. Ne and Mg formation rates are found to be quite low.
References

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