Enhancement of ^{12}C production due to proton and neutron scattering

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The 7.653 MeV state of the ^{12}C, also known as the Hoyle state, plays a key role in the phase of helium burning of stars. This state is involved in the resonant α capture by ^{8}Be, which is also known as the 3-α reaction. The total width of the Hoyle state and partial widths for total electromagnetic decay width, including pair decay, govern the 3-α reaction rate. Recent studies [1, 2] have been conducted to determine whether and how the total and partial widths of the Hoyle state are modified in high-density environments as a result of interactions with neutrons and protons, and how the modified partial widths can improve the 3-α reaction rate. The radiative width Γ_{rad} still determines ^{12}C production at standard nuclear pressure. However, in cases where high temperature and high density of protons or neutrons are available, the enhancement can be significant. The enhancement due to proton and neutron rich environments has been shown in [2, 3], which shows a significant enhancement in reaction rate where proton or neutron density reaches 10^6 gm/cm^3 and temperature reaches 10^9 kelvin or so. In explosive environments, for instance, supernova type II explosions where the temperature can reach the range of 100 GK (T9), the involvement of higher excited energy ^{12}C states is expected [5]. This is the case of the 3^- state at 9.64 MeV whose enhancement over radiative decay we have calculated as reported below.

Several enhancement processes have been studied theoretically in the past. Truran *et al.* [6] considered nuclear-induced processes. Following these theoretical estimates, experimental studies of inelastic proton [3] scattering from the ground state of ^{12}C to the Hoyle state were carried out. A similar investigation was also done for neutrons [4]. The corresponding enhancements were calculated from the inverse rates that correspond to these cross sections. These studies indicated that the enhancements could be significant at the temperatures and densities encountered in supernovae. However, all these studies were focused on the Hoyle state and for the first time we are reporting the enhancement of the 9.64 MeV state decay. There are no reliable measurements of cross sections for neutron inelastic scattering to the 9.64 MeV state. Such cross sections are not easily measurable and must be obtained from theoretical estimates. For this purpose, we have employed the statistical model based Hauser-Feshbach (HF) reaction code TALYS (version 1.96) [7]. The default optical model parameters for protons and neutrons have been used.

The ratio of the radiative lifetime to the particle-induced lifetime (R) is given by [2].

$$R = k_p \rho_p T_9^{-\frac{3}{2}} C_{spin} exp(-11.605(Q - E_{th})/T_9) \times \int_0^{\infty} \sigma_{pp'}(E + E_{th}) exp(-11.605E/T_9) dE \quad (1)$$

The values of k_p and ρ_p are 2.115×10^{-7}, and 10^6 gm/cm^3, respectively. For neutron induced de-excitation $\sigma_{nn'}$ is used and the corresponding multiplying constants k_n and ρ_n are 2.113×10^{-7} and 10^6 gm/cm^3 respectively. C_{spin} is the spin factor given by $C_{spin} = \frac{2I+1}{2I'+1}$, where I and I' are the spins of the initial and final states for forward excitation of ^{12}C, Q is the Q-value for the given inelastic scattering, E is the c.m. energy above the threshold, and E_{th} is the 3-α threshold energy (7.653 MeV).

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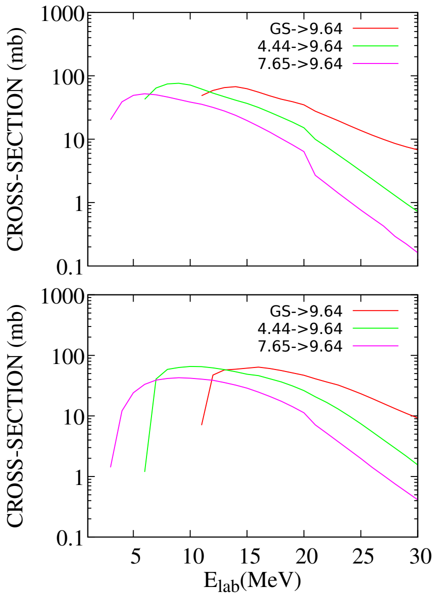

FIG. 1: Inelastic scattering cross sections for neutrons (top panel) and protons (bottom panel)

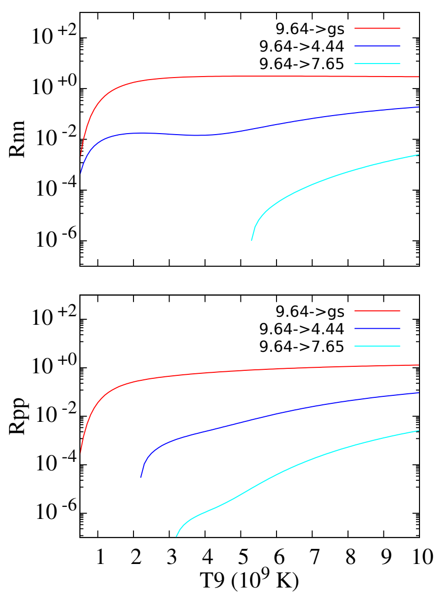

FIG. 2: Ratios of the rate induced by the indicated transitions to the radiative decay rate

The TALYS produced cross-sections for both the nn′ and pp′ reactions are shown in Fig. 1.

The ratio of the radiative lifetime to the particle-induced lifetime can be found out by numerically integrating Eq. 1. Rnn, Rpp are the ratios for nn′ and pp′ processes, respectively and are shown in Fig. 2.

It is observed that, the enhancement due to upscattering can be appreciable when the steller temperature reaches ∼10 GK. This will lead to additional stable ^{12}C production in extreme stellar environments.

Using the TALYS statiscal model code, we have evaluated the cross-sections for neutron and proton inelastic scattering to the 9.64 MeV state from ground state, first excited state (4.44 MeV), and the Hoyle state (7.65 MeV). Using the principle of detailed balance, these cross-sections were used to derive the particle induced de-excitation rate from the 9.64 MeV state, which was found to be appreciable for neutrons and protons in stellar environments reaching 10GK or higher. These kinds of calculations can be useful for studying neucleosynthesis in extreme regions of the universe.

References

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