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Impact of $^{12}C+^{12}C$ Reaction Rate Uncertainties on Carbon Burning in Massive Stars

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ABSTRACT

The fusion reaction $^{12}C+^{12}C$ is a key driver of the carbon-burning phase in massive stars, yet its reaction rate remains poorly constrained because experimental cross-section data at sub-Coulomb energies are extremely limited. To improve these constraints, we calculated theoretical fusion cross sections using multiple formulations of the proximity nuclear potential and evaluated the corresponding thermonuclear reaction rates. Our results show that the predicted rates vary significantly across different potentials, demonstrating the strong sensitivity of carbon-fusion models to the choice of nuclear interaction. These results quantify the nuclear-physics contribution to reaction-rate uncertainties and provide improved theoretical constraints for modelling the thermal structure and evolution of massive stars.

Keyword: nuclear astrophysics, stellar evolution, carbon burning

INTRODUCTION

The fusion of $^{12}C+^{12}C$ is a key reaction governing the carbon-burning phase of massive stars. However, astrophysical energies (1.5–3 MeV) lie deep below the Coulomb barrier, where the fusion cross section drops to 10^{-12} - 10^{-9} barn, making direct measurements extremely challenging. Because of these uncertainties, stellar evolution calculations commonly rely on Caughlan & Fowler (1988) [1] (CF88 hereafter) reaction rates, which are based on a semi-empirical extrapolation from high-energy data. Recent analyses, such as Seong et al. (2024) [2], show that updated fits to S-factor data produce reaction rates 0.35–0.5 less than CF88 rates in the temperature range 0.5–1 GK, altering the thermal structure and neutrino cooling of massive stars. In this work, the $^{12}C+^{12}C$ fusion cross section computed using a large set of nuclear proximity potentials, identify the best-performing models through reduced chi-square comparison with experimental data, and compute the resulting astrophysical S-factors and thermonuclear reaction rates.

METHODOLOGY

1. Nuclear Interaction Potential

The total ion–ion interaction is modeled as

$$V(R) = V_N(R) + V_C(R)$$

where V_c is the Coulomb potential while V_N is taken from 26 different proximity potentials [3], including:

- Prox77 (s1–s13 variants)
- Prox00 / Prox00DP / Prox2010 / Prox88 / Prox81
- BW91, Bass73/77/80, Ngo80, Denisov DP, AW95, Guo2013.

These models differ in their description of the nuclear surface energy coefficient, curvature corrections, and density dependence.

2. Fusion Cross Section Calculation

The $^{12}C+^{12}C$ fusion cross section is calculated assuming s-wave (l=0) barrier penetration:

$$\sigma(E) = \frac{\pi\hbar^2}{2\mu E} T_0(E),$$

where μ is the reduced mass and $T_0(E)$ is the transmission probability through the barrier. The transmission coefficient is obtained with the WKB approximation:

$$T_0(E) = \left[1 + \exp\left(2\int_{R_1}^{R_2} k(R)\,dR\right)\right]^{-1}, \quad k(R) = \sqrt{\frac{2\mu}{\hbar^2}[V(R) - E]}$$

where R_1 and R_2 are the classical turning points defined by V(R)=E.

3. Comparison With Experimental Data

Experimental cross sections from direct measurements [4-11] are interpolated to obtain:

- $\sigma(E)$ (barn),
- $S(E) = \sigma(E)E\,e^{2\pi\eta}$ (keV barn).

The goodness of fit is quantified using the log-scale reduced chi-square:

$$\chi^2_\nu = \frac{1}{N-p}\sum_i \left[\log\sigma_{\rm calc}(E_i) - \log\sigma_{\rm exp}(E_i)\right]^2$$

4. Reaction Rate Calculation

Thermonuclear rate:

$$N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\pi\mu}}\frac{1}{(kT)^{3/2}}\int_0^\infty \sigma(E)\,E\,e^{-E/kT}\,dE.$$

Rates are evaluated for temperatures T_9 = 0.3 - 1.5 GK and normalized to CF88 and Seong 2024 for comparison.

RESULT & DISCUSSION

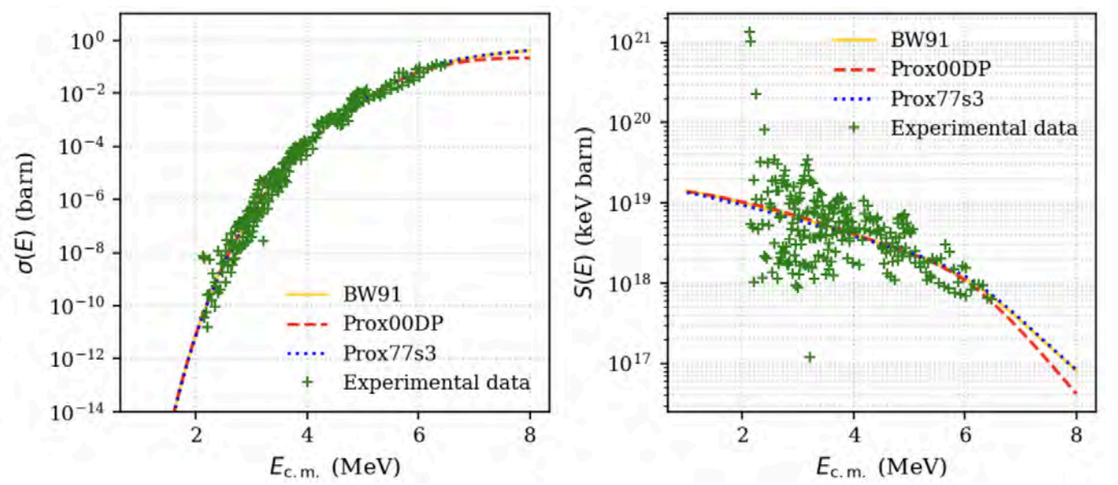


Figure 1. Calculated fusion cross section (left) and astrophysical S-factor (right) for the $^{12}C+^{12}C$ reaction using the three best-fit proximity potentials (BW91, Prox00DP, Prox77s3). Theoretical results are compared with available experimental data.

Calculations using 26 proximity potentials show that three models: BW91, Prox00DP, and Prox77s3–reproduce experimental $^{12}C+^{12}C$ cross sections with good accuracy. These potentials match the observed rise near the Coulomb barrier and give consistent astrophysical S-factors, resulting in the lowest reduced chi-square values.

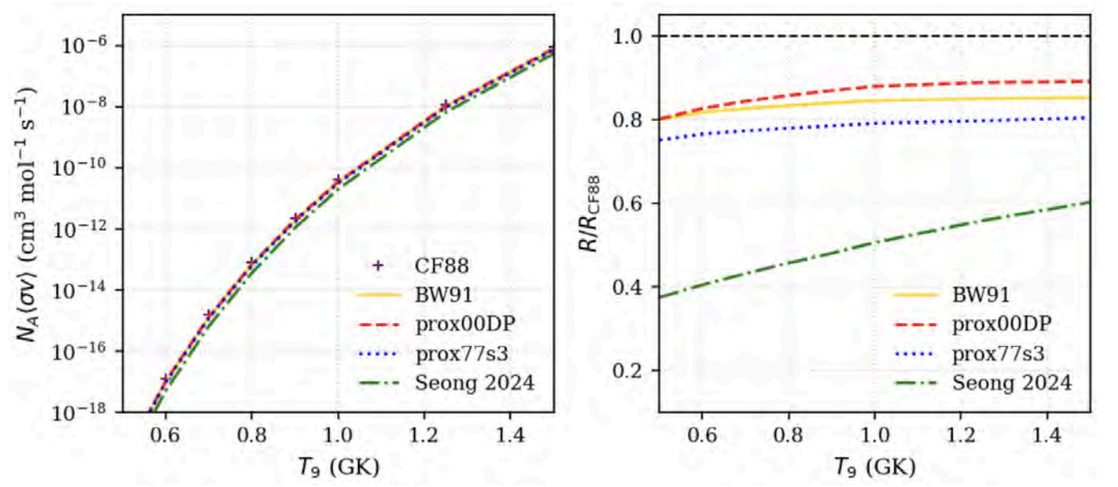


Figure 2. Thermonuclear reaction rates (left) and ratio to the CF88 standard rate (right) for the $^{12}C+^{12}C$ reaction. Rates computed using BW91, Prox00DP, and Prox77s3 are shown alongside CF88 and Seong et al. (2024).

The reaction rates derived from these three potentials are 15–25% lower than CF88 in the carbon-burning temperature range T9=0.5-1.2 GK. This reduction is consistent with updated evaluations such as Seong et al. (2024) [2] and implies that massive-star cores may ignite carbon at slightly higher temperatures and experience stronger neutrino cooling. Overall, the strong dependence of the reaction rate on the chosen nuclear potential highlights the importance of improving low-energy fusion constraints. The three best-performing potentials provide more reliable theoretical inputs for modelling carbon burning in massive stars.

CONCLUSION

This study shows that the $^{12}C+^{12}C$ reaction rate is highly sensitive to the choice of nuclear potential. Among 26 proximity potentials tested, only BW91, Prox00DP, and Prox77s3 closely reproduce experimental cross sections and provide consistent predictions for the astrophysical S-factor. The reaction rates obtained from these models are lower than CF88 in the carbon-burning temperature range, suggesting that massive-star cores may ignite carbon at higher temperatures and experience increased neutrino cooling. These results highlight the need for improved low-energy measurements and provide more reliable theoretical inputs for modelling the late stages of massive-star evolution.

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