How well do we understand the reaction rate of C burning?

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Abstract. Carbon burning plays a crucial role in stellar evolution, where this reaction is an important route to the production of heavier elements. A particle-γ coincidence technique that minimizes the backgrounds to which this reaction is subject and provides reliable cross sections has been used at the Argonne National Laboratory to measure fusion cross-sections at deep sub-barrier energies in the 12C+12C system. The corresponding excitation function has been extracted down to a cross section of about 6 nb. This indicates the existence of a broad S-factor maximum for this system. Experimental results are presented and discussed.

1 Introduction

Reaction rates for C burning are essential ingredients to understand the production of chemical elements heavier than carbon as well as the evolution of massive stars. Carbon burning processes determine whether a star will join to the heavy-ion burning branches following hydrogen and helium burning and if white dwarfs will evolve into type Ia supernovae. It is thus of very high importance to know the 12C+12C fusion cross section with good accuracy from the Coulomb barrier (CB) down to the Gamow window which is centered around $E_c = 1.5 ± 0.3$ MeV at a temperature of $T = 5 \times 10^8$ K [1]. In a stellar environments, C burning occurs essentially via the 12C+12C fusion reaction. The exit channels for this reaction are: 12C(12C,α)20Ne, 12C(12C,p)23Na and 12C(12C,n)23Mg. The associated Q-values are 4.62 MeV, 2.24 MeV and -2.62 MeV MeV respectively. The 23Mg channel with negative Q-value is essentially closed at low sub-barrier energies.

One of the most striking results obtained in the early studies of heavy-ion collisions is the observation of resonant structures in the reaction cross-sections: i.e. elastic, inelastic and fusion channels of some light heavy-ion systems. These structures were found especially strong in the fusion cross section of the 12C+12C system at energies above the CB down to sub barrier energies. These resonances have often been attributed to 12C-12C molecular configurations of the 24Mg compound nucleus, and their strength related to the number of open channels in the reaction which is minimal for this system at the CB [2]. The possible persistence of these resonances at astrophysical energies is still a debated question. For example, the resonance phenomena in 12C+12C have been explained through the impact on the cross section of the relatively large spacings and(602,892),(904,912)
20Ne and 23Na. It should be noted that at the lowest investigated energies, the error bars are large and large discrepancies appear between the different measurements. Interestingly enough, the different extrapolations based on different potentials differ from more than 2 orders of magnitude in the Gamow region. The ubiquitous contamination of helium and deuterium in the target can indeed lead to severe background at low energies for both techniques. Moreover, measurements based on γ-ray detection are subject to room and cosmic γ backgrounds. To suppress these backgrounds, a new technique has been developed at the Argonne National Laboratory recently, based on γ-particle coincidences. Details about the technique as well as spectra describing the drastic suppression of background are given in Ref. [11]. This method was used in the present work.

3 Results and discussion

Figure 3 shows 12C+12C S factors as a function of E\textsubscript{c.m.} measured in the present work in the type IA supernova Gamow energy region (indicated by the yellow region on the figure) together with the most recent results for the same system [12]. The present data, which lowest point corresponds to a cross section of 6 nb, is in fairly good agreement with this measurement but shows smaller error bars. It should be noted that at the lowest measured energies, the data seem to indicate a decreasing S factor, which would be in agreement with the Jiang extrapolation.
For $^{12}$C+$^{12}$C, inside Gammasphere chamber

- S1: 122.0-141.3 degrees, $d\Omega = 12.6\%$ of $4\pi$, DSSD_S1
- S2: 146.0-169.7 degrees, $d\Omega = 7.8\%$ of $4\pi$, DSSD_S2
- S3: 17.7-32.6 degrees, $d\Omega = 5.5\%$ of $4\pi$, DSSD_S1

**Figure 2.** Schematic view of the target chamber showing the 3 annular DSSDs, the Si monitors and the Faraday cup.

[15]. Extrapolations predicting an increasing S factor or a slight decrease at low energies are based on standard potentials and use the sudden model or coupled-channel approach whereas the Jiang extrapolation takes into account the fusion hindrance phenomenon. This phenomenon was introduced by Jiang et al. fifteen years ago in fusion reactions of medium-mass systems, measured below the 0.1 mb regime [17]. Indeed, at low energies, the fusion cross sections are smaller than predicted by coupled-channel calculations using standard Woods-Saxon potentials. Several theoretical descriptions were proposed for this phenomenon: i. a consequence of the saturation properties of the nuclear matter introduced in calculations using a double-folding potential + repulsive core [18], ii. the effects of a 2 steps process involving the capture in a 2 body potential pocket and then the penetration of a one body potential to reach a compound nucleus state [19], iii. Effects of the Pauli repulsion during the fusion process introduced recently by C. Simenel et al. and presented at this Fusion 17 conference.

Two representations have been used to discuss signatures of fusion hindrance, the logarithmic derivative of the energy-weighted cross section and the S factor. In the latter, often used for systems of astrophysics relevance, a maximum and a decrease of S when going down in energy is taken as a signature of fusion hindrance. Interestingly enough, the present data seem to be in agreement with the presence of a broad S factor maximum. This phenomenon may have dramatic consequences on the reaction rate of C burning and the subsequent nucleosynthesis of heavier chemical elements in massive stars.

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**References**

**Figure 3.** Red points: $^{12}\text{C} + ^{12}\text{C}$ S factors measured in this work. Green circles: results from ref. [12]. The blue, black, red and green dashed lines correspond to extrapolations from Fowler [13], Gasques [14], Jiang [15] and Esbensen [16].

