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A new $^{12}C+^{12}C$ reaction rate: Impact on stellar evolution

E. Monpribat[1,*], *A.* Choplin[2], *S.* Martinet[2], *S.* Courtin[1,3], *M.* Heine[1], *P.* Adsley[4,5], *D.* Curien[1], *T.* Dumont[1], *S.* Ekström[6], *D.G.* Jenkins[3,7], *M.* Moukaddam[1], *J.* Nippert[1], *S.* Tsiatsiou[6], and *G.* Meynet[6]

[1]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[2]Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, 1050, Brussels, Belgium
[3]University of Strasbourg Institute of Advanced Studies (USIAS), Strasbourg, France
[4]Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
[5]Department of Physics & Astronomy, Texas A&M University, College Station, Texas 77843, USA
[6]Department of astronomy, University of Geneva, chemin Pegasi 51, 1290 Versoix, Switzerland
[7]Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom

Abstract. Among the reactions driving stellar evolution during carbon burning, ^{12}C + ^{12}C fusion provides the key ingredients. This system reveals many resonances, but also regions with suppressed fusion cross-sections. The reaction was recently measured by the STELLA collaboration utilizing the gamma-particle coincidence technique for precise cross-section measurements reaching down to the Gamow window of massive stars. From the experimental data, reaction rates were determined by approximating a hindrance parametrization and by adding on top a resonance at the lowest measured energy. The impact of these reaction rates on the evolution of massive stars was explored with models of 12 and 25 $M_{\odot}$ using the stellar evolution code GENEC, and a detailed study of the resulting nucleosynthesis with a 1454 elements network was performed. The sensitivity of the STELLA experimental cross-sections on the temperature range for C-burning for the stellar models studied were presented. The final abundances and their impacts on stellar evolution were discussed.

1 Introduction

The origin of the chemical elements, the nucleosynthesis, has always been an important and fundamental subject in physics. By changing the internal composition of stars, nuclear physics plays a key role in this process. That is deeply linked to stellar evolution, to the different types of stars, and their combustion phases. Among these, the carbon-burning phase is the most interesting one for the STELLA collaboration. Indeed, it is a key phase of the stellar evolution–that only massive stars enter and it has an important role in type 1a supernova–during which the ^{12}C + ^{12}C fusion reaction takes place. The latter set the conditions of subsequent important nuclear mechanisms, like fusion of heavy-ions or the neutron seed generation.

During the past decades, numerous experiments have been performed, aiming at the direct measurement of the carbon fusion cross section at sub-barrier energies. These efforts revealed

*e-mail: emma.monpribat@iphc.cnrs.fr

the presence of resonances, possibly due to molecular ^{12}C configurations of the ^{24}Mg nucleus [1]. The most recent results suggest that fusion hindrance, a behaviour observed in a large number of heavier systems [2], is present in the ^{12}C+^{12}C fusion reaction [3–5].

However, at astrophysical energy, *i.e.* at deep sub-barrier energy, in the Gamow Window, experimental results have large uncertainties, and the different theoretical models, like fusion hindrance and the CF88 model – the one currently used in astrophysics [6]– diverge with orders of magnitudes between them. The lack of precise data is caused by tremendous experimental challenges. Indeed, the small cross section associated to this system, around picobarn, requires extended beamtime of months and at sufficiently high intensity. Furthermore, spectra are dominated by background that comes from contaminant reactions, natural radioactivity, and cosmic rays. As a solution, the coincidence method for the ^{12}C+^{12}C fusion reaction has been set-up for reliable measurements deep sub-barrier energies [7].

2 Direct measurements with STELLA UK-FATIMA

By using the coincidence method, the STELLA station is a straight answer to the experimental challenges of the ^{12}C+^{12}C cross section in direct measurements [8]. This method is based on the simultaneous detection of the emitted light particles, here an alpha or a proton, and the associated gamma rays of de-excitation of the daughter nucleus.

The $C^{2+,3+}$ beam required by the ^{12}C + ^{12}C cross section measurement is delivered by the Andromède facility at IJCLab, in Orsay (France) with an intensity up to 6 pμA. In order to allow the heat dissipation and prevent target deterioration, a system of rotating targets has been developed. The large thin targets are made of carbon graphite, with a diameter of about 5 cm and a thickness of 20 to 70 μg/cm^2, and can spin with up to 1000 rpm. Carbon buildup on the target is prevented by the high vacuum (10^{-8} mbar) of the reaction chamber. The detection of light particles is done by two annular charged-particle silicon detectors, with high granularity and nanoseconds timing (trigger). The gamma rays are detected by the $LaBr_3$(Ce) scintillators from the UK-FATIMA (FAst TIMing Array) collaboration.

3 Reaction rates and STELLA sensitivity

In [9], two different fusion scenarios for the excitation functions of the ^{12}C+^{12}C fusion reaction have been studied, based on direct measurement performed with the STELLA experiment [4] and following a χ^2 analysis of the data: the first one employs the so-called fusion hindrance (Hin model) described in [7], and the other is composed of fusion hindrance with a resonance at $E_{\rm rel}$ = 2.14 MeV proposed by [10] (HinRes model). The parameters of the fusion hindrance were kept free during the fits of the excitation functions, made simultaneously in both exit channels, *i.e.* for alpha and proton emission. The obtained fitting parameters are consistent with the ones suggested by [3] from a systematic phenomenological study. We observe in particular a good compatibility of the HinRes model and the STELLA measurements.

The reaction rates have been determined for both fusion scenarios. They are generally lower than the one currently used during the last decades in astrophysical simulations, determined in [6] (CF88 model). The resonance has a strong impact on the reaction rate, where it significantly increases the latter to a level comparable with the CF88 model rate for a temperature around T = 0.85 GK (see Fig. 2 in [9]).

The STELLA sensitivity corresponds to the temperature range where the reaction rates are determined based only on the interpolation of the excitation function proposed by the STELLA collaboration [9]. The temperature range in which the reaction rate is probed by the STELLA experiment was determined by interpreting the relative energy, at which the $^{12}C+^{12}C$ cross sections were measured, as a temperature. The lowest energy measured is $E_{rel} = 2.03$ MeV. By using the Gamow window definition and with the approximation proposed in [11], the STELLA sensitivity reached a minimal temperature $T = 0.6$ GK at 1σ uncertainty width. In this temperature range, the relative uncertainties are around 15% and 30% for the Hin and HinRes models, respectively.

4 Impact on stellar evolution

In order to study the impact of the presented reaction rates, hydrodynamics and nucleosynthesis simulations were carried out using the Geneva stellar evolution code GENEC [12] for two stellar models with $12\,M_\odot$ and $25\,M_\odot$ at solar initial metallicity and without rotation. The evolution was followed until the end of the carbon burning phase, where the fusion temperature for the Hin model is 10% higher than for HinRes model, which reduces the carbon burning lifetime by a factor of two. We explain this by the substantially lower rate of the former model as compared to the latter with lower heat output, thus succumbing the gravitation pressure of the star resulting in contraction and higher temperature for carbon burning. The counter intuitive finding is that lower reaction rates result in higher effective temperatures [13] from permanent readjustment of the star.

Another finding is clearly depicted in the Kippenhahn diagram at the end of core carbon burning of the $25\,M_\odot$ star (see Fig. 4 in [9]) where both reaction rate models evolve in the same way, with the exception that the convective pocket of Hin model extends much further as compared to HinRes model. This is due to the higher temperature of the former with a stronger temperature gradient. Finally, the cooling of the star by neutrino emission (see Fig. 7 in [9]) is affected by the variation in carbon burning lifetimes which likely results in different dynamics during the core collapse and has an impact on the remnant nature.

The $25\,M_\odot$ model was further investigated with the complementary One-Layer code [14] to generate a single layer model of a star, but employing an extended nuclear reaction network, that takes into account more than one thousand isotopes and reactions in between. The temperature trajectory was adapted to the one of the CF88 model. In Fig. 9 in [9], minor variations of the final abundances obtained with CF88, Hin and HinRes models are visible for sodium, aluminium and phosphorus, and some heavier elements. These variations may eventually have an impact on the stellar evolution in the following phases, which would require further investigation to clarify.

We note that in the GENEC simulations, the results of CF88 and HinRes models are very similar as can be expected from comparable reaction rates at the temperatures during carbon burning (see Fig. 2 in [9]). In contrary, the abundances from the One-Layer code of CF88 and Hin models are closer, presenting a somewhat swapped situation. As the CF88 and HinRes rates are comparable with identical temperature trajectories during this run, the reasoning might be the branching with α- and proton-emission, that was adapted to the experimental findings given in Tab. 1 in [9] in the One-Layer code, but could only be accounted for indirectly in the GENEC package [15]. Indeed, the branching during carbon burning from the One-Layer simulation given in Fig. 1, indicates a situation where the CF88 and Hin models are closer to each other than HinRes model (branching of 0.65/0.35 [16]). The latter is given by the ratio of strengths of the resonance at $E = 2.14$ MeV in the carbon-carbon system where α emission is dominating. However, the results need to be taken with care as the temperature trajectories need to be adapted to the actual hydrodynamics constraints in CF88, Hin and HinRes models separately and different paths of nucleosynthesis might open with more robust assumptions. In conclusion, such a finding can demonstrate the sensitivity to resonances in

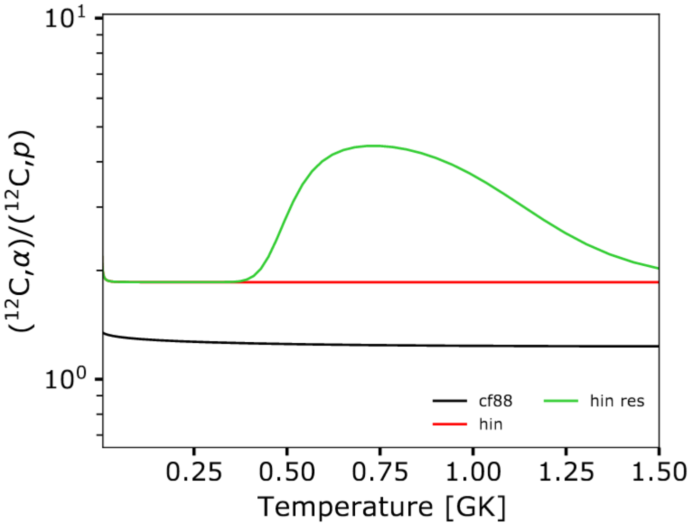

Figure 1. Ratio of the reaction channels in the valid temperature range for carbon burning for CF88, the Hin and HinRes models in the One-Layer code.

the branching of reaction rates for key reactions during nucleosynthesis calculations where straight factorizing of entire energy regions might yield only approximate results.

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