SF2A 2023
M. N'Diaye, A. Siebert, N. Lagarde, O. Venot, K. Baillié, M. Béthermin, E. Lagadec, J. Malzac, J. Richard (eds)

A NEW 12C+12C REACTION RATE FROM THE STELLA COLLABORATION: HOW TO DETERMINE ASTROPHYSICAL PARAMETERS WITH NUCLEAR EXPERIMENTS?

E. Monpribat[1], T. Dumont[1], A. Bonhomme[1], M. Heine[1], J. Nippert[1] and S. Courtin[1,2]

Abstract. Among the nuclear reactions driving stellar evolution, ^{12}C + ^{12}C fusion is the key ingredients to describe the carbon burning. This system is known to show many resonances, and the low energy region might be affected by fusion hindrance. The reaction was recently measured by the STELLA collaboration making use of the gamma-particle coincidence technique for measurement of cross-sections with unprecedent accuracy, reaching energies of astrophysical interest. Reaction rates were extracted from experimental data by approximating a hindrance trend, or by adding on top a resonance at the lowest measured energy. The impact of these new rates on the evolution of massive stars was explored using the stellar evolution code GENEC, and a more detailed study of the nucleosynthesis with a large isotopes network was performed. The sensitivity of the STELLA experiment on the temperature range for C- burning has been thoroughly investigated, showing that the reaction rates determined by this experience are ideally suited for astrophysical studies and simulations.

Keywords: Nuclear reaction, Nucleosynthesis, Stars: evolution

1 Introduction

The origin of chemical elements, known as nucleosynthesis, has always been a significant and fundamental subject in modern physics. Nuclear physics plays a crucial role in this process as it governs composition of stars. These processes are closely tied to stellar evolution, the various types of stars, and the combustion phase.

Among these phases, the one of utmost interest for the STELLA collaboration is the carbon-burning phase. It is of a pivotal importance in stellar evolution, occurring only in massive stars and playing a significant role in type Ia supernovae. It is during this phase that the fusion reaction between ^{12}C and ^{12}C takes place. This reaction leads to several nuclear processes, such as heavy-ion fusion and the generation of neutron seeds.

Over the past few decades, numerous experiments have been conducted with the aim of directly measuring the carbon fusion cross-section at sub-barrier energies (see e.g. Patterson et al. 1969; High & Čujec 1977; Becker et al. 1981; Aguilera et al. 2006; Barrón-Palos et al. 2006; Spillane et al. 2007; Bucher et al. 2015). These experimental measurements have revealed the presence of resonances in the energy range well above and below the Coulomb barrier, possibly associated to molecular configurations of ^{12}C within the ^{24}Mg nucleus (Jenkins & Courtin 2015). The most recent results also suggest the occurrence of fusion hindrance (Fruet et al. 2020; Tan et al. 2020), a behavior at deep sub-barrier energy, observed in many heavier systems (Jiang et al. 2002).

However, at astrophysical energies, specifically deep sub-barrier energies within the Gamow window, experimental results exhibit substantial uncertainties. Different theoretical models, such as fusion hindrance (Jiang et al. 2007) and the CF88 model – commonly used in astrophysics (Caughlan & Fowler 1988) –, show orders of magnitude discrepancy. The lack of precise data is primarily due to the huge experimental challenges imposed by this system. Tiny cross-sections of the picobarn range necessitates extended beam exposure at high intensity, and spectra are often dominated by background noise originating from contaminant reactions, natural radioactivity, and cosmic rays. To address these challenges, a coincidence method for the ^{12}C + ^{12}C fusion reaction has been developed for deep sub-barrier energies (Jiang et al. 2012).

[1] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[2] University of Strasbourg, Institut of Advanced Studies (USIAS), Strasbourg, France

2 Measurements with the STELLA UK-FATIMA Experiment

The STELLA station addresses the formidable experimental challenges associated with direct measurements of the ^{12}C + ^{12}C cross-section through the use of a coincidence method combined with nano-seconds timing gates (Heine et al. 2018). This approach relies on the simultaneous detection of emitted light particles, specifically alpha particles or protons, and the associated gamma rays emitted during de-excitation.

To generate the $C^{2+,3+}$ beam required for the ^{12}C + ^{12}C cross-section measurement, the Andromède facility at IJCLab, located in Orsay, France, is used, able to deliver a beam with an intensity of up to 6 pμA. To facilitate heat dissipation and prevent target deterioration, a rotating system has been implemented. These targets are composed of carbon graphite, with a diameter of 5 cm and a thickness ranging from 20 to 70 μg/cm^2, spinning at a maximum rate up to 1000 rpm, depending of the heat input from the intense beam. Carbon buildup on these targets is monitored and effectively mitigated due to the high vacuum conditions (10^{-8} mbar) maintained within the reaction chamber.

The detection of light particles is achieved through the use of two annular charged-particle silicon detectors, characterized by high granularity and nanosecond triggering capability. Gamma rays, on the other hand, are detected by $LaBr_3$(Ce) scintillators, which are part of the UK-FATIMA (FAst TIMing Array) collaboration's equipment.

3 Reaction rate

In Monpribat et al. (2022), two distinct fusion scenarios concerning the excitation functions of the ^{12}C+^{12}C fusion reaction have been investigated. These scenarios were derived from direct measurements conducted as part of the STELLA experiment (Fruet et al. 2020). The first scenario follows the fusion hindrance model (referred to as Hin model), as described in Jiang et al. (2007), while the second scenario combines fusion hindrance with an additional resonance at E_{cdm} = 2.14 MeV, proposed by Spillane et al. (2007) (referred to as HinRes model). During the fitting procedure, parameters related to the fusion hindrance were not constraint, and these fits were performed simultaneously in both exit channels, assuming a common underlying explanation for hindrance (Jiang et al. 2013). The obtained fitting parameters align with previous findings (Jiang et al. 2018), and there is notable agreement between the resonance and the experimental data collected by STELLA.

The study also determined reaction rates for each of these fusion scenarios. These rates are generally lower than the rates that have been used in astrophysical simulations over the past few decades, as determined by the CF88 model (Caughlan & Fowler 1988). The resonance impacts the reaction rate, significantly increasing it to a level comparable with the CF88 model rate at a temperature of approximately T = 0.85 GK, right in the astrophysics region of interest of massive stars according to Hin and HinRes predictions (Monpribat et al. 2022).

Furthermore, the STELLA sensitivity was defined in Monpribat et al. (2022). This sensitivity corresponds to the temperature range in which reaction rates are determined solely by interpolating the excitation functions provided by the STELLA collaboration. By considering the energy at which the cross sections are measured and employing the Gamow window definition, along with an approximation proposed in Illiadis (2015), the STELLA sensitivity was found to reach a minimum temperature of T = 0.6 GK at 1σ uncertainties. In this temperature range, relative uncertainties are approximately 15% and 30% for the Hin and HinRes models, respectively.

4 Impact on stellar evolution

To investigate the effects of the presented reaction rates, hydrodynamics and nucleosynthesis simulations were conducted using the GENeva stellar Evolution Code GENEC (Eggenberger et al. 2008). Two stellar models were considered, one with a mass of 12 $M_\odot$ and the other with 25 $M_\odot$, both starting with initial solar metallicity and without accounting for rotation. The evolution of these models was tracked until the end of the carbon burning phase.

During this phase, it is observed that the fusion temperature for the 12 $M_\odot$ model (referred to as Hin) was approximately 10% higher than for the 25 $M_\odot$ model (referred to as HinRes), resulting in shorter carbon burning lifetime by a factor of two. This is attributed to the significantly lower reaction rate in the Hin model, which led to lower heat output. Consequently, the star undergoes contraction and eventually reaches higher temperature for carbon burning. This seemingly counter-intuitive finding indicates that lower reaction rates will cause higher core temperatures (see also Pignatari et al. 2013), as the star continuously adjusts itself, within hydrostatic equilibriuum.

The Kippenhahn diagram shows at the culmination of the core carbon burning phase in the 25 $M_\odot$ star (as depicted in Fig.4 in Monpribat et al. (2022)). Both reaction rate models exhibit similar evolutionary trends, except for the fact that the convective region in the Hin model extends much farther compared to HinRes. This difference is attributed to the higher temperature in the former case, resulting in a stronger temperature gradient and dynamic behavior.

Furthemore, the cooling of the star due to neutrino emission (as shown in Fig.7 in Monpribat et al. (2022)) is influenced by variations in carbon burning lifetime. This, in turn, will leave repercussions on the dynamics during core collapse and ultimately impacts the nature of the stellar remnant.

The 25 $M_\odot$ model was investigate using the complementary "One-Layer" nucleosynthesis code by Choplin et al. (2016). This code was used to create a single-layer model of the star, but with an expanded nuclear reaction network that accounts for more than one thousand isotopes and their reactions. The temperature and density trajectory in this model was adjusted to match that of the CF88 model.

In Figure 9 of Monpribat et al. (2022), minor difference in the final abundances were observed when comparing the CF88, Hin, and HinRes models for elements such as sodium, aluminum, phosphorus, and some heavier elements. These variations could potentially have implications for the subsequent phases of stellar evolution, as s-process, although a more in-depth investigation would be required to fully understand their effects and significance.

It is worth noting that in the GENEC simulations, the results obtained with the CF88 and HinRes models are very similar, which is expected given their comparable reaction rates at the temperatures during carbon burning (as shown in Figure 2 of Monpribat et al. (2022)). However, there is a discrepancy in the abundances derived from the One-Layer code for CF88 and Hin, with somewhat different pattern. This could be attributed to the branching ratios involving α- and proton-emission, which were adjusted in the One-Layer code based on experimental data presented in Table 1 of Monpribat et al. (2022), but could only be indirectly accounted for in the GENEC package (Hirschi 2004). Indeed, the branching ratios during carbon burning, as illustrated in Figure 1 of Monpribat et al. (2023), indicate a situation where CF88 and Hin (with a ratio of 0.65/0.35, Bennett et al. (2012)) are closer to each other than for HinRes. The latter is caused by the ratio of strengths of the resonance at $E = 2.14$ MeV in the carbon-carbon system, where α emission dominates. However, it is important to exercise caution when interpreting these results, as the temperature trajectories must be tailored to the specific hydrodynamics constraints of CF88, Hin, and HinRes individually, where different nucleosynthesis pathways may open up with more realistic assumptions.

In conclusion, these results emphazise the sensitivity of nucleosynthesis calculations to resonance branching in reaction rates, particularly for key reactions. It highlights that straightforward factorization of entire energy region may only provide general results, and a more detailed consideration of branching ratios may be necessary for a comprehensive understanding of nucleosynthesis process.

5 Conclusions

Crucial parameters used in stellar simulation models, like reaction rates, are established through values derived from nuclear physics, particularly from experiments conducted under conditions relevant to stellar physics. Achieving these conditions represents a significant challenge, leading to the development of experimental systems dedicated to such measurements. The STELLA experiment has contributed to the determination of new reaction rates for the $^{12}C + ^{12}C$ reaction, considering two different physical scenarios. Notably, the results obtained generally indicate lower rates than those commonly employed in the field. The sensitivity range of the measurements extends to the carbon-burning regions within stellar evolution models, notably 1 $M_\odot$ and 25 $M_\odot$. Preliminary studies of the consequences of these revised reaction rates have already been conducted, revealing various effects on nucleosynthesis and the duration of the carbon combustion phase, among other factors. Beyond their influence on the carbon-burning phase of massive stars, further investigations should explore their impacts in scenarios where carbon fusion reactions are critical at lower temperatures. This is particularly significant in cases where discrepancies with older rate data are most pronounced, such as in the context of carbon burning in the study of limit between intermediate-mass and massive stars (Gerónimo et al. 2023), type Ia supernovae, or even in superbursts (Strohmayer & Brown 2002).

STELLA was funded by the University of Strasbourg IdEX program and CNRS IN2P3. JN acknowledges support from the Interdisciplinary Thematic Institute QMat, as part of the ITI 2021 2028 program of the University of Strasbourg, CNRS and Inserm, which was supported by IdEx Unistra (ANR 10 IDEX 0002), and by SFRI STRAT'US project (ANR 20 SFRI 0012) and EUR QMAT ANR-17-EURE-0024 under the framework of the French Investments for the Future Program. This work was supported by the European Union (ChETEC-INFRA, project no. 101008324).

References

Aguilera, E. F., Rosales, P., Martinez-Quiroz, E., et al. 2006, Phys. Rev. C, 73, 064601

Barrón-Palos, L., Aguilera, E., Aspiazu, J., et al. 2006, Nuclear Physics A, 779, 318

Becker, H. W., Kettner, K. U., Rolfs, C., & Trautvetter, H. P. 1981, Zeitschrift für Physik A Atoms and Nuclei, 303, 305

Bennett, M. E., Hirschi, R., Pignatari, M., et al. 2012, Monthly Notices of the Royal Astronomical Society, 420, 3047

Bucher, B., Tang, X. D., Fang, X., et al. 2015, Phys. Rev. Lett., 114, 251102

Caughlan, G. R. & Fowler, W. A. 1988, Atomic Data and Nuclear Data Tables, 40, 283

Choplin, A., Maeder, A., Meynet, G., & Chiappini, C. 2016, A&A, 593, A36

Eggenberger, P., Meynet, G., Maeder, A., et al. 2008, Astrophysics and Space Science, 316, 43

Fruet, G., Courtin, S., Heine, M., et al. 2020, Phys. Rev. Lett., 124, 192701

Gerónimo, F. C. D., Bertolami, M. M. M., Catelan, M., & Battich, T. 2023, Uncertainties in the 12C+12C reaction rate and their impact on the composition of ultra-massive WDs

Heine, M., Courtin, S., Fruet, G., et al. 2018, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 903, 1

High, M. & Čujec, B. 1977, Nuclear Physics A, 282, 181

Hirschi, R. 2004, Massive rotating stars : the road to supernova explosion (Université de Genève. Thèse)

Illiadis, C. 2015, Nuclear Physics of Stars, 2nd edn. (Wiley-VCH)

Jenkins, D. & Courtin, S. 2015, Journal of Physics G: Nuclear and Particle Physics, 42, 034010

Jiang, C. L., Back, B. B., Esbensen, H., et al. 2013, Phys. Rev. Lett., 110, 072701

Jiang, C. L., Esbensen, H., Rehm, K. E., et al. 2002, Phys. Rev. Lett., 89, 052701

Jiang, C. L., Rehm, K. E., Back, B. B., & Janssens, R. V. F. 2007, Phys. Rev. C, 75, 015803

Jiang, C. L., Rehm, K. E., Fang, X., et al. 2012, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 682, 12

Jiang, C. L., Santiago-Gonzalez, D. and Almaraz-Calderon, S., Rehm, K. E., et al. 2018, Phys. Rev. C, 97, 012801

Monpribat, E., Choplin, A., Martinet, S., et al. 2023, EPJ Web Conf., 279, 11016

Monpribat, E., Martinet, S., Courtin, S., et al. 2022, A&A, 660, A47

Patterson, J., Winkler, H., & Zaidins, C. 1969, The Astrophysical Journal, 157, 367

Pignatari, M., Hirschi, R., Wiescher, M., et al. 2013, ApJ, 762, 31

Spillane, T., Raiola, F., Rolfs, C., et al. 2007, Phys. Rev. Lett., 98, 122501

Strohmayer, T. E. & Brown, E. F. 2002, ApJ, 566, 1045

Tan, W. P., Boeltzig, A., Dulal, C., et al. 2020, Phys. Rev. Lett., 124, 192702