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The ^{12}C + ^{12}C fusion reaction at astrophysical energies

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Abstract. The fusion of two carbon nuclei is a key reaction during the late evolution of massive stars, in explosive nucleosynthesis in supernovae and superbursts in x-ray binary systems. The precise experimental determination of the ultra low carbon fusion cross sections is extremely challenging so that the quantification of this critical reaction still lacks the necessary accuracy to constrain astrophysical models. The STELlar LAboratory (STELLA) experiment has been developed to increase the accuracy of direct carbon fusion reaction measurements, as compared to conventional experiments, by using the coincident detection of the evaporation residues characteristic gamma rays and the emitted charged light particles, which drastically suppresses the backgrounds. STELLA furthermore combines nano seconds timing with this approach for unambigious exit channel identification with timing gates of tens of nanoseconds.

^{12}C+^{12}C measurements have been performed at the Andromede facility in Orsay, France using the STELLA setup, right in the astrophysics region of interest of 25 solar masses stars. These data complement an earlier experiment at the lowest-energy direct measurement carried out so far, where partly only limits could be established, and largely improves the understanding of the fusion excitation function. The results are discussed in terms of molecular resonances in the ^{24}Mg compound nucleus as well as hindrance of the fusion process at the lowest energies.

The impact of the STELLA results on the chemical structure and evolution scenarios of massive stars are discussed, based on hydrodynamics calculations.

1 Introduction

The fusion of carbon is a crucial step of the synthesis of elements in stars and is known to play a role in the quiescent C burning in the cores of massive stars, in type Ia supernovae, and possibly in superbursts of X-ray binary systems [1]. The corresponding ^{12}C+^{12}C excitation function is known to show oscillations from energies of a few MeV/A down to sub barrier energies, possibly attributed to ^{12}C-^{12}C molecular configurations of ^{24}Mg [2]. The temperatures for the quiescent burning correspond to deep sub-barrier energies for the ^{12}C+^{12}C fusion and to cross-sections down to the picobarn range, leading to challenging experiments for direct measurements. Such experiments nevertheless lead to crucial results, essential to constrain indirect studies and theoretical extrapolations. Standard extrapolations for the ^{12}C+^{12}C fusion reaction down to the lowest energies are based on optical calculations and were first performed by Fowler [3]. More recently, empirical extrapolations, based on the hindrance of the fusion cross section has been proposed by Jiang et al. [4]

This contribution describes new direct measurements of the ^{12}C+^{12}C fusion excitation function and results obtained with the STELLA experimental setup.

2 Direct measurements of low-energy cross sections, experimental setup

The STELLA system was installed at the 4 MV Andromede Pelletron accelerator in Orsay, France, to measure the cross sections of heavy ion fusion, particularly in the ^{12}C+^{12}C system, which is crucial for understanding reactions in massive stars and supernovae. The STELLA experiment has been developed to achieve the direct determination of cross sections as low as a few picobarns using a coincidence detection technique between charged particles and gamma rays.

Key innovations of STELLA include: i. a rotating target mechanism to be able to use high beam intensities on ultrathin targets, i.e. 20 to 50 μg.cm^{-2}; ii. a ultrahigh vacuum system which allows to reach pressures down to 10^{-8} mbar)) to avoid target thickening; and iii. nanosecond timing to reduce the background accurately selecting of the p and α channels (see [5] for more details).

The rotating thin-target system has been designed to distribute heat across the target. It can rotate at a rate of up to 100 rpm so that beam intensities up to 10 μA can be used. The particle detectors, based on double-sided silicon strip detectors (DSSSD), are positioned around the tar-

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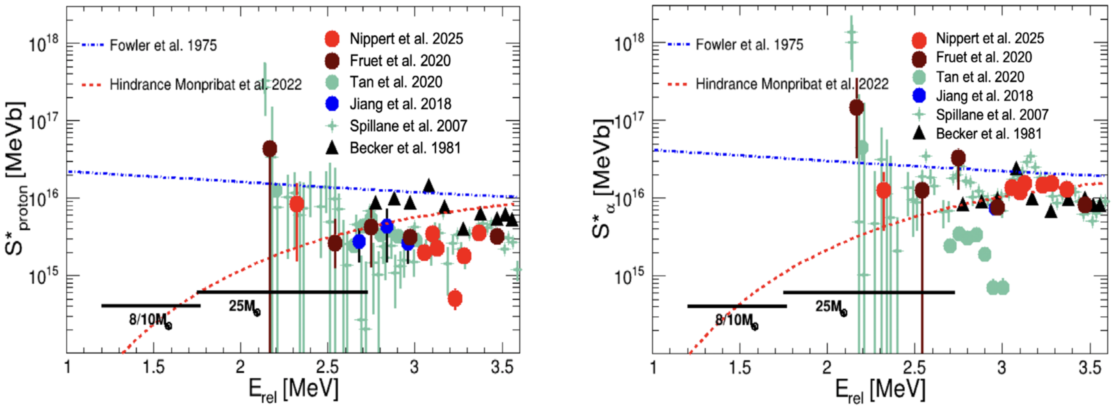

Figure 1. S-factor measurements for the $^{12}C+^{12}C$ fusion reaction as a function of the relative energy E_{rel}. See [6–11] for more details.

get to maximize angular coverage and detection efficiency. Aluminum foils are used to protect the detectors from delta electrons and from beam particles damage, while minimizing the degradation of proton and alpha energies. Gamma rays are detected by an array of 36 $LaBr_3(Ce)$ crystals from the FATIMA collaboration allowing sub-nanosecond time resolution and 3% FWHM energy resolution at 1333 keV. The detectors are configured in a cylindrical layout to maximize the detection efficiency and owing to mechanical development constraints. Calibration of the detectors is performed using standard Co, Cs radioactive sources and $LaBr_3(Ce)$ intrinsic activity lines.

Particle-gamma coincidence measurements and time-stamped data allow to effectively select the p and α exit channels. The coincidence technique is particularly effective in reducing background noise, mainly due to contamination by hydrogen and deuterium present in the target, from ubiquitous water contamination.

The target condition and thickness is rigorously monitored using a system that allows scanning its thickness before / after beam exposure on its whole diameter, i.e. 46 mm. It should be noted that no C buildup was identified during the STELLA $^{12}C+^{12}C$ runs within an accuracy of 10 %.

3 Measured cross sections and reaction rates

During a recent STELLA campaign, measurements of $^{12}C+^{12}C$ fusion cross sections were performed at energies ranging from 2.32 to 3.82 MeV using the Andromede 3μA $2^+/3^+$ carbon beam [6].
In this energy range, the relevant carbon fusion reaction channels are:

$$^{12}C + ^{12}C \rightarrow ^{24}Mg^* \rightarrow ^{20}Ne^* + \alpha, \quad (1)$$

$$\rightarrow ^{23}Na^* + p, \quad (2)$$

The contribution of n channels is negligible at deep sub-barrier energies due to its negative Q-value. The measurements of the final α and p exit channels were converted into alpha and proton cross sections, which were then converted into modified S-factors, S^*, taking into account statistical uncertainties.

$$S^* = \sigma E \exp(2\pi\eta + gE), \quad (3)$$

with $\eta = Z_1 Z_2 e^2/(\hbar v)$ the Sommerfeld parameter where Z_1 and Z_2 are the charge of the nuclei and e the electron charge and $g = 0.122\sqrt{\mu R^3/(Z_1 Z_2)}$ the form factor for angular momentum $l = 0$ states in $^{12}C+^{12}C$ fusion reactions using a square-well potential for a reduced mass μ [1].

The obtained modified S-factors are reported in Fig.1, together with standard Fowler extrapolations and empirical hindrance model behavior.

4 Discussion

S-factors for the $^{12}C+^{12}C$ fusion cross sections have been measured and can be compared with results of previous experimental campaigns. It can be noted that the S-Factor at E_{rel} = 2.32 MeV, a crucial point for the trend of the S-factors in astrophysics regions, tends to be below the standard optical model extrapolation [3]. This is in agreement with a previous interpretation of the cross section. Indeed, three regimes have been explored:

1. At moderate sub-barrier energies, the STELLA experimental method has been validated, comparing the STELLA results to previous direct measurements.

2. At deep sub-barrier energies, hindrance of the fusion cross-section has been observed.

3. At further lower energies, entering the $^{12}C+^{12}C$ Gamow window for 25 $M_\odot$ stars, another regime

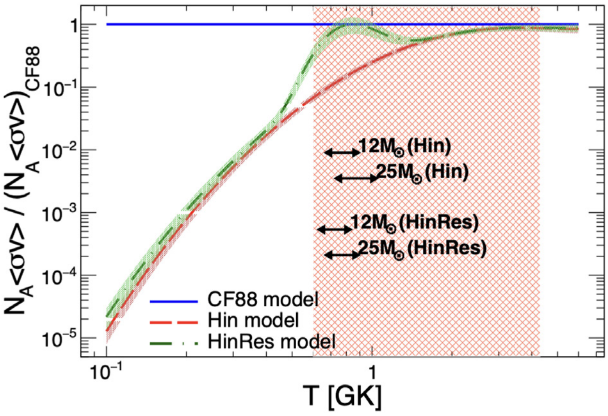

Figure 2. ^{12}C+^{12}C measured reaction rates, normalized to CF88 rates. The orange hatched area indicates the STELLA sensitivity. The black arrows show the regions where carbon fusion occurs for different stellar models, for both Hin and HinRes models (see text).

is identified, based on an increase of the S-factor. This is compatible with the previously-measured resonance at 2.14 MeV ([7] and references therein), which has been discussed in terms of ^{12}C-^{12}C) molecular configurations of the ^{24}Mg compound nucleus.

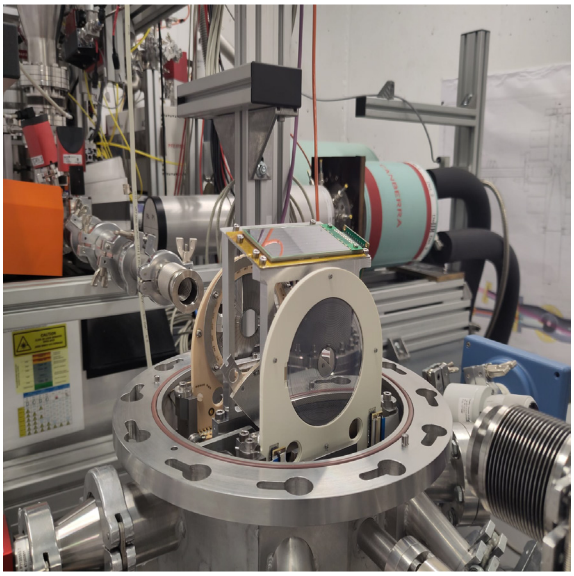

Figure 3. Installation of the STELLA mobile station at the Felsenkeller laboratory. The particle detection with the S3 type Micron annular detectors before and after the target is supplemented my measurements at steep angles with a BB10 Micron detector for improved angular coverage. See [5] for more details.

The impact of STELLA S-factor measurements from the Coulomb barrier down to astrophysical energies on massive star evolution and nucleosynthesis has been discussed in several recent articles of our collaboration [12–14] . In this sense, the measured cross sections have been converted to nuclear reaction rates and used as inputs to state-of-the-art nucleosynthesis and stellar evolution calculations, essentially based on the GENEC code [15]. The reaction rates are reported in Fig.2

The red and green curve represent the Hin and HinRes models respectively, Hin is taking hindrance of the fusion cross sections into account and HinRes, including hindrance and the 2.14 MeV resonance. The blue line shows the Fowler standard calculation used as normalization. The orange hatched area shows the STELLA sensitivity zone, and the shaded areas around the curves show the total uncertainties of the reaction rates, based on the experimental uncertainties of the STELLA measured cross sections. It is worth mentioning that STELLA experimental sensitivity covers the regions where carbon fusion occurs for 12 to 25 solar masses, and thus, no extrapolation of the cross sections is needed.

In our calculations, we have explored 15, 17 and 20 solar masses stars, at solar metallicity, with and without rotation [14]. Our latest measured reaction rates lead to 10% shorter C-burning lifetime and shift the C ignition to higher temperatures and densities. The chemical structure of the core can be impacted, as well as the compactness of the stellar C-burning shells. Accurate reaction rates obtained by the STELLA collaboration for the stellar ^{12}C+^{12}C key process strongly impact stellar burning lifetimes, chemical evolution, and stellar fate.
In conclusion, the measurement setup is optimized for stable and robust detection of fusion reactions with light heavy ions with cross sections measurements below nanobarn. To achieve these, campaigns with beam exposure of typically several μA were carried out over the course of several weeks with continuous monitoring of the principal experimental parameters. In addition, efficient background suppression techniques are employed during data analysis with adapted evaluation techniques accounting for the low counting statistics [5, 7]. As for carbon fusion, future campaigns are designed to extend the range of direct measurement further into the astrophysics region of interest below E_{cm} = 2 MeV.

The STELLA mobile station was therefore installed at the shallow underground laboratory Felsenkeller in Dresden, Germany, that hosts a 4 MeV Pelletron accelerator for high intensity carbon beams. In addition, the rock overburden of about 40 m shields off cosmic muons efficiently [16]. This secondary cosmic radiation was estimated to become a relevant background source in the sub pico-barn cross section range for carbon fusion. The particle detection setup displayed in Figure 3, is employed with a test setup of UK-FATIMA with a novel SiPM readout [17]. Successful high intensity beam and detector tests were carried out with consistent identification spectra and cross section estimations during carbon fusion measurements.

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