EPJ Web of Conferences **109**, 04009 (2016)
DOI: 10.1051/epjconf/201610904009


# First direct measurement of $^{12}$C($^{12}$C,n)$^{23}$Mg at stellar energies

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**Abstract.** Neutrons produced by the carbon fusion reaction $^{12}$C($^{12}$C,n)$^{23}$Mg play an important role in stellar nucleosynthesis. Past studies have shown large discrepancies between experimental data and theory, leading to an uncertain cross section extrapolation at astrophysical energies. We present the first direct measurement which extends deep into the astrophysical energy range along with a new and improved extrapolation technique based on experimental data from the mirror reaction $^{12}$C($^{12}$C,p)$^{23}$Na. The new reaction rate has been determined with a well-defined uncertainty which exceeds the precision required by astrophysics models. Using our constrained rate, we find that $^{12}$C($^{12}$C,n)$^{23}$Mg is crucial to the production of Na and Al in Pop-III Pair Instability Supernovae.

## 1 Introduction

The first stars in the early Universe formed about 400 million years after the big bang. Verification of the existence of these stars is important for our understanding of the evolution of the Universe [1]. It

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has been predicted that for Population-III stellar production yields, the abundances of odd-Z elements are remarkably deficient compared to their adjacent even-Z elements [2]. Astronomers are searching for long-lived, low mass stars with the unique nucleosynthetic pattern matching the predicted yields [3]. The relevance of $^{12}C(^{12}C,n)^{23}Mg$ in the first stars has been discussed by Woosley, Heger, and Weaver [4]. By the end of helium burning in Pop-III stars, the neutron to proton ratio in the ash is almost exactly 1. In the subsequent carbon burning phase,however, frequent $\beta^+$ decay of produced $^{23}Mg$ converts protons into neutrons, thus increasing the neutron to proton ratio. A slight excess of neutrons would significantly affect the abundances of the odd-Z isotopes with neutron to proton ratios higher than 1, e.g. $^{23}Na$ and $^{27}Al$.

$^{12}C(^{12}C,n)^{23}Mg$ is also a potentially important neutron source for the weak s-process occurring in Pop-I and II stars. Pignatari et al. [5] recently performed a study of the weak s-process during carbon shell burning for a 25 $M_\odot$ stellar model using different $^{12}C(^{12}C,n)^{23}Mg$ rates. They found that a factor of 2 precision or better would be desirable to limit its impact on the s-process predictions to within 10%.

Stellar carbon burning has three main reaction channels:

$$\begin{aligned} {}^{12}C + {}^{12}C &\rightarrow {}^{23}Mg + n - 2.60\ \text{MeV} \\ &\rightarrow {}^{23}Na + p + 2.24\ \text{MeV} \\ &\rightarrow {}^{20}Ne + \alpha + 4.62\ \text{MeV} \end{aligned}$$

With $Q < 0$, the probability of decay through the neutron channel is weakest among the three at the low energies relevant for stellar burning conditions. For a typical carbon shell burning temperature of $T_9 = 1.1$, the important energy range for this channel is $2.7 < E_{cm} < 3.6$ MeV. The reaction was first studied in 1969 by Patterson et al. [6] who measured the cross section over the range $E_{cm}$=4.23 to 8.74 MeV by counting $\beta$-rays from $^{23}Mg$ decays. From this measurement, a constant neutron branching ratio, $\beta_n = 2\%$, was deduced [7]. Later Dayras et al. extended the measurement down to $E_{cm}$=3.54 MeV by counting the $\gamma$-rays emitted following the $^{23}Mg$ beta decay. The experimental uncertainty is about 40% at $E_{cm} \approx 3.8$ MeV and increases to 90% at the lowest energy [8]. To estimate the cross section at the stellar burning energies, Dayras et al. had to rely on an extrapolation of the experimental data based on a Hauser-Feshbach statistical model calculation. Because of the unique molecular resonances existing in the $^{12}C+^{12}C$ fusion reaction, their calculation could only be renormalized to the average trend of the data whereas the resonant behavior of the $^{12}C+^{12}C$ fusion reaction was ignored. The maximum deviation between the experimental result and the renormalized statistical model prediction is more than a factor of 4. Nevertheless, based on the statistical model extrapolation, this work recommended a neutron branching ratio of $\beta_n = 0.011\%$, 0.11%, 0.40%, and 5.4% at $T_9 = 0.8$, 1.0, 1.2, and 5, respectively, though no attempt was made to quantify the uncertainties in these predictions [8].

In 1988, Caughlan and Fowler (CF88) excluded this result from their rate compilations [9]. Instead, they recommended $\beta_n = 0$ ($T_9 < 1.75$), $\beta_n = 5\%$ ($1.75 \le T_9 < 3.3$) and $\beta_n = 7\%$ ($3.3 \le T_9 < 6.0$). This rate was adopted by REACLIB after fitting the CF88 ratio with the standard REACLIB formula [10]. So far, to our knowledge, the Dayras rate has only been implemented in the stellar code KEPLER [11, 12].

## 2 Direct measurement of $^{12}C(^{12}C,n)^{23}Mg$ at energies above $E_{cm}$=3 MeV

The experimental work was performed at the University of Notre Dame's Nuclear Science Laboratory using the 11 MV FN tandem Pelletron accelerator. Carbon beams were produced at energies ranging from 5.1 to 8.7 MeV (lab frame) with typical currents on target between 0.5 and 1.5 p$\mu$A. A 1-mm

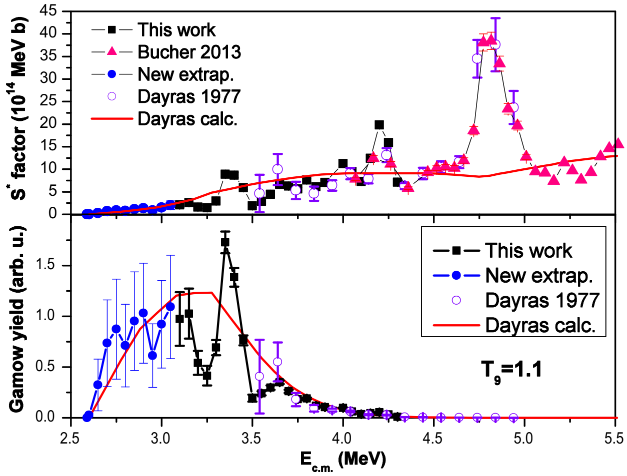


**Figure 1.** (Color online) Upper: The $^{12}C(^{12}C,n)^{23}Mg$ S*-factor results from the present measurement (black squares) compared with previous data sets from Dayras 1977[8] (purple circles) and Bucher 2013[14, 16] (magenta triangles). Also shown is the neutron branching ratio calculated by Dayras applied to the total $^{12}C+^{12}C$ fusion S*-factor recommended by CF88 [9] (red solid line) and the new extrapolation from this work (blue circles). Only statistical errors are shown for the experimental data, while the extrapolation includes both statistical and a 40% systematic error. Lower: The Gamow yield for $T_9$=1.1 is plotted.

thick hydrogen-free Highly Ordered Pyrolytic Graphite (HOPG) target made from natural carbon was used to control the hydrogen-induced background [13]. The target was cooled by circulating deionized water through the supporting flange, which was centered in a block of polyethylene containing 20 $^{3}$He proportional counters arranged around the beam axis in two concentric rings [14, 15].

The main sources of beam-induced neutron background were from the reaction $^{13}C(^{12}C,n)^{24}Mg$ [14]. With a large positive Q-value (8.99 MeV) and the relatively high natural abundance of $^{13}$C in the target (1.1%), neutrons from $^{13}C(^{12}C,n)^{24}Mg$ dominate the total yield at very low beam energies near the $^{12}C(^{12}C,n)^{23}Mg$ reaction threshold. To estimate its contribution, the $^{13}C(^{12}C,n)^{24}Mg$ reaction was studied with the same setup using a $^{13}$C beam with energies ranging between 9.5 and 5.4 MeV. Since the cross section for this reaction is much higher, relatively low beam intensities (≃50 pnA) with shorter run times were sufficient. The normalized $^{12}C(^{13}C,n)^{24}Mg$ yield was then subtracted from the measured total neutron yield recorded with the $^{12}$C beam [16].

The room background rate was measured to be 9.015(92) evts/min, which dominated the yield at energies below $E_{cm}$= 3.0 MeV. The background contribution from $^{2}H(^{12}C,^{13}N)n$ was studied using a thin $TiD_2$ target with thick Cu backing. After removing the room background, this contribution was found to be less than 5% of the total yield at $E_{cm}$= 3.3 MeV increasing to 19% at 3.1 MeV.

The cross section for the $^{12}C(^{12}C,n)^{23}Mg$ reaction was determined by differentiating the thick target yield [17]. In Fig. 1, it has been converted to a modified S-factor (S*) [6, 17] for comparison with previous results. It is seen that the new results display good agreement with previous measurements in the overlapping energy region while extending much deeper into the astrophysical energy range. The 15% systematic uncertainty primarily results from the uncertainties in the beam current (10%), detector efficiency (6%) [15], angular distribution (5%), and stopping power (7%) [16, 18]. The Dayras results also have an additional systematic uncertainty of 16% [8] not shown in Fig. 1.

## 3 Extrapolation based on $^{12}$C($^{12}$C,p)$^{23}$Na

An extrapolation is required to estimate the reaction cross section at the lower energies beyond experimental reach. As mentioned earlier, Dayras et al. provided a renormalized statistical model calculation for this purpose. However, the large discrepancy between the experimental data and their theory calls into question the reliability of the extrapolation. To provide a better prediction including the effect of the molecular resonances in the entrance channel, a novel extrapolation method has been developed based on experimental information from the mirror reaction $^{12}$C($^{12}$C,p)$^{23}$Na. The predicted neutron cross section, $\sigma_{n(\mathrm{pred})}$, is obtained using the formula

$$\sigma_{n(\mathrm{pred})} = \sum_{i=0}^{N} \frac{\sigma_{\mathrm{n}_i(\mathrm{th})}}{\sigma_{\mathrm{p}_i(\mathrm{th})}} \sigma_{\mathrm{p}_i(\mathrm{exp})} \tag{1}$$

where $N$ is the highest available decay channel in the residual $^{23}$Mg, which depends on the reaction energy. For $E_{\mathrm{cm}} \leq 4.6$ MeV, only the $n_0$ and $n_1$ channels are open. The theoretical ratio, $\frac{\sigma_{\mathrm{n}_i(\mathrm{th})}}{\sigma_{\mathrm{p}_i(\mathrm{th})}}$, is calculated using TALYS [19] combined with entrance channel spin populations supplied from a coupled-channels calculation by Esbensen [20]. The resonances in $^{12}$C($^{12}$C,n$_i$)$^{23}$Mg and $^{12}$C($^{12}$C,p$_i$)$^{23}$Na originate from both the molecular resonances in the entrance channel and the characteristic resonances in the final decay channels. The traditional statistical model calculation employed by Dayras uses the optical model and assumes a high level density to describe the entrance and exit channels and therefore could only reproduce the average trend of the experimental data. In our approach, the complicated molecular resonance associated with the entrance channel is embodied in the experimental cross sections ($\sigma_{\mathrm{p}_i(\mathrm{exp})}$) of $^{12}$C($^{12}$C,p$_i$)$^{23}$Na, the mirror system of $^{12}$C($^{12}$C,n$_i$)$^{23}$Mg, whereas the statistical model is only used to predict the decay width ratio between the $n_i$ and $p_i$ channels. Since the proton energy resolution in the Zickefoose experiment from Ref. [21] was insufficient to resolve $p_0$ from $p_1$, only the sum, $\sigma_{\mathrm{p}_0} + \sigma_{\mathrm{p}_1}$, is available for $E_{\mathrm{cm}} < 4$ MeV. Eq. 1 has been modified to accommodate the combination of $p_0$ and $p_1$. Additionally, the measurements of $^{12}$C($^{12}$C,p$_i$)$^{23}$Na performed by Fang *et al.* in the energy range $3 < E_{\mathrm{cm}} < 6$ MeV [22] have also been used to predict the $^{12}$C($^{12}$C,n)$^{23}$Mg cross section [14]. In this case, up to $N$=6 possible decay channels are required for the prediction calculated in Eq. 1.

Figure 2 shows the ratios between our measured $^{12}$C($^{12}$C,n)$^{23}$Mg cross section $\sigma_{n(\mathrm{exp})}$ and the two $\sigma_{n(\mathrm{pred})}$ based on the Zickefoose and Fang proton data sets plotted as a function of $E_{\mathrm{cm}}$. The average ratios (standard deviations) for the Zickefoose and Fang predictions are 0.9(4) and 0.9(3), respectively. The ratios to the Dayras calculation are also shown for comparison. The large deviation at $E_{\mathrm{cm}} \simeq 4.8$ MeV has been eliminated by our approach. The fluctuations, which are larger than the quoted statistical uncertainties, reflect the systematic errors associated with our extrapolation. They consist of the systematic errors in the proton measurements, the assumed entrance channel spin populations, and the TALYS calculation used in the prediction of $\frac{\sigma_{\mathrm{n}_i(\mathrm{th})}}{\sigma_{\mathrm{p}_i(\mathrm{th})}}$. To provide better consistency with the experimental $^{12}$C($^{12}$C,n)$^{23}$Mg data, our extrapolation has been renormalized by the factor 0.9. We have adopted 0.4 as the systematic error in accordance with the Zickefoose-based prediction since that data set was used for the extrapolation, being the only one to reach sufficiently low energies.

## 4 New reaction rate for $^{12}$C($^{12}$C,p)$^{23}$Na and its astrophysical impact

The new cross section defined by our extrapolation and experimental data has been used to calculate the $^{12}$C($^{12}$C,n)$^{23}$Mg reaction rate. To highlight the important stellar energy range for a typical carbon shell burning temperature of $T_9 = 1.1$, the Gamow yield is computed and shown in Fig. 1. Our

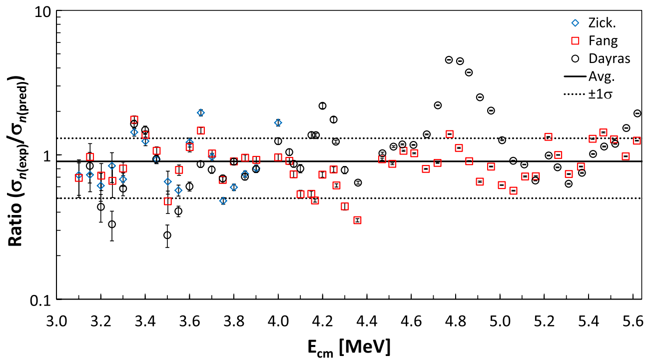


**Figure 2.** (Color online) The ratio of our $^{12}C(^{12}C,n)^{23}Mg$ cross section data $\sigma_{n(\mathrm{exp})}$ to the two $\sigma_{n(\mathrm{pred})}$ based on the $^{12}C(^{12}C,p)^{23}Na$ data from Zickefoose (blue diamonds) [21] and from Fang (red squares) [22]. while the dashed lines represent 1 standard deviation. As a comparison, the ratios of our $\sigma_{n(\mathrm{exp})}$ to the Dayras prediction are shown as black circles.

measurement covers about half of the stellar energy range. It reduces the dependence on extrapolation in the astrophysical reaction rate and provides a base for examining the systematic uncertainty of extrapolation.

A good fit of the $^{12}C(^{12}C,n)^{23}Mg$ reaction rate was difficult to achieve using the standard REACLIB format due to its endothermic character. Following the convention of Dayras [8], our $^{12}C(^{12}C,n)^{23}Mg$ rate has been normalized to the standard CF88 $^{12}C+^{12}C$ total fusion rate. The neutron branching ratio, $\beta_n$, has been fitted and can be found in [23]. The uncertainty for the reaction rate is estimated based on the error bars of experimental and extrapolated cross sections. It is found that only the Dayras rate agrees with our new rate within the quoted uncertainty. At typical carbon shell burning temperatures $T_9 \simeq 1.1$–$1.3$, the uncertainty is less than 40% which is sufficient for studying the weak s-process. The uncertainty is reduced to 20% at $T_9 \simeq 1.9$–$2.1$ which is relevant for explosive carbon burning.

The impact of $^{12}C(^{12}C,n)^{23}Mg$ on the nucleosynthetic pattern of $200\,M_\odot$ Pair Instability Supernovae (PI SNe) has been investigated using the 1D stellar evolution code, KEPLER [11, 12]. It is found that this reaction is important for the nucleosynthesis of odd-Z elements such as Na and Al. By including our $^{12}C(^{12}C,n)^{23}Mg$ rate in the calculation, the production of $^{23}Na$ is increased by a factor of 5 (0.7 dex) with an uncertainty less than $\sim$10%. The yield of $^{27}Al$ is increased by nearly a factor of 2 (0.3 dex). The impact on the nucleosynthesis of 18 $M_\odot$ Pop-III star and Pop-I star can be found in ref. [23].

## 5 Summary

We have measured the $^{12}C(^{12}C,n)^{23}Mg$ cross section for the first time within the Gamow window for the stellar carbon burning processes. Our measurement covers half of the important energy range. For the lower unmeasured energies, we have developed a novel extrapolation method based on the $^{12}C(^{12}C,p)^{23}Na$ channel. A new reaction rate has been determined with, for the first time, a quantified uncertainty that satisfies the precision required from astrophysics models. As a result, the ambiguity arising from the uncertain $^{12}C(^{12}C,n)^{23}Mg$ reaction rate has been eliminated. With our new rate, we find that $^{12}C(^{12}C,n)^{23}Mg$ is crucial for constraining the production of Na and Al in Pop-III pair instability supernovae.

## Acknowledgment

The authors would like to thank H. Esbensen (ANL) for providing the spin population of the $^{12}C+^{12}C$ entrance channel, F. Montes (MSU) for supplying two of the $^{3}$He counters used in the experiment, and F. Strieder (Bochum) for his suggestion of using a HOPG target. This work was supported by the NSF under Grants No. PHY-0758100 and No. PHY-0822648, the National Natural Science Foundation of China under Grant No. 11021504, 11321064, 11475228 and 11490564, 100 talents Program of the Chinese Academy of Sciences, the Joint Institute for Nuclear Astrophysics, and the University of Notre Dame. B.B. acknowledges support for the preparation of this manuscript by the U.S. Department of Energy and Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. M.P. acknowledges support from the "Lendület-2014" Programme of the Hungarian Academy of Sciences (Hungary), from SNF (Switzerland) and from the NuGrid collaboration (www.nugridstars.org). A.H. was supported by a Future Fellowship by the Australian Research Council (FT120100363).

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