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

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Neutrons produced by the carbon fusion reaction $^{12}C(^{12}C,n)^{23}Mg$ play an important role in stellar nucleosynthesis. However, 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 that 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 that 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. It also plays a non-negligible role in the production of weak s-process elements as well as in the production of the important galactic γ-emitter ^{60}Fe.

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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 has been predicted that for Population-III (metal-free stars [2]) stellar production yields, the abundances of odd-Z elements are remarkably deficient compared to their adjacent even-Z elements [3]. Astronomers are searching for long-lived, low mass stars with the unique nucleosynthetic pattern matching the predicted yields [4]. The relevance of $^{12}C(^{12}C,n)^{23}Mg$ in the first stars has been discussed by Woosley, Heger, and Weaver [5]. By the end of helium burning in Pop-III stars, the neutron to proton ratio in the ash is almost exactly 1. However, in the subsequent carbon burning phase, frequent β^+ 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 so-called weak s-process occurring in massive Pop-I (metal-rich [2]) and Pop-II (metal-poor [2]) stars. The weak s-process takes place during the core helium and shell carbon burning phases and is largely responsible for the s-process abundances up to A≈90 [6]. Pignatari et al. 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 [7]. 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 astrophysics. For a typical carbon shell burning temperature $T_9 = 1.1$, 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. [8] who measured the cross section over the range E_{cm}=4.23 to 8.74 MeV by counting β-rays from ^{23}Mg decays. From this measurement, a constant neutron branching ratio, β_n=2%, was deduced [9]. Later Dayras et al. extended the measurement down to E_{cm}=3.54 MeV by counting the γ-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 [10]. 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 [11]. Because of the unique molecular resonances existing in the ^{12}C+^{12}C fusion reaction [12], their calculation could only be renormalized to the average trend of the data while 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 (see Fig. 1). Nevertheless, based on the statistical model extrapolation, this work recommended a neutron branching ratio of β_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 [10].

In 1988, Caughlan and Fowler (CF88) excluded this result from their rate compilations [13]. 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 [14]. Pignatari et al. attempted to use the Dayras rate [7], however it was later discovered that the analytic formula for β_n taken from the paper [10] contained a typographical error resulting in a significant deviation from the intended value below $T_9 = 1.5$ [15]. So far, to our knowledge, the correct Dayras rate has only been implemented in the stellar code KEPLER [16, 17].

In the following, we report on the first direct measurement of this reaction into the stellar energy range as well as an improved method for extrapolating the experimental results through the remaining unmeasured energies relevant for carbon shell burning. Based on the new experimental result, a new reaction rate is recommended together with a well-defined uncertainty. The impact on the nucleosynthesis in massive stars is also discussed.

The experimental work was performed at the University of Notre Dame's Nuclear Science Laboratory using the 11 MV FN tandem Van de Graaff 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 pμA. The beam energy calibration was checked by measuring the reaction thresholds of ^{7}Li(p,n) and ^{19}F(p,n) as well as ^{12}C(p,p) resonant scattering [18]. The maximum energy deviation was less than 0.1%. A 1-mm thick hydrogen-free Highly Ordered Pyrolytic Graphite (HOPG) target made from natural carbon was used to control the hydrogen-induced background [19]. 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 [15, 20].

The main sources of beam-induced neutron background were from the reactions ^{13}C(^{12}C,n)^{24}Mg and, to a lesser extent, ^{2}H(^{12}C,^{13}N)n [15]. 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 approaching 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 ($\simeq$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 [21].

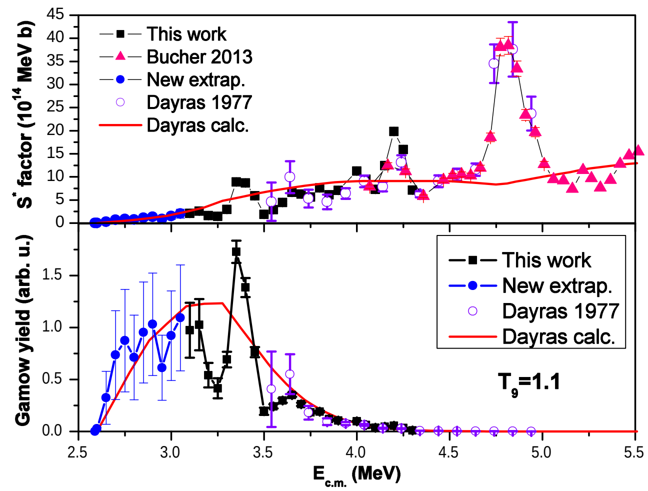

FIG. 1. (Color online) Upper: The ^{12}C(^{12}C,n)^{23}Mg S*-factor results from the present measurement (black squares) compared with previous data sets from Dayras 1977 [10] (purple circles) and Bucher 2013 [15, 21] (magenta triangles). Also shown is the neutron branching ratio calculated by Dayras applied to the total ^{12}C+^{12}C fusion S*-factor recommended by CF88 [13] (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 integrand from Eq. 2 using the various data sets is plotted.

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 detector efficiency has been simulated using Geant4 and MCNP in the range 0 to 3 MeV and experimentally validated with monoenergetic neutrons between 50 and 650 keV [20]. For this experiment, the Geant4 code was modified to include the strong angular dependence of the neutron energy from the ^{12}C(^{12}C,n)^{23}Mg kinematics. An isotropic angular distribution in the center-of-mass frame was assumed for the neutrons produced by ^{12}C(^{12}C,n)^{23}Mg and ^{13}C(^{12}C,n)^{24}Mg. The efficiency was found to vary smoothly between 30% and

50% as the average neutron energy decreases with beam energy [21]. To check the effect of the assumed angular distribution, we changed the isotropic angular distribution to match 2^{nd} and 4^{th} order Legendre polynomials [22], and found a nearly constant relative drop in efficiency of 9% and 5%, respectively, in the range of $E_{\mathrm{cm}}= 3$ to 5 MeV. Since our experiment does not measure angular distribution, a ±5% systematic uncertainty has been assigned for this effect. To test our efficiency calculation, we measured the ^{12}C(^{12}C,n)^{23}Mg cross section independently by detecting the activity of ^{23}Mg [15, 21]. The results gave good agreement in the overlapping energy range (as shown in Fig. 1).

The cross section for the ^{12}C(^{12}C,n)^{23}Mg reaction was determined by differentiating the thick target yield [23]. In Fig. 1, it has been converted to a modified S-factor (S*) for comparison with previous results. S* differs from the standard S-factor only by the multiplier, $\exp(0.46\,E)$, which is added to account for the finite size of the nucleus [8]. 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. A new resonance at $E_{\mathrm{cm}}= 3.4$ MeV is observed in the neutron channel. This resonance was also observed in earlier measurements of the proton and alpha channels [22, 24–27]. Our measurement includes a 15% systematic uncertainty which primarily results from the uncertainties in the beam current (10%), beam energy (2%), detector efficiency (6%) [20], angular distribution (5%), and stopping power (7%) [21, 28]. The Dayras results also have an additional systematic uncertainty of 16% [10] not shown in Fig. 1.

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

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

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, $\sigma_{\mathrm{n}_i(\mathrm{th})}/\sigma_{\mathrm{p}_i(\mathrm{th})}$, is calculated using TALYS [29] combined with entrance channel spin populations supplied from a coupled-channels calculation by Esbensen [30]. 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, while 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. [26] 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 by Fang et al. [27] performed at Notre Dame in the energy range $3 < E_{\mathrm{cm}} < 6$ MeV have also been used to predict the ^{12}C(^{12}C,n)^{23}Mg cross section [15]. 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_{cm}. The average ratios (standard deviations) for the Zickefoose- and Fang-based 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 $\sigma_{\mathrm{n}_i(\mathrm{th})}/\sigma_{\mathrm{p}_i(\mathrm{th})}$. 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.

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 by the following equation:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{kT^{3/2}} \int_{E_{\mathrm{th}}}^{\infty} \sigma(E) E \exp\left(-\frac{E}{kT}\right) \mathrm{d}E \quad (2)$$

To highlight the important stellar energy range for a typical carbon shell burning temperature $T_9 = 1.1$, the integrand of Eq. 2 (Gamow yield) is computed and shown in Fig. 1. Our measurement covers about half of the stellar energy range. It reduces the dependence on extrapolation in the astrophysical reaction rate and provides a

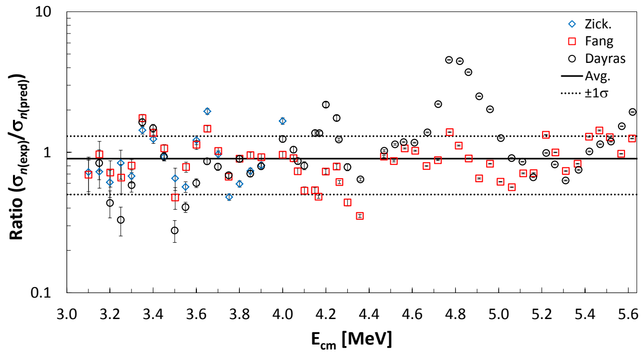

FIG. 2. (Color online) The ratio of our ^{12}C(^{12}C,n)^{23}Mg cross section data $\sigma_{n(\mathrm{exp})}$ to the two $\sigma_{n(\mathrm{pred})}$ based on the ^{12}C(^{12}C,p)^{23}Na data from Zickefoose [26] (blue diamonds) and from Fang et al. [27] (red squares). The solid black line shows the average ratio of the Zickefoose data below 4.0 MeV 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.

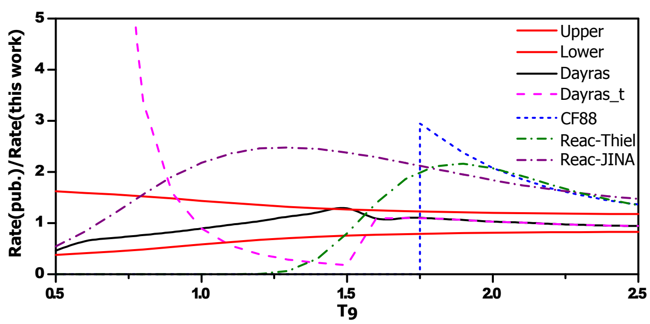

FIG. 3. (Color online) The ratios of various published ^{12}C(^{12}C,n)^{23}Mg rates to the one determined in this work. The uncertainties of our new rate are indicated by the red lines. The rate determined by Dayras is in good agreement with our new rate. The erroneous Dayras rate, stemming from a typo in the publication, is labeled Dayras_t. For comparison, we also show the rates from CF88 [13] and two separate editions of REACLIB (from Thielemann et al. [14] and JINA [31]).

base for examining the systematic uncertainty of extrapolation.

Because of its endothermic character, a good fit of the ^{12}C(^{12}C,n)^{23}Mg reaction rate was difficult to achieve using the standard REACLIB format. Following the convention of Dayras [10], 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, β_n, has been fitted and listed below.

$$
\begin{aligned}
\beta_n = {} & 0.11954 \exp\left[-\left(\frac{0.16446}{{T_9}^3} + \frac{2.57495}{{T_9}^2} + \frac{1.94145}{T_9}\right)\right] \\
& (T_9 \le 1.5) \\
= {} & 0.2212\left[1 - \exp(-0.13597\, T_9 + 0.158)\right] \\
& (1.5 \le T_9 \le 2.5) \\
= {} & 0.048811\left[1 - \exp(-2.1124\, T_9 + 3.8791)\right] \\
& (2.5 \le T_9 \le 5.0) \\
= {} & 0.04875 \quad (T_9 > 5.0)
\end{aligned}
$$

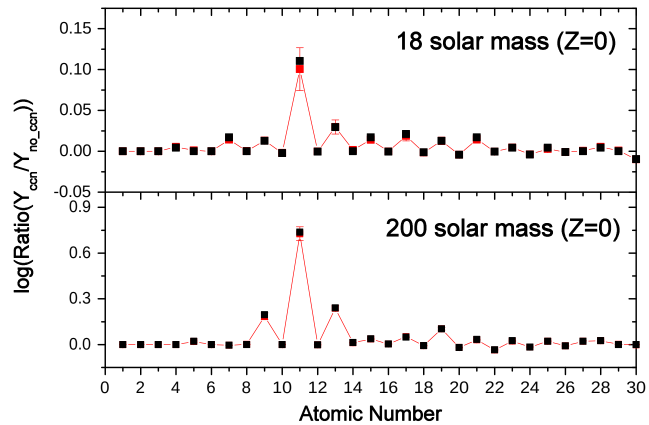

FIG. 4. (Color online) The logarithmic ratio of elemental yields with ^{12}C(^{12}C,n)^{23}Mg to those without ^{12}C(^{12}C,n)^{23}Mg for 18 $M_\odot$ (top) and 200 $M_\odot$ (bottom) Pop-III stars. The red points and their error bars correspond to the result obtained with the average and upper/lower limits determined by this work.The result obtained with the Dayras rate is shown as black points.

The uncertainty for the reaction rate is estimated based on the error bars of experimental and extrapolated cross sections. Comparisons among the existing reaction rates are shown in Fig. 3. The various rates have been plotted as a ratio to our rate in order to compare them on a linear scale over a large temperature range. It is seen 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 a 200 $M_\odot$ Pair Instability Supernovae (PI SNe) has been investigated using the 1D stellar evolution code, KEPLER [16, 17]. The ratio of the production yields with and without ^{12}C(^{12}C,n)^{23}Mg is shown in Fig. 4. It is clear that this reaction is important for the nucleosynthesis of odd-Z elements such as F, 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 ∼10%. The yield of ^{27}Al is increased by nearly a factor of 2 (0.3 dex). We have also explored the impact of ^{12}C(^{12}C,n)^{23}Mg on an 18 $M_\odot$ Pop-III star. A moderate enhancement of up to 30% is found for odd-Z elements.

The role of ^{12}C(^{12}C,n)^{23}Mg in Pop-I stars has been overlooked in most studies of the weak s-process because both CF88 and REACLIB (from Thielemann [14]) essentially turn it off at carbon shell burning temperatures. To illustrate its impact on the nucleosynthesis in massive stars, an $18\,M_\odot$ Pop-I star has been investigated using KEPLER with two different scenarios: including and excluding $^{12}C(^{12}C,n)^{23}Mg$. By comparing these two production yields, an enhancement of $\simeq$10% is found for a number of weak s-process isotopes, such as ^{70}Zn, ^{76}Ge, ^{82}Se, ^{86}Kr, $^{85,87}Rb$ and ^{96}Zr, arising from the additional neutron production from $^{12}C(^{12}C,n)^{23}Mg$. The origins of these elements are rather complicated including He-, C-, Ne-burning, s-process in AGB stars and the r-process. Even within the weak s-process there are a number of uncertainties that can affect the final abundance pattern [6, 7, 32–34]. Our result clarifies the ambiguities associated with the $^{12}C(^{12}C,n)^{23}Mg$ rate. Furthermore, about 10% enhancements are also observed for ^{46}Ca and ^{60}Fe. The production mechanism of ^{46}Ca is important for the understanding of the $^{48}Ca/^{46}Ca$ anomaly in meteorites [35], while the production of ^{60}Fe is an important topic in γ-ray astronomy [36].

In 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, and it plays a non-negligible role in the production of weak s-process elements as well as the production of the important galactic γ-emitter ^{60}Fe.

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[1] V. Bromm, Reports on Progress in Physics **76**, 112901 (2013), arXiv:1305.5178 [astro-ph.CO].
[2] F. LeBlanc, *An Introduction to Stellar Astrophysics* (John Wiley and Sons, Ltd, 2010).
[3] A. Heger and S. E. Woosley, Astrophys. J. **567**, 532 (2002).
[4] W. Aoki, N. Tominaga, T. C. Beers, S. Honda, and Y. S. Lee, Science **22**, 912 (2014).
[5] S. Woosley, A. Heger, and T. A. Weaver, Rev. Mod. Phys. **74**, 1015 (2002).
[6] M. Pignatari, R. Gallino, M. Heil, M. Wiescher, F. Käppeler, *et al.*, Astrophys. J. **710**, 1557 (2010).
[7] M. Pignatari, R. Hirschi, M. Wiescher, R. Gallino, M. Bennett, *et al.*, Astrophys. J. **762**, 31 (2013).
[8] J. Patterson, H. Winkler, and C. Zaidins, Astrophys. J. **157**, 367 (1969).
[9] W. D. Arnett and J. W. Truran, Astrophys. J. **157**, 339 (1969).
[10] R. Dayras, Z. Switkowski, and S. Woosley, Nucl. Phys. A **279**, 70 (1977).
[11] R. Dayras, R. Stokstad, Z. Switkowski, and R. Wieland, Nucl. Phys. A **265**, 153 (1976).
[12] E. Almqvist, J. A. Kuehner, and D. A. Bromley, Phys. Rev. Lett. **4**, 515 (1960).
[13] G. Caughlan and W. Fowler, At. Data Nucl. Data Tables **40**, 283 (1988).
[14] **Reaclib Data**, Tables of reaction rates based on F. Thielemann *et al.*, Adv. Nucl. Astro., 525 (1987). 1991 updated version (updated to Z=46 in 1995 by Ch. Freiburghaus). Downloaded from quasar.physik.unibas.ch on 1-18-1995 (RBF).
[15] B. Bucher, X. Fang, S. Almaraz-Calderon, A. Alongi, A. D. Ayangeakaa, *et al.*, J. Phys. Conf. Ser. **420**, 012141 (2013).
[16] T. A. Weaver, G. B. Zimmerman, and S. E. Woosley, Astrophys. J. **225**, 1021 (1978).
[17] T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, Astrophys. J. **576**, 323 (2002).
[18] J. F. Wilkerson, T. B. Clegg, and E. J. Ludwig, Nucl. Instrum. Methods **207**, 331 (1983).
[19] J. Zickefoose, J. Schweitzer, T. Spillane, F. Strieder, H.-W. Becker, *et al.*, PoS(NIC XI)019.
[20] S. Falahat, A. Best, M. Couder, J. Görres, K.-L. Kratz, *et al.*, Nucl. Instrum. Methods A **700**, 53 (2013).
[21] B. Bucher, Ph.D. thesis, University of Notre Dame (2014).
[22] H. W. Becker, K. U. Kettner, C. Rolfs, and H. P. Trautvetter, Z. Phys. A **303**, 305 (1981).
[23] M. Notani, H. Esbensen, X. Fang, B. Bucher, P. Davies, *et al.*, Phys. Rev. C **85**, 014607 (2012).
[24] K. U. Kettner, H. Lorenz-Wirzba, and C. Rolfs, Z. Phys.

A **298**, 65 (1980).
[25] T. Spillane, F. Raiola, C. Rolfs, D. Schürmann, F. Strieder, *et al.*, Phys. Rev. Lett. **98**, 122501 (2007).
[26] J. Zickefoose, Ph.D. thesis, University of Connecticut (2010).
[27] X. Fang, B. Bucher, S. Almaraz-Calderon, A. Alongi, A. D. Ayangeakaa, *et al.*, J. Phys. Conf. Ser. **420**, 012151 (2013).
[28] J. F. Ziegler, Website, `www.srim.org` (accessed February 2014).
[29] A. Koning, S. Hilaire, and M. Duijvestijn, Website, `www.talys.eu/home/` (accessed November 2013).
[30] H. Esbensen, X. D. Tang, and C. L. Jiang, Phys. Rev. C **84**, 064613 (2011).
[31] R. H. Cyburt, A. M. Amthor, R. Ferguson, Z. Meisel, K. Smith, *et al.*, Astrophys. J. Suppl. Ser. **189**, 240 (2010).
[32] N. Prantzos, M. Hashimoto, and K. Nomoto, Astron. Astrophys. **234**, 211 (1990).
[33] C. Raiteri, M. Busso, R. Gallino, and G. Picchio, Astrophys. J. **371**, 665 (1991).
[34] A. Best, M. Beard, J. Görres, M. Couder, R. deBoer, *et al.*, Phys. Rev. C **87**, 045805 (2013).
[35] O. Sorlin, D. Guillemaud-Mueller, A. Mueller, V. Borrel, S. Dogny, *et al.*, Phys. Rev. C **47**, 2941 (1993).
[36] W. Wang, M. Harris, R. Diehl, H. Halloin, B. Cordier, *et al.*, Astron. Astrophys. **469**, 1005 (2007).