The Role of ^{12}C(^{12}C,n) in the Astrophysical S-Process

B Bucher, J Browne, S Almaraz-Calderon, A Alongi, A D Ayangeakaa, A Best, M Couder, J DeBoer, X Fang, W Lu, M Notani, D Patel, N Paul, A Roberts, R Talwar, W Tan, X D Tang, A Villano

Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana, USA

E-mail: bbucher@nd.edu

Abstract. The elements between iron and strontium are largely produced by the weak s-process occurring in massive stars during the late stages of convective core He burning and the convective shell carbon burning with the primary source of neutrons coming from the reaction ^{22}Ne(α,n)^{25}Mg. However, shell carbon burning may produce hot enough temperatures to activate ^{12}C(^{12}C,n)^{23}Mg as a significant neutron source. Few studies have been done on this reaction, and the extrapolation from experimental data down to the relevant astrophysical energies is uncertain. Recent studies performed at the Nuclear Science Laboratory of Notre Dame aim to improve the existing reaction data using new experimental techniques as well as provide a more reliable extrapolation to the low energies not accessible by experiment. Preliminary results will be presented and the astrophysical implications will be discussed.

1. Introduction

The slow neutron capture process (s-process) is responsible for synthesizing roughly half of all elements heavier than iron. S-Process nucleosynthesis primarily occurs during the AGB phase of stellar evolution, however, an important additional component occurs during convective core He burning and convective shell C burning in massive stars [1]. This additional component, known as the weak s-process, is characterized by a lower neutron exposure (time-integrated flux) than the main component, and generally only contributes to the abundances of elements lighter than mass 100. The primary source of neutrons in the weak s-process is believed to come from the reaction ^{22}Ne(α,n)^{25}Mg, but ^{12}C(^{12}C,n)^{23}Mg (Q = -2.60 MeV) may also produce a significant flux of neutrons during the shell C burning phase [1]. This reaction is not well-studied and the cross-section at the corresponding low energies is uncertain, relying on a dubious statistical model calculation which is unable to account for the resonant structure in the excitation function [2]. Indeed, it has been demonstrated that weak s abundances produced after shell carbon burning are moderately sensitive to this reaction [3] (see figure 1).

In the following, we report on new experimental results on this reaction as well as an improved method for extrapolating the experimental results to the lower energies relevant to shell C burning which are inaccessible by experiment.

2. Experiment

The first measurement of ^{12}C(^{12}C,n)^{23}Mg was by Patterson et al. in 1969 [4]. In that experiment, a beam of ^{12}C ions (4.23-8.74 MeV center-of-mass) bombarded a thin carbon target and the ^{23}Mg

products were collected on a foil behind the target. The β-rays from the ^{23}Mg decays were then counted which provided a measurement of the reaction cross-section. In 1977, the experimental data were extended to lower energies by Dayras et al. [2]. This measurement was made by counting the γ-rays emitted following the ^{23}Mg beta decays. Dayras et al. also provided an extrapolation of the experimental data based on a Hauser-Fechbach statistical model calculation. The calculation had to be renormalized to fit the average trend of the data and could not reproduce the resonant behavior characteristic of ^{12}C+^{12}C fusion. Nevertheless, it still provides the best estimate of the reaction rate to date and has been used in subsequent stellar model codes.
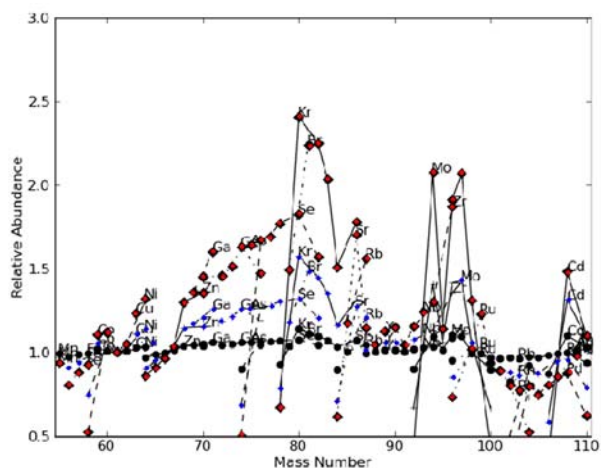

Figure 1. The sensitivity of the carbon shell yields to the ^{12}C(^{12}C,n) reaction is demonstrated [3]. The relative effect on the abundances are shown as a function of mass for the cases that the rate is increased by a factor of 2 (black), factor of 5 (blue), and factor of 10 (red) over the Dayras et al. [2] recommended rate. The change in abundances becomes significant between factors of 2 and 5 enhancements.

To improve the existing experimental data which are available, two experiments, one for high energy (4.0 – 6.5 MeV center-of-mass) and the other for low energy (3.54 – 4.74 MeV center-of-mass), were performed at the Nuclear Science Laboratory of the University of Notre Dame. For both experiments, a cesium sputtering ion source produced negative ^{12}C ions for injection into a FN Tandem Van de Graaff electrostatic accelerator. The beam was passed through a 90° analyzing magnet monitored by a NMR probe to select the charge state and energy of interest. A number of electric and magnet steering elements were used to focus the beam on a carbon target. The maximum beam current which could be delivered to the target was 1 pμa. In both cases, the β-rays from the residual ^{23}Mg decays were counted as a measure of the reaction cross-section. The specific setups for the two experiments are described below.

2.1. Thin target: 4.0 – 6.5 MeV center-of-mass
A diagram of the experimental setup is shown in Figure 2a. The ^{12}C beam impinged on a thin carbon target (20 μg/cm^2) which was held by a target ladder upstream from an annular-shaped catcher attached to a motor-controlled wheel. As the beam reacted with ^{12}C in the target, ^{23}Mg was expelled onto the catcher. In considering the 11 second half-life of ^{23}Mg beta decay, the target was irradiated for 20 seconds after which the catcher was rotated 180° to a plastic scintillating detector used to detect the positrons from the ensuing ^{23}Mg β-decays. The counting period lasted for 40 seconds then the catcher was rotated back into the irradiation position and the procedure was repeated. This cycle was repeated until sufficient counting statistics were obtained. In order to measure the amount of beam going to the target, a Faraday cup was positioned behind the catcher and the beam was collected through a small hole in the catcher. For each run, the current was measured while the catcher was in position and compared with a measurement where the catcher was moved out from behind the target. The difference in the two readings was always negligible meaning that the beam passed uninhibited through the center of the catcher. Since the charge state of the beam was altered upon passing through the target material, the current ratio between successive runs where the target was removed and then moved into position was recorded for each energy. This provided the normalization factor to convert the measured beam current to actual beam current impinging on the target. To help offset the effect of

carbon build-up on the target, multiple targets were used over the course of the experiment. A small Ge detector was placed at the target position outside the beam line to count the online γ-rays. This provided a measurement of the proton and alpha channels of the ^{12}C+^{12}C fusion reaction as well as a measure of the component of the neutron channel due to ^{23}Mg excited state populations. The Ge was surrounded by lead bricks to shield background radiation from the surrounding environment.
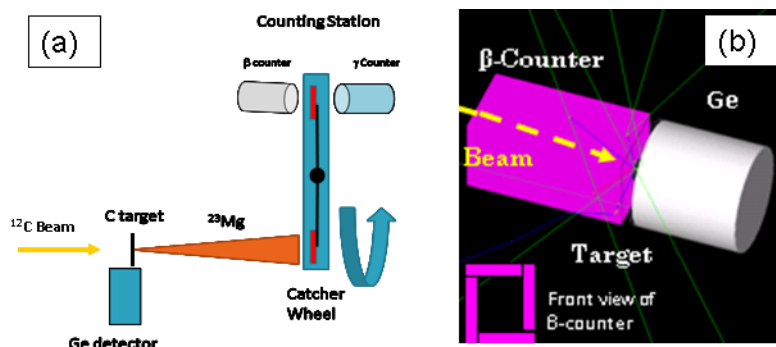

Figure 2. (a) shows the counting station for the thin target experiment. ^{23}Mg accumulates on the catcher and then is rotated to the β counting station. (b) shows the detection system for the thick target experiment. The beam irradiates a thick target which is surrounded on the front side by 4 plastic scintillating paddles (purple) .

2.2. Thick target: 3.54 – 4.74 MeV center-of-mass

As beam energies are pushed lower below the Coulomb barrier, the reaction cross-section begins to decrease more rapidly. To help offset this effect, higher beam currents are required, but this often leads to carbon build-up on the target which is a problem for thin-target measurements [5]. To remove this complication, a thick target can be employed for low-energy measurements. In this experiment, a thick graphite target was positioned at the back of a Faraday cup and surrounded on all sides by a plastic scintillating detector (see figure 2b). The target was thick enough so that the beam and reaction products were stopped entirely inside the target medium. The subsequent ^{23}Mg β-decays were detected by the scintillation detector. The time structure of the measurement was consistent with the thin target experiment in that the target was irradiated for 20 seconds followed by a 40 second counting period. A small Ge detector was placed behind the target, outside of the beam line to measure online γ-rays as well as decay γ-rays during the counting period. The plastic detector consisted of four individual paddle shapes of plastic measuring roughly 3 cm wide by 10 cm long, each coupled to its own photo-multiplier tube. The yields obtained from this detector were compared with the results from the other experiment and found to be consistent for the overlapping energies. In both cases, the characteristic half-life of the ^{23}Mg was pronounced in the decay spectra and found to be the dominant contribution at the relatively high beam energies. The remainder of the spectra was due to a flat background which consisted of PMT noise, activity from ^{24}Na ($t_{1/2} = 15$ h) resulting from ^{12}C+^{13}C fusion, and activity from ^{13}N ($t_{1/2} = 10$ min) resulting from reactions with hydrogen in the targets.

3. Results

The combined results of the two measurements are shown in figure 3 in the form of the modified s-factor (S*) which removes most of the energy-dependence from the reaction cross-section by factoring out the dominant Coulomb penetrability from the reaction cross-section including a next-order term accounting for the finite nuclear size of the reactants [4]. The new results are plotted with the results of Patterson et al. [4] and Dayras et al. [2]. They are consistent with the previous measurements, particularly in the resonance energies and strengths. However, the new data set provides a finer scan of the measured energy range with a step-size of 50 keV in the center-of-mass and gives a better outline of the excitation function. The other interesting point is that the measurements were able to extend as low in energy as the Dayras et al. measurements, but did not succeed in pushing lower. The main complication arises from background due to hydrogen in the targets, as mentioned above, combined with the reaction cross-section dropping off steeply at these low, sub-barrier energies. The

hydrogen in the target is believed to come from residual gases in the vacuum which originate from water vapor on the beam line components and hydrocarbons due to oil in the vacuum pumps and outgassing from the o-rings in the beam tubes. This problem has been recognized previously in studies of ^{12}C+^{12}C fusion and is discussed in [5]. Efforts have been made to prevent the build-up of hydrogen (and carbon) on targets by the use of a cold trap near the target and to remove any hydrogen contamination by heating the target to several hundred °C. Both methods have been explored in various experiments at Notre Dame with successful results, and plans are in place to implement them in the near future to push the measurements to lower energies than were ever measured previously.
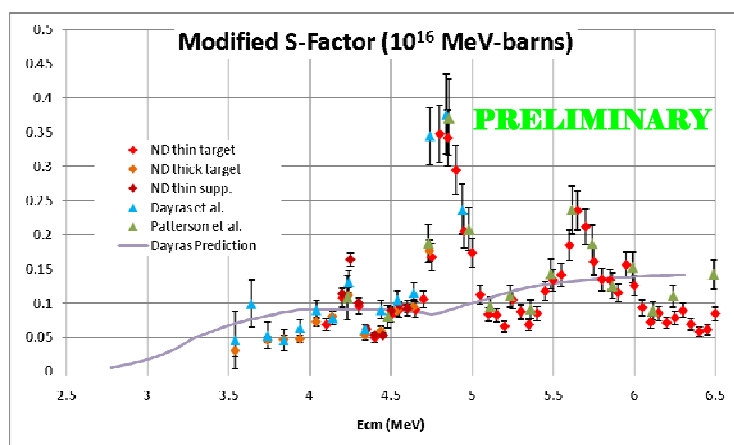

Figure 3. The combined results of the ^{12}C(^{12}C,n) measurements at Notre Dame are shown with the previous measurements of Patterson et al. [4] and Dayras et al. [2]. There is good agreement among the various data sets.

4. Improved Low-Energy Extrapolation

Due to the difficulties described in the previous section, direct measurement of the ^{12}C(^{12}C,n) cross-section in the energy range relevant to stellar shell C burning (below 3.2 MeV center-of-mass) has not yet been reached. As a result, stellar models must rely on an extrapolation of the cross-section down to the low energies occurring in stellar environments. Since the Dayras et al. [2] extrapolation is not capable of accounting for the likelihood of resonances in the low-energy region of the excitation function, we have looked for alternative methods to predict the cross-section at these low energies. Indeed, one can expect at least one resonance to exist in the low-energy portion of the ^{12}C(^{12}C,n) excitation function by examining the other exit channels, i.e. the proton and alpha channels. Measurements by Becker et al. [6] and, more recently, by Spillane et al. [7] both find resonances near 3 MeV and below in the proton and alpha channels. Since the high-energy resonances observed in the proton and alpha channels are also observed in the neutron channel, there is no reason to expect these low-energy resonances will not also occur in the neutron channel. This is, perhaps, even more evident by noting that the neutron and proton systems are mirror to each other, or isospin symmetric. The residual nuclei of the two channels, ^{23}Mg and ^{23}Na, are mirror nuclei and display nearly identical low-lying level structure. As a result, one should expect that the underlying nuclear force governing the level populations in each residual nucleus should be the same, and the only differences arise from the electromagnetic force. Since the proton channel has a positive Q-value (Q = 2.24 MeV), and accounts for a much larger fraction of the total fusion yield (~50%), this reaction has been measured down to lower energies by particle detection which allows partial cross-section measurements of each open channel in the ^{23}Na residual. These measurements were first done by Mazarakis et al. in 1973 [8] and later by Becker et al. [6]. Since Becker et al. measured a larger energy range with a finer step size, their measurements have been adopted here to calculate a corresponding neutron channel cross-section.
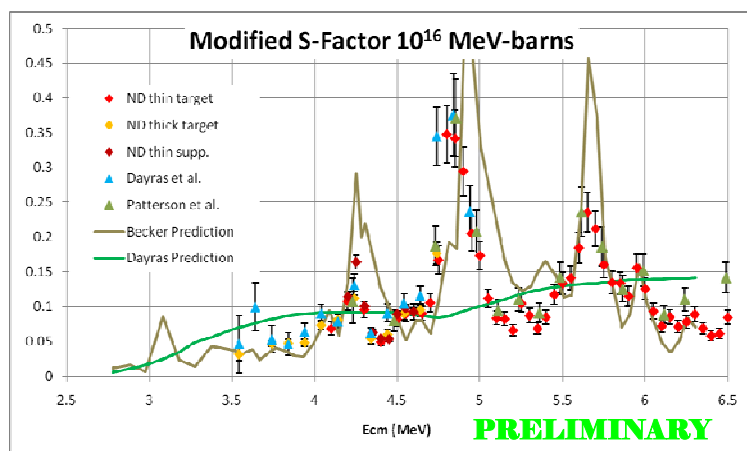
Figure 4. The neutron channel S* prediction generated from the Becker et al. proton measurements [6] (brown) are shown on top of the experimental neutron data. The number of resonances is reproduced but there is a clear mismatch of energy which may be an artefact of the digitization of the Becker et al. data. Also the relative strengths of the resonances do not agree between the prediction and data.

In order to calculate the expected neutron cross-section from the measured proton partial cross-sections, one must know how each open channel in the neutron channel relates to its counterpart in the proton channel. Since the neutron channel has a negative Q-value, there are much less open channels for a given beam energy than in the positive Q-valued proton channel. Therefore, these extra channels in the proton branch must be ignored and only the appropriate ones considered for each reaction energy. Then each channel must be renormalized by some energy-dependent factor which takes into account the difference in phase space and the fact that the proton must penetrate through the Coulomb barrier while the neutron escapes unhindered. The calculation of this normalization may not be so straight-forward and efforts are being made to determine a reliable method for this. However, for now, the statistical model code EMPIRE [9] has been used to calculate these factors. Applying these factors to the Becker et al. results which were obtained by software digitization of the S* plot from [6], results in a neutron S* shown in figure 4. One immediately sees that the number of resonances and relative positions are well-reproduced by the new prediction. There is a shift in the energies of the resonances and the relative strength of the resonances appears to be in conflict with the neutron channel measurements. Part of these discrepancies may arise from the digitization of the Becker et al. data which is a rather imprecise method for extracting numerical information. Motivated by these inconsistencies, nevertheless, particle measurements of the proton channel were made at Notre Dame to provide a check for the digitized Becker et al. data. The data are currently still being analyzed, but the preliminary results indicate resonance energies which agree with those observed in the neutron channel.

5. Astrophysical Rate Calculation

Using the neutron channel cross-section generated from the Becker et al. proton measurements [6] to calculate the stellar reaction rate as a function of temperature, one finds an enhancement in the rate which is primarily due to the low-energy resonance near 3.1 MeV. However, since the resonances observed in this measurement at high energies are shifted relative to the neutron measurements, the low-energy resonance energy predicted here is highly questionable. Then it is reasonable to suppose that the Becker et al. measurements might need to be shifted in energy by an appropriate amount in order to obtain agreement with the three, independent neutron data sets. If this is done, the resulting rate calculation shows an even stronger enhancement due to the shift of the low-energy resonance. The two stellar rate calculations are shown in Figure 5. It is clear that the reaction rate is sensitive to the energy of this low-energy resonance if, indeed, it exists.
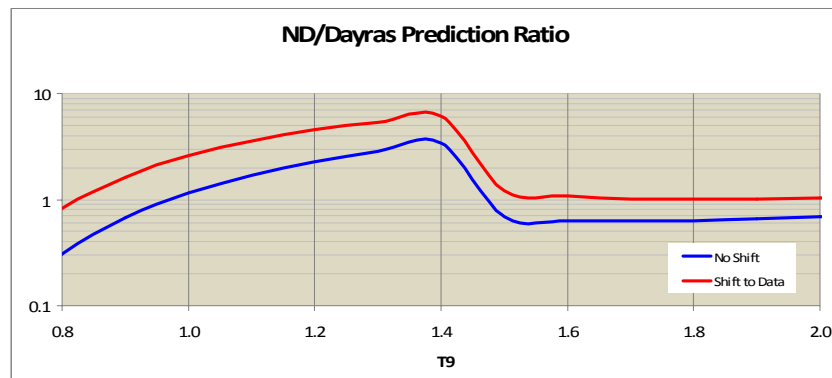
Figure 5. The ratios of reaction rates vs. temperature between the prediction based on the Becker et al. proton measurements [6] and the standard Dayras et al. rate [2] are shown above. Two ratios are calculated for the cases where the energy scale of the Becker et al. measurements is left untouched (blue) and where the energy scale has been shifted down by 80 keV to better match the neutron data sets (red). The sensitivity to the low-energy resonance is evident by the rate change. The difference at T_9 of 1.1 (typical of shell C burning) is a factor of 2 vs. a factor of 4 enhancement in the rate.

6. Conclusion

The results discussed in this report are still preliminary, but it seems likely that the stellar rate of $^{12}C(^{12}C,n)$ is greater than the rate predicted by Dayras et al. [2]. Ultimately, direct measurements of this reaction at the relevant low energies will give the final word on the stellar reaction rate, but these measurements are hindered by a low cross-section and high background. Until these measurements can be made, it is important to provide the most reliable extrapolation for stellar models. Exploiting the isospin symmetry in the $^{12}C+^{12}C$ fusion reaction seems to be a promising method for providing such a reliable extrapolation. Though more work needs to be done, we hope to provide such a result in the near future which can be used with confidence in stellar models until experiment is able to provide the necessary direct measurements.

7. Acknowledgment

References

[1] Pignatari M, Gallino R, Heil M, Wiescher M, Käppeler F, Herwig F and Bisterzo S 2010 *Astrophys J* **710** 1557
[2] Dayras R, Switkowski Z E and Woosley S E 1977 *Nucl Phys* **A279** 70
[3] Pignatari M Priv Comm
[4] Patterson J R, Winkler H and Zaidins C S 1969 *Astrophys J* **157** 367
[5] Aguilera E F, Rosales P, Martinez-Quiroz E, Murillo G and Fernandez M C 2006 *Nuc Instr Meth B* **244** 427
[6] Becker H W, Kettner K U, Rolfs C and Trautvetter H P 1981 *Z Phys A* **303** 305
[7] Spillane T, Raiola F, Rolfs C, Schürmann D, Strieder F, Zeng S, Becker H W, Bordeanu C, Gialanella L and Romano M 2007 *Phys Rev Lett* **98** 122501
[8] Mazarakis M and Stephens W 1973 *Phys Rev C* **7** 1280
[9] Herman M, Capote R, Carlson B V, Oblozinsky P, Sin M, Trkov A, Wienke H and Zerkin V 2007 *Nuc Data Sheets* **108** 2655