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# HOW DOES THE CARBON FUSION REACTION HAPPEN IN STARS?

The $^{12}$C + $^{12}$C fusion reaction is one of the most important reactions in the stellar evolution. Due to its complicated reaction mechanism, there is great uncertainty in the reaction rate which limits our understanding of various stellar objects, such as explosions on the surface of neutron stars, white dwarf (type Ia) supernovae, and massive stellar evolution. In this paper, I will review the challenges in the study of carbon burning. I will also report recent results from our studies: 1) an upper limit for the $^{12}$C + $^{12}$C fusion cross sections, 2) measurement of the $^{12}$C + $^{12}$C at deep sub-barrier energies, 3) a new measurement of the $^{12}$C($^{12}$C, n) reaction. The outlook for the studies of the astrophysical heavy-ion fusion reactions will also be presented.

*Keywords*: $^{12}$C + $^{12}$C, fusion reaction, stellar evolution.

## 1. Introduction

In 1960 Almqvist, Kuehner and Bromley discovered several resonances in collisions between $^{12}$C nuclei. For at least three energies, $E_{c.m.}$ = 5.68, 6.00 and 6.32 MeV, they observed increased yields for the reaction products: $p$, $\alpha$, n and $\gamma$. These resonances have characteristic widths of about 100 keV and were interpreted as signatures for the formation of nuclear molecules [1 - 3]. In the following years, the discoveries of such resonances continued down to the lowest energies. For instance, the most recent published measurement of the $^{12}$C + $^{12}$C fusion reported a strong resonance at $E_{c.m.}$ = 2.14 MeV [4].

Apart from its interest to nuclear reaction studies, the $^{12}$C + $^{12}$C fusion reaction also plays a crucial role in a number of important astrophysical scenarios, such as explosions on the surface of neutron stars, white dwarf (type Ia) supernovae, and massive stellar evolution [5]. For astrophysics, the important energy range extends from 1 to 3 MeV in the center of mass frame, which is only partially covered by experiments. Therefore, an extrapolation is the only resource available to obtain the reaction rate for astrophysical applications. The currently adopted reaction rate is established based on the modified S* factor

$$S^*(E_{c.m.}) = \sigma(E_{c.m.})E_{c.m.}\exp\left(\frac{87.21}{\sqrt{E}_{c.m.}} + 0.46E_{c.m.}\right) \quad (1)$$

An S* factor of $3 \cdot 10^{16}$ MeV · b was obtained by fitting the data measured by Patterson [6], Spinka [7] and Becker [8]. This averaged value was extrapolated towards lower energies by assuming that the averaged S* factor remains constant at sub-barrier energies [6, 9]. At present, there is nothing known about the energies and strengths of resonances in the energy region below $E_{c.m.}$ = 2 MeV. Besides this uncertainty, the recent study of fusion hindrance has suggested a new extrapolation which is smaller than the adopted one [5, 10]. Therefore, our understanding of the $^{12}$C + $^{12}$C fusion rate is highly uncertain.

## 2. The experimental efforts at Notre Dame

To aid in the understanding of this reaction, the carbon fusion project at Notre Dame was established in 2007 with the aim of measuring the reaction cross section and decay branches at low energies as well as providing a reliable extrapolation into the energies that cannot be reached by experiment. In this paper, we report on three studies: 1) an upper limit for the $^{12}$C + $^{12}$C total fusion cross section at astrophysical energies, 2) the measurement of the $^{12}$C + $^{12}$C fusion cross sections at deep sub-barrier energies, 3) a measurement of the neutron branching at low-energy with an improved extrapolation based on the mirror reaction channel, $^{12}$C($^{12}$C, p).

### 2.1. An upper limit for the $^{12}$C + $^{12}$C fusion cross sections

The primary goal of this work was to study the carbon isotope fusion reactions, which display a much smoother excitation function than $^{12}$C + $^{12}$C, at sub-barrier energies in hope to find a better model for the general behavior of $^{12}C + ^{12}C$ at these energies. The modeling of $^{12}C + ^{12}C$ itself is complicated by the potential existence of large resonances, whereas this complication appears to be absent from the isotope reactions. For example, the most recently published measurement at energies below 3 MeV center-of-mass (the energy range of astrophysical interest is 1 - 3 MeV) by Spillane et al. shows a large, narrow resonance at 2.14 MeV [4]. An even stronger resonance at 1.5 MeV is proposed by Cooper et al. based on comparisons between superburst models and observations [10]. By looking at the isotope systems, one can effectively remove the added complication from the resonant structure and more easily study the general behavior of the $^{12}C + ^{12}C$ fusion reaction.

The $^{12}C + ^{13}C$ fusion reaction was measured at Notre Dame with the goal of extending the already existing data from [12] to lower energies. The 11 MV FN tandem accelerator at Notre Dame was used to provide beams of $^{13}C$ ions with intensities up to 1 pμA for bombardment on a thick graphite target. The details of the measurement are given in [13], but the main idea was to measure $^{13}C(^{12}C, p)^{24}Na$ by counting the beta decays from the residual $^{24}Na$ ($t_{1/2}$ = 15 h) using the beta-gamma coincidence technique. After correcting for the contributions from the other decay branches, the total fusion cross section measurements were extended down below 2.7 MeV c.m. where the cross section value drops to 20 nb (a factor of 50 less than the previous lowest measurement). The new data shows good agreement with the data from [12] in the overlapping energies (Fig. 1).

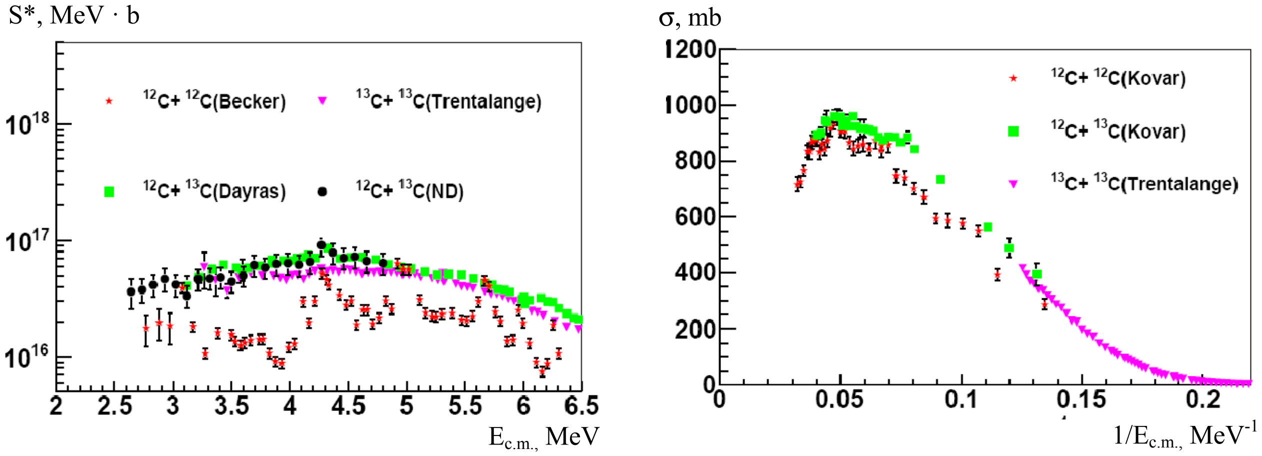

Fig. 1. (Left) The experimental S* factors of three carbon-isotope fusion reactions around or below the Coulomb barrier: $^{12}C + ^{12}C$ (red stars) [8], $^{12}C+^{13}C$ from Ref. [13] (black points) and Ref. [12] (green squares), and $^{13}C + ^{13}C$ [14] (magenta triangles). The systematic uncertainties, 30 % for the $^{12}C + ^{12}C$ data, 15 % for the $^{13}C + ^{13}C$ data, and 30 % for the $^{12}C + ^{13}C$ data from Ref. [12] [$^{12}C + ^{13}C$ (Dayras)], are not shown in the graph. The $^{12}C+^{13}C$ data reported in Ref. [13] [$^{12}C + ^{13}C$(ND)] are dominated by a 20 % systematic uncertainty, which is included in this graph. (Right) The experimental cross sections of three carbon-isotope fusion reactions above the Coulomb barrier: $^{12}C + ^{12}C$ (red points) [15], $^{12}C + ^{13}C$ (green squares) [15] and $^{13}C + ^{13}C$ [14] (magenta triangles). (See color Figure online.)

When the $^{13}C + ^{13}C$ and $^{12}C + ^{12}C$ excitation functions from [14] and [8], respectively, are plotted together with the $^{12}C + ^{13}C$ using the cross section factor defined by Eq. (1), which is traditionally used to study the $^{12}C + ^{12}C$ fusion reaction [6], a striking correlation is realized. The $^{12}C + ^{12}C$ cross section is suppressed relative to the isotope fusion reactions except at the resonant energies where the cross sections are in an excellent agreement! The two isotope systems agree with each other within the systematic uncertainties of the measurements. Considering a systematic uncertainty of 15 - 30 % for the data from Refs. [8, 12, 14] (not shown in Fig. 1), the major resonant cross sections of $^{12}C + ^{12}C$ (Er = 3.1, 4.3, 4.9, 5.7, 6.0, and 6.3 MeV) match remarkably well with the fusion cross sections of the other two carbon isotope combinations within their quoted uncertainties. This correlation between $^{12}C + ^{12}C$ and the isotope reactions holds from the highest measured energy, ~40 MeV, down to the lowest measured energy, 2.7 MeV, in Ref. [8]. In other words, the isotope fusion reactions provide an upper bound on the $^{12}C + ^{12}C$ fusion within the measured energy ranges [13].

Since the isotope excitation functions behave relatively smoothly with energy, they are much more easily modeled. In order to extrapolate the isotope reactions down to the lower, unmeasured energies, a coupled-channels calculation was performed based on the M3Y+repulsion double-folding potential with ingoing-wave-boundary-conditions (IWBC). The details of the calculation are given in [16]. The results of the calculation agree with the experimental data within the systematic uncertainty over the

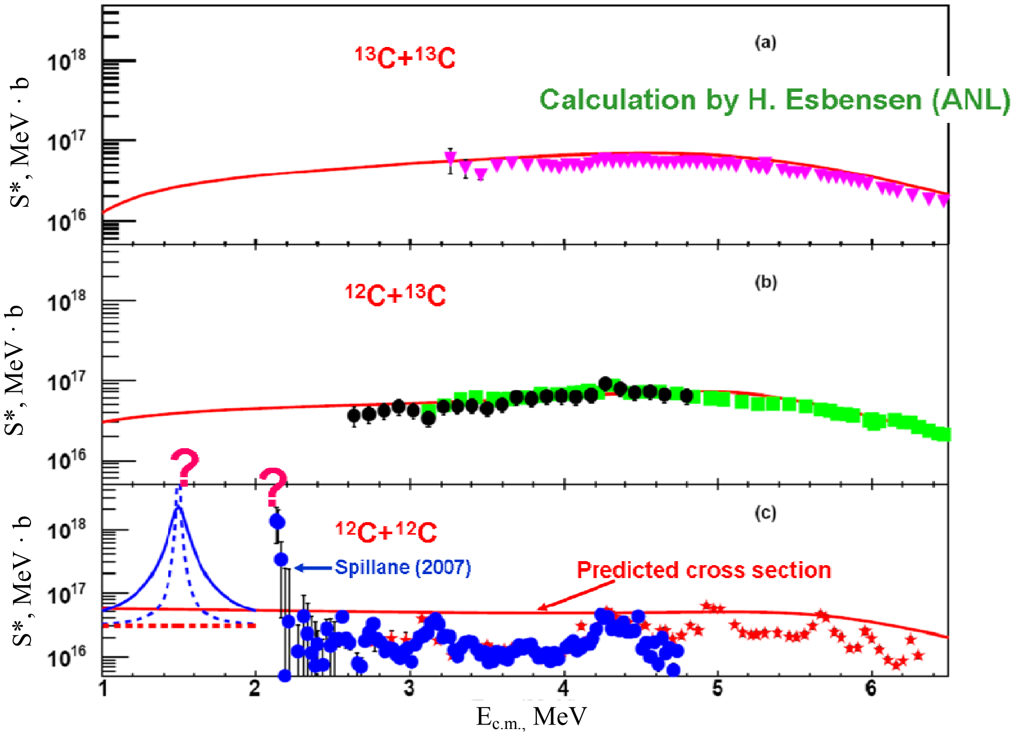

Fig. 2. The coupled channels calculations for: (*a*) $^{13}C + ^{13}C$ with data from [14]; (*b*) $^{12}C + ^{13}C$ with data from [12] (squares) and new ND data (circles) [13]; (*c*) $^{12}C + ^{12}C$ with data from [8] (stars) and [4] (circles). The calculations show good agreement with the experimental data of the isotope systems down to the lowest measured energies. For the $^{12}C + ^{12}C$ system, the calculation matches very well at the resonance energies excepting the last two points of the Spillane et al. data set [4] and the hypothetical Cooper resonance [11]. (See color Figure online.)

measured energy range (Fig. 2). The parameters for the nuclear potentials used in the isotope fusion calculations were then used to constrain the potential for $^{12}C + ^{12}C$. The result of this calculation is in very good agreement with the experimental resonant cross section values except for the lowest few data points defining the large 2.14 MeV resonance measured in [4]. Considering the difficulty of this measurement, peculiarities raised in [13], and the fact that a subsequent measurement by the same group observed a much weaker resonance [17] (within the upper limit established here), these last few data points are questionable and in need of further experimental confirmation. The hypothetical resonance predicted in [11] deviates to even larger values above our upper limit leaving its existence in doubt at this moment.

It is interesting to note that the coupled channel prediction based on IWBC does not describe the average trend of the cross sections, but rather matches the observed $^{12}C + ^{12}C$ peak cross sections. Here we provide a qualitative explanation for our results, which is based on the intrinsic excited nuclear molecule model (Nogami - Imanishi model) [18]. In this model, the resonances of $^{12}C + ^{12}C$ are explained as the result of a coupling effect between the elastic channel and the inelastic channels, such as $^{12}C(0^+$, g.s.$) + ^{12}C(2^+$,4.44 MeV) and $^{12}C(2^+$, 4.44 MeV$) + ^{12}C(2^+$,4.44 MeV). The resonances only happen at certain energies when the ingoing wave matches the inner boundaries for the formation of molecular states. For $^{12}C + ^{12}C$, the resonances are isolated because of the low level density for the molecular states. For the isotope systems ($^{12}C + ^{13}C$ and $^{13}C + ^{13}C$), the $^{12}C + ^{12}C$ core or $^{12}C$ core + $^{12}C$ core may still behave in a way similar to the $^{12}C + ^{12}C$ system. The addition of one or two valence neutrons significantly increases the level density of the molecular states and leads to much more relaxed boundary condition to be matched with the ingoing wave. Therefore, the coupled-channels calculation with IWBC becomes a reasonable approximation for the isotope systems because of their higher level densities than the $^{12}C + ^{12}C$ system. However, the $^{12}C + ^{12}C$ fusion cross sections could only match with the isotope systems at several resonant energies because the level density of the molecular states is low. To verify this qualitative explanation, detailed coupled channel calculations are urgently needed to investigate the role of the valence neutron in the carbon isotope fusion process.

### 2.2. Measurements at deep sub-barrier energies

The measurements at deep sub-barrier energies are important for us to understand the reaction mechanism and provide a more reliable extrapolation towards the region which can not be covered by current experiments. It is also interesting to test the upper limit we have proposed based on our study on carbon isotope fusions. There are two difficulties in measurements: 1. How to identify the few fusion events from the intense background? 2. How to connect the observable reaction channels with the total fusion cross section?

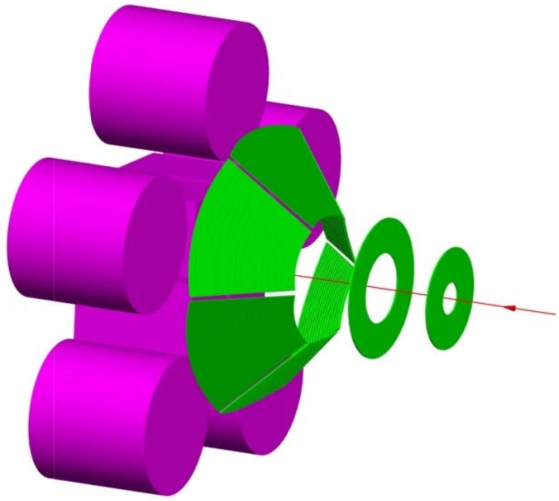

Fig. 3. Setup for SAND silicon detector array (green) in coincidence with GEORGINA gamma detector array (magenta). The direction of $^{12}$C beam is indicated by the red arrow. The thick target on the surface of gamma detectors is blocked by the silicon detectors. (See color Figure online.)

At Notre Dame, we are preparing two experiments: 1) particle-gamma coincidence with GEORGINA (a compact Ge detector array) and SAND (a silicon array covering 2π solid angle) and 2) charged particle detection with a HELIOS-type solenoid spectrometer [19]. In the first approach, the SAND array provides the energy and angle of the light charged particles with which a unique reaction Q-value can be constructed for each decay channel while the GEORGINA array records the energies of emitted gamma-rays. With the coincidence between the two detector arrays, we can greatly suppress contributions from cosmic and room background. To avoid the target thickness variation during the experiment, a 1-mm thick HOPG (Highly Ordered Pyrolytic Graphite) target will be used in the experiment. A test experiment has been done at $E_{\text{c.m.}}$ = 4, 4.5 and 5 MeV using the ATLAS facility at ANL [20]. In this test, a 20 μg/cm$^2$ thin $^{12}$C target was used. The light charged particles and the emitted gamma rays were detected by a large area strip detector and Gammasphere, respectively. The particle-gamma coincidence experiment with GEORGINA and SAND will take place latter this year at Notre Dame when the new 5 MV single end accelerator delivers high intensity $^{12}$C beam.

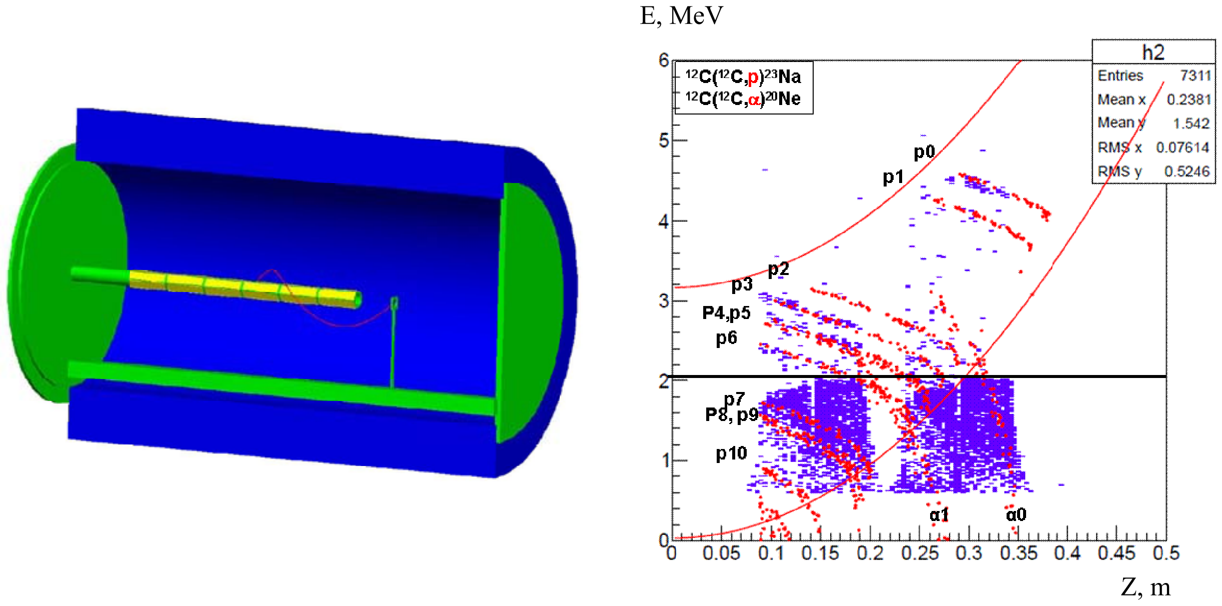

Fig. 4. (Left) The SSNAP solenoid spectrometer at Notre Dame. The beam goes from left to right through the hollow tube and hits the target. A reaction product is emitted at a backward angle and bent back to the axis after one cyclotron period. The 31-cm long position-sensitive Silicon detector located on the axis, records energy, target-to-detector position and TOF with respect to beam pulses. There was only two silicon detectors used in our test. The target distance from the beginning of detector array was set as 8 cm and 23 cm, respectively, to cover a longer distance. The diameter of the vacuum chamber is 28 cm. (Right) The energy vs. position spectrum measured for $^{12}$C + $^{12}$C fusion reaction at $E_{\text{c.m.}}$ = 4 MeV. A 5.7 μm thick aluminum foil was placed before the detectors to stop scattered $^{12}$C particles. The blue points are the experimental result while the red points are produced by a GEANT4 simulation. The $p_0$ and $p_1$ channels are clearly separated from the background which dominates the region below 2 MeV. The scattered points between the $p_1$ and $p_2$ groups may come from the $^{12}$C + $^{13}$C reaction. The two red lines show the acceptance of the spectrometer. (See color Figure online.)

Even though the particle-gamma coincidence provides a much cleaner background than any past experiments using either particle detectors or Ge detectors, there are transitions that only emit particles without gamma-rays (e.g. Transition to ground states of fusion residues) for which the solenoid spectrometer seems to be a better approach. In this approach, both the target and detector are placed on the axis of a uniform magnetic field while the light charged particles generated at the target move on helical orbits and are bent back to the axis after one cyclotron period. The position-sensitive silicon detector array, located on the axis, records energy, target-to-detector position and TOF with respect to beam pulses. The position and the energy of the particles translate into the desired information of excitation energy and center-of-mass angle. A study of the $^{12}C + ^{12}C$ fusion reaction has been done at $E_{c.m.} = 4$, 5 and 6 MeV using one of the existing solenoids of the TWINSOL facility at Notre Dame. Two $1 \times 5$ cm$^2$ 1-D position sensitive detectors were placed around the axis at the upstream direction with respect to the 20 μg/cm$^2$ thick carbon foil. The closest distance between the detectors and target were set as 8 cm initially and latter increased to 23 cm to cover longer distance. To stop the scattered $^{12}C$ particles from reaching the detectors, a 5.7 μm Aluminum degrader was placed on the surface of detectors. The spectrum of the detected energy vs. position plot shown in Fig. 4 indicates that a clean observation of the transitions to the ground state of $^{23}Na$ has been achieved. We are working on the beam collimation system with a hope to get clean observation of the $\alpha_0$ channel in the near future. Meanwhile, it is necessary to look for funding to build a complete silicon array so that the measurement can be efficiently carried out at lower energies.

Because of the complication of the decay schemes of the fusion residues, it is a great challenge to get the total fusion cross section from the observable decay channels. For example, in the past, gamma ray measurements were only focused on the cross sections to two characteristic lines, 440 keV for $^{23}Na$ and 1634 keV for $^{20}Ne$. The charged particle measurements were limited to the channels above the huge background incurred by the H/D contaminants in target. In most analyses in the past, the total $^{12}C + ^{12}C$ fusion cross sections were obtained by a simple summation of the observed decay channels. Using a statistical model, we have estimated the contribution from those unobserved channels. The theoretical result was compared with the predicted cross section based on the partial cross sections measured by Becker et al. [8]. The results shown in Figs. 5 and 6 suggest that the total fusion cross section in the range of 1 to 3 MeV can be determined by combining the infor-

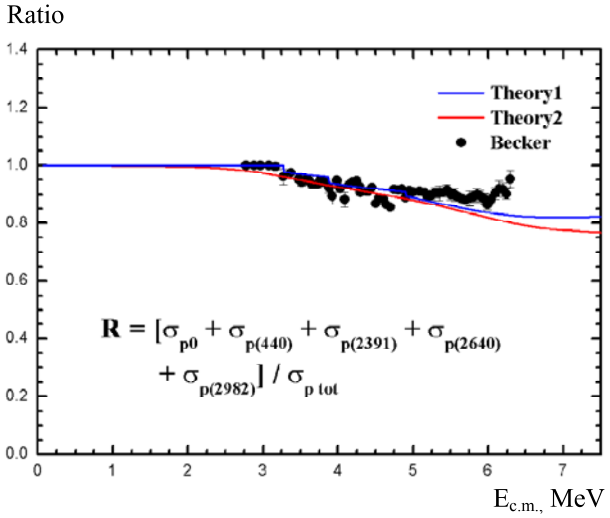

Fig. 5. The ratio of the sum of several observable proton channels to the total cross section of the proton channel ($\sigma_{ptot}$). In the graph, $\sigma_{p0}$ is the cross section for the proton channel to the ground state of $^{23}Na$. $\sigma_{p(440)}$, $\sigma_{p(2391)}$, $\sigma_{p(2640)}$ and $\sigma_{p(2982)}$ are corresponding to the cross sections of the gamma transitions of $^{23}Na$, (440 keV→0), (2390 keV→0), (2639 keV→0) and (2982 keV→0), respectively. The black points are the predicted ratio based on the observed proton cross sections by Becker et al. [8] and the known level scheme. The red line (Theory 1) is a prediction by TALYS [21]. In the experimental data, there are various energy limits for different channels because of the complicated background. To simulate this effect, the experimental energy limits are included in the TALYS calculation and the result is shown as the blue line (Theory 2). (See color Figure online.)

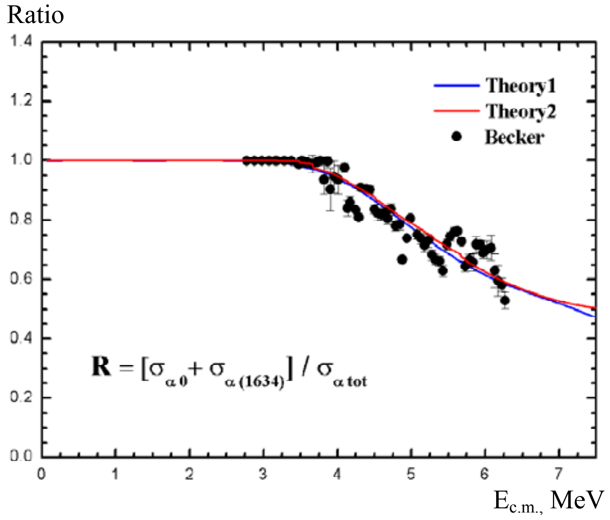

Fig. 6. The ratio of the sum of two observable alpha channels to the total cross section of the alpha channel. In the graph, $\sigma_{\alpha 0}$ is the cross section for the alpha channel to the ground state of $^{20}Ne$. $\sigma_{\alpha(1634)}$ is the cross sections for the gamma transition of $^{20}Ne$, (1634 keV→0). The blue and red lines are the predications with TALYS [21]. See the caption of Fig. 5 for more details. (See color Figure online.)

mation from both particle detection and gamma-ray detections. The fraction for the missing decay channels is well controlled below 4 % at astrophysical relevant energies.

With the combinations of the new high current 5 MV accelerator at Notre Dame and the two new highly efficient detection techniques, a great improvement in the detection yield will be achieved. By comparing our approaches with the Naples experiment [17], we expect the detection yield will be improved by one or two orders of magnitudes, depending on the details of the detector configuration. The lowest event rate measured by the Naples experiment is 0.5 evt/day when $E_{c.m.}$ = 2.1 MeV. If we were lucky and achieved an improvement on the detection yield by two orders of magnitude, this would bring the lowest measured energy down to 1.7 MeV. To map the $^{12}C + ^{12}C$ resonance below 1.7 MeV, we are collaborating with collaborators at the Research Center for Nuclear Physics (RCNP) at Osaka University on a complimentary approach of using the $^{24}Mg(\alpha, \alpha')$ reaction to search the resonances in $^{24}Mg$ which may contribute to the $^{12}C$ fusion cross section at astrophysical energies.

### 2.3. The low-energy resonances in the $^{12}C(^{12}C, n)^{23}Mg$ reaction cross section

Carbon burning in the various astrophysical environments proceeds through 3 main reaction channels: $^{12}C(^{12}C, \alpha)^{20}Ne$ (Q = 4.6 MeV), $^{12}C(^{12}C, p)^{23}Na$ (Q = 2.2 MeV), and $^{12}C(^{12}C, n)^{23}Mg$ (Q =-2.6 MeV). At typical astrophysical energies, the contribution from the neutron branch is estimated to be less than 1 % of the total fusion yield. However, this still may be a significant amount to aid in the nucleosynthesis of heavy elements during the weak s-process occurring in massive stars. 1-D massive star models indicate a sensitivity of the abundances produced during shell-carbon burning to this reaction [22]. Isotopes between 60 < A < 110 are most affected with a typical production increase of ~30 % for a factor of 5 enhancement over the standard Dayras et al. branching ratio [23], depending on the specifics of the model. A typical temperature in the shell-carbon burning environment is 1.1 GK which means the relevant astrophysical energies are from ~3.2 MeV down to threshold at 2.6 MeV. The currently existing experimental data stops above 3.5 MeV [6, 21], so stellar models must rely on an extrapolation of the data to the relevant energies. The standard extrapolation is based on a statistical model calculation which is unable to account for the resonant contribution to the rate that is likely important (Fig. 7).

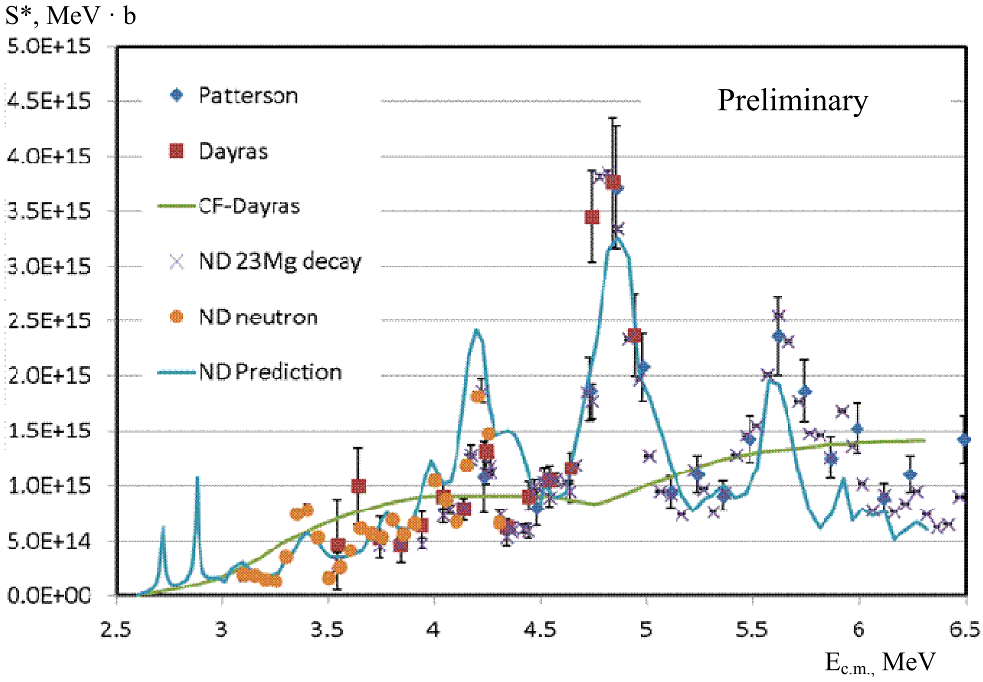

Fig. 7. The existing $^{12}C(^{12}C, p)$ data from Ref. [6] (Patterson) and [23] (Dayras). The statistical model prediction by Dayras et al. is shown as the green line. The important energy range for shell carbon burning extends from 2.8 to 3.2 MeV. Our new prediction based on the measured proton channel data is shown in the blue line. For $E_{c.m.}$ > 3 MeV, the proton data used in the prediction were measured at Notre Dame. The two resonances at the energies below 3 MeV is predicted with resonance information obtained from the observation of the $p_0$ and $p_1$ channels reported in [17]. The new measurements from Notre Dame are labeled as purple crosses and orange circles. (See color Figure online.)

The reaction cross section was measured from 6.5 MeV down to 3.1 MeV using $^{12}$C beams produced with the FN tandem accelerator at Notre Dame. Two different approaches have been used to study the neutron channel. The first approach is to detect the $^{23}$Mg ($t_{1/2}$ = 11.317 s) $\beta^+$ decay using a plastic scintillator. In the experiment, a thin carbon target (thickness 20 μg/cm$^2$) was used, and the $^{23}$Mg reaction product was collected using an aluminum catcher placed behind the target. After 20 s of target irradiation, the $^{23}$Mg $\beta^+$ decays were counted for 40 s after which the process was repeated until sufficient statistics were achieved. The combination of high background yield arising from the hydrogen contaminant in targets and low fusion yield prevented useful measurements below 3.5 MeV. The second method is to detect the neutron directly with a highly efficient $^3$He detector array. To minimize the hydrogen contaminant, a 1-mm thick HOPG target was used. A LN$_2$ cooled cooper tube was placed just before the target to prevent hydrogen contamination from the vacuum. With these measurements, the measurement was pushed down to 3.1 MeV.

We also developed a new extrapolation method to accommodate the complicated resonant feature in the $^{12}$C + $^{12}$C fusion reaction and provide a more reliable prediction for the cross sections at the energies below the experimental limit. In this new method, we take the advantage that any neutron branch $n_i$ (i is corresponding to the i$^{th}$ excited state in $^{23}$Mg) is exactly the mirror reaction channel for the proton branch $p_i$ (i is corresponding to the i$^{th}$ excited state in $^{23}$Na). Any resonance existing in the $^{12}$C + $^{12}$C channel would imprint itself in both proton and the corresponding neutron channels. The code EMPIRE [24] was used to calculate the corresponding ratios between the mirror branches, $p_i$ and $n_i$. Then considering all the open $n_i$'s for a given energy (below 4.6 MeV, only $n_0$ and $n_1$ are open), a total neutron production cross section is generated based on the corresponding $p_i$ production cross sections. The predicted cross sections based on the proton channels are shown in Fig. 7. The results show remarkable accuracy with the measured neutron data and extend into the experimentally inaccessible energy range (see Fig. 2). For most data points, the deviations between the prediction and the measurement are less than 40 %. This discrepancy is not surprising because the optical models used in EMPIRE only describe the average penetrabilties for the $p_i + {}^{23}$Na and $n_i + {}^{23}$Mg. The predicted resonance at 3.4 MeV has been confirmed by our recent measurement using neutron detection. Two more sharp resonances are predicted at energies below 3 MeV based on the experimental data from Ref. [17]. The corresponding new reaction rate is about a factor of 2 of what Dayras has recommended. This leads to the conclusion that the $^{12}$C($^{12}$C, n) role in the weak s-process of Population I massive stars is quite limited compared with the major neutron source, $^{22}$Ne(α, n). The impact to other relevant astrophysical scenarios, such as the nucleosynthesis in metal poor massive stars and explosive carbon burning, is being studied.

## 3. Summary and outlook

The study of the $^{12}$C + $^{12}$C fusion process at deep sub-barrier energies represents a main challenge in nuclear astrophysics. At Notre Dame, we have established an upper limit for the $^{12}$C + $^{12}$C fusion cross sections within the astrophysical energy range. We are developing two different approaches which will enable us to precisely study this important fusion process at lowest energies than have ever been reached in any past experiments. We also collaborate with collaborators at the Research Center for Nuclear Physics (RCNP) at Osaka University on a complimentary approach of using the $^{24}$Mg(α, α') reaction to search the resonances in $^{24}$Mg which may contribute to the $^{12}$C fusion cross section at astrophysical energies. The new measurement of the $^{12}$C($^{12}$C, n) channel and the new extrapolation technique reduced the existing ambiguities in the weak s-process for Population I massive stars.

Besides $^{12}$C + $^{12}$C, the $^{12}$C + $^{16}$O and $^{16}$O + $^{16}$O fusion reactions are also important for nuclear astrophysics. At sub-barrier energies, there are still many mysteries, such as the molecular resonance, hindrance effect and correlation within the isotope systems, which can only be addressed with better experimental data and better theory. The new 5 MV single end accelerator with an Electron Cyclotron Resonance source will soon provide high-current heavy ion beams at Notre Dame. With improvements of the detection techniques discussed in this paper, better experimental data can be expected in the near future.

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## ЯК ВІДБУВАЄТЬСЯ НА ЗІРКАХ РЕАКЦІЯ ЗЛИТТЯ ЯДЕР ВУГЛЕЦЮ?

Реакція злиття $^{12}$C + $^{12}$C є однією з найбільш важливих в еволюції зірок. Через складний механізм реакції існує велика невизначеність в її швидкості, що обмежує рівень нашого розуміння різних зоряних об’єктів, таких як еволюція масивних зірок, вибухи нейтронних зірок і супернових при наростанні маси білих карликових зірок. У статті наведено огляд задач, що виникають при вивченні згоряння вуглецю. Наведено також результати недавніх наших досліджень: 1) верхня межа перетину реакції злиття $^{12}$C + $^{12}$C, 2) вимірювання реакції $^{12}$C + $^{12}$C при глибокопідбар’єрних енергіях, 3) нові вимірювання реакції $^{12}$C + $^{12}$C. Представлено також огляд досліджень по злиттю важких іонів.

*Ключові слова*: $^{12}$C + $^{12}$C, реакція злиття, еволюція зірок.

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## КАК ПРОИСХОДИТ НА ЗВЕЗДАХ РЕАКЦИЯ СЛИЯНИЯ ЯДЕР УГЛЕРОДА?

Реакция слияния $^{12}$C + $^{12}$C является одной из наиболее важных в эволюции звезд. Из-за сложного механизма реакции существует большая неопределенность в ее скорости, что ограничивает уровень нашего понимания различных звездных объектов, таких как эволюция массивных звезд, взрывы нейтронных звезд и суперновых при нарастании массы белых карликовых звезд. В статье приведен обзор задач, возникающих при изучении сгорания углерода. Приведены также результаты недавних наших исследований: 1) верхний предел сечения реакции слияния $^{12}$C + $^{12}$C, 2) измерение реакции $^{12}$C + $^{12}$C при глубокоподбарьерных энергиях, 3) новые измерения реакции $^{12}$C + $^{12}$C. Представлен также обзор исследований по слиянию тяжелых ионов.

*Ключевые слова*: $^{12}$C + $^{12}$C, реакция слияния, эволюция звезд.

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