EPJ Web of Conferences **109**, 09003 (2016)
DOI: 10.1051/epjconf/201610909003

# Fusion cross section of $^{12}$C+$^{13}$C at sub-barrier energies

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**Abstract.** In the recent work at Notre Dame, correlations between three carbon isotope fusion systems have been studied and it is found that the fusion cross sections of $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C provide an upper limit on the fusion cross section of the astrophysically important $^{12}$C+$^{12}$C reaction. The aim of this work is to continue such research by measuring the fusion cross section of the $^{12}$C+$^{13}$C reaction to lower energies. In this experiment, the off-line activity measurement was performed in the ultra-low background laboratory and the fusion cross section for $^{12}$C+$^{13}$C has been determined in the energy range of $E_{c.m.}$=2.5-6.8 MeV. Comparison between this work and several models is also presented.

## 1 Introduction

Heavy-ion fusion reactions between light nuclei such as carbon and oxygen isotopes have been intensively studied because of their importance in a wide variety of stellar burning scenarios. Among them, carbon burning driven by the $^{12}$C+$^{12}$C fusion is a crucial process for the formation of white dwarfs, nucleosynthesis in massive stars, and ignition in type Ia supernovae and superbursts [1, 2]. The temperatures for the hydrostatic carbon burning process range from 0.8 to 1.2 GK, corresponding to $E_{c.m.}$=1-3 MeV. Unfortunately, because of the very low cross sections, this important energy range is only partially measured at energies above $E_{c.m.}$=2.1 MeV. For the unmeasured energy ranges, one has to rely on extrapolation methods. Moreover, the situation is further complicated by the existence of the strong, relatively narrow resonances in $^{12}$C+$^{12}$C reactions. The large resonance reported at energies around $E_{c.m.}$= 2.1 MeV has not been confirmed by following experiment [3].

In an attempt to learn about the resonance structures of the low-energy $^{12}$C+$^{12}$C reaction, the carbon isotope fusion reactions were systematically studied at the University of Notre Dame (UND) [4]. It was found that the cross sections of the $^{12}$C+$^{12}$C fusion reaction at resonant energies match with the cross sections in the $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C systems within their quoted uncertainties (see Fig. 1). The observed correlation is explained by the level density differences among the three carbon isotope systems [4, 5]. As a result, the $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C systems provide an upper limit for $^{12}$C+$^{12}$C in a wide range from $E_{c.m.}$=2.6 MeV up to more than 20 MeV. Since the two carbon fusion cross sections are much easier to be modeled due to their smooth behaviors, such an upper limit could be predicted

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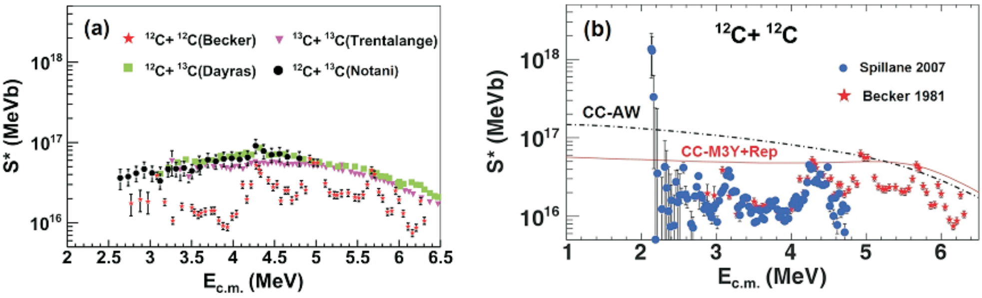

**Figure 1.** The experimental S* factors for the carbon isotope fusion reactions: $^{12}$C+$^{12}$C from Ref. [7] (red stars) and Ref. [3] (blue points) and $^{12}$C+$^{13}$C from Ref. [4] (black points) and Ref. [8] (green squares), and $^{13}$C+$^{13}$C [9] (magenta triangles). In Fig. 1(b), two coupled-channels calculations using Akyüz-Winther potential (CC-AW, dot-dashed line) and M3Y+Rep potential (CC-M3Y+Rep, red solid line), respectively, are shown for comparison. Here the modified S* factor is defined as $S^*(E)=\sigma(E)\cdot E\cdot \exp(87.21/\sqrt{E}+0.46E)$.

within the astrophysical energy range. The coupled-channel calculation with the M3Y+Rep potential was used to fit the $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C data and constrain the effective nuclear potential, which was then used for the prediction of the $^{12}$C+$^{12}$C fusion cross sections [4, 6]. It was found that the coupled-channel calculation using the constrained M3Y+Rep potential provides an excellent upper limit for almost all the data except for the strong resonance at 2.14 MeV, which has not been confirmed [4].

Measurement of $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C at deep sub-barrier energies gives us not only an opportunity to model the resonance strengths in $^{12}$C+$^{12}$C but also a test of the predictive powers of various theoretical models for the carbon fusion cross sections at deep sub-barrier energies. Lacking of experimental data within the energies of astrophysical interest, large discrepancies exist among different nuclear reaction models. Therefore, it is important to push the measurements of the fusion cross sections of $^{12}$C+$^{13}$C and $^{13}$C+$^{13}$C down towards lower energies.

## 2 $^{12}$C+$^{13}$C experiment at IFIN-HH

We report an experiment to measure the cross section of $^{12}$C+$^{13}$C reaction by detecting the residual nucleus $^{24}$Na which $\beta$-decays with a half-life of 15.0 h. Similar measurements have been performed by Notani and Dayras [4, 8]. In the present experiment, the $^{13}$C beam was produced by a cesium sputter ion source and injected into a HVEE Tandetron 3 MV electrostatic accelerator of IFIN-HH [10]. The $^{13}$C beam impinges a natural graphite target with thickness of 1 mm. The reaction has been studied by varying the beam energies between 5.2 and 6.8 MeV in steps of 0.2 MeV. The $^{13}$C beam current used in this experiment varies in the range of 2 to 8 p$\mu$A.

After each irradiation, the target sample would be quickly transported to an underground counting station ($\mu$Bq) in the Unirea salt mine for offline $\gamma$-ray measurement [11]. This salt mine is located in the vicinity of Slanic-Prahova city, about one hundred kilometers away from the Bucharest. In this salt mine, the $\mu$Bq underground laboratory is situated at a depth of 208 m below surface (estimated to 560 m water equivalent). The total gamma background spectrum between 40 keV and 3 MeV was 100 times smaller at laboratory level with respect to the same spectrum recorded at surface in open field. In the $\mu$Bq, a well shielded HPGe detector was used to detect two cascading $\gamma$ rays (1369- and 2754-keV) emitted from the $\gamma$ decay of $^{24}$Na. One typical gamma spectrum is displayed in Fig. 2. In some cases, the measurement was performed in the Low Background Gamma-Ray Spectrometry

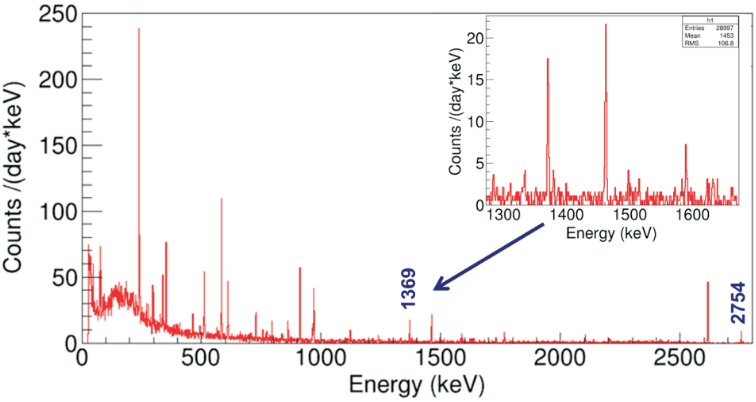

**Figure 2.** A typical gamma spectrum measured in the underground $\mu$Bq lab within 46 hours. Beam energy for this spectrum is 5.2 MeV ($E_{c.m.}$=2.5 MeV), which is the lowest energy point in the experiment. The statistical error for 1369-keV $\gamma$ peak is 11%, much lower than that in the Notani measurement [4].

Laboratory (GamaSpec) in a basement of IFIN-HH [12]. In this lab, limited by the background $\gamma$ rays, only target samples irradiated at higher beam energies (>5.8 MeV) could be measured. Furthermore, this measurement was used to cross check the experimental setup in the two laboratories and validate our results.

The thick-target yield (Y) for $^{12}$C($^{13}$C,p)$^{24}$Na reaction was obtained by normalizing the observed yield to the total incident $^{13}$C beam flux. From the thick-target yield excitation function, the differential yield dY/dE are determined and then the corresponding cross sections are calculated using the equation $\sigma(E)=dY/dE*dE/d(\rho X)/N_{\upsilon}$, where $N_{\upsilon}$ is the number of atoms per unit of volume and $dE/d(\rho X)$ is the stopping power in the target material, given by the SRIM code. Finally, the total fusion cross sections of $^{12}$C+$^{13}$C are deduced from the proton emission channel using the theoretical branching ratio given by Hauser-Feshbach model [8].

## 3 Preliminary results and summary

The preliminary results are shown in Fig. 3. In this work, the lowest cross section for $^{12}$C($^{13}$C,p)$^{24}$Na reaction has been measured down to 3 nb as shown in Fig. 3(a), representing the lowest energy reached for this reaction. This is the great advantage of the ultra-low background underground laboratory. Figure 3(b) shows the modified S factor (S*) deduced from the total fusion cross section. The result agrees with that of the two previous measurements in the energy region from 2.6-3.3 MeV. Limited by the beam time, only one new data point ($E_{c.m.}$=2.5 MeV) is added in our first experiment. It has been observed that the optical model with Woods-Saxon type potential reproduces the experimental data only at energies above 4 MeV. At deep sub-barrier energies, it significantly overestimates the cross section, which is quoted as hindrance effect. The equivalent square-well (ESW) model and coupled-channels (CC) with M3Y+Rep potential can predict the experimental data very well. The hindrance model prediction obtained by fitting the Dayras data also shows a reasonable agreement to the experimental data above 2.7 MeV, but predicts a much sharper decrease at astrophysical energies [13]. In order to test the predictive power of the extrapolation models, we will continue our measurement towards lower energies.

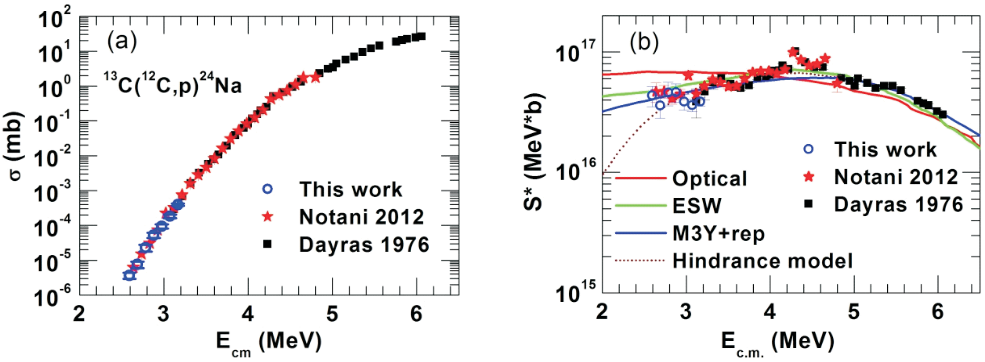

**Figure 3.** The preliminary fusion cross section of $^{12}$C($^{13}$C,p)$^{24}$Na reaction obtained from the present work (a) and the deduced S* factor for the $^{12}$C+$^{13}$C reaction system (b). The results from the previous experiments are also shown.

## 4 Summary and acknowledgement

In summary, in our first-stage experiment performed in IFIN-HH, $^{12}$C+$^{13}$C fusion cross section has been measured down to $E_{c.m.}$=2.5 MeV using thick target technique and activation method. It shows the 3 MV accelerator in IFIN-HH is very suitable for nuclear astrophysics measurements because of high beam intensities and stability in operation. Also, the ultralow background underground laboratory of the institute demonstrates a great potential for measurements of ultra-low activity with lifetime several hours. These facilities offer a new opportunity to measure $^{12}$C+$^{13}$C fusion cross section at even lower energies.

This work is supported by the National Natural Sciences Foundation of China under Grants No. 11405226 and No. 11475228, the 100 Talents Program of the Chinese Academy of Sciences. It is also supported by the grants PN 09 37 01 07 and PN-II-ID-PCE-2012-4-0299 of the Romanian National Authority for Scientific Research and Innovation.

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