EPJ Web of Conferences **165**, 01015 (2017) DOI: 10.1051/epjconf/201716501015
NPA8 2017

Cross section measurements in the $^{12}C+^{12}C$ system

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Abstract. The $^{12}C+^{12}C$ fusion reaction is one of the most important for nuclear astrophysics since it determines the carbon ignition in stellar environments. Two experiments which make use of the gamma-particle coincidence technique to measure the $^{12}C+^{12}C$ S-factors at deep sub barrier energies are discussed. Results are presented showing a decrease of the S-factor below $E_{c.m.} = 3$ MeV.

1 Introduction

The ^{12}C+^{12}C fusion reaction is interesting from the point of view of nuclear structure since resonances have been observed in the cross section at the Coulomb barrier (CB) and below, possibly due to ^{12}C-^{12}C molecular configurations of ^{24}Mg. The persistence of resonances at the lowest energies is still an open question. It is also a very important reaction for nuclear astrophysics since carbon burning occurring essentially via the ^{12}C+^{12}C fusion in stellar environments, determines if a star will join to the heavy-ion burning branches following hydrogen and helium burning and if white dwarfs will evolve into type Ia supernovae. This reaction has thus been subject to numerous experimental studies from the CB to lower energy regions of astrophysical interest. The Gamow window for this reaction is centered at $E_G = 2.42\times T_9^{2/3} \pm 0.75\times T_9^{5/6} = 1.5 \pm 0.3$ MeV at T = 5x10^8 K [1]. The present contribution discusses two experiments aiming at measuring the ^{12}C+^{12}C fusion cross-section using a direct method.

2 Experimental technique

Fusion of ^{12}C+^{12}C leads to the ^{24}Mg compound nucleus and the exit channels for this reaction are ^{12}C(^{12}C,α)^{20}Ne, ^{12}C(^{12}C,p)^{23}Na and ^{12}C(^{12}C,n)^{23}Mg. Due to its negative Q-value (-2.62 MeV), the neutron evaporation exit channel contribution is negligible at energies relevant for astrophysics whereas the Q-values for the α and p channels are respectively 4.62 MeV, 2.24 MeV. Direct measurements of ^{12}C(^{12}C,^{24}Mg) fusion cross-sections where in the past essentially based on the measurement of charged particles (α and p) or gamma-rays of the evaporation residues ^{20}Ne and ^{23}Na. At the lowest energies, such a measurement is subject to very large background, essentially coming from proton and deuteron recoil particles and the d(^{12}C,p) reaction. This is due to the ubiquitous contamination of hydrogen and deuterium in the targets. The present article is based on the detection of charged particles and gamma-rays in coincidence, leading to a drastic reduction of the background [2]. In a first experimental campaign at the Argonne National Laboratory a ^{12}C beam of intensity 600 pnA was delivered by the ATLAS facility impinging on a highly enriched (99.9 %) ^{12}C target of thickness ~ 50 μg.cm^{-2}. Ten energy points have been measured ranging from $E_{c.m.}$ = 4.93 down to 2.68 MeV. Gamma transitions from the evaporation residues were measured using the Gammasphere 100 HPGe detectors array in coincidence with charged particles detected in 3 annular double-sided silicon strip detectors (DSSD) covering ~ 25% of 4π. Two surface barrier silicon monitor detectors where used to normalize the cross section results to Mott scattered ^{12}C nuclei at 45° in the forward direction. Characteristic gamma-rays from ^{20}Ne (1635 keV) and ^{23}Na (440 keV) were measured in the Gammasphere 100 Ge detectors. A further experimental campaign at the Andromede facility in Orsay has used the coincidence technique with the STELLA experimental station coupled to the FATIMA 30 LaBr$_3$ scintillator array [3] and a newly developed rotating target system. The experiment is described in another contribution to this conference [4].
The measured S-factors are presented in the next section.

3 Results and discussion

The cross sections measured during the Argonne campaign at $E_{c.m.}$ between 4.93 and 2.68 MeV converted in S-factors are presented in Fig. 1., together with the most recent results for a direct measurement in the system [5]. The region indicated in blue in this figure is the Gamow region for T = $5x10^8$ K and the yellow region represents the Gamow energy region for type IA supernova. At $E_{c.m.}$ = 2.68 MeV the S-factor corresponds to a cross section of 6 nb. On this figure, the presented extrapolations are based on standard potentials and use the sudden model or coupled-channel approach except the red one which takes into account the fusion hindrance phenomenon. This phenomenon has been observed in numerous fusion reactions of medium mass systems. It was first described by Jiang et al. [6]. At low energies, and for cross sections below ~ 0.1 mb, the measured cross sections were systematically smaller than predicted by standard coupled-channel calculations.

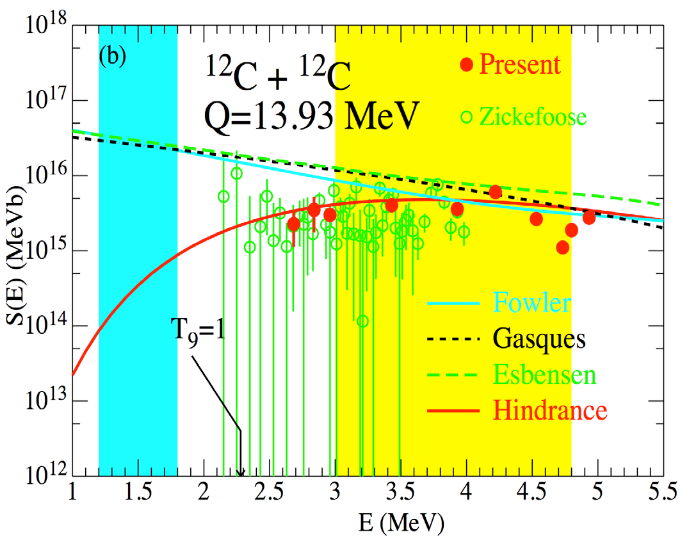

Fig. 1. (color online) S-factors measured in the Argonne $^{12}C+^{12}C$ fusion experiment (red points) as a function of the energy in the center of mass frame together with results from ref. [5]. The blue, black, red and green dashed lines correspond to extrapolations from Fowler [7], Gasques [8], Jiang [9] and Esbensen [10].

The data measured in this experiment are compatible at low energies with the extrapolation based on hindrance.

The coincidence technique is also used in the French-UK STELLA project whose commissioning has measured the $^{12}C+^{12}C$ fusion reaction around and below the Coulomb barrier. Fig. 2 shows preliminary particle spectra measured at E_{Lab} = 11 MeV. On the spectrum in coincidence with a characteristic gamma-ray of ^{23}Na, excellent identification of protons from the $^{12}C(^{12}C,p)^{23}Na$ reaction from p_0 to p_9 is achieved. The few counts remaining in the p_0 zone of the coincident spectrum are from random coincidences. From these spectra, an experimental value for the detection efficiency at E_γ = 440 keV is obtained by taking the ratio of integrated coincident and single p_1 peaks. This gives a result of 6%, which is in agreement with Geant4 simulation of the $LaBr_3$ setup developed within the STELLA project in the configuration which uses 28 $LaBr_3$ detectors [11].

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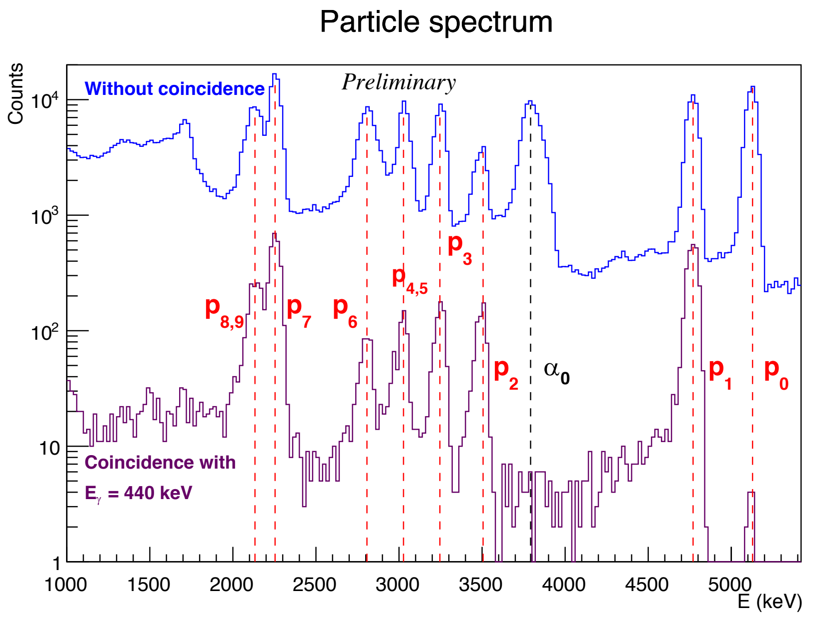

Fig. 2. (color online) Blue: $^{12}C+^{12}C$ fusion reaction particle spectrum measured in the STELLA project at E_{Lab} = 11 MeV. Purple: same spectrum in coincidence with the $5/2^+ \rightarrow 3/2^+$ transition of ^{23}Na, from ^{23}Na+p channel.

4 Conclusions

The gamma-particle coincidence method has been used to measure the direct $^{12}C(^{12}C,^{24}Mg)$ fusion reaction at sub barrier energies. Two different experimental campaigns are discussed, the first one took place at the Argonne National Laboratory using the Gammasphere array and the second one is taking data at Orsay using the STELLA+FATIMA setup. Results from the first campaign are presented. The $^{12}C+^{12}C$ S-factors have been measured down to $E_{c.m.}$ = 2.68 MeV with smaller error bars than the previous studies for this system. This measurement shows a decrease of the S-factors below $E_{c.m.}$ = 3 MeV, after a broad maximum, which could indicate that fusion hindrance may play a role in this reaction and thus in the evolution of massive stars. The impact of fusion hindrance on stellar burning and astrophysics has been studied by Gasques *et al*. in [12]. The fusion hindrance phenomenon, as discussed in this article would indeed drastically reduce the corresponding reaction rates at temperatures below 3 to 10×10^8K affecting the abundance of many species, in particular enhancing ^{26}Al and ^{60}Fe.

Acknowledgements

This work was supported by the US Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02- 06CH11357 and by USIAS, Strasbourg Fellowship of S. Courtin.

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