Preliminary results of the indirect study of the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction via the THM applied to the $^{16}O(^{12}C,\alpha\,^{20}Ne)\alpha$ reaction

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Abstract - The Trojan Horse Method was applied to the $^{16}O(^{12}C,\alpha\,^{20}Ne)\alpha$ 2 to 3 body process to study the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction within the energy range of astrophysical interest. This reaction bears a very important role in the advanced stages of massive star evolution, in particular during the carbon burning phase. The experiment was performed at the Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH (Bucharest, Romania). Preliminary results will be presented in this paper.

Astrophysical Context

The study of the $^{12}C+^{12}C$ reaction is of great interest in astrophysics. Carbon burning is connected with the third phase of massive star evolution [1]. When helium is consumed in the center of the star, the core mainly consists of ^{12}C and ^{16}O. Only in stars with $M > 8\ M_\Theta$ the gravitational contraction increases the central temperature up to trigger ^{12}C burning. In particular the first activated process is the $^{12}C+^{12}C$ fusion, the Coulomb barrier for carbon nuclei being the lowest. The most likely reaction channels are:

$^{12}C(^{12}C,\alpha)^{20}Ne$	(Q = 4.617 MeV)
$^{12}C(^{12}C,p)^{23}Na$	(Q = 2.241 MeV)
$^{12}C(^{12}C,n)^{23}Mg$	(Q = - 2.599 MeV)

On one hand, these reactions are the key processes for the ^{20}Ne, ^{23}Ne and ^{23}Mg nucleosynthesis, on the other hand, they determine the successive stellar evolution. Carbon burning reaction rate is a fundamental parameter to determine the so-called M_{up}, that is, the minimum mass of a star for carbon ignition. Stars with $M < M_{up}$ evolve into CO White dwarf, while stars with $M > M_{up}$ conclude their life as core-collapse Supernovae [2].

The core carbon burning takes place in a temperature range of T = 0.5 - 1.0 GK. For a temperature of 0.5 GK, the corresponding Gamow energy for the $^{12}C+^{12}C$ fusion is $E_G = 1.5 \pm 0.3$ MeV. Accurate determination of the carbon burning reaction rate requires very precise measurement of the $^{12}C+^{12}C$ cross section down to this energy, well below the Coulomb barrier (about 8 MeV).

In spite of the key role of carbon fusion reactions in understanding stellar evolution, its reaction rate is not very well determined right at the energies relevant for astrophysics.

One of the main problem occurring in the experimental study of nuclear reactions of astrophysical relevance is the strong suppression of the cross section due to the Coulomb barrier that strongly decreases the signal-to-noise ratio.

In experiments performed so far ([3] and references therein), involving both charged particle and gamma ray spectroscopy, data were obtained down to carbon-carbon center of mass energy $E_{cm} = 2$ MeV, that is at the higher edge of the Gamow peak. Nevertheless, experimental data below $E_{cm} = 3$ MeV are rather uncertain [2]. For instance, a recent work [4] questions the presence of the claimed resonance at $E_{cm} = 2.14$ MeV [3].

Because of the experimental data uncertainty, up to now the only way to obtain the carbon-carbon fusion reaction rate at astrophysical energies has been the extrapolation from experimental data at higher energy [5]. In the present case, extrapolation might introduce systematic uncertainties owing to the presence of possible resonant structures in the astrophysical energy range as well, like the already mentioned 2.14 MeV or a theoretically predicted resonance at $E_{cm} = 1.5$ MeV [6].

New and accurate experimental data, down to the astrophysical energies, are strongly required.

In this paper, we report on the study of the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction carried out applying the Trojan Horse Method (THM) to the three-body reaction $^{16}O(^{12}C, \alpha\ ^{20}Ne)\ \alpha$. The THM features, briefly described below, allow us to obtain the $^{12}C(^{12}C, \alpha)^{20}Ne$ cross section in a wide energy range including the Gamov peak region.

The Trojan Horse Method

The THM [8-12] is a powerful indirect technique that allows one to extract a two-body reaction cross section, *t(p,a)b,* down to low energies of astrophysical interest by selecting the quasi-free break-up channel of an suitable three-body reaction *A(p,ab)s.* The so-called TH nucleus *A* should have a large probability for a $t \oplus s$ cluster configuration. The three-body reaction is performed at a beam energy larger than the Coulomb barrier in the entrance channel, where the electron screening effect is also negligible. The *p*+A interaction produces *A* break-up into *t* and *s;* in the quasi-free kinematical condition it is assumed that *s* behaves like a spectator while *t* interacts with the nucleus *p* leading to the astrophysically relevant reaction *t(p,a)b.* The high beam energy in the entry channel is compensated for by the $t \oplus s$ binding energy so that the two-boby reaction can takes place at the low astrophysical energies. Moreover, thanks to the $t \oplus s$ inter-cluster motion, the THM allows to measure the two-body cross section in a wide energy using a single beam energy.

The Experiment

The 9 MV Tandem accelerator of the Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH provided a 25 MeV ^{16}O beam with a spot size on the target of about 1 mm and an intensity of about 8 nA. A natural carbon target, 100 *μg/cm²* thick, was used to induce the $^{16}O+^{12}C$ reaction. ^{16}O was used as TH nucleus since it can be described in terms of a $^{12}C+\alpha$ configuration [13-15].

Energy and position of the outgoing particles were detected using six position sensitive silicon detectors (PSD) in a symmetric configuration to double the number of collected events (Fig. 1). In particular, PSD1 (PSD4), covering the 13°-26° angular range, was devoted to the ^{20}Ne detection. To distinguish Ne from other nuclei produced in the oxygen-carbon interaction the ΔE-E technique was employed. To this aim an ionization chamber (IC) was placed in front of PSD1 (PSD4).

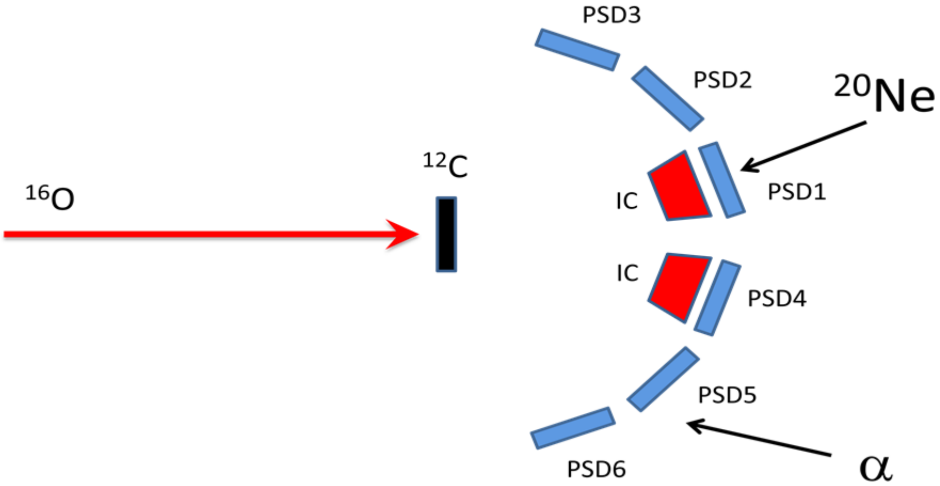

FIG. 1. Experimental set-up.

PSD5 (PSD2) and PSD6 (PSD3), covering the angular range 41° - 55° and 65° - 80° respectively, were placed on the other side with respect to the beam axis, and were dedicated to the α particles detection. ^{20}Ne nuclei and α particles were detected in coincidence. This experimental set-up allowed us to measure the $^{12}C(^{12}C,\alpha)^{20}Ne$ excitation function in a wide range 0-3 MeV ($E_G = 1.5 \pm 0.3$).

In Fig. 2 the experimental ΔE-E 2D plot is shown. The Ne locus is highlighted by a red arrow. This locus is very well separated from loci due to lighter elements (in particular the most intense locus is due to the ^{16}O scattered beam), though it overlaps with the Mg one at low energy.

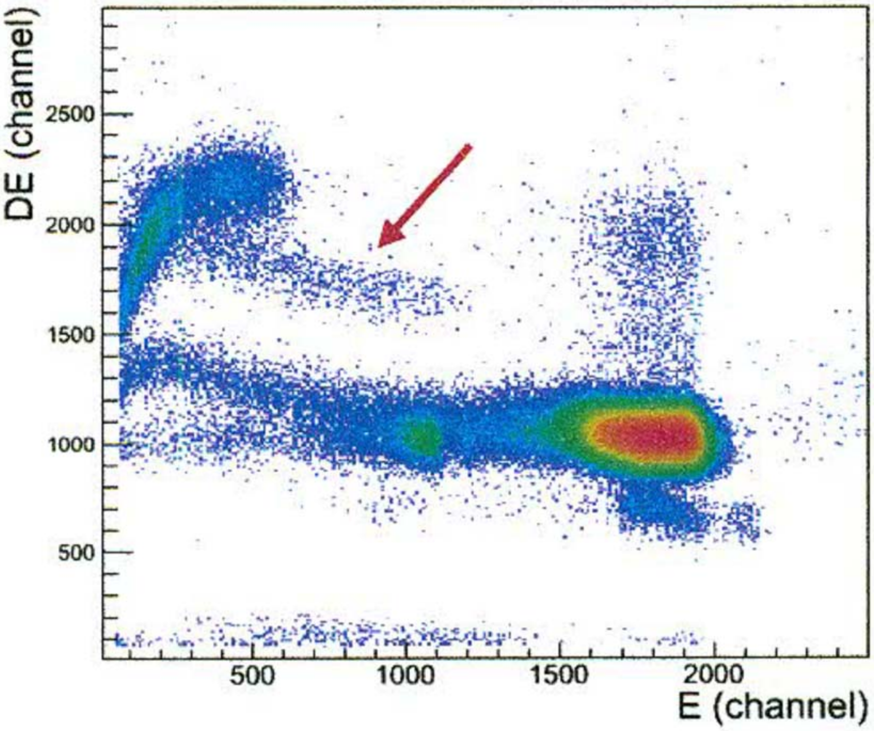

FIG. 2. ΔE-E 2D plot for Ne identification. The red arrow indicates the Ne locus.

To select the events due to the reaction channel $^{16}O(^{12}C,\alpha^{20}Ne)\alpha$, of our interest, a graphical cut was made around the Ne locus. For the selected data, the α energy (E_α) vs ^{20}Ne energy (E_{20Ne}) 2D plot was reconstructed and compared with the simulated kinematical locus (black dots), as shown in Fig. 3.

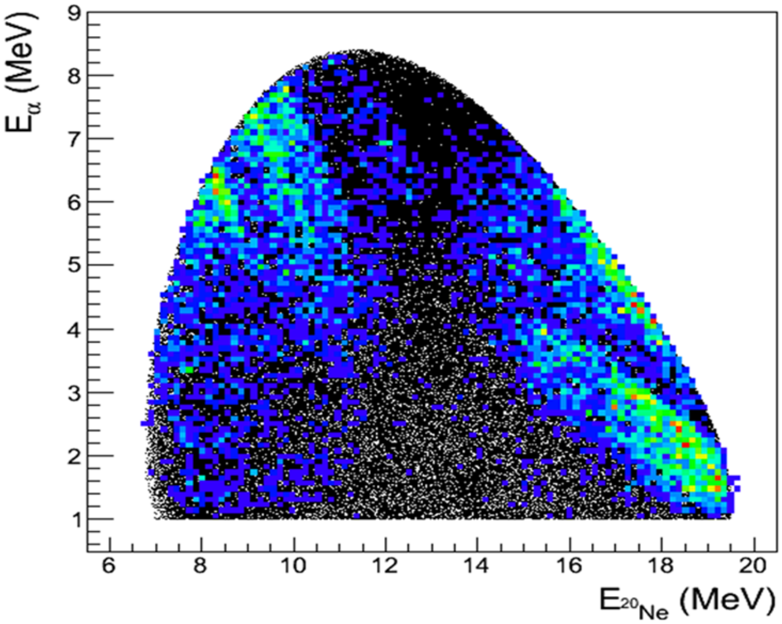

FIG. 3. Alpha particle energy (E_α) vs ^{20}Ne energy (E_{20Ne}). Experimental data are superimposed onto the simulated kinematical locus (black dots).

A good agreement shows up, making us confident on the calibration performed. Experimental data show the presence of additional loci due to two-body reactions as well as to the Mg contamination. An accurate procedure will be applied to disentangle the ^{16}O(^{12}C,α^{20}Ne)α events from background.

Then, next step of the analysis will be the selection of the quasi-free break-up mechanism and the study of the ^{20}Ne-α relative energy spectrum.

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