Indirect study of the $^{12}\text{C}^{(12}\text{C},\alpha)^{20}\text{Ne}$ and $^{12}\text{C}^{(12}\text{C},p)^{23}\text{Na}$ reactions via the Trojan Horse Method applied to the $^{12}\text{C}^{(16}\text{O},\alpha^{20}\text{Ne})^{4}\text{He}$ and $^{12}\text{C}^{(16}\text{O},p^{23}\text{Na})^{4}\text{He}$ three-body reactions

G.G. Rapisarda$^{1,2}$, C. Spitaleri$^{1,2}$, S. Cherubini$^{1,2}$, D. Filipescu$^{1}$, I. Gheorghe$^{1}$, D. Ghita$^{3}$, S. Hayakawa$^{1}$, I. Indelicato$^{1,2}$, M. La Cognata$^{1}$, J. Mrázek$^{4}$, H. Petracus$^{1}$, R.G. Pizzone$^{1}$, R. Spartà$^{4}$, O. Tesileanu$^{5}$, L. Trache$^{3}$

1) INFN Laboratori Nazionali del Sud, Catania, Italy
2) Dipartimento di Fisica e Astronomia Università di Catania, Italy
3) NIPNE, Bucharest, Romania
4) Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic

Abstract - We report about a new experimental run where the Trojan Horse Method (THM) was applied to study carbon-carbon fusion reaction at astrophysical energy. The set-up was optimized to investigate the $^{16}\text{O}^{(12}\text{C},\alpha)^{20}\text{Ne}\alpha$ and $^{16}\text{O}^{(12}\text{C},p)^{23}\text{Na}\alpha$ three-body processes in order to study, via THM, two of the possible carbon-carbon fusion reaction channels, that is: $^{12}\text{C}^{(12}\text{C},\alpha)^{20}\text{Ne}$ and $^{12}\text{C}^{(12}\text{C},p)^{23}\text{Na}$. 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 FRAMEWORK

When helium is consumed in the center of the star, the core mainly consists of $^{12}\text{C}$ and $^{16}\text{O}$. In stars with mass $M > 8\ M_\odot$ the gravitational contraction increases the central temperature up to trigger $^{12}\text{C}$ burning. The first activated process is the $^{12}\text{C}+^{12}\text{C}$ fusion due to the lowest Coulomb barrier. The most likely reaction channels are: $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$, $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$, $^{12}\text{C}(^{12}\text{C},n)^{20}\text{Mg}$ [11]. These reactions are involved in the $^{20}\text{Ne}$, $^{23}\text{Ne}$ and $^{25}\text{Mg}$ nucleosynthesis, but, most important thing, they determine the successive stellar evolution. Carbon burning reaction rate is a fundamental parameter to determine the so-called $M_{\text{up}}$. Stars with $M > M_{\text{up}}$ cannot burn carbon and evolve into CO white dwarf, while stars with $M < M_{\text{up}}$ can trigger carbon burning and conclude their life as core-collapse Supernovae [2].

The core carbon burning takes place in a temperature range of $T = 0.5 - 1.0\ \text{GK}$. For a temperature of 0.5 GK, the corresponding Gamow energy for the $^{12}\text{C}+^{12}\text{C}$ fusion is $E_0 = 1.5 \pm 0.3\ \text{MeV}$ (well below the Coulomb barrier about 8 MeV).

Although carbon fusion reactions take a key role in understanding stellar evolution, its reaction rate is not very well determined right at the energies relevant for astrophysics. Experiments performed so far ([3] and references therein), involving both charged particle and gamma ray spectroscopy, have measured excitation function down to carbon-carbon center of mass energy $E_{\text{cm}} = 2\ \text{MeV}$, that is at the higher edge of the Gamow peak. Nevertheless, experimental data below $E_{\text{cm}} = 3\ \text{MeV}$ are rather uncertain [2]. For instance, a recent paper [4] questions the presence of the claimed resonance at $E_{\text{cm}} = 2.14\ \text{MeV}$ [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].

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 $E_{\text{cm}} = 1.5\ \text{MeV}$ [6], makes the extrapolation a dangerous procedure that can be source of possible systematic uncertainties.

For these reasons new and accurate experimental data, down to the astrophysical energies, are strongly required. In this paper, we report on the study of the $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ and $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ reaction carried out applying the Trojan Horse Method (THM) ([8-9] and references therein) to the three-body reactions $^{16}\text{O}(^{12}\text{C},\alpha)^{20}\text{Ne}\alpha$ and $^{16}\text{O}(^{12}\text{C},p)^{23}\text{Na}\alpha$.

THE EXPERIMENT

The experiment was performed at the Horia Hulubei National Institute of Physics and Nuclear Engineering - IFIN HH. The 9 MV Tandem accelerator provided a 26.5 MeV $^{16}\text{O}$ beam with a spot size on the target of about 1.5 mm and an intensity of about 5 enA. A CH$_2$ target, 100 $\mu$g/cm$^2$ thick, was used to induce the $^{16}\text{O} + ^{12}\text{C}$ reaction. $^{16}\text{O}$ was used as TH nucleus since it can be described in terms of a $^{12}\text{C} \oplus \alpha$ configuration [10]. In the quasi-free breakup framework the interaction between $^{16}\text{O}$ and $^{12}\text{C}$ produces the oxygen breakup in to $^{12}\text{C}$ and $\alpha$, then $^{12}\text{C}$ interacts with the $^{12}\text{C}$ target giving the two-body reaction of astrophysical interest, while $\alpha$ is the so-called spectator since does not interfere with the two-body process.

Energy and position of the outgoing particles were detected using five position sensitive silicon detectors (PSD) 1000 $\mu$m tick (figure 1). To avoid the problems related to the heavy outgoing particles ($^{20}\text{Ne}$ and $^{23}\text{Na}$)
detection, mainly energy and angular straggling, the experimental set-up of this new measure was defined to detect only the light particles that is alphas and protons. PSD1 covered the 4.5°-18.5° angular range where the alpha spectator detection is highly probable. A 8 µm thick gold foil was put in front of PSD1 to preserve this detector from the elastic scattering.

PSD2, PSD3 and PSD4 covering the angular range 17.5° - 31.5°, 33.5° - 47° and 47° - 61° respectively, were dedicated to alpha and proton detection. In order to identify these two particles the ΔE-E technique was employed. For this aim 20 µm silicon detector (ΔE2, ΔE3, ΔE4 in figure1) were placed in front of PSD2-3-4. PSD5 was put behind PSD1 in order to catch protons of higher energy. The trigger to the ACQ system was generated setting multiplicity two between PSD1-2-3-4. This experimental set-up allowed us to measure 12C(12C,α)20Ne and 12C(12C,p)23Na excitation functions in a wide range including the Gamow energy (E_G = 1.5 ± 0.3).

In figure 2 typical ΔE-E 2D plot is shown. It is clear the presence of the proton and alpha loci.

In figure 3 the experimental Q-value for the three-body process \(^{16}\text{O}(^{12}\text{C},\alpha)^{20}\text{Ne})\alpha\) with \(^{20}\text{Ne}\) at ground state ad first excited state respectively.

![Figure 1: Experimental set-up](image1)

**Figure 1:** Experimental set-up

![Figure 2: ΔE-E 2D plot for alpha and proton identification.](image2)

**Figure 2:** ΔE-E 2D plot for alpha and proton identification.

The good agreement between experimental values and the theoretical ones (-2.545 MeV and -4.175 MeV) makes us confident on the calibration performed and on the correct selection of the reaction channel. Similar result has been obtained for the \(^{16}\text{O}(^{12}\text{C},p)^{23}\text{Na})\alpha\) reaction channel.

Next step of the analysis will be the selection of the quasi-free break-up mechanism and the study of the \(^{20}\text{Ne}-\alpha\) and \(^{23}\text{Na}+\text{p}\) relative energy spectrum.

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