Study of the $^{12}C + ^{16}O$ fusion reaction in carbon burning via the Trojan Horse Method

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Abstract. $^{12}C + ^{12}C$ is the main reaction during core and shell carbon burning in massive stars, however, at temperatures higher than $10^9 K$ when most of the carbon is depleted and its abundance is lower than ^{16}O, the $^{12}C + ^{16}O$ fusion can also become relevant. Moreover, $^{12}C + ^{16}O$ reaction can ignite also in the scenario of explosive carbon burning. The astrophysical energy region of interest thus ranges from 3 to 7.2 MeV in the center-of-mass frame. There are various measurements of the cross-section available in the literature, however, they all stop around 4 MeV, making extrapolation necessary at lower energies.

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To try to solve this uncertainty and corroborate direct measurement the Trojan Horse Method was applied to three-body processes ^{16}O(^{14}N, α^{24}Mg)^{2}H and ^{16}O(^{14}N, p^{27}Al)^{2}H to study the ^{16}O(^{12}C, α)^{24}Mg and ^{16}O(^{12}C, p)^{27}Al reactions.

1 Astrophysical Scenario

Carbon burning is a fundamental process for the advanced life of a massive stars since it determines their properties and evolution as well as their contribution to the chemical evolution of the universe. Both during the core and shell carbon burning, the ^{12}C +^{12} C fusion is the main reaction and the first to ignite since it has the lowest Coulomb barrier among all the possible reactions [1, 2]. In truth, the ashes of helium burning are composed also of ^{16}O nuclei, thus, when most of the carbon nuclei in the core are depleted, the abundance of ^{16}O is actually significantly higher [3, 4] than that of ^{12}C. Considering also that at this point of the evolution, the environmental temperature is higher than the one it had when the carbon burning started, other reactions, even with a higher Coulomb barrier, can now occur. In this context, the ^{12}C+^{16}O reaction can indeed play a significant role at temperatures higher than 10^9 K [5]. Carbon burning is also a key process in the evolution of Type Ia supernovae and once again the ^{12}C +^{12} C fusion is thought to be the main energy source. As shown by recent studies [6], the ^{12}C +^{16} O fusion can also play a significant role in this scenario, at temperatures around $3.6 \cdot 10^9$ K. Therefore, to assess the impact of the ^{12}C+^{16}O fusion in the whole context of carbon burning, a precise study of its reaction rate in the energy range of astrophysical interest, namely between 3 and 7.2 MeV in the center of mass frame, is required.

2 Status of the ^{12}C +^{16} O

In the literature, various measurements of the cross-section and rate for the ^{12}C +^{16} O fusion can be found, however, they all stop at around 4 MeV, which imposes the use of extrapolation at lower energies [7]. Unfortunately, this procedure is strongly dependent on the model used, on the presence of nuclear effects not included in the model (clustering, molecular-like behaviour, etc.) and on the stellar environment itself [8]. Therefore, a new measurement is needed to better explore the low-energy region. During both hydrostatic and explosive carbon burning, the ^{12}C +^{16} O fusion process proceeds mainly through ^{12}C(^{16}O, α)^{24}Mg (Q = 6.77 MeV) and ^{12}C(^{16}O, p)^{27}Al (Q = 5.17 MeV) reaction channels and partially through the ^{12}C(^{16}O, n)^{27}Si, less favored due to its negative Q-value. Other reactions such as ^{12}C(^{16}O, 2α)^{20}Ne are hindered by the presence of the Coulombian barrier in the exit channel [7].

3 THM Approach

3.1 The Trojan Horse Method

The Trojan Horse Method (THM) is based on the theoretical formalism of Quasi-Free (QF) break-up reactions: it studies the QF contribution of an appropriate three-body reaction $a + A \rightarrow b + B + s$ measured at energies above the Coulomb barrier to evaluate the cross-section of the two-body reaction of interest $x + A \rightarrow b + B$ at sub-Coulomb energies. The so-called Trojan Horse (TH) nucleus a is assumed to possess a clustered state with a $x+s$ configuration, where the x cluster is called the participant while s is the spectator of the interaction because, under QF kinematic conditions, the momentum transfer to the cluster s is negligible. These conditions correspond to the region of the phase space where the intercluster $x + s$ momentum distribution has its maximum value or, equally, where the distance between the two clusters inside the TH nucleus is maximized. The main advantage of the method is that the two-body cross-section is not affected by any barrier effect, either Coulombian or centrifugal, or by electron screening effects. Moreover, taking advantage of the intercluster motion, with just one fixed beam energy it is possible to actually study an energy range and even cover the subthreshold region. A detailed explanation of the THM formalism can be found in Ref. [9] and references therein.

3.2 The Experiment

The THM has been used to evaluate the ^{12}C(^{16}O, α)^{24}Mg and ^{12}C(^{16}O, p)^{27}Al reactions at astrophysical energies by studying the ^{16}O(^{14}N, α^{24}Mg)^{2}H and ^{16}O(^{14}N, p^{27}Al)^{2}H three-body reactions. The chosen TH nucleus was the ^{14}N since it has a well-known ^{12}C + d cluster structure [10, 11] and it has already successfully used in past THM measurements [11]. The reactions were investigated at the Laboratori Nazionali del Sud (LNS-INFN) in Catania using a 33.7 MeV ^{14}N beam, accelerated by the Van de Graaff tandem, impinging on a 458 μg/cm^2 WO_3 target. The experimental setup was similar to previous THM experiments [11, 12] and consisted of an array of four telescopes, each of which was made up of three silicon detectors, was used to correctly identify the particle of interest in the exit channel. A 35 μm Position Sensitive Detector (PSD) and a 100 μm one were used, respectively, for the first and second stage of each telescope while for the third one a 1500 μm pad detector was used. The experimental setup covered an angular range from 7° to 30° and from 45° to 68° in the laboratory frame, precisely chosen to cover the so-called QF angles, where the contribution of the mechanism is maximized. The setup was symmetrical with respect to the beam axis to increase the statistical count.

3.3 Data Analysis

The energy and angle calibration of the detectors was performed with dedicated experimental runs using an eight-peak alpha source, elastic scattering of ^{14}N and ^{1,2}H, and the ^{2}H(^{14}N, α)^{12}C) reaction. Since the PSDs do not have any segmentation, the angle calibration was performed by covering the detector with a grid with equally spaced slits each of which placed at a known angle. To select the reaction channel of interests, detected particles must be identified first: by means of the ΔE-E technique, using the first two stages of each telescope, it is possible to select only the events in which a deuteron and either an alpha particle or a proton were detected in coincidence. The remaining ^{24}Mg or ^{27}Al nuclei in the exit channel were not detected; therefore, the experimental Q-value was reconstructed assuming the presence of either one in the final state and using the measured energies and the known beam energy. This assumption was then corroborated by comparing the reconstructed experimental Q-value with the theoretical one. In Fig. 1 the presence of events for both the α_0 and α_1 channels for the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction ca be seen. In Fig. 1, to better see the relevant events, a minimum threshold was set in the color axis. However, the presence of background events can still be seen: this is related to an incomplete separation between the deuterons and protons loci in the central ΔE-E telescopes. Further analysis of the data, also including the two peripheral telescopes is thus needed.

4 Conclusions

In this contribution were presented the preliminary results of the data analysis which clearly show the proper execution of the experiment and assess the presence of the

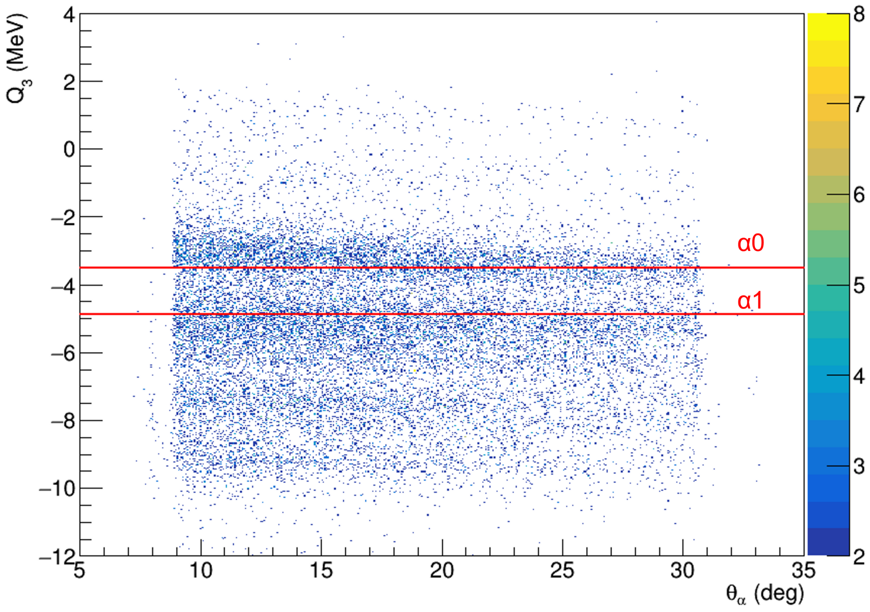

Figure 1. Experimental Q-value vs detection angle of the alpha particle for the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction channel. Colored dots represent the experimental data, according to the scale in the right side figure, while red lines represents the theoretical value for both the ground state (α_0) and the first excited state (α1).

^{16}O(^{14}N, α^{24}Mg)^{2}H reaction channels of interest. Future developments of the data analysis foresee the accurate evaluation of the momentum distribution of the spectator P_s, in order to assess the presence of the QF contribution, which will be then selected to finalize the analysis. The same procedure will be applied to the other reaction channel, the ^{16}O(^{14}N, p^{27}Al)^{2}H and, finally, the THM analysis will be then completed with the evaluation of the ^{12}C +^{16} O fusion cross-section and reaction rate.

References

[1] Pignatari M. et al., Astrophys. J. **762**, 31 (2013)
[2] Chieffi A. et al., Astrophys. J. **916-2**, 79 (2021)
[3] Weaver T. A. et al., Phys. Rep.**227**, 65 (1993)
[4] Buchmann L., Astrophys. J. **468**, L127 (1996)
[5] Woosley S.E. et al., Phys. Rev. Lett. **27**, 213 (1971)
[6] Martínez-Rodríguez H. et al., Astrophys. J. **843**, 35 (2017)
[7] Fang X. et al., Phys. Rev. C **96-4**, 045804 (2017)
[8] Jiang C. L. et al., Phys. Rev. C **75**, 015803 (2007)
[9] Tumino A. et al., Annu. Rev. Nucl. Part. S. **71-1**, 345–76 (2021)
[10] Zurmühle R. W. et al., Phys. Rev. C **49**, 2549 (1994)
[11] Tumino A. et al., Nature **557-7707**, 687 (2018)
[12] Palmerini S. et al., Eur. Phys. J. Plus **136**, 898 (2021)