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

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Summary. — The $^{12}C + ^{16}O$ fusion reaction plays a role in the later stages of carbon burning, influencing the evolution of both massive stars and Type Ia Supernovae: when most of the carbon is depleted, by the main fusion reaction $^{12}C + ^{12}C$, the abundance of ^{16}O nuclei is significantly higher. Therefore $^{12}C + ^{16}O$ can indeed have a strong impact on the process. In this brief contribution, preliminary data analysis results of a new indirect measurement of the $^{12}C + ^{16}O$, performed at astrophysical energies via the Trojan Horse Method, will be presented and discussed.

1. – Astrophysical scenario

Carbon burning is a key process for the advanced evolution of massive stars ($M > 8 \cdot M_\odot$) and for the explosive burning of type Ia supernovae [1,2]. The ^{12}C + ^{12}C fusion is the main process both during the core and shell carbon burning in massive stars, since it has the lowest Coulomb barrier among the other possible reactions. However, when most of the carbon fuel is depleted, the abundance of ^{16}O nuclei, produced by the ^{12}C$(\alpha,\gamma)^{16}$O reaction, is significantly higher [3, 4] than that of ^{12}C nuclei. This, considering also the temperature increase in these final stages, opens up the possibility for other reactions to occur. It has been suggested that, in this scenario, the ^{12}C + ^{16}O reaction can play a significant role at temperatures higher than 10^9 K [5]. Carbon burning is also of fundamental importance for the evolution of Type Ia supernovae and the ^{12}C + ^{12}C fusion is supposed to be the main energy source. In this scenario, which occurs at temperatures around $3.6 \cdot 10^9$ K, the ^{12}C + ^{16}O could also have a significant effect as demonstrated in recent studies [6]. Therefore, to correctly define the actual impact of the ^{12}C + ^{16}O fusion in the aforementioned processes, a precise study of its reaction rate in the energy range of astrophysical interest, between 3 and 7.2 MeV in the center-of-mass (c.m.), is required.

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

It is possible to find in the literature several measurements of the ^{12}C + ^{16}O fusion; however, nearly none of them could help us assessing definitive answers on the impact of this reaction below 4 MeV in the c.m., which in turn forces the use of extrapolation in this region [7]. Unfortunately, extrapolation strongly depends on the chosen model, on the presence of unforeseen nuclear effects (clustering, molecular-like behaviour, etc.) and on the stellar environment [8]. Therefore, a new measurement, devoted to better explore the energy region below 4 MeV, would be beneficial. In the aforementioned astrophysical scenarios, the ^{12}C + ^{16}O fusion proceeds mainly through ^{12}C$(^{16}$O$,\alpha)^{24}$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$,2\alpha)^{20}$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) was developed on the basis of the Quasi-Free (QF) break-up reaction theory and it studies the cross-section of an appropriate three-body reaction $a + A \to b + B + s$ to evaluate the cross-section of the two-body reaction of interest $x + A \to b + B$ at sub-Coulomb energies. In the THM formalism the Trojan Horse (TH) nucleus a is assumed to possess a well-clustered state with a $x + s$ configuration. One of the advantages of the method is that the two-body reaction occurs without barrier effects, both Coulombian and centrifugal, and without electron screening effects. Moreover, as explained in ref. [9], under the QF condition with a fixed beam energy it is possible to study a wide energy range taking advantage of the intercluster motion and even study the sub-threshold region. A detailed explanation of the method and the physics behind it can be found in ref. [9] and references therein.

3˙2. *The experiment.* – The ^{12}C$(^{16}$O$,\alpha)^{24}$Mg and ^{12}C$(^{16}$O, p$)^{27}$Al reactions have been studied at astrophysical energies by applying the THM to the ^{16}O$(^{14}$N$,\alpha^{24}$Mg$)^2$H and

$^{16}O(^{14}N, p^{27}Al)^2H$ three-body reactions, choosing the ^{14}N as the TH nucleus due to its $^{12}C + d$ cluster structure [10, 11]. The experiment was carried out at the Laboratori Nazionali del Sud (LNS-INFN) in Catania, using a ^{14}N beam accelerated by the Van de Graaff tandem to an energy of 33.7 MeV and impinging on a $458\,\mu g/cm^2$ WO_3 target. The experimental setup consisted of four telescopes, each of which was made up of three silicon detectors to correctly identify all the products of interest in the exit channel: the first stage consisted of a $35\,\mu$m Position Sensitive Detector (PSD), the second one of a $100\,\mu$m PSD, and the third one of a $1500\,\mu$m pad detector. The angular coverage, from 7° to 30° and from 45° to 68°, was precisely chosen to cover the so-called QF angles, where the occurrence of the mechanism is favored. The setup was symmetrical with respect to the beam axis to increase the statistical count.

3·3. *Data analysis*. – The energy calibration of the detectors was performed with devoted experimental runs using an eight-peak alpha source, elastic scattering of ^{14}N on $^{1,2}H$ and the $^2H(^{14}N, \alpha)^{12}C$ reaction. Angle calibration was performed, with the same runs, by covering the detector with a shield with equally spaced slits placed at known angles. The first step of a THM analysis consists of precisely selecting the exit channel of the events: by applying the ΔE-E technique to the data collected from each telescope it is possible to perform the desired particle identification and subsequently select only the data corresponding to a coincidence event from a deuteron and either an alpha particle or a proton. The heavy nucleus in the exit channel was not detected, therefore the experimental Q-value was reconstructed by assuming the presence of an undetected ^{24}Mg or ^{27}Al. This assumption was then verified by comparing the experimental Q-value with the theoretical one: as it can data be seen in fig. 1, for the $^{16}O(^{14}N, \alpha^{24}Mg)^2H$ reaction, it is indeed possible to assess the presence of the desired reaction process. To

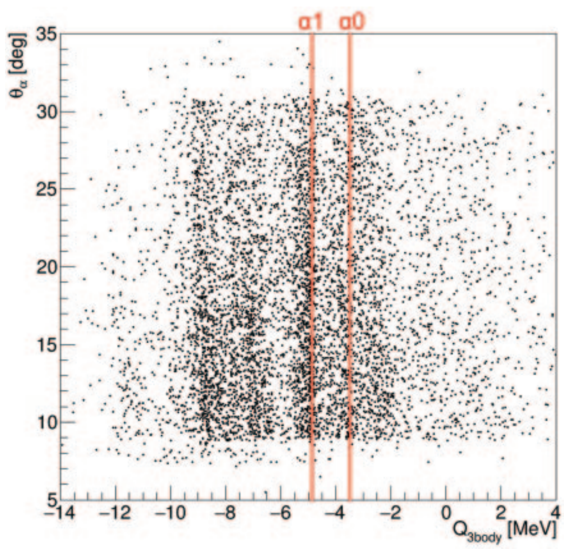

Fig. 1. – Detection angle of the alpha particle *vs.* experimental Q-value for the $^{16}O(^{14}N, \alpha^{24}Mg)^2H$ reaction channel. Black dots represent the experimental data, while red lines represent the theoretical value for both the ground state ($\alpha0$) and the first excited state ($\alpha1$).

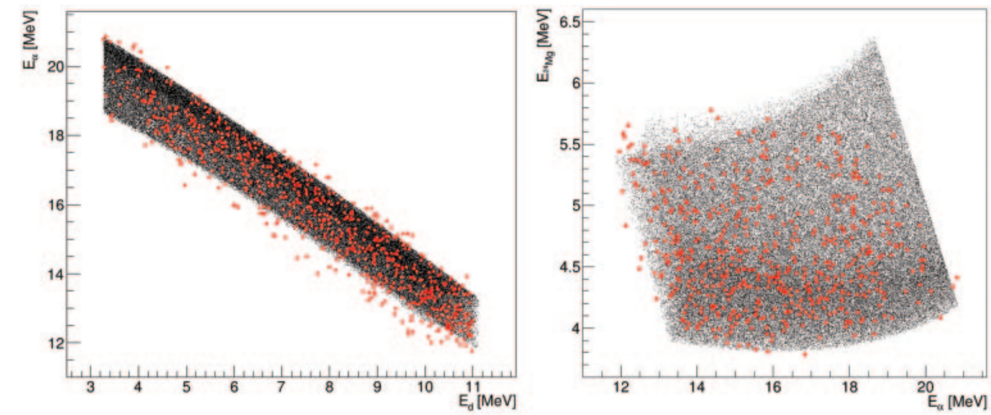

Fig. 2. – E_α-E_d kinematical loci for the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction channel, taking into account only the $\alpha0$ data. Red points refer to the experimental data, while black ones refer to the Monte Carlo kinematical simulation.

further test the goodness of the selection, a series of tests, typical of the THM data analysis, were performed. An example is presented in fig. 2 where the experimental kinematical locus is compared with the theoretical one, calculated by means of a Monte Carlo simulation. Future steps of the data analysis foresee the study of the experimental momentum distribution to asses the presence of the QF mechanism among the selected events.

4. – Conclusions

The preliminary results presented in this brief contribution clearly show the correct execution of the experiment and the presence, among the data collected, of the events of interest for the application of the Trojan Horse Method. It was possible to correctly select the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction channels of interest. The next steps will involve the accurate analysis of the P_s distribution, to assess the presence of the QF contribution, and the application of the same procedure to the other reaction channel, the ^{16}O(^{14}N, p^{27}Al)^{2}H. The THM analysis will be then finalized with the evaluation, for both reaction channels, of the cross-section and the corresponding reaction rate.

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