The ^{12}C +^{16} O fusion reaction in carbon burning: study at energies of astrophysical interest using the Trojan Horse Method

A. A. Oliva[1,2], A. Tumino[2,3], N. Soic[4], P. M. Prajapati[2,5], L. Acosta[6], R. Alba[2], F. Barba[7], S. Cherubini[1,2], G. D'Agata[1,2], D. Dell'Aquila[4], A. Di Pietro[2], J.P. Fernandez[8], P. Figuera[2], D. Galaviz Redondo[7], L. Guardo[1,2], M. Gulino[2,3], F. Hammache[9], D. Jelavic Malenica[4], A.I. Kiliç[10], M. La Cognata[2], M. La Commara[11,12], L. Lamia[1,2,13], D. Lattuada[2,3], C. Maiolino[2], G. Manicò[1,2], M. Mazzocco[14,15], M. Milin[4,16], Ma Nanru[17], A. Nurmukhanbetova[18], D. Nurkic[4,16], S. Palmerini[19], T. Parascandolo[11], D. Pierroutsakou[11], R.G. Pizzone[2], R. Popocovski[4], G.G. Rapisarda[1,2], S. Romano[1,2,13], D. Santonocito[2], M.L. Sergi[1,2], A. Shotter[20], R. Spartà[1,2], A. Spiridon[20], L. Trache[21], N. Vukman[4], and H. Yamaguchi[17]

[1]Dipartimento di Fisica e Astronomia "E. Majorana", Univ. di Catania, Italy
[2]INFN-LNS, Laboratori Nazionali del Sud, Catania, Italy
[3]Facoltà di Ingegneria e Architettura, Università degli Studi di Enna "Kore", Enna, Italy
[4]Rudjer Boskovic Institute, Zagreb, Croatia
[5]Manipal Centre for Natural Sciences, Manipal, India
[6]Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[7]Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal
[8]University of Seville, Seville, Spain
[9]IPN-Orsay, IN2P3-CNRS, Universite Paris XI, Orsay, France
[10]Nuclear Physics Institute of ASCR, Rez near Prague, Czech Republic
[11]Dipartimento di Fisica, Università degli Studi di Napoli "Federico II", Napoli, Italy
[12]INFN-Sezione di Napoli, Napoli, Italy
[13]Centro Siciliano Fisica Nucleare e Struttura della Materia, Catania, Italy
[14]Dipartimento di Fisica, Università degli Studi di Padova, Padova
[15]INFN-Laboratori Nazionali di Legnaro, Legnaro, Italy
[16]Physics Department, Faculty of Science, University of Zagreb, Zagreb, Croatia
[17]Center for Nuclear Study, The University of Tokyo, Tokyo, Japan
[18]Nazarbayev University, Astana, Kazakhstan
[19]Dipartimento di Fisica e Geologia, Univ. di Perugia, Italy.
[20]School of Physics - The University of Edinburgh, Edinburgh, Scotland
[21]IFIN-HH, Bucharest-Magurele, Romania

Abstract. The carbon-burning process in massive stars mainly occurs via the ^{12}C +^{12} C. However, at temperatures higher than $10^9 K$ and considering the increased abundance of ^{16}O produced during the later stages of the helium-burning, the ^{12}C+^{16}O fusion can also become relevant. Moreover, ^{12}C+^{16}O also plays a role in the scenario of explosive carbon burning. Thus, the astrophysical energy region of interest ranges from 3 to 7.2 MeV in the center-of-mass frame. However, the various measurements of the cross-section available in the literature stop around 4 MeV, making extrapolation necessary. To solve this uncertainty and corroborate direct measurement we applied the Trojan Horse Method 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 ^{12}C(^{16}O, α)^{24}Mg and ^{12}C(^{16}O, p)^{27}Al reactions in their entire energy region of astrophysical interest. In this contribution, after briefly describing the method used, the experiment and the preliminary phases of the data analysis will be presented and discussed.

1 Introduction

Carbon burning is one of the main advanced stages in the evolution of massive stars (M > 8·M$_\odot$) and type Ia supernovae [1, 2]. The main process of this stage is the ^{12}C +^{12} C fusion that ignites first during core and shell carbon burning. Indeed, among all the possible processes that can take place in the ashes of helium burning, this process has the lowest value for the Coulomb barrier. However, in the final phases of carbon burning, the abundance of ^{16}O nuclei is significantly higher [3, 4] than that of ^{12}C nuclei. Moreover, considering that also the temperature increases in these final phases, there is the possibility for other reactions with higher Coulomb barriers value to occur. It has been suggested[5] that the ^{12}C +^{16} O reaction temperatures higher than 10^9 K can have a significant impact on carbon burning. The latter is also of fundamental importance for Type Ia supernovae, since ^{12}C +^{12} C fusion is supposed to be its main energy source. Also in this case, where the relevant temperatures are around $3.6 \cdot 10^9$ K, ^{12}C+^{16}O could also have a significant effect, as demonstrated in recent studies [6]. Thus, to define the importance of the ^{12}C+^{16}O fusion in all the aforementioned environments, it is necessary to precisely study this process in the energy range of astrophysical interest, namely between 3 and 7.2 MeV in the center of mass (cm).

In the literature there are several measurements of the ^{12}C +^{16} O fusion, however, they stop around 4 MeV, thus not covering all the Gamow region down to 3 MeV. This means that extrapolation must be used[7]: since this procedure strongly depends on the model used, on unforeseen nuclear effects and on the environment considered [8], results between different extrapolation at 3 MeV can vary up to two orders of magnitude [8]. Therefore, a new measurement also covering the energy region below 4 MeV could solve this uncertainty. In the aforementioned astrophysical scenarios, the ^{12}C +^{16} O fusion proceeds through the following reaction channels: ^{12}C(^{16}O, α)^{24}Mg (Q = 6.77 MeV), ^{12}C(^{16}O, p)^{27}Al (Q = 5.17 MeV) and partially ^{12}C(^{16}O, n)^{27}Si (Q = - 0.424 MeV). Reactions such as ^{12}C(^{16}O, 2α)^{20}Ne, similar to the case of ^{12}C +^{12} C fusion, are hindered by the presence of the Coulombian barrier in the exit channel [7, 11].

2 New THM Experiment

2.1 The Trojan Horse Method

The Trojan Horse Method (THM) is based on the well-established quasi-free break-up reaction theory (QF). To evaluate the cross-section of the two-body reaction of interest $x + A \rightarrow b + B$, the method studies an appropriate three-body reaction $a + A \rightarrow b + B + s$ where the nucleus a is assumed to possess a well-clustered state with a $x + s$ configuration. In this formalism, a is referred to as the Trojan Horse (TH) nucleus, the x cluster is called the participant, while s is called the spectator. Indeed, under the QF kinematic conditions, the momentum transfer to the cluster s is negligible acting as a spectator of the interaction between x and A [9]. Since the break-up of the TH nucleus occurs in the nuclear field between a and A, one of the advantages of the method is that the two-body reaction is not hindered by any barrier effects, both Coulombian and centrifugal, or effected by the electron screening [9]. Other peculiar advantages of the method are that with a fixed beam energy it is possible

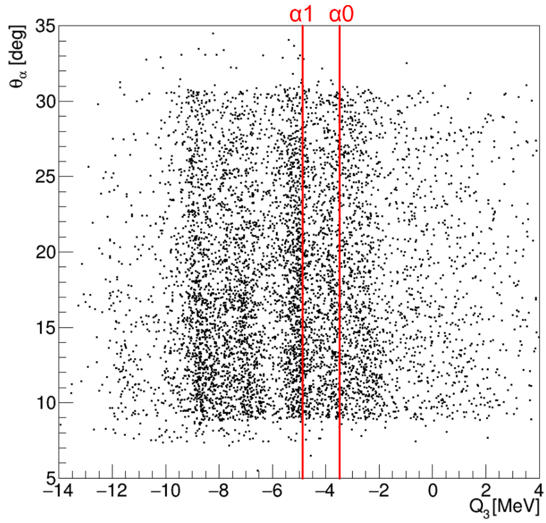

Figure 1. Detection angle of the alpha particle vs experimental Q-value for the $^{16}O(^{14}N, \alpha^{24}Mg)^2H$ reaction channel. Black dots represent the experimental data, while red lines represent the theoretical value for both the ground state (α0) and the first excited state (α1). From Ref. [12] with kind permission of Società Italiana di Fisica

to study a wide energy range in the center of mass frame between x and A, by taking advantage of the intercluster motion, and that it possible to study the sub-threshold energy region. A detailed explanation of the physics can be found in the already mentioned Ref. [9] and references therein.

2.2 Experimental Setup

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 $^{16}O(^{14}N, \alpha^{24}Mg)^2H$ and $^{16}O(^{14}N, p^{27}Al)^2H$ three-body reactions. ^{14}N was chosen as the TH nucleus since it has a ^{12}C + d cluster structure [10] which was already successfully employed in a THM measurement [11]. Thus, a ^{14}N beam was accelerated by the Van de Graaff tandem of the Laboratori Nazionali del Sud (LNS-INFN) in Catania at an energy of 33.7 MeV to impinge on a 458 μg/cm^2 WO_3 target. Four telescopes, each of which was made up of three silicon detectors, were deployed to correctly detect and identify the particles in the exit channel. The first stage of each telescope consisted of a 35 μm Position Sensitive Detector (PSD), the second one of a 100 μm PSD, and the third one of a 1500 μm pad detector. The pad detector was placed to collect protons with high energy that can escape the second detector; meanwhile, the first stage was used in combination with the second stage to perform the $\Delta E - E$ technique for particle identification. The telescopes were placed to cover the QF angular range from 7° to 30° and from 45° to 68° which was obtained by means of a Monte Carlo simulation. Moreover, the setup was symmetrically doubled with respect to the beam axis in order to increase the statistics.

2.3 Data Analysis

The second-stage detectors were calibrated both in energy and position with devoted experimental runs using an eight-peak alpha source, elastic scattering of the ^{14}N on $^{1,2}H$ and the

^{2}H(^{14}N, α)^{12}C) reaction. Since the PSD does not have a segmentation, it was covered with a shield with equally spaced slits placed at known angles in order to perform the angular calibration. The third-stage detectors were calibrated only in energy. 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 be seen in Fig. 1, for the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction, it is indeed possible to assess the presence of the desired reaction process.

3 Conclusion and future perspectives

In this brief contribution, we show the preliminary results of the data analysis that demonstrate the correct execution of the experiment and the presence, among the data collected, of the ^{16}O(^{14}N, α^{24}Mg)^{2}H reaction channel of interest. The following steps of this analysis will involve the evaluation of the moment distribution of the spectator, to verify the presence of the QF mechanism, and the extraction of the cross section of the two-body reaction of interest. The same procedure will be then applied to the other reaction channel, the ^{16}O(^{14}N, p^{27}Al)^{2}H and, finally, the reaction rate of the $^{12}C +^{16} O$ process will be evaluated.

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