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Study of ^{16}O(^{12}C,α^{20}Ne)α for the investigation of carbon-carbon fusion reaction via the Trojan Horse Method.

G.G. Rapisarda[1,2], **C. Spitaleri**[1,2], **C. Bordeanu**[3], **Z. Hons**[4], **G.G. Kiss**[1], **M. La Cognata**[1], **J. Mrazek**[4], **C. Nita**[3], **D. Pantelica**[3], **H. Petrascu**[3], **R.G. Pizzone**[1], **S. Romano**[1,2], **T. Szücs**[5], **L. Trache**[3,6], **A. Tumino**[1,7], **G. Velisa**[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*
[5] *ATOMKI, Debrecen, Hungary*
[6] *Cyclotron Institute Texas A&M University, College Station, TX, USA*
[7] *Università degli studi di Enna Kore Enna, Italy*

E-mail: `grapisarda@lns.infn.it`

Abstract. Carbon-carbon fusion reaction represents a nuclear process of great interest in astrophysics, since the carbon burning is connected with the third phase of massive stars ($M > 8\ M_{\odot}$) evolution. In spite of several experimental works, carbon-carbon cross section has been measured at energy still above the Gamow window moreover data at low energy present big uncertainty. In this paper we report the results about the study of the reaction ^{16}O(^{12}C,α^{20}Ne)α as a possible three-body process to investigate ^{12}C(^{12}C,α)^{20}Ne at astrophysical energy via Trojan Horse Method (THM). This study represent the first step of a program of experiments aimed to measure the ^{12}C+^{12}C cross section at astrophysical energy using the THM.

1. Introduction

The ^{12}C+^{12}C reaction is of great interest both in nuclear physics, producing the first evidence of nuclear molecular phenomena, as well as in astrophysics. In particular in this last field Carbon burning is connected with the third phase of massive star evolution in stars with $M > 8\ M_{\odot}$ [1]. ^{12}C+^{12}C 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_{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. In spite of the key role of carbon fusion reactions in understanding stellar evolution, experimental data available ([3] and references therein) cover down to carbon-carbon center of mass energy $E_{cm} = 2$ MeV, that is at the higher edge of the Gamow peak. Moreover experimental data below $E_{cm} = 3$ MeV are rather uncertain [2]. Up to now people calculate the reaction rate by means of the from data at higher energy, but this procedure can lead to wrong result since the ^{12}C+^{12}C excitation function is characterized by resonant structures also at the low energy of astrophysical interest

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[3] . In this framework new and accurate experimental data, down to the astrophysical energies, are strongly required.
A possible way to measure ^{12}C+^{12}C excitation function down to astrophysical energies, overcoming the problems connected to the direct measurement, mainly the strong suppression of the cross section due to the Coulomb barrier, is by using indirect methods. Among of them the Trojan Horse Method (THM) [5, 6, 7] is a consolidated method applied successfully for the study of nuclear reaction of astrophysical interest. In this paper we report on the measurement of the ^{16}O(^{12}C, α^{20}Ne)α in quasi-free kinematic condition to study the possibility to apply the THM to this three-body reaction for the indirect study of the ^{12}C(^{12}C, ^{20}Ne) α reaction, that is the alpha channel of the carbon-carbon fusion. This represent the first measurement of a experimental program devoted to the study of the carbon-carbon fusion reaction via THM.

2. The Trojan Horse Method

The THM is a powerful technique that allows to extract a two-body reaction cross section, $A + x \rightarrow c + C$, down to the low energies of astrophysical interest by selecting the quasi-free break-up channel of a suitable three-body reaction $A+a \rightarrow c+C+s$. Nucleus a is selected to have an high probability for a cluster configuration $x \oplus s$. The $A + a$ interaction induces the nucleus a breakup into x and s. Selecting the quasi-free kinematic condition it is assumed that s acts as a spectator while x interacts with the nucleus A leading to the astrophysically relevant two-body reaction. The $A + a$ reaction is induced at energies higher than the Coulomb barrier, in this way the breakup can take place inside the nuclear field and accordingly the $A + x$ interaction takes place without suffering the Coulomb barrier suppression and the electron screening. Moreover thanks to $x \oplus s$ inter-cluster motion, the THM allows to measure the two-body cross section in a wide energy using a single beam energy.
THM has been widely applied to study nuclear reaction involved in several astrophysical scenario including reactions induced by unstable nuclei and by neutrons [8, 9, 10, 11, 13, 14].

3. Experimental set-up

In the present case ^{16}O(^{12}C, α^{20}Ne)α had been selected as possible three-body reaction for the indirect study of the ^{12}C(^{12}C, ^{20}Ne)α reaction via THM. For the first time ^{16}O has been selected as Trojan Horse nucleus for is possible ^{12}C $\oplus$ α configuration. The experiment took place at the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Bucharest, Romania. The 9 MV Tandem accelerator provided a 25 MeV ^{16}O beam with a spot size on the target of about 2 mm and an intensity of about 8 nA. A natural carbon target, 100 μg/cm^2 thick, was used to induce the ^{16}O+^{12}C reaction. Energy and position of the outgoing particles were detected using six charge-partition position sensitive silicon detectors (PSD) in a symmetric configuration to double the number of collected events. PSDs 1,2,3 covered the angular rages 13°-26°, 41° - 55° and 65° - 80° respectively; PSDs 4,5,6 were placed on the other side with respect to the beam axis, covering the same angular ranges. Particle identification was carried out with ΔE-E technique. In particular two ionization chambers (IC) filled by P10 (average pressure 23 mb) placed in front of PSD1 and PSD4. The two telescopes (IC-PSD) were devoted to the neon detection and identification. The experimental set-up described above had been set to measure the ^{12}C(^{12}C,α ^{20}Ne) excitation function in a wide range 0-3 MeV, including the Gamov region.
Signals produced by detectors were processed through standard electronic. The trigger signal was produced by the coincidence between PSD1 (PSD4) and the total OR between PSD4-5-6 (PSD1-2-3). For the energy calibration we used a ^{12}C beam on Au target to get carbon from elastic scattering, ^{12}C beam on carbon target to get alphas for the ^{20}Ne+α exit channel and a standard alpha source.

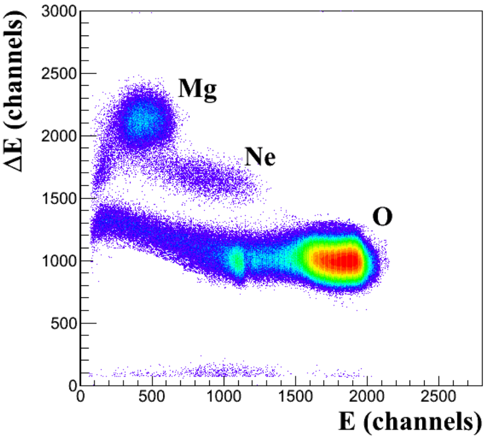

Figure 1. ΔE-E matrix for neon identification.

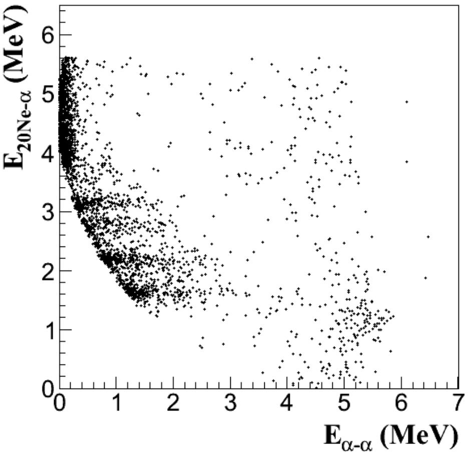

Figure 2. ^{20}Ne-α relative energy $E_{^{20}Ne\alpha}$ versus α-α relative energy $E_{\alpha\alpha}$

4. Data Analysis

To identify the reaction channel ^{16}O(^{12}C, α^{20}Ne)α of our interest we performed the study of ΔE-E matrices. In fig.1 typical experimental result is shown.

We can identified three loci related to oxygen (mainly due to the beam scattering) neon and magnesium. To select data of our interest a graphical cut was made around the neon locus. The experimental q-value for the three-body process was reconstructed considering alpha particles detected on PSD5-6 (PSD2-3) and assuming that the third undetected particle is an alpha particle. The experimental values obtained -2.66 MeV, -4.23 MeV, corresponds with good approximation to the theoretical q-value of the ^{16}O(^{12}C, α^{20}Ne)α reaction with ^{20}Ne at g.s and 1^{st} excited state respectively. This result confirm the correct selection of the reaction channel. For the following analysis we selected events related to ^{20}Ne at g.s. In fig.1 we can observe also that magnesium partially overlap the neon locus. This is partially due to the resolution of the detection system, on the other hand the loci are overlapped since we are in a energy range corresponding to the Bragg pick region. In particular the contamination is evident for events corresponding to a kinematic region with high probability for the quasi-free process. For this reason we applied a procedure in order to remove spurious events avoiding to put sharp cuts.

In order to study the reaction mechanism populating our three-body channel, we reconstructed the relative energy matrices. In particular in fig.2 we have ^{20}Ne-alpha relative energy ($E_{^{20}Ne\alpha}$) versus alpha-alpha relative energy ($E_{\alpha\alpha}$). The vertical locus for a fix alpha-alpha relative energy corresponds to the formation of the ^{8}Be g.s. It means that our exit channel is populated by a sequential process $^{16}\mathrm{O} + {}^{12}\mathrm{C} \longrightarrow {}^{20}\mathrm{Ne} + {}^{8}\mathrm{Be}^{*} \longrightarrow {}^{20}\mathrm{Ne} + \alpha + \alpha$. The horizontal loci for fix $E_{^{20}Ne\alpha}$ energy correspond to the population of ^{24}Mg excited states. Due to the $l = 0$ ^{12}C-α intercluster motion inside the ^{16}O, the region where we aspect to have the highest probability for the quasi-free process corresponds to low values for momentum of the alpha particle spectator (p_s) (lass than 100 MeV/c.) The study of the ^{20}Ne-alpha relative energy as function of p_s indicates that the quasi-free region shows a very low statistic, moreover there is no evidence of ^{24}Mg excited states. We have to say that this region corresponds to low-energy ^{20}Ne area where we had the strong contamination of spurious events. So the low-statistic could be due to wrong selection of the events in this region. On the other hand the ^{24}Mg excited states are populated in correspondence of high momenta. This result indicates that these levels are populated by a sequential mechanism $^{16}\mathrm{O} + {}^{12}\mathrm{C} \longrightarrow {}^{24}\mathrm{Mg}^{*} + \alpha \longrightarrow {}^{20}\mathrm{Ne} + \alpha + \alpha$. In fig.3 the spectrum of the ^{24}Mg exited states populated is shown. We can seen five levels. The experimental data did not

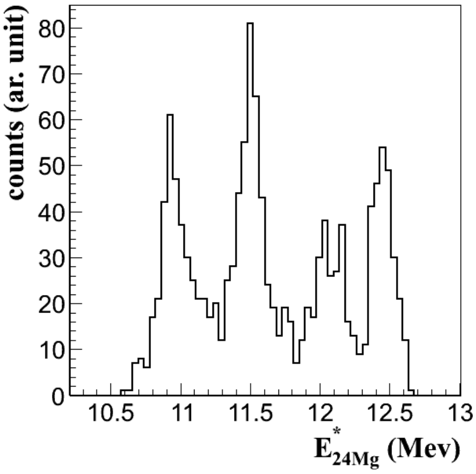

Figure 3. ^{24}Mg exited states populated in the present work.

E^*_{24Mg} MeV present work	E^*_{24Mg} MeV E. Goldberg et	J^π *al.*
10.94		
11.50	11.52	2^+
12.03	11.96	2^+
12.16		
12.45	12.46	1^-

Table 1. ^{24}Mg exited states energy obtained in the present work compared with the excited levels measured in E. Goldberg *et al.* [15]

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allow to make J^π assignment, on the other hand this energy range shows a very high density of ^{24}Mg levels. In tab.1 we report a comparison between our data and the results obtained by E. Goldberg *et al.* [15] where the ^{24}Mg levels were observed via ^{20}Ne-alpha resonant scattering.

5. Conclusion

In the framework of the study carbon-carbon fusion reaction at astrophysical energy via THM, we have studied the ^{16}O(^{12}C, α^{20}Ne)α using for the first time the ^{16}O as Trojan Horse nucleus. Experimental results obtained, in the experimental conditions described, have shown that three-body exit channel is mainly populated by sequential decay mechanism while no clear evidence of quasi-free process has been observed. The strong contamination of spurious events in the quasi-free energy region could be the reason of wrong selection of quasi-free events. ^{24}Mg excited states have been populated and compared with data present in literature. On the basis of this results a new experimental run has been performed with a different experimental set-up in order to increase the resolution and avoid the contaminations problems. Moreover we performed a experimental run where THM have been applied to the ^{14}N(^{12}C, α ^{20}Ne)^{2}H three-body reaction using for the first time ^{14}N (^{12}C $\oplus$ d cluster configuration) as Trojan Horse nucleus.

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