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β-Delayed α Decay of ^{16}N and the $^{12}C(\alpha,\gamma)^{16}O$ Cross Section at Astrophysical Energies: a New Experimental Approach

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Abstract. The $^{12}C(\alpha,\gamma)^{16}O$ reaction at energies corresponding to the quiescent helium burning in massive stars is regarded as one of the most important processes in nuclear astrophysics. Although this process has being studied for over four decades, our knowledge of its cross section at the energies of interest for astrophysics is still widely unsatisfactory. Indeed, no experimental data are available around 300 keV and in the energy region of astrophysical interest extrapolations are performed using some theoretical approaches, usually R-matrix calculations. Consequently, the published astrophysical factors range from 1 to 288 keVb for $S_{E1}(300)$ and 7 to 120 keVb for $S_{E2}(300)$, especially because of the unknown contribution coming from subthreshold resonances. To improve the reliability of these extrapolations, data from complementary experiments, such as elastic and quasi- elastic α scattering on ^{12}C, α-transfer reactions to ^{16}O, and ^{16}N decay are usually included in the analysis. Here the β-delayed α decay of ^{16}N is used to infer information on the $^{12}C(\alpha,\gamma)^{16}O$ reaction and a new experimental technique is suggested.

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I. INTRODUCTION

$^{12}C(\alpha,\gamma)^{16}O$ and the 3-α process are the most important reactions that occur during the helium burning stage in red giants. It begins with the 3-α reaction among helium nuclei forming ^{12}C, that can radiatively capture another helium nucleus to form ^{16}O. In principle, this process can produce heavier elements such as ^{20}Ne, ^{24}Mg and so on, but, because of the increase in the Coulomb barriers and the properties of the resonances in the critical energy region for the first relevant reaction, $^{16}O(\alpha,\gamma)^{20}Ne$, the helium is mainly converted into ^{12}C and ^{16}O. Carbon and oxygen abundance depends on the relative cross section of the reaction and on stellar temperature and density.

Despite the simultaneous interaction of 3-α nuclei to form ^{12}C is energetically possible, the probability for this direct process is too small to account for observed abundance in stars. To overcome this problem, in the 50's Salpeter [1] and Öpik [2] proposed that carbon was created via a two step process. In the first stage, two alphas produce ^{8}Be in its ground state, and then, in the second step, ^{8}Be can capture another helium nucleus producing ^{12}C, thus completing the carbon creation process. Assuming this is true, Hoyle [3] showed that the amount of carbon produced in this way is insufficient to explain the observed abundance in red giants. So, in 1953, he proposed that a proper carbon quantity could be synthesized if the $^{8}Be+\alpha$ reaction took place through an s-wave resonance near the threshold at about 7.65 MeV, as the existence of such a resonance would greatly accelerate the rate of the 3-α process. This was later verified and a narrow resonance near the Q-value (7.68 MeV) of the reaction was found.

As just mentioned, the $^{12}C(\alpha,\gamma)^{16}O$ reaction near the Gamow energy corresponding to helium burning temperatures ($T_9 \sim 0.2$) represents one of the most important reactions in nuclear astrophysics, but the measurement of its cross section is extremely complicated. Indeed, its cross section is extremely low (10^{-17} b). Moreover, if we look at the energy level diagram of ^{16}O (Fig. 1) we can conclude that two resonant processes contribute to the total cross section. One is the E_1 capture mode proceeding through the f-resonance at E* = 9.632 MeV and the subthreshold state 1^- at E* = 7.117 MeV, and the other is the E_2 capture mode that includes the contribution of direct capture and the tail of the subthreshold state 2^+ at E* = 6.917 MeV.

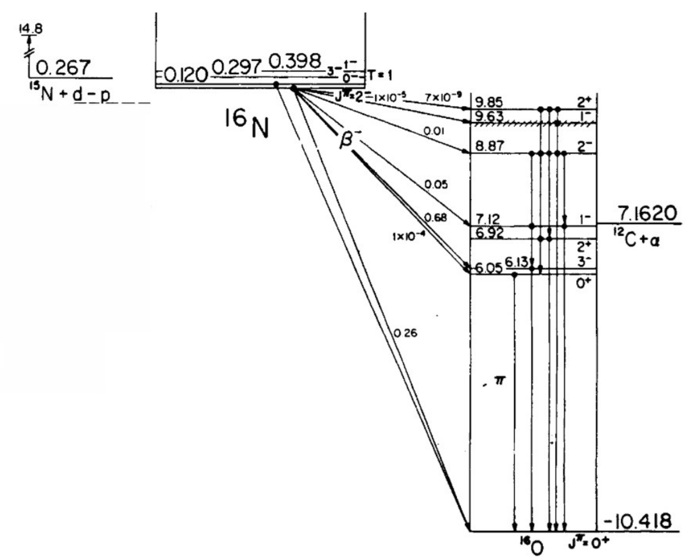


FIGURE 1. The diagram shows the levels of the ^{16}O nucleus. The branching ratios of the β^- decay of ^{16}N to ^{16}O are also indicated [4].

For both the E_1 and E_2 capture, interference effects between the involved resonances and the direct capture process must be taken into account. As the interference may be either constructive or destructive, data should provide information on the sign of interference. Finally, the total capture cross section is the incoherent sum of the E_1 and E_2 contributions.

Information about the total cross section at stellar energy is then obtained through extrapolation using theoretical models, such as R-matrix calculations, leading to a wide range of values for the calculated astrophysical factor S(E).

Indeed, at $E_{c.m.}$ = 300 keV it varies from 1 keVb to 288 keVb for the E_1 component, and from 7 keVb to 120 keVb for the E_2 [5,6].

Since direct measurements of the cross section under $E_{c.m.}$ = 0.9 MeV are presently not possible, indirect approaches are used to get complementary informations.

II. STATE OF THE ART

In 1971, Barker [7] proposed an experimental method to investigate the $^{12}C+\alpha$ reaction cross section based on the β-delayed α decay of ^{16}N. The decay of ^{16}N into $^{12}C+\alpha$ proceeds through a first step governed by the beta decay of ^{16}N (τ = 10.24 s, Q = 10.42 MeV) into $^{16}O^*$, which can in turn decay to $^{12}C+\alpha$. Information about the E_1 component of the astrophysical factor can be extracted from the height of the peak located at roughly $E_{c.m.}$ = 1.1 MeV in the β-delayed α spectrum of the $^{12}C+\alpha$ (Fig.2). This peak originates from the interference of the high-lying 1^- state of ^{16}O at E* = 9.632 MeV with the subthreshold one at E* = 7.117 MeV. This is presently considered the best method to investigate the value of $S(E_1)$.

All previous experiments were based on the ^{16}N implantation in a thin carbon foil and on the detection of the outgoing particles by means of either solid state or gas detectors. Following this idea, Tang et al. [8] performed an experiment using an intense in-flight produced beam of ^{16}N sent into a gas cell chamber and implanted on a thin carbon foil. In order to detect in coincidence ^{12}C-α pairs, after 15 s of implantation time, the foil was rotated between two ionization chambers, decay products were collected and their spectrum measured.

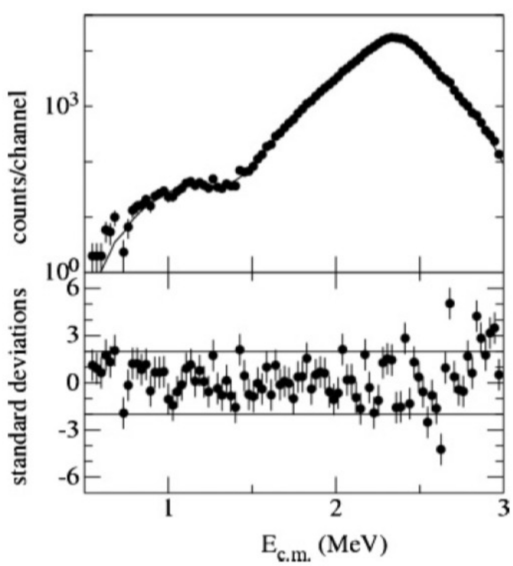


FIGURE 2. Spectrum of α particles from decay of ^{16}N plotted as function of $E_{c.m.}$ as obtained in the experiment of Ref. [8]. The solid line is the result of an R-matrix least-squares fit. The bottom plot shows the deviations of the data from the fitted values in units of standard deviations [8]. *Reprinted (figure 12) with permission from X.D.Tang et al., Phys. Rev. C81, 045809 (2010). Copyright (2010) by the American Physical Society (http://link.aps.org/abstract/PRC/v81/p045809).*

The obtained results are shown in Fig. 2, where one can distinguish a main peak, due to the α-decay of 1^- state at $E_{c.m.}$ = 2.418 MeV ($E^*(^{16}O)$ = 9.632 MeV), and a secondary one at about $E_{c.m.}$ = 1.1 MeV arising from interference effects between above and subthreshold states. The height of this last peak is proportional to the astrophysical factor at the Gamow energy. So, it is possible to infer information about the cross section of the $^{12}C+\alpha$ reaction at astrophysical energies by knowing the amplitude of the low energy interference peak. It is worth to note that less of 1% of the total statistics lie in the region of astrophysical interest. Data were collected down to 450 keV and the implantation efficiency, i.e. the percentage of ^{16}N ions captured in the foil, was only 6%.

Here we present a new experimental method based on the use of a TPC thus preventing implantation techniques.

II.I A New Experimental Approach: Time Projection Chamber Based Experiment

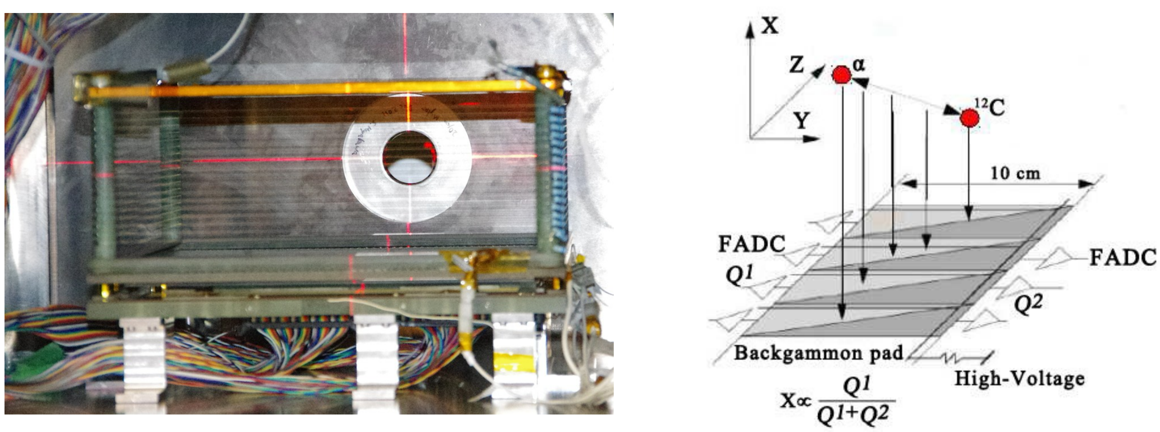
The basic idea is to avoid implantation techniques using a Time Projection Chamber as an active target, in order to increase detection efficiency to about 19%. The experiment was performed using the radioactive ^{16}N beam provided by CRIB apparatus of the Center for Nuclear Study of the University of Tokyo at RIKEN campus in Wako, in September 2013.

The beam was produced using the ^{15}N(d,p)^{16}N reaction, as in Tang et al. [8]. A beam of ^{15}N was used to bombard a nitrogen cooled deuterium gas target at about 400 Torr pressure. The ^{16}N beam was selected by using the double achromatic spectrometer and the Wien filter of CRIB and was sent into the scattering chamber. The produced ^{16}N beam had a purity of 90% and a maximum intensity of 10^6 pps. During the experiment the average beam intensity was 10^5 pps. A TPC detector was installed in the scattering chamber, and the whole scattering chamber was filled with P10 gas. The gas pressure was tuned to stop the ^{16}N beam in the middle of the TPC active volume. A pressure of 150 Torr was kept during the measurement. A picture of the TPC is shown in Fig. 3a.

The TPC was used as an active target to detect in coincidence the ^{12}C and the α particles coming from the decay of ^{16}O, produced by the beta decay of ^{16}N. It was chosen to use a gas detector like the TPC because of its insensitivity to beta background. The TPC was equipped in the bottom plane with two Gas Electron Multipliers (GEMs) that multiply the ionization electrons that then were collected into a backgammon pad detector plane. The ^{16}N ion was stopped inside the TPC for 50 ms and the ^{12}C-α decay back to back was collected. The tracks produced by the decay particles are reconstructed in the three directions. Indeed, the fired pad gives information of the track position along the beam axis (z-axis). The position along the pad is reconstructed by using the charge partition at its ends. Finally, in the direction orthogonal to the pad plane the position is given by measuring the drift time of the electrons. A typical track reconstruction is pictorially shown in Fig. 3b.

Since the charge collected at the pads is proportional to the energy loss of the particles, the signal amplitude from the anode also provides information on this energy loss. If the momentum of the particles is known, this information can be used to identify the particles. Moreover, the TPC was equipped with a Gating Grid used for switching off the TPC during the beam implantation to prevent the GEMs to be destroyed by too high currents. Finally, signals coming from the TPC were sent to a CAEN 12-bit Flash ADC V1740 for the digital acquisition.

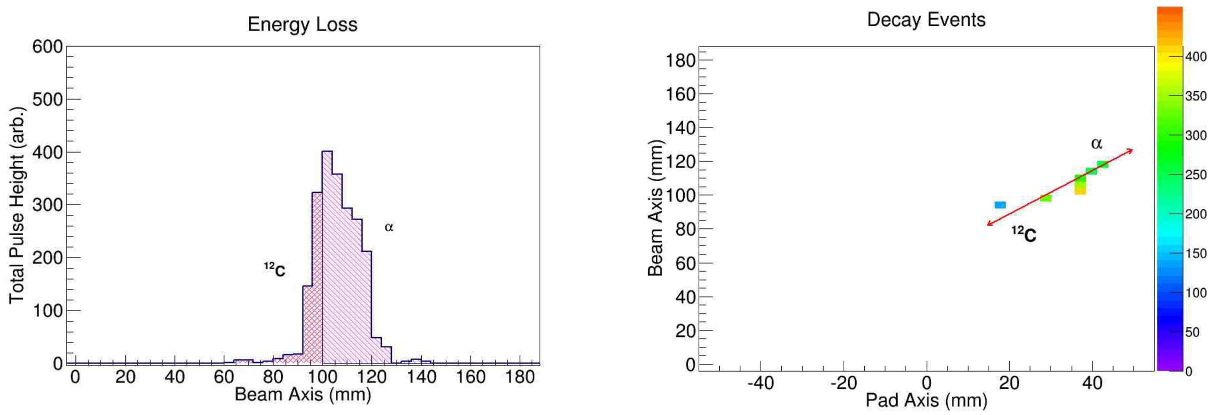
The configuration of the TPC allowed for a sensitive volume of 2000 cm^3, with an active length of 20 cm along the beam axis and 10 cm along the other two directions. The TPC spatial resolution was 2 mm along the beam axis and 1 mm in the other directions.



(a) (b)

FIGURE 3. (a) The TPC chamber: the entire structure is surrounded by a certain numbers of thin wires that allows the electrons drift until two Gas Electron Multipliers (GEMs). The electrons were collected into backgammon pads based on the bottom plane of the TPC. (b) Typical decay event: the two red particles are decay products of ^{16}N [9].

The data analysis is in progress. In Fig. 4 the energy loss in the TPC and the reconstructed tracks of a typical decay event are shown.



(a) (b)

FIGURE 4. (a) Energy loss in the TPC along the beam axis: spectrum shape is consistent with a typical Bragg's peak in which we are in presence of two particles, one (more massive) looses its energy faster than the other. (b) The same event projected onto yz plane: we can distinguish the trace of a back to back decay.

CONCLUSIONS

"A measurement of the β-delayed α decay of ^{16}N is considered to be the best method presently available to provide a constrain for the E_1 component of $S_{E1}(300)$, of the C(α,γ) reaction" [8]. Our analysis is in progress so the results will be available in the future.

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