β-Delayed α decay of \(^{16}\text{N}\) and the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) cross section at astrophysical energies: a new experimental approach

S. Sanfilippo\(^1\), S. Cherubini\(^{1,2}\), S. Hayakawa\(^2\), A. Di Pietro\(^3\), P. Figuera\(^3\), M. Gulino\(^{2,3}\), M. La Cognata\(^3\), M. Lattuada\(^{1,2}\), C. Spitaleri\(^{1,2}\), H. Yamaguchi\(^9\), D. Kahl\(^9\), T. Nakao\(^4\), S. Kubono\(^5\), Y. Wakabayashi\(^5\), T. Hashimoto\(^6\), N. Iwasa\(^7\), Y. Okada\(^7\), K. Ushio\(^7\), T. Teranishi\(^7\), M. Mazzocco\(^7\), C. Signorini\(^9\), D. Torresi\(^2\), J.Y. Moon\(^{10}\), T. Komatsubara\(^{10}\), P.S. Lee\(^{11}\), K.Y. Chae\(^{12}\), M.S. Gwak\(^{12}\).

1) Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Via S.Sofia 64, 95123 Catania, Italy; 2) INFN – Laboratori Nazionali del Sud, Catania, Italy; 3) Università Kore, Enna, Italy; 4) Center for Nuclear Study, University of Tokyo, Wako Branch, Saitama, Japan; 5) RIKEN Nishina Center, Wako, Saitama, Japan; 6) RCNP, Osaka University, Osaka, Japan; 7) Department of Physics, Tohoku University, Sendai, Japan; 8) Department of Physics, Kyushu University, Fukuoka, Japan; 9) Dipartimento di Fisica e Astronomia, Università di Padova and INFN-Sez. Padova, Padova, Italy; 10) Institute for Basic Science, Daejeon, Korea; 11) Department of Physics, Chung Ang University, Seoul, Korea; 12 Department of Physics, Sungkyunkwan University, Seoul, Korea.

Abstract - The \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) 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 been studied for over four decades, our knowledge of its cross section at the energies of interest is still widely unsatisfactory. Indeed, in the energy region of astrophysical interest extrapolations are performed using some theoretical approaches, usually R-matrix calculations. To improve the reliability of these extrapolations, data from complementary experiments, such as elastic and quasi-elastic \(\alpha\) scattering on \(^{12}\text{C}\), \(\alpha\)-transfer reactions to \(^{16}\text{O}\), and \(^{14}\text{N}\) β-delayed α decay are usually included in the analysis. Here a new experimental technique has been used to study the \(^{16}\text{N}\) β-delayed α decay of \(^{14}\text{N}\) is used to infer information on the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction.

INTRODUCTION

\(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) and the 3-\(\alpha\) process are the most important reactions that occur during the helium burning stage in red giants. This begins with the 3-\(\alpha\) reaction among helium nuclei to form \(^{12}\text{C}\) that can radiatively capture another helium nucleus producing \(^{16}\text{O}\). In principle, this process can produce heavier elements 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, \(^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}\), the helium is mainly converted into \(^{12}\text{C}\) and \(^{16}\text{O}\). 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-\(\alpha\) nuclei to form \(^{12}\text{C}\) is energetically possible, the probability for this direct process is too small to account for observed abundance in stars. To overcome this problem, Salpeter [1] and Öpik [2] proposed that carbon was created via a two step process: two alphas produce \(^{8}\text{Be}\) in its ground state, and then, in the second step, \(^{8}\text{Be}\) can capture another helium nucleus producing \(^{12}\text{C}\). Hoyle [3] showed that the amount of carbon produced in this way is insufficient to explain the observed abundance in red giants. So, he proposed that a proper carbon quantity could be synthesized if the \(^{8}\text{Be}+\alpha\) 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-\(\alpha\) 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 \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\) reaction near the Gamow energy corresponding to helium burning temperatures \((T_\odot \sim 0.2)\) 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 \((10^{-17} \text{ b})\). Moreover, 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 one 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.
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_{cen} = 300 keV it varies from 1 keVb to 288 keVb for the E1 component, and from 7 keVb to 120 keVb for the E2 [4,5].

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

**STATE OF THE ART**

Barker [6] 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 (t = 10.24 s, Q = 10.42 MeV) into $^{16}$O*, which can in turn decay to $^{12}$C+$\alpha$. Information about the E1 component of the astrophysical factor can be extracted from the height of the peak located at roughly E_{ecn} = 1.1 MeV in the spectrum of the $^{12}$C+$\alpha$. This peak originates from the interference of the high-lying l = 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(E1).

Tang et al. [7] 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. The obtained results are shown in [7]. Data were collected down to 450 keV and 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.

**A new experimental approach: Time Projection Chamber based experiment**

The 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 Multi Sampling TPC and the CNS Radioactive Ion Beam (CRIB) of the Center for Nuclear Study of the University of Tokyo based at RIKEN campus in Wako, Japan.

A beam of $^{15}$N was used to bombard a nitrogen cooled deuterium gas target at about 400 Torr pressure. The $^{15}$N beam was selected by means of CRIB and sent into the scattering chamber. The produced $^{15}$N beam had a purity of 90% and a maximum intensity of $10^7$ 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. This pressure of 150 Torr was kept during the measurement.

The TPC was used as an active target to detect in coincidence the $^{12}$C and the $\alpha$ particles coming from the decay of $^{16}$O, produced by the beta decay of $^{16}$N. It must be stressed that a gas detector like the MSTPC is practically insensitive 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-shaped pad detector plane. The $^{16}$N ions were implanted inside the TPC for 50 ms and the $^{12}$C-α back to back decays were collected for the next 50 ms and then the cycle started over again. The TPC is 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.

The tracks produced by the decay particles are reconstructed in the three directions. Since the charge collected at the pads is proportional to the energy loss of the particles, the signal amplitude from the anode provides information on this energy loss along with position one. This piece of information can be used to identify the particles.

The configuration of the TPC allowed for a sensitive volume of 2000 cm³, with an active length of 20 cm along the beam axis and 10 cm along the other two directions. The TPC spatial resolution is 2 mm along the beam axis and 1 mm in the other directions.

The data analysis is still in progress.

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**REFERENCES**