

Helium burning: Carbon and oxygen formation studied with an optical readout TPC (O-TPC)

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Stellar Helium Burning: Carbon and Oxygen Formation (Studied with Optical-TPC at HI γ S) ¹

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Abstract. An Optical Readout Time Projection Chamber (O-TPC) operating with the gas mixture of $CO_2(80\%) + N_2(20\%)$ at 100 torr with gamma beams from the HI γ S facility of TUNL at Duke was used to study the formation of carbon and oxygen during helium burning. Measurements were carried out at beam energies: $E_\gamma = 9.51, 9.61, 9.72, 10.00, 10.54, 10.84$ and 11.14 MeV. We have begun the process of extracting complete angular distributions for the $^{12}C(\alpha, \gamma)^{16}O$ reaction using energy bins of approximately 90 keV in order to determine the values of S_{E1} , S_{E2} and the mixing phase ϕ_{12} . The rate of carbon formation at high temperatures ($T > 3$ GK) may increase due to contributions from higher lying states. We searched for such contributions including a contribution from the predicted higher lying second 2^+ state of ^{12}C . No significant contributions from higher lying states including the known 1^- state at 10.84 MeV were found and specifically no evidence was found for the predicted second 2^+ state of ^{12}C .

1. Introduction

The outcome of helium burning is the formation of the two elements: carbon and oxygen [1]. The ratio of carbon to oxygen at the end of helium burning has been identified two decades ago as one of the key open questions in Nuclear Astrophysics [1] and it is still today an open question. To solve this problem one must extract the p-wave [$S_{E1}(300)$] and d-wave [$S_{E2}(300)$] cross section factors of the $^{12}C(\alpha, \gamma)^{16}O$ reaction at the Gamow peak (300 keV) with an accuracy of approximately 10% or better. Our current knowledge of these astrophysical cross section factors is not near the required accuracy.

Several new measurements of the $^{12}C(\alpha, \gamma)^{16}O$ reaction using gamma-ray detectors have been reported [2, 3] with energies in the vicinity of 1.0 MeV. However, the S-factors are measured with very low accuracy ($\pm 40-80\%$) and most importantly one cannot rule out a low value (close to 10 keV-b if not zero) of the E1 S-factor [4, 5]. These new experiments use some of the highest intensity alpha-particle beams (10 - 500 μ Amp) with an impressive luminosity of 10^{33} [2] and $10^{31} \text{ cm}^{-2}\text{sec}^{-1}$ [3], and a 4π array of HPGe and BaF gamma-detectors, respectively, that provides large counting statistics. Yet the obtained accuracy of the S-factors is limited due to the limited accuracy of the measured angular distribution. A major disadvantage of measuring gamma rays is the large background. This large background is not expected in our proposed experiment using a Time Projection Chamber (TPC) and in addition we will measure complete

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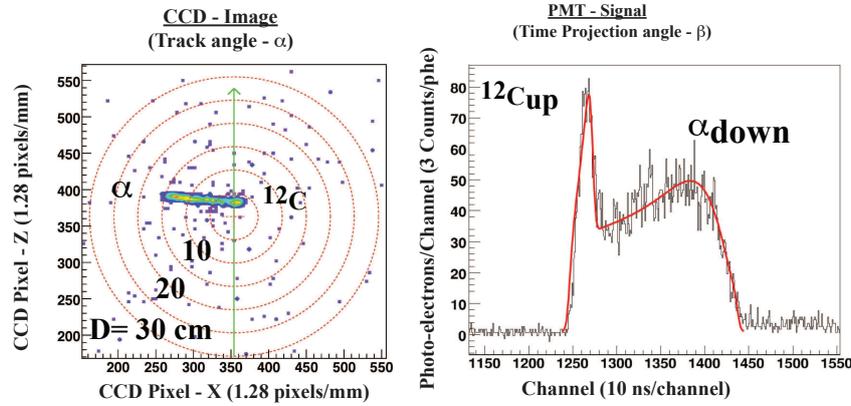


Figure 1. A typical $\alpha + {}^{12}\text{C}$ event registered by the CCD camera with the associated PMT signal and the predicted Time Projection line shape for the measured out of plane angle (β).

and detailed angular distributions at all angles (including the essential backward angles) and thus we anticipate a large sensitivity to the E2/E1 ratio and the mixing angle ϕ_{12} .

2. Measurement of the ${}^{16}\text{O}(\gamma, \alpha){}^{12}\text{C}$ Reaction With O-TPC.

We have used the upgraded optical readout system of the O-TPC, including the large area (142 mm diameter) design lens, to measure the ${}^{16}\text{O}(\gamma, \alpha){}^{12}\text{C}$ reaction [6, 7, 8, 9]. Measurements were carried out at $E_\gamma = 9.512(10)$, $9.611(10)$ and $9.720(10)$ MeV with beam widths FWHM = 293, 285 and 294 keV, respectively. A typical ${}^{16}\text{O}$ dissociation event is shown in Fig. 1 and the measured spectra of the photodisintegration of oxygen nuclei are shown in Fig. 2. The detector resolution is considerably smaller than the beam width and we plan to bin the measured data in three bins of approximately 90 keV each. Preliminary angular distributions were measured and the data analysis is in progress to determine the values of: S_{E1} , S_{E2} and the mixing phase ϕ_{12} . We note that the rapid variation of ϕ_{12} across the 1^- resonance in ${}^{16}\text{O}$ which is required by unitarity, was not observed in [2, 3], suggesting a significant problem with gamma-ray measurements.

3. Measurement of the ${}^{12}\text{C}(\gamma, 3\alpha)$ Reaction With O-TPC.

Carbon is formed during stellar helium burning in the "triple-alpha process", the ${}^8\text{Be}(\alpha, \gamma){}^{12}\text{C}$ reaction, that is mostly governed by the 0^+ state at 7.654 MeV. At high temperatures ($T > 3$ GK) higher lying states in ${}^{12}\text{C}$ may contribute. Indeed a broad ($\Gamma = 560$ keV, $\Gamma_\gamma = 0.2$ eV) 2^+ state at 9.11 MeV in ${}^{12}\text{C}$ was included in the NACRE compilation [10] following theoretical prediction for the 2^+ member of the rotational band built on top of the 0^+ (Hoyle) state at 7.654 MeV. It increases the production of carbon at temperatures in excess of 1 GK by up to a factor of 15. The non-existence of the 2^+ member of the rotational band build on top of the Hoyle state would give credence to the conjectured alpha condensate and a spherical Hoyle state.

We used our Optical-Readout Time Projection Chamber (O-TPC) operating with CO_2 gas to search for such states via the identification of triple alpha events from the ${}^{12}\text{C}(\gamma, 3\alpha)$ reaction as shown in Fig. 3. We have studied this reaction at $E = 9.51$, 9.61 , 9.72 , 10.00 , 10.54 , 10.84 and 11.14 MeV. The gamma width of the known 1^- state at 10.84 MeV was measured, as shown in Fig. 4, but no evidence was found for the predicted 2^+ at 9.11 MeV, as shown in Fig. 4. Stringent upper limit on Γ_γ of the predicted 2^+ at 9.11 MeV as well as any other higher lying 2^+ state in ${}^{12}\text{C}$ between 9.0 - 11.0 MeV were reported [11].

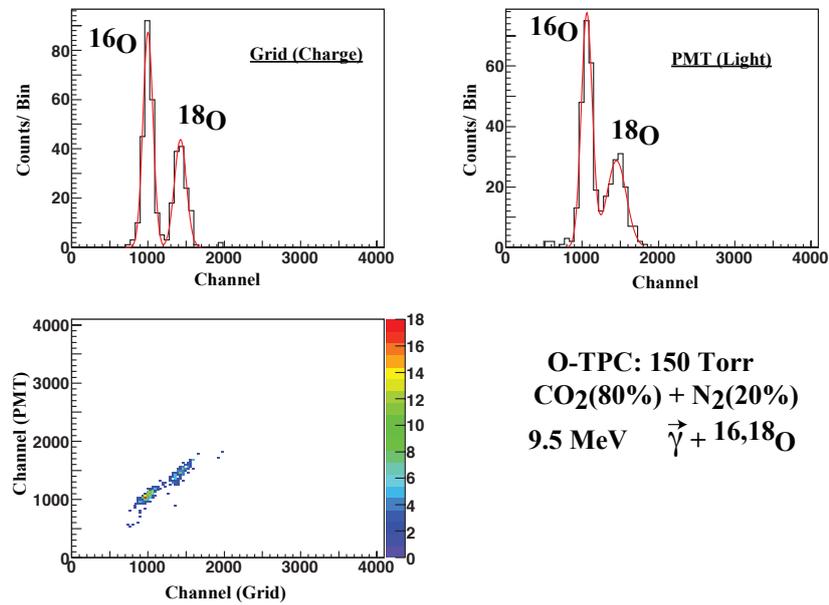


Figure 2. Typical oxygen spectra measured by the correlated grid (charge) and PMT (light) signals together with a two Gaussian fit.

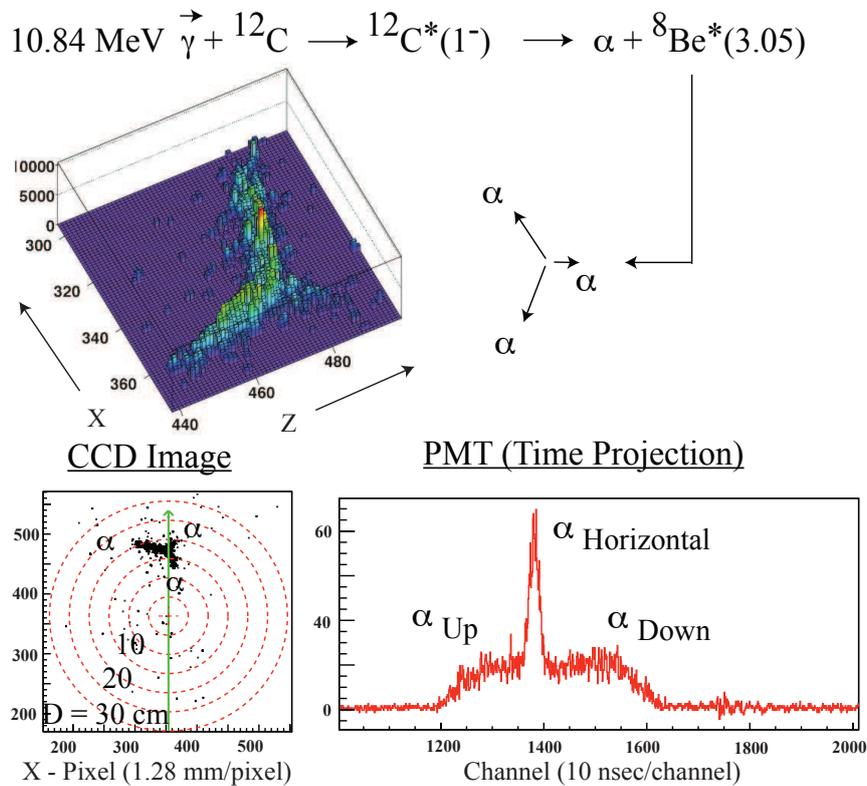


Figure 3. A typical three alpha event detected by the O-TPC.

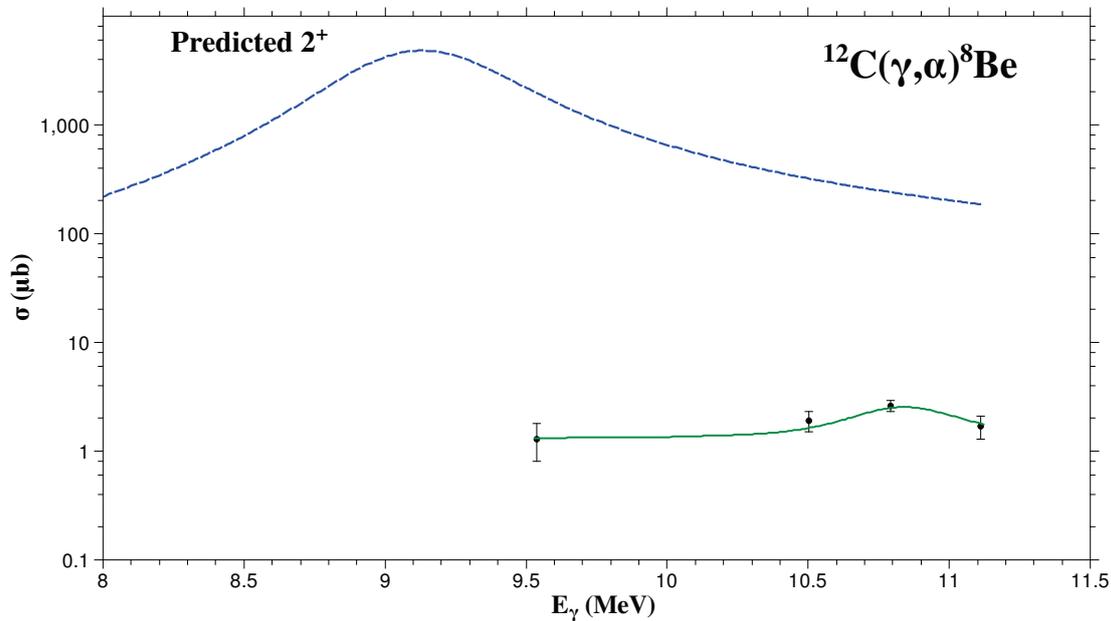


Figure 4. The measured cross section of the $^{12}\text{C}(\gamma, 3\alpha)$ reaction compared to the cross section for the predicted 2^+ at 9.11 MeV. The line through the data point is the sum of the cross section due to the 1^- resonance at 10.84 MeV plus a constant background term.

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During stellar helium burning both oxygen and carbon are formed; the two elements essential for life as we know it. There is a renewed interest in carbon formation at high temperatures (above 1 GK) via the so called triple alpha process, the ${}^8\text{Be}(\alpha, \gamma){}^{12}\text{C}$ reaction [1]. The formation of oxygen via the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction that was declared by Willie Fowler twenty five years ago 'the holy grail' of Nuclear Astrophysics [2], is not yet well known, in spite of repeated strong statements in the literature. Estimates for S_{E1} and $\frac{S_{E2}}{S_{E1}}$ vary in some cases by as much as a factor 8. Furthermore, the recent measurement of the beta-delayed alpha-particle emission of ${}^{16}\text{N}$ performed at Argonne [3] was found to be in disagreement with the TRIUMF data, but in agreement with the Yale-UConn data and the old Mainz data.

We have undertaken a completely new approach [4] to study the time reversed reactions with photon beams extracted from the HI γ S facility of TUNL at Duke University [5] with the target-detector being an optical readout Time Projection Chamber (O-TPC) operating with $\text{CO}_2(80\%) + \text{N}_2(20\%)$ gas mixture [6]. Several in beam measurements with the O-TPC target/detector were already performed at $E_\gamma = 9.55, 10.54, 10.84,$ and 11.14 MeV to study the broad 1^- states in ${}^{16}\text{O}$ and ${}^{12}\text{C}$ at 9.58 and 10.84 MeV, respectively. The results of these measurements will be discussed.

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