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# Stellar Helium Burning Studied with an Optical Readout TPC (O-TPC) at HI $\gamma$ S

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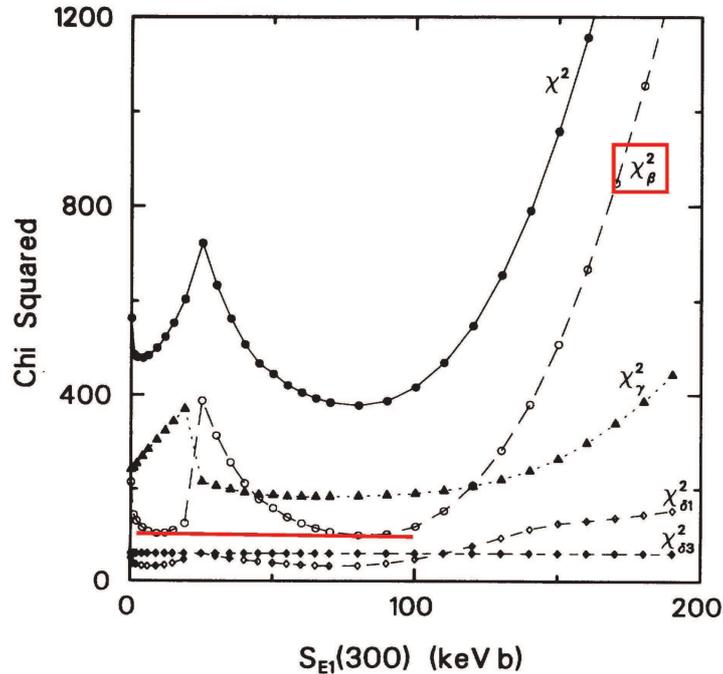
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**Abstract.** An Optical Readout Time Projection Chamber (O-TPC) operating with the gas mixture of CO<sub>2</sub>(80%) + N<sub>2</sub>(20%) at 100 torr with gamma beams from the HI $\gamma$ S facility of TUNL at Duke University were used to study the formation of carbon and oxygen during helium burning. Measurements were carried out with circularly polarized gamma-ray beams at energies:  $E_\gamma = 9.08, 9.38, 9.58, 9.78, 10.08, 10.38$  and  $10.68$  MeV. We have begun the process of extracting complete angular distributions for the  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  reaction and the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction (eventually with energy bins of approximately 100 keV) in order to determine the values of  $S_{E1}$ ,  $S_{E2}$  and the mixing phase  $\phi_{12}$  of the  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$  reaction. The rate of carbon formation at high temperatures ( $T > 3$  GK) was suggested to increase due to contributions from a higher lying  $2^+$  state. We have measured an angular distribution of (essentially) pure E2 transition at  $E_\gamma = 9.78$  MeV of the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction, providing conclusive evidence for the elusive  $2_2^+$  state in  $^{12}\text{C}$ .

## 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 three 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  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  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. In particular the data on the beta-delayed alpha-particle emission of  $^{16}\text{N}$  does not determine whether the interference between the bound  $1^-$  state at 7.117 and the broad ( $\Gamma = 420$  keV)  $1^-$  state at 9.585 MeV in  $^{16}\text{O}$  is constructive or destructive leading to large  $S_{E1} = 80$  keV-b or small  $S_{E1} = 10$  keV-b, respectively, since the measured minima of  $\chi^2$  for the  $^{16}\text{N}$  data are identical for both cases [2] as shown in Fig. 1.

Several new measurements of the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction using gamma-ray detectors have been reported [3, 4] 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 [5, 6]. These new experiments use some of the highest intensity alpha-particle beams (10 - 500  $\mu\text{Amp}$ ) with an impressive luminosity of  $10^{33}$  [3] and  $10^{31} \text{ cm}^{-2}\text{sec}^{-1}$  [4], and a  $4\pi$  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



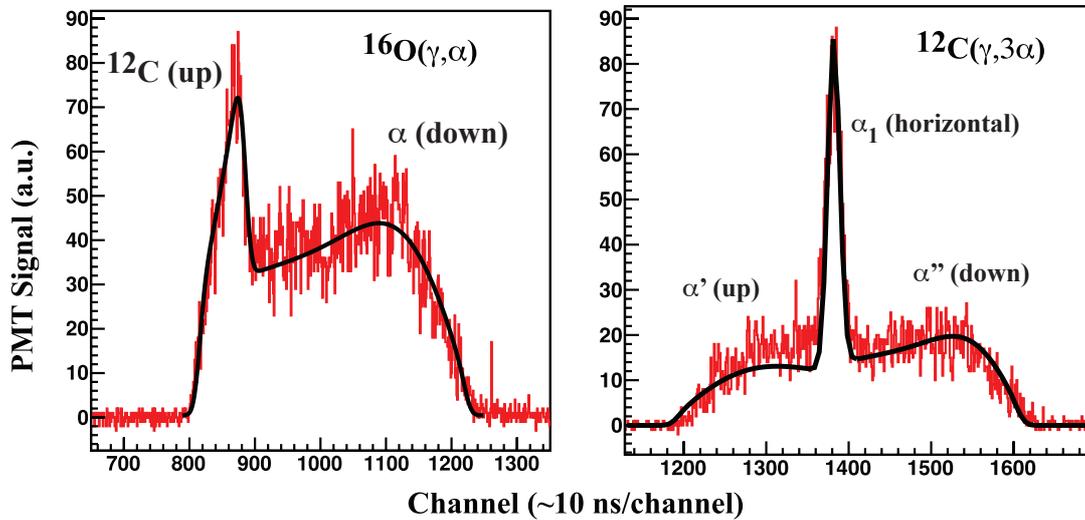
**Figure 1.** The  $\chi^2$  obtained from world data as shown in Ref. [2]. The  $\chi^2$  for the  $^{16}\text{N}$  data show two minima at the same low values of  $\chi^2$  which does not allow us to distinguish between the destructive and constructive interference solutions as discussed in the text.

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 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  $\phi_{12}$ .

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 contribution of the  $0^+$  Hoyle 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 [7] following theoretical prediction [8] 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. A larger production of  $^{12}\text{C}$  at high temperatures increases the neutron density as required for an r-process, due to the competition between the  $^8\text{Be}(\alpha, \gamma)$  reaction and the  $^8\text{Be}(n, \gamma)$  reaction [9, 10]. A  $2^+$  member of the rotational band build on top of the Hoyle state is not predicted in the conjectured alpha condensate [11] which predicts a spherical Hoyle state. In this BEC model the  $2_2^+$  is predicted to be an alpha-vibration state. An evidence for the broad second  $2^+$  state at 9.6 MeV was found in a  $^{12}\text{C}(\alpha, \alpha')$  [12] and a  $^{12}\text{C}(p, p')$  measurement [13] but such a state was not observed in the beta-decay of  $^{12}\text{B}$  and  $^{12}\text{N}$  [14].

## 2. Measurements of the photo-dissociation of $^{16}\text{O}$ and $^{12}\text{C}$

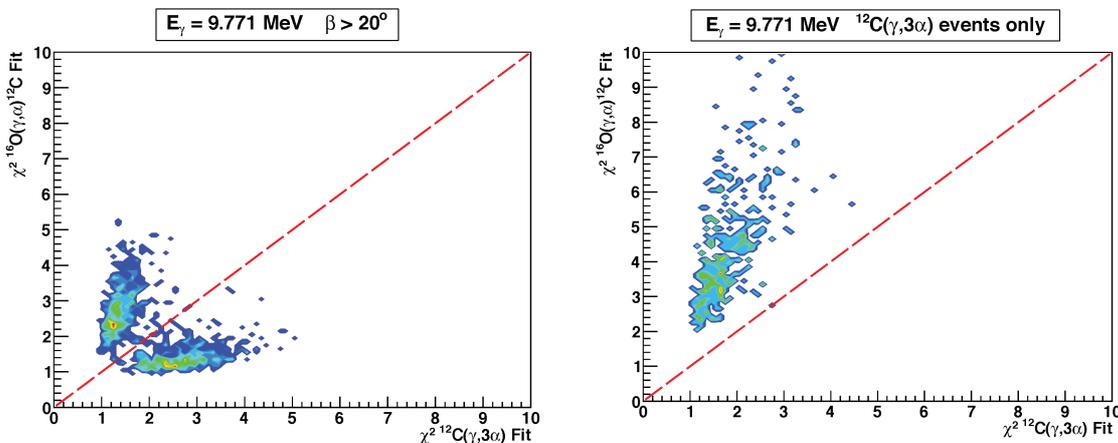
We used our Optical-Readout Time Projection Chamber (O-TPC) [15] operating with  $\text{CO}_2$  gas with circularly polarized gamma-ray beams extracted from the HI $\gamma$ S facility of TUNL at Duke University [16] to study the  $^{16}\text{O}(\gamma, \alpha)$  and the  $^{12}\text{C}(\gamma, 3\alpha)$  reactions at  $E = 9.08, 9.38, 9.58, 9.78,$



**Figure 2.** The measured PMT signal compared to the predicted line shape for  $^{16}\text{O}$  (left) and  $^{12}\text{C}$  (right) dissociation events.

10.08, 10.38 and 10.68 MeV. The outgoing particle resulting from the photo-dissociation of target nuclei are fully determined by the tracks recorded in the O-TPC in three dimensions. Thus all relevant kinematical variables are measured by the O-TPC [15]. The total energy deposited (grid charge-signal) in the O-TPC detector is determined by the Q-value for the dissociation event;  $E_{total} = E_{\gamma} - Q$ ;  $Q = 6.227, 7.162$  and  $7.275$  eV for the dissociation of  $^{18}\text{O}$ ,  $^{16}\text{O}$  and  $^{12}\text{C}$ , respectively. The Q-values for  $^{16}\text{O}$  and  $^{18}\text{O}$  dissociations are sufficiently different (935 keV) and differ considerably more than the beam width of  $\text{FWHM} \approx 300$  keV, hence these events are well separated in the total energy spectrum measured by the charge signal. However one major drawback for using  $\text{CO}_2$  gas is that the difference of Q-values (112 keV) for the dissociation of  $^{16}\text{O}$  and  $^{12}\text{C}$  is considerably smaller than the beam width and comparable to the detector resolution of approximately 90 keV [15]. In addition the larger quenching factor for the low energy  $^{12}\text{C}$  projectiles leads to a smaller grid charge-signal from the dissociation of  $^{16}\text{O}$  with very similar energy as for the dissociation of  $^{12}\text{C}$ . Hence the total energy deposit cannot be used to separate (and thus identify)  $^{12}\text{C}$  and  $^{16}\text{O}$  dissociation events.

To identify and distinguish  $^{12}\text{C}$  dissociation events we relied on the line shape of the PMT signal which is very well determined by the calculated  $dE/dX$  along the track. In Fig. 2 we compare the observed PMT signal to the calculated line shape for a co-linear  $\alpha + ^{12}\text{C}$  event. In this calculation we used the drift velocity of  $1.14$  cm/ $\mu\text{s}$  (at 100 torr) measured with a well collimated  $^{148}\text{Gd}$  source [15]. The measured line shape of the PMT signal is compared to 181 calculated functions of the out-of-plane angle (in  $\beta = 1^\circ$  increments) to determine the best fit. The calculated line shape shown in Fig. 2 has essentially only one free parameter, the out of plane angle ( $\beta$ ). A good  $\chi^2$  is found for the  $^{16}\text{O}$  dissociation events shown in Fig. 2. The line shape of  $^{12}\text{C}$  dissociation events arise from a considerably more complicated  $dE/dx$  of the three body (non-collinear) decay pattern. The line shape of  $^{12}\text{C}$  events requires  $181 \times 9 = 1,629$  functions that are calculated with sufficient angular bin size ( $\beta = 1^\circ$ ) as well as sufficient bin size ( $30^\circ$ ) for the  $\theta$  and  $\phi$  angles of the two alphas ( $\alpha'$  and  $\alpha''$ ) from the decay of  $^8\text{Be}$ . For ( $\alpha_1$ ) decay into the excited states, as shown in Fig. 2, we also considered the energy of the excited  $^8\text{Be}$ . A good  $\chi^2$  is found for the  $^{12}\text{C}$  dissociation events shown in Fig. 2.



**Figure 3.** The  $\chi^2$  obtained by fitting the PMT signal with the line shape predicted for  $^{16}\text{O}$  and  $^{12}\text{C}$  events and for selected well identified  $^{12}\text{C}$  events (right).

Unfortunately the noise level in the CCD camera was too high and it did not permit line shape analysis of the pixel-content. Hence only out of plane events with out of plane angle  $\beta$  larger than  $20^\circ$  (approximately 40% of the data) could be analyzed in the current setup. A new cleaner camera has been installed that permits including all data. In addition the resolution of the optical system did not permit resolving the two outgoing alphas emitted from the decay of the ground state of  $^8\text{Be}$ . Due to the poor resolution such decays most of the time appear co-linear in the image recorded by the CCD camera but are clearly distinguished from  $^{16}\text{O}$  events in the PMT signal. In contrast the two outgoing alphas emitted in the decay of the first excited state of  $^8\text{Be}^*(3.0)$  are well resolved as shown in Fig. 2. The very low energy of the  $^8\text{Be}^*(3.0)$  yield a decay pattern which are almost as for a decay in rest.

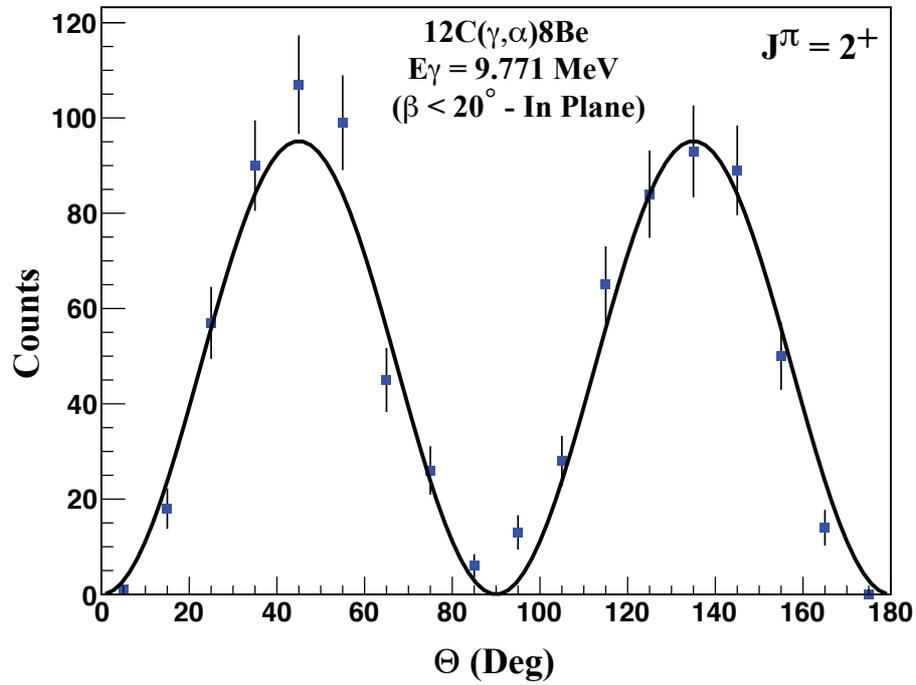
### 3. A measurement of the $^{12}\text{C}(\gamma, \alpha)$ reaction.

The in plane angle ( $\alpha$ ) measured by the track registered in the CCD image and the out-of-plane angle ( $\beta$ ) measured by the Time projection signal of the PMT allow us to deduce for each event the scattering angle ( $\theta$ ) and the azimuthal angle ( $\phi$ ) of the polar coordinate system used in scattering theory:  $\cos\theta = \cos\beta \times \cos\alpha$  and  $\tan\phi = \tan\beta/\sin\alpha$ . The so obtained angular distribution is shown in Fig. 4 together with that predicted for a pure  $0^+ \rightarrow 2^+$  E2 transition. For these data we used only in plane ( $\beta < 20^\circ$ ) data for which the scattering angle ( $\theta$ ) is determined with high accuracy.

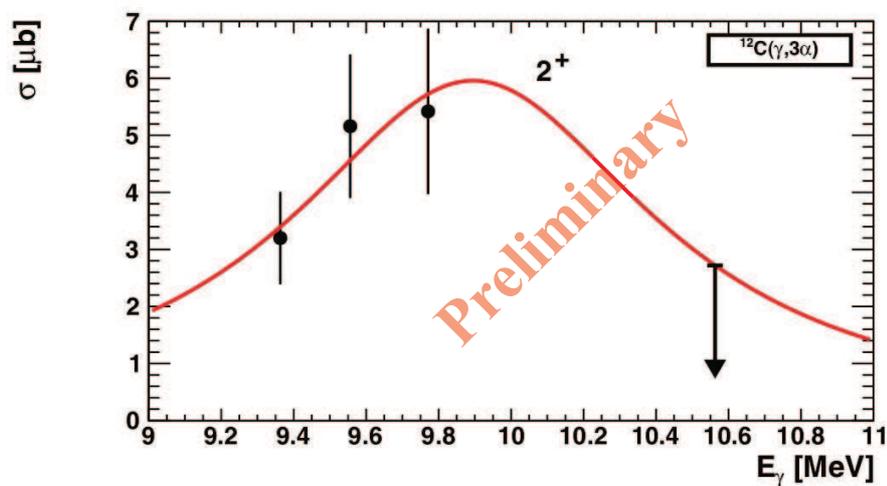
We also measured an excitation curve for the  $^{12}\text{C}(\gamma, \alpha)$  reaction. The accuracy of these data is limited by the measured beam intensity. A considerably more accurate beam monitoring system has been developed using the known cross section of the photo-dissociation of deuterium. The result of the limited accuracy study is shown in Fig. 5.

### 4. Conclusions

Dissociation events from the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction were identified in our measurement using an O-TPC detector and clear evidence is observed for a pure E2 angular distribution most likely arising from a  $2^+$  state just below 10.0 MeV. These data are being remeasured with an improved setup including a CCD camera with lower background. This study is in progress.



**Figure 4.** Measured angular distribution for in plane ( $\beta < 20^\circ$ )  $^{12}\text{C}(\gamma, 3\alpha)$  events compared to the prediction for a pure  $0^+ \rightarrow 2^+$  E2 transition.



**Figure 5.** Preliminary measured excitation curve for the  $^{12}\text{C}(\gamma, 3\alpha)$  reaction.

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