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The structure of ^{12}C and stellar helium burning *

Moshe Gai
for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration

Laboratory for Nuclear Science at Avery Point
University of Connecticut, 1084 Shennecossett Rd, Groton, CT 06340-6097, USA

E-mail: moshe.gai@yale.edu

Abstract. The rate of stellar formation of carbon at high temperatures (T > 3 GK) may increase beyond that which is expected from the Hoyle state at 7.654 MeV due to contributions from higher lying states in ^{12}C. The long sought for second 2^+ state predicted at 9 - 10 MeV excitation energy in ^{12}C was predicted to significantly increase the production of ^{12}C. 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 HIγS facility of TUNL at Duke was used to study the formation of carbon (and oxygen) during helium burning. Preliminary measurements were carried out at beam energies: E = 9.51, 9.61, 9.72, 10.00, 10.54, 10.84 and 11.14 MeV. Extra attention was paid for separating the carbon dissociation events, $^{12}C(\gamma, 3\alpha)$, from the oxygen dissociation events, $^{16}O(\gamma, \alpha)^{12}C$. Complete angular distributions were measured giving credence to a newly identified 2^+ state just below 10.0 MeV.

1. Introduction

Carbon is formed during stellar helium burning in the triple-alpha process, the $^8Be(\alpha, \gamma)^{12}C$ 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}C may contribute. Indeed a broad (Γ = 560 keV, Γ_γ = 0.2 eV) 2^+ state at 9.11 MeV in ^{12}C was included in the NACRE compilation [1] following theoretical prediction [2] 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}C at high temperatures increases the neutron density as required for an r-process, due to the competition between the $^8Be(\alpha, \gamma)$ reaction and the $^8Be(n, \gamma)$ reaction [3, 4]. A 2^+ member of the rotational band build on top of the Hoyle state is not predicted in the conjectured alpha condensate [5] which predicts a spherical Hoyle state. An evidence for the broad second 2^+ state at 9.6 MeV was found in a $^{12}C(\alpha, \alpha')$ [6] and a $^{12}C(p, p')$ measurement [7] but such a state was not observed in the beta-decay of ^{12}B and ^{12}N [8].

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

We used our Optical-Readout Time Projection Chamber (O-TPC) [9] operating with CO_2 gas with gamma beams extracted from the HIγS facility of TUNL at Duke University [10] to search for such states via the identification of triple alpha events from the $^{12}C(\gamma, 3\alpha)$ reaction as shown in Fig. 1. We have studied this reaction at E = 9.51, 9.61, 9.72, 10.00, 10.54, 10.84 and 11.14 MeV [11].

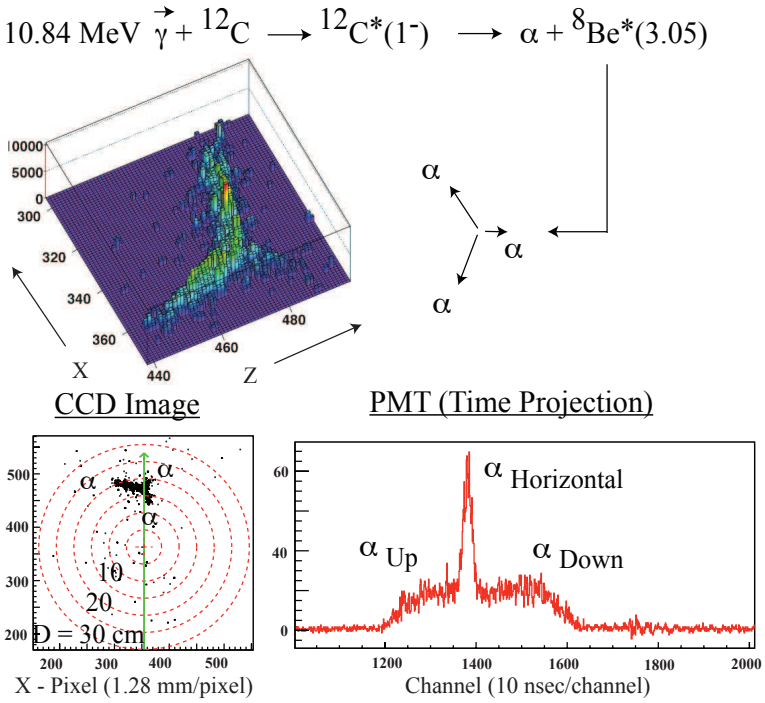

Figure 1. A typical three alpha dissociation event detected by the O-TPC, with the γ-beam (indicated by a green arrow) along the positive z-axis. The large opening angle between the two emitted alpha-particle indicates dissociation to $\alpha + {}^{8}Be^{*}(3.0)$; into the first excited state of ${}^{8}Be$.

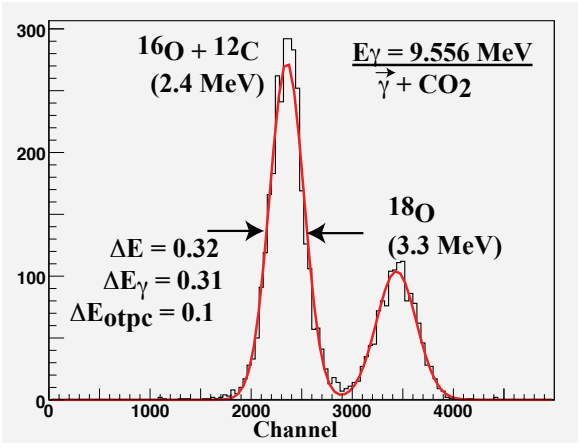

Figure 2. A typical total energy spectrum (grid-charge signal) recorded by the O-TPC.

2.1. Event Identification

The outgoing particle resulting from the photo-disscoiation 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 [9]. 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 for the dissociation of ${}^{18}O$, ${}^{16}O$ and ${}^{12}C$, respectively. The Q-values for ${}^{16}O$ and ${}^{18}O$ dissociations are sufficiently different (935 keV) and differ considerably more than the beam width of FWHM $\approx$ 300 keV, hence these events are well separated in the total energy spectrum shown in Fig 2. However one major draw back for using CO_2 gas is that the difference

of Q-values (112 keV) for the dissociation of ^{16}O and ^{12}C is considerably smaller than the beam width and comparable to the detector resolution of approximately 80 keV [9]. In addition the larger quenching factor for the low energy ^{12}C projectiles leads to a smaller grid charge-signal from the dissociation of ^{16}O with very similar energy as for the dissociation of ^{12}C, as can be seen in Fig. 3. Hence the total energy deposit cannot be used to separate (and thus identify) ^{12}C and ^{16}O dissociation events.

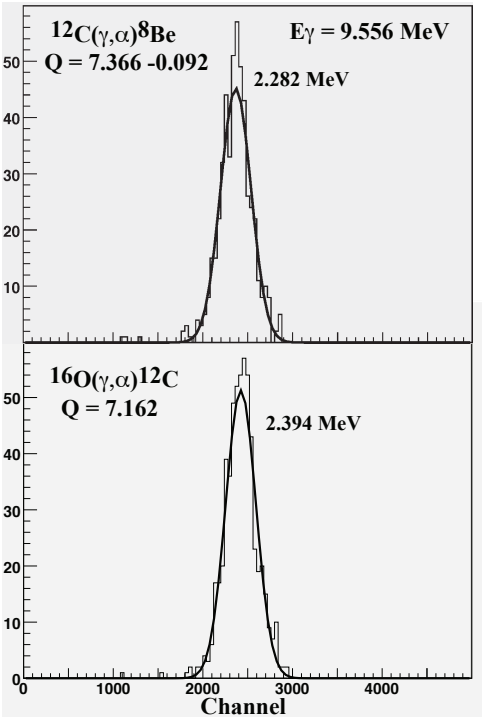

Figure 3. A typical total energy spectrum (grid-charge signal) recorded by the O-TPC for well identified ^{12}C and ^{16}O dissociation events.

To identify and distinguish ^{12}C dissociation events we relied on the line shape of the PMT signal. 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 β larger than 20° (approximately 40% of the data) could be analyzed in the current setup. A new cleaner camera is being installed that will permit 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}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}O events in the PMT signal. In contrast the two outgoing alphas emitted in the decay of the first excited state of $^{8}Be^{*}(3.0)$ are well resolved as shown in Fig. 1. The very low energy of the $^{8}Be^{*}(3.0)$ yield a decay pattern which are almost as for a decay in rest.

The line shape of the (PMT) signal is very well determined by the calculated dE/dX along the track. In Fig. 4 we compare the observed PMT signal to the calculated line shape. In this calculation we used the drift velocity that we measured with a ^{148}Gd source of 1.05 cm/μs at 100 torr [9]. A similar value of the drift velocity is calculated by MAGBOLTZ [12]. Hence the calculated line shape shown in Fig. 4 has essentially only one free parameter, the out of plane angle beta. A good "effective reduced χ^2" is found for ^{16}O dissociation events as shown in Fig. 4. In this calculation we did not include the single photo-electron calibration for the PMT signal and the error is considered to be the square root of the signal. Hence the deduced χ^2 is determined up to an over all (calibration) constant and must be considered "effective χ^2". As can be seen from Fig. 4 the χ^2 for ^{16}O events is of the order of unity. The line shape of

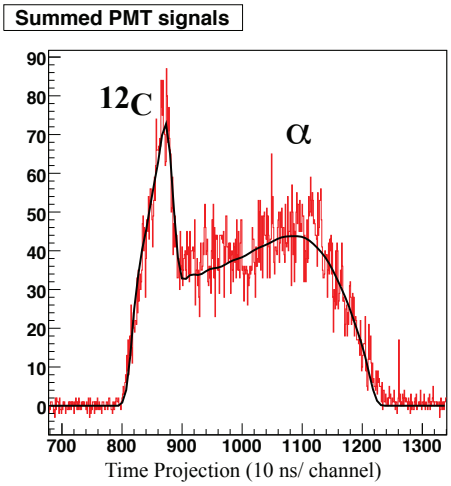

Figure 4. The measured PMT signal compared to the predicted line shape for an $\alpha + {}^{12}C$ dissociation event.

^{12}C dissociation events arise from a considerably more complicated dE/dX of the three body (non-colinear) decay pattern. Hence the "effective χ^2" for ^{12}C dissociation events fitted with the line shape calculated for an ^{16}O dissociation is seldom unity.

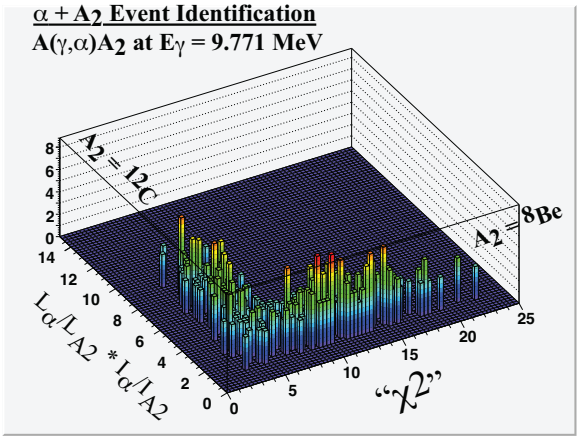

Figure 5. Event identification surface plot (1 count suppressed) for all events as discussed in the text.

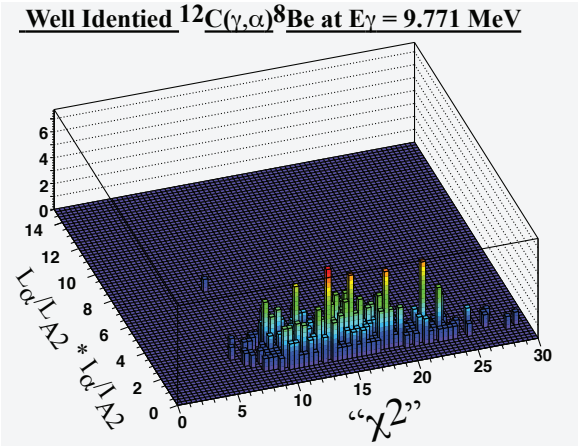

Figure 6. Event identification surface plot (1 count suppressed) for well identified ^{12}C dissociation events as discussed in the text.

The energy shared by the two body $\alpha + A_2$ decay differs for ^{16}O and ^{12}C events. We define the ratio: $R = \frac{E(\alpha)}{E(A_2)}$. This ratio is 3 for $16O$ events and 2 for ^{12}C events. Due to the attenuation factor of the outgoing ^{12}C the measured ratio R for ^{16}O events is in fact closer to 4. Thus the ratio R can be used in addition to the χ^2 to distinguish and identify ^{12}C events. The ratio R can be measured by measuring the ratio of the emitted light (integrated yield of the signal shown in Fig. 4) as well as the ratio of the track length in time. In addition a similar measurement can be performed using the pixel content of the CCD camera as long as the CCD camera provides clean signals. Thus the ratio R can be measured four times. A multiplication of the measured R values yield a separation which is approximately a factor of 2 better since the fluctuation increase by approximately the square root of 4.

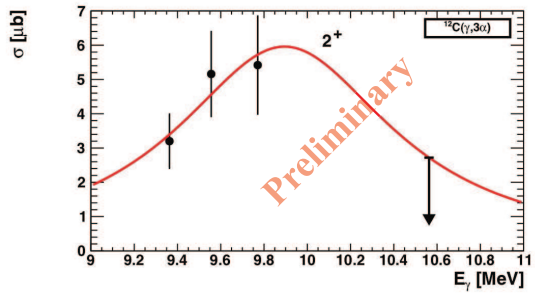

Figure 7. Preliminary measured excitation curve.

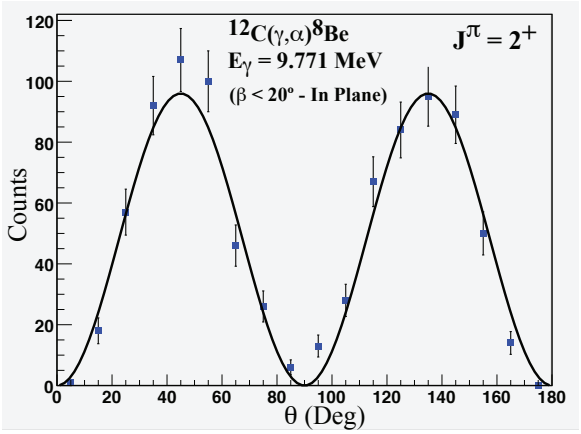

Figure 8. Measured angular distribution for in plane ($\beta < 20°$) $^{12}C(\gamma, 3\alpha)$ events compared to the prediction for a pure $0^+ \rightarrow 2^+$ E2 transition.

In Fig. 5 we show the so obtained surface plot of event identification using the "effective χ^{2}" and the multiplication of the ratio R as obtained from the PMT signal; the ratio of the integrated light (I) times the track length (L). In Fig. 6 we show the same surface plot for events that were clearly identified as ^{12}C events by observing kinks in the PMT signal or in the CCD image. In both Figs. 5 and 6 we show data bins including at least two events. The separation of ^{12}C events using the above discussed method is estimated to yield an uncertainty which is smaller than 10%. The so obtained ^{12}C events allow us to measure the excitation curve shown in Fig. 7.

3. Angular Distribution

The in plane angle (α) measured by the track registered in the CCD image and the out-of-plane angle (β) measured by the Time projection signal of the PMT allow us to deduce for each event the scattering angle (θ) and the azimuthal angle (ϕ) of the polar coordinate system used in scattering theory: $\cos\theta = \cos\beta \mathrm{x} \cos\alpha$ and $\tan\phi = \tan\beta / \sin\alpha$. The so obtained angular distribution is shown in Fig. 8 together with that predicted for a pure $0^+ \rightarrow 2^+$ E2 transition. For these data we used only in plane ($\beta < 20°$) data for which the scattering angle (θ) is determined with high accuracy.

4. Conclusions

Dissociation events from the $^{12}C(\gamma, 3\alpha)$ 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.

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