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THE STRUCTURE OF ^{12}C AND STELLAR HELIUM BURNING* **

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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 to 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.

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1. Introduction

Carbon is formed during stellar helium burning in the triple-alpha process, the ^{8}Be$(\alpha, \gamma)^{12}$C reaction, that is mostly governed by the contribution from the 0^+ Hoyle state at 7.654 MeV in ^{12}C. At high temperatures ($T > 3$ GK) higher lying states in ^{12}C may contribute. Indeed a broad

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($\Gamma = 560$ keV, $\Gamma_\gamma = 0.2$ 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 is predicted to increase 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 (required for example for an r-process) due to the competition between the ^{8}Be(α,γ) reaction and the ^{8}Be(n,γ) reaction [3, 4]. A 2^+ member of the rotational band built 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(α,α') [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

An Optical-Readout Time Projection Chamber (O-TPC) [9] operating with the CO_2(80%) + N_2(20%) gas mixture (at 100 Torr) was used 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. The O-TPC was placed in the gamma-ray beams extracted from the HIγS facility of TUNL at Duke University [10]. We have studied this reaction at $E = 9.51, 9.61, 9.72, 10.00, 10.54, 10.84$ and 11.14 MeV [11].

2.1. Event identification

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 [9]. The total energy deposited (grid charge-signal) in the O-TPC detector is determined by the Q-value for the dissociation event; $E_{\rm total} = E_\gamma - Q$ and $Q = 6.227, 7.162$ 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 considerably larger than the beam width of FWHM ≈ 300 keV, hence these events are well separated in the total energy spectrum shown in Fig 2. However, one major drawback for using CO_2 gas is that the difference of the 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 90 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.

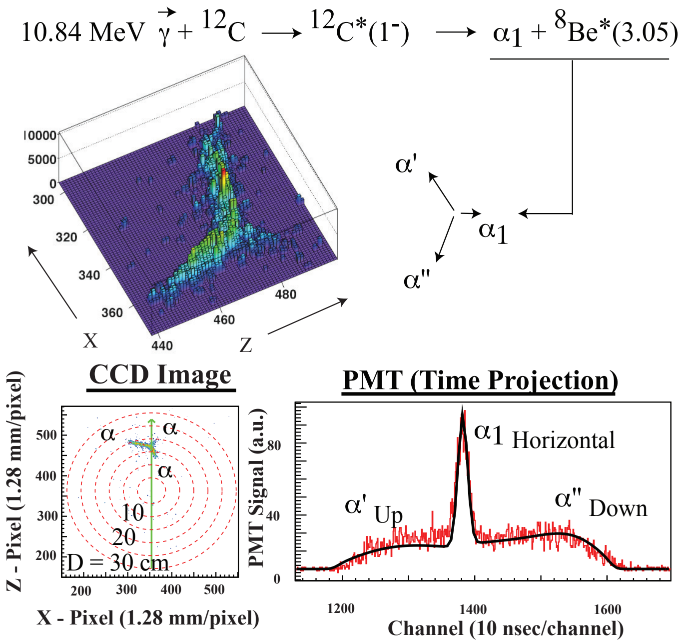

Fig. 1. Three alpha-particle event from the dissociation of ^{12}C measured at 100 Torr. The projected 2D track and time of this event are shown in the lower part of the figure together with the fitted line shape of the light detected from the emerging three alpha-particles. The geometry of the reconstructed event is shown schematically with α_1 emitted horizontally and the ^{8}Be decay products, α' and α'', emitted upward and downward, respectively.

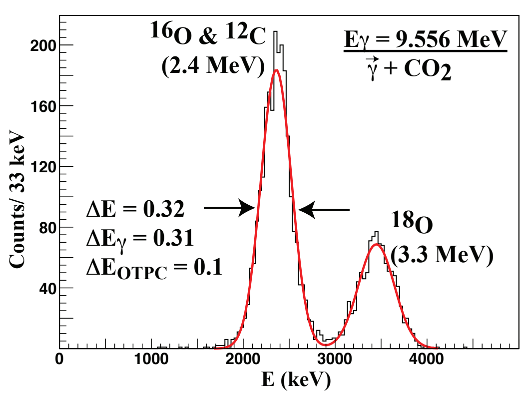

Fig. 2. A typical total energy spectrum (grid-charge signal) recorded by the O-TPC.

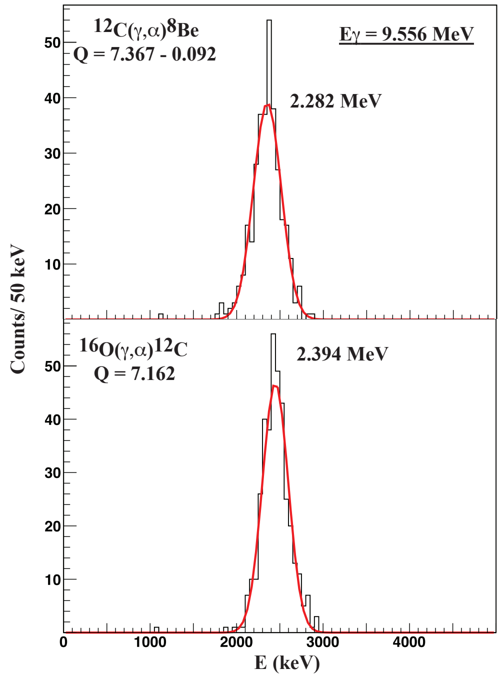

Fig. 3. A typical total energy spectrum (grid-charge signal) recorded by the O-TPC for well identified ^{12}C and ^{16}O dissociation events.

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 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 alpha-particles 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 in the CCD image, as shown in Fig. 1. The very low energy of the recoiling ^{8}Be*(3.0) yield a decay pattern which are almost as for a decay at rest.

The line shape of the (PMT) signal is very well determined by the (calculated) dE/dx along the track which is broadened by the detector resolution. In Fig. 4 we compare the observed PMT signal to the calculated line shape for a co-linear α+^{12}C event. In this calculation we used the drift velocity of 1.14 cm/μs (at 100 Torr) measured with a well collimated ^{148}Gd source [9].

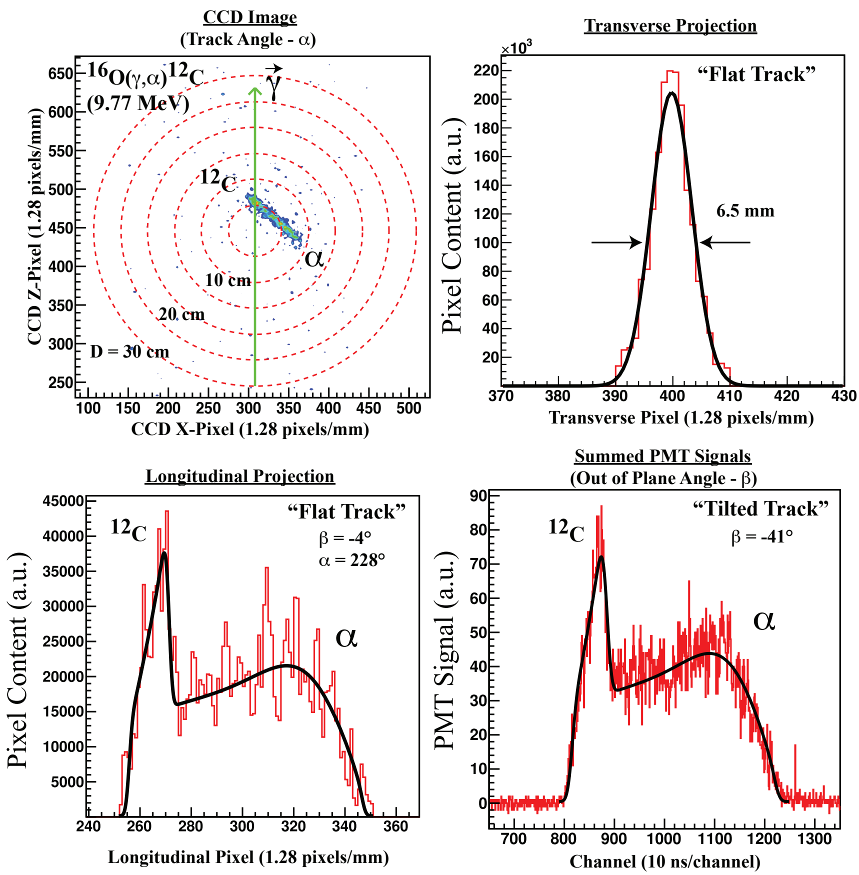

Fig. 4. A typical 63 mm long $\alpha+^{12}$C track recorded at 100 Torr by the CCD camera (top left) from the dissociation of ^{16}O by 9.77 MeV gamma-rays. The transverse (top right) and longitudinal (bottom left) projections of the nearly horizontal ($\beta \approx 0°$) track are shown together with the fitted line shapes (Gaussian and dE/dx, respectively). The PMT time projected pulse-shape (bottom right) of another tilted track ($\beta = -41°$) is also shown together with the fitted dE/dx line shape (in black). The extracted in-plane angle (α) and out of plane angle (β) are indicated for the two different events. The large light variations observed in the longitudinal projection arise from the fiber structure of the window in the back of the MCP.

A similar value of the drift velocity is calculated by MAGBOLTZ [12]. The measured line shape of the PMT signal is compared to 180 calculated functions of the out-of-plane angle (in $\beta = 1°$ increments) to determine the best fit. The calculated line shape shown in Fig. 4 has essentially only one free parameter, the out of plane angle (β). A good χ^2 is found for the ^{16}O dissociation events shown in Fig. 4. The line shape of ^{12}C dissociation events arise from a considerably more complicated dE/dx of the three body (non-colinear) decay pattern. The line shape of ^{12}C events requires $819 \times 2 = 1,638$ functions that are calculated with sufficient angular bin size ($\beta = 1°$) as well as sufficient bin size (30°) for the θ and ϕ angles of the two alphas (α' and α'') from the decay of ^{8}Be. For (α_1) decay into the excited states, as shown in Fig. 1, we also considered the energy of the excited ^{8}Be. A good χ^2 is found for the ^{12}C dissociation events shown in Fig. 1.

Each event is compared to a table of 180 functions calculated for the ^{16}O events. The so obtained smallest χ^2 is designated as the $\chi^2_{^{16}\mathrm{O}(\gamma,\alpha)}$, as shown in Fig 5. The same procedure is repeated for each event using a table of the 1,638 functions calculated for ^{12}C events to extract the lowest $\chi^2_{^{12}\mathrm{C}(\gamma,3\alpha)}$ of the event. In Fig. 5 we show the so obtained $\chi^2_{^{12}\mathrm{C}}$ and $\chi^2_{^{16}\mathrm{O}}$ for each events. This surface plot allows event identification.

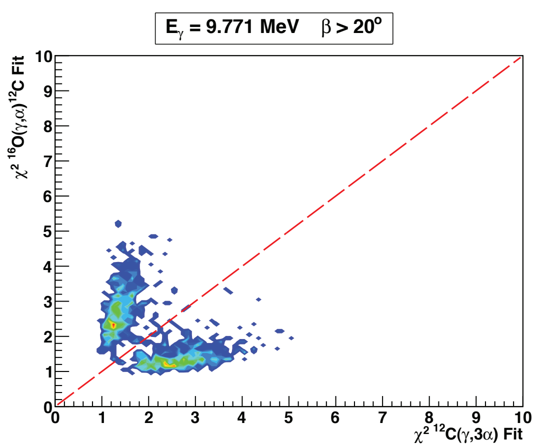

Fig. 5. Event identification surface plot (1 count suppressed) for all events as discussed in the text.

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 lead to an uncertainty of the extracted yield that is smaller than 10%.

The so obtained ^{12}C events allow us to measure the yield at each measured energy from which we derive the preliminary excitation curve shown in Fig. 7. The large uncertainties shown in Fig. 7 is due to ill determined gamma-ray beam intensity.

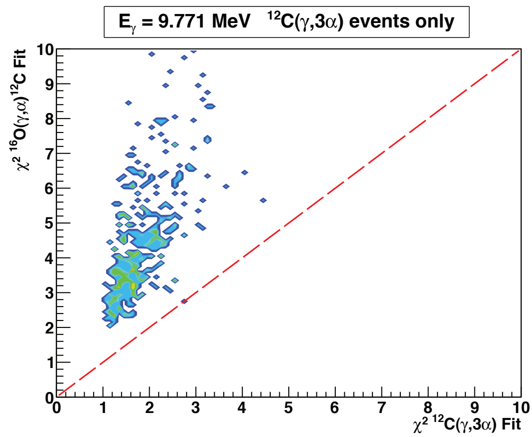

Fig. 6. Event identification surface plot (1 count suppressed) for well identified ^{12}C dissociation events as discussed in the text.

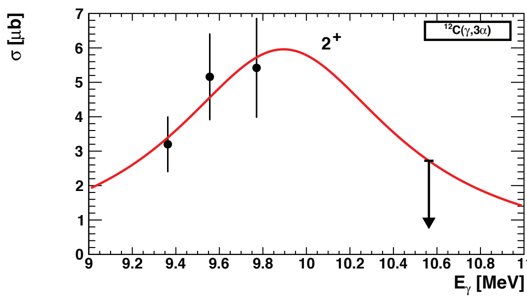

Fig. 7. Preliminary measured excitation curve and a (symmetric) Breit–Wigner expected for the broad 2^+ state.

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 commonly 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. 8 together with that predicted for a pure $0^+ \to 2^+ E2$ transition. For these data we used only in plane ($\beta < 20°$) data for which the scattering angle (θ) is determined with high accuracy.

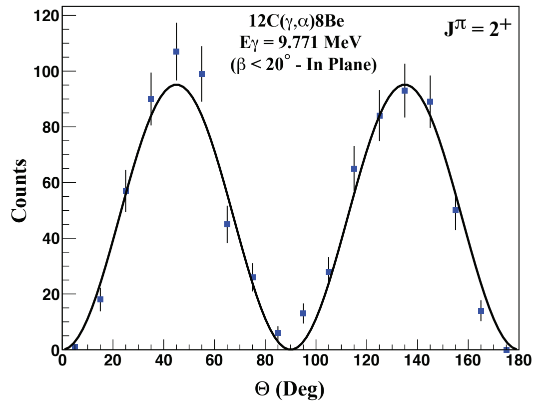

Fig. 8. Measured angular distribution for in plane ($\beta < 20°$) ^{12}C$(\gamma, 3\alpha)$ events compared to the prediction for a pure $0^+ \to 2^+ E2$ transition.

4. Conflict with beta-decay results

The lack of observation of the second 2^+ in ^{12}C in beta-decays [8] is troubling. We attempted to fit the measured ft^{-1} values as reported in [8] with two symmetric Lorentzians as shown in Fig. 9. The best fit yields two states at 9.63 and 10.61 MeV with widths $\Gamma = 1.91$ and 1.43 MeV respectively (in contrast, the measured 0^+ state at 10.3 ± 0.3 MeV in ^{12}C is reported to be 3.0 MeV wide). The agreement of this attempted fit with data is provocative (and perhaps fortuitous) since we do not use asymmetric Lorentzian as expected for state near the Coulomb barrier where the alpha-width is energy dependent.

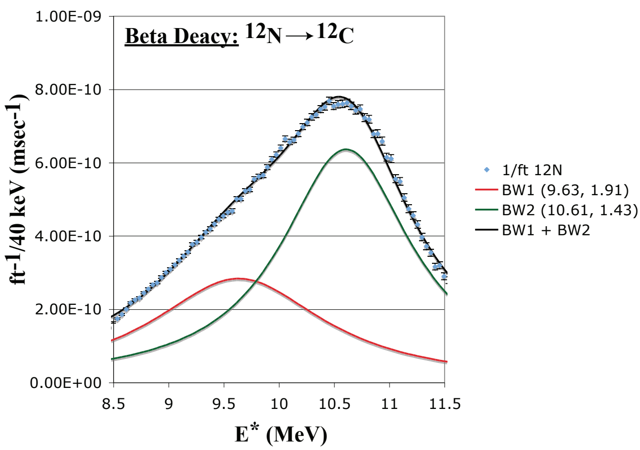

Fig. 9. The measured ft^{-1} values fitted with two symmetric Lorentzians as discussed in the text.

5. 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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