No evidence of an 11.16 MeV 2^+ state in ^{12}C

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An experiment using the ^{11}B(^{3}He,d)^{12}C reaction was performed at iThemba LABS at an incident energy of 44 MeV and analyzed with a high energy-resolution magnetic spectrometer, to reinvestigate states in ^{12}C published in 1971. The original investigation reported the existence of an 11.16 MeV state in ^{12}C that displays a 2^+ nature. In the present experiment, data were acquired at laboratory angles of 25°, 30°, and 35°, which is part of the center-of-mass (c.m.) angle range in the original measurements where a clear signature of such a state was observed. These new low-background measurements revealed no evidence of the previously reported state at 11.16 MeV in ^{12}C.

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The ^{12}C nucleus, through the triple-alpha configured 0^+ state at 7.65 MeV (known as the Hoyle state), provides the gateway for the synthesis of all elements from itself to the heaviest elements occurring naturally [1]. Locating the 2^+ excited state associated with the Hoyle state in ^{12}C will provide information of a structural nature about the triple-alpha configuration of this 0^+ state. Of even greater significance is the fact that the 2^+ excited state is deemed to contribute to the formation of ^{12}C through helium burning at high temperatures, as experienced in Type II supernovae. Cluster calculations [2] predict the existence of this associated 2^+ state at an excitation energy of 9.11 MeV. Purely on the strength of these cluster calculations, a 2^+ state at 9.11 MeV has been included in the European based complilation of reaction rates, NACRE [3], used in astrophysical nucleosynthesis calculations.

Published data [4] do, however, exist where a state with a suggested 2^+ nature was observed, but it is at an excitation energy of 11.16 MeV, well above the energy where it is expected from cluster calculations. These measurements were performed at an incident energy of 44 MeV, using the ^{11}B(^{3}He,d)^{12}C reaction on an enriched ^{11}B target, with the reaction particles analyzed using a double-focusing magnetic spectrometer equipped with photographic plates at the focal plane. For many years this was the only existing candidate, in the data, for the first excited state of the Hoyle state. To date these data remain unconfirmed.

Interest in the 2^+ state gained new momentum since the (α,α') data of Itoh *et al.* [5] was first published in 2004, in which it was suggested that a weak 2^+ state exists in ^{12}C at $E_x \sim 10$ MeV, where it is partially obscured by the other strong states in the excitation energy region of 9–11 MeV. High energy-resolution (p, p') data at 66 and 200 MeV [6] acquired at iThemba LABS confirmed that a broad state with a 2^+ character exists at 9.6(1) MeV, buried beneath the very strong 3^- state at 9.64 MeV. Recently, Itoh *et al.* [7] presented a refined analysis of their (α,α') study at 386 MeV, using both peak-fitting and multipole decomposition techniques. They concluded that a 2^+ state with a width of 1.01 ± 0.15 MeV exists at $E_x = 9.84 \pm 0.06$ MeV. Further support for the existence of a broad state with a 2^+ character in the region of 9.6 MeV came from a study of low-energy (25 MeV) inelastic proton scattering by Zimmerman *et al.* [8], as well as a ^{12}C(γ,3α) experiment by Gai *et al.* [9]. Gai *et al.* explicitly state that no evidence of a state at 11.16 MeV was found. Also of interest is work published [10] where the ^{11}B(^{3}He,d)^{12}C reaction at an incident energy of 8.5 MeV was used to investigate ^{12}C breakup into three α particles. Although not explicitly mentioned, no strength for a state at 11.16 MeV can be seen in Fig. 6 of this paper [10].

In view of the great interest in the latest evidence on the location of the 2^+ state, as well as even a possible 4^+ state at 13.3 MeV [11], it has become necessary to revisit the measurement of Ref. [4] for a more rigorous investigation with the improved equipment and analysis techniques available today.

The repeat of the ^{11}B(^{3}He,d)^{12}C measurements ($Q = +10.463$ MeV) reported here were performed at iThemba LABS, South Africa at an identical incident beam energy of 44 MeV as used by Reynolds *et al.* [4]. Data were acquired at laboratory angles of 25°, 30°, and 35° over the course of two and a half days. The present experiment was performed with the K600 magnetic spectrometer [12]. Emitted deuterons were detected with a focal-plane detector system that consisted of two multiwire drift chambers (MWDCs) and a plastic scintillator. Event-by-event data were acquired enabling multiparameter offline analysis leading to improved background discrimination.

The target used for this experiment was a self-supporting ^{11}B foil with an areal density of 395 μg/cm^2 made from 98%

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enriched material. In addition, a self-supporting 600 μg/cm^2 natural boron target was used to investigate the influence of possible contamination from the remnant ^{10}B in the enriched target. (It should be noted that in Ref. [4] it was stated that an enriched target was used, but no further details were given.) An elastic recoil detection analysis (ERDA) was performed on the enriched ^{11}B target to determine the extent of the contaminants in the target. The target contained approximately 212 μg/cm^2 of ^{11}B as well as strong ^{16}O contamination of approximately 170 μg/cm^2 ($Q = -4.893$ MeV) and to a lesser extent ^{12}C with a thickness of approximately 6 μg/cm^2 ($Q = -3.550$ MeV). Weak ^{14}N contamination, approximately 7 μg/cm^2 ($Q = +1.803$ MeV), was also measured. Although the oxygen contamination of the target was strong, the Q-value difference between the reactions on ^{11}B and ^{16}O moved contamination peaks out of the energy region of interest.

In the present experiment, data were taken at three laboratory angles, namely 25°, 30°, and 35° corresponding to center-of-mass angles 29.7°, 35.5°, and 41.3°, respectively. This is part of the angle range where in the original experiment a clear signature for a 2^+ state was recorded [4]. A further advantage of this choice of angles was that a well shielded external beam stop some 10 m away from the scattering chamber could be used. It was the external beam pipe to the beam dump that placed a lower limit on the angles which the spectrometer could reach. At smaller angles, an internal beam stop inside the scattering chamber would have been required that could have led to unwanted background.

With the dipole magnets at the required field settings, only deuterons and tritons had the necessary magnetic rigidity to reach the focal-plane detectors. As can be seen in Fig. 1, the deuteron and triton signatures were well separated. In the offline analysis a software gate was set to include only the deuterons. Empty frame runs were also made to characterize possible beam background contamination, but only a negligible number of events were observed in the deuteron gate.

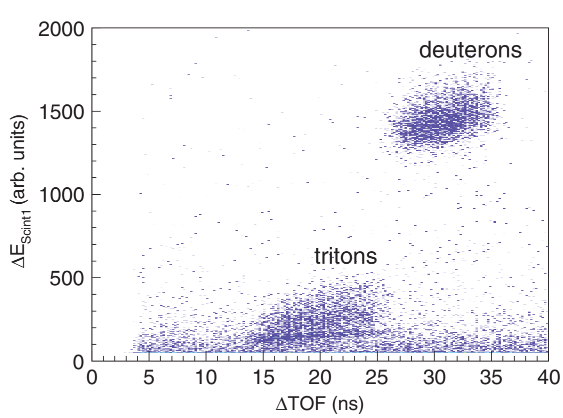

FIG. 1. (Color online) A particle identification spectrum of the pulse height in the scintillator vs the time of flight (ToF) through the spectrometer. Deuterons and tritons are clearly separated. The vertical axis of the spectrum represents energy deposited in the scintillator while the horizontal axis is the time of flight (ToF) of the particles through the spectrometer measured between the separated sector cyclotron radio-frequency (RF) signal and the scintillator trigger.

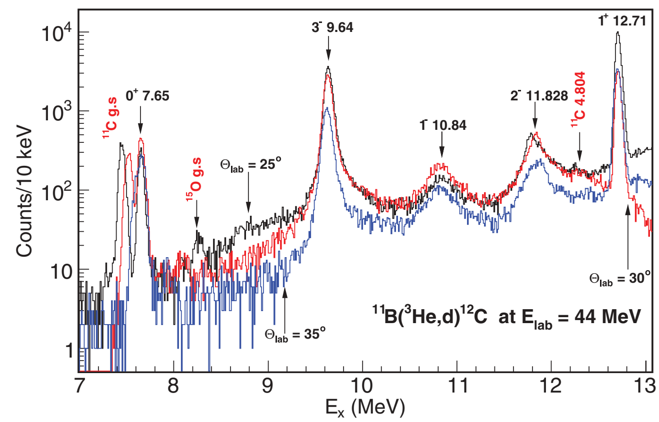

FIG. 2. (Color online) Excitation energy spectra for the ^{11}B(^{3}He,d)^{12}C reaction at laboratory emission angles of 25° (black), 30° (red), and 35° (blue).

Figure 2 shows the ^{12}C excitation energy spectra measured at the three emission angles. Note that there is a deep valley where the 11.16 MeV state is expected. In the original paper [4], a broad state with strength almost equal to that of the 10.84 MeV state can be seen filling in the valley between the 10.84 MeV state and the 11.83 MeV state. No such strength is indicated at 11.16 MeV in the present data set.

The two-dimensional plot in Fig. 3 of deuteron emission angle versus ^{12}C excitation energy clearly indicates the capabilities of modern equipment and analysis techniques. Here, the spectrometer settings and data analysis have been optimized so that the ^{11}B(^{3}He,d)^{12}C reaction appears as vertical loci while the (^{3}He,d) reaction on heavier target nuclei (e.g., see ^{15}O) slopes forward, and conversely for lighter target nuclei (e.g., see ^{11}C), slopes backward. The projection of this spectrum onto the horizontal axis yields the one-dimensional excitation energy spectrum of the data at 25°, as seen in Fig. 2. Such an overview assists in determining whether a broad peak in the one-dimensional spectrum belongs to the nucleus of interest, or if it is from other contaminant nuclei with different kinematic corrections resulting in a broad peak. A good example of this is the ^{15}O ground state which appears

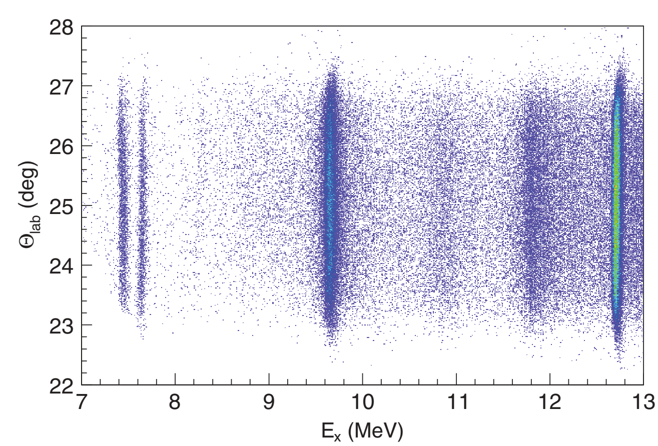

FIG. 3. (Color online) A two-dimensional plot of the deuteron emission angle vs ^{12}C excitation energy for $\Theta_{lab} = 25°$.

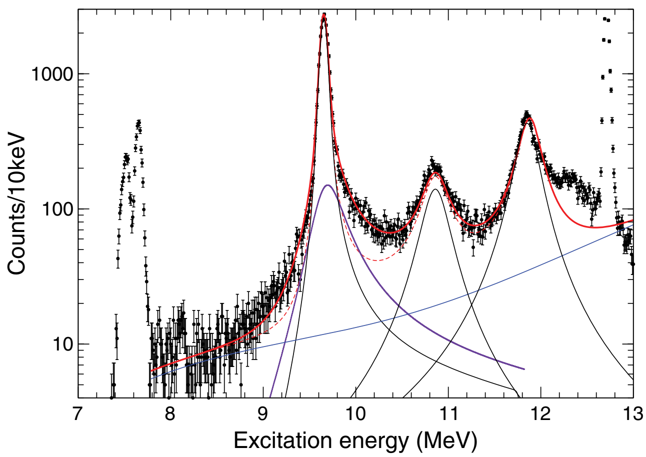

FIG. 4. (Color online) Excitation energy spectrum at $\Theta_{\text{lab}} = 30^\circ$ with the peaks at 10.84 and 11.83 MeV fitted with a Lorentzian lineshape, with $\Gamma = 315$ keV and $\Gamma = 260$ keV, respectively. At 9.64 MeV the 3^- peak was generated from an R-matrix calculation convoluted with the 65 keV experimental energy resolution. Added to that is a 2^+ resonance peak at 9.7 MeV also generated from an R-matrix calculation. Here, the blue curve is a background, the solid red curve is an overall fit with a 2^+ state at 9.7 MeV, and the dashed red curve is a fit without a 2^+ state at 9.7 MeV.

in the spectra at an excitation energy of 8.3 MeV in Fig. 2, and can be seen in Fig. 3 to be a locus with a slope. Thus, Fig. 3 also allows one to form a visual impression of the extent of the background contamination.

By way of example, shown in Fig. 4 are fits to the peaks of the 30° data. The sum of all fits is indicated by the solid red curve. Good overall agreement is achieved to the data in the energy region around 11.16 MeV excitation, indicating that no other strength is required in this energy region. It also indicates the desirability of adding a peak at an excitation energy of 9.7 MeV to achieve a good fit in this region.

An investigation was made into the origin of the 11.16 MeV peak seen in Ref. [4]. Both deuterons and tritons were considered as emitted reaction particles impinging on ^{10}B, O, C, and N contaminants. No clear cause could, however, be found for the signature seen in the original experiment. Experiment-specific causes which cannot be investigated such as beam halo and small -angle collimator scattering remain as possibilities.

In summary, the ^{11}B(^{3}He,d)^{12}C measurement at an incident energy of 44 MeV of Reynolds *et al.* [4] was repeated with a high energy-resolution magnetic spectrometer. No evidence was found for the previously reported 2^+ state at 11.16 MeV in ^{12}C. In a 4–5 MeV excitation energy region above the Hoyle state at 7.65 MeV, the only remaining 2^+ state is that reported to be in the region of 9.6–9.8 MeV [5–9]. There is now a need for theoretical cluster calculations to investigate this state as a possible member of a band associated with the Hoyle state. Theoretical studies of the astrophysical implications of the energy and strength of this 2^+ state, as well as the possible 4^+ state identified at 13.3 MeV in ^{12}C, should also prove to be very interesting.

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[1] H. O. U. Fynbo *et al.*, Nature (London) **433**, 136 (2005).
[2] P. Descouvemont and D. Baye, Phys. Rev. C **36**, 54 (1987).
[3] C. Angulo *et al.*, Nucl. Phys. A **656**, 3 (1999).
[4] G. M. Reynolds, D. E. Rundquist, and M. Poichar, Phys. Rev. C **3**, 442 (1971).
[5] M. Itoh *et al.*, Nucl. Phys. A **738**, 268 (2004); M. Itoh, Mod. Phys. Lett. A **21**, 2359 (2006).
[6] M. Freer *et al.*, Phys. Rev. C **80**, 041303(R) (2009).
[7] M. Itoh *et al.*, Phys. Rev. C **84**, 054308 (2011).
[8] W. R. Zimmerman, N. E. Destefano, M. Freer, M. Gai, and F. D. Smit, Phys. Rev. C **84**, 027304 (2011).
[9] M. Gai (for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration), J. Phys. Conf. Ser. **267**, 012046 (2011); Acta Phys. Pol. B **42**, 775 (2011).
[10] O. S. Kirsebom *et al.*, Phys. Rev. C **81**, 064313 (2010).
[11] M. Freer *et al.*, Phys. Rev. C **83**, 034314 (2011).
[12] R. Neveling *et al.*, Nucl. Instrum. Methods. A. **654**, 29 (2011).