Evidence for a new 12C state at 13.3 MeV


DOI:
10.1103/PhysRevC.83.034314

License:
None: All rights reserved

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
https://doi.org/10.1103/PhysRevC.83.034314

Link to publication on Research at Birmingham portal
Evidence for a new $^{12}$C state at 13.3 MeV

M. Freer,1 S. Almaraz-Calderon,2 A. Aprahamian,2 N. I. Ashwood,1 M. Barr,1 B. Bucher,2 P. Copp,3 M. Couder,2 N. Curtis,1 X. Fang,2 F. Jung,2 S. Lesher,3 W. Lu,2 J. D. Malcolm,1 A. Roberts,2 W. P. Tan,2 C. Wheldon,1 and V. A. Ziman1

1School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom
2Institute for Structure and Nuclear Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA
3Department of Physics, University of Wisconsin–La Crosse, La Crosse, Wisconsin 54601, USA

(Received 13 January 2011; revised manuscript received 4 February 2011; published 15 March 2011)

The two reactions $^{12}$C($^4$He,$^4$He $^4$He $^4$He) and $^{9}$Be($^4$He, $^4$He + $^4$He + $^4$He) were measured using an array of four double-sided strip detectors. Excited states in $^{12}$C were reconstructed filtered by the condition that the $\alpha$-decay proceeded via the $^8$Be ground state. In both measurements, evidence was found for a new state at 13.3(0.2) MeV with a width 1.7(0.2) MeV. Angular correlation measurements from the $^{12}$C($^4$He, $^4$He + $^4$He + $^4$He)$n$ reaction indicates that the state may have $J^\pi = 4^+$. 

DOI: 10.1103/PhysRevC.83.034314 PACS number(s): 21.10.Re, 25.70.Ef, 25.70.Mn, 27.20.+n

I. INTRODUCTION

There are few nuclei in nature more important than $^{12}$C. Despite being one of the simplest, constituting only 12 nucleons, it has defied a detailed understanding. Moreover, it lies at the limits of state-of-the-art nuclear calculations such as the Green’s-function Monte Carlo approach [1]. The first excited state at 4.4 MeV (2$^+$) can be understood as a collective excitation of the ground state [2], as can the 14.1 MeV excitation (4$^+)$. The structure of the ground state has long been believed to be associated with a cluster state in which three $\alpha$ particles are arranged at the vertices of a triangle [3]. However, the ground state lies 7 MeV below the $\alpha$-decay threshold, and hence, it is likely that the cluster structure is strongly suppressed [4]. Nevertheless, the symmetry persists; $^{12}$C is oblate in the ground state. Above the $\alpha$-decay threshold, enhancement of the cluster structure is possible. The 3$^+$ state at 9.64 MeV may be associated with the threefold symmetry, which exists for a system associated with three $\alpha$ particles in an equilateral triangular arrangement, and recent measurements point to a 4$^+$ state at 13.35 MeV [5,6] (previously assigned to be 2$^-$ [7]) associated with a collective rotation around an axis perpendicular to the plane of the triangle.

Aside from the above understanding, the structure of the second excited state at 7.65 MeV, 0$^+$, has yet to be determined. It is likely that it is associated with a pronounced cluster structure, but the arrangement of the clusters remains to be determined. The state was first proposed by Hoyle [8] as the gateway for the triple-$\alpha$ process, the mechanism by which $^{12}$C is formed in stellar nucleosynthesis. Subsequently, the state was experimentally verified [9]. However, over 50 years later, the structure is not precisely determined. It has even been proposed to have a Bose condensate structure [10,11]. Recent measurements indicate that there may be a 2$^+$ excitation between 9 and 12 MeV [12–14], which may be associated with a collective rotational or vibrational excitation. However, the precise detail of the structure of $^{12}$C in this important region remains to be fixed.

In the present paper we present evidence for a previously unknown state at 13.3 MeV that may be linked to the Hoyle state.

II. EXPERIMENTAL DETAILS

The present measurements were performed at the Notre Dame tandem facility. Beams of $^4$He nuclei at energies between 22 and 30 MeV were incident on targets of 1 mg cm$^{-2}$ $^9$Be, 45 $\mu$g cm$^{-2}$ $^{12}$C, and 2.5-$\mu$m-thick mylar. Beam intensities were typically 5 nA ($Q = 2^+$).

The reactions of particular interest here were $^{12}$C($^4$He, $^4$He + $^4$He + $^4$He)$^4$He and $^{9}$Be($^4$He, $^4$He + $^4$He + $^4$He)$n$, where in each case three $\alpha$ particles were detected. In order to detect such a complex, multiparticle, final state, an array of four 500-$\mu$m-thick, double-sided silicon strip detectors (DSSSDs) were employed. These were capable of stopping $\alpha$-particle energies of up to 32 MeV and were operated with energy thresholds of 700 keV, with a typical energy resolution of 100 keV (full width at half maximum, FWHM). The DSSSDs each had a surface area of 5 $\times$ 5 cm$^2$, which was subdivided into 16 horizontal and 16 vertical strips on the front and back faces, respectively. The detectors were arranged centered on the horizontal plane defined by the beam axis and the reaction chamber. For the measurements of the $^{12}$C($^4$He, $^4$He + $^4$He + $^4$He)$^4$He reaction, the detectors were placed at distances 9.4, 13.0, 13.0, and 10.3 cm from the target at angles 50.0$^\circ$, 20.0$^\circ$, −27.5$^\circ$, and −55.0$^\circ$, respectively (angles relative to the beam axis). Here the different signs of the angles indicate opposing sides of the beam axis. For the $^{9}$Be($^4$He, $^4$He + $^4$He + $^4$He)$n$ measurements the distances were 6.8, 10.9, 10.7, and 6.5 cm at angles of 71.0$^\circ$, 33.0$^\circ$, −30.0$^\circ$, and −69.0$^\circ$, respectively.

The detectors were calibrated with $\alpha$ particles produced by $^{148}$Gd (3.183 MeV) and $^{241}$Am (5.486 MeV) sources and elastic scattering of the beam from a $^{208}$Pb target.

III. ANALYSIS AND RESULTS

Given that the detectors had no explicit particle selection, reaction-channel identification was achieved via a reconstruction of the reaction kinematics. Events in which three of the four final-state particles were detected were processed. The detection system provides a determination of the energy and angle of each particle. Starting from an assumption...
that each detected particle is an \( \alpha \) particle, it is possible to reconstruct the momentum for each. The principle of momentum conservation then permits the momentum and energy of the fourth, unobserved, particle (recoil) to be reconstructed:

\[
P_{\text{rec}} = P_{\text{beam}} - \sum_{i=1}^{3} P_{\alpha i},
\]

\[
E_{\text{rec}} = \frac{P_{\text{rec}}^2}{2m_{\text{rec}}}.
\]

Here \( P_{\text{beam}} \) is the beam momentum, and \( P_{\alpha i} \) are the calculated momenta of the three \( \alpha \) particles. In the two reactions from the \(^9\text{Be}\) and \(^{12}\text{C}\) targets the recoil mass is assumed to be that of a neutron and \( \alpha \) particle, respectively. The reaction \( Q \) value may then be calculated using

\[
Q = E_{\text{rec}} + \sum_{i=1}^{3} E_{\alpha i} - E_{\text{beam}},
\]

where \( E_{\alpha i} \) is the energy of each detected particle and \( E_{\text{beam}} \) is the beam energy. The reaction of interest may then be identified from an associated \( Q \)-value spectrum. The \( Q \)-value spectra for the \(^{12}\text{C}(^4\text{He}, ~ ^4\text{He}+^4\text{He})^8\text{He}\) and \(^{9}\text{Be}(^4\text{He}, ~ ^4\text{He}+^4\text{He})n\) reactions are shown in Figs. 1(b) and 1(a), respectively. In each case, there is only one peak that unambiguously identifies the reaction of interest. The \( Q \) value for the reaction proceeding from the \(^{12}\text{C}\) target is \(-7.275\) MeV and from the \(^9\text{Be}\) target is \(-1.574\) MeV. The data in Fig. 1(b) correspond to reactions reconstructed from the carbon component of the thick target, which provided the highest statistics data set. The peaks in the spectra in Fig. 1 lie at \(-6.65\) MeV and \(-0.89\) MeV. The small discrepancy from the actual values may be attributed largely to the energy loss of particles in the thick targets. In particular, the identification of decays proceeding via the \(^8\text{Be}\) ground state (which is unbound to \( \alpha \) decay by \( 92\) keV) is possible. Figure 1(c) shows the \(^9\text{Be}\) decay spectrum reconstructed from pairs of the detected \( \alpha \) particles for events falling within the peak in Fig. 1(b). The relative energy \( E_{\text{rel}} \) was calculated according to

\[
E_{\text{rel}} = \frac{1}{2} \mu v_{\text{rel}}^2,
\]

where \( \mu \) is the reduced mass of a pair of \( \alpha \) particles and \( v_{\text{rel}} \) their relative velocity. The decays proceeding via the \(^8\text{Be}\) ground state can be clearly identified with the peak at \( E_{\text{rel}} = 92\) keV. Again, events within this peak were selected for further analysis.

A. The \(^9\text{Be}(^4\text{He}, ~ ^4\text{He}+^4\text{He}+^4\text{He})n\) reaction

The events associated with the \(^9\text{Be}(^4\text{He}, ~ ^4\text{He}+^4\text{He}+^4\text{He})n\) reaction were first selected by gating on the \( Q \)-value spectrum shown in Fig. 1(a). Second, it was demanded that two of the three detected \( \alpha \) particles should arise from the decay of the \(^9\text{Be}\) ground state. In this manner, the final state was constrained to be \(^4\text{He}+^4\text{Be}+n\). There are a number of possible decay processes that can generate these three particles: (i) the \( \alpha \) decay of \(^{12}\text{C}\) states, (ii) neutron decay of states in \(^9\text{Be}\), or (iii) neutron decay of states in \(^8\text{He}\). In order to disentangle these possibilities a Dalitz plot has been constructed, as shown in Fig. 2. Here the reconstructed \(^{12}\text{C}\) excitation energy (horizontal axis) is plotted versus the \(^9\text{Be}\) excitation excitation energy (vertical axis). The \(^{12}\text{C}\) excitation energy was calculated from the measured energies and angles of the three detected \( \alpha \) particles according to

\[
E_{\alpha}(^{12}\text{C}) = \sum_{i}^{3} E_{i}(\alpha) - E(^{12}\text{C}) + 7.272,
\]

where

\[
E(^{12}\text{C}) = \frac{\left[\sum_{i}^{3} p_i(x)\right]^2 + \left[\sum_{i}^{3} p_i(y)\right]^2 + \left[\sum_{i}^{3} p_i(z)\right]^2}{2M_{\alpha}}.
\]

With \( p_i(x) \), \( p_i(y) \), and \( p_i(z) \) being the \( x, y, \) and \( z \) components of the \( i \)th \( \alpha \) particle and \( M_{\alpha} \) the mass of \(^{12}\text{C}\). The excitation energy of the \(^9\text{Be}\) nucleus was calculated by assuming the third \( \alpha \) particle (not associated with the \(^8\text{Be}\) decay) was the recoil in the \(^9\text{Be}(^4\text{He}, ~ ^4\text{Be})^8\text{He}\) reaction and subtracting the ground-state \( Q \) value (\(-10.739\) MeV). Figure 2 reveals a series of vertical loci associated with \(^{12}\text{C}\) states. In particular, the well-known 9.64-MeV (3\(^+\)), 10.84-MeV (1\(^-\)), and 14.08-MeV (4\(^+\)) states are populated. It should be noted that the selection of decays to the \(^8\text{Be}\) ground state eliminates unnatural-parity
FIG. 2. (Color online) Dalitz plot for the $^9\text{Be}(^4\text{He},^4\text{He}+^4\text{He})^8\text{Be}$ reaction measured at a beam energy of 22 MeV. The reconstructed $^{12}\text{C}$ excitation energy (horizontal axis) is plotted against the calculated $^9\text{Be}$ excitation energy. States associated with the decay of $^9\text{Be}$ form diagonal loci.

states. Similarly, states in $^9\text{Be}$ are found that may be associated with the 1.68-MeV (1/2$^+$) state and most probably with the 2.43 MeV, 5/2$^+$ state. Finally, there is a diagonal band with a gradient of $-1$ that would be associated with the decay of $^3\text{He}$. In order to reveal the nature of the $^{12}\text{C}$ spectrum the data in Fig. 2 have been projected onto the horizontal axis, as shown in Fig. 3(a).

This latter spectrum clearly shows the three aforementioned states. However, there also appears to be an additional broad component close to 13 MeV. Such a component appears not to be associated with other final-state interactions, such as the decay of $^3\text{He}$ or $^9\text{Be}$. However, if the broad structure were to a be due to these other reaction processes, then a change of beam energy would result in a Dalitz plot in which the center-of-mass energy is increased and components move in energy relative to one another. Figure 3(a) also shows the projected spectra for a beam energy of 26 MeV. It is found that the two $^{12}\text{C}$ spectra below an excitation energy of 15 MeV are almost identical, particularly the 14.08-MeV 4$^+$ state and the broad structure. An alternate explanation for the additional strength close to 13 MeV could be that the gate on the $^8\text{Be}$ ground state is not entirely successful in excluding the unnatural-parity states. Figure 3(c) shows the $^{12}\text{C}$ excitation energy spectrum, which, rather than gating on the $^8\text{Be}$ ground state, excludes this state. This would permit unnatural-parity states decaying via $^8\text{Be}(2^+)$ to be observed. The resulting spectrum reveals peaks associated with the 11.83-MeV (2$^-$) and 12.71-MeV (1$^+$) states together with the 14.08-MeV, state which has a 83.0% ($\pm 0.4\%$) decay branch [15] to the $^8\text{Be}(2^+)$ state. It is clear that the structure in this latter spectrum is not replicated in Fig. 3(a) and hence is not the origin of the broad structure.

Alternatively, possible contaminants in the $^{12}\text{C}$ excitation energy spectrum may arise from backgrounds lying beneath the peaks in Figs. 1(a) and 1(c). Figure 3(a) shows the $^{12}\text{C}$ excitation spectra for (i) the $^8\text{Be}$ peak moved up in energy by 180 keV (labeled $^8\text{Be}$ bkgnd) and (ii) the average background from moving the gate on the $Q$-value spectrum to both above and below the peak in the spectrum in Fig. 1(c) (labeled Q bkgnd). It is clear that the contribution from the first of these is negligible, although the corresponding $^8\text{Be}$ excitation energy spectrum does emphasize the 2.43-MeV (5/2$^+$) state, which is known to preferentially decay to the low-energy tail of the $^8\text{Be}(2^+)$ state [16]. The background from the $Q$-value spectrum is more significant. The 3$^-$ state is evident, which is believed to originate from the $^{16}\text{O}(^4\text{He},^4\text{He}+^4\text{He})^8\text{Be}$ reaction, arising from the $^{16}\text{O}$ contaminant arising from oxidation of the beryllium target. This background was reconstructed by averaging the background spectra from above and below the peak found in Fig. 1(a). It does not reveal any evidence for the broad structure identified above. Figure 3(b) shows the 26-MeV spectrum that appears in Fig. 3(a), but fitted with four peaks and a background component. The background has been selected to be a fifth-order polynomial with peaks associated with the known states at 9.64, 10.84, and 14.08 MeV. These have been modeled by Gaussian line shapes with 260-, 460-, and 560-keV resolutions (FWHM).
respectively; it is known that the excitation energy resolution in
the invariant mass technique increases as the square root of the
energy above the decay threshold. The fourth and previously
unrecorded state was again modeled by a Gaussian line shape
centered at 13.3 MeV with a FWHM of 1.7 MeV [as shown
by the shaded region in Fig. 3(b)]. Given the uncertainty in
the shape of the background, the uncertainty on the width and
centroid is of the order of 200 keV in both cases.

Although the measurements at both energies reveal the new
structure at exactly the same energy and the Dalitz plot shown
in Fig. 2 appears to show a vertical locus associated with the
structure, further verification of its association with the decay
of $^{12}$C would be desirable. To this end, a similar analysis
of the $^{12}$C($^4$He, $^4$He$+^4$He$+^4$He)$\alpha$ reaction is presented
below.

### B. The $^{12}$C($^4$He, $^4$He$+^4$He$+^4$He)$\alpha$ reaction

In order to select the reaction of interest the peak observed
in Fig. 1(b) was selected, and subsequently, events in which
two of the $\alpha$ particles were produced from the decay of $^8$Be
were chosen by gating on the peak in the $^8$Be relative energy
spectrum [Fig. 1(c)]. As with the analysis of the reactions from
the $^9$Be target, there are three possible ways the final state can
arise: (i) the three detected $\alpha$ particles were produced from the
decay of $^8$Be, (ii) the $^8$Be and the undetected $\alpha$ particle
were associated with the decay of $^{12}$C, or (iii) the reaction
was $^{12}$C($^8$Be,$^8$Be)$^8$Be. In the last case the “recoil” $^8$Be nucleus
could be in a ground or excited state. The corresponding
Dalitz plot for a beam energy of 30 MeV is shown in Fig. 4.

Here the excitation energy in $^{12}$C calculated from the three
detected $\alpha$ particles (horizontal axis) is plotted versus that
calculating the unobserved $\alpha$ particle was produced from the
decay of $^{12}$C (vertical axis). In the latter case, it was assumed that the third detected $\alpha$ particle, i.e., the one
not associated with the decay of $^8$Be, was the recoil in the
$^{12}$C($^4$He,$^4$He$+^4$He$+^4$He)$\alpha$ reaction. Here the three detected
$\alpha$ particles are labeled 1, 2, and 3, with particles 1 and 2
being from the decay of $^8$Be. The forth, undetected $\alpha$ particle is labeled 4. The final state then consists of $^8$Be$+\alpha_3+\alpha_4$.
The excitation energy on the horizontal axis of Fig. 4 was
calculated using equations (5) and (6). The excitation energy
on the vertical axis was calculated from the measurement of the
momentum of $\alpha_3$ while assuming the other particles to
arise from the decay of $^{12}$C and momentum conservation
and two-body kinematics:

$$E_x(12C) = E_{\text{beam}} - [E_3(\alpha) + E_{\text{rec}}], \tag{7}$$

where

$$E_{\text{rec}} = \frac{p_3(x)^2 + p_3(y)^2 + [p_{\text{beam}} - p_3(z)]^2}{2 \times 12}, \tag{8}$$

with $p_{\text{beam}}$ being the beam momentum. In this instance,
the reconstructed $^{12}$C excitation energy resolution is inferior
(FWHM = 600 keV) at lower excitation energies than the
invariant mass approach, but it is energy independent
and thus close to equivalent at higher excitation energies. A very
similar spectrum of states is observed in both the horizontal
and vertical directions and is also similar to that seen in Fig. 2.
The loci running diagonally (with a gradient of $-1$) correspond
to states in $^8$Be; the ground state is seen at the highest side of
the Dalitz region. Similar evidence for the excitation of the
$^8$Be $2^+$ and $4^+$ states can be found for excitations at 3.0 and
11.3 MeV, respectively. In both the horizontal and vertical
versions of the $^{12}$C spectrum a broad band can be found just
below the 14.08-MeV excitation.

The Dalitz plot shown in Fig. 4 is projected vertically and
horizontally, as shown in Figs. 5(a) and 5(b), respectively. As
with the $^9$Be target, the states observed are the 9.64-, 10.84-, and
14.08-MeV states. In addition, there is some contribution
from the 7.65-MeV state, which was not strongly observed
with the $^9$Be target due to the experiential acceptance. Just as
before, there is an additional contribution that lies below the
14.08-MeV state, which appears in both spectra. Figure 5(c)
shows the excitation energy spectrum for the condition when
a pair of the detected $\alpha$ particles was not produced from the
decay of the $^8$Be ground state. This would include decays
proceeding to $^8$Be excited states. Once again, the structure of the
spectra in Figs. 5(a) and 5(b) does not follow that in Fig. 5(c).
These spectra have been fitted in an identical fashion to
Fig. 3(b), i.e., a fifth-order polynomial background and
peaks at 9.64-, 10.84-, 14.08-, and 13.3-MeV. The spectra are
consistent with the same line shape for the new component.
the correlation analysis, it is necessary to define two angles: \( \theta^* \) and \( \psi^* \). The angle \( \theta^* \) defines the center-of-mass emission angle of the \( ^{12}\text{C} \) nucleus in the \( ^{12}\text{C}(\alpha,^{12}\text{C})\alpha \) reaction. Then \( \psi^* \) defines the angle of emission of the first \( \alpha \) particle from the decay of the excited \( ^{12}\text{C} \) nucleus, within the \( ^{12}\text{C} \) center-of-mass frame. Both angles are measured with respect to the beam axis. Using the Dalitz plot in Fig. 4, it is possible to place event selection windows around the various loci that determine both the excitation energy and the origin of the particles detected. Using this procedure, the angular correlation plots shown in Figs. 6(a)–6(d) were created for the \( 0^+ \), 7.65-MeV; 1\(^-\), 10.84-MeV; 3\(^-\), 9.64-MeV; and 4\(^+\), 14.08-MeV states, respectively. These spectra illustrate the key features of angular correlations. The correlation structure in the \( \theta^*-\psi^* \) plane is governed, to first order, by

\[
W(\theta^*, \psi^*) \propto |P_J[\cos(\psi^* + \Delta \psi)]|^2, \tag{9}
\]

where a small change in \( \psi^* \), \( \Delta \psi^* \), is related to a small change in \( \theta^*, \Delta \theta^* \), via

\[
\Delta \psi^* = \Delta \theta^* \frac{I_g - J}{J}, \tag{10}
\]

where \( J \) is the spin of the state and \( I_g \) is the dominant entrance channel angular momentum, usually called the grazing angular momentum \([17]\). \( P_J \) is a Legendre polynomial of order \( J \). Hence, at \( \theta^* = 0 \), the correlation pattern should follow an intensity given by \( |P_J[\cos(\psi^*)]|^2 \). Away from \( 0^\circ \), the periodicity remains the same, but there is a shift in phase that is roughly linear with the change in angle \( \Delta \theta^* \). This gives rise to a series of sloping ridges. The gradient of the ridges \( \Delta \theta^*/\Delta \psi^* \) is given by \( J/(I_g - J) \). Hence, both the periodicity and the gradient may be used to extract the spin of the \( ^{12}\text{C} \) state decaying to \( ^{8}\text{Be}_{\text{gs}} + \alpha \). For a spin-zero state, as with the state at 7.65 MeV, the gradient should be zero. Figure 6(a) shows a series of horizontal bands cut by the experimental acceptance. The correlations for the \( 1^- \) and \( 3^- \) states are shown in Figs. 6(b) and 6(c), respectively. The ridges referred to above can most clearly be seen for the \( 3^- \) state. In order to characterize the periodicity, the data are typically projected parallel to the ridges onto the \( \psi^* \) axis. The angle at which the data are projected then provides one determination of the spin of the state. For the \( ^{12}\text{C}(^{4}\text{He},^{4}\text{He}) \) reaction at 30 MeV, we estimate that the grazing angular momentum is \( 9h \). The optimum angles for the projection of the data for the \( 1^- \), \( 3^- \), and \( 4^+ \) states

\[ \text{FIG. 5. (Color online) Carbon-12 excitation energy spectra. (a) Projection of the data in Fig. 4 onto the vertical axis (dots). The fit to the data (blue line) is shown together with the polynomial background (red line) and the proposed peak (shaded region). The vertically displaced spectrum is extracted from the previously reported }^{8}\text{Be}(^{4}\text{He},^{12}\text{C}) \text{ measurements (see Fig. 1 in Ref. \[20]\). (b) Projection of the data in Fig. 4 onto the horizontal axis (dots). The fit to the data (blue line) is shown together with the polynomial background (red line) and the proposed peak (shaded region). (c) Excitation energy spectrum for events not proceeding via the decay to the }^{8}\text{Be} \text{ ground state.} \]

\[ \text{FIG. 6. (Color online) Angular correlation plots for states of known spin and parity. (a) 7.65 MeV, 0^+; (b) 10.84 MeV, 1^-; (c) 9.64 MeV, 3^-; and (d) 14.08 MeV, 4^+.} \]
was found to be $\Delta \theta^*/\Delta \psi = 14^\circ$, 27$^\circ$, and 44$^\circ$, respectively, which would correspond to 5, 9, and 8+ states, which is reasonably close to the calculated value. The corresponding projections are shown in Figs. 7(a), 7(b), and 7(c), respectively. The data are compared with Legendre polynomials of the appropriate order in each case. The reproduction of the periodicity of the oscillations found in the data is reasonably good, confirming the robustness of the technique to extract the spins. It should be noted that the Legendre polynomials shown in Fig. 7 have not been fed through the experimental acceptance as they are used only to illustrate the periodicity. In order to reproduce the amplitudes of the oscillations a full reaction model calculation predicting the variation of the $m$ substates as a function of scattering angle $\theta^*$ would be required, which is beyond the scope of the current work.

In order to gain an insight into the possible spin of the broad peak found in the $^{12}$C excitation energy spectrum the corresponding correlations were analyzed. In order to select the appropriate events, two windows were placed to the low-energy sides of the two 14.08-MeV loci in Fig. 4, making sure that possible contributions from the $^{12}$C and $^{9}$Be 4+ states were excluded. The correlation data were then projected at the optimum angles found for the 1−, 3−, and 4+ states. These projections are shown in Figs. 7(d), 7(e), and 7(f). Of these three possibilities, the data appear to agree best with the periodicity of the Legendre polynomial for the $J^\pi = 4^+$ case.

Figures 7(g) and 7(h) correspond to projections at 20$^\circ$ and 53$^\circ$ and are compared with Legendre polynomials of orders 2 and 5, respectively. Due to the rather constrained cut placed on the Dalitz plot of Fig. 4, this analysis does not yield an unambiguous result for the spin of a state associated with the broad bump. However, they would appear to exclude $J^\pi = 1^-$ and 2+, and the striking similarity between the periodicity of the oscillations found in Figs. 7(c) and 7(h) would favor $J^\pi = 4^+$.

V. DISCUSSION

The present measurements indicate the presence of a new state in $^{12}$C at 13.3(0.2) MeV with a width of 1.7(0.2) MeV. Given that the line shape is similar for the two different beam energies with the $^{9}$Be target and the $^{12}$C target data, then it is assumed that the peak corresponds to a single state rather than a collection of unresolved states. The state must have natural parity, $(-1)^I$, as the decay proceeds to the $^3$He + $^8$Be decay channel that contains exclusively spin-zero nuclei. The present measurements would indicate $J^\pi = 4^+$, although other spins cannot be excluded.

There are several measurements that previously probed the structure of $^{12}$C in the present region. The measurement of the $^{12}$C($^{12}$C,3$\alpha$) reaction [6] is the closest to those presented here. In that case, the $\alpha$ decay to the $^8$Be ground and excited
states was separately analyzed. In the decay to the ground state the 7.65-MeV ($0^+$), 9.64-MeV ($3^-$), 10.84-MeV ($1^-$), and 14.08-MeV ($4^+$) states were clearly identified. The main focus was the analysis of the decay of the unnatural-parity states. No strong feature was observed close to 13.3 MeV (although a background contribution peaking close to 12.5 MeV was required). Angular correlation studies appeared to indicate dominant $L = 1$ and 3 strength between the 10.84- and 14.08-MeV peaks, with the $L = 3$ strength being located close to 12.5 MeV. No clear peaks were identified in this region.

Measurements of the $^{11}\text{B}(^3\text{He},3\alpha)$ reaction have recently been reported [5]. Again, the decay channel selection was possible, and in the current region, no feature close to 13.3 MeV was observed that could be associated with unnatural-parity states. Indeed, predominantly, unnatural-parity states were strongly populated in this reaction.

Analysis of the $\beta$ decay of $^{12}\text{B}$ and $^{12}\text{N}$ to $^{12}\text{C}$ followed by the detection of three $\alpha$ particles has been measured by the Aarhus group on several occasions [12,18]. Such studies are sensitive to states with spin and parity $0^+$, $1^+$, and $2^+$. The most recent of these measurements indicates that a broad $2^+$ state exists between 10.5 and 12 MeV and that a further $2^+$ state lies close to 16.5 MeV, with no indication of a $0^+$ or $2^+$ state close to 13.3 MeV.

One earlier measurement of the $^9\text{Be}(\alpha,n)$ reaction was found at an incident energy of 35 MeV, close to the present energy [19]; this result, though unpublished, is presented in Fig. 1 of Ref. [20] (and is shown in Fig. 5(a)). The measurement was made at a laboratory angle of 32° and shows that the unnatural-parity states are not strongly populated as in the present case. The 14.08-MeV, $4^+$ state is clearly observed as is an unresolved broad structure extending to lower excitation energies. This feature appears to be identical to the one observed in the present measurements.

VI. CONCLUSION

The current measurements of the $^9\text{Be}(^4\text{He},^{12}\text{C})\beta$ and $^{12}\text{C}(^4\text{He},^4\text{C})\beta$ reactions reveal evidence for a resonance at 13.3(0.2) MeV with a width of 1.7(0.2) MeV. Angular correlation measurements from the $^{12}\text{C}$ target measurements do not provide an unambiguous spin determination but indicate that the state has a spin and parity $J^\pi = 4^+$. Unambiguously, the state must have natural parity. It is suggested that this state could be a collective excitation of the Hoyle state, a description that is consistent with earlier reports of a $2^+$ state close to 9.6 MeV.