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Measurement of α and neutron decay widths of excited states of ¹⁴C

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The ${}^{12}C({}^{16}O, {}^{14}O){}^{14}C$ reaction was studied at a beam energy of 234 MeV. The ${}^{14}O$ ejectile was detected by a Q3D spectrometer at forward angles. The energies and angles of the excited ${}^{14}C$ recoil break-up fragments were measured in coincidence with the ${}^{14}O$ ejectile using a double sided silicon strip detector array at backward angles. A complete kinematic reconstruction of the reaction was performed to reconstruct the ${}^{14}C^* \rightarrow {}^{10}Be + \alpha$ and ${}^{14}C^* \rightarrow {}^{13}C + n$ decay channels and the branching ratios and widths of these decays were calculated. Theoretical decay branches were calculated using barrier penetrability factors and were compared to the measured ratios to provide information on the spins, parities, and configurations of the states. Neutron emission was found to be favored for the 11.73, 12.96, 14.87, 16.72, and 18.6 MeV states. The 14.87, 18.6, and 21.4 MeV states were found to have a considerable width for α -decay and are candidates for the three bodied molecular cluster structure of ${}^{14}C$.

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I. INTRODUCTION

It is well known that ⁸Be has a well developed α - α cluster structure [1,2]. The ⁸Be nucleus is unstable as the α - α interaction is weak and has a repulsive core due to the Pauli principle. However, the addition of a neutron produces enough binding energy to make the ⁹Be nucleus stable. The binding energy which stabilizes the system is provided by the neutron which resides in delocalized orbits around the α -cores. In the case of ¹⁰Be, linear combinations of the two valence neutron orbitals produce π - and σ -bonds which bind the dimer core [3]. There is now strong evidence for these molecular-like α -cluster structures in ^{9,10}Be [4–10]. Antisymmetrized molecular dynamics (AMD) calculations provide further support for these molecular structures in ^{9–12}Be; where they reproduce these molecular characteristics despite the fact that no explicit cluster content is assumed [3,11–16].

These concepts can be extended to the neutron-rich carbon isotopes, in which the core has a three α -particle cluster configuration. Again, the valence neutrons would reside in delocalised molecular orbits around the cores and would increase the binding energy and stability of the system. These ideas have been explored extensively by Milin and von Oertzen *et al.*, in which the complete spectroscopy of ¹³C [17] and ¹⁴C [18] states were examined. In this method, the single-particle shell-model states are eliminated and the remaining states are assigned to rotational bands associated with prolate, linear-chain structures and oblate, triangular configurations. In ¹⁴C, three different molecular cluster configurations can be expected: triangular configurations with the neutrons in

 σ -bonds between two of the α -particles, linear reflectionsymmetric chains in which the valence neutrons are equally distributed among the three α -cores (α -n- α -n- α) and linear intrinsically reflection-asymmetric configurations in which the two neutrons reside between two of the α -cores (α -2n- α - α). This final configuration gives rise to parity inversion doublets.

These proposed molecular configurations should exhibit strong α -decay. Here we present measurements of the neutron and α -decay branching ratios associated with highly excited states in ¹⁴C. The experimentally determined branching ratios are compared with theoretical decay branches to provide information on the spins, parities, and configurations of these states. Additional information on the widths and population of the states, which depend on dynamical matching conditions, are used to help indicate their properties.

II. EXPERIMENTAL PROCEDURE

The two-neutron transfer reaction ${}^{12}C({}^{16}O,{}^{14}O){}^{14}C$ was studied at a beam energy of 234 MeV, in two separate measurements, at the Ionen-Strahl-Labor (ISL) facility, at the Hahn-Meitner-Institut (HMI), Berlin. This reaction has a ground state *Q*-value of $Q_0 = -15.763$ MeV. In the first set of measurements the beam was incident on a 200 μ g cm⁻²¹²C target and in the second the target used was a 20 μ g cm⁻²¹²C foil.

The measurements were performed with a Q3D magnetic spectrometer [19–21] and an array of charged particle detectors. The ¹⁴O ejectile was identified in the Q3D focal plane detector using proportional wires for energy loss and a plastic scintillator to measure time of flight and total energy. The position of the ¹⁴O along the focal plane was measured using the delay-line read-out technique. The ¹⁴O nucleus has no

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FIG. 1. (Color online) The ¹⁴C excitation energy spectra fitted with Gaussian peaks, whose centroids are indicated, and a smooth background. The peaks ranging from 6.73 to 21.4 MeV represent the ¹⁴C states populated in the two-neutron transfer reaction ¹²C(¹⁶O,¹⁴O)¹⁴C. The angular range of the Q3D acceptance aperture is indicated. In (b) the magnetic-field settings of the Q3D have been chosen to emphasize the higher-excitation-energy region. The feature at 28.4 MeV is not an excited state, but rather an edge effect at the low-energy side of the detector.

bound excited states and thus its position along the focal plane yields the excitation energy of the ¹⁴C nucleus, as shown in Fig. 1. In the first set of measurements, the magnetic rigidity of the Q3D spectrometer was set to observe ¹⁴C states with

excitation energies 6.73 to 21.4 MeV (a). In the second set of measurements, the spectrometer was set for the excitation energy range 11.73 to 21.4 MeV (b).

The distance traveled by a particle within the Q3D spectrograph primarily depends on its emission angle. Hence the time of flight depends on the length of the trajectory and can thus be used to deduce the scattering angle within the horizontal acceptance aperture of the Q3D. Due to the excellent time resolution an angular resolution of 0.3° was achieved. The scattering angle of the ¹⁴O and the excitation energy of the ¹⁴C can be used to determine the laboratory energy of the ¹⁴O and thus a complete reconstruction of the binary reaction can be performed.

The decay products of the excited ¹⁴C recoil were detected, in coincidence with the ¹⁴O ejectile, using an array of solid state charged particle detectors. This array initially comprised two $50 \text{ mm} \times 50 \text{ mm}$ double sided silicon strip detectors (DSSSD) approximately 500 μ m thick and for the second set of measurements was composed of four such detectors. Each detector face was subdivided into 16 independent 3 mm wide strips, with the direction of the strips on the front face being perpendicular to those on the back. Hence each detector was essentially formed from 256, 9 mm², pixels. The detectors had an angular resolution of $\Delta \theta_{lab} \leq 1.3^{\circ}$ and a typical energy resolution of 150 keV. For the first set of measurements three different angular arrangements of the spectrometer and the DSSSDs were used and for the second measurement, only one setting was used. The details of the various experimental setups are shown in Table I.

III. ANALYSIS AND RESULTS

Below 20.6 MeV the excited ¹⁴C nucleus only has two available decay channels: ¹⁰Be + $\alpha(E_{\text{thresh}} = 12.01 \text{ MeV})$ and ¹³C + $n(E_{\text{thresh}} = 8.18 \text{ MeV})$. The majority of ¹⁴O events detected in the spectrometer were in coincidence with only one ¹⁴C decay product in the DSSSD array. Thus, particles detected in the DSSSD array were assumed to be either ¹³C or ¹⁰Be nuclei. For both decay channels momentum conservation was used to reconstruct the energy and the angle of the undetected breakup particle and the three-body *Q*-value, *Q*₃, was calculated as

$$Q_3 = E_{^{14}\text{O}} + E_{\text{D}_1} + E_{\text{D}_2} - E_{\text{beam}},\tag{1}$$

where D_1 and D_2 represent the two decay products of the excited ¹⁴C recoil. The excitation energy of the breakup

TABLE I. Details of the detector arrangements for the various measurements. The angles (θ_x, θ_y) and distances are measured from the center of the reaction target to the center of the associated detector.

Setup	Q3D angle (degrees)		θ_x, θ_y (degrees), distance (mm)										
		DSSSD1			DSSSD2			DSSSD3		3	DSSSD4		
1	10.5–13.5	73.0	0.0	169.5	50.5	0.0	169.5						
2	10.5-13.5	55.5	0.0	169.5	33.0	0.0	169.5						
3	6.5–9.5	59.5	0.0	169.5	37.0	0.0	169.5						
4	8.5–11.5	47.5	13.1	142.7	47.5	-10.1	141.2	25.0	11.4	167.3	25.0	-8.4	165.8

fragments was calculated by comparing Q_3 with the threebody Q-value in which the decay products are produced in their ground states, Q_{3_0} :

$$E_x(D_{1,2}) = |Q_{3_0} - Q_3|.$$
⁽²⁾

In each decay channel only one of the daughter nuclei can be in an excited state, as the first excited state of an α particle is 20.2 MeV. Thus, the excitation energy of the breakup fragments corresponds to the excitation energy of either the ¹³C or the ¹⁰Be. So, for example, the detection of a ¹⁰Be nucleus with $E_x(^{10}\text{Be}) = 3.368 \text{ MeV}$ corresponds to the ¹⁴C* α -decaying to the first excited state of ¹⁰Be.

The various decay channels were analyzed using Monte Carlo simulations of the reaction and detection processes. The simulations reproduce the experimental acceptances and smear the energies and angles in accordance with the experimental resolutions. The outputs of the simulations were subsequently processed as if they were real events using the same analysis procedures as those used for the experimental data. These simulations permitted the theoretical peak line-shapes in the decay products excitation energy spectra to be reconstructed. These line-shapes were normalized to fit the experimental data and the integrated area of the line-shapes were compared with the number of counts in the associated state in the Q3D, ¹⁴C, excitation energy spectrum, in order to deduce branching ratios.

Figure 2 shows the ¹³C excitation energy spectra, produced for various ¹⁴C states by gating on the appropriate peak in the ¹⁴C excitation energy spectrum [Fig. 1(a)]. The spectra are obtained from the measurements involving setup 3 (Table I), after the coincident detection of the ¹³C decay fragment and the ¹⁴O ejectile and assuming a missing neutron. The histograms correspond to the experimental data. The peaks centered at $E_x(^{13}C) = 0$ MeV correspond to the ¹⁴C* decaying via neutron emission to the ground state of ¹³C. The peaks centered at $E_x(^{13}\text{C}) \sim 3.8$ MeV correspond to events in which the ¹⁴C* decays to one of the first three excited states in ¹³C. These three states are the $J^{\pi} = 1/2^+(3.089 \text{ MeV}), 3/2^-(3.6845 \text{ MeV})$ and $5/2^+(3.854 \text{ MeV})$ and are unresolved in the spectra. The ¹³C excitation energy spectra (Fig. 2) and the ¹⁴C excitation energy spectra (Fig. 1) were used to calculate the branching ratios for the neutron decay of the ¹⁴C* nuclei to various states in ¹³C.

The relative branching ratio, BR_{rel} , of a particular ¹⁴C state, is the ratio between the decay rates, N_A and N_B , of two different individual decay channels of that state and is

$$BR_{rel} = \frac{N_A/\varepsilon_A}{N_B/\varepsilon_B},$$
(3)

where ε is the detection efficiency and is given by the Monte Carlo simulations. The values of N_A and N_B , are given by the number of counts in the associated peaks, in the decay fragments excitation energy spectrum (DSSSD counts). As noted, the number of counts in a peak was calculated by integrating the normalized function which corresponds to the peak line-shape. The absolute branching ratio, BR_{abs}, is the ratio between the decay rate, N_A , of an individual decay channel of a particular ¹⁴C state and the total decay rate, N_T , of that state and is

$$BR_{abs} = \frac{N_A/\varepsilon_A}{N_T} = \frac{No. \text{ of Counts in } DSSSD/\varepsilon_A}{No. \text{ of Counts in } Q3D \text{ Detector}}.$$
 (4)

The value of N_T , for the ¹⁴C state being studied, is given by the number of counts in the associated peak, in the ¹⁴C excitation energy spectrum (Q3D counts).



FIG. 2. (Color online) ${}^{13}C$ states populated in the decay of excited states in ${}^{14}C$. The spectra are produced by gating on the appropriate peak in the ${}^{14}C$ excitation energy spectrum [Fig. 1(a)] following the coincident detection of the ${}^{14}O$ ejectile and the ${}^{13}C$ decay fragment and assuming a missing neutron. The spectra are obtained from the setup 3 (Table I) measurement and are fitted with the simulated peak line-shapes and a smooth polynomial background. In each spectrum the excitation energy of the decaying ${}^{14}C$ state is indicated.



FIG. 3. (Color online) The simulated angular distribution of the 13 C decay fragments for the measurements involving setups 3 and 4. The outlines of the DSSSDs are shown.

A. Detection efficiencies

To calculate the branching ratios, the detection efficiencies must be calculated using the simulations. As an example, the ${}^{12}C({}^{16}O, {}^{14}O){}^{14}C^*[{}^{13}C + n]$ reaction was simulated for the 12.96 MeV ${}^{14}C^*$ state, for setup 3 (two DSSSDs). The in-plane and out-of-plane angles of the ${}^{13}C$ decay fragments with respect to the beam direction are shown in Fig. 3(a). The outlines of the DSSSDs are shown. The 'breakup circle' formed by the detection of the ${}^{13}C$ nuclei is clearly evident. Events which fall outside of the active area of the detectors are rejected and the detection efficiency, ε , is given by

$$\varepsilon = \frac{\text{No. of Events Detected in the DSSSD Array}}{\text{No. of Events Detected in the Q3D Spectrometer}}.$$
 (5)

As the spins of many of the states are unknown the simulations are performed assuming an isotropic decay. In reality the decay is anisotropic, resulting in a slightly different angular distribution of the decay fragments. This will affect the distribution of the yield across the breakup circle. From Fig. 3(a) it is evident that only a fraction of the ${}^{13}C$ decay fragments are detected. The fraction of detected particles depends on the angular distribution of these particles and thus, for large breakup cones an error is introduced into the efficiency calculations and subsequently into the branching ratios. This is not a problem for the lower energy ${}^{14}C^*$ states $(E_x)^{14}$ C) < 10.74 MeV) as the detection efficiencies are very close to 100%. Similarly, the detection efficiencies are also close to 100% for ¹⁴C^{*} states, with $E_x(^{14}C) \leq 12.96$ MeV, which decay to excited states in ¹³C. However, as the excitation energy of the ¹⁴C increases, the detection efficiencies of the decay fragments decrease and the effect of this problem increases. This is accentuated for the ${}^{10}\text{Be} + \alpha$ decay channel as the ¹⁰Be decay fragments are emitted with a greater angular range than the ¹³C decay fragments.

The second experiment described (setup 4), used a silicon array constructed from four detectors. Figure 3(b) shows the simulated angular distribution of the ¹³C nuclei, emitted in their ground states from the ¹⁴C* nuclei (E_x (¹⁴C) = 12.96 MeV). With the exception of the dead areas between

the detectors, the entire angular distribution is observed. The improvement in the observation of a greater fraction of the angular distribution is mainly achieved by simply increasing the number of detectors. However, it is also improved by reducing the size of the breakup circle with respect to the detectors. In a comparison between Figs. 3(a) and 3(b), it is evident that the breakup circle is indeed smaller in the measurements involving setup 4. This is achieved in two ways. Firstly, the detectors were moved closer to the target at the expense of the angular resolution. Secondly, the angle of the Q3D spectrometer was increased. As the Q3D angle increases, the energy of the ¹⁴C increases, thus reducing the size of the breakup cone. The one disadvantage is that the number of detected ¹⁴O particles exponentially decreases as the scattering angle increases and thus the statistical uncertainties increase. For the four DSSSD setup, the entire breakup circle of the ¹³C decay fragments falls within the limits of the array, for all the ¹⁴C states studied. Thus, the errors introduced into the detection efficiency calculations, by the assumption of an isotropic decay, are significantly reduced for setup 4 and the branching ratios can be calculated without the need to know the spin of the decaying 14 C state.

B. Experimental uncertainties and background contributions

From Eqs. (3), (4), and (5) it is clear that the branching ratios depend on the number of counts in the Q3D spectrometer, the number of counts in the DSSSDs and the detection efficiencies. Each of these values have inherent statistical errors which are associated with any random process. However, the statistical errors associated with the detection efficiencies are negligible as the simulations were run for a large number of events. In addition, there are systematic errors associated with the uncertainty in the smooth background fit to the data, and the parameters used in the simulations.

In several cases, the dominant source of error in the number of counts in the DSSSD array arises from the fitting of the simulated line-shapes, and background functions, to the experimental data. Figure 2(c) shows the ¹³C states populated in the decay of the 11.73 MeV ¹⁴C state. The two peaks are



FIG. 4. (Color online) Two possible fits for the peak line-shapes and background to the 13 C states populated in the decay of the 18.6 MeV 14 C state.

well resolved and the background contribution is smooth and small. As a consequence, errors in the fitting process are small. Figure 4, on the other hand, shows two possible ways of fitting the line shapes and backgrounds to the ¹³C states populated in the decay of the 18.6 MeV ¹⁴C state. In this case the fitting process is far more subjective resulting in larger errors. These errors are especially a problem in the ¹⁰Be excitation energy spectra, where the peaks lie on large and uneven backgrounds.

To reduce these 'fitting' errors, analysis was performed to understand the shapes of the backgrounds, in the excitation energy spectra of the decay fragments. One contribution to the background arises from the lack of particle identification. Thus, ¹⁰Be events were processed as ¹³C events in the ¹³C+*n* analysis and vice versa. Monte Carlo simulations were performed to analyze the background contributions that arise from this ambiguity. It was found that ¹⁰Be events analyzed as ¹³C events, would produce an even, low-lying background in the ¹³C excitation energy spectra. Thus, peaks in the ¹³C excitation energy spectra lie on this even background and are largely unaffected. Conversely, ¹³C events analyzed as ¹⁰Be events, produce a background in which the counts are bunched up in the higher ¹⁰Be excitation energy region.

The second contribution to the background arises from the coincident detection of background events in the Q3D and background events in the DSSSD array. To determine the approximate shape of such background contributions, regions of the ¹⁴C excitation energy spectra, in which there are only background events, are analyzed as if they were real excited states. For example, in the ¹⁴C excitation energy spectra (Fig. 1), the region between the 19.8 and 21.4 MeV peaks contains Q3D background counts only. These counts were analyzed as a 20.6 MeV ¹⁴C state and the decay products excitation energy spectra were obtained. The histograms produced gave an approximate shape of the background contribution for the 18.6 and 21.4 MeV states.



FIG. 5. (Color online) The 6.73 MeV 14 C state populated in the $^{12}C(^{16}O,^{14}O)^{14}$ C reaction. The spectrum is obtained after the coincident detection of the $^{14}C^*$, in the DSSSD array, with the ^{14}O ejectile, in the Q3D. The data is fitted with a simulated peak line-shape and a smooth background.

C. The binary reaction

The 6.73 MeV ¹⁴C state is strongly populated in the two neutron transfer reaction as shown in Fig. 1. The state is bound and thus the ¹⁴C nucleus is detected directly in the DSSSD array after it undergoes γ -decay. This provides a means of testing the procedure by which the detection efficiencies are calculated. Simulations show that the efficiency of detecting this state in the DSSSD array is 95–100%. Figure 5 shows the ¹⁴C excitation energy spectrum, obtained after the coincident detection of the excited ¹⁴C nuclei and the ¹⁴O ejectile. The ratio of the number of hits in the Q3D focal plane to the number of 6.73 MeV ¹⁴C hits in the DSSSD array is 0.96 ± 0.10. As expected, the experimental detection efficiency and the simulated detection efficiency are equal within errors.

D. The ${}^{13}C + n$ decay channel

Figure 6 shows the ¹⁴C states which have sufficient excitation energy to decay via the ¹³C + n channel. The ¹³C states populated in the decay of excited states in ¹⁴C are shown in Figs. 2 and 7. The two sets of spectra are obtained with measurements from setup 3 and 4, respectively, after the coincident detection of the ¹³C decay fragment and the ¹⁴O ejectile and assuming a missing neutron. The branching ratios for the neutron decays of excited ¹⁴C states are shown in Table II and the decay widths are shown in Table III.

The 8.32 MeV and 10.74 MeV ¹⁴C states only have sufficient excitation energy to neutron decay to the ground state of ¹³C. Thus, these two states provide a good method for testing the validity of the procedure used to calculate the branching ratios. The ¹³C excitation energy spectra for these two states are shown in Figs. 2(a) and 2(b), respectively. The peaks centered at $E_x(^{13}C) = 0$ MeV correspond to the ¹³C nuclei being emitted in their ground states. Using Eq. (4), the absolute branching ratios, for the decay of the 8.32 MeV and

TABLE II. The branching ratios for the decay of excited ¹⁴C states via the ¹³C + *n* and ¹⁰Be + α channels. For the neutron channel the branching ratios are shown for the decay to the ¹³C[1/2⁻] ground state (g.s.) and the 1/2⁻(3.089 MeV), 3/2⁻(3.6845 MeV) and 5/2⁺(3.854 MeV) first three excited states (ES_{1,2,3}). For the α -channel the branching ratios are shown for the decay to the ¹⁰Be[0⁺] ground state (g.s.), the 2⁺(3.3680 MeV) first excited state (ES₁) and the 2⁺, 1⁻, 0⁺ and 2⁻ quartet at ~6 MeV (ES_{2,3,5}).

¹⁴ C state (MeV)	¹³ C	+n	$^{10}\mathrm{Be} + \alpha$					
	g.s.	ES _{1,2,3}	g.s.	ES_1	ES _{2,3,4,5}			
8.32	1.02 ± 0.09							
10.74	1.03 ± 0.03							
11.73	0.72 ± 0.04	0.28 ± 0.04						
12.96	0.34 ± 0.06	0.59 ± 0.08	< 0.10					
14.87	0.21 ± 0.04	0.57 ± 0.08	0.16 ± 0.03					
18.6	< 0.21	0.57 ± 0.16	< 0.10	0.33 ± 0.10	< 0.05			
21.4	< 0.05	< 0.05	< 0.10	0.66 ± 0.15	0.22 ± 0.07			

10.74 MeV states to the ground state of 13 C, are calculated to be 1.02 ± 0.09 and 1.03 ± 0.03 , respectively. Thus, these values are both equal to one, as expected.

For the 11.73 MeV, ¹⁴C state, the peak centered at E_x (¹³C) = 3.089 MeV corresponds to events in which the ¹⁴C decays to the 3.089 MeV first excited state in ¹³C. For the excited ¹⁴C states, with E_x (¹⁴C) \ge 12.96 MeV, the peaks centered at E_x (¹³C) ~3.8 MeV correspond to events in which the ¹⁴C* decays to one of the first three excited states in ¹³C. The 3.089, 3.6845, and 3.854 MeV states have a separation of 765 keV and are unresolved.

From Fig. 6, it is clear that the ¹⁴C* states with $E_x(^{14}C) \ge 16.72$ MeV have sufficient excitation energy to neutron decay to ¹³C states which lie above the ¹²C+*n* decay threshold. A ¹³C nucleus emitted in one of these excited states will subsequently neutron decay to ¹²C. In such an event the ¹²C nucleus detected in the DSSSD is analyzed as a ¹³C nucleus. Thus, these events will contribute to the backgrounds in the ¹³C and ¹⁰Be excitation energy spectra. As an example, a simulation was performed to study the reaction in which a 16.72 MeV ¹⁴C state neutron decays to a 6.864 MeV ¹³C state, which subsequently neutron decays to the ground state of ¹²C. In order to model this process the outputs of the simulations, which represent the energies and angles of the ¹²C, were analyzed as if they were ¹³C nuclei and the ¹³C

excitation energy spectrum was produced [Fig. 8(a)]. The two vertical lines represent the positions of the ground state and the 3.854 MeV energy levels of the ¹³C. The ¹³C excitation energy spectrum obtained from the setup 4 data set, for the decay of the 16.72 MeV ¹⁴C state is shown in Fig. 8(b). In a comparison between the two spectra it is evident that the histograms have a similar shape. Thus it is not possible to determine if the peak centered at $E_x(^{13}C) \sim 3.8$ MeV corresponds to the ^{14}C decaying to a bound excited state in ¹³C or to the ¹²C ground state. Thus the ${}^{13}C + n$ branching ratios cannot be determined for the 16.72 MeV state. However, by analyzing the number of counts in the broad peak in Fig. 8(b), it can be concluded that the 16.72 MeV state has a significant width for decay to excited states in ¹³C. The decay to the ¹³C ground state is not observed. Similar simulations show that the ¹²C background is not a problem for the ¹⁴C^{*} states with $E_x({}^{14}C) \ge 18.6$ MeV.

The ¹³C ground state is weakly populated in the decay of the 18.6 MeV ¹⁴C state. It is evident from Fig. 7(c) that the ground-state peak lies on a large background and contains a limited number of counts. As a consequence the uncertainties associated with the fitting procedure are large for this particular decay channel. Thus, the branching ratio is quoted as an upper limit.

The decay of the 21.4 MeV 14 C state via the 13 C + *n* channel is not observed.

TABLE III. The neutron and α -decay widths of excited states in ¹⁴C. The total decay widths are taken from Ref. [18].

¹⁴ C State (MeV)	${}^{13}\mathrm{C} + n$ deca	y width (keV)	10 Be	$e + \alpha$ decay width (Total decay width (keV)		
	g.s.	ES _{1,2,3}	g.s.	ES_1	ES _{2,3,4,5}		
8.32	3.40					3.4	
10.74	10.00					10	
11.73	21.60 ± 1.20	8.40 ± 1.20				30	
12.96	8.50 ± 1.50	14.75 ± 2.00	<2.50			25	
14.87	7.35 ± 1.40	19.95 ± 2.80	5.60 ± 1.05			35	
18.6	<21.00	57.00 ± 16.00	<10.00	33.00 ± 10.00	< 5.00	100	
21.4	<27.50	<27.50	<55.00	363.00 ± 82.50	121.00 ± 38.50	550	



FIG. 6. An energy level diagram illustrating the possible decay channels available to various 14 C states. The energy thresholds for the various decay channels are indicated.

E. The ¹⁰Be + α decay channel

1. Multiplicity 1 events

Figure 6 shows the ¹⁴C^{*} states which have sufficient excitation energy to decay via the ¹⁰Be + α channel. The ¹⁰Be states populated in the decay of excited states in ¹⁴C are shown in Fig. 9. The branching ratios and α -decay widths of various excited ¹⁴C states are shown in Tables II and III, respectively.

The spectra in Fig. 9(a)–9(c) are obtained from the setup 4 data set (Table I), after the coincident detection of the ¹⁴O in the Q3D spectrometer, with the ¹⁰Be in the DSSSD array and assuming a missing α -particle.



FIG. 7. (Color online) ¹³C excited states populated in the decay of excited states in ¹⁴C. The excitation energy of the decaying ¹⁴C ¹²C + n re obtained from the measurement involving setup 4 (Table I) and are fitted with the simulated peak line-shapes and a smooth polynomial background.



FIG. 8. (Color online) (a) shows the simulated ¹³C excitation energy spectrum obtained following the detection of ¹²C nuclei which are analyzed as if they were ¹³C nuclei. The energies and angles of the ¹²C were obtained from Monte Carlo simulations of the ¹⁴C*(16.72 MeV) \rightarrow ¹³C*(6.864 MeV) + *n*, ¹³C*(6.864 MeV) \rightarrow ¹²C + *n* reaction. (b) shows the ¹³C excitation energy spectrum obtained from the setup 4 data set, following the coincident detection of the ¹⁴O with one of the 16.72 MeV ¹⁴C decay fragments and assuming a missing neutron.



FIG. 9. (Color online) ¹⁰Be excited states populated in the decay of excited states in ¹⁴C. The multiplicity 1 spectra [(a)-(c)] are obtained after the coincident detection of the ¹⁴O ejectile and the ¹⁰Be decay fragment and assuming a missing α -particle. The data are fitted with the simulated peak line shapes and a smooth polynomial background. The multiplicity 2 spectra [(d)-(f)] are obtained following the coincident detection of the three final state particles. The vertical lines represent the positions of the ground state, the 3.3680 MeV and the 5.960 MeV energy levels of ¹⁰Be. The excitation energy of the decaying ¹⁴C state is indicated.

It has already been noted that ¹³C events form backgrounds in the ¹⁰Be excitation energy spectra which are compressed into the higher excitation-energy regions. For the 12.96 MeV state, this region coincides with the ¹⁰Be ground state energy. Consequently, the ¹³C background forms a peak at $E_x(^{10}\text{Be}) \sim$ 0 MeV and thus it is not possible to determine if the 12.96 MeV ¹⁴C state decays via the ¹⁰Be + α branch. However, from the ¹³C + *n* analysis (Table II) it is evident that this branch must be small if it exists at all.

For the 14.87 MeV state of ¹⁴C the peak centered at $E_x({}^{10}\text{Be}) = 0$ MeV [Fig. 9(a)] corresponds to the α -decay to the ground state of ${}^{10}\text{Be}$.

The 16.72 MeV ¹⁴C state has sufficient excitation energy to α -decay to both the ground state and first excited state in ¹⁰Be. However, a significant width for decay via the ¹⁰Be + α branch is not observed. Thus it is concluded that the dominant decay mode for this state is neutron decay.

The 18.6 MeV ¹⁴C state has sufficient excitation energy to α -decay to ¹⁰Be states with $E_x(^{10}\text{Be}) < 6.589$ MeV. In Fig. 9(b) the peak centered at $E_x(^{10}\text{Be}) = 3.368$ MeV corresponds to the ¹⁰Be nuclei being emitted in the first excited state. The α -decay to the ¹⁰Be ground state and to the group of states at $E_x(^{10}\text{Be}) \sim 6$ MeV is not observed.

The 21.4 MeV state of ¹⁴C has a substantial width for the α -decay to both the first excited state in ¹⁰Be and the group of states at $E_x(^{10}\text{Be}) \sim 6$ MeV. The peak centered at $E_x(^{10}\text{Be}) \sim 6$ MeV corresponds to the ¹⁴C* decaying to either the 5.9583, 5.960, 6.179, or 6.263 MeV, ¹⁰Be states, which are unresolved. The decay to the ¹⁰Be ground state is not observed. The 21.4 MeV ¹⁴C state has sufficient excitation energy to α -decay to the 7.371, 7.542, and 9.27 MeV states. These states lie above the ⁹Be+*n* decay threshold ($E_{\text{thresh}} = 6.8121$ MeV) and will subsequently neutron decay to ⁹Be. The two neutrons produced in such a decay are not observed and, therefore, the reaction Q-value cannot be determined for such decays.

2. Multiplicity 2 events

There were a number of events in which the ¹⁴O ejectile was detected in coincidence with both the ¹⁰Be and α decay products. In such events the energies of the three final-state particles are measured directly and the Q-value and excitation energies of the decay fragments are calculated using Eqs. (1) and (2). In order to accurately reproduce the excitation energies of the decay fragments the energy lost by the particles in traversing the target must be calculated and added to the energy of the detected particle. However, this is impossible as the identification of the decay fragments is ambiguous. Thus, such calculations can only be performed if the target is thin enough that the energy loss is smaller than the energy resolution and can thus be ignored. This was the case for the measurements involving setup 4, in which the target was $20 \,\mu \text{g cm}^{-2}$. The ¹⁰Be excitation energy spectra, produced after the coincident detection of all of the three final-state particles are shown in Fig. 9(d)-9(f). In this instance the detection efficiency is small and thus the number of observed counts is reduced. The 12.96 MeV state was not observed to decay via the ${}^{10}\text{Be} + \alpha$ branch. The peak in Fig. 9(d) corresponds to the 14.87 MeV ¹⁴C state, α -decaying to the ground state of ¹⁰Be. The two peaks in the 18.6 and 21.4 MeV spectra, centered at $E_x({}^{10}\text{Be}) \sim 3$ MeV, correspond to the decay of the ${}^{14}\text{C}$ to the first excited state in ¹⁰Be. The decay of the 21.4 MeV state, to the group of ¹⁰Be states with $E_x(^{10}Be) \sim 6$ MeV, is not strongly observed. However, the population of this group of states is relatively weak and it is highly probable that it is

TABLE IV. The theoretical decay branch ratios for the neutron decay of various ¹⁴C^{*} states to the ¹³C ground state (1/2⁻) as a fraction of the neutron decay to any of the first three excited states (1/2⁺, 3/2⁻, 5/2⁺). The ratios are shown for $J_i = 0$ to 8 for both the even and odd parity states. The numbers in the brackets represent the strength of the 1/2⁺, 3/2⁻ and 5/2⁺ decay widths as a fraction of their total width. Also shown are the associated experimental relative branching ratios. A comparison between the experimental and theoretical ratios provides information on the spin, parity and structure of the decaying ¹⁴C state.

J_i^π		E_x (MeV)									
	11.73	12.96	14.87	16.72	18.6						
0-	5.12 (1, 0, 0)	1.55 (0.75, 0.23, 0.02)	0.78 (0.51, 0.34, 0.15)	0.59 (0.44, 0.34, 0.22)	0.51 (0.40, 0.34, 0.26)						
1-	8.66 (1, 0, 0)	1.23 (0.34, 0.44, 0.23)	0.72 (0.26, 0.44, 0.30)	0.59 (0.24, 0.42, 0.34)	0.54 (0.23, 0.42, 0.36)						
2^{-}	3.51 (1, 0, 0)	0.50 (0.37, 0.42, 0.21)	0.29 (0.33, 0.40, 0.27)	0.23 (0.31, 0.40, 0.29)	0.20 (0.30, 0.40, 0.30)						
3-	404.42 (1, 0, 0)	1.82 (0.14, 0.27, 0.59)	0.79 (0.19, 0.31, 0.50)	0.59 (0.20, 0.33, 0.48)	0.51 (0.19, 0.34, 0.47)						
4-	64.22 (1, 0, 0)	0.99 (0.32, 0.62, 0.06)	0.39 (0.31, 0.49, 0.20)	0.30 (0.31, 0.45, 0.24)	0.25 (0.31, 0.43, 0.27)						
5-		14.25 (0.03, 0.10, 0.87)	1.56 (0.06, 0.21, 0.73)	0.88 (0.11, 0.28, 0.61)	0.66 (0.15, 0.31, 0.55)						
6-		3.79 (0.25, 0.74, 0.01)	0.47 (0.21, 0.72, 0.07)	0.30 (0.24, 0.62, 0.14)	0.26 (0.27, 0.54, 0.19)						
7-		302.46 (0.02, 0.05, 0.93)	5.88 (0.02, 0.09, 0.90)	1.84 (0.03, 0.14, 0.84)	1.07 (0.04, 0.19, 0.76)						
8-		21.92 (0.28, 0.72, 0.00)	0.71 (0.14, 0.83, 0.03)	0.27 (0.15, 0.79, 0.06)	0.19 (0.17, 0.74, 0.09)						
0^+	2.49(1, 0, 0)	0.87 (0.56, 0.33, 0.11)	0.54 (0.42, 0.34, 0.24)	0.46 (0.39, 0.34, 0.27)	0.43 (0.37, 0.34, 0.29)						
1^{+}	25.10(1, 0, 0)	1.21 (0.36, 0.49, 0.15)	0.53 (0.29, 0.46, 0.26)	0.39 (0.26, 0.44, 0.30)	0.33 (0.24, 0.43, 0.33)						
2^{+}	36.10(1, 0, 0)	1.20 (0.23, 0.31, 0.46)	0.65 (0.21, 0.33, 0.46)	0.52 (0.20, 0.34, 0.46)	0.46 (0.19, 0.34, 0.47)						
3+	10.98(1, 0, 0)	0.43 (0.23, 0.31, 0.46)	0.25 (0.24, 0.32, 0.44)	0.20 (0.25, 0.33, 0.42)	0.18 (0.25, 0.33, 0.42)						
4+	7922.09(1, 0, 0)	3.93 (0.06, 0.17, 0.77)	1.03 (0.13, 0.29, 0.59)	0.70 (0.17, 0.31, 0.52)	0.57 (0.18, 0.32, 0.49)						
5+	415.67(1, 0, 0)	0.42 (0.06, 0.17, 0.77)	0.21 (0.13, 0.29, 0.58)	0.19 (0.18, 0.31, 0.52)	0.18 (0.20, 0.32, 0.48)						
6^{+}		66.55 (0.02, 0.07, 0.91)	2.89 (0.03, 0.13, 0.84)	1.22 (0.05, 0.21, 0.74)	0.82 (0.09, 0.26, 0.65)						
7+		0.82 (0.02, 0.07, 0.91)	0.09 (0.03, 0.13, 0.84)	0.08 (0.05, 0.21, 0.74)	0.09 (0.09, 0.26, 0.65)						
8+		1319.19 (0.02, 0.05, 0.93)	11.90 (0.01, 0.07, 0.92)	2.87 (0.01, 0.10, 0.89)	1.44 (0.02, 0.13, 0.84)						
Expt.	$2.57 {\pm} 0.39$	0.57 ± 0.13	0.37 ± 0.09		< 0.37						

not observed due to the low statistics and the small detection efficiency. Thus, the multiplicity 1 and 2 data are found to be consistent.

F. Decay widths

The theoretical decay branches of the various decay channels were calculated using R-matrix penetrabilities [22]. For neutron decay from an initial ¹⁴C state feeding a ¹³C state, the decay width is given by

$$\Gamma_{^{13}\mathrm{C}[J_f]} = \sum_{j_n \ell_n} \Gamma_{J_f j_n \ell_n}^{J_i}.$$
(6)

Here $\Gamma_{J_f j_n \ell_n}^{J_i} = 2\gamma^2 P_\ell$, where P_ℓ is the JWKB penetration factor of Ref. [22] and γ^2 is the reduced width. For the purpose of comparison γ^2 has been assumed to be 1. J_i is the total angular momentum of the parent nucleus and J_f is the angular momentum of the daughter nucleus. The permissible angular momentum combinations $(j_n \ell_n)$ for the outgoing neutron are subject to the condition $\vec{J_i} = \vec{J_f} + \vec{j_n}$ and ℓ_n is either even or odd depending on the transition. The decay branches were calculated for each allowed neutron decay channel of the excited ¹⁴C states of interest. The ratios of the decay branches associated with two different decay channels were then calculated over a range of J_i^{π} values.

The decay branch ratio for the neutron decay of the ¹⁴C* to the ¹³C ground state $(1/2^{-})$ as a fraction of the neutron decay to any of the first three excited states $(1/2^{+}, 3/2^{-}, 5/2^{+})$, is

given by

$$R = \frac{\Gamma_{13}C[\frac{1}{2}^{-}]}{\Gamma_{13}C[\frac{1}{2}^{+}] + \Gamma_{13}C[\frac{3}{2}^{-}] + \Gamma_{13}C[\frac{5}{2}^{+}]}.$$
 (7)

Here the decay branches of the first three excited states are summed together as they were experimentally unresolved. The ratios were calculated for $J_i = 0$ to 8 for both the even and odd parity states and are shown in Table IV. Also shown are the associated experimental relative branching ratios calculated from the absolute branching ratios of Table II.

The theoretical and the experimentally determined ratios were then compared to provide information on the spin, parity and possible single particle structure of the decaying ¹⁴C state. Differences between the ratios also provides information on the relative reduced widths as γ^2 has been assumed to be 1.

For the α -decay from an initial ¹⁴C^{*} state feeding a ¹⁰Be final state, the decay branches were calculated for each allowed α -decay channel and various ratios of the decay branches were calculated. The ratio of the α -decay branch to the ¹⁰Be ground state (0⁺) as a fraction of the α -decay branch to the first excited state (2⁺), is given by

$$R = \frac{\Gamma_{^{10}\text{Be}[0^+]}}{\Gamma_{^{10}\text{Be}[2^+]}}.$$
(8)

Table V shows these ratios for $J^{\pi} = 0$ to 8 for natural parity states. Note that the α -decay of an unnatural parity state to the ¹⁰Be ground state is forbidden.

Table VI shows the ratios of the neutron decay branch to the ¹³C ground state as a fraction of the α -decay branch to the

TABLE V. Theoretical ratios of the α -decay branch to the ¹⁰Be[0⁺] ground state as a fraction of the α -decay branch to the first excited state (2⁺). Also shown are the associated experimental relative branching ratios.

J_i^{π}	E_x (M	leV)
	18.6	21.4
0+	3.56	1.74
1-	1.68	0.88
2+	0.96	0.57
3-	1.07	0.63
4+	1.14	0.68
5-	1.15	0.68
6+	1.21	0.58
7-	1.39	0.47
8+	1.71	0.41
Expt.	< 0.33	< 0.15

¹⁰Be ground state $(\Gamma_{^{13}C[1/2^-]}/\Gamma_{^{10}Be[0^+]})$ and the ratios of the decay branch to the ¹³C ground state compared to the decay branch to the first excited state in ¹⁰Be $(\Gamma_{^{13}C[1/2^-]}/\Gamma_{^{10}Be[2^+]})$. These ratios provide information on the α -cluster content of a state.

IV. DISCUSSION OF THE EXCITED ¹⁴C STATES

The present spectrum of the excited states of ¹⁴C with $E_x > 11.66$ MeV is summarized in Table VII. The fifth panel shows the ¹⁴C states which have been observed to decay via α -emission.

The ¹⁴C states which are strongly populated in the twoneutron stripping reaction depend sensitively on dynamical matching conditions [29] and have been dominantly connected to stretched two-neutron configurations [30]. Such configurations are built by coupling the ¹²C ground state with the two stripped neutrons which can occupy a combination of various orbits. The population strength of these orbits have been examined by Bohlen *et al.* [30]. The population of the $s_{1/2}$ orbital is very weak, the population of states containing $p_{1/2}$ and $d_{3/2}$ components are expected to be medium and the $d_{5/2}$ is expected to be strong. At higher ¹⁴C excitation energies there will also be combinations with the $f_{7/2}$ which is also expected to be strongly populated. As an example, the 6.73 and 10.74 MeV states have (${}^{12}C_{g.s.} \otimes p_{1/2} \otimes d_{5/2}$) and (${}^{12}C_{g.s.} \otimes d_{5/2} \otimes d_{5/2}$) configurations, respectively. Thus, one would expect these two states to be strongly populated in the two-neutron stripping reaction, as confirmed by an examination of Fig. 1.

Some of the ¹⁴C^{*} states at higher excitation energies which are less strongly populated can be related to core excitations $({}^{12}C_{2^+}^* \text{ and } {}^{12}C_{3^-}^*)$. For a 2⁺ core excitation, the states would be populated in a multistep process, the first step being the collective excitation of the system followed by the transfer of the two neutrons into the final orbits [31]. Again the matching conditions favor the population of stretched configurations of the two neutrons in the final state and high-spin states.

Below, is a list of some of the individual ${}^{14}C^*$ states populated in the two-neutron transfer reaction. The population and decay characteristics of the states, along with the penetrability ratio calculations, are used to extract information on their spins, parities and configurations. A summary of the results can be found in Table VIII. The third column shows the predicted excitation energies of the ${}^{12}C$ core plus two-neutron configurations which have been calculated by von Oertzen *et al.* [18] using the simple shell-model approach of Chan [32,33].

A. 11.73 MeV

The 11.73 MeV state is observed to neutron decay to both the ${}^{13}C 1/2^{-}$ ground state and the $1/2^{+}$ first excited state with a ratio of 2.57 \pm 0.39. From Fig. 6 it is evident that these are the only two decay channels available for this state. In Ref. [18]

TABLE VI. Theoretical ratios of the neutron decay branch to the ¹³C ground state as a fraction of the α -decay branch to the ¹⁰Be ground state ($\Gamma_{1^3C[1/2^-]}/\Gamma_{1^0Be[0^+]}$) and the ratio of the decay to the ¹³C ground state compared to the decay to the first excited state in ¹⁰Be ($\Gamma_{1^3C[1/2^-]}/\Gamma_{1^0Be[2^+]}$). Also shown are the associated experimental relative branching ratios.

$\overline{E_x (\text{MeV})}$	12.96	14.87	16.72	18.6	21.4	16.72	18.6	21.4
J_i^{π}		г Г	$\frac{\Gamma_{13}_{C[\frac{1}{2}^{-}]}}{\Gamma_{10}_{Be[2^{+}]}}$					
0^{+}	35.79	2.25	1.54	1.32	1.18	89.57	4.69	2.05
1-	162.35	5.43	3.33	2.76	2.41	43.81	4.64	2.12
2^{+}	716.31	8.10	3.84	2.94	2.48	18.88	2.83	1.42
3-		17.83	5.22	3.37	2.61	32.29	3.62	1.65
4^{+}		61.32	9.47	4.47	2.90	91.93	5.09	1.97
5-		295.36	24.95	7.68	3.59	431.68	8.84	2.42
6^{+}			86.30	18.13	5.50		21.99	3.20
7-			299.12	50.86	10.89		70.57	5.13
8+			863.09	132.42	24.20		225.92	9.81
Expt.	<3.4	1.31 ± 0.35					< 0.64	< 0.08

TABLE VII. Proposed energy levels of ¹⁴C for $E_x > 11.66$ MeV. The second panel shows the indicated levels taken from the ¹³C(*n*, *n*) measurement of Ref. [23] and the latest compilation [24]. The fifth panel shows a compilation of the ¹⁴C states which are observed to decay via α -emission. Evidence for the α -decay of these states is from ⁷Li(⁹Be, ¹⁰Be + α) [25], ¹⁴C(¹³C, ¹⁰Be + α) [26] and ¹⁴C(¹⁴C, ¹⁰Be + α) [27] measurements.

$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	This work			[23,24]		2 <i>n</i> transfer [18]		$^{13}\mathrm{C}(\vec{p},\pi^+)$ [28]		${}^{9}\text{Be}({}^{7}\text{Li},d)$ [18]		States which α- decay [25–27]	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\overline{E_x}$ (MeV)	J^{π}	$\frac{E_x}{(\text{MeV})}$	J^{π}	Ref.	$\frac{E_x}{(\text{MeV})}$	J^{π}	$\frac{E_x}{(\text{MeV})}$	J^{π}	$\frac{E_x}{(\text{MeV})}$	J^{π}	$\frac{E_x}{(\text{MeV})}$	Ref.
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			11.666	4-	[24]	11.66	4-	11.7	4-	11.66	4-		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	11.73	$0^{-}, 1^{-}, 2$	2-11.73	5-	[24]	11.73(3)	4^{+}			11.73	4^{+}		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			11.9(3)	(1^{-})	[23]								
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			12.20	1-	[23]								
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			12.61	2^{-}	[23]					12.58	(3-)		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			12.863		[24]					12.86			
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	12.96	$0^{-}, 2^{-}, 3^{-}$	3-12.963	(3-)	[24]	12.96(4)	3-	12.96		12.96			
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			(13.50)		[24]								
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			13.7	2 -	[23]	13.7(1)		13.56					
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	14.1					14.0(1)				14.03		14.3(1)	[27]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			14.63	(1^{-})	[23]	14.67(5)	6^{+}			14.67	6^{+}		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		_	14.717	4+	[23]		_		_		_		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	14.87	5-	14.91	(1^{+})	[23]	14.87(4)	5-	14.87	5-	14.87	5-	14.8(1)	[25-27]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			15.20	4-	[24]					15.18	(5 ⁻)		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			(15.37)		[24]					15 40			
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			15.44	2-	[24]					15.40	(2^{+})	15 55(10)	[05.07]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			15.56	3-	[23]	15 55(0)						$15.55(10)^{a}$	[25,27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	15.75		15.8	(1^{-})	[23]	15.75(8)						15.0	[0(]
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$			15.91	4 '	[23]							15.9	[26]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			(16.02)		[24]	16 4(1)	(\mathcal{L}^{+})			16.42	C^{\pm}	16 42(10)	[25, 27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			10.45		[24]	10.4(1)	(0')			10.45	(2^+)	10.43(10)	[23-27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	16 70		(10.57)	(1+)	[24]	1(70(5)	(C^{+})			16.53	(2^{+})		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	10.72		10./15	(1 ')	[24]	16.72(5)	(0))	17.2	4-	10.72	(1)	17.2(1)	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	17.5		(17.5)	(1+)	[24]	17.5(1)		17.5	4	17.50	(2^+)	17.5(1)	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	17.3		(17.5) 17.05	(1^{+})	[24]	17.3(1)				17.52	(2^+)		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			17.95		[24]					18.03	(2^{+}) (7^{-})	(18.1)	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			16.10		[24]			18 53	(A^{-})	18.05	(7)	(10.1) 18 5(1)	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	18.6	$2^{-} 4^{-}$	5-			18 6(1)		10.55	(4)	18.59		18.5(1)	[23,20]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	10.0	2, 7, 9	5			10.0(1)				19.00		(19.07(1))	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$										17.14		(19.3(1))	[25-27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$						19.8(1)	(2^{+})			19 73	(2^{+})	(19.3(1)) 19.83(1)	[27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			20.4		[24]	17.0(1)	(2)			20.02	(2)	(20.3(1))	[25 27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			20.1		[2]]					20.75		20.6(1)	[25,27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$										21.00		2010(1)	[=0,=7]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	21.4					21.4(2)				21.41		21.43(1)	[25-27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$			22.1		[24]	22.5(3)						22.45(3)	[25.27]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$					r= .1	23.5		23.2				(23.15(1))	[25.27]
24.5 [24]			24.3		[24]							24.0(3)	[25]
			24.5		[24]								L - J

^aAssigned a spin-parity of 3⁻ [27].

the state is given a possible $({}^{12}C_{g.s.} \otimes p_{1/2} \otimes f_{7/2})$ or $({}^{12}C_{g.s.} \otimes d_{5/2} \otimes d_{3/2})$ configuration. For the $(p_{1/2} \otimes f_{7/2})$ configuration the neutron decay to the $1/2^{+13}C$ state is suppressed and in the $(d_{5/2} \otimes d_{3/2})$ configuration the decay to the $1/2^{-1}$ is similarly less probable. For both decays to occur strongly one of the transferred neutrons must be in an even parity orbit and the

other neutron in an odd parity orbit. This indicates that it is a negative parity state. The experimental width of the state is 30 keV.

An examination of the penetrability calculations of Table IV suggests that the state is associated with a spin 0^- , 1^- or 2^- . From the arguments given above, the original spin-parity

TABLE VIII. A summary of the properties of various excited ¹⁴C states populated in the twoneutron transfer reaction. The configurations are based on a ¹²C core, in either the ground state or first excited state (2^+), coupled to the two stripped valence neutrons which occupy various orbits. The theoretically calculated excitation energies associated with the configurations and the experimental total decay widths are taken from Ref. [18]. The spins and parities show the allowed values determined from this work. The 11.73 MeV state has two possible configuration entries which are consistent with the ¹⁴C excitation energy.

E_x (MeV)	J^{π}	Neutron conf. ${}^{12}C \otimes (nlj) \otimes (nlj)$	E_x (MeV) Ref. [18]	Width (keV) Ref. [18]
11.73	1-, 2-	$(g.s.) \otimes p_{1/2} \otimes d_{3/2}$	11.43	30
11.73	$0^{-}, 1^{-}, 2^{-}$	$(2^+) \otimes p_{1/2} \otimes d_{5/2}$	11.52	30
12.96	$0^{-}, 2^{-}, 3^{-}$	$(2^+) \otimes p_{1/2} \otimes d_{5/2}$	11.52	25
14.87	5-	$(2^+) \otimes p_{1/2} \otimes d_{5/2}$	11.52	35
16.72		$(g.s.)\otimes d_{5/2}\otimes f_{7/2}$	17.83	60
18.6	$2^{-}, 4^{-}, 6^{-}$			100
21.4				550

assignments of 4⁺ [18] and 5⁻ [23] have to be considered to be wrong. The narrow width of the state and the spin and parity assignments coupled with the energy calculations of the ¹²C core plus two-nucleon model of [18] show that the properties of the state are consistent with the (¹²C₂₊ \otimes $p_{1/2} \otimes d_{5/2}$) or (¹²C_{g.s.} $\otimes p_{1/2} \otimes d_{3/2}$) configurations. For the (¹²C_{g.s.} $\otimes p_{1/2} \otimes d_{3/2}$) configuration the allowed spins are 1⁻ or 2⁻ and for the (¹²C₂₊ $\otimes p_{1/2} \otimes d_{5/2}$) configuration all three spin values are allowed.

The weaker population of the state, in regards to its neighbours with $d_{5/2}$ components, suggests it has a $({}^{12}C_{g.s.} \otimes p_{1/2} \otimes d_{3/2})$ configuration, as these two orbitals are only populated with a medium strength in the two-neutron transfer reaction. The narrow width of the state suggests a tentative spin-parity assignment of 2^- .

B. 12.96 MeV

This state is observed to neutron decay to the ¹³C ground state and the first three excited states with a ratio of 0.57 ± 0.13 . The relatively narrow width (25 keV) and strong population of the state suggests that it has a (${}^{12}C_{2^+} \otimes p_{1/2} \otimes d_{5/2}$) configuration and a negative parity. From Table IV the state would be associated with spins of 0^- to 4^- . The cross section and analyzing power angular distributions of Ref. [28] exclude the 1^- and the 4^- . This state has previously been observed in a number of reactions [18,23,28,34–36] and has been given a tentative spin-parity assignment of 3^- from the results of a ${}^{14}C(\alpha, \alpha')$ study [37].

C. 14.87 MeV

This state has been observed in the ${}^{13}C(p, \pi)$ reaction [28,38] where it was assigned a spin-parity of 5⁻. It is not observed in the ${}^{14}C(e, e')$ [39] and ${}^{14}C(\pi, \pi')$ [40,41] measurements; supporting the assignment of a 5⁻ configuration which cannot be reached by 1 *p*1*h* excitations from the ground state of ${}^{14}C$. It can thus be clearly described as a core excitation and it is demonstrated to be the analog of a 5⁻ state in ${}^{14}N$. Thus it is

proposed to have a (${}^{12}C_{2^+} \otimes p_{1/2} \otimes d_{5/2}$) configuration [28,38] and consequently a negative parity. The state has a considerable width for α -decay to the ground state of 10 Be. Such a decay is only allowed for natural parity states. The ratio for the neutron decay to the ground state to the decay to the first three excited states is 0.37 \pm 0.09. A comparison with Table IV suggests that the state can be assigned a spin 1⁻, 3⁻, or 5⁻. The cross section and analyzing power angular distributions of Ref. [28] exclude the possibility of the 1⁻ and 3⁻ spins. Thus, a spin of 5⁻ would be indicated for this state in agreement with the previous measurements [18,28].

Another possible configuration would be $({}^{12}C_{gs} \otimes p_{1/2} \otimes f_{3/2})$. Such a configuration would have positive parity and would only strongly decay to negative parity states $(1/2^{-} \text{ and } 3/2^{-})$ in ${}^{13}C$. However, this configuration would favor decay to the ground state for positive, natural, parity states and can thus be excluded.

From the penetrability calculations of Table VI, it is evident that neutron decay is favored over α -decay. For a spin of 5⁻ the simple barrier penetrability argument indicates that it is 215 times more favorable for the 14.87 MeV state to neutron decay to the ¹³C ground state than α -decay to the ¹⁰Be ground state. Thus, the experimental ratio of 1.31 ± 0.35 demonstrates that this state has a very large α -decay width indicating a cluster structure. This state has previously been linked to an oblate rotational cluster-band [18].

D. 16.72 MeV

This state is not observed to neutron decay to the ground state of ¹³C. This suggests that it does not contain a strong $p_{1/2}$ component. This is consistent with the previously assigned $[{}^{12}C_{g.s.} \otimes d_{5/2} \otimes f_{7/2}]_{6^-}$ configuration of Ref. [18]. The state is not observed to α -decay to the ground state of ¹⁰Be, suggesting that it has unnatural parity; this is also consistent with the previously assigned spin-parity of 6⁻. An examination of Table IV shows that unnatural parity states favor neutron decay to excited states. Again this is consistent with the decay characteristics of the state.

E. 18.6 MeV

The neutron decay of this state proceeds mostly to the first three excited states in ¹³C. The state has a substantial width for α -decay to the first excited state in ¹⁰Be[2⁺]. The decay to the ${}^{10}\text{Be}[0^+]$ ground state is very weak if present at all. This is in contrast with Soić et al. [25] in which a broad state at 18.5 MeV was observed to have a substantial width for α -decay to both the ${}^{10}\text{Be}[2^+]$ and ${}^{10}\text{Be}[0^+]$. This broad structure has previously been associated with both the 18.39 and 18.6 MeV states in two-neutron transfer reactions [18]. It must now be assumed that the state in Ref. [25] is the 18.39 MeV state which has been observed in various other measurements [18,26,28,41] and the present structure is the 18.6 MeV state. This structure may still involve several states, however, if it is a single state its broad width suggests that it has a low spin. The fact that it does not decay to the ${}^{10}\text{Be}[0^+]$ indicates that it has unnatural parity.

An examination of Table IV suggests that the state is associated with spins 2^- , 4^- , or 6^- . It is also evident that an unnatural parity state strongly favors neutron decay to excited states, as was experimentally observed. This state is populated in the ${}^{13}C(p, \pi^+)$ [28,38] and ${}^{14}C(\pi, \pi')$ [40,41] reactions, indicating a core excitation. It has previously been given a tentative spin-parity assignment of 6^- [18].

From Table VI it is evident that neutron decay to the ground state is favored over α -decay to the 2⁺ in terms of the penetrability factors. Thus, the fact that α -decay is favored indicates that this state has a large α -decay width and is a possible cluster-structure candidate.

F. 21.4 MeV

This state has previously been observed as a broad structure in a number of reactions [18,25,26,28,41,42]. The large width (550 keV) suggests that it has a component with low spin. However, it may involve several states. It is seen to α -decay to both the 2⁺ and the group of states at ~6 MeV but the decay to

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the 0⁺ ground state is not observed. This is consistent with a previous decay study using the ⁷Li(⁹Be, ¹⁴C \rightarrow ¹⁰Be+ α) reaction [25]. The state is not observed to neutron decay. The large α -decay width suggests that it is a possible cluster state.

V. CONCLUSIONS

The decay modes and associated branching ratios of various excited ¹⁴C states populated in the ¹²C(¹⁶O,¹⁴O)¹⁴C reaction have been studied. The strong dependence of the transfer cross section on dynamical matching conditions for different final configurations has been used to make tentative configuration assignments for many of the observed states. Theoretical decay branch ratios have been calculated from barrier penetration factors and have been used to provide information on the spins, parities, and single-particle configurations of the states.

The 14.87, 18.6, and 21.4 MeV states have been shown to possess large α -decay widths and are possible cluster structure candidates. The 16.72 MeV state has no α -decay width and appears to have a single-particle structure. The 11.73 and 12.96 MeV states lie close to the ¹⁰Be+ α decay threshold and are thus not seen to α -decay. Thus, it is hard to determine the nature of their structure.

The present measurements of the partial widths may be combined with subsequent measurements of spins to provide definitive evidence for the cluster nature of the states. Such measurements are planned for the near future.

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