\(\alpha\)-decay of excited states in \(^{11}\text{C}\) and \(^{11}\text{B}\)

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Abstract

Studies of the \(^{16}\text{O}(^{9}\text{Be},\alpha^{7}\text{Be})^{14}\text{C}\) and \(^{7}\text{Li}(^{9}\text{Be},\alpha^{7}\text{Li})^{5}\text{He}\) reactions at \(E_{\text{beam}}=70\) MeV have been performed using resonant particle spectroscopy techniques. The \(^{11}\text{C}\) excited states decaying into \(\alpha+^{7}\text{Be}(\text{gs})\) are observed at \(8.65, 9.85, 10.7\) and \(12.1\) MeV as well as possible states at \(12.6\) and \(13.4\) MeV. This result is the first observation of \(\alpha\)-decay for excited states above \(9\) MeV. The \(\alpha+^{7}\text{Li}(\text{gs})\) decay of \(^{11}\text{B}\) excited states at \(9.2, 10.3, 10.55, 11.2, (11.4), 11.8, 12.5, (13.0), 13.1, (14.0), 14.35, (17.4)\) and \(18.6\) MeV is observed. The decay processes are used to indicate the possible three-centre \(2\alpha+^{3}\text{He}(^{3}\text{H})\) cluster structure of observed states. Two rotational bands corresponding to very deformed structures are suggested for the positive-parity states. Excitations of some observed \(T=1/2\) resonances coincide with the energies of \(T=3/2\) states which are the isobaric analogs of the lowest \(^{11}\text{Be}\) states. Some of these states may have mixed isospin.

Key words: Nuclear reactions \(^{16}\text{O}+^{9}\text{Be}\) and \(^{7}\text{Li}+^{9}\text{Be}\); \(^{11}\text{C}\) and \(^{11}\text{B}\) levels deduced; \(^{4}\text{He}+^{7}\text{Be}\) and \(^{4}\text{He}+^{7}\text{Li}\) decays; cluster structure

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1 Introduction

It is well known that many light nuclei possess a prominent cluster structure and that the $\alpha$-particle has an important impact on their structure. In recent years, special attention has focused on beryllium isotopes where well developed cluster structure was found in $^{8,9,10}$Be and tentative evidence for such behaviour was found in $^{11,12,14}$Be [1,2, and references therein]. For example, recent measurements have provided evidence for an $\alpha^+6$He cluster structure in $^{10}$Be [3,4,5,6,7] and for a $^6$He$^+6$He structure in $^{12}$Be [4], and the unusual structural properties of $^{11}$Be have also attracted significant interest [8,9,10,11]. Measurements of the helium-cluster breakup and neutron removal cross-sections suggest that neutron-rich Be isotopes possess a strong structural overlap with an $\alpha+Xn+\alpha$ configuration [12]. It appears that properties of beryllium nuclei may be well described in terms of the sharing of the valence neutrons between the two $\alpha$-cores in a manner which is reminiscent of the covalent binding of atomic molecules. The presence of a $3\alpha$ cluster structure in $^{12}$C provides an extension to this idea. The recent studies of the $\alpha$-decaying states in $^{13}$C [13] and $^{14}$C [14] have found indications of molecular structures in these nuclei and tentative evidence for the chain structure has been found in $^{13}$C [15].

It is interesting to investigate influence of $\alpha$-clustering on the structural properties of the neutron deficient nucleus $^{11}$C and also on boron isotopes which are situated between the beryllium and carbon nuclei. One particularly interesting issue is the existence of multi-centre structures in $^{11}$B, are they two-centre, as in Be isotopes, or three-centre as in C isotopes? Detailed knowledge of the structure of boron isotopes may help in understanding of the molecular nature of light nuclei and its evolution from two- to three-centre structures. Although $^{11}$C and particularly $^{11}$B nuclei have been studied extensively, the experimental evidence for cluster structures is rather scarce. It is worth mentioning that $\alpha^+7$Be and $\alpha^+7$Li reactions and structure of $^{11}$C and $^{11}$B are also of considerable astrophysical interest: the $^7$Be($\alpha,\gamma$)$^{11}$C reaction is starting point of the hot pp chain and $^7$Li($\alpha,\gamma$)$^{11}$B is the main production process of $^{11}$B in the big-bang nucleosynthesis. We present here results of the experimental studies which probe cluster structure of $^{11}$C and $^{11}$B via the $\alpha$-decay of their excited states. The $^{11}$C excited states have been studied using the $^{16}$O($^9$Be,$\alpha^7$Be)$^{14}$C reaction and study of the $^{11}$B excited states has been performed using the $^7$Li($^9$Be,$\alpha^7$Li)$^5$He reaction. It is the two-nucleon transfer processes onto the cluster nucleus $^9$Be which provides a possible mechanism by which the multi-

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centre cluster structures may be populated.

2 Experimental Details

The measurements were performed at the Australian National University’s 14UD tandem accelerator facility. A 70 MeV $^9$Be beam, of intensity 3 enA, was incident on a 100 $\mu$gcm$^{-2}$ Li$_2$O$_3$ foil.

Reaction products formed by interaction of $^9$Be with the target were detected in an array of four charged particle telescopes. These telescopes contained three elements which allowed the detection of a wide range of particle types, from protons to $Z=4$ to 5 nuclei. The first elements were thin, 70$\mu$m, $5\times5$ cm$^2$ silicon detectors segmented into four smaller squares (quadrants). The second elements were position-sensitive strip detectors with the same active area as the quadrant detectors, but divided into 16 position-sensitive strips. These strips were arranged so that the position axis gave maximum resolution in the measurement of scattering angles. Finally, 2.5 cm thick CsI detectors were used to stop highly penetrating light particles. These detector telescopes provided charge and mass resolution up to Be, allowing the final states of interest to be unambiguously identified. The position and energy resolution of the telescopes was $\sim$1 mm and 300 keV, respectively. Calibration of the detectors was performed using elastic scattering measurements of $^9$Be from $^{197}$Au and $^{12}$C targets. The four telescopes were arranged in a cross-like arrangement, separated by azimuthal angles of 90°. Two opposing detectors were located with their centres at 17.3° and 17.8° (telescopes 1 and 2) from the beam axis and with the strip detector 130 mm from the target, covering angular range from $\sim$7° to $\sim$28°. The remaining pair were at the slightly larger angles of 28.6° and 29.7° (telescopes 3 and 4), 136 mm from the target and these telescopes covered angles from $\sim$20° to $\sim$38°. In the data acquisition system singles events were suppressed by factor 1000 and coincident events between any pair of telescopes were recorded.

3 Results

3.1 $^{11}$C

The $\alpha$-decay of excited states in $^{11}$C has been studied using the $^{16}$O($^9$Be, $^{11}$C$^* \rightarrow \alpha^+$Be)$^{14}$C reaction ($Q = -14.602$ MeV). The $^4$He and $^7$Be loci are well resolved in the particle identification spectra and the measurement of the energies and angles of these detected particles permitted the kinematics of the
reaction to be fully reconstructed. Figure 1 shows the spectra for the total energy in the reaction (a) for events when decay products were coincidently detected in telescopes T1 and T2 and (b) in the case when both $\alpha$ and $^7$Be were detected in the same telescope T1 or T2, assuming a $^{14}$C recoil. The strongest peak in the spectrum shown in Fig. 1(a) at $E_{\text{tot}}=55.4$ MeV corresponds to the $^{16}$O($^9$Be,$\alpha^7$Be)$^{14}$C reaction. The energy resolution in this spectrum is 1.3 MeV, hence the contributions from the $^7$Be ground state and the first excited state, separated 429 keV, are unresolved. The three less intense peaks at lower total energy correspond to the $^{12}$C($^9$Be,$\alpha^7$Be)$^{10}$Be reaction ($E_{\text{tot}}=50.5$ MeV), the reaction on $^{16}$O when the recoiled $^{14}$C nucleus is excited to the second excited $J^\pi=0^+$ state at 6.5894 MeV ($E_{\text{tot}}=48.8$ MeV) and the reaction on $^{12}$C target when the undetected $^{10}$Be is excited to the first excited state ($E_{\text{tot}}=47.1$ MeV). There is small peak at the proper total energy ($E_{\text{tot}}=55.4$ MeV) also in the spectrum shown in Fig. 1(b), but the background contribution in this case is comparable to the reaction contribution. These events, double hits in T1 or T2, predominantly correspond to the small relative energy between the fragments and therefore to the excitations in $^{11}$C* close to the decay threshold.

By selecting only the events associated with the peaks in the total energy spectra corresponding to the $^{16}$O($^9$Be,$\alpha^7$Be)$^{14}$C reaction it is possible to reconstruct the $^{11}$C excitation energy from the relative velocity of the two decay fragments. Figure 2 shows the $^{11}$C excitation energy spectra for (a) the events
detected in the two opposing telescopes (T1+T2) and for (b) double hits in the same telescope (T1 or T2). However, given that there are three particles in the final state, it is possible that they arise from decays of either \(^{18}\)O into \(\alpha+^{14}\)C or \(^{21}\)Ne into \(^7\)Be+\(^{14}\)C. Both of these possibilities were reconstructed and it is clear that there are no contributions from either of these decay processes. Figure 2 also shows results of the detection efficiency calculations for the specific detection geometry performed using Monte Carlo simulations in which isotropic \(^{11}\)C production and decay was assumed. The spectrum in Fig.2(a) is shown normalised for the detection efficiency in Fig. 6(b). The excitation energy range covered for the coincidence events in T1+T2 is from 8.4 to 17.5 MeV and for the double hit events is from the threshold energy for the \(\alpha+^{7}\)Be decay \((E_{thr}=7.543 \text{ MeV})\) up to 10.5 MeV. The experimental excitation energy resolution is calculated to be 200-300 keV, close to the values found for the \(\alpha+^{9}\)Be [13] and \(\alpha+^{10}\)Be [14] events in the same data. The uncertainty in the excitation energy is 100 keV. The excitation energy spectrum in Fig. 2(a) shows strong peaks at 8.65, 9.85, 10.7 and 12.1 MeV and there is some evidence for additional peaks at 12.6 and 13.4 MeV. We note that no further peaks could be found in other telescope combinations. The spectrum in Fig. 2(b) provides evidence for a peak at 8.65 MeV. The observed states are presented in Table 1. Given that the decays to the \(^7\)Be ground and the first excited state are unresolved in the total energy spectra, both processes may contribute to the \(^{11}\)C excitation energy spectra. These may be resolved in a two dimensional total energy versus \(^{11}\)C excitation energy spectrum. The peaks in the excitation spectrum corresponding to decays to the first excited state in \(^7\)Be should appear at the lower energy side of the peak in total energy spectrum and would lie 429 keV below the peaks from the decays to the ground state. Such satellite peaks are not observed and main peaks observed in the \(^{11}\)C excitation energy spectra spread over the entire range of the reaction peak in the total energy spectrum. In other words, identical excitation energy spectra were obtained gating on the lower and higher energy side of the reaction peak in the total energy spectrum. Consequently, this analysis provides evidence for only \(\alpha+^{7}\)Be(gs) decay of \(^{11}\)C states. However, a weak contribution of the \(\alpha+^{7}\)Be\(^{+}(1/2^-)\) decay cannot be excluded and is probably obscured in our data by the more intense decay to the \(^7\)Be ground state. Because of the considerable background for events of double hits in the same telescope, the excitation energy spectra were reconstructed for events below and above the reaction peak in the total energy spectrum. These spectra corresponding to the background events showed no evidence for the 8.65 MeV peak.

The coincident detection of decay fragments in T1+T2 corresponds mainly to \(^{11}\)C\(^*\) emission at forward angles up to 20\(^\circ\) in the centre-of-mass system, there are almost no events for centre-of-mass emission angles greater than 30\(^\circ\). In the case of double hits in the same telescope (T1 or T2) the \(^{11}\)C\(^*\) emission angle is larger than in the former case, the largest part of the events corresponds to the centre-of-mass angles between 20\(^\circ\) and 35\(^\circ\). The number of
Fig. 2. $^{11}$C excitation energy spectra (a) for decays detected in telescopes T1 and T2 in coincidence and (b) for the events when both particles were detected in the same telescope T1 or T2. Error bars represent statistical errors. The curves represent $\alpha+^{7}$Be detection efficiency calculated for the particular setup of detectors (right scale).

An analysis of the angular distributions and angular correlations for the states observed in Fig. 2 using the techniques given in Ref. [16] was performed, but these were found to be featureless. This is a consequence of the number of reaction amplitudes contributing to the reaction process due to the presence of nonzero spin nuclei in both the entrance and exit channels.
Fig. 3. Total energy spectra for the $^4\text{He}^+^7\text{Li}$ (a) events coincidently detected in telescopes T1 and T2, (b) events when both particles are detected in the same telescope T1 or T2 and (c) coincident events in telescopes T3 and T4.

A study of the $\alpha$-decay of $^{11}\text{B}$ excited states has been performed using the $^7\text{Li}(^9\text{Be},^\alpha^7\text{Li})^5\text{He}$ reaction ($Q = -2.4$ MeV). The $^7\text{Li}$ locus is resolved in the particle identification spectra and only partially overlaps with the intense $^6\text{Li}$ locus. The total energy spectra for this reaction are shown in Fig. 3(a) for coincident events where decay products were detected in telescopes T1 and T2, (b) in the case when both $\alpha$ and $^7\text{Li}$ were detected in the same telescope T1 or T2 and (c) for coincident detection in telescopes T3 and T4. The most intense peak in these spectra, at $E_{\text{tot}} = 67.5$ MeV, corresponds to the above reaction. Due to the experimental resolution and width of the $^5\text{He}$ ground state (600 keV), the contributions from the $^7\text{Li}$ ground and
Fig. 4. $^{11}$B excitation energy spectra (a) for events detected in telescopes T1 and T2 in coincidence, (b) for the events when both particles were detected in the same telescope T1 or T2 and (c) for the decays detected in T3 and T4. Error bars represent statistical errors. The curves represent $\alpha+^{7}$Li detection efficiency calculated for the particular setup of detectors (right scale).

the first excited state (separated 478 keV) are unresolved and the widths of the peaks in the total energy spectra are $\sim$2 MeV. The highest energy peak at 72.6 MeV seen in Fig. 3(a) arises from $\alpha+^{6}$Li coincidences from the very strong $^1$H+${^9}$Be $\rightarrow$ $\alpha+^{6}$Li reaction leaking through the $^7$Li selection windows. The $\alpha+^{6}$Li*(3.56 MeV, T=1) events from the same reaction produce a shoulder on the reaction peak around $E_{tot}$=69 MeV. The threshold for the $^7$Li+${^9}$Be $\rightarrow$ $2\alpha+^{7}$Li+n channel is at 68.4 MeV and both the $^5$He* $\rightarrow$ $\alpha+n$ and $^8$Li* $\rightarrow$ $^7$Li+n processes may contribute at lower total energy. A broad bump with a maximum around 63 MeV results from the contributions of very broad $^5$He*(1/2−) state and broad $^8$Li states between 5 and 10 MeV and also from the $^7$Li($^9$Be,$\alpha^{6}$Li) events. This is also seen in Fig. 3(c). There is also
another bump in spectrum (a) around 57.5 MeV arising from the $(^9\text{Be},\alpha^7\text{Li})$ reaction on the oxygen component in the target.

By gating on the reaction peak in the total energy spectra, and selecting only the events associated with the $\alpha+^7\text{Li}+^5\text{He}$ exit channel, $^{11}\text{B}$ excitation energy spectra can be reconstructed. Figure 4 shows such spectra for (a) the small angle detector pair events (T1+T2), (b) double hit events in T1 or T2, and (c) for the larger angle pair events (T3+T4). Again, no additional information on the $^{11}\text{B}$ excitation energy spectrum was obtained from other telescope combinations. The three-body final state can be also produced via the decay of either $^9\text{Be}$ into $\alpha+^5\text{He}$ or $^{12}\text{B}$ into $^7\text{Li}+^5\text{He}$. The reconstructed $^{12}\text{B}$ excitation energy spectra show no evidence for the $^7\text{Li}+^5\text{He}$ decay. In addition, the $^9\text{Be}$ excitation spectra for T1+T2 events and double hit events in T1 or T2 show that there is no contribution from the $\alpha+^5\text{He}$ decay for these detection geometries. The $^9\text{Be}$ excitation spectra for T3+T4 events show evidence for the known $\alpha+^5\text{He}$ decay of the excited states at 2.4, $\sim$6.5 and $\sim$11.5 MeV which was also observed in [17]. The contributions from the $^9\text{Be}$ states below 8.6 MeV in excitation were removed from the spectrum in Fig. 4(c) but a weak contribution from the 11.5 MeV state, and possible higher states, remains. The results of the detection efficiency calculations for the $\alpha+^7\text{Li}$ decay of $^{11}\text{B}$ are also presented in Fig. 4. Again, the spectrum in Fig. 4(a) is shown in Fig. 6(a) normalised for the variation in detection efficiency. The $^{11}\text{B}$ excitation energy spectra extend from the threshold at 8.664 MeV (Fig. 4(b)) to $\sim$30 MeV (Fig. 4(c)). The uncertainty in the excitation energy is 100 keV, and the experimental excitation energy resolution for the low excitations is again calculated to be 200-300 keV. The spectrum in Fig. 4(a) shows clear resonances at 10.3, 10.55, 11.2, 11.8, 12.5, 13.1 and 14.35 MeV and there are indications for additional peaks at 11.4, 13.0, 14.0 and $\sim$17.4 MeV. In the spectrum for the events in the same telescope, Fig. 4(b), peaks are observed at 9.2, 10.25 and 11.15 MeV. The 9.2 MeV state is also observed in the T3+T3 and T4+T4 data. The spectrum for the T3+T4 events, Fig. 4(c), indicates a state at 17.4 MeV and a weak state at 18.6 MeV. The observed states are presented in Table 2. These spectra contain possible contributions from both the decays to the ground and the first excited state of $^7\text{Li}$. An analysis identical to the one performed for the $^{11}\text{C}$ data, gives evidence for only $\alpha+^7\text{Li}(\text{gs})$ decay of the $^{11}\text{B}$ excited states. Thus, the much weaker $\alpha+^7\text{Li}^*(1/2^−)$ decay is again hidden in our data by the dominant decay into $^7\text{Li}(\text{gs})$.

The main reaction mechanism for the population of $^{11}\text{B}$ excited states when decay fragments were detected at forward angles (T1+T2 coincidences for which the $^{11}\text{B}^*$ centre-of-mass emission angle was mainly less than 20°) is expected to be neutron (or n+p) pickup from $^7\text{Li}$ to $^9\text{Be}$. At larger $^{11}\text{B}^*$ emission angles (for the largest part of T3+T4 coincidences centre-of-mass emission angle was between 10° and 30° and for double hits in T1 or T2 it is mainly between 30° and 60°) contributions from $\alpha$-transfer from $^9\text{Be}$ to $^7\text{Li}$
are also possible.

The analysis of the angular distributions and angular correlations were performed for the main states observed in Fig. 4 but these were found to be featureless and did not give any information about the spin of the states. The angular distributions for the detection of $^{11}$B* in T1+T2 showed a strong peak at very forward angles and then a decrease in yield with increasing $^{11}$B* angle. These characteristics are consistent with the direct reaction mechanism.

4 Discussion

4.1 $^{11}$C

The $^{11}$C excited states observed in the present measurement as well as the information about $\alpha$-decaying states from previous measurements [18,19] and known levels from the tabulation of the $^{11}$C states [20] are presented in Table 1. The threshold energy for the $\alpha+^{7}$Be, $p+^{10}$B, $2\alpha+^{3}$He, $^{8}$Be+$^{3}$He and $n+^{10}$C decays are at 7.543, 8.6896, 9.131, 9.223 and 13.120 MeV respectively. Our results show a number of $\alpha$-decaying states above the proton threshold energy, which may be an indication of their $\alpha$-cluster structure.

The only published coincidence measurement of the $^{11}$C* $\rightarrow \alpha+^{7}$Be decay performed using the $^{6}$Li$(^{10}$B, $\alpha^{7}$Be)$^{5}$He reaction at $E_{\text{beam}}$=65 MeV [18] reports states at 8.10, 8.42 and 8.655 MeV also decaying only to the $^{7}$Be ground state. In both this and the present measurement, the contributions to the peak at 8.65 MeV may come from the very narrow states at 8.655 (7/2+) and 8.699 MeV (5/2+) [21]. It is worth mentioning that the 5/2+ state, which is only 10 keV above the threshold for proton decay, strongly enhances the cross section of the astrophysically important $^{10}$B(p,$\alpha$) reaction [22]. We do not observe the 8.10 (3/2-) and 8.42 MeV (5/2-) states in our spectra. These two negative-parity states were observed in the only published study of the $^{7}$Be($\alpha,\gamma$) reaction [19] which provided following results: $\Gamma_{\gamma}$=0.35 eV, $\Gamma_{\alpha}$=4-18 eV (most probable value is 6 eV) for the 8.1045 MeV state and $\Gamma_{\gamma}$=3 eV, $\Gamma_{\alpha}$=13 eV for the 8.42 MeV state. Their very small widths for the $\alpha$-decay may be understood to be a consequence of the Coulomb barrier and also the centrifugal barrier in the case of the 5/2− state for which decay proceeds with L=2.

From Fig. 2(b) it is evident that the detection efficiency for these lower excitations is higher than for the 8.65 MeV state and absence of these two states in the present spectrum cannot be a consequence of the detection geometry. One possible explanation is that the different $^{11}$C* population mechanisms
Table 1

$^{11}$C excited states decaying into $\alpha+^{7}\text{Be(gs)}$ from the present measurement, the previous measurements of the $^{6}\text{Li}(^{10}\text{B},\alpha^{7}\text{Be})$ [18] and $^{7}\text{Be(\alpha,\gamma)}$ [19] reactions and known levels at these excitations from the tabulations of Ref. [20]. The uncertainty in the excitation energy of the present measurement is 100 keV.

| Present | Ref. [18] | Ref. [19] | Tabulations [20] |
|---------|-----------|-----------|------------------|
| $E_x$ (MeV) | $E_x$ (MeV) | $E_x$ (MeV) | $E_x$ (MeV) | Width (keV) | $J ; T$ | Reference |
| 8.10 | 8.105 | 8.1045 | 11 eV | 3/2− | [23,57] |
| 8.42 | 8.421 | 8.420 | 15 eV | 5/2− | [21,23,24,25,32,35,57] |
| 8.65 | 8.655 | 8.655 | ≤ 5 | 7/2+ | [21,23,24,35,57] |
| 9.20 | 500 | 210 | (3/2−) | [24,25] |
| 9.699 | 15 | 5/2+ | [21,22,23,24,25,25,57] |
| 9.78 | 240 | (5/2−) | [23,24,25,27,28] |
| 9.97 | 120 | (7/2−) | [24,57] |
| 10.083 | 230 | 7/2+ | [23,24,27,28] |
| 10.679 | 200 | 9/2+ | [23,24,26,27,57] |
| 11.03 | 300 | [23,33] |
| 11.44 | 360 | [26,29] |
| 12.1 | 12.16 | 270 | T=3/2 | [30] |
| 12.4 | 1-2 MeV | $\pi=-$ |
| 12.51 | 490 | 1/2−; 3/2 | [30,31,32,33,34,35] |
| (12.6) | 12.65 | 360 | (7/2+) | [26,33] |
| (13.01) | | |
| 13.33 | 270 | [26,33] |
| (13.4) | 13.4 | 1100 | [57] |

play a role, i.e. single proton transfer to $^{10}\text{B}(3^+)$ in Ref. [18] and two proton transfer to $^{9}\text{Be}(3/2^-)$ in the present case. But, given that $^{10}\text{B}$ ground state corresponds to p$_{3/2}$ proton coupled to the $^{9}\text{Be(gs)}$ core, these two reactions are expected to be quite similar.

Simple semiclassical considerations, which assume that the transfer cross-section would be large when the velocities of the incident and final nuclei are the same, shows that the kinematics of the present measurement prefers population of $^{11}\text{C}$ states with transferred value L=3-4, while the measurements in Ref. [18] prefer L=1-2 transfers. It should be mentioned that the results from
the measurements of the \(^9\)Be\((^3\)He,n\)\(^{11}\)C reaction [23] at \(E_{beam}=10.5\) and \(13\) MeV (this kinematics prefers \(L=2\) transfer of two protons) provided also clear evidence for the \(3/2^-, 5/2^-\) states. From the angular distributions obtained in these measurements, it was concluded that the \(8.105\) MeV state structure should be \((p_{3/2}^6 s_{1/2})_3 s_{1/2}\), the \(8.42\) MeV state has structure \((p_{3/2}^6 s_{1/2})_3 p_{1/2}\), the \(5/2^+, 7/2^+\) states at \(8.7\) MeV show large components of \(s_{1/2}\) and also \(d_{5/2}\) particles added to \((p_{3/2}^6 s_{1/2})_3\) and the most probable configuration of the \(10.679\) MeV state is \((p_{3/2}^6 s_{1/2})_3 d_{5/2}\).

The next peak in the present spectra at \(9.85\) MeV corresponds to at least two known \(\alpha\)-decaying states at \(9.65\) and \(10.083\) MeV, but contributions of the all four known states between \(9.6\) and \(10.1\) MeV are possible. The list of levels between \(8\) and \(11\) MeV accepted in the tabulations of Ref. [20] was established in a detailed study of the \(^{10}\)B\((p,\gamma)^{11}\)C reaction [24] which found three negative-parity states for excitations between \(9.6\) and \(10.0\) MeV. A recent measurement of the astrophysically important \(^{10}\)B\((\vec{p},\gamma)^{11}\)C reaction at low energy [25] has shown that the two \(p\)-wave resonances at \(9.65\) and \(9.78\) MeV, as well as the \(8.420\) MeV \(J^\pi=5/2^-\) subthreshold state, also contribute to the capture process.

The \(10.7\) MeV peak in the present spectrum corresponds to the known \(9/2^+\) \(\alpha\)-decaying state at \(10.679\) MeV. The \(10.67, 12.65\) and \(13.33\) MeV states were observed in the measurement of the \(^{10}\)B\((p,\alpha)^7\)Be(gs) reaction [26] which also provided evidence for the \(11.44\) MeV state in \(^7\)Be\(*(1/2^-)\) channel and for some states at higher excitations. The other measurements of the same reaction report states at \(10.09, 10.68\) MeV [27] and \(9.76, 10.06\) MeV [28]. Absence of the \(11.03\) MeV state, which is populated in two proton transfer reaction [23], in our spectra provides evidence for its very small \(\alpha\) width and preferential decay by proton emission. The \(\alpha+^7\)Be\(*(1/2^-)\) decay of the \(11.44\) MeV state was also observed in the measurements of the \(^{10}\)B\((p,\alpha\gamma)\) reaction [29]. Evidently, it does not decay, or decays weakly, into \(^7\)Be(gs) channel which may imply that its spin is \(1/2^-\).

The unexpected result observed in the present data is the strong \(\alpha+^7\)Be(gs) decay of the \(12.1\) MeV state (which means \(T=1/2\)), which is believed to be the isobaric analogue state of the \(T=3/2\) \(^{11}\)Be ground state. This value of isospin has been accepted in the tabulations of the \(^{11}\)C properties [20], but comes from only one published experimental work [30]. These measurements of the \(^{11}\)B\((^3\)He,t\), \(^9\)Be\((^3\)He,n\) and \(^{10}\)B\((p,p')^{10}\)Be\(*(1.74\) MeV, \(T=1)\) reactions gave very tentative evidence for isobaric analogue states of the three lowest \(^{11}\)Be states at \(12.17, 12.57\) and \(13.92\) MeV. The observed weak peaks attributed to the \(12.17\) MeV state are questionable in the spectra of all these reactions, which populate states of both isospin values \(1/2\) and \(3/2\). In the other measurement of the \(^9\)Be\((^3\)He,n\) reaction [31] levels observed at \(12.5, 13.7\) and \(14.7\) MeV were tentatively identified as the analogs of the three lowest excited states in \(^{11}\)Be. Measurements of the \(^{13}\)C\((p,t)\) reaction [32,33,34] provided evidence for
the T=3/2, J^\pi=1/2^- state at 12.47 MeV with total width of 500 keV which is the analog of the first excited state in ^{11}\text{Be}. This state was also observed in the ^{12}\text{C}(\pi^+,p) but not in the ^{12}\text{C}(p,d) reaction which confirms its T=3/2 character [35].

It seems from these results that the 1/2^- and even 5/2^+ state have been identified experimentally, but the status of the 1/2^+ state is unclear. Our result provides evidence for a previously unobserved T=1/2 state at 12.1 MeV whose width is comparable to the width of the 10.679 MeV state, which is 200 keV (the peaks at 10.7 and 12.1 MeV in Fig. 2(a) have the same experimental width of 400 keV). This state may be the same state observed in Ref. [30]. We should emphasize that, except in Ref. [30], the present result is the only observation of the state in this excitation region (11.4-12.4 MeV). If this state is really the isobaric analogue state of the ^{11}\text{Be} ground state, as was claimed in [30,20], it has a very strong and unexpected isospin mixing. A simpler explanation may be that the 12.1 MeV level is indeed T=1/2 and possesses an alternative (rotational) structure, and the true (1/2^+,3/2) state in ^{11}\text{C} has not yet been identified experimentally. We return to this point later (section 4.3).

4.2 ^{11}\text{B}

Table 2 presents the observed \alpha-decaying ^{11}\text{B} excited states in the present measurement and known states from the tabulations of Ref. [20]. The threshold energies for the \alpha+^7\text{Li}, 2\alpha+t, ^8\text{Be}+t, p+^{10}\text{Be}, n+^{10}\text{B} and d+^{9}\text{Be} decays are at 8.664, 11.131, 11.223, 11.228, 11.454 and 15.815 MeV, respectively. Once again, the observed \alpha-decay of states above the thresholds for other decay channels may indicate the \alpha-cluster structure of these states.

The lowest energy peak in our ^{11}\text{B} excitation spectra (Fig. 4) appears at 9.2 MeV and corresponds to the 7/2^+, 5/2^+ doublet of very narrow states at this excitation. Absence of the 8.9202 MeV 5/2^- state, which is only 256 keV above the threshold, can be explained in terms of the Coulomb and centrifugal barrier (it decays with L=2). These three states have been observed in the measurement of the ^7\text{Li}(\alpha,\gamma) reaction [19] in which radiative and \alpha-partial widths for these states were extracted. A very small \alpha width for the 8.9202 MeV state was found (\Gamma_\gamma/\Gamma \approx 1) and for the 9.185 MeV state it was found that \gamma width is about 10% of the total width.

The next peaks in the present spectra are at 10.3 and 10.55 MeV which correspond to the 3/2^- state at 10.26 MeV and 5/2^- at 10.33 MeV, and the 10.597 MeV 7/2^+ state. The strongest observed peak corresponds to the 11.265 MeV 9/2^+ state. Slight asymmetry in its shape at higher energy may be due to the
Table 2
$^{11}$B excited states decaying into $\alpha + ^7$Li(gs) from the present measurement and known unbound states below 19 MeV from the tabulations of Ref. [20]. The uncertainty in the excitation energy of the present measurement is 100 keV.

| Present | Tabulations [20] |
|---------|-----------------|
| $E_x$ (MeV) | $E_x$ (MeV) | Width (keV) | $J; T$ | Reference |
| 8.9202 | 4.37 eV | 5/2$^-$ | [19,32,34,43,45] |
| 9.2 | 9.1850 | 2 eV | 7/2$^+$ | [19,38,43] |
| 9.2744 | 4 | 5/2$^+$ | [19,37,38,43] |
| 9.82 | | (1/2$^+$) | |
| 9.876 | 110 | 3/2$^+$ | [36,37,38,43] |
| 10.26 | 150 | 3/2$^-$ | [36,37,38,39,43,45] |
| 10.33 | 110 | 5/2$^-$ | [36,37,38,39,43,45] |
| 10.597 | 100 | 7/2$^+$ | [36,37,38,40,43,45] |
| 10.96 | 4500 | 5/2$^-$ | [36,38] |
| 11.2 | 11.265 | 110 | 9/2$^+$ | [36,38,41,43] |
| (11.4) | | 103 | |
| 11.600 | 170 | 5/2$^+$ | [34,36,38,40,43] |
| 11.8 | 11.886 | 200 | 5/2$^-$ | [36,40,43] |
| 12.0 | $\sim$1000 | 7/2$^+$ | [36] |
| 12.5 | 12.557 | 210 | 1/2$^+$(3/2$^+$); 3/2 | [30,36,39,41,42,43] |
| (13.0) | 12.916 | 200 | 1/2$^-$; 3/2 | [30,32,33,34,42,43,45] |
| 13.1 | 13.137 | 426 | 9/2$^-$ | [36,40,43] |
| 13.16 | 430 | 5/2$^+$, 7/2$^+$ | [39,40] |
| (14.0) | 14.04 | 500 | 11/2$^+$ | [36,39,40,42] |
| 14.35 | 14.34 | 254 | 5/2$^+$; 3/2 | [30,39,41,42,43] |
| 14.565 | $\leq$30 | | |
| 15.29 | 250 | (3/2, 5/2, 7/2)$^+$; (3/2) | [40,42,45] |
| 16.437 | $\leq$30 | T=3/2 | [43,44,45] |
| 17.33 | $\sim$1000 | | |
| (17.4) | 17.43 | 100 | T=3/2 | [43,44] |
| 18.0 | 870 | T=3/2 | [43] |
| (18.6) | 18.37 | 260 | (1/2,3/2,5/2)$^+$ | [44] |
11.444 MeV state. The next weak peak is the 11.886 MeV 5/2⁻ state. These states are all known as α-decaying states from many studies.

The measurements of the ⁷Li+α elastic and inelastic scattering to the first excited state of ⁷Li [36] found evidence for the states at 10.34, 10.60, 11.29, 11.49 and 12.55 MeV in the elastic channel and 9.88, 10.25, 10.60, 10.96, 11.29, 11.49, 11.60, 11.88 and 12.55 MeV in the inelastic channel, and also indications of levels at 12.04, 13.03, 14.05, 14.69 and 15.79 MeV. A study of the ⁷Li(α,γ)¹¹B and ⁷Li(α,γα)⁷Li*(0.478 MeV) reactions [37] reported states at 9.28, 9.88, 10.26, 10.32 and 10.62 MeV and also an indication of a level at 10.45 MeV. In a kinematically complete measurement of the ¹⁴N(u,2α)⁷Li reaction [38] the α+⁷Li(gs) decay of the states at 9.19, 9.277, 10.25 and 10.60 MeV was observed. Coincidence measurements of the ⁹Be+⁶Li reaction [39] provided evidence for the α-decaying levels in ¹¹B at 10.3, 11.4, 12.6, 13.16, 13.5, 14.0 and 14.4 MeV.

Our results show a peak at 13.1 MeV, which corresponds to both the 13.137 MeV 9/2⁻ and 13.16 5/2⁺ (or 7/2⁺) state [40] and also indicate a weak broad state at 14.0 MeV which corresponds to the 11/2⁺ state at 14.04 MeV and there may be some indication of the state at 18.6 MeV in Fig. 4(c).

A curious feature of the present results is the observation of the α+⁷Li(gs) decay, which means isospin T=1/2, of the excited states at 12.557, 12.916, 14.34 and 17.43 MeV proposed to be the isobaric analogue states of the ¹¹Be states which have T=3/2. The 12.557 MeV state, which should be the analogue of the ground state, is strong in our spectra as well as 14.34 MeV 5/2⁺ state. The widths of these states estimated from Fig. 4(a) are in agreement with their accepted values 200-250 keV [20]. The 12.916 1/2⁻ state is close to the peak at 13.1 MeV, but there is good evidence for an additional peak around 13.0 MeV in our spectra. The peak observed in Fig. 4(c) at 17.4 MeV may correspond to the previously observed state at 17.43 MeV claimed to be T=3/2 state. The 12.55 MeV state was also observed in the ⁷Li+α scattering [36] and the ⁹Be+⁶Li reaction [39] where the 14.4 MeV state was also observed. The resonances at 12.5 and 14.3 MeV (and also 11.3 MeV) have also been observed in recent measurement of the ⁷Li(⁷Li,⁷Liα) reaction [41].

Information about T=3/2 states in ¹¹B has been obtained from a number of measurements of different reactions. A measurement of the ¹⁰Be(p,γ) reaction provided evidence for the states at 12.55, 12.91, 14.33 and 15.3 MeV which were identified as the analogues of the lowest four states in ¹¹Be [42]. A study of the ⁹Be(³He,p) and ⁹Be(α,d) reactions [43] found evidences for the T=3/2 states at 12.56, 12.92, 14.47, 16.44, 17.69, 18.0, 19.15 and 21.27 MeV. It was concluded that the 16.44, 17.69, 18.06 and 19.15 MeV states had a rather pure isospin 3/2, whereas the first two may have small admixtures of T=1/2 since they were seen in the isospin-forbidden ⁹Be+d reaction [44]. The 14.47 MeV
state was suggested to correspond to the 14.33 MeV excitation and thus to have a strongly mixed isospin because it appeared in the spectra from both reactions (detailed discussion of its properties was presented in Ref. [43]). We note that these observations are in good agreement with the present results. The 17.69 MeV state observed in the above work may be the 17.43 MeV state observed in the present measurements.

A measurement of the $^{14}$C(p,$\alpha$) reaction [45] showed the population of broad resonances at 12.92, 15.29, 16.50 and 19.07 MeV which were proposed to be T=3/2 negative parity states. The 12.92 MeV state was also observed in the $^{13}$C(p,3He) reaction [32,33,34]. From all the available data on T=3/2 states in $^{11}$B it seems that, at least, the lowest states have been identified experimentally. However, the earlier measurements together with the present analysis points to a significant T=1/2 contribution.

We should note that as in the case of $^{11}$C there is an alternative explanation of the some of the states observed in the present measurement in terms of rotational bands.

### 4.3 Common features of the $^{11}$B and $^{11}$C excited states

As just indicated, there are two possible interpretations of the present data. The first is that several of the observed states coincide with known T=3/2 states, in which case isospin mixing is signalled. Alternatively, the peaks may have a genuine T=1/2 character and may be linked to rotational bands. We deal with each of these possibilities in turn.

First the T=3/2 states in both nuclei will be examined. If the presented states are indeed those identified with T=3/2 character, then our results show that the lowest three T=3/2 levels in $^{11}$B and the first T=3/2 level in $^{11}$C probably have large isospin mixing. In the $^{11}$B case this is confirmed by other published results of observations of the T=1/2 resonances at excitations proposed for the T=3/2 levels.

The results of several calculations [46,47] suggest that the 1/2+, T=3/2 levels in $^{11}$B and $^{11}$C have been misidentified. But the latest published results [48] of potential-model calculations using more appropriate R-matrix definitions for the energy and width of an unbound level, and many-channel R-matrix theory, have found reasonable agreement with the experimental excitations but possible disagreement in the widths. It has been proposed that isospin mixing can resolve confusion with T=3/2 states in $^{11}$B and $^{11}$C. Shell-model calculations [48,49,50] suggest a 1/2+, T=1/2 partner state near the 1/2+, T=3/2 state. Also, both the shell-model [51,52,53] and three-cluster model calculations [54] of $^{11}$B predict 1/2−, T=1/2 state above the $\alpha$+7Li decay.
threshold which may mix with the T=3/2 partner state, but this state has not been observed. Two parentages appear in these states, wave functions of \(^{11}\text{B}\) T=3/2 states contain one third of \(^{10}\text{Be}\otimes p\) and two thirds of \(^{10}\text{B}^*(T=1)\otimes n\) while \(^{11}\text{C}\) states are two thirds of \(^{10}\text{B}^*(T=1)\otimes p\) and one third of \(^{10}\text{C}\otimes n\). The weak coupling model calculations in a complete \(1\hbar\omega\) basis [49] showed that the T=3/2 \(^{11}\text{B}\) positive parity states wave functions are quite simple, these states consist mainly of the proton in the sd-shell coupled to the \(^{10}\text{Be}\) ground state and components of the sd-shell proton coupled to the \(^{10}\text{Be}\) first excited state. There is the possibility for T=1/2 positive parity states at these excitations based upon the configurations with the ground state of \(^{8}\text{Be}\) as an inert core and three particles in (2s,1d) shell [55] and also for negative parity states with two particles in the sd-shell, which have large overlap with the \(\alpha+^7\text{Li}\) structure. These states may then mix with the observed T=3/2 states of the same spin and parity.

We now examine the possible rotational behaviour of the mirror nuclei. An interesting result was obtained in the Nilsson-Strutinsky cranking model calculations for the positive-parity yrast states of \(^{11}\text{C}\) and \(^{11}\text{B}\) [56]. Based on available experimental data, rotational bands with K=5/2\(^+\) were proposed beginning at 7.286 and 6.905 MeV in \(^{11}\text{B}\) and \(^{11}\text{C}\) respectively, with rotational
members at 9.185 and 8.655 (7/2\(^+\)), 11.265 and 10.679 (9/2\(^+\)) and 14.04 and 13.33 MeV (11/2\(^+\)) (see Fig. 5). The moment of inertia I of these bands is very large, with a rotational parameter \(\hbar^2/2I\) of 0.25 MeV for \(^{11}\)B and 0.24 MeV for \(^{11}\)C (for comparison rotational parameter for the \(^8\)Be ground state band is 0.5 MeV) which would correspond to an extremely deformed structure. Two alternative explanations were offered for these bands, the first was that there are three particles promoted to the sd-shell \([220]1/2^+\), but that was in conflict with the generally accepted signature selection rule. The second explanation, which seems more likely, was that the bands could be a 1p-1h excitation to the sd-shell, presumably the oblate coupled \([202]5/2^+\) orbit leaving an unpaired neutron and proton in the p-shell.

What is interesting here, is that the present results show the population of the members of rotational bands in the reactions which involve two-nucleons transferred to the cluster nucleus \(^9\)Be and their strong \(\alpha+^7\)Li\(^7\)Be decay. This fact indicates that the configurations of these states are rather complicated, because simple 1p-1h configuration would strongly decay by single-nucleon emission.

In \(^{11}\)B spectra all the members 7/2\(^+\), 9/2\(^+\) and 11/2\(^+\) are present while in \(^{11}\)C spectra the 7/2\(^+\) and 9/2\(^+\) states are clearly seen and there is small bump in the \(^{11}\)C spectra at 13.4 MeV. The assigned 11/2\(^+\) member in Ref. [56], the 13.33 MeV state with width of 270 keV observed in Ref. [26], has no experimentally measured spin and parity. Comparing the widths of the known states of both nuclei in the compilations [20], it seems that the broad state observed at 13.4 MeV is better candidate for that level. The excitation of this level is not unambiguously confirmed and it may correspond to broad state observed in the \(^{12}\)C(p,d) measurement [57] at 13.22 \(\pm\) 0.25 MeV.

Interestingly, there is another possible positive-parity band in both \(^{11}\)B and \(^{11}\)C with K=3/2\(^+\), beginning at excitation energies 7.97784 and 7.4997 MeV, respectively. Rotational members at 9.274 and 8.699 MeV (5/2\(^+\)) and 10.597 and 10.083 MeV (7/2\(^+\)), which are observed in the present spectra, form the linear J(J+1) energy plot presented in Fig. 5. The rotational parameter \(\hbar^2/2I\) of these two bands would be 0.215 MeV.

It should be noted that the 9/2\(^+\) members of these bands (open circles in Fig. 5) would be at 12.6 MeV in \(^{11}\)B and 12.1 MeV in \(^{11}\)C, they are very close to the excitations of the proposed 1/2\(^+\) T=3/2 states and exactly at excitations where are resonances in the present spectra. This offers an alternative explanation of these peaks in our spectra: they may be the 9/2\(^+\) T=1/2 members of the very deformed bands and their excitations just coincide with the energies of the first T=3/2 states. In that case there is no isospin mixing between states of different isospin. Clearly, determination of the spins and parities of these states will answer this ambiguity.
Fig. 6. Comparison of the $^{11}$B and $^{11}$C excitation energy spectra from the present measurements. Spectra are normalised for detection efficiency and shifted so that the $7/2^+$, $5/2^+$ doublets are aligned. Lines mark positions of the states with the same value of the spin and parity populated in both nuclei. The positions of the bands members are marked with the same symbols as in Fig. 5. The excitations of the isobaric analogs of the lowest three $^{11}$Be states are marked with stars.

An interesting feature of the present results (see Fig. 6, which shows the efficiency corrected excitation energy spectra) is that we observe the same series of excited states at the lower excitations in both nuclei: unresolved doublet of $7/2^+$, $5/2^+$ states (marked ‘a’ in Fig. 6), a $3/2^-$, $5/2^-$, $7/2^+$ triplet (‘b’ in Fig. 6) which is $\sim 1.2$ MeV above the doublet, $9/2^+$ state (‘c’) at an excitation of 2 MeV higher then the doublet, then the proposed isobaric analogs of the $^{11}$Be ground state (‘d’) which are $\sim 3.4$ MeV above the doublet, and then weak states, which are probably $7/2^+$ (‘e’) and $11/2^+$ (‘f’), and which are 3.9 and 4.8 MeV above the doublet’s excitation. All states observed in $^{11}$C appear also as strong resonances in the $^{11}$B spectra. However, we have
observed more states at higher excitations in $^{11}$B and also some weak states at lower excitations, which are missing in the $^{11}$C spectra. This is probably due to the very different Q-value of the reactions used in the studies of the $^{11}$B (Q=-2.461 MeV) and $^{11}$C (Q=-14.602 MeV) and the different kinematical conditions in the reactions. These strongly excited states observed in α-decay of both the $^{11}$B and $^{11}$C should have the same structure. Observed strong $\alpha+^{7}\text{Li}(\alpha+^{7}\text{Be})$ decay of these mirror states produced in the reactions involving transfer of two nucleons onto the $2\alpha+n$ cluster nucleus $^{9}\text{Be}$ and known $\alpha+^{3}\text{H} (\alpha+^{3}\text{He})$ cluster structure of $^{7}\text{Li} (^{7}\text{Be})$ suggest $2\alpha+^{3}\text{H} (2\alpha+^{3}\text{He})$ three-centre cluster structure of the $^{11}$B ($^{11}$C) excited states. Support for existence of such structure in $^{11}$B and $^{11}$C can be found in the three-cluster Generator Coordinate Method calculations [54], simple cluster model calculations [58] and three-cluster orthogonality condition model calculations [59] which provide a reasonable description of the $^{11}$B and $^{11}$C. This three-centre structure is also consistent with the results of the antisymmetrized molecular dynamics calculations of $^{11}$B [60] and $^{11}$C [61] which showed that even ground state and the lowest excited states possess deformed three-centre structure. The existing cluster models calculations have not examined the rotational structures of the three-centre configurations and such calculations would be extremely useful for the understanding of the $^{11}$B and $^{11}$C properties.

The Nilsson deformed single-particle level scheme indicates that for oblate deformations the [202]5/2$^+$, [202]3/2$^+$ and [200]1/2$^+$ orbits descend from the sd-shell. Excitations of a proton (neutron) in $^{11}$B ($^{11}$C) to these orbits would permit the formation of $K=5/2^+$ and $3/2^+$ bands in the case of the first two. This gives an indication that the observed structures may be oblate in character.

An additional neutron introduced into the $2\alpha+^{3}\text{He}$ system produces well known 3α structure of $^{12}$C which is then three-centre core for proposed molecular structures formed by addition of valence neutrons around it [15,62,63]. In contrast, the $2\alpha+^{3}\text{H}$ system in $^{11}$B is the most stable three-centre structure in boron isotopes and addition of a neutron would result in molecular neutron orbital around that core. Indications for such structure in $^{12}$B have been found in the $\alpha+^{8}\text{Li}$ decay of excited states in the present data [64] and some other studies of the $^{7}\text{Li}+^{9}\text{Be} \rightarrow 2\alpha+^{8}\text{Li}$ [65,66] and $^{7}\text{Li} (^{7}\text{Li},^{8}\text{Li}\alpha) [41]$ reactions.

### 5 Summary

Measurements of the $^{16}\text{O}(^{9}\text{Be},\alpha^{7}\text{Be})^{14}\text{C}$ and $^{7}\text{Li}(^{9}\text{Be},\alpha^{7}\text{Li})^{5}\text{He}$ reactions at $E_{\text{beam}}=70$ MeV provide evidence for $\alpha+^{7}\text{Be(gs)}$ and $\alpha+^{7}\text{Li(gs)}$ decay of excited states in $^{11}$C and $^{11}$B. The $^{11}$C excitation energy spectra provides evidence for resonances at 8.65, 9.85, 10.7 and 12.1 MeV and indications for peaks at
12.6 and 13.4 MeV. This result is the first direct observation of $\alpha$-decay for states above 9 MeV. The $^{11}$B excitation energy spectra show resonances at 9.2, 10.3, 10.55, 11.2, (11.4), 11.8, 12.5, (13.0), 13.1, (14.0), 14.35, (17.4) and (18.6) MeV. The observed $\alpha+^{7}$Li decay extends the excitation energy range in $^{11}$B for this decay channel. Given the nature of the reaction processes, two-nucleon transfer onto the $2\alpha+n$ cluster nucleus $^{9}$Be, and the $\alpha$-decay of excited states at excitations where various decay channels are possible, as well as known $\alpha+t(^{3}$He) structure of $^{7}$Li(+$^{7}$Be), it is possible that these states are linked with the three-centre $2\alpha+t(^{3}$He) cluster structure. This cluster structure appears to be more prominent in the positive-parity states, where two rotational bands corresponding to very deformed structure are suggested. The $K=5/2^+$ bands consist of $5/2^+$, $7/2^+$, $9/2^+$ and $11/2^+$ members and have rotational parameter $\hbar^2/2I$ of 0.25 MeV. The rotational parameter of the $K=3/2^+$ bands with $3/2^+$, $5/2^+$, $7/2^+$ and possible $9/2^+$ members is 0.215 MeV. It is likely that these states are associated with oblate type structures similar to those found recently in the calculations of the rotational behaviour of $^{14}$C [62].

Excitations of some of the observed $T=1/2$ resonances coincide with the positions of $T=3/2$ states which are the isobaric analogue states of the lowest $^{11}$Be states, which would indicate mixed isospin. In this case, the states observed at excitations which correspond to the analogs of the $^{11}$Be ground state with $J^\pi=1/2^+$ may be the $1/2^+$, $T=1/2$ states which mix with the analogues, or alternatively the $9/2^+$ members of the $K=3/2^+$ rotational bands. It is clear that the determination of the spins and parities of these states are imperative in order to understand structure of $^{11}$B and $^{11}$C excited states. Due to the large number of reaction amplitudes contributing to the reaction processes, resulting from the presence of nonzero spin nuclei in the entrance and exit channels, the angular distributions and angular correlations in the present measurements did not provide information on the spin and parity of the observed states. Additional measurements capable of determining such information are planned for the near future. The available theoretical calculations have not examined such three-centre systems, where there are holes rather than particles being exchanged between $\alpha$-particles. Additional calculations are important to further improve our understanding of the proposed structures.

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