Cluster structure of $^{13}$C probed via the
$^7$Li($^9$Be,$^{13}$C$^* \rightarrow ^9$Be+$\alpha$) reaction

N. Soić$^a$, M. Freer$^a$, L. Donadille$^{a,2}$, N. M. Clarke$^a$, P. J. Leask$^a$, W. N. Catford$^b$, K. L. Jones$^{b,3}$, D. Mahboub$^b$, B. R. Fulton$^c$, B. J. Greenhalgh$^c$, D. L. Watson$^c$ and D. C. Weisser$^d$

$^a$School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, U. K.
$^b$School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 5XH, U. K.
$^c$Department of Physics, University of York, Heslington, York, YO10 5DD, U. K.
$^d$Department of Nuclear Physics, The Australian National University, Canberra ACT 0200, Australia

Abstract

A study of the $^7$Li($^9$Be,$^4$He$^9$Be)$^3$H reaction at $E_{\text{beam}}=70$ MeV has been performed using resonant particle spectroscopy techniques and provides a measurement of $\alpha$-decaying states in $^{13}$C. Excited states are observed at 12.0, 13.4, 14.1, 14.6, 15.2, 16.8, 17.9, 18.7, 21.3 and 23.9 MeV. This study provides the first measurement of the three highest energy states. Angular distribution measurements have been performed and have been employed to indicate the transferred angular momentum for the populated states. These data are compared with recent speculations of the presence of chain-like structures in $^{13}$C.

Key words: Nuclear reactions, $^{7}$Li+$^{9}$Be, $^{13}$C levels deduced, $^{4}$He+$^{9}$Be decay, angular distributions, molecular structure
PACS: 21.60.Gx, 23.20.En, 25.70.Ef, 27.20.+n

1 Permanent address: Ruder Bošković Institute, Bijenička 54, HR-10000 Zagreb, Croatia
2 Present address: CEA-Saclay, DAPNIA/SPhN, Bt. 703, Pice 162, F-91191 Gif sur Yvette Cedex, France
3 Present address: GSI, Gesellschaft für Schwerionenforschung mbH, Planckstrasse 1, D-64291 Darmstadt, Germany

Preprint submitted to Elsevier Science 30 March 2022
1 Introduction

The structure of light nuclei has always provided a certain fascination, given that a full range of structural properties are displayed from spherical shell model like structure via deformation to clustering. In particular even-even nuclei, composed of equal numbers of protons and neutrons offer the possibility that the nucleus may be decomposed into a collection of $\alpha$-particles. This was the picture developed by Ikeda [1], who speculated that at the point that the $N\alpha$ decay threshold was encountered the associated cluster degree of freedom should be liberated. Correspondingly, this picture would suggest that the $^8\text{Be}$ ground state should possess an $\alpha-\alpha$ cluster structure, and the $3\alpha$ cluster structure should appear at an excitation energy close to 7.3 MeV in $^{12}\text{C}$. Indeed, it has been recently speculated that certain states above the $3\alpha$ decay threshold in $^{12}\text{C}$ (e.g. the 7.65 MeV state), or the $4\alpha$ decay threshold in $^{16}\text{O}$, should possess properties reminiscent of a Bose gas [2].

These highly developed cluster systems have been shown to have an important impact on the structure of neutron-rich isotopes of beryllium and carbon. For example, in the case of $^9\text{Be}$ the properties of the valence neutron may be explained in terms of the sharing of the neutron between the two $\alpha$-cores in a manner which is reminiscent of the covalent binding of atomic molecules [3,4,5]. For valence neutrons based on $\alpha$-particle cores, linear combinations of the $p$-type orbits lead to analogues of the atomic $\sigma$ and $\pi$-bonds. Indeed, such a description provides a useful basis for the understanding of the low lying spectroscopy of the $^9\text{Be}$ nucleus, with the ground state structure forming a rotational band with $\pi$-like character.

The presence of $3\alpha$ cluster structures in $^{12}\text{C}$ provides an extension to the ideas developed for the two-centre systems. Calculations which explicitly contain the molecular-orbital structure [6] show that unlike the linear $3\alpha$ system, which is unstable against bending modes and thus collapse into more compact structures, the $3\alpha + Xn$ systems are stable against the bending mode [6,7]. Thus, there would appear to be an opportunity for observing linear chain configurations, partially stabilized by the valence neutrons in covalent type orbits. A recent analysis of available data by Milin and von Oertzen has provided tentative evidence for the existence of such a structure in $^{13}\text{C}$ [8]. Via a careful examination of previous experimental spin and parity assignments, two rotational bands were proposed ($K = 3/2^+, 3/2^-$) whose deformations indicated a chain-like structure and which were split in energy due to the intrinsic asymmetry of the $3\alpha + n$ structure. This analysis provided information on such rotational structures up to $E_x \sim 17$ MeV. Although, such a picture is appealing the relationship between the states considered by Milin and von Oertzen has not been demonstrated since the spins and parities remain to be confirmed.
In the present paper we present a measurement of the $^7\text{Li}(^9\text{Be},^{13}\text{C}^*\rightarrow^9\text{Be}+\alpha)^3\text{H}$ reaction. The $\alpha$-transfer process provides a possible mechanism by which the chain-like structures in $^{13}\text{C}$ may be populated. The measurement covers the excitation energy range of 12 to 28 MeV, the interval over which the higher energy and spin members of the two rotational bands are believed to exist.

2 Experimental Details

The measurements were performed at the Australian National University's 14UD tandem accelerator facility. A 70 MeV $^9\text{Be}$ beam, of intensity 3 enA, was incident on a 100 $\mu$gcm$^{-2}$ Li$_2$O$_3$ foil. The integrated beam exposure was 0.45 mC.

Reaction products formed in reactions of the $^9\text{Be}$ beam 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 $^9\text{Be}$ from $^{197}\text{Au}$ and $^{12}\text{C}$ 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° (detectors 1 and 2) from the beam axis and with the strip detector 130 mm from the target, whilst the remaining pair were at the slightly larger angles of 28.6° and 29.7° (detectors 3 and 4), 136 mm from the target.

3 Results

The detection system employed in the present measurements allowed a measurement of the charge, mass, energy and emission angle (and hence a determination of the momentum) of each particle. This provides a complete determination of the reaction kinematics in the case of a three particle final
state. Figure 1 shows the total energy spectrum of the three final state particles assuming a $^3$H recoil ($E_{\text{tot}} = E_{\text{Be}} + E_{\alpha} + E_t$), after gating on $^9\text{Be} + \alpha$ in the particle identification spectra. The large peak in this spectrum corresponds to the observation of the $^7\text{Li}(^9\text{Be},^9\text{Be}\alpha)^3\text{H}$ reaction ($Q=-2.468$ MeV), where all particles are produced in their ground states ($^9\text{Be}$ only possesses one state bound against particle decay). The energy resolution in the total energy spectrum is $\sim 1.9$ MeV, considerably worse than the intrinsic energy resolution of the detectors (300 keV). This is due to in fact the uncertainty imposed by the measured momenta of the two detected particles limits the resolution of the reconstructed momentum of the undetected triton. Given the relatively small mass of the recoil particle the uncertainty in momentum is magnified in energy. The first peak at lower total energy corresponds to reactions involving the oxygen and carbon components in the target: $^{16}\text{O}(^9\text{Be},^9\text{Be}\alpha)^{12}\text{C}$ ($Q=-7.162$ MeV) and $^{12}\text{C}(^9\text{Be},^9\text{Be}\alpha)^8\text{Be}$ ($Q=-7.367$ MeV), predominantly the former, with the lowest energy peak coinciding with the 4.4 MeV excitation of the $^{12}\text{C}$ recoil. Unfortunately, the underlying background means that these channels cannot be analyzed.

By selecting only the events associated with the $^7\text{Li}(^9\text{Be},^9\text{Be}\alpha)^3\text{H}$ reaction the $^{13}\text{C}$ excitation energy can be calculated from the relative velocity of the two decay fragments. Figures 2a (top) and 2b (bottom) show such spectra for the small angle detector pair (1 and 2) and the larger angle pair (3 and 4) respectively. As expected these spectra sample slightly different excitation energy ranges due to the minimum opening angle required for the fragments to reach the detectors. Given the presence of three particles in the final state the possibility remains that at least some of the yield in Figures 2a and 2b arises from decays of either $^7\text{Li}$ into $t+\alpha$ or $^{12}\text{B}$ to $t+^9\text{Be}$. Both of these decay processes were reconstructed and only evidence for decays of $^7\text{Li}$ was found, where the states at 4.63 and 6.68 MeV were observed in the coincidence spectra for detectors 3 and 4. This contribution was removed from the spectrum in Figure 2b by eliminating all data corresponding to $^7\text{Li}$ excitations less than 7 MeV.

The resulting excitation energy spectra extend from the threshold at 10.65 MeV to $\sim 28$ MeV. Characteristically, the states are narrow at low energies, becoming broad at the other limit. The excitation energies and widths of these states are presented in Table 1. In the region of overlap between the two spectra it is clear that there is good agreement with in particular the 18.7 MeV peak being represented in both spectra, and to a lesser extent the 21.3 MeV peak. The diminished strength in the spectrum in Figure 2a at high excitation energies is related to the decrease in the detection efficiency. The spectra show a number of strong peaks at 13.4, 14.1, 14.6, 16.8, 18.7, 21.3 and 23.9 MeV, and there is some evidence for additional states at 12.0, 15.2, 16.0, 17.9 and 27.3 MeV. These weak states are not clearly observed in the spectra in Fig 2, which represent the total sum of good events recorded by
Fig. 1. Total energy spectrum for $^4\text{He}+^9\text{Be}$ coincidences detected in telescopes 1 and 2, assuming a $^3\text{H}$ recoil. The highest energy peak corresponds to the observation of the $^7\text{Li}(^9\text{Be},^9\text{Be}\alpha)^3\text{H}$ reaction. Statistical uncertainties are presented only.

telescopes 1-2 and 3-4, but were observed in some individual spectra for the coincidences and are moreover required to provide a good reproduction of the shape of the spectra with multiple peak and a linear background fitting. The experimental excitation energy resolution can be observed from the width of the 13.4 MeV peak to be 180 to 200 keV. This limit only permits widths of the broader states to be quoted. This has been done in Table 1 by deconvolving the experimental resolution assuming that the experimental and physical width add in quadrature. The energy dependence of the excitation energy resolution has been calculated and suggests moderate change of the excitation energy resolution with energy: at 17 MeV excitation the resolution is 230 keV, at 19 MeV it is 240 keV and at 24 MeV it is 340 keV. Given the difference in the widths of the resonances observed at 18.7, 21.3 and 23.9 MeV and those appearing in the tabulations [9], it is probable that these peaks correspond to new resonances in this nucleus, which may possess a structural (rotational) link with those at lower energies.
Fig. 2. $^{13}$C excitation energy spectra for decays detected in detectors 1 and 2 (a) top, and 3 and 4 (b) bottom. Observed peaks are labelled with excitation energies (MeV). The details of the peaks observed in these spectra are presented in Table 1. Error bars represent statistical errors.

The angular distributions of the $^{13}$C* nuclei produced in the $^7$Li($^9$Be,$^{13}$C*)$^3$H reaction prior to break-up may be reconstructed from the measured momenta of the detected $^9$Be+$\alpha$ decay products. These angular distributions ($d\sigma/d\Omega$) are shown plotted as a function of centre-of-mass emission angle of the $^{13}$C nucleus in Figure 3 for the main states observed in the excitation energy spectra in Figure 2. It should be noted that the angular distributions have been normalised arbitrarily so that all the distributions may be plotted in the same figure. The distributions have been corrected for the efficiency of the detection of the $^{13}$C* $\rightarrow ^9$Be+$^4$He decay process using Monte Carlo simulations.
Table 1
Excitation energies of $^{13}$C states $\alpha$-decaying into the ground state of $^9$Be. The uncertainty in these energies is 100 keV. The previous measurements are from the tabulations of [9]. Note that the excitation energy resolution is 180 to 200 keV from an analysis of the 13.4 MeV peak, and therefore widths are only quoted where the experimental resolution permits, and the experimental resolution has been unfolded. The states shown in italics are states observed at the same energies as those in the present measurements, but have different experimental widths.

| Present $E_x$ | Width (MeV) | Present $E_x$ | $J$ | Width (MeV) |
|-------------|------------|-------------|-----|------------|
| (MeV)       | (keV)      | (MeV)       |     | (keV)      |
| 12.0        | 11.95      | 5/2$^+$     | 500 |
| 13.4        | 13.41      | (9/2)$^-$   | 35  |
| 14.1        | 14.13      | 3/2$^-$     | ~150|
| 14.6        | 14.58      | (7/2$^+$, 9/2$^+$) | 230 |
| (15.2)      | 15.27      | 9/2$^+$     |     |
| (16.0)      | 16.08      | (7/2$^+$)   | 150 |
| 16.8        | 310        | 16.95       | 330 |
| (17.9)      | 17.92      |             |     |
| 18.7        | 570        | 18.70       | (3/2$^+$, 5/2$^+$) | 100 |
| 21.3        | 530        | 21.28       | 159 |
| 23.9        | 1100       | 24.00       | 4000|
| (27.3)      | 27.5       |             |     |

Due to the decay of the $^{13}$C nucleus into two fragments which then are detected at large angles, it is possible to measure the angular distributions all the way down to zero degrees. At the other limit these distributions extend up to centre-of-mass angles of ~80°. These distributions are typical of such heavy-ion reactions in that they are not highly structured. Nevertheless, for certain of the distributions, most notably those associated with the 14.1 to 21.3 MeV peaks there is some oscillatory behaviour. The curious feature of the structured angular distributions is that the minima shift with increasing excitation energy in a very systematic fashion, as indicated by the dash lines. An examination of the angular correlations, using the techniques outlined in [10], shows that there is no structure in the distributions in the decay reference frame. This is as expected for non-zero spin particles involved in the reaction, and is due to the presence of the large number of reaction amplitudes contributing to the excitation and decay processes.
Differential cross section (A.U.)

Fig. 3. The experimental angular distributions ($d\sigma/d\Omega$) for the states observed between 13 and 24 MeV. The distributions have been normalised so that the data for the 7 states can be displayed simultaneously. The dash lines indicate the location of the minima in the angular distributions. It should be noted that for the 21.3 and 23.9 MeV states distributions do not extend to zero degrees due to the limit acceptance of the detection system in this region.

4 Discussion

It is useful to draw a comparison with the present measurement and that also using the $^7\text{Li}(^9\text{Be},^9\text{Be}^2\alpha)^3\text{H}$ reaction at $E_{\text{beam}}=58.5$ MeV [11]. This earlier study was much more limited in statistics and in terms of the excitation energy range in $^{13}\text{C}$, but found evidence for the $\alpha$-decay of a series of states between 10.5 and 14.5 MeV. Close to 12.0 MeV, the 11.848 MeV ($7/2^+$) and 11.95 MeV ($5/2^+$) states were observed to play an important role and close to 13.4 MeV, states at 13.28 MeV (with a tentative assignment of $3/2^-$) and 13.41 MeV (tentatively
assigned $9/2^−$). Similar resonance states were observed in the measurements of the $^9\text{Be}(\alpha,\alpha)^9\text{Be}$ reaction [12]. In this latter study resonant structures were observed corresponding to $^{13}\text{C}$ excitations of 13.28, 13.42, 14.11 and 14.63 MeV which coincide with the main features in the present data. Thus, there is good agreement with the present excitation energy spectrum and those observed in other reactions which probe an overlap with $^9\text{Be}+\alpha$.

On the other hand, the angular momentum and parity of many of these states are far from clear, especially above 12 MeV. As an example, the 14.13 MeV state which is recorded in [9] as possessing a firm spin and parity assignment of $3/2^−$, from measurements of $n^{+^{12}}\text{C}$ [13] scattering and $p^{+^{13}}\text{C}$ inelastic scattering [14], is found in the measurements of $^9\text{Be}(\alpha,\alpha)^9\text{Be}$ to be $5/2^−$ [12] and was recently proposed by Milin and von Oertzen [8] to possess spin and parity $9/2^−$. In this latest analysis four new assignments have been suggested for states in $^{13}\text{C}$. The spin and parities suggested by these latter authors are given in Table 2. The two rotational bands identified in this table are believed to be linked with a $3\alpha+n$ chain structure in $^{13}\text{C}$. Corresponding to the predicted positive parity band shown in this table, the 11.950, 13.41, 15.28 and 16.95 MeV states are observed in the present measurements, and for the negative parity band the 14.13 and 16.08 MeV states are represented. However, this compilation does not include the 14.6 MeV state observed in both the present measurements and those of the $^9\text{Be}(\alpha,\alpha)^9\text{Be}$ reaction, which may be an important omission given the strength with which the state is observed.

The angular distributions in Figure 3 appear to show two features, the first is that the distributions for the five states at 14.1, 14.6, 16.8, 18.7 and 21.3 MeV all have a similar character, and secondly it is distinct from that of the distributions for the 13.4 and 23.9 MeV states. This difference is in terms of the reduced oscillatory structure for the distributions of the latter two states, and that the distributions for these two states appear to possess a gradient which differs to that of the remaining states. This feature would suggest that the two sets of states possess different characters, either in terms of their parity or the angular momentum transfer. In the present case positive parity states would be populated by odd angular momentum $L_f$ values ($L_f$ being the angular momentum of the orbit into which the $\alpha$-particle is transferred), whilst negative parity states would be populated by even $L_f$ values. The spins which could be populated in the transfer of an $\alpha$-particle with this angular momentum would be in the range $|L_f - 3/2| \leq J \leq L_f + 3/2$. Thus, for example, for the sequence of states $3/2^+, 5/2^+, 7/2^+, 9/2^+$ and $11/2^+$ the $L_f$ values would be (1,3), (1,3), (3,5), (3,5) and (5,7) respectively. Here $L_i$, the initial angular momentum of the $\alpha$-particle in $^7\text{Li}$, is equal to 1. The transferred angular momentum $L$ is given by $L = L_f - L_i$, and is even for positive parity states and odd for those with negative parity.

The ($^7\text{Li},t$) reaction has a long history in the population of $\alpha$-cluster states.
Table 2
Excitation energies and assigned spins from the analysis of states populated in reactions involving an overlap with an $\alpha+^9\text{Be}$ structure from [8]. The spins proposed by Milin and von Oertzen are given in the first column and those appearing in data tabulations [9] are given in the last column.

| $J^\pi$ proposed | $E_x$ (MeV) | $J^\pi$ from [9] |
|------------------|-------------|------------------|
| $3/2^-$          | 9.897       | $3/2^-$          |
| $5/2^-$          | 10.818      | $5/2^-$          |
| $7/2^-$          | 12.438      | $7/2^-$          |
| $9/2^-$          | 14.13       | $3/2^-$          |
| $11/2^-$         | 16.08       | $7/2^+$          |
| $3/2^+$          | 11.080      | $1/2^-$          |
| $5/2^+$          | 11.950      | $5/2^+$          |
| $7/2^+$          | 13.41       | $(9/2^-)$        |
| $9/2^+$          | 15.28       | $9/2^+$          |
| $11/2^+$         | 16.950      | None             |

in light nuclei, and the angular distributions for differing $L_f$-values have been collated (in particular for $L_f = 0$ and 2) by Bethge [15], together with those for the ($^6\text{Li},d$) $\alpha$-transfer reaction. Typically, the ($^7\text{Li},t$) angular distributions are less oscillatory than those for the ($^6\text{Li},d$) reaction, and are reminiscent of those that appear in Figure 3. The reduced structure in the ($^7\text{Li},t$) angular distributions is related to the presence of two transfer angular momentum values, $L$, for each $L_f$ [15,16], for $L_f > 0$. Nevertheless, the compilation of the $\alpha$-transfer reaction in [15] indicates the sensitivity to the orbital angular momentum of the orbit into which the $\alpha$-particle is transferred. These data indicate that the second maximum for $L_f=0$ and $L_f=2$ transfers appear at centre-of-mass angles $20^\circ$-$30^\circ$ and $40^\circ$-$50^\circ$, respectively. Via the properties of Bessel functions the corresponding locations of the maxima for $L_f=1$ and $L_f=3$ transfers would appear at $30^\circ$-$40^\circ$ and $47^\circ$-$57^\circ$, respectively. For the five states with similar angular distributions the secondary maxima shift a little with increasing excitation energy (as indicated by the dashed line in Figure 3), but lie within the region $29^\circ$ to $41^\circ$. We note that the secondary maxima appear to be less strong in the case of the 14.1 and 14.6 MeV states. The observed small change of about 10 degrees of the maxima with excitation energy may reflect the changing amplitudes of the two contributing angular momentum transfer values. The data thus appear to indicate that the five states possess the same value of $L_f$ which may be either 1 or 2. From the perspective of the excitation energy of the observed states the latter is most likely. However, we
note that the angular distributions in [15] were measured at centre-of-mass energies approximately a factor of 2 smaller than in the present case, which may result in some variations of the distributions in [15] and those measured here.

These data would suggest that the five states at 14.1, 14.6, 16.8, 18.7 and 21.3 MeV all correspond to a similar angular momentum transfer and thus may be structurally linked, whereas the two states at 13.4 and 23.9 MeV may possess an alternative character. This observation appears to be inconsistent with the assignments made by Milin and von Oertzen.

We have attempted to reproduce the experimental angular distributions using the DWBA formalism. However, the calculated distributions were found to be overly sensitive to the details of the interaction potentials, and moreover required an approximation to bound state wave-functions for the unbound resonant states. These features of the calculations have not permitted spin information to be accurately and unambiguously extracted from the present data.

## 5 Summary

A measurement of the $^7\text{Li}(^9\text{Be},^9\text{Be}\alpha)^3\text{H}$ at $E_{\text{beam}}=70$ MeV has been performed using an array of charged particle detector telescopes. The measurement of the $^{13}\text{C}$ excitation energy spectrum corresponding to decays into $\alpha+^9\text{Be}$ produced evidence for excited states between 12 and 28 MeV. Evidence is found for three new broad resonances at 18.7, 21.3 and 23.9 MeV. Given the nature of the reaction process, $\alpha$ transfer onto the $\alpha+n+\alpha$ cluster nucleus $^9\text{Be}$, it is possible that some of the states observed in the present measurement may be linked with the $3\alpha+n$ chain structure suggested by Milin and von Oertzen [8]. An analysis of the angular distributions suggests that the group of states at excitation energies 14.1, 14.6, 16.8, 18.7 and 21.3 MeV correspond to the $\alpha$-transfer to a common orbital in $^{13}\text{C}$. The measurements suggest that there may be inconsistencies in the assignments made in reference [8], in identifying the chain-structure. Particularly the resonance at 14.6 MeV observed in the present data is strongly populated, and thus would be expected to feature strongly in the rotational systematics. Further, the measurements indicate that the states may not be ordered into the bands suggested by Table 2.

Clearly, spin determinations are imperative in order to fully understand the nature of the states above the $^9\text{Be}+\alpha$ decay threshold. Due to the large number of reaction amplitudes, resulting from the presence of non-zero spin particles, the angular correlations measured here were featureless. It is possible that reactions such as $^{12}\text{C}(^9\text{Be},^{13}\text{C})^8\text{Be}$ and $^{16}\text{O}(^9\text{Be},^{13}\text{C})^{12}\text{C}$, possessing spin-zero
nuclei in the initial and final state will provide a more promising avenue for resolving this issue. Alternatively, an analysis of the $^6\text{Li}(^9\text{Be},^13\text{C})^2\text{H}$ reaction should produce angular distributions which are more oscillatory than those observed in the present study.

**Acknowledgments**

The authors would like to acknowledge the assistance of ANU personnel in running the accelerator. This work was carried out under a formal agreement between the U.K. Engineering and Physical Sciences Research Council and the Australian National University. PJL, BJG and KLJ would like to acknowledge the EPSRC for financial support.

**References**

[1] K. Ikeda, Suppl. Prog. Theor. Physics (Japan) Extra Numbers, 464 (1968).

[2] A. Tohsaki, H. Horiuchi, P. Schuck, and G. Ropke, Phys. Rev. Lett., 87 192501 (2001).

[3] W. von Oertzen, Z. Phys., A354 37 (1996).

[4] W. von Oertzen, Z. Phys., A357 355 (1997).

[5] W. von Oertzen, Nuovo Cimento A, 110 895 (1997).

[6] N. Itagaki, S. Okabe, K. Ikeda, and I. Tanihata, Phys. Rev. C, 64 014301 (2001).

[7] N. Itagaki, private communication

[8] M. Milin, and W. von Oertzen, Eur. Phys. J. A, 14 295 (2002).

[9] F. Ajzenberg-Selove, Nucl. Phys., A523 1 (1991).

[10] M. Freer, Nucl. Instr. Meth. A383, 463 (1996).

[11] C. Lee, D.D. Caussyn, N.R. Fletcher, D.L. Gay, M.B. Hopson, J.A. Liendo, S.H. Myers, M.A. Tiede, and J.W. Baker, Phys. Rev. C, 58 1005 (1998).

[12] J.D. Goss, S.L. Blatt, D.R. Parsignault, C.D. Porterfield, and F.L. Riffle, Phys. Rev. C, 7 1837 (1973).

[13] W. Tornow, et al., J. Phys. G, 11 379 (1985).

[14] S.F. Collins, et al., Nucl. Phys., A481 494 (1988).

[15] K. Bethge, Ann. Rev. Nucl. Sci., 20 255 (1970).

[16] F. Pühlofer, H. Ritter, R. Bock, G. Brommundt, H. Schmidt and K. Bethge, Nucl. Phys., A147 258 (1970).