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Search for analog molecular chain states in ^{16}C

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Searches have been made for states in ^{16}C with a structural overlap with an α:$2n$:α:$2n$:α configuration using reactions of a 130 MeV ^{18}O beam with a Li_2O target. Upper limits of 1.9 ± 0.4 μb, 0.012 ± 0.003 μb, and 15.5 ± 3.9 μb have been set on the total cross sections for the ^{16}O(^{18}O, ^{10}Be*(6 MeV)+^{6}He)^{18}Ne, ^{7}Li(^{18}O, ^{10}Be*(6 MeV)+^{6}He)^{9}B, and ^{16}O(^{18}O, ^{6}He+^{6}He+α)^{18}Ne reactions, respectively.

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Clustering has long been known to play an important role in the structure and properties of light nuclei such as ^{8}Be and ^{12}C. For example, the rotational band built on the ground state of ^{8}Be has a moment of inertia similar to that of two touching alpha particles. This two center nature of ^{8}Be has a large impact on the structure of nuclei such as ^{9}Be, ^{9}B, ^{10}Be, and ^{10}B which are formed by the addition of nucleons to the $\alpha+\alpha$ core. These nucleons experience a two-center potential forming states whose wave functions are very different from normal shell model states. Theoretical studies of these nuclei have been successful using molecular-type models [1,2] as well as the antisymmetrized molecular dynamics (AMD) model [3–5]. The valence nucleon orbits in the resulting Be and B isotopes are found to be very similar to the orbits of electrons in covalently bonded atomic dimers, and consequently the states have been termed molecular states.

von Oertzen [6–8] recently compiled data from several previous measurements which support these theoretical findings. The rotational bands inferred from these studies show moments of inertia consistent with large deformations. The natural progression from these ideas is to consider whether more complex moleculelike structures exist. The strongest candidate for a state with a three center basis is the 7.65-MeV 0_2^+ level in ^{12}C. This state has long been considered to consist of three α particles in a chain or bent linear configuration [9,10] and is of important astrophysical significance as it forms a primary role in the production of carbon in stellar material. Levels with similar properties to those predicted by von Oertzen may exist in nuclei such as ^{14}C and ^{16}C at higher degrees of excitation energy [7]. Recent molecular orbital calculations on ^{16}C [11] have indicated that the linear chain of three α particles, bonded by four valence neutrons, is stable and therefore the most promising candidate of the carbon isotopes to possess the $3\alpha+xn$ molecular structure. In these states the valence neutrons would occupy two-center molecular orbits between pairs of alpha particles with a concentration of the wave function in the regions between the alpha particles. In classical terms the structure resembles α:$2n$:α:$2n$:α, with the neutrons providing additional binding to stabilize the chain structure. These structural considerations suggest that the dominant decay mode for such states might be the ^{10}Be+^{6}He or ^{6}He+^{6}He+^{4}He channels. The expected signal would be the occurrence of a sequence of states observed in these breakup channels, whose spin-energy systematics show a rotational behavior with a large moment of inertia consistent with the highly deformed molecular structure.

There has recently been a reported search for the ^{16}C molecular states. Leask *et al.* [12] used fragmentation of a radioactive ^{16}C beam from the GANIL facility. No evidence was found for any breakup to the ^{6}He+^{6}He+^{4}He channel while decays to the ^{10}Be+^{6}He channel were found to be extremely weak. While this measurement used a simple reaction process, inelastic excitation of the ^{16}C beam, the low intensity of the beam was a serious disadvantage. In the present measurement we report on an alternate approach employing a much more intense stable beam, using the two proton transfer reaction (^{18}O, ^{16}C) off a compound Li_2O target to form the excited ^{16}C nuclei.

A beam of 130-MeV $^{18}O^{8+}$ ions was provided by the Australian National University (ANU) 14UD tandem accelerator which was then incident on the Li_2O target which had an areal density of 100 $\mu g\,cm^{-2}$. Coincident detection of the breakup products of ^{16}C, for example ^{10}Be+^{6}He and ^{6}He+^{6}He+^{4}He, was achieved with four, three-detector telescopes comprising of a 70-μm-thick silicon ΔE detector, divided into four quadrants, a 500-μm-thick, 16-strip position sensitive silicon detector (PSSD) and a CsI(Tl) detector. The telescopes were arranged in pairs symmetrically about the beam axis, one pair in the horizontal plane and the other in the vertical plane. The detectors were centered at 17° (horizontal) and 28° (vertical) and at a distance of 140 mm from the target so that the 50×50-mm^2 area of the detectors subtended approximately $\pm20.2°$ in the vertical and horizontal planes. The silicon quadrant detector provided energy loss (ΔE) measurements and the PSSD provided energy and position measurements for each event. For those events of sufficient energy to pass through both the quadrant and the PSSD, a CsI(Tl) detector was employed to record the remaining energy. Calibration of the detection telescopes was

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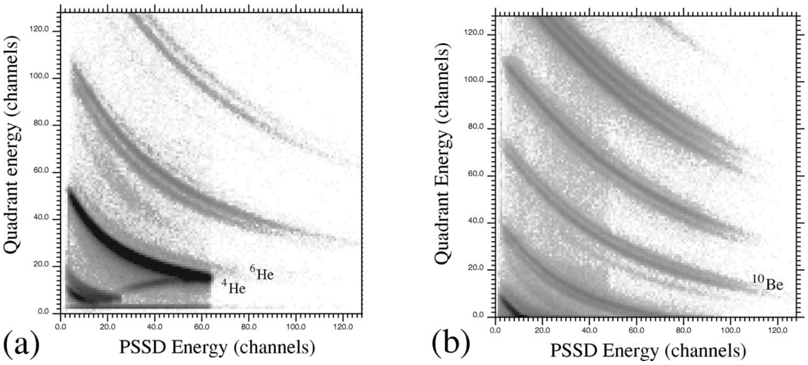

FIG. 1. Example particle identification spectra showing the various ion species detected in this experiment: (a) the helium region and (b) the heavier berylium and carbon regions.

achieved by analyzing the elastic scattering of 70-MeV ^{9}Be ions from a ^{197}Au target. Identification of the reaction products was determined from their characteristic energy loss in the detection telescopes detailed in Figs. 1(a) and (b). Measurement of the mass, energy, and primary scattering angle of the ^{16}C breakup products allowed the energy of the undetected recoil particle to be determined from conservation laws.

A check of the experimental setup and detector calibration was carried out by investigating the (^{18}O, ^{18}O*$\rightarrow$ ^{14}C+α) reactions for which previous data are available [13]. Coincidences between ^{14}C and α were selected and the three body Q value for the reaction calculated (see Fig. 2). Events where all final state particles were emitted in their ground states corresponded to events that fall under the peak in the Q-value spectrum labeled Q_{ggg} at -6.23 MeV with a resolution of $\sim$2 MeV. The difference between the measured experimental centroid of this peak and the expected theoretical value (-6.226 MeV) was seen to be less than 1%. Events falling in the Q_{ggg} were subsequently reconstructed to produce an excitation spectrum for the resonant ^{18}O nucleus, shown in Fig. 2. The states observed correspond to known states in ^{18}O and their energies are in excellent agreement with the work of Rae *et al.* [13] to within 0.5%. It was observed that significant quantities of carbon had accumulated on the Li_2O target by analyzing a plot of the missing energy of the recoil particle plotted against the missing momentum in order to identify the recoil mass (see Ref. [14], for example). Therefore in all subsequent analysis the tri-elemental nature of the target was taken into account when reconstructing reaction Q values.

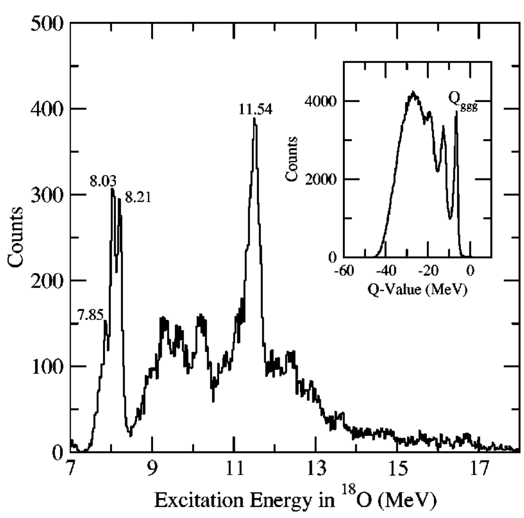

FIG. 2. Excitation energy spectrum, gated on the inset Q-value spectrum peak labeled Q_{ggg} (described in the text), for the decay of ^{18}O$\rightarrow$ ^{14}C+α for reactions off ^{16}O (reactions also occur off ^{12}C and ^{7}Li as discussed in the text). The energies of various states observed in ^{18}O are labeled.

Having confirmed the validity of the analysis, events resulting from the possible breakup of the ^{16}C nucleus were studied. Initially the binary channel ^{10}Be+ ^{6}He was investigated. Breakup into this particular mass partition from molecular states in ^{16}C is likely to occur, according to von Oertzen [7], to the group of four states around 6 MeV in excitation in ^{10}Be which themselves have been shown to possess a deformed molecular structure [2]. Breakup to the deformed ground state of ^{10}Be should also be possible from the expected molecular structure of ^{16}C and searches were also initiated into this particular channel. Coincidences between ^{10}Be and ^{6}He were analyzed and the three body Q values were reconstructed for the three different target components [Fig. 3(a)]. The low energy thresholds for the detection of the ^{6}He and ^{10}Be ions were $\sim$11 MeV and $\sim$30 MeV, respectively. This was the energy required to pass through the silicon quadrant detector and therefore be registered in the correct position in the particle identification spectra. It can be seen that for breakup into ^{10}Be (ground state)+ ^{6}He (labeled Q_{ggg}) and into ^{10}Be*($\sim$6 MeV) + ^{6}He (labeled Q_{gg}) there is no enhancement of the yield in the locations of interest. A large degree of background is seen to be present in these Q value spectra. Possible sources of background could be, e.g., misidentification of particles from the particle identification spectra, contributions of four body breakup channels, pileup in the detectors, etc. If evidence of a final state corresponding to breakup from states in ^{16}C is to be seen, then this background contribution must be reduced.

In order to achieve this a series of kinematic cuts were implemented based on the results of Monte Carlo simulations performed for a range of excitation energies in ^{16}C from 22 MeV to the maximum excitation allowed by the beam energy, assuming an exponential fall off for the primary scattering and then an isotropic distribution of the breakup of the resonant nucleus in the center of mass frame, for the (^{18}O, ^{16}C*$\rightarrow$ ^{10}Be+ ^{6}He) reactions. The simulated energies and primary scattering angles of the ^{10}Be and ^{6}He

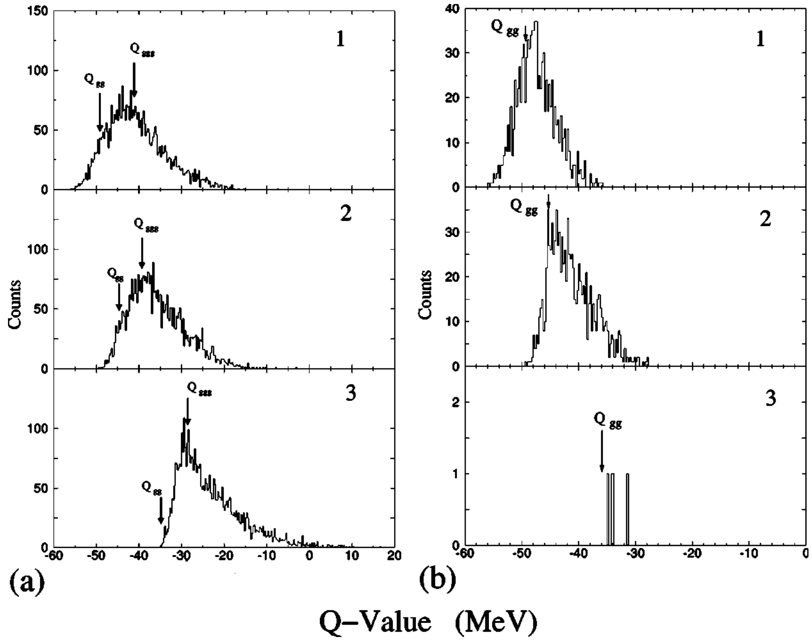

FIG. 3. Q-value spectra for the (^{18}O, ^{16}C) reactions assuming the three different target nuclei (1) ^{16}O, (2) ^{12}C, and (3) ^{7}Li, for (a) all the data and (b) the post kinematically cut data discussed in the text.

breakup fragments were studied for events incident on the detection telescopes above the low energy thresholds (for both the ^{10}Be ground state and states with ~6 MeV in excitation) and cuts to the real data were applied whenever the measured values of these quantities fell outside the simulated range. In addition a series of two dimensional cuts were made to various kinematic parameter spaces occupied by the breakup fragments. For example cuts were made in the energy against angle space and to the momentum (in all three Cartesian directions) spaces considering all combinations of the two breakup fragments. By application of two dimensional software gates, events falling outside of these simulated boundaries were removed for all target combinations and for simulations resulting in breakup to the ^{10}Be states around ~6 MeV in excitation. Breakup to the ^{10}Be ground state was also considered but the effect of the kinematic cuts to the real data were minimal and so are not shown. The post kinematically cut Q-value spectra are shown in Fig. 3(b). These Q-value spectra were then analyzed so that events in the marked region (Q_{gg}) were used to produce an excitation energy spectrum in ^{16}C. This spectrum is shown in Fig. 4(a) together with the associated Monte Carlo simulated efficiency profile for the present detection setup. No evidence for any states in ^{16}C was seen.

Coincidences between ^{6}He+ ^{6}He+ α were also observed and could potentially have arisen from the decay of states in ^{16}C via the ^{10}Be+ ^{6}He or ^{12}Be+ α channels. Due to the inherently lower background in this higher multiplicity data no kinematic cuts were applied to this threefold data. The excitation energy for ^{16}C was reconstructed for this three body channel directly without assuming the intermediate decay step and can be seen in Fig. 4(b) for reactions with the oxygen and carbon targets. For reactions with the lithium target the beam energy was insufficient to excite the ^{16}C nucleus above the ^{6}He+ ^{6}He+ α decay threshold. Again, no evidence for any states in ^{16}C was seen.

A clear signature of molecular states in ^{16}C would be their decay to the excited molecular states in ^{10}Be around 6 MeV

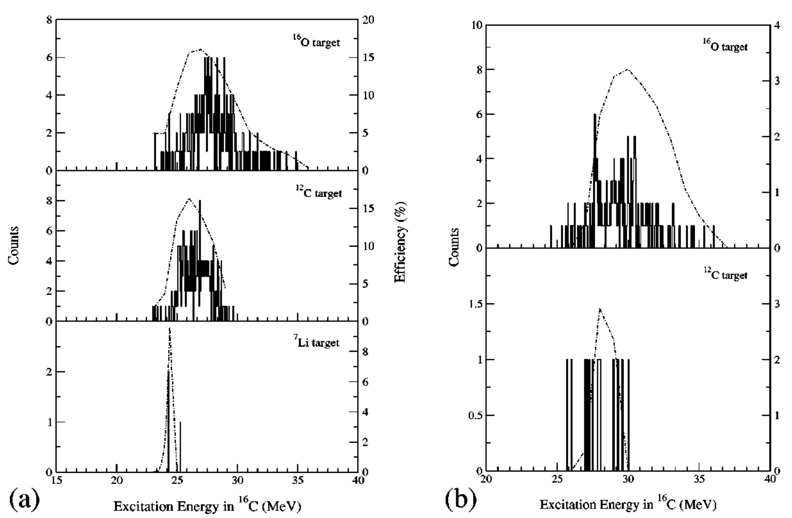

FIG. 4. Excitation energy spectrum for the decay of ^{16}C to (a) ^{10}Be+ ^{6}He for the post kinematically cut data, and to (b) ^{6}He+ ^{6}He+ α for the raw data. The dot-dashed curve on each plot shows a Monte Carlo simulation of the experimental detection eficiency.

in excitation. The present measurement found no evidence for this process. Upper limits on the total cross sections of 1.9 ± 0.4 μb for the ^{16}O(^{18}O, ^{16}C*$\rightarrow$ ^{10}Be(6 MeV)+ ^{6}He) reaction and 0.012 ± 0.003 μb for the ^{7}Li(^{18}O, ^{10}Be*(6 MeV)+ ^{6}He)^{9}B reaction were extracted from the data on the basis of the observed number of counts in the excitation range of interest (282 and 2, respectively) and on the total detection efficiency calculated from Monte Carlo simulations (average of 10% for the oxygen target and 6% for the lithium target for the excitation range in ^{16}C expected to be populated in this measurement). Similarly an upper limit of 15.5 $\pm$3.9 μb was calculated for the total cross section of the ^{16}O(^{18}O, ^{16}C*$\rightarrow$ ^{6}He+ ^{6}He+ α) reaction.

If the molecular states exist, their nonobservation in this experiment may be because the yield of the (^{18}O, ^{16}C) reactions are too low or the reaction does not select the relevant states. Typical cross sections for other two proton transfer reactions such as (^{12}C, ^{10}Be) [15] and (^{16}O, ^{14}C) [15–17] to the ground and low lying excited states, are in the range 20–500 μb. We have performed a series of statistical model calculations using the program STATIS [18] for the decay from specific excited states of given spin in ^{16}C, over a range of excitation energies (22–30 MeV), by ^{6}He, α, triton, neutron, ^{5}He, and deuteron emission. The transmission coefficients in each channel were calculated using optical potentials from Perey and Perey [19]. The results indicate total decay cross sections of the order 100–170 mb dominated by partial cross sections via neutron emission of the order 60–110 mb. The same calculations predict the decay by ^{6}He emission to the group of four states in ^{10}Be at an excitation energy of 6 MeV to yield cross sections of the order 0.4–1.6 mb indicating a decay probability of about 1 in 100–200 to this specific exit channel. On this basis, our observed upper limit of 1.9 ± 0.4 μb for this channel would imply a total two-proton transfer yield of $\sim$200–400 μb, which can be compared to the typical range of 20–500 μb reported above. Although this would require the ^{16}O(^{18}O, ^{16}C* $\rightarrow$ ^{10}Be(6 MeV)+ ^{6}He) reaction yield to be at the upper limit of the range one must also take into consideration the fact that these calculations do not take into account any structural overlap that may exist between the ^{16}C molecular states and the ^{10}Be* (6-MeV) daughter states. Such an overlap would be expected to enhance this decay mode considerably and therefore the partial cross sections for the exit channel, ^{10}Be(6 MeV)+ ^{6}He quoted previously (0.4–1.6 μb), can be interpreted as lower limits. It is therefore reasonable to assume that despite the large width for neutron decay, breakup from molecular states in ^{16}C to ^{10}Be(6 MeV)+ ^{6}He would be expected to occur with sufficent yield for us to observe. However, if the cross sections for the reactions of interest were lower than those expected from the statistical model then an improvement in the experimental sensitivity would be required in order to detect the desired states. Possibilities for improving the present measurements sensitivity, would include improving the resolution of the particle identification spectra by optimizing the thickness of the silicon quadrant detectors, with perhaps a higher degree of segmentation, or using a target that was not compound in nature. In the present measurement the beam energy of 130 MeV was sufficient only to populate a narrow ($\sim$1–2 MeV) window of excitation range in ^{16}C for reactions off the lithium target due to the lower center of mass energy in this entrance channel. Future investigations would therefore benefit from a higher beam energy. A two neutron pickup study with a ^{14}C beam would also be of interest as it might be expected to have some spectroscopic overlap with the molecular states.

In summary, a search for possible molecular states in ^{16}C decaying to ^{10}Be+ ^{6}He or to ^{6}He+ ^{6}He+ α has found no evidence for decay to either channel. Upper limits on the total reaction cross sections of 1.9 ± 0.4 μb, 0.012 $\pm$0.003 μb, and 15.5 ± 3.9 μb have been extracted for the ^{16}O(^{18}O, ^{10}Be*(6 MeV)+ ^{6}He)^{18}Ne, ^{7}Li(^{18}O, ^{10}Be*(6 MeV)+ ^{6}He)^{9}B, and ^{16}O(^{18}O, ^{6}He+ ^{6}He+ α)^{18}Ne reactions, respectively.

[1] M. Seya, M. Kohno, and S. Nagata, Prog. Theor. Phys. **65**, 204 (1981).
[2] N. Itagaki and S. Okabe, Phys. Rev. C **61**, 044306 (2000).
[3] Y. Kanada-En'yo and H. Horiuchi, Phys. Rev. C **52**, 647 (1995).
[4] Y. Kanada-En'yo, H. Horiuchi, and A. Dote, J. Phys. G **24**, 1499 (1998).
[5] Y. Kanada-En'yo, H. Horiuchi, and A. Dote, Phys. Rev. C **60**, 064304 (1999).
[6] W. von Oertzen, Z. Phys. A **354**, 37 (1996).
[7] W. von Oertzen, Z. Phys. A **357**, 355 (1997).
[8] W. von Oertzen, Z. Phys. A **110**, 895 (1997).
[9] D. M. Brink, *"Many-body description of nuclear structure and reactions,"* in Proceedings of International School of Physics "Enrico Fermi," Course XXXVI, Varenna, 1965, edited by C. Bloch (Academic, New York, 1966), p. 247.
[10] N. de Takacsy and S. das Gupta, Phys. Lett. **36B**, 189 (1971).
[11] N. Itagaki, S. Okabe, K. Ikeda, and I. Tanihata, Phys. Rev. C **64**, 014301 (2001).
[12] P.J. Leask *et al.*, J. Phys. G **27**, B9 (2001).
[13] W.D.M. Rae and R.K. Bhowmik, Nucl. Phys. **A420**, 320 (1984).
[14] N. Curtis *et al.*, Phys. Rev. C **62**, 034603 (2000).
[15] F. Becchetti, D.G. Kovar, B.G. Harvey, D.L. Hendrie, H. Homeyer, J. Mahoney, W. von Oertzen, and N.K. Glendenning, Phys. Rev. C **9**, 1543 (1974).
[16] Y. Eisen, H.T. Fortune, W. Henning, D.G. Kovar, S. Vigdor, and B. Zeidman, Phys. Rev. C **13**, 699 (1976).
[17] C.A. Ogilvie, J.M. Nelson, D. Barker, S.J. Bennett, B.R. Fulton, S.D. Hoath, M.C. Mannion, P.J. Woods, L. Zybert, and R. Zybert, Phys. Rev. C **39**, 139 (1989).
[18] R. G. Stockstad, Wright Nuclear Structure Laboratory Internal Report No. 52, Yale University, 1987 (unpublished), STATIS, a Hauser-Fesbach computer code.
[19] C.M. Perey and F.G. Perey, At. Data Nucl. Data Tables **17**, 1 (1976).