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^{15}N cluster states in triton transfer and their alpha decay

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The technique of resonant particle decay spectroscopy is used to show that states selectively excited in the three-particle transfer reaction ^{12}C(^{7}Li,α)^{15}N have significantly large alpha-particle decay widths. These results imply that simple $t/^3$He and alpha-particle cluster models will not explain the rather simple spectra observed in three-particle transfer reactions. New spectroscopic information on highly excited states in ^{15}N is presented.

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The selective nature of three- and four-particle transfer reactions has suggested that three- and four-particle cluster structures occur in light nuclei. Although the cluster model calculations of Buck and co-workers have been extremely successful in explaining the $t/^3$He and alpha-particle clustering in the mass 19 system [1,2], the success of these calculations in the mass 15 system is less certain [3,4] because the high density of states inhibits one's knowledge of whether the same or different states are populated in three- or four-particle transfer reactions. A cluster model prediction that strong excitation in ^{15}N near 10.7 MeV with both (^{7}Li,t) and (^{6}Li,^{3}He) reactions is actually the population of two different states, with (^{7}Li,t) populating the 10.702, $\frac{3}{2}^-$ state and (^{6}Li,^{3}He) populating the 10.693, $\frac{9}{2}^+$ state, was tested by performing particle/gamma-ray coincidence experiments [5]. They showed that both reactions in fact populated the 10.693, $\frac{9}{2}^+$ state, which implies a large mixing between triton and alpha-particle cluster structures for that state. Their method, however, is not generally applicable since many of the selectively populated states of ^{15}N are above the particle decay thresholds.

In this paper, three-particle cluster states in ^{15}N are populated with the reaction ^{12}C+^{7}Li→^{15}N*+α and the presence of alpha-particle strength in the ^{15}N states populated is observed by use of the method of resonant particle decay spectroscopy (RPDS) in which energies and directions of the decay products, α+^{11}B, are measured in coincidence. Kinematic reconstruction of the coincident events allows us to construct spectra for the ^{15}N decay energy for chosen values of the center of mass formation angle, $\theta^*_{\mathrm{c.m.}}$, and the in-plane decay angle relative to the beam direction, ψ_Z. The RPDS method was developed as a tool for low energy nuclear physics primarily by Rae and his co-workers at Oxford [6] and Berkeley [7], and recently has been extended to important applications in exotic cluster structures in light nuclei [8] and particle decay widths and angular correlation symmetries [9].

In the current experiment, alpha particles are detected in a 5 cm long position sensitive detector and the ^{11}B decay particles are identified in a 1 cm diameter position sensitive counter telescope. The two position signals and two energy signals are recorded in time coincidence sufficient to identify their origin within one beam pulse from the FSU Tandem/LINAC. Bombarding energies are E(^{7}Li)=52.5 MeV for the singles experiment ^{12}C(^{7}Li,α)^{15}N*, and E(^{12}C)=90 MeV for the kinematically reversed coincidence experiment ^{7}Li(^{12}C,^{15}N* → α+^{11}B)α, to obtain the same center of mass energies. In the coincidence experiment, the position measurements of the detected pair, α+^{11}B, along with measured energies and assumed masses, allow one to completely reconstruct the event. A Q-value spectrum is formed from which we can gate on only those events which result in the ground state decay, ^{15}N* → α+^{11}B$_{\mathrm{g.s.}}$. The coincidence data shown in this work are the result of a week of data accumulation with approximately 15 nA of ^{12}C^{+6} beam on a 200 μg/cm^2 ^{7}Li target.

Figure 1 shows a sample ^{12}C(^{7}Li,α)^{15}N* singles spectrum obtained at a laboratory angle of 5° by use of a surface barrier counter telescope. This spectrum contains the same excited states up to E_x=16.2 MeV which were observed in the same reaction at a bombarding energy of 35 MeV [10] and it has all states observed with a 48 MeV ^{7}Li beam [11]. The primary differences in these experiments are the stronger population of the state at 15.39 MeV and the continued selective population of states up to 25 MeV in excitation for the higher bombarding energies. While the ^{12}C(^{7}Li,α) reaction populates a greater number of strong states at high excitation than are observed in other more mismatched three-particle transfer reactions [12,13], there is a set of strongly populated states in all reactions. There are two strong excitations at 13.85 and 17.05 MeV which appear in the ^{11}B(^{7}Li,t)^{15}N reaction [14], but are not observed at forward angles in three particle reactions, otherwise the sets of spectra are

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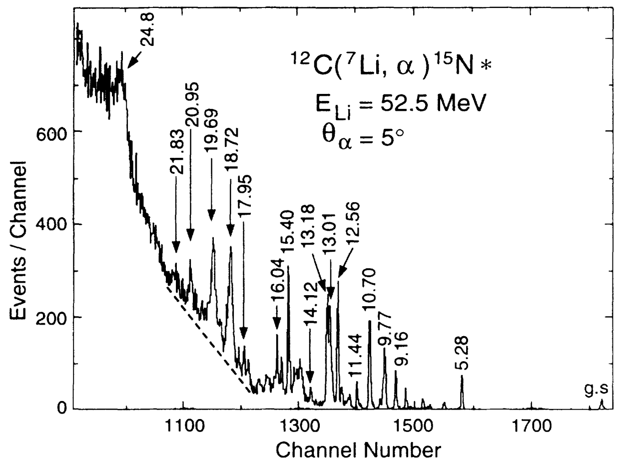

FIG. 1. Energy spectrum for alpha particles produced in the reaction ^{12}C(^{7}Li,α)^{15}N*. Excitation energies indicated in MeV are directly from a calibration based on the bound state energies and correspond closely to known excitation energies in ^{15}N.

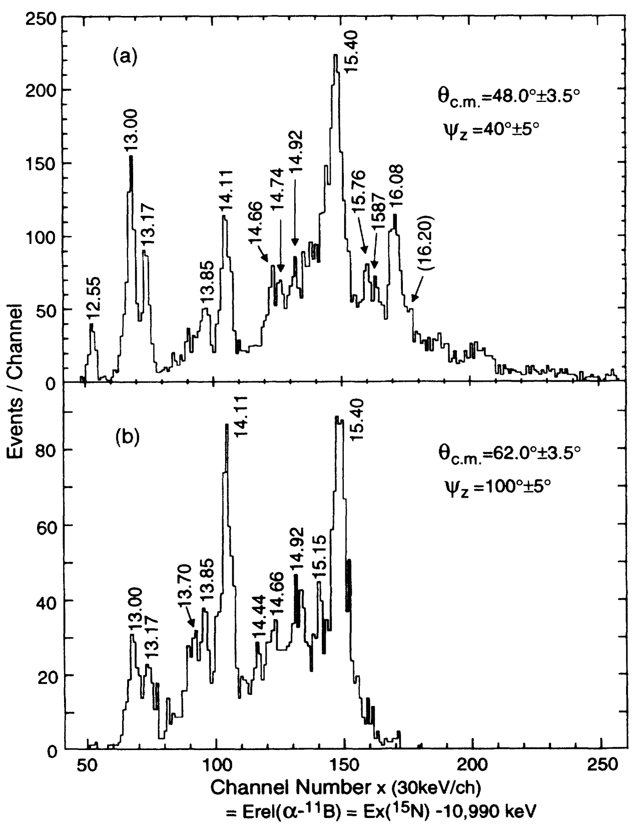

FIG. 2. Decay energy ($E_{\rm rel}$) spectra for ^{15}N* $\rightarrow \alpha+^{11}$B$_{\rm g.s.}$ following ^{15}N* formation in the reaction ^{7}Li(^{12}C,^{15}N*) at E_C(lab)=90 MeV. The angle $\theta_{\rm c.m.}$ is the formation angle of ^{15}N* and ψ_Z is the alpha-particle decay angle relative to the beam direction. The centers of the alpha-particle detector and the ^{11}B detector are $\theta_\alpha \simeq 27°$ and $\theta_B \simeq 8°$, respectively, from the beam direction.

extremely similar.

Figures 2 and 3 show several decay energy spectra that emphasize different regions of excitation in ^{15}N. As can be seen, the proposed three particle cluster states [3,4] at E_x(MeV), J^π=12.55, $\frac{9}{2}^+$; 13.00, $\frac{11}{2}^-$; and 15.39, $\frac{13}{2}^+$, have significant alpha decay widths. A method for the integration of the complete angular correlation is presented in Ref. [9] where the authors have determined the ground state branching fraction for alpha-particle decay of the 12.55 MeV state to be 0.60±0.04 with an absolute uncertainty of 15%. Monte Carlo calculations are used to determine pair detection efficiency at different ^{15}N excitation energies. Although the spectra in Fig. 2 are for angular cuts which have low efficiency for the detection of the 12.55 MeV state, it is clear from the many decay spectra and formation spectra that several states have appreciable alpha-particle widths, for example the states at 13.85 and 17.05 MeV. Alpha-particle branching fractions cannot be determined for many states at the higher excitation energies because of background problems and angular phase space limitations of the detector arrangement. This investigation clearly shows the existence of the 17.05 MeV state which has appeared in the most recent ^{15}N compilation as uncertain [15]. The width of this state is less than 80 keV based on the (^{7}Li,t) experiment [14] and the current work.

The states listed in Ref. [15] at E_x=18.70 and 19.72 MeV with no known decay channels, obviously have alpha-particle decay branches, as observed in Figs. 3(b) and 4(b). Other excitations in the neighborhood of 20 MeV are shown in Fig. 4. The singles spectrum at θ(lab)=5°, Fig. 4(a), has the linear background shown

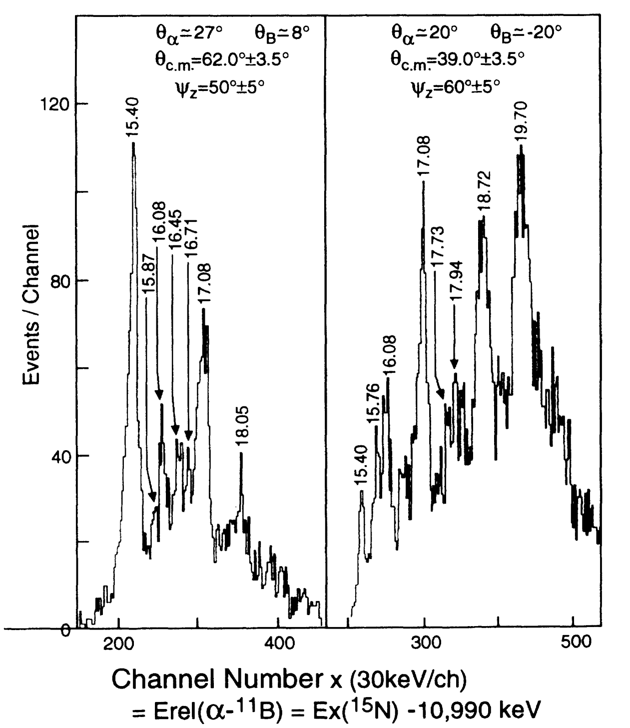

FIG. 3. Decay energy ($E_{\rm rel}$) spectra for ^{15}N* $\rightarrow \alpha+^{11}$B$_{\rm g.s.}$ (see also Fig. 2 caption).

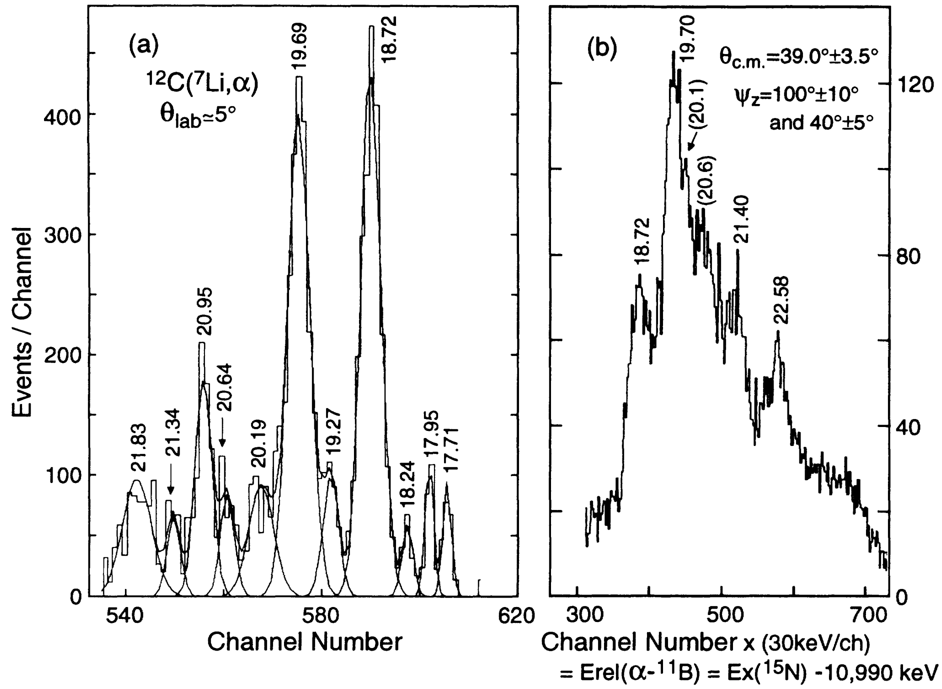

FIG. 4. Formation and decay spectra for $^{15}N^*$ at $E_x \sim 20$ MeV. Part (a) is a background subtracted region from Fig. 1. Part (b) is a decay energy (E_{rel}) spectra for $^{15}N^* \rightarrow \alpha + ^{11}B_{g.s.}$ (see also Fig. 2 caption).

by the dashed line in Fig. 1 subtracted out, so the peak widths shown in Fig. 4(a) are not necessarily representative of the combination of natural and experimental widths. The state at E_x=20.95 MeV has been reported in the literature [11,14]. The excitation energy which appears in the Ajzenberg-Selove compilation [15], however, appears to be a combination of the results of Zeller *et al.* [11], who report a state at 20.93 MeV from the same reaction currently under study, and the work of Del Bianco *et al.* [16], who report E_x=21.26 MeV with a width of 1750 keV. These cannot be the same states. The present work would indicate that there are two different states with the current experiment giving a state at E_x=20.94 MeV ± 30 keV with a width, extracted from the current work by considering various background possibilities, of 250 keV $\leq \Gamma \leq$ 450 keV. The state near 21.37 MeV, which we observe in both formation and its alpha-particle decay, [see Figs. 3(a) and 3(b)], is also not the state reported by Del Bianco [16] that appears in the compilation, if we are to believe their width value, since our data implies a width of less than 400 keV. We note that the state we observe at 21.83 MeV has a width which is entirely consistent with the 600 keV width tabulated by Ajzenberg-Selove for a state at 21.82 MeV. The state which we observe at 21.37 MeV may be the same as the one strongly excited in the $^{14}N(p,\pi^+)$ reaction reported to be at E_x=21.5 MeV [14]. The broad state reported by Del Bianco [16] is not observed in the present study. Other high energy excitations are the previously unreported state at 22.58 MeV which has an alpha-particle decay branch, Fig. 3(b), and a broad state observed in the ^{15}N formation reaction, Fig. 1, at E_x=24.8 MeV, which has been previously reported [15].

The strong overlap between three-particle and four-particle cluster in ^{15}N has been demonstrated. Previously unlisted [15] alpha-particle decays have been observed for ^{15}N states at E_x=11.29, 11.44, 12.35, 12.55, 13.00, 15.4, 16.45, 17.08, 18.7, 19.7, 20.5, 21.4, and 22.6 MeV. The state at E_x=22.6 MeV is a new excited state of ^{15}N and other states at 17.05, 21.4, and 20.95 MeV have been confirmed. A possible new state at 15.15 MeV and doublet structure near the previous 15.78 MeV state require further verification. New width information for some highly excited states has also been determined from this investigation. The method of RPDS is shown as a very useful tool for high energy cluster spectroscopy in light nuclei.

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