(^{6}Li,t), (^{6}Li,^{3}He), and (^{7}Li,t) reactions into the $A = 19$ nuclei

L. M. Martz,* S. J. Sanders,† and P. D. Parker
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520

C. B. Dover
Physics Department, Brookhaven National Laboratory, Upton, New York 11973
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We have studied the ^{16}O(^{6}Li,t)^{19}Ne, ^{16}O(^{6}Li,^{3}He)^{19}F, and ^{15}N(^{7}Li,t)^{19}F reactions at a laboratory angle of 15° and at incident energies of $E(^6\text{Li}) = 46$ MeV and $E(^7\text{Li}) = 40$ MeV. A selective population of final states leads to the identification of probable 3p-0h and 4p-1h configurations. Through the application of a folded-potential model to the ground-state band of ^{19}F, we provide evidence for triton clustering outside a closed-shell core. In a comparison between (^{7}Li,t) reactions leading to ^{19}F and ^{20}Ne, the relationship between 4p-1h and 4p-0h configurations suggests that weak-coupling structure is involved.

[NUCLEAR REACTIONS ^{15}N(^{7}Li, t), $E(^7\text{Li}) = 40$ MeV, ^{16}O(^{6}Li, t) and ^{16}O(^{6}Li, ^{3}He), $E(^6\text{Li}) = 46$ MeV, $\theta_{\text{lab}} = 15°$, measured ^{19}Ne and ^{19}F energy levels, calculated triton-cluster states.]

I. INTRODUCTION

The selectivity of multinucleon transfer reactions provides information on the particle-hole configurations and cluster structure of the residual nuclear states. In measurements using the (^{7}Li, t) and (^{6}Li, d) reactions,[1-4] four-particle multihole (4p-nh) excitations and α-particle clustering have appeared as relatively simple nuclear phenomena at the beginning of the sd shell. The (^{6}Li, t), (^{6}Li, ^{3}He), and (^{7}Li, α) reactions,[5-8] though less extensively studied, have revealed a sensitivity to 3p-nh configurations in this same mass region. In parallel work on nuclear models,[9-12] calculations of cluster structure have shown a significant correspondence to such transfer data.

The results presented in this paper are part of a systematic investigation[13,14] of the (^{6}Li, t) and (^{6}Li, ^{3}He) reactions on targets of ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, and ^{18}O. These reactions facilitate the measurement of three-nucleon stripping with good energy resolution and high angular-momentum transfer. The (^{7}Li, α) reaction is less selective because its better angular-momentum matching allows a stronger population of low-spin states.[15] Since the closed shell of an ^{16}O target is expected to enhance clustering among the transferred nucleons and since spin values are known for many of the relevant final states, we focus initially on the $A = 19$ residual nuclei.

Measurements using the (^{6}Li, t) and (^{6}Li, ^{3}He) reactions reflect the dominance of a direct mechanism.[5,7,16] For the first $\frac{5}{2}^+$ and $\frac{9}{2}^+$ states of ^{19}Ne/^{19}F, the observation of featureless excitation functions[17] and strongly forward-peaked angular distributions[18] is largely reproduced by standard DWBA calculations. The presence of a cluster-transfer process is suggested by the substantial ^{3}He + t parentage of ^{6}Li, as recently reviewed in Ref. 19. In the (^{7}Li, t) reaction, the behavior of cross sections as a function of energy and angle[1,3,20] again indicates a primarily direct mechanism, and the dominance of $^7\text{Li} = \alpha + t$ parentage[21] probably increases the role of cluster transfer. (^{6}Li, d) data are in general characterized by less selectivity and by smaller cross sections.[1,3,22] As in the ^{16}O(^{6}Li, ^{3}He)^{19}F reaction,[18] the structureless character of angular distributions in the ^{15}N(^{7}Li, t)^{19}F reaction[2] implies that forward-angle spectra contain useful information on relative spectroscopic factors. Since the angular-momentum mismatch between the incoming and outgoing channels is typically $6\hbar$ in both reactions, kinematic effects are expected to have little part in any differences between these triton and α-particle transfer spectra.

A comparison of the ^{16}O(^{6}Li, ^{3}He)^{19}F and ^{15}N(^{7}Li, t)^{19}F data, therefore, is a sensitive probe of 3p-0h and 4p-1h structure. In previous work, the ^{16}O(^{6}Li, t)^{19}Ne and ^{16}O(^{6}Li, ^{3}He)^{19}F reactions were measured at $E_{\text{Li}} = 24$ MeV for excitation energies of $E_x < 6$ MeV[23] and at $E_{\text{Li}} = 30$ MeV for $E_x < 9$ MeV[24,25]; ^{15}N(^{7}Li, t)^{19}F data were obtained at $E_{\text{Li}} = 20$ MeV for $E_x < 9$ MeV.[2] The present experiments at higher bombarding energies enhance the direct nature of these reactions and extend the observable region of excitation energy to $E_x \gtrsim 15$ MeV. In addition to $(sd)^3$ and $p^{-1}(sd)^4$ configurations, fp-shell excitations are expected to become important at these energies in the $A = 19$ nuclei.

II. EXPERIMENT

The Yale MP tandem accelerator was used to generate lithium beams with energies in the range from 40 to 46 MeV and with currents of ~200 nA at the target. ^{15}N or ^{16}O gas targets at a pressure of $\frac{1}{16}$ or $\frac{1}{8}$ atmosphere were contained in a 2.5-cm diameter gas cell with a 0.51-μm nickel entrance window and a 2.54-μm Havar exit window. Reaction products were observed using standard Si(SB), $\Delta E/E$ telescopes. At a laboratory angle of 15°, the total energy resolution was typically 150 keV.

The energy calibrations for the experimental spectra were based on known levels of ^{19}Ne or ^{19}F (see the footnotes to Table I). After corrections were made for outgoing-energy losses in the gas and in the exit window, a linear fitting procedure led to estimated uncertainties of 15–50 keV in excitation energy (Table I). Following the subtraction of a Gaussian continuum attributable to Coulomb dissociation, the extraction of differential cross sections for the peaks of interest proceeded by means of a Gaussian fitting routine. Statistical uncertainty in the yield and systematic uncertainties in the target density and in the detector slit width had a total effect of $\lesssim 20\%$ on the absolute cross sections listed in Table I.

III. THEORY

Several features of three- and four-nucleon transfer reactions can be interpreted in a simple and intuitive way through the application of a cluster model. The excitation energies of cluster states in light nuclei can be calculated to first order with the folded-potential method. In view of the encouraging results[9] for α-particle clustering in ^{16}O and ^{20}Ne and for triton clustering in ^{15}N, we have been motivated to extend such calculations to the $A = 19$ system. A cluster model is based on the assumption that wave functions for the states of interest are dominated by leading SU(3) representations in the shell model. Eventually, this simple approach must be supplemented by a full shell-model calculation.

We will compare (Sec. IV) the final states strongly populated by three-nucleon transfer reactions with the bound states and resonances of a potential which exists between the transferred cluster and the target or "core." In the folding method,[26,27] this potential $V(r)$ is approximated by the convolution of the cluster and core densities ρ_A and ρ_B with an effective nucleon-nucleon interaction g:

$$V(r) = \int \rho_A(\vec{r}_1)\,\rho_B(\vec{r}_2)\,g(\vec{r}+\vec{r}_1-\vec{r}_2)\,d\vec{r}_1 d\vec{r}_2 . \quad (1)$$

The function g is chosen to be

$$g(r) = \frac{-2\pi\hbar^2}{M}\,\frac{\bar{f}}{(\pi r_0^2)^{3/2}}\,\exp(-r^2/r_0^2), \quad (2)$$

where M is the nucleon mass and the range r_0 is taken to be 1 fm. In high-energy scattering, $\bar{f}$ would be the nucleon-nucleon forward scattering amplitude. At low energies, however, $\bar{f}$ is difficult to determine accurately from first principles. We therefore treat $\bar{f}$ as a real parameter, which is adjusted phenomenologically to reproduce one of the experimental energy levels. In Eq. (1), the density of a triton cluster is obtained from the experimental charge density[28]

$$\rho^A_{\rm ch}(r) = \rho_0 \exp(-3r^2/2a^2), \quad (3)$$

where $a = 1.64$ fm. In order to use this result as a point mass density ρ_A, we unfold the proton form factor in $\rho^A_{\rm ch}(r)$ and assume that neutron and proton densities have the same radial shape. A theoretical mass density ρ_B for the ^{16}O core is provided by Hartree-Fock calculations.[29]

In analogy to $V(r)$, the Coulomb potential $V_C(r)$ has the folded form

$$V_C(r) = e^2 \int \rho^A_{\rm ch}(\vec{r}_1)\,\rho^B_{\rm ch}(\vec{r}_2)\,\frac{1}{|\vec{r}+\vec{r}_1-\vec{r}_2|}\,d\vec{r}_1 d\vec{r}_2 . \quad (4)$$

Since the triton cluster has spin $s = \frac{1}{2}$, a Thomas spin-orbit potential $V_{SO}(r)$ is also included:

$$V_{SO}(r) = -V_{SO}\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{\bar{f}} \left| \frac{1}{r}\frac{dV(r)}{dr} \right| \vec{L}\cdot\vec{\sigma}, \quad (5)$$

where $\vec{\sigma}$ equals $2\vec{s}$ and V_{SO} is adjusted to reproduce the experimental level splitting. We solve[30] the Schrödinger equation using the total potential $V(r) + V_C(r) + V_{SO}(r)$ and a fixed value of

$$2N + L = \sum_{i=1}^{n_c} (2n_i + l_i) . \quad (6)$$

Here, n_i and l_i are the principal and orbital quantum numbers of the shell-model levels which contribute to the cluster, and n_c is the number of nucleons in the cluster. The principal quantum number N and the orbital angular momentum L thus refer to the motion of the cluster as a whole. By restricting n_i and l_i to shell-model orbitals beyond those occupied by an unexcited core, we satisfy the basic requirements of the Pauli principle.

TABLE I. Excitation energies and differential cross sections from the present experiments are listed with particular known levels of the $A=19$ nuclei.

^{19}Ne (Ref. 31)		^{16}O(^{6}Li, t)^{19}Ne		^{16}O(^{6}Li, ^{3}He)^{19}F		^{15}N(^{7}Li, t)^{19}F		^{19}F		
		$E_{Li}=46$ MeV, $\theta_{lab}=15°$				$E_{Li}=40$ MeV, $\theta_{lab}=15°$				
J^π	E_x (MeV)	E_x [c] (MeV)	$d\sigma/d\Omega_{c.m.}$ [d] (μb/sr)	E_x [e] (MeV)	$d\sigma/d\Omega_{c.m.}$ [d] (μb/sr)	E_x [f] (MeV)	$d\sigma/d\Omega_{c.m.}$ [g] (μb/sr)	E_x (MeV)	J^π	Ref.
$\frac{1}{2}^+$	g.s.							g.s.	$\frac{1}{2}^+$	31
$\frac{5}{2}^+$	0.238	0.23	63	0.20	69	0.19		0.197	$\frac{5}{2}^+$	31
$\frac{1}{2}^-$	0.275							0.110	$\frac{1}{2}^-$	31
$\frac{5}{2}^-$	1.508			1.32		1.34		1.346	$\frac{5}{2}^-$	31
$\frac{3}{2}^+$	1.536	1.54		1.54				1.554	$\frac{3}{2}^+$	31
$\frac{3}{2}^-$	1.616					1.46		1.459	$\frac{3}{2}^-$	31
$\frac{9}{2}^+$	2.795	2.80	148	2.78	128	2.78	77	2.780	$\frac{9}{2}^+$	31
$(\frac{9}{2}^-)$	4.140							4.032	$\frac{9}{2}^-$	31
$(\frac{7}{2}^-)$	4.197	4.21		4.01	50	4.02	317	3.999	$\frac{7}{2}^-$	31
$\frac{7}{2}^+$	4.379	4.38		4.37				4.377	$\frac{7}{2}^+$	31
								4.550	$\frac{5}{2}^+$	31
						4.56		4.556	$\frac{3}{2}^-$	31
$\frac{13}{2}^+$	4.635	4.64	182	4.64	180			4.647	$\frac{13}{2}^+$	31
								5.425	$\frac{7}{2}^-$	31
$(\frac{7}{2}^+)$	5.424	5.42	143	5.45	147	5.46	263	5.465	$\frac{7}{2}^+$	31
								5.500	$\frac{3}{2}^+$	31
	6.094	6.08		6.10		6.10	122	6.090	$\frac{3}{2}^-$	31
	6.289	6.28				6.32	162	6.330	$\frac{7}{2}^+$	31
				6.52				6.500	$\frac{11}{2}^+$	31
	6.862	6.85	95	6.92	115	6.94		6.925	$\frac{7}{2}^-$	31
		7.21		7.25				7.265		31
						7.54		7.56	$\frac{7}{2}^+$	31
	8.06	8.08								31
	8.44	8.45		8.29		8.29	495	8.288	$\frac{13}{2}^-$	31
	etc.	8.94	321	8.96	314	8.95	795	8.953	$\frac{11}{2}^-$	43
						9.35		9.365		46
				9.7				9.710		46
								9.819	$\frac{5}{2}^-$	31
								9.834		46
		9.81	364	9.88	521			9.872	$\frac{11}{2}^-$	31
						9.92	~1800	9.90		34
		10.01	246	10.41	379	10.40		10.411	$\frac{13}{2}^+$	31
		11.08 }		11.24 }				11.217	$\frac{11}{2}^+$	31
		11.24 }	200	11.46 }	221	11.5		etc.		
		11.40 }		11.67 }		11.7				
						12.01				
						12.30 } [b]	1411			
						12.57 }				
		12.56	273	12.71 [a]	383					
		13.1								
		13.22								
				13.76		13.78				
		14.18	72	14.10	156	14.12				
		14.44				14.50	758			
		14.78	181	15.00	280	14.92	3366			

TABLE I. (*Continued*)

	^{19}Ne (Ref. 31)	^{16}O(^{6}Li, t)^{19}Ne $E_{Li}=46$ MeV $\theta_{lab}=15°$		^{16}O(^{6}Li, ^{3}He)^{19}F		^{15}N(^{7}Li, t)^{19}F $E_{Li}=40$ MeV $\theta_{lab}=15°$		^{19}F		
J^π	E_x (MeV)	E_x [c] (MeV)	$d\sigma/d\Omega_{c.m.}$ [d] (μb/sr)	E_x [e] (MeV)	$d\sigma/d\Omega_{c.m.}$ [d] (μb/sr)	E_x [f] (MeV)	$d\sigma/d\Omega_{c.m.}$ [g] (μb/sr)	E_x (MeV)	J^π	Ref.
				15.56	87					
						16.09				
						16.45				
						17.4				
						18.2				
						18.7				
				18.92	49					
						19.93				

[a] Or 12.63/12.77.
[b] Or 12.32/12.46/12.62.
[c] Calibrated from ^{19}Ne*(0.238, 2.795, 5.43), consistent with ^{15}O*(5.241, 7.276, 10.45, 12.835, 15.05), $\Delta E \simeq \pm 20$ keV, $E_x < 13$ MeV, $\Delta E \simeq \pm 30$ keV, $E_x > 13$ MeV.
[d] ±(1%–4%), statistical, ~±10%, absolute.
[e] Calibrated from ^{19}F*(0.197, 2.780, 4.648, 6.925, 8.953, 10.411), $\Delta E \simeq \pm 15$ keV, $E_x < 11$ MeV, $\Delta E \simeq \pm 30$ keV, $E_x > 11$ MeV.
[f] Calibrated from ^{19}F*(2.780, 4.016, 8.953), $\Delta E \simeq \pm 15$ keV, $E_x < 9$ MeV, $\Delta E \simeq \pm 30$ keV, 9 MeV $< E_x <$ 15 MeV, $\Delta E \simeq \pm 50$ keV, $E_x > 15$ MeV.
[g] ±(1%–5%), statistical, ~±15%, absolute.

IV. THREE-NUCLEON TRANSFER

The ^{16}O(^{6}Li, t)^{19}Ne and ^{16}O(^{6}Li, ^{3}He)^{19}F reactions exhibit a combination of kinematic and structural selectivity in the forward-angle spectra for the $A=19$ nuclei [Figs. 1(a), 1(b)]. Preferential population of the ground-state (g.s.) band, which includes ^{19}F*(g.s., $\frac{1}{2}^+$; 0.197, $\frac{5}{2}^+$; 1.554, $\frac{3}{2}^+$; 2.780, $\frac{9}{2}^+$; 4.647, $\frac{13}{2}^+$; 5.465, $\frac{7}{2}^+$; 10.411, $\frac{13}{2}^+$)[31–33] is characterized by enhanced yields for the high-spin members. In contrast, although the ^{16}O(^{6}Li, ^{3}He)^{19}F reaction has an angular-momentum mismatch of ~6$\hbar$, additional $\frac{11}{2}^+$ states at 6.500, 7.937, and 9.266 MeV are populated only weakly if at all. The selection of final states in these spectra, therefore, is not merely a statistical effect, as would be observed in a compound-nucleus process, but is correlated with particular $(sd)^3$ configurations, as expected from a direct mechanism.

The role of a cluster-transfer mechanism in the (^{6}Li, ^{3}He) reaction is reflected in a theoretical study of the final-state structure, specifically an application of the folded-potential model to the ground-state band of ^{19}F (Fig. 2). Given the hypothesis of an $(sd)^3$ triton cluster in motion about an unexcited ^{16}O core, the folded potential generates a $2N+L=6$ band [Eq. (6)] with an approximately $L(L+1)$ spacing. Each eigenstate of the orbital angular momentum is then split by the triton spin-orbit interaction. The two free parameters $\bar{f}$ and V_{SO} [Eqs. (2) and (5)] are adjusted to fit known $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states (at $E_x=5.465$ and 2.780 MeV, respectively) which are strongly populated by the ^{16}O(^{6}Li, ^{3}He)^{19}F reaction. The labeled experimental levels in Fig. 2 exclude the peaks corresponding to known negative-parity states, which are discussed in the next paragraph. Allowing for the simplicity of this model and the high-spin selectivity of this reaction, we find an underlying correspondence between predicted triton-cluster states and the observed triton-transfer spectrum. The calculated $\frac{5}{2}^+$-$\frac{3}{2}^+$ doublet is in good agreement with the experimental excitation energies (Fig. 2), and a reasonable result is obtained even for the ground state of ^{19}F. Although the observed cross section for $J^\pi=\frac{13}{2}^+$ is split between levels at 4.647 MeV and 10.411 MeV, the calculated position of the $\frac{13}{2}^+$ cluster state does approximate their unweighted centroid. The relatively weak population of the $\frac{11}{2}^+$ state at 11.217 MeV suggests that important triton spectroscopic strength lies in other $\frac{11}{2}^+$ states which have not yet been identified. As one relevant candidate, a state of unknown spin at 9.90 MeV is resolved from a multiplet (Table I) by the ^{16}O(α, p)^{19}F reaction.[34] The overall agreement between the predictions of a folded-potential model and the ground-state band of ^{19}F is evidence that triton clustering can be highly developed among $(sd)^3$ nucleons outside the closed-shell core of ^{16}O. Shell-model calculations using SU(3) wave functions support this conclusion by yielding substantial triton spectroscopic factors for the members of this band.[35,36] A cluster model based on a symme-

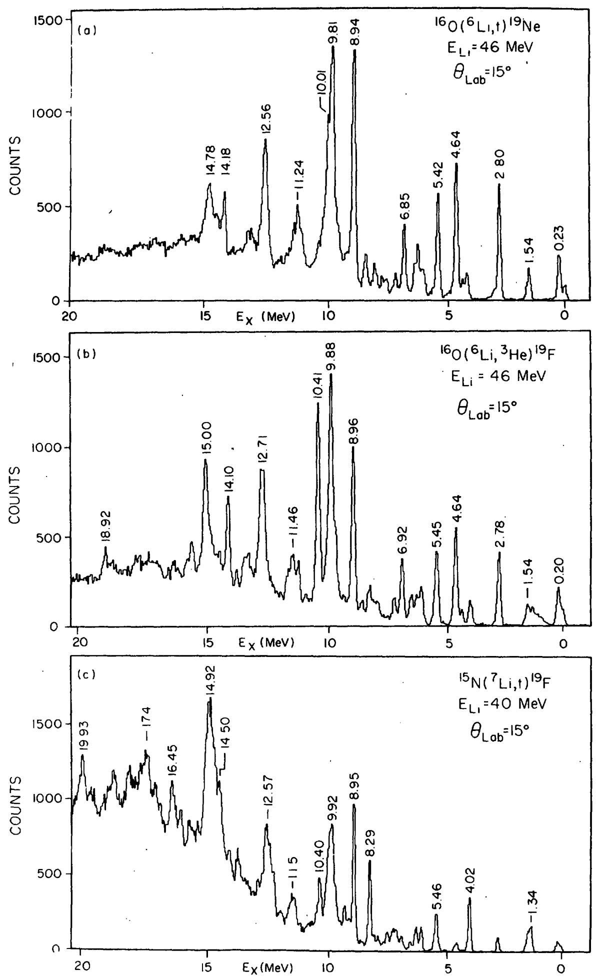

FIG. 1. Comparison of three-nucleon and four-nucleon transfer data for the A = 19 nuclei. The excitation energies shown here are from the present experiments (see Table I).

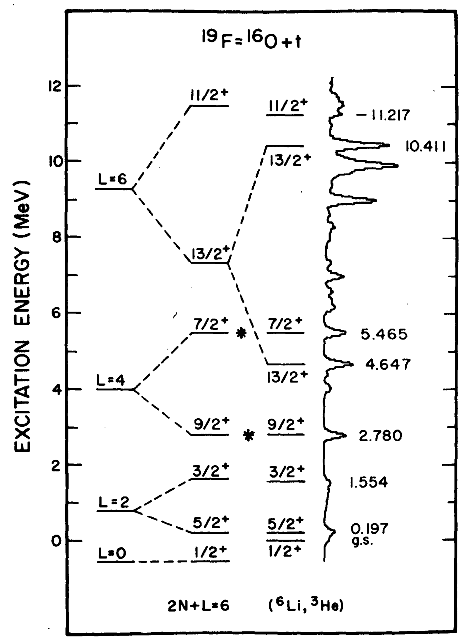

FIG. 2. Comparison of triton-cluster states from the folded-potential model with triton-transfer data from Fig. 1(b). With $\bar{r}$ = 1.514 fm and V_{SO} = 0.016, the theoretical excitation energies (MeV) are −0.57 ($\frac{1}{2}^+$), 0.20 ($\frac{5}{2}^+$), 1.63 ($\frac{3}{2}^+$), 2.78 ($\frac{9}{2}^+$), 5.46 ($\frac{7}{2}^+$), 7.30 ($\frac{13}{2}^+$), and 11.46 ($\frac{11}{2}^+$). The experimental excitation energies and J^π values are from Ref. 31.

trized Woods-Saxon potential[37] also predicts a level scheme similar to that in Fig. 2.

In view of the kinematic and structural selectivity exhibited by the (^{6}Li, ^{3}He) reaction in the case of the ground-state band of ^{19}F, the large peaks in Fig. 1(b) at excitation energies of 12.71, 14.10, and 15.00 MeV in ^{19}F are expected to correspond to additional high-spin states with substantial triton-cluster structure. [Analog states in ^{19}Ne at 12.56, 14.18, and 14.78 MeV can be identified from the ^{16}O(^{6}Li, t)^{19}Ne spectrum in Fig. 1(a), although a more negative Q value reduces their cross sections in Table I.] The strong population of these same states of ^{19}F by the (α,p) and (^{10}B, ^{7}Be) reactions[38-40] is a further indication of their high-spin values. [The (α,p) reaction has an angular-momentum mismatch of ~9$\hbar$ at $E(\alpha)$ = 40 MeV, and an angular-momentum transfer of $\gtrsim 5\hbar$ is predicted in the (^{10}B, ^{7}Be) reaction at $E(^{10}$B$)$ = 100 MeV. These reactions are found to favor the $\frac{13}{2}^+$ states at ^{19}F*(4.647, 10.411) even more strongly than does the (^{6}Li, ^{3}He) reaction.] States with lower spin are populated in the relatively well-matched ^{16}O(^{7}Li, α)^{19}F reaction, e.g., at $E_x \approx 8.5$ MeV[15] and 13.4 MeV.[41] Since nearly all the $(sd)^3$ triton-cluster structure has already been identified in the ^{16}O(^{6}Li, ^{3}He)^{19}F spectrum in Fig. 2, the structure of additional levels, e.g., at ^{19}F*(12.71, 14.10, and 15.00), is expected to be based on one or more fp-shell excitations outside the closed p shell. An $(sd)^2fp$ configuration, in particular, is probable for the negative-parity states[42,43] at ^{19}F* (6.925, $\frac{7}{2}^-$; 8.953, $\frac{11}{2}^-$; 9.872, $\frac{11}{2}^-$) which are prominent in Fig. 1(b).

V. α-PARTICLE TRANSFER

The structure of ^{19}F can be studied in greater detail through a comparison of ^{16}O(^{6}Li, ^{3}He)^{19}F and ^{15}N(^{7}Li, t)^{19}F spectra [Figs. 1(b), 1(c)]. Although 3p-0h configurations are accessible in both reactions, little formation of triton-cluster structure is expected in α-particle transfer. Final states strongly populated in the (^{6}Li, ^{3}He) reaction but clearly inhibited in the (^{7}Li, t) reaction, e.g.,

^{19}F* (2.78, 4.64, 6.92, 10.41, 14.10), therefore appear to have primarily ^{16}O + t parentage. Conversely, minor peaks in (^{6}Li, ^{3}He) data which are prominent in (^{7}Li, t) data, e.g., ^{19}F* (4.02, 8.29, 14.50), probably reflect major 4p-1h components, which are inaccessible to one-step three-nucleon transfer on a closed-shell target. Since the two reactions yield similar relative cross sections for the $\frac{11}{2}^-$ state at 8.953 MeV, large spectroscopic factors are indicated for both α-particle and triton clusters, presumably in $p^{-1}(sd)^4$ and $(sd)^2fp$ configurations, respectively. An identification of specific states in the ^{15}N(^{7}Li, t)^{19}F spectrum is more uncertain at $E_x = 5.46$ and 9.92 MeV (see Table I), and an observation of multiplets near 12 MeV and 15 MeV in excitation further hinders a direct comparison with the ^{16}O(^{6}Li, ^{3}He)^{19}F spectrum. In a detailed analysis, the apparent triplet at 12.32/12.46/12.62 MeV in α-particle transfer has only a limited overlap with the possible doublet at 12.63/12.77 MeV in triton transfer. Overall, except for one major case of mixed structure, the two reactions demonstrate complementary selectivity in their population of states in ^{19}F.

One tentative interpretation of the ^{15}N(^{7}Li, t)^{19}F data in Fig. 1(c) is based on a comparison with the ^{16}O(^{7}Li, t)^{20}Ne reaction at $E_{\rm Li} = 38$ MeV,[1] which identifies 4p-0h states associated with α-particle clustering in ^{20}Ne.[9,11,12] The excitation energies of narrow, negative-parity doublets observed in ^{19}F are consistent with the weak coupling of a $p_{1/2}$ hole to the $(sd)^4$ ground-state band of ^{20}Ne (Table II).[2] In support of this simplified picture, the SU(3) shell model predicts large spectroscopic factors for a $(\lambda\mu) = (01) \otimes (80)$ coupling.[44] In view of the small (^{7}Li, t) cross section for the $J^\pi = 8^+$ member of the ground-state band at ^{20}Ne* (11.95), the large peak at ^{19}F*(12.57) [Fig. 1(c)] may instead correspond to a suggested $(fp)^4$ configuration[45] at ^{20}Ne* (12.59, 6$^+$). Positive-parity doublets in ^{19}F have been mentioned[37] in connection with the low-spin members of the 0$^-$ band in ^{20}Ne (Table II) and, for example, some of the missing $\frac{1}{2}^- \otimes 3^-$ strength may exist at ^{19}F* (7.56, $\frac{7}{2}^+$) (Table I). In the case of fp-shell excitations with $J^\pi = 5^-$ and 7$^-$ in ^{20}Ne (Table II), candidates at $E_x = 9.92$ and 14.92 MeV in ^{19}F have the appropriate (^{7}Li, t) cross sections at $\theta_{\rm lab} = 15°$ (Table I, Ref. 1). Although additional spin assignments are needed to confirm such a relationship, a comparison of the α-particle transfer reactions populating states in ^{19}F and ^{20}Ne suggests considerable $p^{-1} \otimes (^{16}{\rm O} + \alpha)$ structure in ^{19}F.

VI. CONCLUSION

The (^{6}Li, ^{3}He) reaction selectively populates members of the ground-state band in ^{19}F and identifies probable fp-shell excitations at ^{19}F* (6.925, $\frac{7}{2}^-$; 9.872, $\frac{11}{2}^-$; 12.77; 14.10; and 15.00). The (^{6}Li, t) reaction leads to a mirror spectrum for ^{19}Ne with, for example, analogous peaks at ^{19}Ne* (6.85; 9.81; 12.56; 14.18; and 14.78). Through a correspondence between the observed $(sd)^3$ configurations and the predicted $2N + L = 6$ cluster structure, the folded-potential model provides evidence of triton clustering outside the closed-shell core of ^{16}O. By establishing a contrast with the three-nucleon transfer data, the (^{7}Li, t) reaction generally confirms the 3p-0h character of the above final states and identifies predominantly 4p-1h configurations, e.g., at ^{19}F* (4.032, $\frac{9}{2}^-$; 8.288, $\frac{13}{2}^-$; and 14.50). A tentative weak-coupling relationship between 4p-1h states of ^{19}F and 4p-0h states of ^{20}Ne suggests that a $p_{1/2}$ hole has little effect upon α-particle clustering. The role of this weak coupling in triton-cluster structure is presently being studied through an analysis of the ^{15}N(^{6}Li, ^{3}He)^{18}O reaction.

TABLE II. Members of the 4p-0h bands in ^{20}Ne are listed with 4p-1h candidates in ^{19}F.

^{19}F(Refs. 2, 31, 37, 43)		^{20}Ne(Refs. 1, 31, 45)	
0.110	$\frac{1}{2}^-$	g.s.	0$^+$
1.346	$\frac{5}{2}^-$	1.634	2$^+$
1.459	$\frac{3}{2}^-$		
3.999	$\frac{7}{2}^-$	4.248	4$^+$
4.032	$\frac{9}{2}^-$		
8.288	$\frac{13}{2}^-$	8.777	6$^+$
8.953	$\frac{11}{2}^-$		
5.337	$\frac{1}{2}^+$	5.784	1$^-$
5.500	$\frac{3}{2}^+$		
6.282	$\frac{5}{2}^+$	7.168	3$^-$
6.330	$\frac{7}{2}^+$		
(7.560	$\frac{7}{2}^+$)		
9.92		10.261	5$^-$
14.92		15.34	7$^-$
12.57		12.59	6$^+$
(17.4)		17.30	8$^+$
(16.45)		16.63	7$^-$
		21.08	9$^-$

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*Present address: Bell Laboratories, Holmdel, New Jersey 07733.
†Present address: Physics Division, Argonne National Laboratory, Argonne, Illinois 60439.

[1]M. E. Cobern, D. J. Pisano, and P. D. Parker, Phys. Rev. C14, 491 (1976).
[2]R. Middleton, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, 1969,* edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 263.
[3]K. Bethge, Annu. Rev. Nucl. Sci. 20, 255 (1970).
[4]A. A. Ogloblin, Sov. J. Part. Nucl. 3, 467 (1973).
[5]H. G. Bingham, M. L. Halbert, D. C. Hensley, E. Newman, K. W. Kemper, and L. A. Charlton, Phys. Rev. C 11, 1913 (1975).
[6]I. Tserruya, B. Rosner, and K. Bethge, Nucl. Phys. A213, 22 (1973).
[7]R. A. Lindgren, H. H. Gutbrod, H. W. Fulbright, and R. G. Markham, Phys. Rev. Lett. 29, 798 (1972).
[8]G. Bassani, A. Cunsolo, A. Foti, C. Gérardin, M. Lepareux, G. Pappalardo, N. Saunier, A. Strazzeri, and M. Wéry, Report No. CEA-N-1600, 15 (1972).
[9]B. Buck, C. B. Dover, and J. P. Vary, Phys. Rev. C 11, 1803 (1975).
[10]N. Anyas-Weiss, J. C. Cornell, P. S. Fisher, P. N. Hudson, A. Menchaca-Rocha, D. J. Millener, A. D. Panagiotou, D. K. Scott, D. Strottman, D. M. Brink, B. Buck, P. J. Ellis, and T. Engeland, Phys. Rep. 12C, 201 (1974).
[11]A. Arima, H. Horiuchi, K. Kubodera, and N. Tagikawa, Adv. Nucl. Phys. 5, 345 (1972).
[12]T. Matsuse, M. Kamimura, and Y. Fukushima, Prog. Theor. Phys. 53, 706 (1975).
[13]L. M. Martz, S. J. Sanders, P. D. Parker, C. B. Dover, and D. J. Millener, Bull. Am. Phys. Soc. 22, 634 (1977); 23, 501 (1978); in *Proceedings of the International Conference on Nuclear Structure,* contributed papers, Tokyo, 1977, p. 177.
[14]L. M. Martz, Ph.D. thesis, Yale University, 1978 (unpublished).
[15]I. Tserruya, B. Rosner, and K. Bethge, Nucl. Phys. A235, 75 (1974).
[16]G. Bassani, N. Saunier, B. M. Traoré, G. Pappalardo, and A. Foti, Suppl. J. Phys. (Paris) 32, C6-133,135 (1971); and G. Bassani, A. Calamand, G. Pappalardo, N. Saunier, and B. M. Traoré, Report No. CEA-N-1390, 27 (1970).
[17]H. G. Bingham and H. T. Fortune, Phys. Rev. C 7, 2602 (1973).
[18]J. D. Garrett, H. G. Bingham, H. T. Fortune, and R. Middleton, Phys. Rev. C 5, 682 (1972).
[19]M. I. Haftel, R. G. Allas, L. A. Beach, R. O. Bondelid, E. L. Petersen, I. Slaus, J. M. Lambert, and P. A. Treado, Phys. Rev. C 16, 42 (1977).
[20]K. Bethge, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, 1969,* edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 277.
[21]T. A. Tombrello and G. C. Phillips, Phys. Rev. 122, 224 (1961); T. A. Tombrello and P. D. Parker, *ibid.* 131, 2582 (1963).
[22]K. Meier-Ewart, K. Bethge, and K. -O. Pfeiffer, Nucl. Phys. A110, 142 (1968).
[23]H. G. Bingham, H. T. Fortune, J. D. Garrett, and R. Middleton, Phys. Rev. Lett. 26, 1448 (1971).
[24]M. Wery, Ph.D. thesis, Strasbourg, 1972 (unpublished).
[25]A. D. Panagiotou and H. E. Gove, Nucl. Phys. A196, 145 (1972).
[26]J. P. Vary and C. B. Dover, Phys. Rev. Lett. 31, 1510 (1973); J. P. Vary and C. B. Dover, Brookhaven National Laboratory Report No. BNL-19360, 1974 (unpublished); C. B. Dover and J. P. Vary, Brookhaven National Laboratory Report No. BNL-19332, 1974 (unpublished).
[27]C. B. Dover, P. J. Moffa, and J. P. Vary, Phys. Lett. 56B, 4 (1975); P. J. Moffa, C. B. Dover, and J. P. Vary, Phys. Rev. C 16, 1857 (1977).
[28]H. R. Collard and R. Hofstadter, in *Landolt-Börnstein,* edited by K. -H. Hellwege and H. Schopper (Springer, Berlin, 1967), Vol. I2, p. 21.
[29]J. W. Negele, Phys. Rev. C 1, 1260 (1970).
[30]E. H. Auerbach, Comput. Phys. Commun. 15, 165 (1978).
[31]F. Ajzenberg-Selove, Nucl. Phys. A300, 1 (1978).
[32]H. G. Bingham and H. T. Fortune, Phys. Rev. C 6, 1900 (1972).
[33]T. J. M. Symons, L. K. Fifield, M. J. Hurst, A. Pakkanen, F. Watt, C. H. Zimmerman, and K. W. Allen, Phys. Lett. 63B, 409 (1976).
[34]R. Kouzes, D. Mueller, F. Calaprice, and D. J. Millener, Bull. Am. Phys. Soc. 22, 553 (1977).
[35]D. Strottman and D. J. Millener, in *Proceedings of the International Conference on Nuclear Physics, Munich, 1973,* edited by J. de Boer and H. J. Mang (North-Holland, New York, 1973), Vol. 1, p. 107.
[36]T. J. M. Symons, L. K. Fifield, E. F. Garman, M. J. Hurst, F. Watt, C. H. Zimmerman, and K. W. Allen, in *Proceedings of the International Conference on Nuclear Structure,* contributed papers, Tokyo, 1977, p. 192.
[37]B. Buck and A. A. Pilt, Nucl. Phys. A280, 133 (1977).
[38]K. van der Borg, R. J. de Meijer, and A. van der Woude, Nucl. Phys. A273, 172 (1976).
[39]M. Hamm, C. W. Towsley, R. Hanus, K. G. Nair, and K. Nagatani, Phys. Rev. Lett. 36, 846 (1976).
[40]M. Hamm, Ph.D. thesis, Texas A & M University, 1976 (unpublished).
[41]M. Wery, Nucl. Phys. A210, 329 (1973).
[42]W. R. Dixon and R. S. Storey, Nucl. Phys. A284, 97 (1977).
[43]L. K. Fifield, T. J. M. Symons, C. H. Zimmerman, M. J. Hurst, F. Watt, and K. W. Allen, Phys. Lett. 68B, 125 (1977).
[44]A. A. Pilt, D. J. Millener, H. Bradlow, O. Dietzsch, P. S. Fisher, W. J. Naude, W. D. M. Rae, and D. Sinclair, Nucl. Phys. A273, 189 (1976).
[45]S. J. Sanders, L. M. Martz, and P. D. Parker, J. Phys. Soc. Jpn. 44, Suppl. 648 (1978).
[46]T. J. M. Symons, Ph.D. thesis, University of Oxford, 1976 (unpublished).