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Rotational Bands in ^{22}Ne Excited by the ^{18}O(^{7}Li, t)^{22}Ne Reaction*

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The ^{18}O(^{7}Li,t)^{22}Ne reaction has been studied at 12-MeV incident energy. Angular distributions have been extracted for 22 triton groups leading to states in ^{22}Ne up to 8.59 MeV in excitation energy. The experimental angular distributions have been compared with the predictions of the Coulomb-distorted plane-wave model. L values have been assigned and relative α-cluster widths have been extracted for the strong transitions. Significant α clustering has been observed for 10 states in ^{22}Ne between 6.24- and 8.59-MeV excitation energy. Spin and parity assignments have been made to these states from the combined results of the ^{18}O(^{7}Li,t)-^{22}Ne and ^{21}Ne(d,p)^{22}Ne reaction. The classification of the α-cluster states into rotational bands has been discussed within the framework of the SU(3) model.

I. INTRODUCTION

This paper describes an investigation of ^{22}Ne using the ^{18}O(^{7}Li, t)^{22}Ne reaction. In recent years the (^{7}Li, t) reaction has been used extensively to populate α-cluster states in light nuclei.[1-9] The available experimental evidence indicates that, especially for nuclei at the beginning of the 2s-1d shell, the dominant reaction process for the strong transitions at intermediate bombarding energies is the direct transfer of an α cluster with zero spin and isospin.[2-9] It has also been demonstrated that a plane-wave direct-reaction model which incorporates Coulomb distortions and the relative p-state nature of the α-plus-triton clusters in the ^{7}Li projectile, can give a good description of the shape of the angular distributions and the kinematic dependence of the cross sections.[6] The success of the direct-reaction plane-wave model allows the (^{7}Li, t) reaction to be used as a useful spectro-

scopic tool in locating α-cluster states in the final nucleus, determining the angular momentum of the transferred α cluster, and extracting α-cluster widths.

A study of the $^{16}O(^7Li, t)^{20}Ne$ reaction has shown that the α-clustering strength in ^{20}Ne is selectively located within the members of a few rotational bands.[3] Such strength is expected to be spread over more configurations in ^{22}Ne than in ^{20}Ne, which is the simplest $A = 4n$ nucleus in the $2s$-$1d$ shell. Nevertheless, the $^{18}O(^7Li, t)^{22}Ne$ reaction is still expected to excite selectively rotational bands in ^{22}Ne. Furthermore, if the direct process proceeds via transfer of a correlated α cluster, there exists a connection between the cluster-model state and the SU(3) classification of the states in the final nucleus such that the cluster-model state can be expanded into a small number of representations of SU(3).[5,10] In deformed light nuclei, such as ^{22}Ne, the SU(3) classification yields a good first-order description of the actual nuclear states, each representation containing one or several rotational bands.[11-14] Thus, one expects that the $(^7Li, t)$ reaction leading to deformed nuclear states would preferentially populate the members of a selected group of rotational bands. In favorable cases the assignment of SU(3) quantum numbers to these bands may be possible.[5]

In the preceding paper, results have been presented from a high-resolution study of the $^{21}Ne(d, p)^{22}Ne$ reaction in which neutron angular momentum transfers and parity assignments are given for most levels in ^{22}Ne up to 9.10-MeV excitation energy.[15] A detailed discussion of previous work and known spin assignments can also be found in this paper. The present study covers a range of excitation energies from 0 to 8.59 MeV. Triton angular distributions have been measured for most states in this region. Spin and parity assignments have been made for the strongly excited states from the results of a plane-wave analysis of the triton angular distributions in conjuction with the parities determined from the results of the $^{21}Ne(d, p)^{22}Ne$ reaction study. Tentative SU(3) quantum numbers have been assigned to rotational bands strongly populated by the α-transfer reaction.

II. EXPERIMENTAL PROCEDURE

The $^{18}O(^7Li, t)^{22}Ne$ reaction was induced with a 12-MeV $^7Li^{+++}$ beam from the University of Pennsylvania tandem Van de Graaff accelerator. The outgoing tritons were analyzed simultaneously at 23 angles, ranging from $3\frac{3}{4}$ to $168\frac{3}{4}°$ in $7\frac{1}{2}°$ steps, with a multiangle magnetic spectrograph. Ilford K2 plates of 50-μ emulsion thickness were used to detect the outgoing tritons. Some 0.002-in.-thick Mylar absorbers were placed in front of the plates in the first 12 gaps to absorb elastically scattered ^7Li ions. With a Q value of 7.199 MeV the transition leading to the ^{22}Ne ground state could just be recorded with the maximum magnetic fields obtainable.

The targets were prepared by evaporating 50–70 $\mu g/cm^2$ natural calcium onto approximately 100-$\mu g/cm^2$ gold foils, and then oxidizing the calcium with deuterated water enriched to 99% in ^{18}O. Previous experiments had shown that the cross section for ^7Li-induced reactions on ^{40}Ca is extremely small, and no evidence was found in the present experiment for triton groups arising from the calcium in the target. The targets were transferred *in vacuo* to the spectrograph scattering chamber in a bell jar, which was lifted off with a small electric motor after the spectrograph had been pumped down. The fragility of the targets restricted the beam currents used to less than about 150 nA.

No attempt was made to determine accurately the absolute cross sections because of the large uncertainties in the ^{18}O content of the target. A rough estimate was obtained by measuring the yield of recoiling deuterons at $22\frac{1}{2}°$ with a solid-state detector. Since the ^{18}O isotope was supplied almost completely in the form of $D_2{}^{18}O$, the ^{18}O content of the target could be inferred from the deuteron yield. This leads to a peak differential cross section of 3.3 mb/sr for the strongest transition in the spectrum leading to the state at 8.59 MeV. The uncertainty associated with this number is estimated to be ±50%.

III. RESULTS AND ANALYSIS

A triton spectrum measured at $11\frac{1}{4}°$ is shown in Fig. 1. The width of the groups (45 keV full width at half maximum) is mainly due to target thickness. The triton groups are labeled by the measured excitation energies in MeV. Groups arising from ^{12}C and ^{16}O contaminants leading to the ^{16}O ground state and the ^{20}Ne ground and first excited state are labeled $^{16}O_0$, $^{20}Ne_0$, and $^{20}Ne_1$, respectively. 27 triton groups corresponding to states in ^{22}Ne are observed. A comparison of the excitation energies measured in this experiment with those obtained from the $^{21}Ne(d, p)^{22}Ne$ reaction is presented in the first two columns of Table I. In several instances, such as for the transitions to the 5.37-, 6.82-, 7.64-, and 8.59-MeV states, the observed transitions lead to one member of a closely spaced doublet and a weak transition to the other member cannot be ruled out from the experimental data.

Angular distributions of tritons leading to 22 states in ^{22}Ne are shown in Figs. 2 and 3. Be-

cause of kinematic shifts, only partial angular distributions could be measured for the higher excited states. The angular distributions leading to the weakly excited states at 7.92, 8.08, 8.38, and 8.50 MeV could only be followed through a small angular range and are therefore not shown. The groups leading to the 6.64- and 6.70-MeV state were obscured by an impurity group leading to the ^{20}Ne first excited state. The differential cross sections given are in relative units and the error bars are statistical only. Absolute values can be derived using the estimated cross section for the 8.59-MeV state at $3\frac{3}{4}°$ of 3.3 mb/sr.

Since the strong transitions in the (^{7}Li, t) reaction are believed to proceed via the transfer of an α cluster of zero spin and isospin,[3-6] the isospin of the residual nuclear state must be equal to the isospin of the target and the final-state parity equals $\pi_f = (-)^L \pi_i$, where π_i and π_f are the initial and final parity, and L is the orbital angular momentum of the transferred α cluster. Furthermore, for a spin-zero target such as ^{18}O the spin of the residual nuclear state J_f is equal to the orbital angular momentum transfer L. In such a case, the (^{7}Li, t) α-transfer reaction selectively populates natural-parity states.

However, there is evidence to show that the reaction mechanism is not one of purely direct α transfer. Many of the angular distributions show nonnegligible yield of backward angles, presumably indicating the presence of competing nondirect or higher-order direct processes. Significant yield at backward angles is especially noticeable for the high-spin states. An unnatural-parity state, for example, is expected to be excited solely by such competing processes.

The ^{18}O(^{7}Li, t)^{22}Ne angular distributions can therefore be classified to fall into two broad categories. The first includes those corresponding to strong transitions and indicative of a direct α-transfer process. In the second class are the distributions corresponding to weak transitions which exhibit little or none of the characteristic features of a stripping reaction. The two classes of angular distributions are shown in Figs. 2 and 3. It is important to bear in mind that an angular distribution which does not show the characteristic features of a direct α-transfer process does not nec-

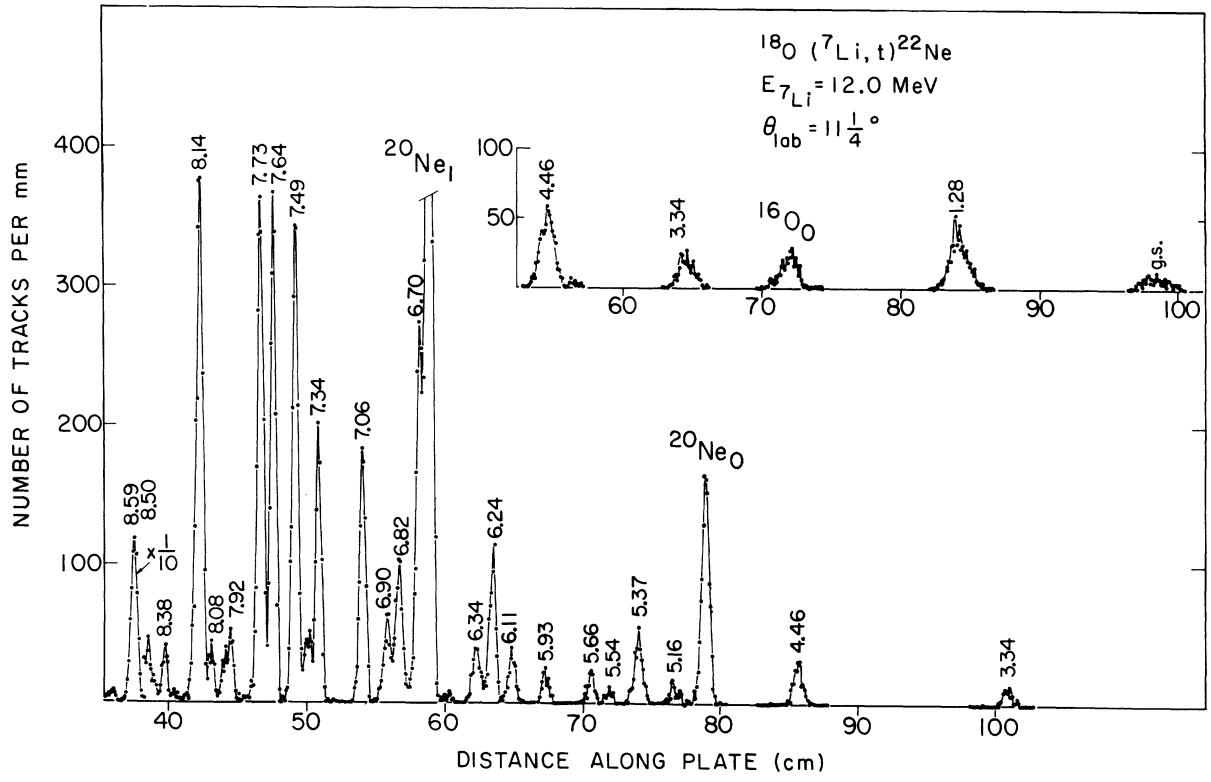

FIG. 1. Triton energy spectrum from the ^{18}O(^{7}Li,t)^{22}Ne reaction measured at a laboratory angle of $11\frac{1}{4}°$ and 12-MeV incident beam energy. The inset at the upper right corner shows the results of a separate exposure utilized to study the lowest three states in ^{22}Ne. The triton groups are labeled with the excitation energy of the corresponding residual state in ^{22}Ne. Contaminant groups are indicated by the symbol and level number of the residual nuclear state.

essarily indicate that the transition leads to an unnatural-parity state, or that it violates the isospin selection rule. The α-transfer cross section is strongly affected by the α-cluster width of the residual state. Also, the projectile form factor can play an important part by inhibiting the direct-reaction cross section at low excitation energies.[6]

Figure 2 shows angular distributions that exhibit features characteristic of a direct process. As for instance, the 0^+, 2^+, 4^+, and 6^+ members of the ground-state rotational band at 0.0, 1.28, 3.34, and 6.34 MeV[16,17] show a more or less pronounced stripping peak which, with increasing spin of the final state, becomes progressively broadened and shifted to larger angles. Pronounced direct characteristics are displayed by the strongly excited group of states around 7-MeV excitation energy. The width and position of the forward maximum appears to be characteristic of the L value of the transition. However, the large momentum transferred by the α cluster to the residual nucleus, especially at high excitation energies, tends to make all angular distributions more or less forward peaked. The effect is also enhanced by the strong absorption present in the incoming and outgoing channels. Consequently, it is sometimes difficult to distinguish between adjacent L values, even after comparison with the predictions of the Coulomb-distorted plane-wave model.[6] In cases of ambiguity, the L values indicated in Fig. 2 are those consistent with the results of the ^{21}Ne(d,p)-^{22}Ne reaction for the spin-parity combination of the state in question. The state at 6.11 MeV is not excited by stripping in the (d,p) reaction. The L value for the corresponding transition in the ^{18}O-(^{7}Li, t)^{22}Ne reaction cannot be identified unambiguously from the shape of the angular distribution, and is hence given within parentheses.

Figure 3 shows angular distributions of weak transitions exhibiting no characteristic patterns. Of these, the two states at 5.16 and 5.66 MeV have $J^\pi = 2^-$ and 3^+, respectively, and therefore unnatural parity.[15,18-20] The 5.54- and 5.93-MeV states have been assigned $J^\pi = 4^+$ and 2^+, respectively,[15,19,20] and their relatively weak excitation is presumably due to a nuclear-structure effect. The 5.37-MeV state is known to be 1^+ or 2^+ from the results of the ^{21}Ne$(d,p)^{22}$Ne reaction.[15] The observed relative cross section at forward angles (Fig. 3) is somewhat larger than that expected for a transition to an unnatural-parity state and a tentative spin-parity assignment of 2^+ is indicated. The structure of the angular distribution at forward angles is consistent with this contention. About the 7.41-MeV state only its negative parity is known.[15] Generally all of the angular distributions shown in Fig. 3 display approximate symmetry about 90° in the center-of-mass system, suggesting the presence of a compound-nuclear mechanism in the excitation of these states.

Figure 4 compares the predictions of the Coulomb-distorted plane-wave model[6] with experimental angular distributions corresponding to strong transitions. The cut-off radius R was varied to obtain best fit. Usually best results were obtained with $R = 7.5$ F, although $R = 8.5$ F gave better fits for the $L = 2$ angular distributions. The narrow peaks at extreme forward angles in the angular distributions corresponding to the states at 4.46, 6.82, and 7.73 MeV are not reproduced by the model. These sharp peaks are believed to be due to the strong absorption present in the incoming and outgoing channels in the (^{7}Li, t) reaction.[21] The plane-wave model simulates such absorption effects merely through the use of a

TABLE I. Results from the ^{18}O(^{7}Li, t)^{22}Ne reaction.

Level No.	E_x (MeV) (Ref. a)	E_x (MeV) (Ref. b)	L	R (F)	$\theta^2(L)$ (relative)
g.s.	0.0	0.0	0	7.5	0.013
1	1.275	1.28	2	8.5	0.056
2	3.358	3.34			
3	4.458	4.46	2	8.5	0.030
4	5.152	5.16			
5	5.331	···			
6	5.359	5.37			
7	5.516	5.54			
8	5.638	5.66			
9	···	5.93			
10	6.120	6.11			
11	···	6.24	0	7.5	0.25
12	6.350	6.34			
13	6.644	···			
14	···	6.70			
15	6.821	6.82	2	7.5	0.06
16	6.858	···			
17	···	6.90	0	7.5	0.14
18	7.055	7.06	1	7.5	0.12
19	7.341	7.34	0	7.5	0.36
20	7.402	7.41			
21	7.488	7.49	1	7.5	0.15
22	7.630	7.64	2	8.5	0.19
23	7.658	···			
24	7.722	7.73	3	7.5	0.24
25	7.927	7.92			
26	8.079	8.08			
27	8.141	8.14	2	8.5	0.26
28	8.387	8.38			
29	8.504	8.50			
30	8.548	···			
31	8.585	8.59	2	8.5	1.00

[a] Ref. 15, ^{21}Ne$(d,p)^{22}$Ne reaction, estimated error ±10 keV.

[b] Present work, ^{18}O(^{7}Li, t)^{22}Ne reaction, estimated error ±25 keV.

radial cutoff. A detailed optical-model analysis appears to be necessary to reproduce adequately the fine structure at extreme forward angles, at least for transitions to 2^+ and higher spin states. No fits are shown to the $L=4$ and $L=6$ angular distributions for the transitions leading to the 3.34- and 6.34-MeV states, since comparatively large contributions from nondirect processes appear to be present. Relative reduced widths extracted with the plane-wave model are listed in Table I for the strongly excited states, together with the L value of the transitions and the cut-off radius.

IV. DISCUSSION

Altogether 10 levels in ^{22}Ne are strongly excited between 6.24 and 8.59 MeV by the α- transfer reaction, indicating significant α clustering for these states. As has been discussed in Sec. III, the angular momentum transfer in a direct α transfer uniquely determines the spin and parity of the final state.

The states at 6.24, 6.90, and 7.34 MeV are excited by $L=0$ transitions in the ^{18}O(^{7}Li, t)^{22}Ne reaction, indicating 0^+ assignments for all three states. The $l_n=2$ transition leading to the 7.34-MeV state in the ^{21}Ne(d, p)^{22}Ne reaction[15] is consistent with the 0^+ assignment for this state. The (d, p) transition leading to the 6.24-MeV state is too weak to allow identification of the angular momentum transfer. The state at 6.90 MeV is not excited at all in the (d, p) reaction. The states at 6.82, 7.64, 8.14, and 8.59 MeV are all excited by

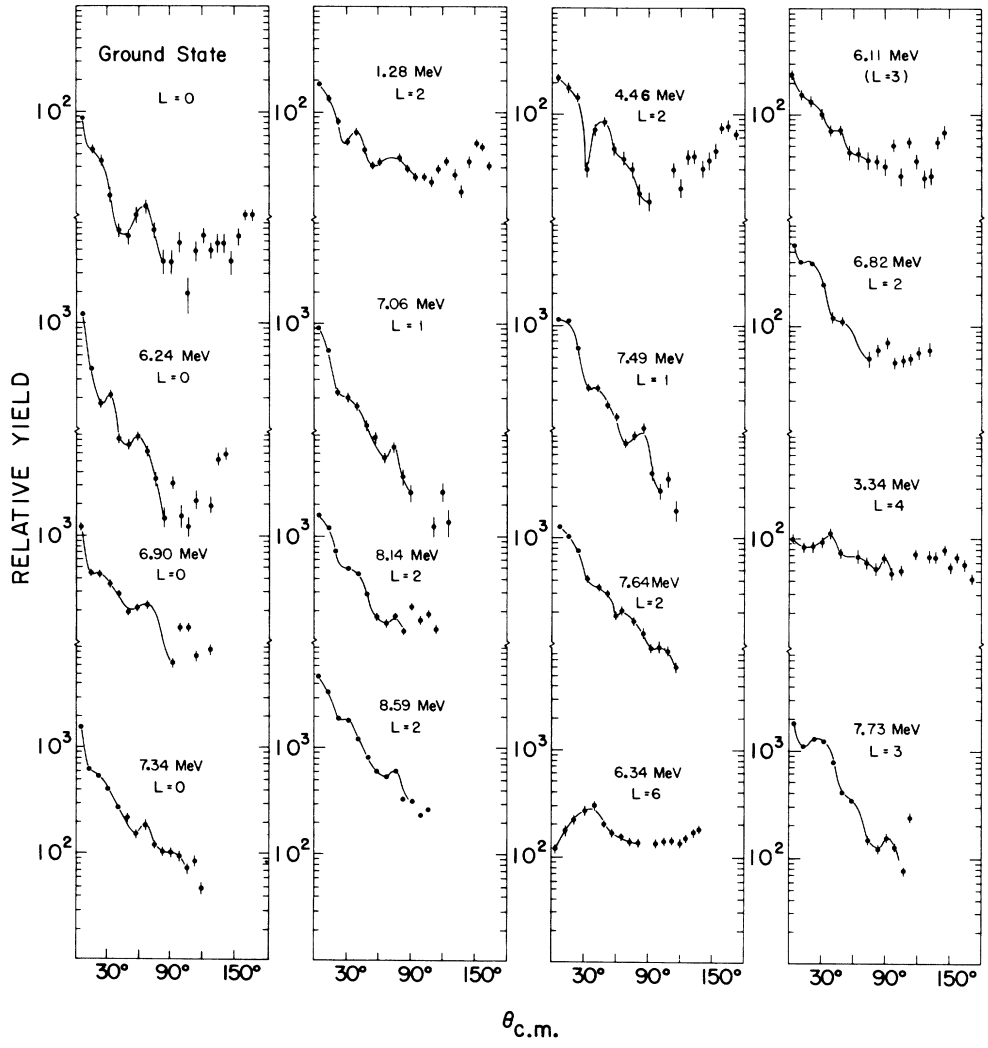

FIG. 2. Triton angular distributions corresponding to strong transitions in the ^{18}O(^{7}Li,t)^{22}Ne reaction and exhibiting features indicative of a direct α-transfer reaction. L signifies the orbital angular momentum transfer. The lines through the data points are not the results of a fitting process and are included only as an interpretive guide.

strong $L=2$ transitions in the (^{7}Li, t) reaction, indicating 2^+ assignments to these states. The (d, p) reaction has identified the parity of all four states to be positive,[15] leading support to the 2^+ assignments. The states at 7.06 and 7.49 MeV have been assigned $J^\pi = 1^-$ in view of the strong $L=1$ transitions observed in the present reaction study. Possible 2^+ assignments are ruled out by the $l_n = 1$ transitions to these states observed in the (d, p) reaction.[15] Lastly, the state at 7.73 MeV is strongly excited by the (^{7}Li, t) reaction, the angular distribution of triton showing a broad stripping peak that can be fitted by an $L=3$ plane-wave-model prediction. The 3^- assignment that follows is supported by the results of the (d, p) reaction which show that the state has odd parity.[15]

Elliott has shown that the SU(3) classification is a useful first-order approximation for the description of nuclei at the beginning of the ($2s, 1d$) shell.[11] According to this model the lowest states in ^{22}Ne have permutational symmetry [42] and arise from the leading representation with $(\lambda\mu)=(82)$. This representation contains the ground-state rotational band with its 0^+, 2^+, 4^+, and 6^+ members at 0.0, 1.28, 3.34, and 6.34 MeV, and a $K^\pi = 2^+$ band. Either the 2^+ state at 4.46 MeV or the probable 2^+ state at 5.37 MeV [15] are possible candidates for the $K^\pi = 2^+$ band head.

The lowest excited configurations in ^{22}Ne are also expected to belong to the [42] representation. Within a given permutational symmetry and for a pure quadrupole-quadrupole force the wave functions classified according to SU(3) are diagonal with energy eigenvalues given by[11, 13]

$$\tfrac{1}{4}b(Q\cdot Q) = bg(\lambda\mu) - \tfrac{3}{4}bL(L+1),$$

where

$$g(\lambda\mu) = (\lambda^2 + \lambda\mu + \mu^2) + 3(\lambda+\mu)$$

is the eigenvalue of the Casimir operator of SU(3) and L is the angular momentum. The proportionality constant b can be derived from nuclei like ^{18}O or ^{20}Ne, in which the position of the excited representation is believed to be known, leading to a value of $b \approx -0.2$ MeV.[13] Applied to ^{22}Ne one expects the lowest excited rotational bands to be associated with the (63), (71), and (44) (twice) representations of SU(3).[11] The first representation contains $K^\pi = 1^+$ and 3^+ bands, the second a $K^\pi = 1^+$ band, and the two (44) representations contain $K^\pi = 0^+$, 2^+, and 4^+ bands. Using the value of b given above, the lower spin states belonging to these bands are expected to be found around

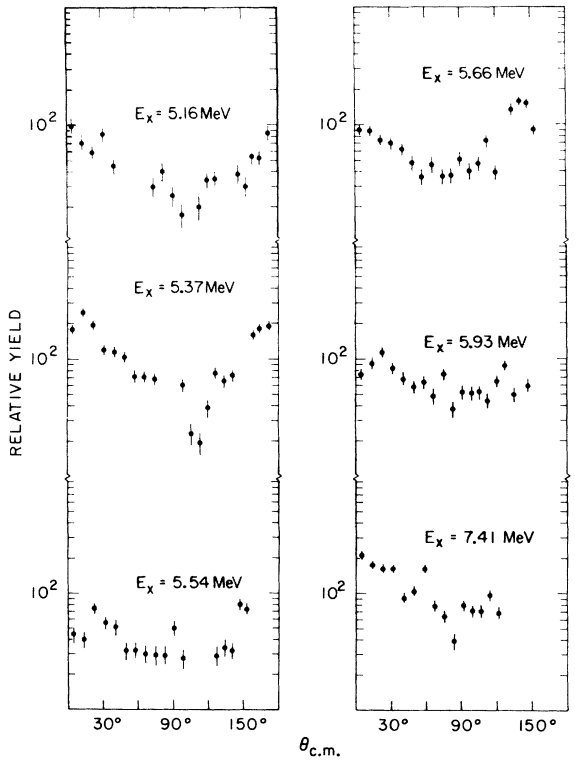

FIG. 3. Triton angular distributions corresponding to weak transitions in the ^{18}O(^{7}Li,t)^{22}Ne reaction and showing little of the characteristic features of a direct reaction.

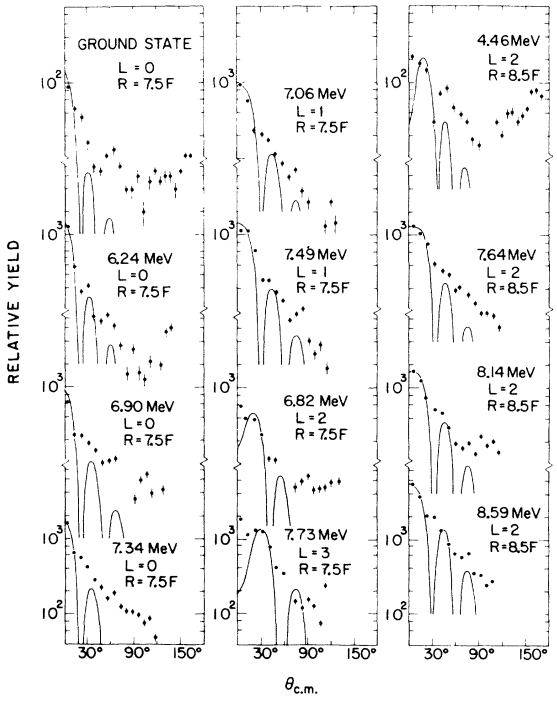

FIG. 4. Plane-wave fits to ^{18}O(^{7}Li,t)^{22}Ne angular distributions. L and R indicate, respectively, the orbital angular momentum transfer and the cut-off radius.

5- to 8-MeV excitation energy.

Additional information can be had from the experiment for those states that are strongly excited by a direct α-cluster transfer. It has been pointed out that α-cluster-model states can be expanded into a limited number of representations of SU(3) and, therefore, the angular momentum states in these representations are likely to be preferentially excited by direct α transfer.[5,10] Applied to the reaction ^{18}O(^{7}Li, t)^{22}Ne we obtain the following results. Starting with the assumption that the ^{18}O ground state has a [2] supermultiplet character, the states in ^{22}Ne which have the configuration of the ^{18}O ground state plus an α cluster must belong to the [42] partition. The cluster-model states associated with the $(1s)^4(1p)^{12}(2s, 1d)^6$ configuration require eight quanta of relative motion between the unexcited ^{18}O nucleus and the α cluster. In the SU(3) model this corresponds to the $(\lambda\mu) = (80)$ representation. Assuming further that the ^{18}O ground state belongs predominantly to the (40) representation,[11,13] we obtain the SU(3) representations in ^{22}Ne which can be carried by the cluster-model state from the outer product; $(80)\otimes(40) = (12,0)\oplus(10,1)\oplus(82)\oplus(63)\oplus(44)$. The (12, 0) and (10, 1) representations, however, cannot be made with six particles in the $(2s, 1d)$ shell,[11] thus leaving only the last three terms in the outer product.

From the nuclear structure and nuclear reaction arguments presented above we are led to the conclusion that two of the three excited 0^+ states around 7 MeV are likely to be associated with the two (44) representations. Several of the excited 2^+ states at 6.82, 7.64, 8.14, and 8.59 MeV might also arise from these two representations. Little can be said about the states belonging to the (63) and (71) representation, especially in view of the fact that the α-transfer reaction excites natural-parity states only. Two $K^\pi = 1^+$ bands with band heads at 5.33 and 6.86 MeV are indicated from the results of the ^{21}Ne$(d, p)^{22}$Ne reaction.[15] The lower one of these two would presumably have to be assigned to the (63) representation. Either the 2^+ level at 4.46 MeV or the probable 2^+ level at 5.37 MeV [15] could be the state more strongly associated with the lowest $K^\pi = 1^+$ band, the remaining state being the band head of the $K^\pi = 2^+$ band arising from the (82) representation. It is also likely that configuration mixing is present, since it is known that representations with the same value of $\lambda + 2\mu$ are being mixed by the residual spin-orbit force.[22]

The strong excitation of a third excited 0^+ state cannot be understood on the basis of the pure SU(3) model assumed above. Furthermore, the appearance of a third 0^+ state in the excitation region around 7 MeV cannot be accounted for by the shell model with six particles in the $(2s, 1d)$ shell.[23] A similar situation exists for the 0^+ state at 5.33 MeV in ^{18}O and one of the two 0^+ states at 6.72 and 7.20 MeV in ^{20}Ne.[23-25] It has been suggested that these states arise from particle-hole configurations.[24,25] This could also provide an explanation for the excitation mechanism of the third excited 0^+ state in ^{22}Ne via the particle-hole amplitude in the ^{18}O ground-state wave function.[24] Another possible explanation would be configuration mixing in the residual nuclear state.

The lowest odd-parity SU(3) representations in ^{22}Ne are expected to be (84) and (11, 1), which have configurations $s^4p^{11}(sd)^7$ and $s^4p^{12}(sd)^5(fp)$, respectively.[11] Of these only the (11, 1) representation contains a $K^\pi = 1^-$ rotational band, indicating that the 1^- and 3^- states at 7.06 and 7.73 MeV are to be associated with the (11, 1) representation. The 2^- member, being an unnatural-parity state, is not expected to be excited strongly by the (^{7}Li, t) reaction. No simple configuration can be suggested for the additional 1^- state at 7.49 MeV excited by the (^{7}Li, t) reaction. The (11, 1) representation also occurs in the expansion of α-cluster states with nine quanta of relative motion between the α cluster and the ^{18}O nucleus, corresponding to the transfer of three particles into the $2s$-$1d$ and one particle into the $1f$-$2p$ shell. Thus it is possible to understand the strong excitation of the 7.06- and 7.73-MeV states in the α-transfer reaction. The situation is similar to that observed in the ^{16}O(^{7}Li, t)^{20}Ne reaction where the (90) representation arising from the promotion of a $(2s, 1d)$ shell particle into the $(2f, 1p)$ shell is strongly excited.[3]

If pure configurations are assumed the negative-parity states arising from the (84) representation obtained by promoting a particle from the $1p$ into the $2s$-$1d$ shell cannot be excited by the (^{7}Li, t) α-transfer reaction. The lowest band expected from this representation is a $K^\pi = 2^-$ band, its band head being presumably the 2^- state[18,20] at 5.16 MeV. The $K^\pi = 0^-$ band resulting from this configuration is expected to be raised in energy compared to the 2^- and 4^- bands since it cannot arise in the extreme model of rigid-body rotations.[12] No excited members of the $K^\pi = 2^-$ band have been identified in this experiment.

V. CONCLUSION

It has been shown that the ^{18}O(^{7}Li, t)^{22}Ne α-transfer reaction can yield useful spectroscopic information, especially when combined with previous results from the ^{21}Ne$(d, p)^{22}$Ne reaction.[15] Strong transitions indicating significant α clustering have been observed to 10 states in ^{22}Ne lying between

6.24 and 8.59 MeV. Spin and parity assignments have been made to these states on the basis of the combined results of the (^{7}Li, t) and (d, p) reaction studies, and relative α widths have been extracted by comparison with the predictions of the plane-wave model.[6] The three strongly excited states at 6.24, 6.90, and 7.34 MeV have been assigned spin and parity 0^+ and are presumably forming $K^\pi = 0^+$ band heads. On the basis of the transition strength at least two of these are believed to belong to the two (44) SU(3) representations that exist in ^{22}Ne, whereas the third one is most likely a many-particle-hole state. Of the seven remaining strongly excited states, the four states at 6.82, 7.64, 8.14, and 8.59 MeV have been assigned spin 2^+. Three of these are likely to be the 2^+ members of the three excited $K^\pi = 0^+$ bands. The states at 7.06 and 7.49 MeV have been assigned spin and parity 1^-, while a 3^- assignment has been made to the state at 7.73 MeV. The states at 7.06 and 7.73 MeV appear to form a $K^\pi = 1^-$ rotational band contained in the (11, 1) representation of SU(3), which results from promoting a particle from the $2s$-$1d$ shell into the $1f$-$2p$ shell.

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