^{3}He cluster structure of ^{12}C

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The reaction ^{9}Be(^{6}Li,t)^{12}C was studied at 32 MeV. Selective population of states was observed up to the 14.1 MeV state in ^{12}C. The high probability for three or more body processes resulted in a large continuum yield which prevented the observation of the population of states in the 17–22 MeV excitation region of ^{12}C. Hauser-Feshbach calculations show that the statistical compound nucleus contribution to the cross section is small. The experimental angular distributions are well reproduced by distorted-wave Born approximation calculations. The extracted relative spectroscopic strengths are in good agreement with theoretical values. The $T=1$ 15.1 and 16.1 MeV states were not observed. A measurement of the ^{9}Be(^{6}Li,^{3}He)^{12}B cross sections to their analog states shows that these states would have a peak height of only 10% of the continuum yield, making it difficult to determine if these states are populated in the present reaction.

I. INTRODUCTION

The demonstration of selective excitation of stretched 1p-1h states by medium energy electron and hadron probes has provided an important new tool for probing structure calculations and for studying effective interactions. Especially fruitful studies[1] have been carried out in ^{16}O, where three 4^- states of $d_{5/2}-p_{3/2}^{-1}$ character have been identified at about 19 MeV of excitation. While only two 4^- states were expected, three states were found experimentally. It has been proposed that mixing with a nearby 4^-, 3p-3h, $T=1$ state is responsible for the spreading of the 1p-1h strength. The three particle transfer reaction ^{13}C(^{6}Li,t)^{16}O weakly populates these stretched 1p-1h states, suggesting little mixing between 3p-3h and 1p-1h states.[2] A very strong peak was observed in the reaction ^{13}C(^{6}Li,t)^{16}O at 20.5 MeV of excitation, which, based on knowledge[3] of ^{16}N, should contain a large fraction of the 4^-, 3p-3h, $T=1$ state.

Similar medium energy studies[4] of ^{12}C have been carried out. Here the situation is considerably more confused because the level widths of the preferentially populated states are around 400 keV with the proposed 4^- stretched states overlapping with 2^- states. The present study, ^{9}Be(^{6}Li,t)^{12}C, was undertaken to search for major 3p-3h strength around 20 MeV in excitation in ^{12}C similar to that observed in ^{16}O at 20.5 MeV. In addition, this reaction can provide information on the α structure of ^{12}C if ^{9}Be is considered to have a strong $\alpha+\alpha+$n configuration.[5] A signature for the population of α states should be the population of the "linear α chain" 7.65 MeV state with a characteristic $L=1$ angular distribution. As will become apparent, the loose binding of ^{9}Be yields an enormous continuum in the spectra, which makes it almost impossible to gain information on the population of states in the 20 MeV region of excitation in ^{12}C.

The present work reports angular distributions for the ^{9}Be(^{6}Li,t)^{12}C reaction taken at a bombarding energy of 32 MeV. Relative spectroscopic strengths were determined by comparing finite range distorted-wave Born-approximation (DWBA) calculations with the experimental data. In addition, the statistical compound nucleus contribution to the transfer cross sections were determined from Hauser-Feshbach calculations. Data were taken for the ^{9}Be(^{6}Li,^{3}He)^{12}B reaction to provide estimates of the expected strengths of the $T=1$ states in ^{12}C.

II. EXPERIMENTAL PROCEDURE

The experiments were performed at Florida State University using the Super FN Tandem Accelerator. ^{6}Li^{3+} ions originating from a sputter source were accelerated to the energy of 32.0 MeV. The target used was a 140 μg/cm^2 self-supporting ^{9}Be foil in an 85 cm diam carbon free scattering chamber. Light particles emitted from the reaction were detected by a ΔE-E telescope, where the ΔE counter was a 300 μm Si surface barrier detector and the E counter was a 5 mm Si(Li) detector, cooled to -20°C. The thicknesses of the ΔE and E counters were selected to stop the elastically scattered ^{6}Li in the ΔE, to yield optimum separation between p, d, and t groups, and to stop the highly energetic d and t particles. A 300 μm Si surface barrier detector was placed at $\theta=45°$ and used as a monitor of the target condition.

The different particle groups were separated by means of the usual ΔE-E two-dimensional plot and each particle group was gated to produce energy spectra. The individual measurements were normalized to each other via the total charge of the beam measured in a Faraday cup and the elastic scattering peak in the monitor counter.

A typical spectrum for the reaction ^{9}Be(^{6}Li,t)^{12}C obtained at $\theta_{lab}=11°$ is shown in Fig. 1(a). The high energy part of the spectrum is free of continuum events, but a large continuum not typical[6] of (^{6}Li,t) reactions on other targets starts at the energy near the threshold for the ^{9}Be(^{6}Li,t)3α reaction. This background is due to simultaneous fragmentation of target and projectile. The valence neutron is loosely bound in ^{9}Be($E=1.67$ MeV) and so is the deuteron in ^{6}Li($E=1.47$ MeV). Separation of ^{9}Be to ^{8}Be + n and of ^{6}Li to $\alpha+$d leads to the four-particle final state reaction ^{9}Be(^{6}Li,t)3α and causes the observed continuum beginning at the 7.65 MeV state in ^{12}C. In this spectrum all the states up to $E_x = 14.08$ MeV appear clearly and well separated, but there is no indication of the $T=1$ states at excitation energies above 14.08 MeV. As can be seen from Fig. 1(b), the continuum background and the weak population of the $T=1$ states are also observed in the ^{9}Be(α,n)^{12}C reaction[7] at a similar energy.

In an early run, the tritons were measured simultaneously with ^{6}Li elastic scattering using a thin ΔE detector, which permitted the elastic events to pass through. Cross sections for the ^{12}C states at several angles were then obtained by normalizing the elastic events to the previously determined elastic scattering cross sections of Ref. 8. The error in the absolute triton cross sections is $\pm 15\%$.

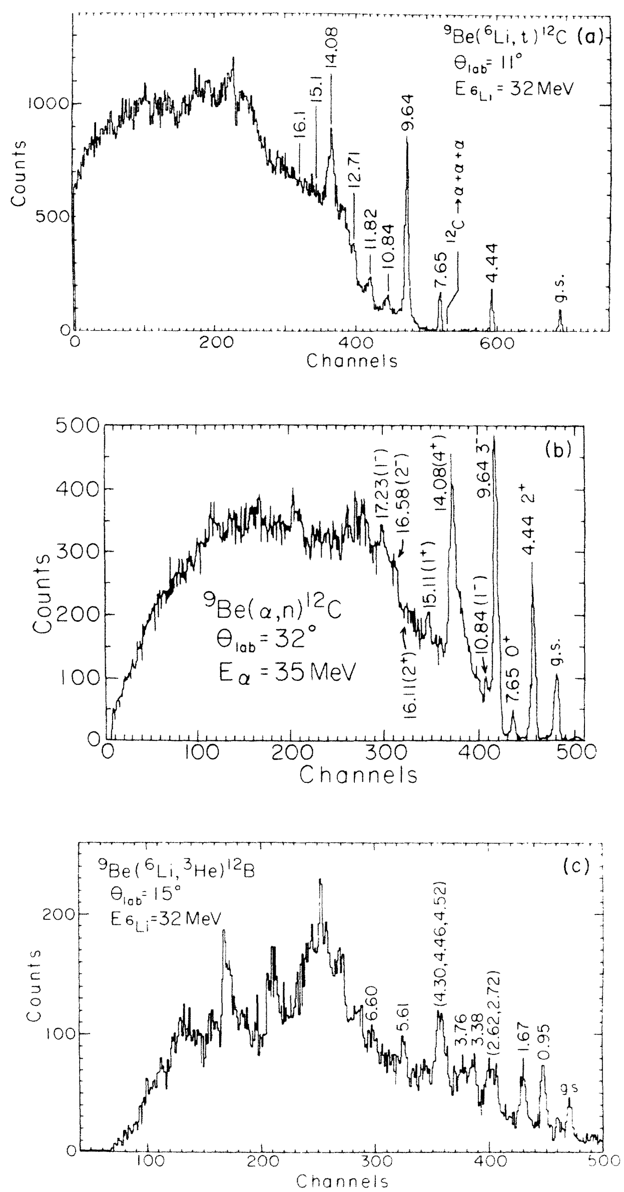

FIG. 1. (a) Typical spectrum from the reaction ^{9}Be(^{6}Li,t)^{12}C at $\theta_{lab} = 11°$ and bombarding energy 32 MeV. (b) Spectrum from the reaction ^{9}Be(α,n)^{12}C taken from Ref. 7. (c) Spectrum from the reaction ^{9}Be(^{6}Li,^{3}He)^{12}B.

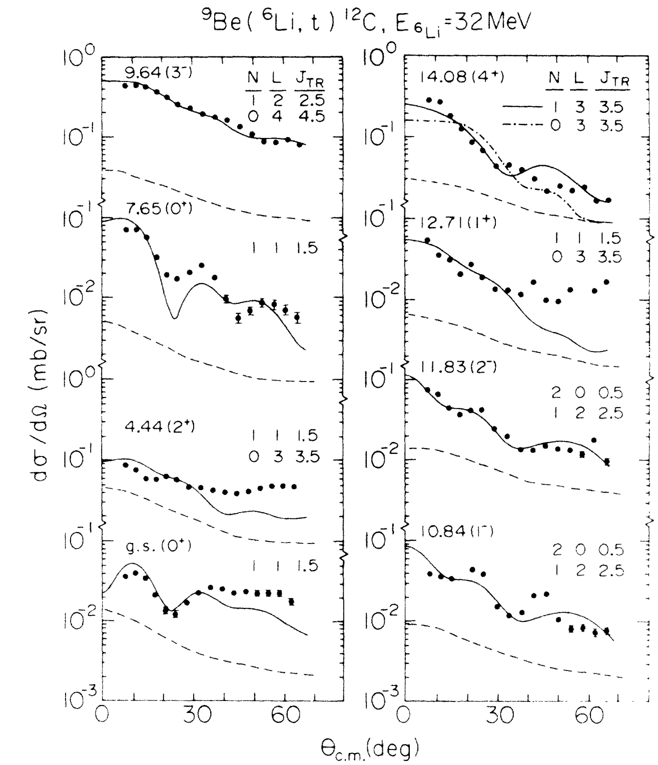

FIG. 2. Angular distributions for the reaction ^{9}Be(^{6}Li,t)^{12}C at bombarding energy $E_{lab} = 32$ MeV. Dashed lines represent the HF cross section and solid lines represent the DWBA calculations.

To get a better understanding of the $T=1$ strengths, a separate run was performed for the reaction ^{9}Be(^{6}Li,^{3}He)^{12}B. A spectrum from this reaction taken at $\theta_{lab} = 15°$ is shown in Fig. 1(c). These measurements are dominated by an extremely high number of low energy α particles from the reaction ^{9}Be(^{6}Li,t)3α. Incomplete separation between the ^{3}He group from the intense ^{4}He group results in the continuum under the ^{3}He peaks. The relative population of states in ^{12}B is similar to that determined earlier[9] in the ^{9}Be(^{7}Li,α)^{12}B reaction. Cross sections were determined for these states also by normalizing to the elastic scattering.

Angular distributions for the reaction ^{9}Be(^{6}Li,t)^{12}C were taken at 16 laboratory angles between 6° and 50° for the eight states up to 14.08 MeV excitation. Most of the angular distributions show a strong direct transfer reaction character, with forward peaking and pronounced structure (Fig. 2). In the reaction ^{9}Be(^{6}Li,^{3}He)^{12}B, two measurements were taken at angles $\theta_{lab} = 15°$ and 30° to make certain of peak identification in the spectra.

III. EXPERIMENTAL RESULTS

The spectrum for the ^{9}Be(^{6}Li,t)^{12}C reaction, found in Fig. 1(a), shows that the 0^+(0.0 MeV)-2^+(4.44 MeV)-

4^{+}(14.08 MeV) ground state rotational band is excited in this reaction, but that the 9.64 MeV (3^{-}) state is the most strongly excited state. In single nucleon transfer studies, the 9.64 MeV state is weakly populated, and the 14.08 MeV state is not observed. The 7.65 MeV state is as strongly populated in (^{6}Li,t) as is the ground state, in contrast to single nucleon transfer,[10] where the ground state population is 10 times stronger. The structure of the 7.65 and 9.64 MeV states are thought to be dominated by an α particle substructure,[11,12] as is the ground state band. The ^{3}He transferred from the (^{6}Li,t) reaction, combined with the excess neutron in ^{9}Be, can strongly excite these alpha cluster states. The $T=1$ states at 15.1 and 16.1 MeV are not observed in this reaction. An estimate of the expected yield for these states can be made from the population of their ^{12}B analog states in the ^{9}Be(^{6}Li,^{3}He)^{12}B reaction [Fig. 1(c)]. These states in ^{12}B have a cross section similar to that of the ground state of ^{12}C. The 15.1 and 16.1 MeV states in ^{12}C are expected to have half their strength, because the ratio of the square of the Clebsch-Gordon coefficient coupling the isospin of the transferred particle and the target to produce the isospin of the residual nucleus is 0.5. Thus, these peaks are expected to rise by only 50—70 counts above the 600 count continuum yield, making it difficult to determine whether or not they are observed in this reaction. However, even at angles larger than 30°, where the continuum is greatly reduced, no population of the 15.1 and 16.1 MeV states is observed. The rising continuum yield makes it difficult to learn anything about the excitation of states in ^{12}C above 15 MeV unless a narrow state is populated. No narrow state equivalent to the strongly excited 20.5 MeV ^{16}O peak[2] is observed in ^{12}C. Shown in Fig. 1(b) is a ^{9}Be(α,n)^{12}C spectrum taken at the University of Colorado.[7] The relative population of states in ^{12}C is the same as in (^{6}Li,t), which reinforces the selective nature of the three particle transfer reaction to ^{12}C. The (α,n) reaction also weakly populates the 15.1 and 16.1 MeV states, although, again, a large continuum occurs because of the low ^{9}Be breakup energy.

IV. CALCULATIONS AND ANALYSIS

The earliest (^{6}Li, t/^{3}He) reaction studies[6] showed a high degree of selectivity, suggesting that these reactions can be represented to a large degree as single step t or ^{3}He cluster transfers for strongly excited states. Subsequent angular distribution measurements[13] carried out at many energies are consistent with this interpretation. However, it has been established that the population of weak states has a large statistical compound nucleus (CN) contribution.[14] Consequently, the present analysis contains both Hauser-Feshbach calculations to assess the statistical contribution to the measured cross sections and finite-range DWBA calculations.

A. Hauser-Feshbach calculations

To estimate the CN contribution to the ^{9}Be(^{6}Li,t) reaction, Hauser-Feshbach (HF) calculations[15] were performed using the code HELGA.[16] The optical model parameters used for the construction of the transmission coefficients were taken from the literature and are listed in Table I. The level density parameters, to which HF calculations are very sensitive, were computed using the method described in Ref. 19 with the expression

$$W(E^*)=\begin{cases}\dfrac{1}{T}\exp[(E^*-E_0)/T], & E^*\le E_x & (1)\\ \exp(2\sqrt{aU})/12\sqrt{2}a^{1/4}U^{5/4}\sigma, & E^*>E_x & (2)\end{cases}$$

with

$$\sigma^2=0.1459\sqrt{aU}A^{2/3},$$

where $W(E^*)$ represents the number of levels between the ground state and excitation energy E^*. Expression (1) was fitted to the known number of levels in the discrete spectrum up to excitation energy E_x, and the parameters E_0 and T were determined. Then by matching the values of expressions (1) and (2) for both magnitude and slope, the level density parameter a is extracted. The parameter U is the excitation energy minus the pairing energy. The calculated level density parameters are listed in Table II.

The calculated compound nucleus cross sections (Fig. 2) are much smaller than the experimental ones and do not reproduce the shape of the data. This finding, that statistical compound nucleus cross sections do not make a significant contribution to the forward angle experimental cross section, is consistent with the extensive studies of Ref. 14. A variation of ±30% should be assigned to the

TABLE I. Optical parameters used in statistical model calculations.

System	V (MeV)	r_0[a] (fm)	a_0 (fm)	W (MeV)	W_D (MeV)	r_I[a] (fm)	a_I (fm)	Ref.
^{6}Li+^{9}Be	174.0	1.22	0.75	5.84	0	2.81	0.75	8
n+^{14}C	$47.01-0.27E_{c.m.}$	1.31	0.66	0	$9.52-0.053E_{c.m.}$	1.25	0.48	17
p+^{14}N	$52.7-0.55E_{c.m.}$	1.25	0.65	0	13.5	1.25	0.47	17
d+^{13}C	92.4	1.04	0.79	0	9.75	1.43	0.69	18
t+^{12}C	162.9	1.18	0.50	11.84	0	1.89	0.56	5
α+^{11}B	52.5	1.91	0.60	0	6.33	1.49	0.60	17
^{3}He+^{12}B	115.9	1.07	0.85	13.3	0	1.74	0.72	17
^{6}He+^{9}B	174.0	1.22	0.75	5.84	0	2.81	0.75	8

[a] $R_x=r_xA_T^{1/3}$.

TABLE II. Level density parameters for statistical model calculations.

Channel	E_0 (MeV)	T (MeV)	a (MeV^{-1})	E_x
^{6}Li+^{9}Be	−13.26	6.11	1.53	38.99
p+^{14}C	3.25	3.02	2.18	13.51
n+^{14}N	−0.63	2.96	2.03	4.44
α+^{11}B	0.73	3.58	1.67	7.88
d+^{13}C	−5.17	4.06	2.11	23.28
t+^{12}C	−7.58	5.65	1.59	36.6
^{3}He+^{12}B	−7.11	3.62	2.39	18.86

magnitude of these calculated cross sections because of uncertainties in the input parameters for the HF calculations.

B. Finite range DWBA calculations

DWBA finite range calculations were performed for the reaction ^{9}Be(^{6}Li,t)^{12}C, assuming a ^{3}He cluster transfer mechanism, using the code DWUCK5.[20] The optical model parameters necessary to generate the distorted waves in the entrance and exit channels were found in the literature. For the channel ^{6}Li+^{9}Be the distorting potential[8] had a real part of $V=174$ MeV, a total interaction radius of $R=2.54$ fm, and a diffuseness of $a=0.75$ fm, while the imaginary part of the potential had an imaginary potential value of $W=5.84$ MeV, radius $R=5.85$ fm, and a diffuseness $a=0.63$ fm. The radius of the Coulomb potential was 4.87 fm. For the outgoing channel only very low energy t+^{12}C elastic scattering data are available, so optical model parameters for the system ^{16}O+t from Cunsolo *et al.*[6] were used. This potential had a real part $V=162.9$ MeV, radius $R=2.61$ fm, and diffuseness $a=0.50$ fm. The imaginary part was given by $W=11.84$ MeV, a radius $R=4.17$, and a diffuseness $a=0.56$ fm. The radius of the Coulomb potential was 2.98 fm.

For the construction of the bound state wave functions for (t+^{3}He) and (^{3}He+^{9}Be), harmonic oscillator wave functions were used with the principal quantum number N and the orbital quantum number L given by the Talmi-Moshinsky rule:

$$2N+L=\sum_{i=1}^{3}(2n_i+l_i)\ ,$$

where n_i,l_i are the quantum numbers of the transferred nucleons. The potential used was of Woods-Saxon type, with the depth adjusted so that it reproduces the separation energies of ^{3}He in ^{6}Li and ^{12}C. The ^{3}He-t system was assumed[21] to be bound in a $1S$ state in a potential well with $V=81.8$ MeV, radius $R=2.49$ fm, and diffuseness $a=0.45$ fm.

For the system ^{9}Be-^{3}He, the single particle configuration assumed was $(0p)^3$ for the positive parity states and $(0p)^2(0d)$ for the negative parity states. The depth of the Woods-Saxon bound state potential was varied to yield the ^{3}He binding energy for each state and the radius and diffuseness of the potential were kept fixed at $R=4.16$ fm and $a=0.65$ fm.

The results of the DWBA calculations are presented in Fig. 2 together with the experimental data and the HF calculated cross section. The compound nucleus cross section is subtracted from the experimental one to yield the experimental direct reaction cross section (σ_{DR}). The DWBA cross sections were fitted to σ_{DR} and the spectroscopic strengths were derived via the expression

$$\frac{d\sigma_{DR}}{d\Omega}=\frac{2J_F+1}{2J_I+1}C^2S_1\left[\sum_L C^2S_L\frac{d\sigma_L}{d\Omega}\text{DWUCK5}\right],$$

where C^2S_1 is the spectroscopic strength for ^{6}Li→t+^{3}He, L are the permitted values of angular momenta in the system ^{9}Be+^{3}He, and C^2S_L their corresponding spectroscopic strengths.

The L values used in the calculations for each state are given in Table III. A spectroscopic strength C^2S_1 of 0.5 was assumed,[21] to obtain the absolute ^{9}Be+^{3}He→^{12}C spectroscopic strengths found in Table III. The agreement between the shape of the calculated and measured angular distributions is good, further confirming the hypothesis that the reaction is a direct ^{3}He transfer process.

The $J^\pi=0^+$ states (g.s. and 7.65 MeV) are well reproduced by an $L=1$ transition, with the 7.65 MeV state having a stronger ^{9}Be+^{3}He character than the ground state. In the case of the 2^+ and 3^- states at 4.44 and 9.65 MeV, which can be populated by more than one L transfer, it is found that the angular distribution shows a much larger contribution from the higher allowed L transfer than from the lower.

The negative parity 1^- and 2^- states at 10.84 and 11.83 MeV are populated almost equally by $L=0$ and 2. These two states also have the smallest relative spectroscopic strength. The fit to the 1^+ $E_x=12.71$ MeV state by a

TABLE III. Cluster spectroscopic strengths C^2S for ^{9}Be+^{3}He→^{12}C.

E_x	J^π	L	C^2S (10^{-2})	$C^2S/C^2S_{g.s.}^{(expt)}$	$C^2S/C^2S_{g.s.}^{(theor)c}$
0.0	0^+	1	13.28	1.0	1.0
4.44	2^+	1	0.72	0.054	0.298
		3	9.08	0.684	0.112
7.65	0^+	1	22.16	1.669	
9.64	3^-	2	5.74	0.432	
		4	24.54	1.848	
10.84	1^-	0	1.41	0.106	
		2	1.52	0.114	
11.83	2^-	0	1.02	0.077	
		2	1.14	0.086	
14.08	4^+	3	7.94[a]	0.598	0.190
		3	2.54[b]	0.191	

[a]Assumed transfer to $(0p)^3$ configuration.
[b]Assumed transfer to $(0p)^1(0d)^2$ configuration.
[c]Reference 22.

combination of $L=1$ and 3 is poor at larger angles and no conclusions can be reached about the spectroscopic strength for this state. The angular distribution of the 4^+ state at 14.08 MeV must have a pure $L=3$ behavior if the transfer is to a state composed of a $(0p)^3$ configuration. A calculation was also performed assuming the three nucleons to go into a $(0p)^1(0d)^2$ configuration. The shape of the experimental angular distribution clearly favors the latter configuration for the transferred nucleons. Both spectroscopic strengths are given in Table III.

The spectroscopic factors obtained from the present analysis are compared with those found by Kurath and Millener[22] (KM) for a transfer of a $(0p)^3$ group in Table III. The KM calculations predict that the ground state transition will be the strongest and the first 0^+ and 2^+ states will have about 65% of the transition strength, which agrees with the present results. In the case of the 14.08 MeV 4^+ state, the shape of the angular distribution agrees with the assumption of a $(0p)^1(0d)^2$ transfer, rather than $(0p)^3$ transfer. The absolute ground state spectroscopic factor obtained by the DWBA analysis is a factor of 4 lower than the one calculated by KM.

Recently, Hamill and Kunz[23] showed that the cross section of the reaction ^{40}Ca(^{6}Li,t)^{43}Ti could be correctly predicted by exact finite range DWBA calculations, while calculations for the reaction ^{40}Ca(α,p)^{43}Sc were 100 times smaller than the data. The present results confirm the fact that the absolute magnitude of the (^{6}Li,t) reaction can be predicted to within a factor of 2, with this factor depending on the choice of the optical model potential parameters and the bound state geometry.

V. CONCLUSIONS

The purpose of this work was to study the transfer behavior of the reaction ^{9}Be(^{6}Li,t)^{12}C at 32 MeV. The highly excited states expected around 20 MeV and the $T=1$ states above 15 MeV were not observed because of the large continuum introduced from the reaction ^{9}Be(^{6}Li,t)3α.

Selective population of states up to 14.1 MeV was observed, and the angular distributions were found to exhibit typical direct transfer characteristics. The exact finite range DWBA calculations performed reproduced both the shape and magnitude of the experimental cross section, and the spectroscopic factors extracted are in good agreement with the ones predicted by Kurath and Millener. The present results show that the ^{3}He+^{9}Be cluster strength in ^{12}C is rather evenly distributed over the first four states in ^{12}C, which correlates with the predicted $\alpha+^{8}$Be strength for these states. However, because of the possibility that the neutron in ^{9}Be combines with the ^{3}He to form an excited α particle in the transfer to ^{12}C, rather than a ground state α particle, it is difficult to assess the usefulness of the reaction ^{9}Be(^{6}Li,t) as a probe of the α structure of ^{12}C.

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