Location of major α strength in ^{13}C at 10.75 MeV

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Strong selectivity for populating a doublet of states at 10.75 MeV in ^{13}C has been observed in the $^{9}Be(^{6}Li, d)^{13}C$ reaction. The spectroscopic strength to other states is a factor 10 less than that observed at 10.75 MeV. Narrow peaks are observed also at 13.41 and 14.12 MeV. The $\frac{9}{2}^{+}$ state at 9.5 MeV is weakly populated here in contrast to $^{10}B(^{6}Li,^{3}He)^{13}C$, where it and the 10.75 MeV states are both strongly excited. The large 10.75 MeV spectroscopic strength is not consistent with a $1p$-shell origin for these states.

I. INTRODUCTION

The nucleus ^{13}C continues to be an important testing ground for both nuclear structure ideas and reaction theories. The finding[1] that pion inelastic scattering to the 9.5 MeV state in ^{13}C yields the predicted free neutron π^- to π^+ scattering strength rekindled interest in the structure of the higher-lying states in ^{13}C. Extreme selectivity for the population of states in ^{13}C is observed in 135 MeV (p,p') (Ref. 2) and $^{12}C(p,\pi^+)$,[3] with the latter reaction strongly populating the 9.5 MeV state and then a peak at 21.4 MeV, while (p,p') weakly excites the 9.50, but strongly excites the 21.4 MeV state. Inelastic electron scattering[4,5] displays similar selectivity to (p,p').

The present work, $^{9}Be(^{6}Li,d)$, was undertaken to provide information on possible α-cluster structure in ^{13}C. The importance of complementary reaction studies was shown for the nucleus ^{13}C with the reaction $^{10}B(^{6}Li,^{3}He)^{13}C$ giving a clear signature[6] that the 9.5 MeV state was of high spin, and therefore corroborating the initial pion inelastic scattering assignment[1] of $\frac{9}{2}^{+}$ to this state. The principal goal of the present work was to investigate states above 8 MeV in ^{13}C and to determine if there is any concentration of α strength in ^{13}C. The relatively high $\alpha+{}^{9}Be$ threshold of 10.65 MeV means that four particle transfer reactions must be used to accomplish this goal.

The reactions $(^{6}Li,d)$ and $(d,^{6}Li)$ have been extensively used to establish the α spectroscopic structure of light nuclei,[7] and the successful interpretation of the transfer data with structure calculations have shown these reactions to be useful for obtaining relative α strengths in a nucleus. In the present work, angular distributions have been measured for the $^{9}Be(^{6}Li,d)^{13}C$ reaction. Alpha spectroscopic factors have been obtained for these data by comparing finite-range DWBA calculations to the data. The α strength in ^{13}C is concentrated in a doublet of states at 10.75 MeV that are reached via $L=2$ transfer. The structure of these states is probably outside a $1p$-shell basis[5].

II. EXPERIMENTAL PROCEDURE

The 32 MeV ^{6}Li beams needed for the experiment were produced by extracting $^{6}Li^{-}$ from an inverted sputter source and then stripping and accelerating the beam with the F.S.U. Super FN Tandem Van de Graaff. The target was a self-supporting ^{9}Be foil of thickness 140 $\mu g/cm^2$. Several detector combinations were used in the $\Delta E\times E$ counter telescopes to allow different excitation regions in ^{13}C to be studied with optimum resolution. A typical combination was a 150 μm Si surface-barrier ΔE detector followed by a 5 mm Si(Li) E counter cooled to $-20\,^{\circ}C$. The target condition was monitored by a 300 μm Si surface-barrier detector.

For the separation of the particle groups, $\Delta E\times E$ plots were formed and the different mass groups were gated to produce the energy spectra. A typical spectrum is shown in Fig. 1. The resolution was about 110 keV. As can be seen, extremely selective population of states in ^{13}C up to 14 MeV in excitation is observed. The 10.75+10.81 MeV doublet[8] is strongly excited, while the 9.5 MeV $(\frac{9}{2}^{+})$ state is weak. The latter state is strongly excited[1,3] in (p,π) and $\pi^{-}+{}^{13}C$, whereas the 10.75+10.81 doublet is weakly excited in these reactions. The reaction $^{10}B(^{6}Li,^{3}He)$ excites[6] both the 9.5 and 10.75 MeV doublet with the 9.5 MeV state being stronger than the 10.75 MeV doublet. A spectrum and angular distributions for the $^{9}Be(^{6}Li,d)$ reaction have been reported[9] for a ^{6}Li energy of 23.8 MeV. The peak at 10.8 MeV is also observed to be the strongest in that spectrum although the selectivity of the reaction is not as great as observed here.

The mass 13 compilation[8] shows that the peak observed at about 10.75 MeV can be composed of a doublet whose member states would be 10.753 ($\frac{7}{2}^{-}$, $\Gamma=55$ keV) and 10.818 [($\frac{5}{2}^{-}$), $\Gamma=24$ keV]. To determine the energy of the strong peak at 10.75 MeV a separate run was made. Spectra were taken with a target that contained 30 $\mu g/cm^2$ ^{9}Be and 5 $\mu g/cm^2$ ^{12}C, so that the $^{12}C(^{6}Li,d)^{16}O$ states would provide additional calibration points. The result was that the centroid of the peak was 10.75

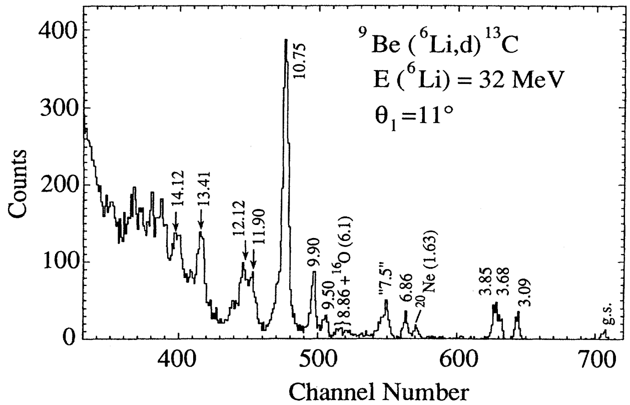

FIG. 1. Experimental spectrum for the ^{9}Be(^{6}Li,d)^{13}C reaction.

MeV±18 keV. However, the width of the peak after removal of the 70 keV experimental resolution in this run was 130 keV, so that either a new state is being formed or, more likely, both members of the 10.753 and 10.818 MeV doublet are populated. This mixed target also ensured that misidentification of the ^{13}C peaks with those from [^{12}C(^{6}Li,d)]^{16}O did not occur.

A doublet is observed at around 12 MeV in ^{9}Be(^{6}Li,d) whose peaks have widths that are consistent with proposed $\frac{3}{2}^-$ strength[8] at 11.85 MeV and a $\frac{5}{2}^-$ state at 12.13 MeV. A moderately strong peak has been observed in both (π,π') (Ref. 1) and (p,p') (Refs. 2 and 10) at about 11.85 MeV that is a proposed $(\frac{7}{2}^+,\frac{5}{2}^+)$ doublet. Since (p,p') only very weakly excites the 9.9 and 10.75 MeV states, which have large α spectroscopic strengths, probably a new state is seen in the inelastic scattering that is relatively narrow and does not appear in the present ^{13}C compilation.

Angular distributions for the ^{9}Be(^{6}Li,d)^{13}C reaction were taken from $\theta_{lab}=6°$ to 50° in 2.5° increments at $E_{lab}(^6\mathrm{Li})=32$ MeV. The absolute cross section was determined by comparing the elastic scattering taken with the present setup to previously reported results.[11] The uncertainty in the absolute cross section is about 15%.

III. ANALYSIS

To determine the transition strengths and the transferred orbital angular momenta, exact finite-range DWBA calculations were carried out assuming a one-step α-transfer process with the computer code DWUCK5.[12] The optical-model parameters used for the construction of the entrance- and exit-channel distorted waves are listed in Table I. For the ^{6}Li+^{9}Be entrance channel, the parameters were taken from the elastic scattering analysis of Cook and Kemper.[11] These parameters have yielded good descriptions of other reaction data. The $d+^{13}$C optical parameters of Newman *et al.*[13] were used in the exit channel. The $d+^{13}$C data were also reanalyzed to determine if a different optical parameter set could be found which gave an equivalent fit to the $d+^{13}$C data as the Newman *et al.*[13] parameters and a superior description of the (^{6}Li,d) data. None was found.

The alpha and the deuteron in ^{6}Li were assumed to be bound in a relative $1s$ state, in a Woods-Saxon potential of depth $V=79.9$ MeV, radius $R=1.9$ fm, and diffuseness $a=0.65$ fm.[14] The single-particle configuration for the system (^{9}Be+α) was taken to be $(0p)^4$ for the negative parity states and $(0p)^3(0d)$ for the positive parity states, except for the $\frac{1}{2}^+$ first excited state, for which a configuration $(0p)^3(1s)$ was considered. The Woods-Saxon potential binding the ^{9}Be and the α particle had a radius of $R=2.76$ fm and diffuseness $a=0.65$ fm, while the depth was adjusted so that it reproduced the separation energy of the α particle in the various excited states. The 10.75 MeV state is unbound by 100 keV but in the analysis here it was assumed that the state was bound by 100 keV.

In cases where only one L value contributes to the transition, the DWBA cross section was normalized to the data to extract the spectroscopic strength. In the more usual case, more than one L value contributed to the experimental cross section so that a linear combination of the DWBA cross sections for each transition was formed and the coefficients representing different transfers were varied to give the best fit to the data.

The results of the DWBA calculations with the parameters presented here were typically of the same order of magnitude as the data, but, as has been reported extensively earlier, the magnitude of the calculated cross section was found to vary drastically with the choice of the optical-model parameters used and the radius of the bound-state wave function, thus excluding any possibility of extracting realistic absolute spectroscopic strengths.

The experimental angular distributions and corresponding calculations are shown in Figs. 2 and 3. The description of the data except for the strong 10.75 MeV doublet is in general poor, especially for the positive parity states. The combined $3.68(\frac{3}{2}^-)+3.85(\frac{5}{2}^+)$ data are displayed as well as the resolved data at four angles. The angular region for the better resolution data was chosen because the $L=0$ and $L=1$ contributions are maximum,

TABLE I. Optical-model parameters[a] for the DWBA calculations.

Channel	V (MeV)	r_R (fm)	a_R (fm)	W (MeV)	$W'=4W_D$ (MeV)	r_I (fm)	a_I (fm)	r_C (fm)	Ref.
^{6}Li+^{9}Be	174.0	1.22	0.75	5.84		2.81	0.63	2.34	11
$d+^{13}$C	92.41	1.038	0.79		39.0	1.426	0.693	1.3	13

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

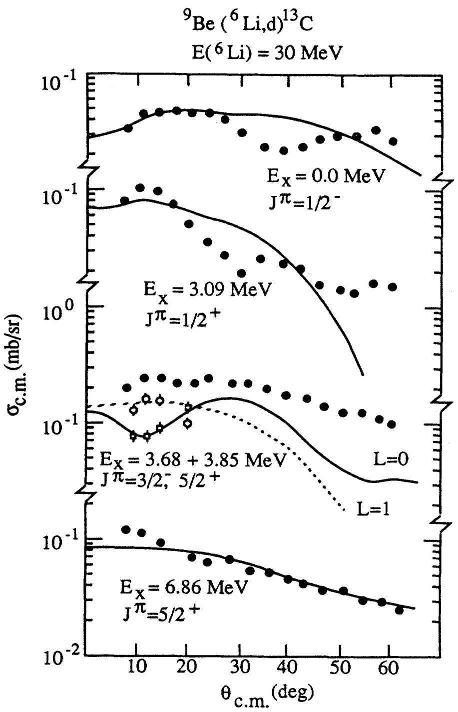

FIG. 2. Measured angular distributions for the reactions indicated. The statistical errors are shown on the data points, or are the size of the data point or smaller. The solid curves are the results of finite-range DWBA calculations.

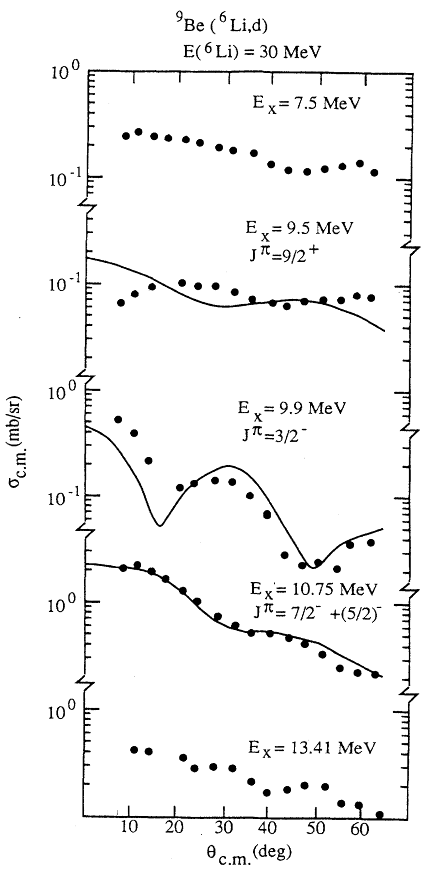

FIG. 3. Same as for Fig. 2.

allowing the spectroscopic factors for these states and L transfers to be found. Table II gives the spectroscopic factors found from the present analysis. A comparison is also made for the negative parity states with the α spectroscopic factors computed for the $1p$ shell by Kurath.[15] While the ratio of the $\frac{1}{2}^-$, ground and $\frac{3}{2}^-$, 3.68 MeV states are in reasonable agreement, neither the 9.9 MeV $\frac{3}{2}^-$ nor 10.75 MeV $\frac{7}{2}^- + (\frac{5}{2}^-)$ states appear to correlate with the $1p$-shell-basis hypothesis for these α transfers.

Other peaks appear in the spectrum of Fig. 1 which correspond to narrow states reported earlier in ^{9}Be(α,n) and (α,α) works.[16,17] The presence of a narrow state at 13.42 MeV observed in ^{9}Be(α,α) is confirmed. Its proposed assignment[17] of $\frac{9}{2}^-$ is supported by the featureless angular distribution shown in Fig. 2, but the L transfer is not characteristic enough to yield more detailed conclusions. The width of the peak at 14.13 MeV is broader than that of the 13.41, showing that both the $\frac{5}{2}^-$ and $\frac{7}{2}^+$ states reported[8] at 14.11 and 14.16 MeV in ^{13}C are excited.

In summary, the present work has investigated the ^{9}Be(^{6}Li,d)^{13}C reaction. The major $\alpha+^9$Be strength in ^{13}C is located in the 10.75+10.81 MeV states. Comparisons between the derived spectroscopic factors and those with a shell-model $(0p)^4$ basis show that this strength arises from higher orbits. The results[5] of recent electron scattering to states in ^{13}C suggest that the 9.9 MeV $(\frac{3}{2}^-)$ state has the configuration $(0p)^2(1s0d)^2$ and suggests this same configuration for the states at 10.75 MeV.[5,18]

Large-angle elastic scattering between light nuclei that differ by an α particle, such as ^{7}Li+^{11}B,[19] ^{14}N+^{10}B,[20] and ^{13}C+^{9}Be,[21] tends to have a much larger cross section than between non-α pairs such as ^{7}Li+^{13}C.[19] Generally, calculations are carried out for the α-particle differing pairs that describe the large-angle cross section as a sum

TABLE II. Spectroscopic strengths for ^{9}Be$+\alpha \rightarrow ^{13}$C.

E_x(MeV)	J^π	L	S_L(exp)[a]	S_L(th)[b]
0.0	$\frac{1}{2}^-$	2	1.9	0.41
3.09	$\frac{1}{2}^+$	1	2.3	
3.68	$\frac{3}{2}^-$	0	1.7	0.24
3.85	$\frac{5}{2}^+$	1	1.4	
6.86	$\frac{5}{2}^+$	1	0.19	
		3	0.38	
9.50	$\frac{9}{2}^+$	3	0.55	
9.90	$\frac{3}{2}^-$	0	7.2	0.003
		2	1.45	0.002
10.75	$\frac{7}{2}^-$	2	24.6	0.047
+	+			
10.82	$(\frac{5}{2}^-)$			

[a]The spectroscopic factor for $\alpha+d \rightarrow ^6$Li was taken to be 0.69.
[b]Ref. 15.

of elastic scattering and an α-transfer reaction. The α transfer is assumed to take place between the ground states of the interacting nuclei. In the case of $^{13}C+{}^{9}Be$, it is clear that one must include the contribution from the 10.75 MeV peak and perhaps this is true for all of the α pairs studied to date. The failure to include virtual α transfer to excited states could be the reason for the relatively poor description of the large-angle cross sections,[19,20] although the relatively weak excitation[2] of the 10.8 MeV states in $^{13}C(p,p')$ makes the importance of this process in $^{9}Be+{}^{13}C$ scattering difficult to assess without detailed calculations. The importance of inelastic virtual transitions to unbound levels has been demonstrated through coupled-channels calculations[22] of vector-polarized ^{6}Li and ^{7}Li elastic scattering. The possible contribution of virtual α-particle transfer to elastic scattering needs to be investigated also.

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