Direct and compound components of the $^{27}Al(^6Li,\alpha)^{29}Si$ reaction at 32 MeV

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At a bombarding energy of 32 MeV, angular distributions have been measured for seven states populated in the reaction $^{27}Al(^6Li,\alpha)^{29}Si$. Angular distributions and angle-integrated cross sections have been compared with results of distorted-wave Born-approximation and statistical compound-nucleus calculations, in order to assess the relative importance of direct and compound processes.

I. INTRODUCTION

Several studies[1,2] have demonstrated the complicated nature of the $(^6Li,\alpha)$ reaction. Both zero- and exact finite-range distorted-wave Born-approximation (DWBA) calculations failed to describe the angular-distribution data[1,2] at 34 MeV on ^{12}C and ^{16}O. Recently, Cook *et al.*,[3] in their study of the $^{16}O(^6Li,\alpha)^{18}F$ reaction at 48 MeV discussed "enhanced" back-angle cross sections, and the inability of exact finite-range DWBA theory to describe the data. Exchange contributions were also included, but these too failed to account for the large-angle data. The authors also carried out a statistical analysis in order to extract the compound-nucleus contribution. This contribution was stated to be only one percent as large as the data.

In order to examine the relative importance of the direct and compound contributions, we have studied the $^{27}Al(^6Li,\alpha)^{29}Si$ reaction at 32 MeV. We have carried out zero-range DWBA calculations along with a statistical analysis (based on the Hauser-Feshbach formalism) in order to extract the direct and compound nuclear components, respectively.

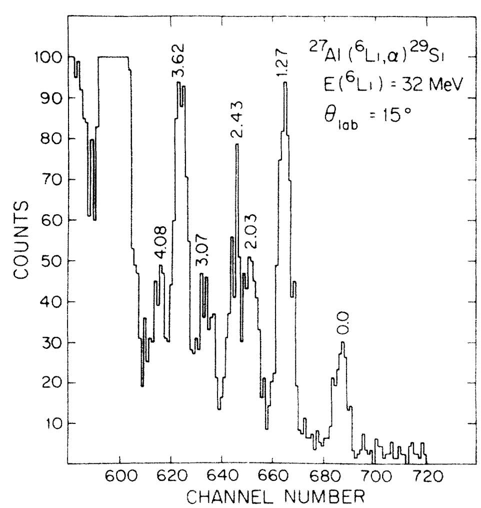

FIG. 1. Alpha-particle spectrum for the reaction $^{27}Al(^6Li,\alpha)^{29}Si$, at $E(^6Li)=32$ MeV and $\theta_{lab}=15°$.

II. EXPERIMENTAL

A 32-MeV $^6Li(3^+)$ beam from the University of Pennsylvania tandem van de Graaff accelerator bombarded a self-supporting aluminum foil of nominal areal density 100 $\mu g/cm^2$. The outgoing alpha particles were detected in an array of four solid-state detectors, which were placed 10° apart in the scattering plane. As the Q value for the alpha channel is sufficiently large and positive, there was no need for particle identification. A 0.064-mm nickel foil in front of each detector stopped the elastically scattered particles. Data were collected in 5° steps from 10° to 85° (in the laboratory). The absolute cross-section scale was determined by measuring $^{27}Al(\alpha,\alpha)^{27}Al$ at 25 MeV, and normalizing the forward-angle data to that of Kemper *et al.*[4] This normalization is believed to be accurate to within 10%. A typical spectrum is displayed in Fig. 1. The first six levels of ^{29}Si are clearly resolved. No impurity peaks are apparent in the region of interest. All the low-lying levels of ^{29}Si have known values[5] of J^π and hence provide for a range of known L transfer values. Excitation energies were not determined in the present work, but were taken from the compilation. Angular dis-

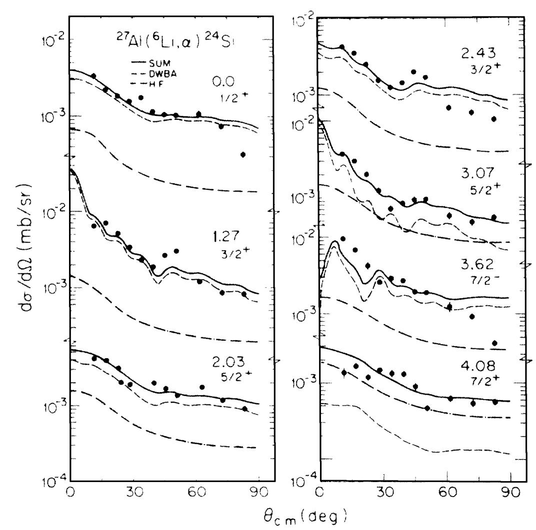

FIG. 2. Angular distributions of low-lying levels with DWBA (dashed) and HF (dot-dashed) curves and their sum (solid). The experimentally determined spectroscopic factors are used.

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TABLE I. Results of the ^{27}Al(^{6}Li,α)^{29}Si reaction.

E_x[a] (MeV)	J^π	σ_{expt}[b] (μb)	σ_{dir}[c] (μb)	σ_{HF}[d] (μb)	σ_{comp}[e] (μb)	$\frac{\sigma_{expt}-\sigma_{HF}}{\sigma_{dir}}$
0.00	$\frac{1}{2}^+$	6.26±0.31	2.726	1.03	0.9±0.1	1.92
1.27	$\frac{3}{2}^+$	12.17±0.61	10.192	1.98	1.8±0.2	1.00
2.03	$\frac{5}{2}^+$	9.87±0.49	3.234	2.74	2.7±0.3	2.20
2.43	$\frac{3}{2}^+$	7.19±0.36	2.804	1.83	1.8±0.2	1.91
3.07	$\frac{5}{2}^+$	5.29±0.27	1.713	2.59	2.7±0.3	1.58
3.62	$\frac{7}{2}^-$	11.30±0.57		3.41	3.6±0.4	
4.08	$\frac{7}{2}^+$	4.77±0.48	0.744	3.47	3.6±0.4	1.75
				Average		1.73

[a]Reference 5.
[b]$\sigma_{expt}=2\pi\int d\sigma/d\Omega_{expt}\sin\theta\, d\theta$.
[c]$\sigma_{dir}=2\pi\int d\sigma/d\Omega_{th}\sin\theta\, d\theta$, see the text [Eqs. (1), and (2)].
[d]Angle-integrated (0°–90°) cross sections calculated with the code STATIS (Ref. 10).
[e]$\sigma_{comp}=(2J_f+1)\sigma_{cn}$, see the text [Eq. (4)].

tributions for the low-lying states of ^{29}Si, along with DWBA and Hauser-Feshbach curves, are shown in Fig. 2. The DWBA and Hauser-Feshbach calculations are described below. Angle-integrated (0°–90°) cross sections are listed in Table I for seven states.

III. RESULTS AND ANALYSIS

No trend is apparent when we look at σ_{expt} vs $2J_f+1$, where J_f is the total angular momentum of the final state. However, if we assume that, at this energy, the only contributions to the cross section arise solely from direct one-step cluster transfer and compound processes, and that the two are incoherent, then states with a small σ_{expt} (e.g., those at 3.07 and 4.08 MeV) probably possess a small direct cross section. Similar effects were observed in a recent study[6] of the ^{27}Al(α,d)^{29}Si reaction, at $E_\alpha=26$ MeV.

Theoretical DWBA angular distributions were calculated with the code DWUCK4 (Ref. 7) using the optical-model parameters[8,9] listed in Table II. In zero-range DWBA one assumes the ^{27}Al(^{6}Li,α)^{29}Si reaction to be a direct deuteron cluster transfer, and that the low-lying positive-parity states can be populated with $L=0$, 2, and 4, with the exception of the g.s. ($\frac{1}{2}^+$), for which $L=0$ is not allowed. We have carried out zero-range DWBA calculations for the allowed multiple (J,L) transfers, using the cluster relation $2N+L=4$ to fix the radial quantum number N. For the negative-parity state at 3.62 MeV ($\frac{7}{2}^-$), we set $2N+L=5$. The theoretical (DWBA) differential cross section as evaluated by the code DWUCK4 is of the form

$$\frac{d\sigma}{d\Omega_{th}}=\frac{(2J_f+1)}{(2J_i+1)}\sum S(J,L)\frac{\frac{d\sigma}{d\Omega_{J,L}}(\text{DWBA})}{(2J+1)}\,, \quad (1)$$

where J_i, J, and J_f are, respectively, initial, transferred, and final angular momentum, L is the transferred orbital angular momentum, and $S(J,L)$ are cluster transfer spectroscopic factors. The evaluation of the above expression requires the knowledge of these spectroscopic factors. In the present analysis the spectroscopic factors were determined from microscopic two-nucleon amplitudes using the SU(3) coefficients listed in Ref. 9. The necessary two-nucleon amplitudes were taken from the literature.[6,9]

TABLE II. Optical-model and level-density parameters.

Channel	V (MeV)	r (fm)	a (fm)	W_0 (MeV)	r_w (fm)	a_w (fm)	r_c (fm)	a[a] (MeV^{-1})	δ[b] (MeV)
^{6}Li + ^{27}Al	170.0	1.210	0.300	−16.2	1.950	0.760	1.300	3.456	2.25
^{4}He + ^{29}Si	228.0	1.366	0.557	−23.3	1.242	0.557	1.400	3.567	2.25
d + ^{27}Al	c	1.150	0.350				1.150		
n + ^{32}S			Transmission coefficients for these					3.392	4.50
p + ^{32}P			channels were parametrized (Ref. 10)					3.456	0.00
d + ^{31}P								3.875	2.25
t + ^{30}P								3.480	0.00

[a]Level densities (Ref. 11).
[b]Pairing energies (Ref. 10).
[c]Potential depth adjusted to give proper binding energy.

Calculated spectroscopic factors for the dominant (J,L) configurations are listed in Table III. Knowing $d\sigma/d\Omega_{th}$, it is then a simple matter of using the expression

$$\sigma_{dir} = 2\pi \int \frac{d\sigma}{d\Omega_{th}} \sin\theta \, d\theta \tag{2}$$

to calculate the (0°–90°) angle-integrated direct cross section. To compare this quantity with σ_{expt}, we have plotted σ_{expt} vs σ_{dir}, both quantities being weighted by $1/(2J_f+1)$. The result is shown in Fig. 3. The 1.27-MeV $(\frac{3}{2}^+)$ state is not included because the theoretical spectroscopic factors yield a σ_{dir} which is too large by a factor of 2 to 3. If

$$\sigma_{expt} = N\sigma_{dir} + \sigma_{comp} \tag{3}$$

and

$$\sigma_{comp} = (2J_f+1)\sigma_{cn} \tag{4}$$

then data in this plot should have a slope of N and an intercept of σ_{cn}. The line through the data points represents a least squares fit with slope 2.0±0.2 and intercept 0.45±0.05 μb. The linear relationship indicates that the two-nucleon amplitudes used in the calculations adequately describe the microscopic structure of the low-lying states. Also, the nonzero intercept implies the existence of a nondirect component in the cross section. If we assume this component to be of compound origin, and further assume that its magnitude is given by Eq. (4), then this would lead to a compound cross section of 3.6 μb for the 4.08 MeV $(\frac{7}{2}^+)$ state. Note that this is 75% of the total cross section (Table I) measured for this state.

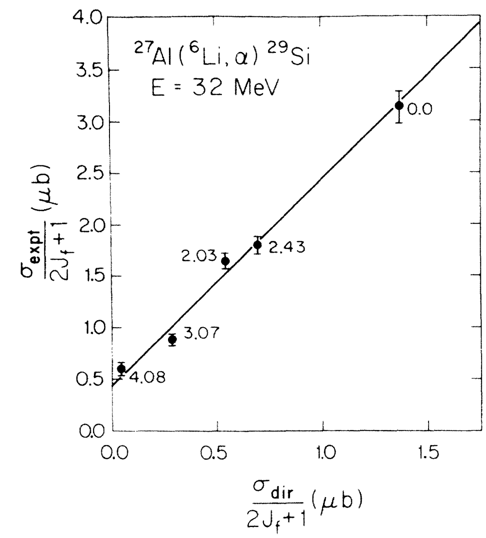

FIG. 3. Plot of σ_{expt} vs σ_{dir} with both quantities weighted by $1/(2J_f+1)$. σ_{expt} and σ_{dir} are defined in the text and listed in Table I. The 1.27-MeV $(\frac{3}{2}^+)$ state is not included.

TABLE III. Calculated and experimentally extracted spectroscopic factors.

E_x[a] (MeV)	J^π	1	J	S_{JL}(cal)[b]	S_{JL}(expt)
0.00	$\frac{1}{2}^+$	2	3	0.5939	0.117
		4	3	0.0138	0.490
1.27	$\frac{3}{2}^+$	0	1	0.2940	0.219
		2	2	0.1368	0.335
		4	4	0.4931	
2.03	$\frac{5}{2}^+$	0	1	0.0435	
		2	2	0.0363	0.047
		4	5	0.1181	0.210
2.43	$\frac{3}{2}^+$	0	1	0.1385	
		2	2	0.0875	0.125
		4	3	0.0099	0.230
3.07	$\frac{5}{2}^+$	0	1	0.0302	0.029
		2	1	0.0592	0.074
		4	5	0.0137	
3.62	$\frac{7}{2}^-$	1	2		0.034
		3	3		0.293
4.08	$\frac{7}{2}^+$	0	1	0.0010	
		2	2	0.0230	
		4	4	0.0123	0.037

[a]Reference 5.
[b]References 6 and 9.

Rather than assuming that compound cross sections are proportional to $2J_f+1$, another way of rewriting Eq. (3) is the following:

$$\sigma_{expt} = \alpha\sigma_{HF} + \beta\sigma_{dir} , \tag{5}$$

where σ_{HF} is the compound cross section calculated with the statistical model of Hauser and Feshbach. The extraction of the normalization constants α and β from the data is discussed below. Of course, if the absolute magnitude of HF calculations were known, α would be equal to one. The compound-nuclear cross sections σ_{HF} have been calculated with the code STATIS.[10] The necessary optical-model parameters, pairing energies, and level-density parameters were taken from the literature.[10,11] These are listed in Table II. The fusion cross section for the ^{6}Li + ^{27}Al reaction at 32 MeV is not known, but a reasonable estimate can be made by using the model of Glas and Mosel[12] with the parameters suggested by Kovar *et al.*[13] This parametrization results in a cross section of 1084±76 mb at 32 MeV. We reproduced this cross section with STATIS by employing an L cutoff for the transmission coefficients in the entrance channel. The effect of this procedure and the sensitivity of the angular distributions to variations in the level-density parameters has been discussed by many authors.[14,15] The main conclusion drawn by these authors was that the calculated cross sections may vary by as much as 30–50%, depending on the uncertainties in the level-density parameters.

To test the validity of Eq. (5), we have plotted [in Fig. (4)] σ_{HF} vs σ_{dir}, both quantities being weighted by $1/\sigma_{expt}$. As expected the linear behavior is borne out by the data. The line represents a least squares fit to the data. From

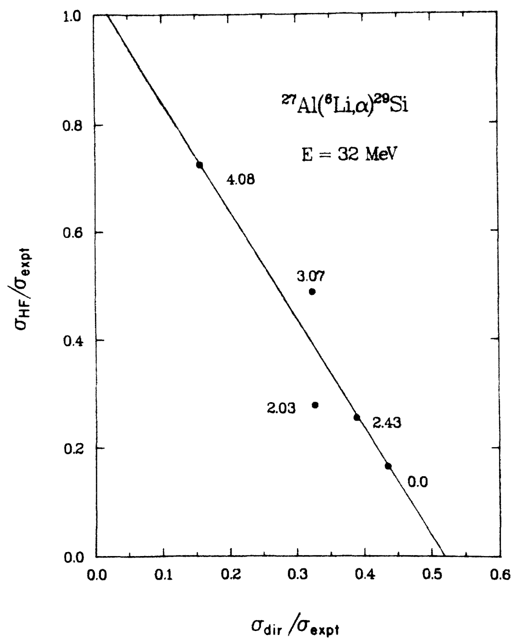

FIG. 4. Plot of σ_{hf} vs σ_{dir}, with both quantities weighted by $1/\sigma_{expt}$. σ_{HF} and σ_{dir} are defined in the text and listed in Table I. The 1.27-MeV state is omitted.

the slope and intercept we have determined the normalization constants α and β to be 0.96 ± 0.05 and 1.92 ± 0.13, respectively. The resulting compound and direct contributions to the cross section of the low-lying levels of ^{29}Si are listed in Table I. Also listed are the cross sections determined by the intercept method. The agreement with predictions of the more sophisticated statistical model is surprisingly good.

Knowing the compound cross section, we can extract experimental spectroscopic factors. These are listed in the last column of Table III. If S_{JL}(expt) is absent, there is no evidence for that L value. The angular distributions calculated with DWUCK4 and STATIS are shown (dashed and dot-dash, respectively) in Fig. 2, using the experimentally determined spectroscopic factors. The solid line is the sum of the two distributions. Clearly, zero-range DWBA does a reasonable job in describing the shape of the angular distributions of all the low-lying states of ^{29}Si. From the spectroscopic factors (Table III) we note the dominance of the $L=4$ transfer for the 0.0-, 2.03-, 2.43-, and 4.08-MeV levels. However, for the 1.27-, 3.07-, and 3.62-MeV levels, considerable admixtures of all the allowed L transfers are seen. These observations are in qualitative agreement with the work of Bland *et al.*,[9] who studied the ^{27}Al(α,d)^{29}Si reaction at 27 MeV, and carried out a DWBA analysis employing both cluster and microscopic form factors.

In terms of the magnitudes of the cross sections, it is quite clear that for the 0.0-, 1.27-, 2.03-, and 2.43-MeV levels, the direct mechanism dominates. The statistical model underpredicts the total cross section for these states by at least a factor of 3. For the 3.07- and 4.08-MeV states on the other hand, the compound-nuclear cross section amounts to 49% and 73% of the total experimental cross section, respectively. Also, the shapes of the angular distributions calculated by STATIS for these states are essentially in perfect agreement with the data. For the negative-parity state at 3.62 MeV, we were not able to calculate the direct component of the cross section, as the necessary two-nucleon spectroscopic amplitudes were not available. However, the compound contribution to this state is small, implying the transition to be mainly direct.

IV. CONCLUSIONS

The shapes and the magnitudes of the angular distributions for the states populated in the ^{27}Al(^{6}Li,α)^{29}Si reaction at 32 MeV have been described in the context of two models: (1) the DWBA model and (2) the compound-nuclear model based on the Hauser-Feshbach formalism. The two basic trends of the data are well reproduced by DWBA, in that the angular distributions are slightly forward peaked and for the most part are structureless. In DWBA, this structureless feature arises quite normally as a consequence of the addition of multiple (J,L) transfers that are possible for the (^{6}Li,α) reaction on a nonzero spin target. However, the question of absolute magnitude of the cross sections is not so easily answered in this model. The two methods of extracting the "unhappiness factor" (β or N) to multiply the DWBA cross section are in agreement—$N=2.0\pm0.2$, $\beta=1.92\pm0.13$. On the other hand, if we subtract the HF cross sections from the measured ones and divide the result by σ_{dir}, the ratios vary from 1.0 to 2.2 with an average value of 1.73 ± 0.17. In this respect the compound-nuclear model was shown to be very useful. If the fusion cross section and the various level-density parameters are accurately known, then the statistical model leads to the prediction of the absolute cross section. In fact, the compound contribution was shown to be non-negligible for all the transitions studied. In particular, for the 3.07- and 4.08-MeV levels, the compound contribution was shown to be 49% and 73% of the total measured cross section, respectively. So it is quite clear from this study that the (^{6}Li,α) reaction, even at a relatively high energy of 32 MeV, cannot be simply considered as a direct deuteron cluster transfer. If one is to gain better understanding of the underlying dynamics of the (^{6}Li,α) reaction, clearly the compound-nuclear aspect cannot be ignored and indeed needs further investigation.

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