Mechanism of the $^{12}C(^{6}Li, d)^{16}O$ Reaction at $E_{^6Li} = 19$–24 MeV*

D. P. Balamuth

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174

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The mechanism of the $^{12}C(^{6}Li,d)^{16}O$ reaction has been studied in the energy range $E_{6Li}=19$–24 MeV. For the states at $E_x=6.92$ and 7.12 MeV we have (a) measured excitation functions in 200-keV steps where the deuterons were detected at 0°, and (b) measured d-γ angular correlations at three bombarding energies where the deuterons were also detected at 0°. The excitation curves are found to be relatively smooth functions of bombarding energy. The angular correlations are similar at all three bombarding energies. The results of the angular-correlation measurements are compared with the predictions of both an α-transfer mechanism (using the distorted-wave Born approximation) and a compound-nucleus mechanism (using the Hauser-Feshbach theory). The observed correlations are not completely consistent with the predictions of either theory. Angular correlations measured at lower energies were found to show strong changes with bombarding energy.

I. INTRODUCTION

In the past few years transfer reactions induced by heavy ions have been the subject of considerable interest, both experimental and theoretical. Part of this interest results from recent theoretical predictions[1] concerning the energies of states composed of four-nucleon clusters (or quartets) moving approximately independently of one another. A natural way to study such states is to use a nuclear reaction in which four (or more) nucleons are transferred in a simple one-step process to a target which remains inert (direct reaction). Such reaction studies yield information concerning the overlap of the nuclear wave functions with the target-plus-α-particle system, just as the more usual sort of direct reaction (e.g., single-nucleon transfer) gives information on the single-particle degrees of freedom in the residual nucleus. Many heavy-ion-induced reactions have, in fact, been studied with the aim of seeing which, if any, of them can be considered direct reactions.[2] The criteria usually employed in such studies are forward-peaked angular distributions, the selective excitation of final states, and excitation functions which vary smoothly as a function of bombarding energy. However, these criteria are not unambiguous; in fact, heavy-ion reactions have been found which selectively populate final states but whose excitation functions fluctuate strongly with energy.[3] The mechanism of such reactions is still an open question. Since an understanding of the reaction mechanism is a necessary prerequisite for applying cluster-transfer reactions to nuclear spectroscopy, it is important that experiments be performed which test the reaction mechanism directly.

There have been several such efforts recently. Measurement of the relative magnetic substate populations using the $^{16}O(^{7}Li, t\gamma)^{20}Ne$ and $^{16}O(^{6}Li, d\gamma)^{20}Ne$ reactions have been compared with the predictions of a simple α-transfer mechanism.[4] The results indicated that direct α transfer accounted for some of the strength, but other processes were occurring as well. Détraz *et al.* have compared the α-pickup reaction (^{3}He, ^{7}Be) with the (^{3}He, ^{7}Li) reaction in order to study the pickup of four particles coupled to $T=1$.[5] They concluded that this mechanism can contribute as much as 20% to the (^{3}He, ^{7}Be) cross section. Artemov *et al.*[6] have measured angular correlations of α particles and deuterons in the reaction $^{12}C(^{6}Li, d)^{16}O^* \to \alpha + ^{12}C_{g.s.}$ where the deuterons were detected at 0 and 10° in the lab. The beam energies were 26 and 30.7 MeV. Their conclusions were that at these beam energies the mechanism is dominated by α transfer. However, no attempt was made to assess quantitatively the presence of other competing reaction mechanisms.

In this paper we present a study of the mechanism of the $^{12}C(^{6}Li, d)^{16}O$ reaction leading to several final states in ^{16}O. This reaction has been extensively studied by many experimental groups. In 1966 Loebenstein *et al.*[7] measured differential cross sections for the $^{6}Li(^{12}C, d)^{16}O$ reaction at a center-of-mass energy of 7 MeV. The motivation for this experiment was the importance of the α width of the 7.12-MeV state in ^{16}O in determining the rate of the $^{12}C(\alpha, \gamma)^{16}O$ reaction at energies of astrophysical interest. (The relevance of the α width of this state to astrophysics has recently been reviewed by Barnes.[8]) By comparing the yield to natural- and unnatural-parity states (and using a Hauser-Feshbach analysis) it was concluded that direct α transfer could account for 52% of the total cross section of the 6.92-MeV 2^+ state and 34% of the total cross section of the 7.12-MeV 1^- state.

Qualitatively similar conclusions were reached by Meier-Ewart, Bethge, and Pfeiffer,[9] who measured differential cross sections at a center-of-mass energy of 13.33 MeV using the $^{12}C(^6Li, d)^{16}O$ reaction. These authors estimate the total compound-nuclear cross section from the yield to the 2^- unnatural-parity state at 8.87 MeV and then use this to normalize a Hauser-Feshbach calculation of the total cross section leading to the natural-parity states. The result for the 6.92- and 7.12-MeV states are that the observed total cross sections are about 1.5 times the estimated yield from compound-nuclear processes.

The problem of the mechanism of the $^{12}C(^6Li, d)$-^{16}O reaction leading to the 6.92- and 7.12-MeV states has also been recently studied by Carlson[10] at $3 \leq E_{c.m.} \leq 4.33$ MeV. Arguments are given that the momentum matching is more favorable for a direct process at these energies. The measurements involved the angular distribution of γ rays following the $^{12}C(^6Li, d)^{16}O$ reaction; the average magnetic substate populations were calculated for a direct reaction assuming the plane-wave Born approximation and integrating over the (assumed) deuteron angular distribution. These predictions, when compared with the data, were used to suggest that the 6.92-MeV 2^+ state is formed by a direct α-transfer reaction, whereas the 1^- state at 7.12 MeV is not. These conclusions are open to several questions. One problem with simply comparing the measured population parameters with the predictions of a direct-transfer model is that it is implicitly assumed that an alternative model for the reaction mechanism would predict different values for these quantities. It is clearly worthwhile to check this assumption if possible. This problem is common to a previous study of the $^{16}O(^7Li, t)^{20}Ne$ reaction.[4] A second difficulty with the conclusions of Ref. 10 is that they rest on the use of the plane-wave Born approximation. This approximation is certainly questionable, and especially so at the deuteron energies involved in Ref. 10, where strong resonance effects have been observed.[11] Further investigation of the mechanism of this reaction thus seems to be indicated.

We have approached the problem from two different directions. First, excitation functions have been measured at $\Theta_d = 0°$ over the range $E_{^6Li} = 19$–24 MeV in 200-keV steps. The motivation here was to see whether the differential cross sections were smooth functions of energy, as one might expect for a simple direct reaction. It is, of course, important to point out that smooth variation of the cross section with energy does not necessarily imply that a direct reaction is taking place (although a strongly fluctuating cross section is sufficient to exclude such a process). At the high excitation energies of the ^{18}F compound nucleus involved here, the density of levels is probably high enough to guarantee a reasonably smooth excitation function even for a compound-nuclear reaction. Of course the cross section can still fluctuate even if the ratio of the average level width to the average level spacing is much larger than unity (Ericson fluctuations).[12] The observation of an excitation function which varies smoothly with energy implies that either (a) the dominant process is direct reaction, (b) the averaging obtained by the finite energy spread in the target is sufficient to damp out fluctuations (target thickness > coherence width), or (c) some combination of these effects.

In addition, we have measured angular correlations of deexcitation γ rays in coincidence with the emergent deuterons. The purpose of the angular-correlation measurements was to determine the relative population of the various magnetic substates in the residual nucleus ^{16}O. These numbers were then compared with the predictions of various models of the reaction mechanism. Specifically, in the present work the measured angular correlations have been compared with the predictions of both a direct-reaction model (including spin-orbit coupling) and the statistical compound-nucleus (Hauser-Feshbach) model.[13] The calculations of the theoretical angular correlations according to these models is described in Sec. III. It should be emphasized that the angular-correlation geometry has been chosen to maximize the sensitivity of the experiments to the gross features of the reaction mechanism. Thus, except for the effects of spin-orbit coupling, it is possible to generate predictions for the angular correlation based on a direct-reaction model which are independent of the distorting potentials used. Similarly, the predictions generated from the statistical compound-nuclear model also seem to reflect mainly the geometrical aspects of the problem (see below).

It is worthwhile to comment briefly on the choice of bombarding energies for the angular-correlation measurements. The original purpose of these measurements was to give information concerning the mechanism for transitions to natural-parity states at tandem accelerator energies, where some evidence exists (mainly from angular distributions) that the cross section contains a direct-reaction component. Consequently, angular correlations have been measured at laboratory energies of 20, 21.5, and 23 MeV, corresponding to $E_{c.m.} = 13.33$, 14.33, and 15.33 MeV. The aim of these measurements was to attempt a semiquantitative determination of the fraction of the reaction mechanism which resulted from direct α transfer. During the course of the measurements it was decided to obtain additional angular correlations under circumstances where the direct mechanism might be less important or absent. Specifically, angular correlations have been measured for the transition to the unnatural-parity state at 8.87 MeV (which cannot be formed in a one-step α-transfer process). These measurements were made at $E_{c.m.} = 8$ and 10 MeV; their purpose was to test the predictions of the statistical compound-nucleus model of the reaction mechanism (see Sec. III). In addition, angular correlations leading to the 1^- and 2^+ states were measured using the $^{12}C(^6Li, d)$-^{16}O reaction ($\Theta_d = 0°$) at $E_{c.m.} = 7.33$ and 8.26 MeV, and using the $^6Li(^{12}C, d)^{16}O$ reaction ($\Theta_d = 0°$) at $E_{c.m.} = 7$ and 8.33 MeV. Of course, the last measurement is equivalent to measuring the deuterons at 180° in the $(^6Li, d)$ reaction. These lower-energy measurements are discussed in the second part of Sec. IV.

II. EXPERIMENTAL PROCEDURE AND DATA REDUCTION

A. Excitation Functions

Excitation functions were obtained for the ^{12}C-$(^6Li, d)^{16}O$ reaction leading to the states at 6.92 and 7.12 MeV over the energy range $E_{^6Li} = 19-24$ MeV. The step size was 200 keV. The deuterons were detected at zero degrees with respect to the beam direction by a position-sensitive detector (PSD) located at the focus of a magnetic spectrometer.[14] The energy resolution was about 75 keV; the 6.92- and 7.12-MeV states were completely resolved. The magnetic spectrometer used in the excitation-function measurements has one undesirable feature which should be pointed out; the magnification is approximately nine in the direction perpendicular to the dispersion. It is thus important to make sure that small movements of the beam spot (due to slow changes in the accelerator beam optics) do not cause the image of the spot to be deflected off the detector. The problem is illustrated in Fig. 1. The problem was solved by using a target consisting of 1-mm strips of gold and carbon (respectively, 50 and 100 $\mu g/cm^2$ thick) evaporated onto a thin (0.000 063-cm) nickel backing. (See Fig. 2.)

The carbon and gold strips were evaporated through the same mask and coincided precisely. The image of the carbon target was thus ≈9 mm wide at the PSD; the detector itself had a width of 17 mm, so no counts were missed. (Such strip targets have been previously used[15] with the short dimension of the strip parallel to the dispersion; the contribution to energy resolution resulting from finite beam spot size can be reduced considerably in this way.) The excitation functions were normalized to the elastic scattering of ^6Li from gold using a monitor detector at an angle of 40° with respect to the beam. The energy dependence of the elastic scattering from gold was assumed to be $1/E^2$, characteristic of Rutherford scattering. Carbon buildup was minimized by maintaining the system vacuum at a pressure of about 3×10^{-6} Torr. In addition, isolated points along the excitation curves were remeasured later. The quoted experimental errors accommodate both statistical uncertainties and the over-all reproducibility of the data. For each point signals corresponding to the zero degree and monitor detectors were stored in separate halves of a 4096-channel pulse-height analyzer. The spectra for each point were written on magnetic tape for subsequent analysis.

In order to check the performance of the entire system, additional data were accumulated for the $^{12}C(^6Li, d)^{16}O$ reaction leading to the ^{16}O ground state over the energy range $E_{^6Li} = 9-12.4$ MeV. A measurement over the same region has recently been reported by Johnson and Waggoner.[16] The results obtained with the present system are compared with the results of Johnson and Waggoner in Fig. 3; agreement is seen to be very good.

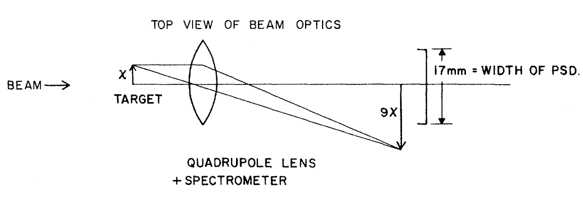

FIG. 1. Beam optics in the zero degree spectrometer, illustrating the problem of horizontal magnification.

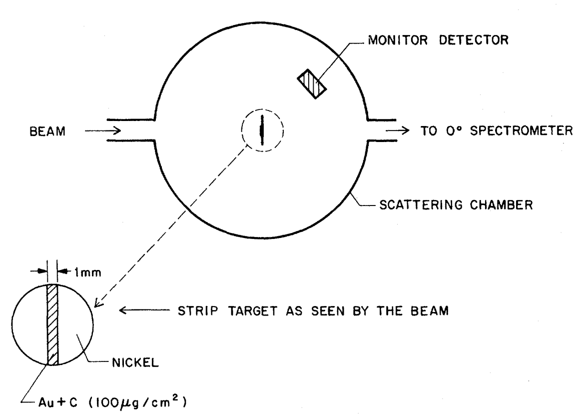

FIG. 2. Schematic indicating how strip targets were used, as discussed in the text.

B. Angular Correlations

The angular-correlation apparatus has been described[14] in the literature and need be discussed only briefly here. Deuterons were detected at zero degrees with respect to the beam using the same spectrometer discussed above. γ rays were detected in time coincidence with the deuterons using an array of four 7.62-$\times$10.16-cm NaI(Tl) scintillation counters. These were placed at angles of 90, 113, 136, and 159° with respect to the incident beam. The targets for the coincidence measurements involving the ^{6}Li beam were carbon foils of thickness 100–200 μg/cm^2. For the measurements involving a ^{12}C beam the targets were 50 μg/cm^2 of ^{6}LiF evaporated on carbon backings. Conventional fast-slow coincidence circuitry was employed. The data were recorded on magnetic tape on an event-by-event basis. For each event the parameters digitized were pulses corresponding to γ energy, deuteron momentum, time difference between particle and γ signals, and routing information to identify the γ-ray detector which recorded the event. The data were acquired (and subsequently reduced off line) using a PDP-9 computer.

C. Data Reduction and Extraction of Population Parameters

The raw data for the excitation curves were reduced as follows. At each energy, the number of counts in the appropriate deuteron group (6.92- or 7.12-MeV states) was divided by the number of counts in the gold elastic scattering peak from the monitor spectrum. The result was divided by the square of the beam energy (to account for the $1/E^2$ falloff of the monitor counts). The results, plotted as a function of energy, yielded the required excitation curves in arbitrary units. No attempt was made to measure absolute cross sections in the present work, since the principal question to be answered by the excitation functions was whether or not they exhibited fluctuations with energy.

In obtaining the angular correlations from the raw data, the contribution of accidental coincidences was subtracted using the region of the multiparameter space corresponding to a flat portion of the time spectrum. Since both the 6.92- and 7.12-MeV states decay 100% to the ground state[17] it was possible to integrate the entire spectrum above the 511-keV peak to obtain the number of counts at each angle. Other methods of peak integration included taking only the full-energy, first- and second-escape peaks. The errors quoted include both those resulting from counting statistics and an estimate of the uncertainty in setting the limits of peak integration. For the 8.87-MeV state the branch to the ground state comprises only 7% of the total decay strength.[17] Consequently in this case it was necessary to integrate only the region of the γ spectrum above approximately 7.5 MeV.

Since in all cases the γ transitions studied are of the form $J^\pi \to 0^+$, they are of pure multipolarity. The only unknown parameters involved in the angular correlation are the relative populations of the magnetic substates in the residual nucleus. These population parameters are related to the experimental angular correlation by a simple linear transformation; solution of the equations produces values for the population parameters. (See, for example, Refs. 4 and 10.)

III. CALCULATION OF POPULATION PARAMETERS

A. Direct-Reaction Mechanism

One advantage of the geometry chosen for measuring the angular correlations in this work is that the predictions of various models are largely independent of the details of the model and depend mainly on basic (essentially geometrical) considerations. For example, in a single-step process in which an α particle is transferred to a spinless target only the $M_B = 0$ magnetic substate can be populated, provided we neglect spin-orbit coupling in the optical potentials describing the entrance and exit channels. This result is independent of the distorting potentials. However, there is considerable experimental evidence for a spin-orbit term in the deuteron-nucleus optical potential.[18] (For the ^{6}Li optical potential there is almost no experimental evidence for the existence of a spin-orbit term; simple considerations lead one to ex-

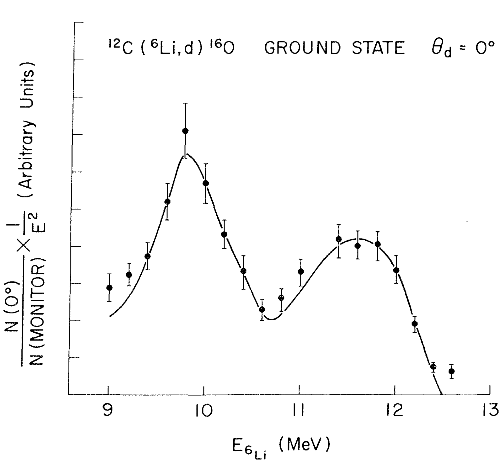

FIG. 3. Comparison of excitation functions measured with the present method (♦) with those reported in Ref. 16 (—).

TABLE I. Optical-model parameters used in the DWBA calculations.

Particle	V (MeV)	r_v (fm)	a_v (fm)	$W'=4W_D$ (MeV)	r_w (fm)	a_w (fm)	V_{so} (MeV fm^2)	r_{so} (fm)	a_{so} (fm)	Ref.
^{6}Li	35	1.42	1.04	33.8	2.17	0.49	...	...	...	21
d-1	118.9	0.97	0.93	37.6	1.80	0.47	20.0	0.90	0.18	22
d-2	113.8	1.06	0.56	21.2	1.87	0.48	16.4	0.99	0.45	22
d-3	109.5	1.06	0.56	11.2	1.87	0.98	8.8	0.91	0.68	22

pect it to be small.)

With these considerations in mind, the zero-range distorted-wave Born approximation (DWBA) has been used to generate predictions for the relative population of the magnetic substates in the residual nucleus. The code DWUCK was employed[19]; the amplitudes necessary to calculate the substate populations were printed out and the final results were calculated from the formula

$$P(M_B) = \sum_{m_b m_a} |\beta_{s J_B}^{l 0 m_b m_a}(\Theta)|^2_{\Theta=0°}, \quad M_B = m_b - m_a, \qquad (1)$$

where the amplitudes are defined, e.g., by Satchler.[20]

Once spin-orbit coupling in the deuteron channel is included, however, the predicted substate populations depend on the choice of the optical-model parameters which describe the elastic scattering in both the entrance and exit channels. Because our knowledge of the ^{6}Li optical potential is quite poor, we have arbitrarily fixed the parameters in the $^6Li + ^{12}C$ channel as those found to describe the elastic scattering of 20-MeV ^{6}Li on ^{12}C.[21] In the deuteron channel three different potentials were used, all of which have recently been found to describe reasonably well the vector polarization of deuterons elastically scattered from ^{16}O.[22] The various optical potentials are given in Table I. The number of nodes in the radial wave function of the transferred α cluster was fixed by the requirement that the number of oscillator quanta transferred be eight for the 2^+ state and five for the 1^- state. That is, for the 2^+ state the transfer of four nucleons into the $2s$-$1d$ shell was assumed. For the 1^- state three nucleons were assumed to be transferred into the $1p$ shell and one into the $2s$-$1d$ shell. The bound-state wave function was assumed to be an eigenfunction of a real Woods-Saxon potential well ($r_0 = 2.1$ fm, $a = 0.6$ fm) with the well depth chosen to reproduce the correct α-particle binding energy.

The principal purpose of the DWBA calculations was to obtain a quantitative estimate of the influence of a reasonable amount of spin-orbit coupling on the population of magnetic substates with $M_B \neq 0$. (With no spin-orbit coupling only the $M_B = 0$ substate can be populated.) In addition, some attempt has been made to assess the dependence of the DWBA predictions on the parameters involved in the calculations, in order to estimate their overall reliability.

One significant feature of all the DWBA calculations was that the population of the $|M_B| = 2$ magnetic substates (for the 2^+ state) was predicted to be quite small, less than 3% in every case tried and often less than 1%. This fact seemed to be relatively insensitive to parameter variations.

It might be expected from perturbation-theory considerations that the population of the $M_B \neq 0$ magnetic substates would be a monotonic function of the strength of the spin-orbit potential. In or-

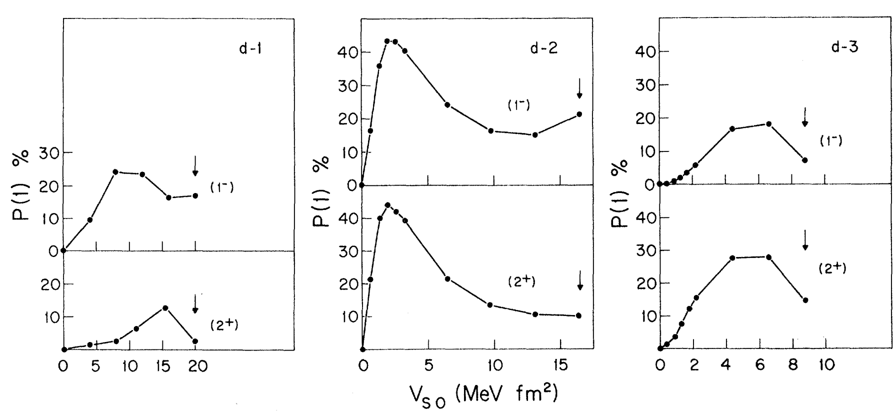

FIG. 4. Plot of theoretical value of the $|M| = 1$ substate population as a function of spin-orbit strength using the DWBA.

der to test this hypothesis the following tests were performed. For all three potentials the strength of the spin-orbit coupling was increased from zero to the value found to fit the deuteron polarization data. The effect of this on the population of the $|M_B|=1$ substates is shown in Fig. 4. While the numbers differ considerably, the trend is the same in every case: $P(1)$ increases to some maximum value (which can be quite large, e.g., >40% for set d-2) and then decreases. The vertical arrows in Fig. 4 indicate the value of V_{so} found to fit the deuteron polarization data.

Two additional tests were performed to explore further effects of variation of the distorted-wave parameters. First, to test the question of whether the proximity of the states of interest to the α-particle separation energy affects the results, all calculations were repeated with the binding energy artificially increased to 2 MeV. In most cases the population of $M_B \neq 0$ substates increased, although they occasionally remained constant. This result is not unexpected, since the effect of increasing the binding energy is to "pull in" the bound-state wave function, thereby weighting more the regions of space where the spin-orbit potential is stronger. In a similar vein, the effect of increasing the absorptive potential is (usually) to reduce the population of the $M_B \neq 0$ substates.

As can be seen from Fig. 4 and the above discussion it is impossible to determine a unique "prediction" for the population parameters from the DWBA calculations. In order to obtain numbers which can be compared with the experimental data, we have arbitrarily averaged the results obtained with the three different deuteron potentials. It is these "averaged" numbers which are referred to as the DWBA predictions in the subsequent discussion. From the spread in the values alone a theoretical uncertainty of about 5–7% (standard deviation) should be assumed.

B. Statistical Compound-Nucleus Model

The fact that unnatural-parity states are observed[9] to be populated with appreciable strength in the $^{12}C(^6Li, d)^{16}O$ reaction at the energies employed in the present work shows that a single-step α-transfer process cannot be the only one occurring. In order to attempt to account for the contribution to the angular correlations from the compound-nuclear processes, predictions for the population parameters were calculated assuming the level density to be sufficiently high that all fluctuations are effectively damped out.

The usual expression for the differential cross section for a nuclear reaction calculated using the statistical model[13] is not useful for predicting the population parameters. The reason for this is that the dependence of the cross section on the magnetic quantum numbers has been summed out using $\bar{Z}$ coefficients. However, an expression for the relative population of the various magnetic substates in the residual nucleus can be obtained using the same procedure as in the derivation[23] of the differential cross section, except that the sum over M in the residual nucleus is not performed. The details are given in the Appendix. The resulting expression for the cross section leading to the $M_{I'}^{\text{th}}$ magnetic substate of the residual nucleus is, using the notation of Ref. 23,

$$P(M_{I'}) = \text{const.} \sum_{ll'Js'm_{s'}} (2l+1)(2l'+1)(l0sm_{s'}|Jm_{s'})^2(l'0s'm_{s'}|Jm_{s'})^2(I'M_{I'}i'm_{s'}-M_{I'}|s'm_{s'})^2 \frac{T_{ls}(\alpha)T_{l's'}(\alpha')}{\sum_{\alpha''l''s''} T_{l''s''}(\alpha'')}. \quad (2)$$

In the above equation all quantities which are independent of $M_{I'}$ have been subsumed into the normalizing constant, since only *ratios* of the substate populations are required.

In order to generate predictions for the substate populations it is necessary to know the transmission coefficients $T_{ls}(\alpha)$, $T_{l's'}(\alpha')$, and the sum $\sum_{\alpha''l''s''} T_{l''s''}(\alpha'')$ where the sum is to be taken over all channels α'' to which the compound state with spin-parity J^π can decay. In principle the calculation of the complete expression (2) requires the availability of suitable optical-model potentials in all the open channels, in addition to level-density information for the available final states.

In the present work it is argued that the predictions of (2) for the relative substate populations are largely insensitive to the details of the transmission coefficients, but rather reflect a kind of average of the geometrical properties of the states as given by their angular momentum and parity. This is shown in detail in the Appendix.

IV. RESULTS AND COMPARISON WITH THEORY

A. Measurements from $E_{^6\text{Li}} = 19–24$ MeV

1. Excitation Curves

The excitation functions at $\Theta_d = 0°$ for the 6.92-MeV (2^+) state and the 7.12-MeV (1^-) state are shown in Figs. 5 and 6. The energy loss of the

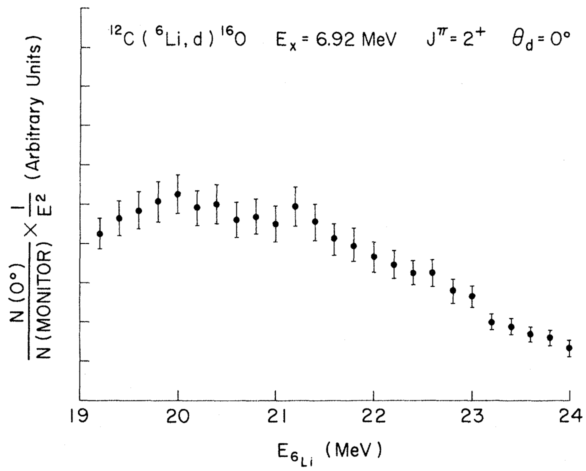

FIG. 5. Excitation curve for the 6.92-MeV state obtained at $\Theta_d = 0°$.

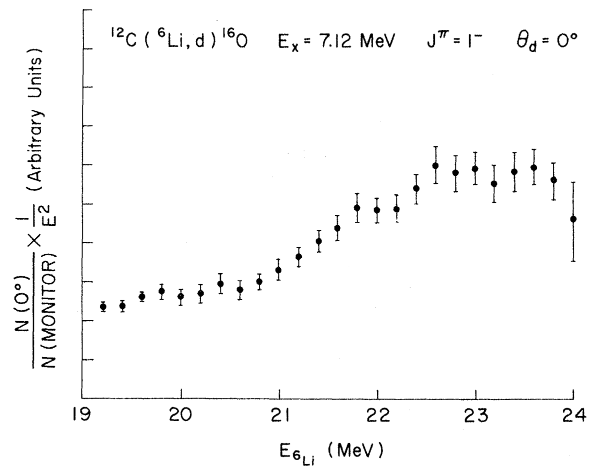

FIG. 6. Excitation curve for the 7.12-MeV state obtained at $\Theta_d = 0°$.

^{6}Li beam in the target corresponds to about one third of the distance between adjacent points. Both curves are seen to be relatively smooth functions of bombarding energy. However, it should be emphasized that the significant feature of *both* the distorted-wave calculations and the Hauser-Feshbach calculations performed in the present work is that they predict a smooth variation of the cross section with bombarding energy.

2. Angular Correlations

The angular correlations obtained for the 2^+ state at $E_{^6Li} = 20$, 21.5, and 23 MeV are shown in Fig. 7, along with the population parameters deduced from them. It can be seen that the results are similar at the three energies, although the $|M| = 1$ substates receive a slightly larger share of the cross section at 20 MeV. It is interesting

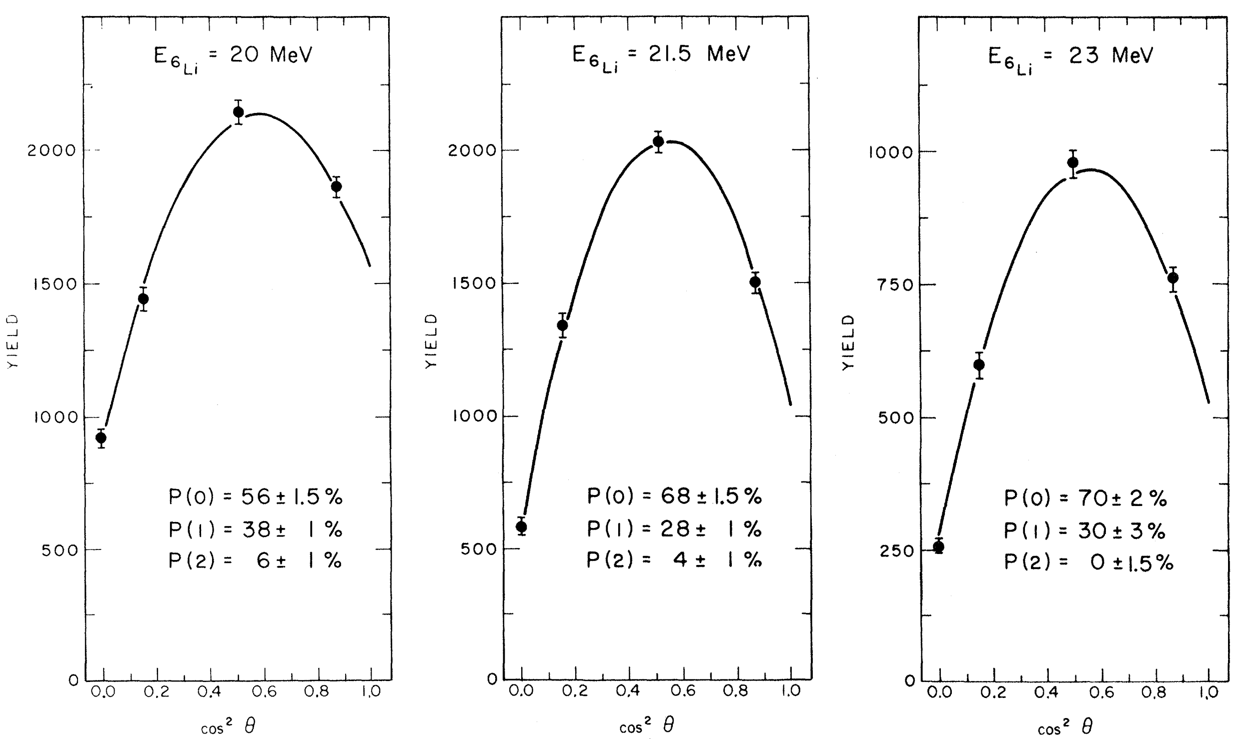

FIG. 7. Angular correlations for the $^{12}C(^{6}Li,d\gamma)^{16}O$ reaction leading to the 6.92-MeV ($J^{\pi} = 2^+$) state at bombarding energies 20, 21.5, and 23 MeV.

to note that the correlations at 21.5 and 23 MeV are almost identical even though the differential cross section at 23 MeV has fallen to 60% of its value at 21.5 MeV.

The angular correlations obtained under the same conditions for the 1^- state at 7.12 MeV are shown in Fig. 8. Once again the correlations are quite similar despite the fact that the differential cross section increases by almost a factor of 3 between 20 and 23 MeV.

These results are compared with the theoretical predictions for the various models in Table II. The optical potentials required for the DWBA calculations were taken from the literature as discussed in the previous section; the spin-orbit coupling value is consistent with that observed from deuteron polarization measurements.[22] The transmission coefficients required for the Hauser-Feshbach calculations were generated using the parametrization discussed in the Appendix; however, the results are essentially the same if transmission coefficients from an optical potential are used.

The predictions of the DWBA calculations have been averaged over the three parameter sets used. As stated above, this introduces a spread of about 5% in $P(0)$ and $P(1)$. The average predictions are almost identical for the three beam energies employed, although for the individual potentials changes in $P(0)$ of up to 10% were observed for a 3-MeV change in bombarding energy. The predictions given in the last column of Table II are the averages over the three parameter sets; an uncertainty of ±5% is estimated, e.g., $P(1) \cong 15 \pm 5\%$. Even with this uncertainty it is clear that the DWBA and Hauser-Feshbach mechanisms predict quite different values for these population parameters.

From the results displayed in Table II it is apparent that the direct-reaction process makes a significant contribution to the reaction mechanism at these energies. For the 1^- state the experimental results are closer to the DWBA prediction than to the Hauser-Feshbach one; a naive incoherent sum of the two mechanisms would give a best fit for 70–90% direct. However, it must be emphasized that to say this implies that the distorted-wave theory can account for 70–90% of the cross section is probably wrong. For example, all the distorting potentials used predict a forward-peaked deuteron angular distribution in the (^{6}Li, d) reaction, whereas the experimental[9] distribution at $E_{^6\text{Li}} = 20$ MeV shows a pronounced backward peak.

For the 2^+ state the same spin-orbit coupling strength produces DWBA predictions which do not give enough strength to the $|M| = 1$ substates; a least-squares fit to the 21.5- and 23-MeV data

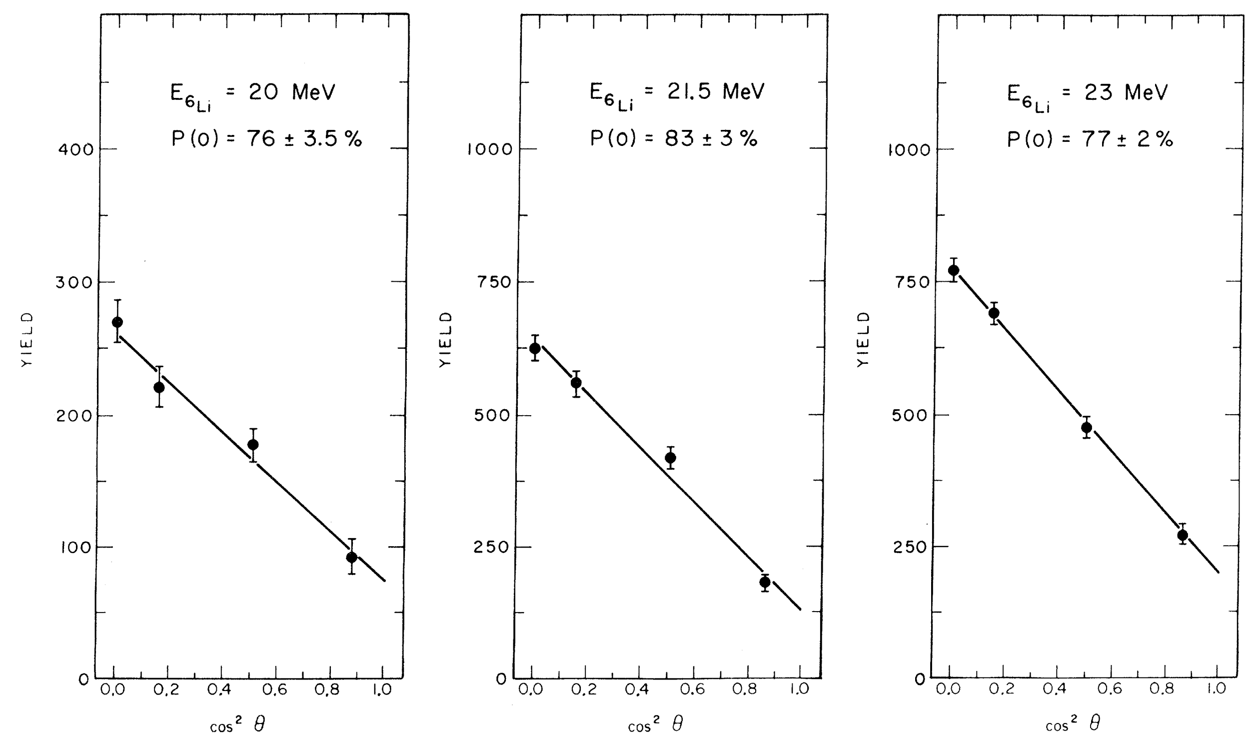

FIG. 8. Angular correlations for the ^{12}C(^{6}Li, $d\gamma$)^{16}O reaction leading to the 7.12-MeV ($J^\pi = 1^-$) state at bombarding energies 20, 21.5, and 23 MeV.

would imply about equal direct and compound contributions, with somewhat more compound cross section at 20 MeV.

B. Measurements at Lower Energies

1. Unnatural-Parity States

The principal reason for measuring the angular correlation for the 8.87-MeV 2^- state was to obtain empirical information on the population parameters resulting from processes other than direct α transfer. Because of the relatively low yield to this state and because the γ transition of interest is only a 7% branch, it was necessary to use a relatively thick target to obtain an adequate coincidence yield. The target used for these measurements was a self-supporting carbon foil of nominal thickness 500 $\mu g/cm^2$ tilted at 30° to the beam; the energy loss of the ^{6}Li beam was of the order of 600 keV. Since no other final states are near the 8.87-MeV state, the use of a thick target presented no problem. In addition to the benefit of a higher coincidence counting rate, the fact that the angular correlation is effectively averaged over 600-keV bombarding energy implies that the results should be better accounted for by the statistical theory, which is assumed to be energy averaged.

The results obtained at bombarding energies of 12 and 15 MeV are shown in Fig. 9; note that the 15-MeV measurement has considerably higher precision. In both cases the $|M| = 1$ substates received the majority of the strength; this is well accounted for by the Hauser-Feshbach calculations, which predict $P(0) = 30\%$, $P(1) + P(-1) = 53\%$, and $P(2) + P(-2) = 17\%$. It should perhaps be mentioned in passing that unnatural-parity states can also be excited by multistep direct processes, in addition to compound-nuclear ones. No attempt has been made to investigate the population parameters to be expected from such multistep processes.

2. Natural-Parity States

In a further attempt to elucidate the population parameters which might be obtained from nondirect processes, angular correlations were measured for the $^6Li(^{12}C, d)^{16}O$ reaction at bombarding energies of 21 and 25 MeV ($E_{c.m.} = 7$ and 8.33 MeV, respectively). Since at $\Theta_d = 0°$ a simple stripping mechanism would involve ^{10}B transfer it was felt that compound-nucleus formation would probably be the dominant reaction process. The angular correlations for the 2^+ state are shown in Fig. 10, and for the 1^- state in Fig. 11. It can be seen that the population parameters show considerable changes with bombarding energy. This is presumably indicative of compound-nucleus formation; perhaps at these lower energies the target thickness (~100 keV) is insufficient to damp out fluctuations.

Measurements were also made at similar center-of-mass energies for the reaction using ^{6}Li as projectile and detecting the deuterons at zero degrees. For the 1^- state the angular correlations also change strongly with bombarding energy (as in the case of the ^{12}C projectile) whereas for the 2^+ state the change is somewhat less pronounced. (These angular correlations are shown in Figs. 12 and 13 for the 1^- and 2^+ states, respectively.)

TABLE II. Comparison of the measured population parameters with those predicted by the DWBA and Hauser-Feshbach theories.

$E_{^6Li}$	J^π	$\|M\|$	$P(M)\|_{exp}$ (%)	$P(M)\|_{CN}$ (%)	$P(M)\|_{DWBA}$ (%)
20	1^-	0	76 ± 3.5	53.2	85.3
		1	24 ± 3.5	46.8	14.7
21.5	1^-	0	83 ± 3	53.2	85.3
		1	17 ± 3	46.8	14.7
23	1^-	0	77 ± 2	53.2	85.3
		1	23 ± 2	46.8	14.7
20	2^+	0	56 ± 1.5	44.9	90.5
		1	38 ± 1	41.1	8.5
		2	6 ± 1	14.0	1.0
21.5	2^+	0	68 ± 1.5	44.9	90.5
		1	28 ± 1	41.1	8.5
		2	4 ± 1	14.0	1.0
23	2^+	0	70 ± 2	44.9	90.5
		1	30 ± 3	41.1	8.5
		2	0 ± 1.5	14.0	1.0

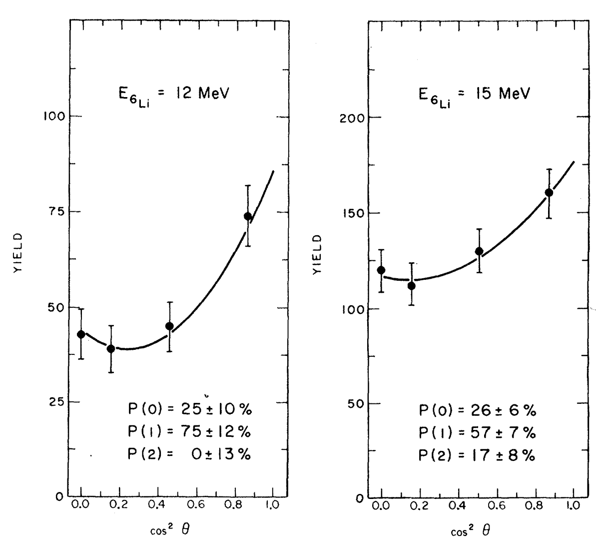

FIG. 9. Angular correlation for the transition 8.87 MeV → 0 MeV measured with the $^{12}C(^6Li, d\gamma)^{16}O$ reaction ($J^\pi = 2^-$) at bombarding energies of 12 and 15 MeV.

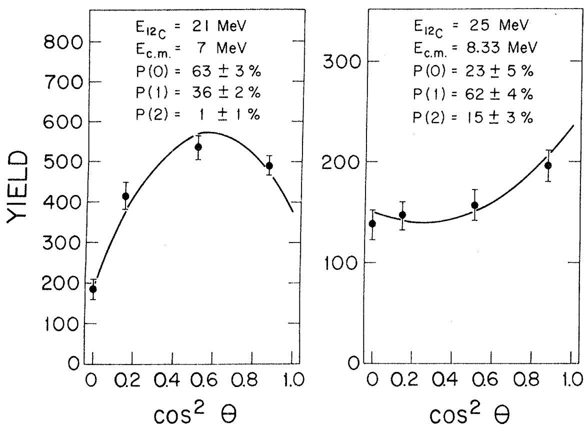

FIG. 10. Angular correlation for the $^{6}Li(^{12}C, d\gamma)^{16}O$ reaction ($J^{\pi}=2^{+}$) leading to the 6.92-MeV state at $E_{c.m.}=7$ and 8.33 MeV, $\Theta_d=0°$.

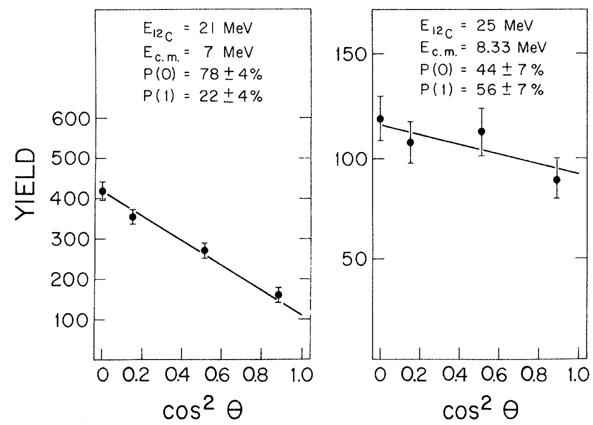

FIG. 11. Angular correlation for the $^{6}Li(^{12}C, d\gamma)^{16}O$ reaction ($J^{\pi}=1^{-}$) leading to the 7.12-MeV state at $E_{c.m.}=7$ and 8.33 MeV, $\Theta_d=0°$.

V. CONCLUSIONS

The main conclusion of the present work is that, for the $^{12}C(^{6}Li, d)^{16}O$ reaction at tandem accelerator energies, it is not possible to classify the reaction mechanism simply as either a direct reaction or a compound-nuclear process. Further, while it has been shown that angular correlation measurements of the type reported here are capable of elucidating the mechanism (because of the different predictions for the different theories) it appears that present theories of the reaction mechanism cannot account for all the observed facts, at least for this one reaction.

It is probably fair to conclude, though, that at energies around 20 MeV some appreciable fraction of the ($^{6}Li, d$) cross section does result from direct transfer of an α particle. If a complete quantitative assessment of the contribution of different reaction mechanisms is to be made, it would probably be worthwhile to measure the angular correlations as a function of deuteron angle. We are considering such measurements for the future.

With regard to the question of the α parentage of the 7.12-MeV state, the present work can add little to what is already known, although it does seem fair to say that the α width *can* be determined from this kind of measurements. Probably the most sensible thing to do is to perform the reaction at the highest feasible energy (to minimize compound-nuclear effects) and then analyze the results in a way which properly treats the long tail of the weakly bound cluster. We have been informed that such measurements have been made and are presently being analyzed.[24]

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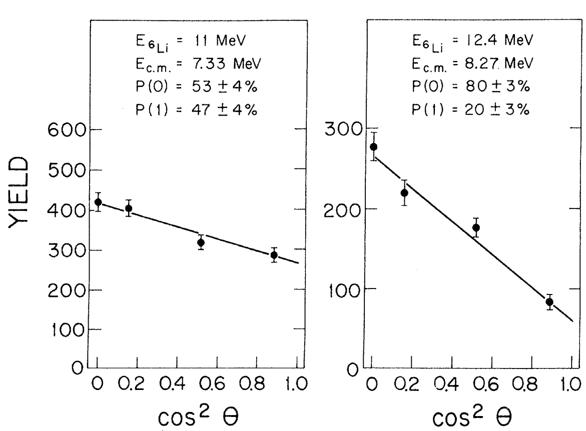

FIG. 12. Angular correlation for the 7.12-MeV 1^{-} state measured with the $^{12}C(^{6}Li, d\gamma)^{16}O$ reaction at $E_{c.m.}=7.33$ and 8.27 MeV.

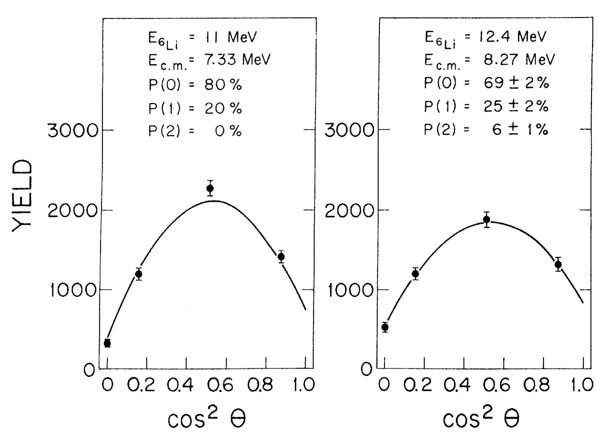

FIG. 13. Angular correlation for the 6.92-MeV 2^{+} state measured with the $^{12}C(^{6}Li, d\gamma)^{16}O$ reaction at $E_{c.m.}=7.33$ and 8.27 MeV.

tance in various phases of the experimental work reported here. Thanks are due Dr. R. R. Betts for help with the DWUCK modifications, and to C. Mosley for valuable computational assistance. The author is especially grateful to Professor S. E. Darden for an enlightening discussion concerning the role of angular momentum coupling in compound-nuclear reactions. Thanks are due Professor P. D. Kunz for the code DWUCK, and to Professor R. G. Stokstad for supplying his comcomputer program STATIS which was used to check the Hauser-Feshbach denominators, as well as to Professor C. R. Gould and Professor E. Sheldon for several useful discussions. Finally, the author is grateful to Professor R. W. Zurmühle for a critical reading of the manuscript, in addition to many valuable suggestions in all phases of this work.

APPENDIX. CALCULATION OF POPULATION PARAMETERS USING THE STATISTICAL MODEL

The assumptions involved in obtaining an expression for the differential cross section using the statistical model have been reviewed recently by Vogt.[23] In this Appendix we merely adapt his treatment to the cross section leading to the individual M states of the residual nucleus. (We restrict our treatment to observations in an axially symmetric geometry; consequently the density matrix describing the final state is diagonal and the population parameters form a complete description of the alignment.)

Vogt obtains an amplitude $q_{\alpha' s' m_{s'}; \alpha s m_s}(\Theta, \varphi)$ whose square, suitably summed over (unmeasured) projections and channel spins gives the differential cross section. In the present case measuring the angular correlation is equivalent to measuring the projection $M_{I'}$ of the residual nucleus spin I'. (Coupling scheme is $\vec{\imath}' + \vec{I}' = \vec{s}'$.) We thus define a new amplitude

$$Q_{\alpha' M_{I'} m_{i'}; \alpha s m_s} = \sum_{s' m_{s'}} (I' M_{I'} i' m_{i'} | s' m_{s'}) q_{\alpha' s' m_{s'}; \alpha s m_s}$$

and the measured population parameters are proportional to

$$\sum_{s m_s m_{i'}} |Q_{\alpha' M_{I'} m_{i'}; \alpha s m_s}|^2$$

Here i', I' refer to the spins of the outgoing particle and residual nuclear states, respectively.

The amplitudes $q_{\alpha' s' m_{s'}; \alpha s m_s}$ are exact; they contain the elements of the true collision matrix. We now make the assumption [Eq. (45) of Ref. 23] that these collision matrix elements can be treated as rapidly varying functions of energy with random phases, implying that the averaging process removes any interference between the various partial waves. In this case the expression for the population parameters becomes

$$P(M_{I'}) = \sum (2l+1)(2l'+1)(l0sm_{s'}|Jm_{s'})^2(l'0s'm_{s'}|Jm_{s'})^2(I'M_{I'}i'm_{s'}-M_{I'}|s',m_{s'})^2 \frac{T_{ls}(\alpha)T_{l's'}(\alpha')}{\sum_{\alpha'' l'' s''} T_{l''s''}(\alpha'')}, \quad \text{(A1)}$$

where the sum is over l, l', s', $m_{s'}$, J and we have assumed a spin-zero target so that s = initial channel spin = spin of incident particle. In the sum only values of l, l' are included which satisfy the condition $\pi_f = (-)^{l+l'}\pi_i$, where π_f, π_i are the parities of the initial and final states.

A computer program has been written to calculate the expression (A1) as a function of $M_{I'}$; the results are then normalized such that $\sum_{M_{I'}} P(M_{I'}) = 1$, yielding the theoretical population parameters. In the program the quantities

$$F(l, l', J) = \frac{T_{ls}(\alpha)T_{l's'}(\alpha')}{\sum_{\alpha'' l'' s''} T_{l''s''}(\alpha'')} \quad \text{(A2)}$$

were treated as input. Ideally the transmission coefficients $T_{ls}(\alpha)$, $T_{l's'}(\alpha')$ should be obtained from optical-model potentials appropriate to the entrance and exit channels, respectively. Similarly the denominator should be constructed by appropriately summing the transmission coefficients for all open channels through which the compound nucleus can decay.

For most of the calculations presented in the present work a simplified approach has been adopted. First, the transmission coefficients in both the entrance and exit channels were assumed to be given by[25]:

$$T_l = \left[1 + \exp\left(\frac{E_B - E_\alpha}{\Delta E_B}\right)\right]^{-1}, \quad \text{(A3)}$$

where $E_B = (\hbar^2/2\mu R_\alpha^2)(l+\frac{1}{2})^2 + Z_1 Z_2 e^2/R_\alpha$. In this expression μ is the reduced mass in the appropriate channel and R_α is the channel radius, assumed equal to $1.4(A_1^{1/3} + A_2^{1/3})$. The quantity Δ essentially changes the rate at which the transmission coefficients vary with l (smooth cutoff model). The Hauser-Feshbach denominator was also approximated using the expression given by Eberhard *et al.*[26]:

$$\sum_{\alpha l s} T_{ls}(\alpha) = \text{const.}(2J+1)e^{-J(J+1)/2\sigma^2}. \quad \text{(A4)}$$

(The normalizing constant cancels in the computation of the population parameters.) Of course the constant must be chosen such that the condition

$$\frac{T_{l's'}(\alpha')}{\sum_{\alpha l s} T_{ls}(\alpha)} < 1$$

is always met for the relevant l values. The principal advantage of using the simple parametrizations discussed here is that it is relatively easy to investigate the sensitivity of the results to the variour parameters employed. For example, calculations with $\Delta = 0.075$ and $\Delta = 0.01$ for a 2^+ state produced virtually identical results. Similarly, values of $2\sigma^2 = 15$ or 20 produced results which differed by less than the experimental uncertainty in the population parameters.

As a final test, representative calculations were performed using transmission coefficients obtained from the optical potentials of Table I (although spin-orbit coupling was neglected). The results were quite similar to those obtained with the parametrization described above. In addition, replacing the simplified form of the denominator (A4) by the actual sum over proton, neutron, deuteron, α particle, and ^{6}Li channels [using the form of $T_l(\alpha)$ given in Eq. (A3)] was tried. A computer program STATIS written by Stokstad, was used for this purpose.[25] Once again the resulting population parameters were quite similar to those obtained from the simplified equations. Consequently it is felt that the predictions generated for the population parameters using the statistical model are mainly sensitive to the spin and parity of the final state, and not to the details of the calculation. For example, significantly different predictions were generated for 2^+ and 2^- states. The reason for this is essentially geometrical, as has been pointed out by Darden.[27]

There is a well-known selection rule in the (d, α) reaction which states that at $\Theta_\alpha = 0°$ only unnatural-parity states can be populated in the $M=0$ magnetic substate, provided the target has $J^\pi = 0^+$.[28] This is a consequence of the vanishing of the vector-coupling coefficient $(l010|l0)$ for any l and does not depend on the reaction mechanism. In this (trivial) case clearly the predictions of Eq. (A1) will depend strongly on the parity of the final state independent of the transmission coefficients used in the calculation. In the case of the $(^6\text{Li}, d)$ reaction, an analogous rule can be formulated[26] for that fraction of the incident beam which is in the $m_i = 0$ substate. The last requirement implies that the compound nucleus is in the $M=0$ substate; in the exit channel there will be a Clebsch-Gordan coefficient $(l'0s'0|J_c0)$ where s' is the exit channel spin and $J_c = l \pm 1$. (l, l' are the orbital angular momenta in the entrance and exit channels, respectively.) The requirement that we detect the outgoing deuterons at 0° implies $m_{l'} = 0$ and consequently $m_{s'} = 0$. Since this Clebsch-Gordan coefficient vanishes unless $\{l' + s' + J_c = l' + s' + l \pm 1 = \text{even}\}$ this implies that only channel spin-parity combinations $s'^{(-)^{s'+1}}$ are allowed. Since $\vec{s}' = \vec{1} + \vec{J}_f$ where $\vec{1}$ refers to the deuteron spin and J_f to the spin of the residual state, when $\vec{s}'$ is decomposed we obtain a factor $(10J_f0|s'0)$ which now implies $J_f = s' \pm 1$. The net result is that only natural-parity states ($0^+, 1^-, 2^+, \ldots$) can be populated in the $M_{I'} = 0$ substate, provided the ^{6}Li beam is in the $m_{i'} = 0$ substate.

The statistical model calculations reflect this general rule; representative results are given in Table III. We can see that the predictions for the natural-parity states are a monotonically decreasing function of $M_{I'}$ whereas for the *unnatural*-parity states the $M_{I'} = 0$ state is somewhat depleted. This effect was found to be insensitive to the details of calculation and is a manifestation of the rule discussed above. We thus see that even for a completely statistical population of compound-nuclear levels the conservation of angular momentum and parity have important consequences for the observation of population parameters. It would thus be quite wrong, for example, to use the *observed* results for the unnatural-parity 2^- state as somehow "representative" of the population parameters to be expected following a statistical compound-nuclear reaction.

It is also worth mentioning that these particular observations are peculiar to spin-1 particles. The same formulas applied to the $(^7\text{Li}, t)$ reaction do not exhibit the same selectivity between natural-parity and unnatural-parity states. In that case the Hauser-Feshbach predictions for both 2^+ and 2^- states favor the $M = \pm 1$ substates, yielding roughly 25, 50, 25% for $M = 0, \pm 1, \pm 2$, respective-

TABLE III. Values of the population parameters $P(M)$ predicted by the Hauser-Feshbach theory as a function of J^π.

J^π	$\lvert M \rvert$ 0 (%)	1 (%)	2 (%)
1^-	53.2	46.8	···
1^+	36.5	63.5	···
2^-	29.6	52.9	17.5
2^+	44.9	41.1	14.0

ly. This would seem to suggest that the experimental observation[4] that the $M=0$ substate is favored in the $^{16}O(^7Li, t\gamma)^{20}Ne$ is more clearly indicative of a direct process in that case.

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