$d + {}^6$Li reactions at low energy

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Recent differential and total cross-section data relating to the ^{6}Li$(d,\alpha)^4$He, ^{6}Li$(d,p)^7$Li, and ^{6}Li$(d,n)^7$Be reactions at deuteron energies between 0.1 and 1.0 MeV are analyzed in terms of the Wigner-Eisenbud formalism with the R-matrix elements assumed constant, i.e., independent of the energy of the incident deuteron. For the (d,p) and (d,n) reactions the possibility of an additional coherent direct-reaction contribution is also considered. The data are reasonably well reproduced by these calculations. The results thus give an indication of the magnitude of the direct contributions to these reactions. The results also show that the observation of a resonance-like structure in, e.g., the ^{6}Li$(d,\alpha)^4$He reaction, does not necessarily imply a corresponding state in ^{8}Be.

[NUCLEAR REACTIONS R-matrix and DWBA analysis of ^{7}Li(d,p) and ^{6}Li(d,n) reactions, $E \simeq 0.1$–1.0 MeV; R-matrix analysis of ^{6}Li(d,α) reaction, $E \simeq 0.1$–2.0 MeV.]

I. INTRODUCTION

The current interpretation of the even-spin, positive-parity level structure in ^{8}Be at 20–25 MeV excitation is largely based on analyses[1-4] over limited energy ranges of individual ^{6}Li(d,α) and ^{7}Li(p,α) reactions in terms of nearby resonances, and on the observed positions of anomalies in a phase-shift analysis[5] of α-α elastic scattering data. As shown in Fig. 1, the analysis of the various reactions leads to interpretations in terms of states in ^{8}Be which are quite different, particularly in the region of excitation near 22 MeV. For example, the interpretation of the various (d,α) experiments leads to 2^+, 0^+, and/or 4^+ assignments[1,2] for a state (or states) near 22.5 MeV, while the α-α scattering results[5] and the (p,α) analysis of Kumar and Barker[3] provide evidence for a single 2^+ state a few hundred kilovolts lower—in fact, *below* the deuteron binding energy. This last observation is consistent with recent results[6] which show that the energy dependence of the integrated yields for various outgoing channels in $d + {}^6$Li reactions can be accounted for solely in terms of the s-wave surface functions in the incident channel, at least for energies up to ~500 keV. This suggests the possibility that structure observed, e.g., in the (d,α) cross section at deuteron energies below 1 MeV, which have been interpreted in terms of resonance states in ^{8}Be, may in large part simply be a manifestation of the energy dependence of the surface functions that enter into the Wigner-Eisenbud theory.[7]

Recently, a fairly complete experimental study of the angular distributions in (d,α), (d,p), and (d,n) reactions on ^{6}Li at energies below 1 MeV has been completed.[8] The present note describes attempts to investigate the mechanism governing the energy dependence of the differential and total reaction cross sections for these processes.

As mentioned above, an analysis of previous ^{6}Li$(d,\alpha)^4$He data in terms of 0^+ and 2^+ resonances in ^{8}Be has been given by Freeman and Mani.[1] It seemed of interest to determine whether the resonance parameters given in Ref. 1 (with values of the nucleon widths consistent with the quoted total widths) could also describe the observed (d, nucleon) angular distributions. Calculations indicated that this was not possible even if provisions are made to include direct-reaction contributions to these reactions (see the discussion below). Therefore, we conclude that the parameters given in Ref. 1, particularly those for a 22.5 MeV(2^+) and a 24 MeV(0^+) state, do not describe energy levels in ^{8}Be.

Furthermore, the fact that local resonances are not required to explain the energy dependence of the integrated yields for the various outgoing channels suggests the possibility that the differential cross sections for these processes can also be interpreted as nonresonant. In the remainder of the report we discuss some calculations performed to investigate this possibility. In particular, the (d,α) angular distributions are analyzed in terms of a multichannel R-matrix formalism[7] in which the R-matrix elements for each pair of reaction channels are represented as constants (nonenergy dependent terms), and the (d,p) and (d,n) reactions are analyzed as described below.

The traditional approach[9] to the interpretation of (d,p) and (d,n) reactions at low energy is in terms of an incoherent sum of a direct component and a compound contribution estimated on the basis of statistical theories. At these very low energies,

however, and for ^{6}Li targets such an approach is probably unwarranted. In the present case, therefore, the measured (d,p) and (d,n) differential cross sections are investigated in terms of a coherent superposition[10] of a direct (surface-type) interaction with a compound-nucleus contribution that is consistent with the results of the (d,α) analysis.

The results of the calculations presented here can be summarized as follows. (i) A possible explanation for discrepancies in proposed[1-4] level structures in ^{8}Be in the region of excitation near 22 MeV may lie in the fact that previous analyses neglected effects of "distant" levels in the calculations. (ii) There is evidence that there are non-negligible direct and direct-compound interference contributions to the ^{6}Li$(d,$ nucleon) reactions. (iii) Although the R-matrix parameters obtained by a simultaneous fitting to five of the reactions that proceed (at least in part) via the compound nucleus ^{8}Be are not unique, there are indications that these values are beginning to converge to a consistent description of such reactions.

II. CALCULATIONS

In the present work we present the results of a simultaneous description of five of the reactions that result from the interaction of low-energy deuterons with ^{6}Li. These are the (d,α) reaction, and the (d,p) and (d,n) reactions to the ground and first-excited states of ^{7}Li and ^{7}Be. The ^{6}Li$(d,\alpha)^4$He process is assumed to proceed entirely through "distant" states of the compound nucleus ^{8}Be, whose properties are parametrized in terms of the R-matrix theory. For the (d,p) and (d,n) reactions the same R-matrix parametrization is used for the interpretation of the interaction of the deuteron with the bulk of the ^{6}Li nucleus, while an additional interaction between a proton and neutron is assumed to take place in the external (or surface) region and is treated by a first-order perturbation calculation.

In the Wigner-Eisenbud formalism[7] the R-matrix is frequently considered in the form

$$\underline{R}=\underline{R}^0+\sum(\underline{\gamma}_\lambda\times\underline{\gamma}_\lambda)/(E_\lambda-E), \tag{1}$$

where $\underline{R}^0$ contains contributions from levels with eigenenergies E_λ sufficiently far from the energy E of interest that they can be considered to be independent of E, and the sum over λ contains the contribution from local levels. Since our present

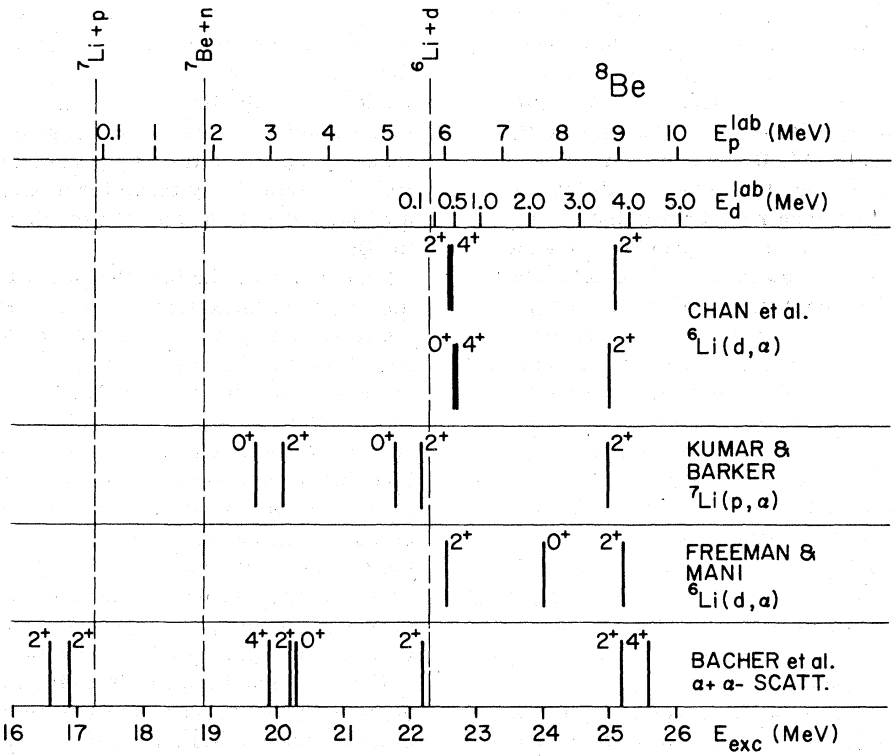

FIG. 1. Even-spin, positive-parity states in ^{8}Be as a function of excitation energy based on various analyses of the given reactions (Refs. 1–3), generally over a limited energy range. The α-α scattering results are taken from the observed positions of anomalies from an experimental phase-shift analysis (Ref. 5). The vertical dashed lines represent the energies at which ^{8}Be breaks up into the indicated particles.

interest is the extent to which reactions may be described as nonresonant, we set equal to zero the contribution from local levels so that Eq. (1) reduces to $\underline{R}=\underline{R}^0$.

For the (d,p) and (d,n) reactions, the calculation is augmented to take into account direct-reaction contributions. This extension is based on a formalism originally suggested by Thomas[10] for pickup processes. In this method the total collision matrix element for the (d,p) reaction (for example) appears as a sum of the compound-nucleus contribution, which in the present work involves the same R-matrix parameters as used for the (d,α) reaction, and the external stripping component, represented as an np interaction in the surface region, which is treated as a correction to the internal (compound-nucleus) term. The cross section will then contain terms representing the compound-nucleus contribution, the direct component, and interference contributions between the two.

The direct-reaction calculation is a distorted-wave Born approximation (DWBA) with the distorted waves formally[10] defined in terms of the compound-nucleus collision matrix elements that describe elastic scattering in the entrance and exit channels. The DWBA matrix elements thus depend not only on the relative angular momentum but also on the channel and total spin that define a given channel. In this representation there are several thousand distinct direct-reaction matrix elements that can contribute to the ^{6}Li$(d,$ nucleon) reactions which we wish to consider. Because it did not seem practical to carry out the direct-reaction calculation in this representation, the distorted waves were calculated from optical-model potentials that have been previously used to describe elastic scattering by light nuclei. This is approximately equivalent to the Thomas prescription[10] provided that the compound-nucleus collision matrices are chosen to reproduce the elastic scattering predictions of the optical-model potential.

The present calculation gives direct contributions identical to those obtained from the DWBA code DWUCK[11] when a cutoff radius of 4.5 fm is used in the latter code. The distorted waves were obtained from optical-model potentials fixed at those values of Satchler[12] for the deuteron channel, and of Watson *et al.*[13] for the nucleon channels. These values are given in Table I. Spectroscopic factors for the ground and first-excited ^{7}Li and ^{7}Be states were obtained from the compilation of Cohen and Kurath.[14]

With the parameters associated with the direct-reaction calculation kept fixed, simultaneous fits to the measured (d,α), (d,p), and (d,n) reaction cross sections were obtained by allowing the various R-matrix parameters $R^0_{cc'}$ to vary. For various reasons that include in some cases the lack of reliable data in the energy region of interest, we do not consider explicitly other reactions (e.g., $\alpha+\alpha$ elastic scattering, $\alpha+\alpha \longleftrightarrow p+{}^7$Li, $\alpha+\alpha \longleftrightarrow n+{}^7$Be, $d+{}^7$Li elastic scattering) that are described in terms of the same set of R-matrix parameters. But even though we consider the simultaneous description of only five of the possible reactions via ^{8}Be, the number of relevant parameters is large. On the assumption that only 0^+ and 2^+ ^{8}Be levels contribute[15] to the reactions, Table II shows the quantum numbers associated with each allowed channel c for each J^π, and Table III indicates that the calculation involves the specification of 17 values of $R^0_{cc'}$ (for 0^+ states) and 27 values

TABLE I. Parameters used in DWBA calculations for various values of the energies $E^{\rm lab}$ for the incident and outgoing particles.[a]

	Incident[b] particle (deuteron)	Outgoing[c] particle (proton)	Outgoing[c] particle (neutron)	Captured particle (p or n)
$E^{\rm lab}$ (MeV)	0.118–0.975	5.30–6.58	3.55–4.61	
V_0 (MeV)	115	63.1–62.8	62.9–62.7	
r_0 (fm)	0.9	1.14	1.15	1.14, 1.15
α_0 (fm)	0.9	0.57	0.57	0.57
W_D (MeV)	6.6–6.8	4.4–5.1	3.4–4.0	
r_D (fm)	2.46	1.14	1.15	
α_D (fm)	0.45	0.5	0.5	
V_{so} (MeV)	0.0	0.0	0.0	$\Lambda=25$

[a] The notation is standard: $V=V_C-V_0 f(x_0)+4iW_D(d/dx)f(x_D)+(\hbar/m_\pi c)^2 V_{so}\vec{\sigma}\cdot\vec{l}\,(1/r)(d/dr)f(x_{so})$, where V_C is the Coulomb potential due to a uniformly charged sphere with radius $r_c A^{1/3}$ ($r_c=0.9$ for deuterons and $=1.14$ fm for protons), and $f(x_i)=[1+\exp(x_i)]^{-1}$ with $x_i=(r-r_i A^{1/3}/a_i)$. Λ is the spin-orbit parameter multiplying the usual Thomas term.

[b] Ref. 12.

[c] Ref. 13.

of $R^0_{cc'}$ (for 2^+ levels). These numbers are reduced to 11 and 18, respectively, by requiring that $R^0_{cc'}$ for neutron channels are set equal to the values for the corresponding proton channels in accordance with the principle of charge symmetry of nuclear reactions which is expected[16] to hold to a good approximation for the (d,p) and (d,n) processes.

The calculational procedure outlined above is not expected to yield unique values for the elements of the matrix $\underline{R}^0$. Indeed the objective here is considerably more modest. The cross section for a reaction from channel α to channel β is

$$\sigma_{\alpha\beta}(E) \propto \left|\left[(\underline{l}-\underline{R}^0\underline{L}^{0*})^{-1}\underline{R}^0\right]_{\alpha\beta}\right|^2, \tag{2}$$

where $\underline{R}^0$ is independent of the energy E and

$$\underline{L}^0 = \underline{S} - \underline{b} + i\underline{P}. \tag{3}$$

The (diagonal) boundary condition matrix $\underline{b}$ is also independent of E and the shift and penetrability matrices, $\underline{S}$ and $\underline{P}$, are monotonic and, except for the deuteron channel, slowly varying functions of E. Thus the energy dependence of $\sigma_{\alpha\beta}$ is considerably restricted, and one question we wish to address is simply whether the resonance-like structure observed in the (d,α) reaction between ~0.1 and ~1.5 MeV can be reproduced by Eq. (2) for parameters which also reproduce the yields observed in the other channels. In the R-matrix calculations radii of 3.8 fm for the $d+{}^6$Li channel, 4.5 fm for the $\alpha+\alpha$ channel, and 4.22 fm for the nucleon channels were used. Boundary values for the various channels were chosen to be equal to the corresponding shift function at zero relative energy.

III. RESULTS AND DISCUSSION

The calculations discussed in the previous section are compared to recently published data of Elwyn *et al.*,[8] in which angular distributions were

TABLE II. Quantum numbers for each channel c for those levels included in the analysis (l is the orbital angular momentum and s is the channel spin).

	$J^\pi=0^+$			$J^\pi=2^+$	
c	l	s	c	l	s
$d+{}^6$Li	0	0	$d+{}^6$Li	0	2
$d+{}^6$Li	2	2	$d+{}^6$Li	2	0
$\alpha+\alpha$	0	0	$d+{}^6$Li	2	1
$p_0+{}^7$Li	1	1	$d+{}^6$Li	2	2
$n_0+{}^7$Be	1	1	$\alpha+\alpha$	2	0
$p_1+{}^7$Li*	1	1	$p_0+{}^7$Li	1	1
$n_1+{}^7$Be*	1	1	$p_0+{}^7$Li	1	2
			$n_0+{}^7$Be	1	1
			$n_0+{}^7$Be	1	2
			$p_1+{}^7$Li*	1	1
			$n_1+{}^7$Be*	1	1

TABLE III. Reactions $c \leftrightarrow c'$ for which $R^0_{cc'}$ values are included in the analysis. N_0 and N_2 are the number of $R^0_{cc'}$ values that were included in the analysis for $J^\pi=0^+$ and $J^\pi=2^+$, respectively.

$c(c')$	$c'(c)$	$N_0(J^\pi=0)$	$N_2(J^\pi=2^+)$
$d+{}^6$Li	$d+{}^6$Li	2	4
$d+{}^6$Li	$\alpha+\alpha$	2	4
$d+{}^6$Li	$p_0+{}^7$Li	1	2
$d+{}^6$Li	$n_0+{}^7$Be	1	2
$d+{}^6$Li	$p_1+{}^7$Li*	1	1
$d+{}^6$Li	$n_1+{}^7$Be*	1	1
$\alpha+\alpha$	$\alpha+\alpha$	1	1
$p_0+{}^7$Li	$p_0+{}^7$Li	1	2
$n_0+{}^7$Be	$n_0+{}^7$Be	1	2
$p_1+{}^7$Li*	$p_1+{}^7$Li*	1	1
$n_1+{}^7$Be*	$n_1+{}^7$Be*	1	1
$p_0+{}^7$Li	$\alpha+\alpha$	1	2
$n_0+{}^7$Be	$\alpha+\alpha$	1	2
$p_1+{}^7$Li*	$\alpha+\alpha$	1	1
$n_1+{}^7$Be*	$\alpha+\alpha$	1	1

measured for the ^{6}Li$(d,\alpha)^4$He, ^{6}Li$(d,p)^7$Li, and ^{6}Li$(d,n)^7$Be reactions at deuteron energies of 0.1–1.0 MeV, and to (d,α) data of McClenahan and Segel[17] at higher energies. The comparisons are presented in terms of the coefficients B_L in the Legendre polynomial expansion of the differential cross sections. Thus, e.g., the total (angle-integrated) cross section is given by $4\pi B_0$.

The best simultaneous fit to the (d,α), (d,p), and (d,n) measurements is shown as the solid curves in Figs. 2, 3, and 4. These results represent calculations in which the values of the parameters $R^0_{cc'}$, specifying the compound-nucleus contribution, are the same for all five reactions.[18] It is interesting to note that both diagonal (i.e., R^0_{cc}) and off-diagonal (i.e., $R^0_{cc'}$) parameters in which one or both of the c, c' are associated with nucleon channels have a signficant effect on calculations for the (d,α) reaction. For example, the fits represented by the solid curves include small but nonzero values for at least some of the off-diagonal parameters associated with $\alpha(\alpha,p)^7$Li and $\alpha(\alpha,n)^7$Be reactions, shown as the last four entries in Table III. The fits are less good when these parameters are all set equal to zero.

The dashed curve on Fig. 2 is the result of a calculation in which we do not require a fit to the data for all five reactions simultaneously. It indicates that with this added freedom better fits to the results for individual reactions can be obtained even within the framework of the physical assumptions of the given reaction model.

The solid curves on Figs. 3 and 4 represent the coherent addition of direct and compound-nucleus contributions, and thus include the effects of interference between the two mechanisms. The magnitude of such interference contributions depends

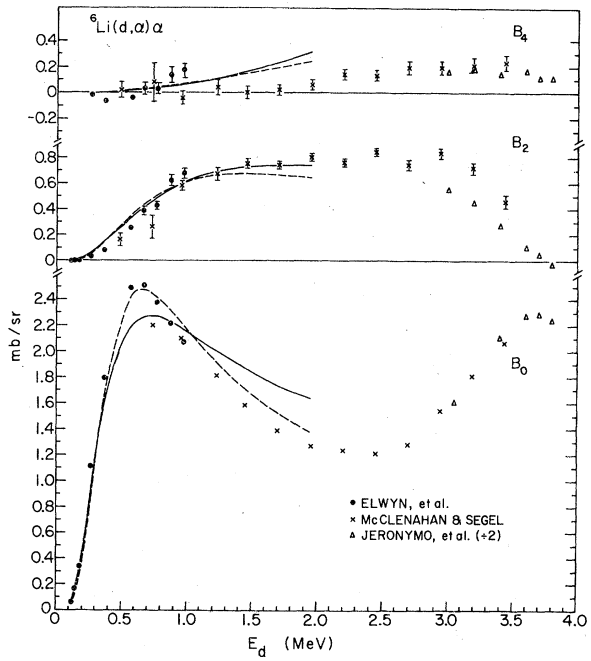

FIG. 2. Comparison of calculations with experimental B_L values for the ^{6}Li$(d,\alpha)^4$He reaction. The solid curves represent the results of the best simultaneous fit (within the framework of the model discussed in the text) to (d,α), (d,p), and (d,n) data, while the dashed curves are the fits to the (d,α) measurements alone. The resonance near $E_d \simeq 3.5$ MeV is not included in the calculations. The data are from Refs. 8, 17, and 20.

on the values of the parameters utilized in the calculation and can be observed by comparing the solid with the dot-dashed curves, the latter representing an *incoherent* sum of compound and direct processes.[19] Although the sizes of the interference effects are apparently quite small for the ground state (d,p) and (d,n) reactions, their effect on the first-excited state calculations is considerably larger and, as observed, the calculations in which interference effects are included are a better fit to the data (particularly for B_0 and B_1 coefficients).

The calculations based on direct reaction contributions alone (dashed curves on Figs. 3 and 4), while in fairly good agreement with angular distribution coefficients B_1 through B_4, disagree completely with the measured total cross sections B_0. Although we have not investigated other sets of optical-model potential parameters, it does not seem likely that a calculation based on a direct interaction alone can lead to a reasonable simultaneous fit to all of the data. It is equally unlikely that any simple compound-nucleus reaction could duplicate the behavior of the coefficients B_L for the higher values of L.

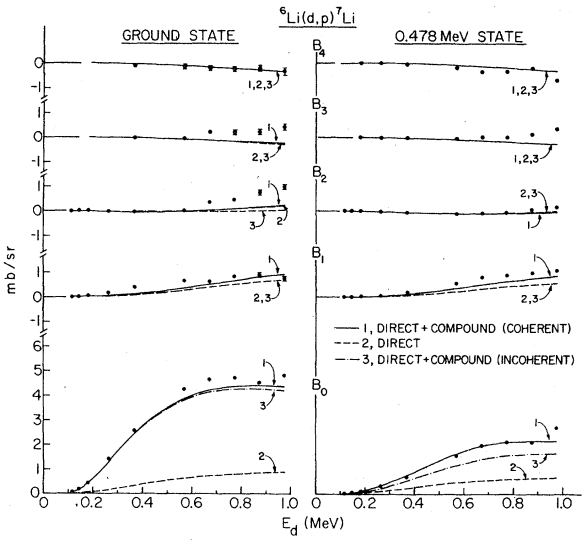

FIG. 3. Comparison of calculations with experimental B_L values for the ^{6}Li$(d,p)^7$Li reactions. The solid curves represent the results of the best simultaneous fit (within the framework of the model discussed in the text) to (d,α), (d,p), and (d,n) reactions, while the other two curves are based on the calculations indicated (see text). The data are from Ref. 8.

The present results demonstrate that in the low-energy region in the interaction of deuterons with ^{6}Li the data can in large part be represented by a compound-nucleus contribution that involves only

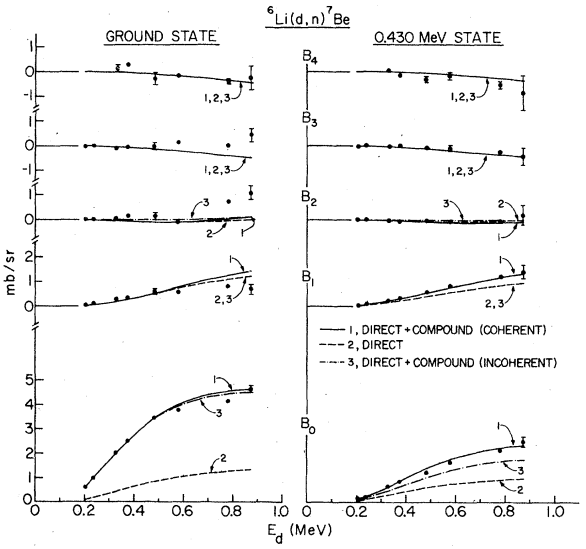

FIG. 4. Comparison of calculations with experimental B_L values for the ^{6}Li$(d,n)^7$Be reactions. The solid curves represent the results of the best simultaneous fit (within the framework of the model discussed in the text) to (d,α), (d,p), and (d,n) reactions, while the other two curves are based on the calculations indicated (see text). The data are from Ref. 8.

constant R-matrix elements which within the formalism are interpreted as arising from distant levels. A more complete analysis, in which the data for other two-body reaction channels are included, should, of course, contain explicitly the energy dependence of nearby resonances. Resonances in ^{8}Be are apparently observed in the phase-shift analysis of α-α elastic scattering experiments[5] as well as in the ^{6}Li(d,α) (see Fig. 2, particularly the higher energy data of Jeronymo, *et al.*[20]) and ^{7}Li(p,α) reactions.[3] A consistent interpretation of $d+^6$Li reaction data must include such effects. The present results, however, indicate that such an interpretation must also incorporate the properties of distant levels before a unique explanation of the level structure of ^{8}Be at 20–25 MeV excitation can be given.

As discussed in Sec. II, optical-model potentials were used to calculate the distorted waves in the DWBA to the direct-interaction matrix elements. A crude measure of the consistency of this calculation is obtained by comparing the elastic scattering obtained using the R^0 matrices with that predicted by the optical-model potentials. In general the cross sections given by these two calculations show very similar behavior as functions of energy. Furthermore, the magnitude of the ^{7}Li elastic scattering cross sections obtained from our final R^0-matrix values for those protons that correspond to the ground state in the ^{6}Li$(d,p)^7$Li reaction are less than 5% smaller than the magnitude given by the optical-model potential of Ref. 13, and the results for the ^{4}He(α,α) phase shifts calculated with our final R^0-matrix values agree to within 10% with these from the optical-model potential description of Igo.[21] However, for protons with energies that correspond to the ^{6}Li(d,p) first-excited state reaction, the ^{7}Li elastic scattering cross sections calculated with final R^0-matrix values are larger by factors of 2 to 2.5 than the optical-model potential calculations. The differences in the predictions for the other elastic scattering channels are intermediate to these.[22]

It should be mentioned that no effort was made to adjust the R-matrix parameters or the optical-model potentials to minimize these differences. Although these discrepancies seem large by usual standards, there are certain regularities that would not be expected if the present R-matrix parametrization was entirely devoid of physical meaning. On the other hand, these differences are sufficiently large that consistency with the calculation proposed in Ref. 10 cannot be claimed. However, only the direct-reaction matrix elements are involved in these comparisons and their contributions to the $d+^6$Li reactions that we have considered are relatively small. We feel that none of the qualitative conclusions that have been based on these calculations are materially altered by this inconsistency with the Thomas prescription.[10]

As mentioned in Sec. I, our initial effort was to determine whether the resonance parameters given by Freeman and Mani[1] in their analysis of ^{6}Li(d,α) angular distributions could also describe the recently measured ^{6}Li$(d,$ nucleon) differential cross sections. As this analysis proceeded, it became obvious that this was not possible and, perhaps more important, none of the data indicated an unambiguous resonance behavior in the energy interval of interest. The difficulties in the interpretation of these data are not unique and it is of interest to understand them more completely. The dependence of the cross section for a given reaction, e.g., $\sigma_{d\alpha}$, on parameters associated with a third channel ($c=p$, e.g.) can be quite pronounced. It arises through the coupling inherent in a multichannel R-matrix description because of the matrix inversion (see Eq. 2), whether reduced widths, constant R-matrix elements, or both are used to parametrize the interaction. This observation is clearly not new. In fact, it is the reason that a resonance shape is observed in a (p,n) reaction through an isobaric analog resonance.[23] However, the generality of these effects seem not to be fully appreciated. It is this coupling between observed and unobserved channels that makes it impossible to obtain a unique interpretation through piecemeal fitting to data in a single two-channel reaction when many reaction channels are actually involved. Furthermore, over an energy interval in which the matrix elements L_l^0, Eq. (3), are rapidly varying functions of energy for one or more channels, this coupling can give rise to a complex energy-dependent cross section in other channels. Since the interpretation of the ^{8}Be energy levels in the region of 20–25 MeV excitation is based in general on the analysis of a small fraction of the possible reactions, and over a considerable part of this region the matrix elements L_l^0 for the deuteron channels vary rapidly with energy, not only should the specific values of the resonance parameters given in the literature be considered uncertain, but also the existence of such resonances is subject to question.

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