Successive pickup contributions to the ^{98}Mo(d,α)^{96}Nb reaction

W. R. Coker and Takeshi Udagawa
Center for Nuclear Studies, University of Texas, Austin, Texas 78712*

J. R. Comfort
Physics Department, Ohio University, Athens, Ohio 45701
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The mechanism for (d, α) reactions is discussed, with special attention given to the ^{98}Mo(d, α) ^{96}Nb reaction leading to the presumed $[(g_{9/2})_p(d_{5/2})^{-1}{}_n]$ multiplet in ^{96}Nb. The analysis relies on the coupled-reaction-channel approach for including contributions from the successive pickup processes (d,t)-(t,α) and $(d,{}^3\mathrm{He})$-$({}^3\mathrm{He},\alpha)$. An excellent description of both the shape and magnitude of the available data is possible with adjustment of only a single parameter, namely the effective strength D_0 of the direct plus nonorthogonality terms in the reaction amplitude. The effective direct term dominates for low-spin final states of unnatural parity, while the (d,t)-(t,α) term dominates for high-spin final states of natural parity. Extension of the results to the ^{92}Mo(d, α) ^{90}Nb reaction is also discussed.

[NUCLEAR REACTIONS ^{92,98}Mo(d,α), $E=17$ MeV; calculated $\sigma(E_\alpha,\theta)$, DWBA and coupled-reaction channels, including two-step (d,t)-(t,α) and $(d,{}^3\mathrm{He})$-$({}^3\mathrm{He},\alpha)$.]

I. INTRODUCTION

The (d, α) reaction in recent years has become a popular spectroscopic tool despite suspicions concerning the nature of the reaction mechanism. Typical microscopic analyses of (d, α)-reaction data, assuming a direct one-step pickup of a spin-triplet isospin-singlet neutron-proton pair in a relative s state, are discussed in detail by Curry, Coker, and Riley[1] and by Schneider and Daehnick,[2] for example. A relatively large number of experimental studies of (d, α) reactions, on a wide range of nuclei, may be found in the current literature. All of these studies involve data displaying common features that are somewhat disturbing.

In general, predictions of the cross sections by the usual zero-range distorted-wave Born approximation (DWBA), whether the transferred nucleons are described by a point cluster[1,2] or microscopically,[1-4] show a slight shift in diffraction structure relative to the data. This shift is sometimes masked by the fact that in certain cases two different orbital-angular-momentum transfers can make roughly equal contributions to the DWBA cross section, but it is a general feature of the analyses that cannot be explained away by optical-model parameter ambiguities.

Secondly, if a fixed zero-range strength D_0^2 is adopted in the DWBA, calculations that make use of detailed shell-model configurations for the initial and final nuclear states do not always account successfully for the relative magnitudes of the cross sections for various final nuclear states. There is an apparent systematic discrepancy, depending on the J^π of the final state, between predicted and measured cross sections. This discrepancy is worrisome but is not drastic, amounting to factors of 2 to 10 for instance.[5,6]

In addition, the values of D_0^2 used in the various analyses vary over quite a wide range. A recent analysis[7] of a number of nuclei yielded normalization constants that varied by a factor of 4 between targets of ^{48}Ca and ^{208}Pb. An earlier analysis[8] of the data from the ^{208}Pb target had yielded a normalization factor two orders of magnitude lower, while a more recent study[6] in the mass-90 region gave values as much as an order of magnitude larger. Of course, a considerable amount of these variations can be attributed to different prescriptions of DWBA parameters and correction factors.[6] Nevertheless, the variations attest to the difficulty in understanding the details of the reaction mechanism.

Finally, (d, α) cross sections are in general quite small, ranging from 1 to 100 μb/sr at forward angles for typical incident deuteron energies (10–25 MeV).

These observations are quite reminiscent of the situation with regard to $({}^3\mathrm{He}, t)$ reactions.[9,10] It is now rather well accepted that the $({}^3\mathrm{He}, \alpha)$-$(\alpha, t)$ pickup-stripping process makes an important contribution to $({}^3\mathrm{He}, t)$ reactions and accounts for the observed anomalies in the shape and magnitude of $({}^3\mathrm{He}, t)$ cross sections.[11-14] Schaeffer and Bertsch[11] have suggested that the successive pickup reactions (d, t)-(t, α) and $(d, {}^3\mathrm{He})$-$({}^3\mathrm{He}, \alpha)$ might contribute to (d, α) reactions. These processes are investigated here for the particular case of the ^{98}Mo(d, α)-^{96}Nb) reaction, at 17 MeV incident deuteron energy.[6] We have previously given two oral reports of this work.[15]

We first present details of the nuclear spectroscopic information used in the calculation; then, the results of a conventional DWBA calculation for the direct process; next, the results of coupled-reaction-channel (CRC) calculations of the cross sections due to pickup-pickup processes (d, t)-(t, α) and $(d, {}^3\text{He})$-$({}^3\text{He}, \alpha)$; and, finally, an analysis of the data for the ^{98}Mo$(d, \alpha)^{96}$Nb reaction[6] that assumes a coherent competition between all processes considered. It is shown that the available data can be reproduced very well in both shape and magnitude, without adjustment of parameters from state to state. In order to test the results, the analysis is extended to similar data for the ^{92}Mo$(d, \alpha)^{90}$Nb reaction[6] and an attempt is made to draw some general conclusions.

II. DATA AND SPECTROSCOPIC AMPLITUDES

The angular distributions for six states below 0.7 MeV in ^{96}Nb from the (d, α) reaction on ^{98}Mo, along with a microscopic DWBA analysis, have been previously reported.[6] These states had been previously ascribed[16] as arising predominantly from a $[(g_{9/2})_p(d_{5/2})^{-1}{}_n]$ configuration. The angular distributions from the (d, α) reaction, and the DWBA analysis, supported the previous interpretation. Relevant supporting spectroscopic information, from ^{98}Mo(d, t) and ^{98}Mo$(d, {}^3\text{He})$ reactions, is also available.[17,18]

These states are very suitable to the analysis considered here. Within the framework of the simple shell model, they can be anticipated to have quite pure configurations since few other positive-parity states are expected in the region.[6] The $J^\pi = 4^+$ and 5^+ states could be mixed with terms involving an $s_{1/2}$ neutron, but the requisite configuration impurity in the ^{98}Mo ground state appears to be quite small.[17] All states could have admixtures from a $[(g_{9/2})_p(g_{9/2})^{-1}{}_n]$ configuration, but the centroid for these states is expected to be about 3 MeV away.[6] In addition, the intrinsic (d, α) cross sections for this impurity are an order of magnitude less than for the predominant configuration. Thus the CRC analysis is not constrained by high sensitivity to small and unknown configuration admixtures.

The spectroscopic amplitudes A_{lsj} needed for the single-nucleon-transfer reactions, as defined in Ref. 19, were computed by assuming a pure $[(g_{9/2})^2{}_p(d_{5/2})^6{}_n]$ configuration for the ground state of ^{98}Mo. They are summarized in Table I. The form factors appropriate to these amplitudes were obtained by using the standard separation-energy method, with geometry $r_0 = r_{so} = r_c = 1.25$ fm, $a_0 = a_{so} = 0.65$ fm, $V_{so} = 5.8$ MeV.

The form factors for the direct (d, α) reactions were computed by using a recent version of the program TWOPAR of Bayman and Kallio[3,20] which constructs a microscopic form factor for any two nucleons in an s state of relative motion. The separation energy of a deuteron from ^{98}Mo was divided equally between the neutron and the proton. The two-nucleon spectroscopic amplitude defined by Bayman and Kallio is related to the one we use by $A^{\text{CRC}}_{LSJ} = (i^L/\hat{J})A^{\text{BK}}_{LSJ}$, where L, S, and J are the orbital, spin, and total angular momenta transferred in the reaction and $\hat{J} = (2J+1)^{1/2}$. Note that only $S=1$ is allowed. For the normal-parity final states $J^\pi = 2^+$, 4^+, and 6^+, only one L value is allowed, $L=J$. For the unnatural-parity final states 3^+, 5^+, and 7^+, $L = J \pm 1$ is allowed in general, with the exception of $J^\pi = 7^+$ where $L=8$ is impossible.

III. DWBA AND CRC CALCULATIONS

Coupled-reaction-channel calculations, neglecting basis nonorthogonality, were first carried out by Rawitscher,[21] who studied the (d,p)-(p,d) contributions to deuteron elastic scattering, and by Ohmura *et al.*,[22] who treated (d,p) reactions to all orders in the effective interaction V_{np}. The case for the necessity for such a treatment of nuclear reactions in general, and in particular for $({}^3\text{He}, t)$ reactions, was first argued by Schaeffer and Bertsch.[11] A large number of detailed studies of $({}^3\text{He}, t)$ reactions, in which the successive $({}^3\text{He}, \alpha)$-(α, t) and $({}^3\text{He}, d)$-(d, t) mechanisms are treated with the second-order distorted-wave Born approximation[12-14] or by solving the CRC equations, also neglecting basis nonorthogonality,[13,19] have since been reported.

Our calculations were performed by using the CRC formalism as detailed by Coker, Udagawa, and Wolter.[19] The coupled equations were solved exactly in zero range but with neglect of "backward" transitions [e.g., (α, t) and (t, d)]. Thus our results are numerically equivalent to the

TABLE I. Spectroscopic amplitudes used in the DWBA and CRC calculations, expressed in terms of the total angular momentum J of ^{96}Nb.

Target	Reaction	l_j	A_{lsj}
^{98}Mo	$(d, {}^3\text{He})$	$g_{9/2}$	$-\sqrt{2}$
	(d,t)	$d_{5/2}$	$\sqrt{6}$
^{97}Nb	$({}^3\text{He}, \alpha)$	$d_{5/2}$	$-(2J+1)^{1/2}$
^{97}Mo	(t, α)	$g_{9/2}$	$[(2J+1)/5]^{1/2}$
^{98}Mo	(d, α)	$J-1,J$	$i^{J-1}/\sqrt{10}$
		$J+1,J$	$i^{J+1}/\sqrt{10}$

TABLE II. Optical-model potentials used in the calculations.

Set	V	W (MeV)	W_D	r_0	a	r' (fm)	a'	r_c	Ref.
				Deuteron					
$D1$	98.1	0.0	14.87	1.127	0.848	1.394	0.655	1.127	a
$D2$	90.0	0.0	16.6	1.2	0.75	1.3	0.7	1.30	a
				Triton or ^{3}He					
$H1$	173.0	18.0	0.0	1.14	0.723	1.55	0.80	1.4	b
$H2$	157.8	11.71	0.0	1.174	0.706	1.596	1.032	1.25	c
				^{4}He					
$A1$	228.0	23.3	0.0	1.366	0.557	1.242	0.557	1.40	a
$A2$	181.3	15.0	0.0	1.20	0.75	1.70	0.60	1.30	a

[a] Quoted in Ref. 6.
[b] Reference 17.
[c] R. Kozub and D. Youngblood, Phys. Rev. C 4, 535 (1971).

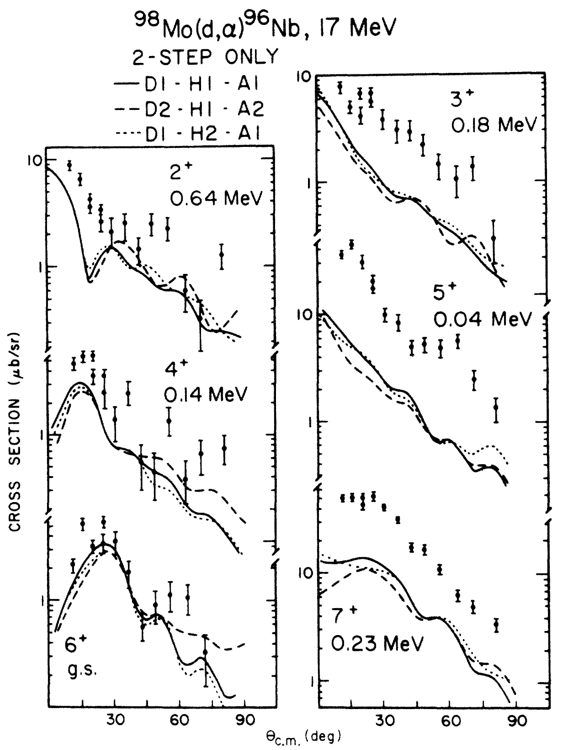

FIG. 1. Experimental and calculated angular distributions for states of the presumed $[(g_{9/2})_p(d_{5/2})^{-1}{}_n]$ multiplet in ^{96}Nb, for the ^{98}Mo(d,α) ^{96}Nb reaction at 17 MeV incident deuteron energy. The calculations assume a pure two-step-pickup mechanism with coherent contributions from $(d-t)$-(t,α) and $(d,{}^3\mathrm{He})$-$({}^3\mathrm{He},\alpha)$ processes. The cross sections are based on the spectroscopic amplitudes of Table I and are absolute. Separate curves show the effects of different optical-potential combinations, obtained from Table II. The data are from Ref. 6.

second Born approximation[11-14] which is an excellent approximation for strongly absorbed particles such as we have in this case.[19] It is worth stressing that in the second-order Born amplitude, which describes the processes (d,t)-(t,α) and $(d,{}^3\mathrm{He})$-$({}^3\mathrm{He},\alpha)$, no adjustable parameters appear. The optical potentials, zero-range strengths, and spectroscopic amplitudes were taken from previous experiments[17,18] or simple shell-model theory.[19] Thus the successive pickup contributions are given absolutely and cannot be adjusted except by changing from one optical-model potential to another.

The optical potentials used are given in Table II. There are two potentials listed for each mass partition, as indicated. The combination $D1$-$H1$-$A1$ was used in most of the calculations. The other potentials were used only in studies of the sensitivity of the results to potential ambiguities. The combination $D1$-$A1$ was favored in the DWBA analysis of Ref. 6.

In Fig. 1 are shown the results of the CRC cal-

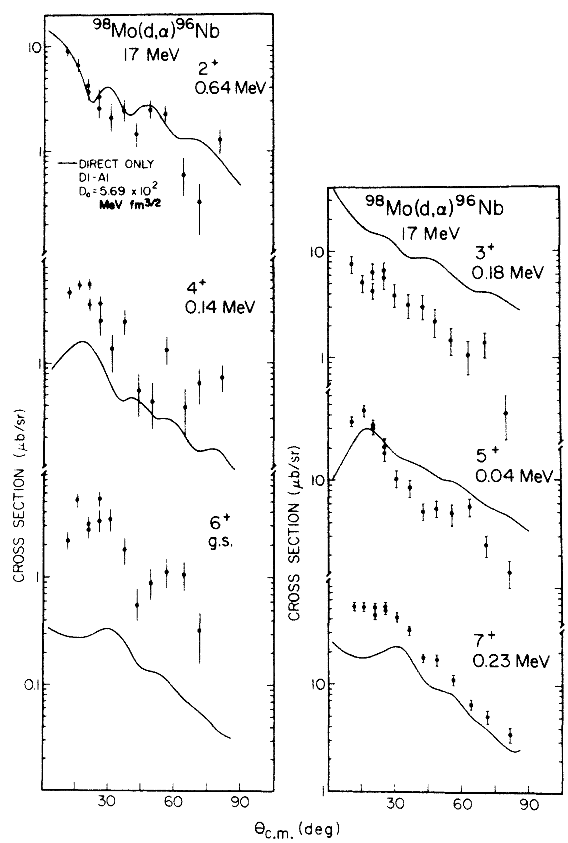

FIG. 2. Calculations of the angular distributions for the ^{98}Mo(d,α) ^{96}Nb reaction that assume a pure direct two-nucleon-pickup process. The effective zero-range strength is $D_0(d,\alpha) = 569$ MeV fm$^{3/2}$. The data are the same as in Fig. 1.

culations that assume a pure multistep process, which is predominantly (d, t)-(t, α) but also includes a coherent contribution from $(d, {}^3\mathrm{He})$-$({}^3\mathrm{He}, \alpha)$. The predicted magnitudes are absolute, using the D_0 values of Table I, Ref. 19. Calculations are shown for three different choices of potentials sets, namely, $D1$-$H1$-$A1$, $D2$-$H1$-$A2$, and $D1$-$H2$-$A1$. The results are seen to be reasonably insensitive, particularly in magnitude, to optical-potential ambiguities.

For comparison Fig. 2 displays similar DWBA calculations that assume a pure direct-pickup process, in which a neutron-proton pair in a relative s state, with total spin $S = 1$, is removed from ${}^{98}\mathrm{Mo}$. Again, predictions are absolute, using a $D_0(d, \alpha)$ value of 569 MeV fm$^{3/2}$. This empirical $D_0(d, \alpha)$ may be compared to the empirical D_0^2 values routinely used by experimentalists in DWBA fitting as follows:

$$D_0(d, \alpha) = [D_0^2(\exp)/3]^{1/2}\,.$$

Since experimentalists have used values in effect ranging from $<10^2$ to $>10^3$ MeV fm$^{3/2}$, and since the magnitudes of the predicted cross sections are extremely sensitive to relatively tiny amounts of configuration mixing, our value for D_0 is chosen simply to fit the cross section for the 2^+ state. It is then seen clearly that the direct contribution, assuming a pure configuration, decreases with increasing J both for natural- and unnatural-parity states. The relative magnitudes of the experimental cross sections therefore cannot be explained in this way.

In Fig. 3 are shown the results of coherent contributions from all three mechanisms, direct (d, α), (d, t)-(t, α), and $(d, {}^3\mathrm{He})$-$({}^3\mathrm{He}, \alpha)$. For these calculations the direct $D_0(d, \alpha)$ was changed to -380 MeV fm$^{3/2}$. The reason for the magnitude reduction is obvious. The motivation for the sign change is discussed below. It is seen that the relative magnitudes of the (d, α) cross sections are now quite well reproduced, particularly in the case of the natural-parity states.

Finally, in Fig. 4 are shown breakdowns of the contributions of the various processes for four of the six states. It is apparent that the reaction mechanism has varying contributions from the direct and two-step components, with direct (d, α) dominating for low J and (d, t)-(t, α) for high J.

The successive single-nucleon-transfer processes considered here are (d, t)-(t, α) and $(d, {}^3\mathrm{He})$-$({}^3\mathrm{He}, \alpha)$, which are both pickup-pickup processes. The CRC treatment of successive nucleon-transfer processes, taking into account basis nonorthogonality, has been given by Udagawa, Wolter, and Coker.[23] Since the pickup calculations are done

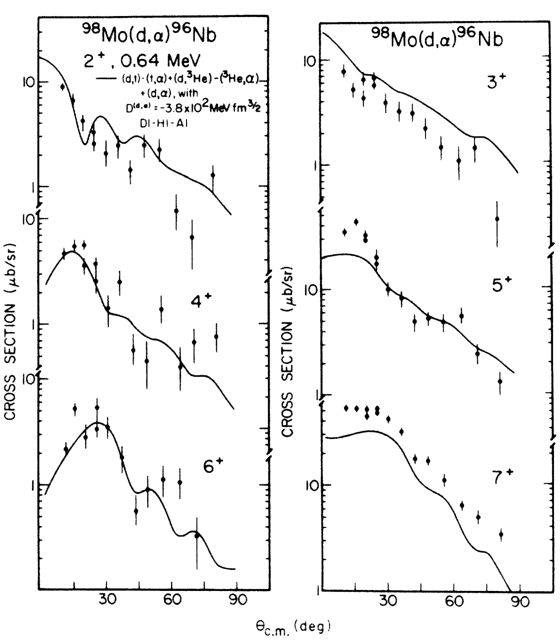

FIG. 3. Calculations for the data of Fig. 1 that include a coherent summation of direct-(d,α) and two-step processes. All parameters are the same as in Figs. 1 and 2, except that $D_0(d,\alpha)$ has been changed to -380 MeV MeV fm$^{3/2}$, for reasons given in the text. All cross sections are absolute.

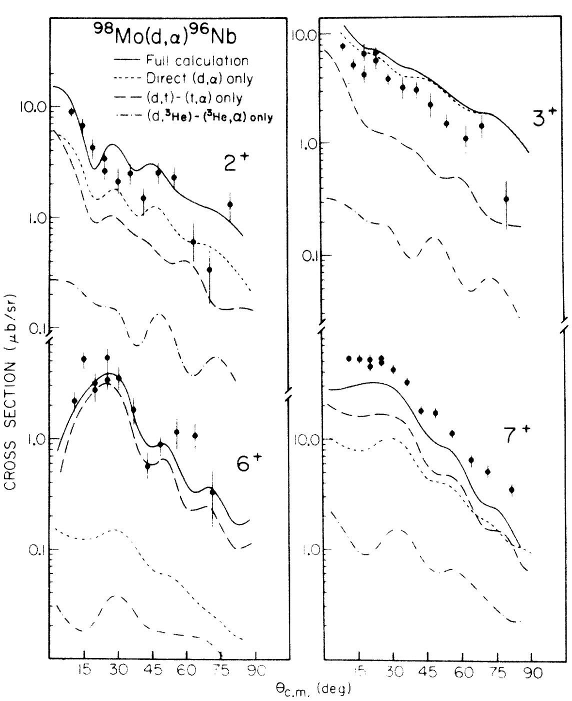

FIG. 4. Decomposition of the CRC calculations for four states of ${}^{96}\mathrm{Nb}$ into the components for the direct-(d,α), the (d,t)-(t,α), and the $(d,{}^3\mathrm{He})$-$({}^3\mathrm{He},\alpha)$ two-step processes.

in the prior representation,[24] there is a nonnegligible nonorthogonality amplitude that must be included coherently. As argued by Udagawa *et al.*, in zero range this amplitude has the same form as the direct amplitude, but opposite phase.[23] Thus we can include it effectively by changing the sign of the direct term and using its strength D_0 as an adjustable parameter. This has been done in obtaining the final fits to the data as shown in Figs. 3 and 4. Note that the final magnitude of D_0, 3.8 $\times 10^2$ MeV fm$^{3/2}$, is very close to the initial empirical value of 5.69×10^2 MeV fm$^{3/2}$, as one would expect if the nonorthogonality contribution is a little less than twice the direct contribution.[23]

IV. EXTENSION OF THE ANALYSIS

It was noted in Ref. 6 that the average normalization factor needed in DWBA for states of the presumed $[(g_{9/2})_p(g_{9/2})^{-1}{}_n]$ multiplet in ^{90}Nb was about a factor of 4–5 larger than for the multiplet in ^{96}Nb discussed above. In view of the over-all success of the CRC analysis for a single multiplet in ^{96}Nb, it is of interest to inquire whether the approach can be extended to other multiplets and nuclei. The parameters of the calculation, and in particular the effective value of $D_0(d, \alpha)$, should not change much.

It is not possible to consider all of the published data. Thus, the discussion will be restricted here to the set of states in ^{90}Nb that have been associated with the $(g_{9/2})^2$ multiplet mentioned above.[6,25,26] A direct one-step (d, α) reaction should populate only the states with odd angular momentum. The 8^+ ground state is very weakly populated, while the 2^+ state undoubtably has substantial configuration mixing. Other positive-parity states are not identified. The 1^+ state lies near 2.1 MeV excitation and also must have a complicated structure.[6]

If one performs conventional DWBA calculations, as described in Sec. III, with $D_0(d, \alpha)$ taken arbitrarily to be 600 MeV fm$^{3/2}$, the resulting cross sections are smaller than the observed cross sections by factors of from 0.2 (for $J^\pi = 1^+$) to 0.1 (for $J^\pi = 5^+, 7^+$). The discrepancy is even greater for the 9^+ state, but this particular state was not clearly resolved from nearby probable 2^+ states.[6,27] The pickup-pickup CRC calculations, again performed much as described in Sec. III, with the same potential set $D1$-$A1$-$H1$, account for only about 0.04 of the observed cross section for each state. However, for the 8^+ state which cannot be populated directly by two-nucleon pickup, the two-step calculations account for the entire observed cross section, within experimental error (which is large).

The explanation of these results is rather clear. If the 1^+, 3^+, 5^+ and 7^+ states contain even small admixtures of other configurations, say $[(g_{9/2})_p\text{-}(d_{5/2})^{-1}{}_n]$, then the form factors for the direct two-nucleon transfer processes as well as the successive one-nucleon pickup processes will be radically different. The resulting calculated direct *and* two-step cross sections will increase dramatically. As an example, if the 3^+ and 5^+ states are taken to have the configuration $80\%(g_{9/2})_p(g_{9/2})^{-1}{}_n + 20\%(g_{9/2})_p(d_{5/2})^{-1}{}_n$, then about two-thirds and one-third of the observed cross sections for the 3^+ and 5^+ states, respectively, are obtained with DWBA (D_0 still 600 MeV fm$^{3/2}$). There are similar strong effects on the (d, t)-(t, α) contributions.

In short, the difficulty is that the predominant configuration does not make the predominant contribution to the cross section, unlike in the ^{98}Mo$(d, \alpha)^{96}$Nb case. Thus the ^{92}Mo$(d, \alpha)^{90}$Nb analysis is rendered rather unattractive and not straightforward. By treating the strength of the second configuration as a second adjustable parameter *for each state* [in addition to the effective $D_0(d, \alpha)$, which can as before be fixed at −380 MeV fm$^{3/2}$], it is possible to explain all of the observed cross sections except that for the 9^+ state. The admixtures required are unlikely to exceed 30%. It is difficult to think of a simple configuration that could admix with the 9^+ state, but it seems also that further experimental effort will be required to determine whether in fact a spin of 9^+ was properly assigned, and what enhancement of the present cross section is in fact due to contamination by other states.[6,27] These experimental uncertainties, plus the lack of detailed shell-model state functions for ^{92}Mo and ^{90}Nb, presently preclude a ^{92}Mo$(d, \alpha)^{90}$Nb analysis.

V. CONCLUSIONS

In the case of the ^{98}Mo$(d, \alpha)^{96}$Nb reaction, where the dominant $[(g_{9/2})_p(d_{5/2})^{-1}{}_n]$ configuration also makes the dominant contribution to the theoretical cross sections, we have been able to show that the (d, α) angular distributions for the entire multiplet of states $J^\pi = 2^+ - 7^+$ can be described in both shape and absolute magnitude by a combination of successive (d, t)-(t, α) and direct-(d, α) pickup mechanisms. The only adjustable parameter used in the calculations is the strength of the zero-range effective interaction resulting from combining the direct-(d, α) term with a nonorthogonality correction term of approximately the same form but opposite phase.

It is clear that the assumption of a pure direct mechanism[1-6] would not have led to wrong assignments of the total angular momentum of the residual nuclear states, or of their predominant parentage, in the ^{98}Mo(d, α) case. However, the anomaly in the calculated cross sections as shown in Fig. 2 would have suggested far more configuration mixing in ^{96}Nb than is probably present. The final CRC calculations, shown in Figs. 3 and 4, are consistent with small (including zero) admixtures, in contrast to the pure DWBA results of Fig. 2. It is very pleasing to see that inclusion of the successive pickup mechanism removes the magnitude anomaly and leads to a reasonably consistent description of all the experimental angular distributions for the members of the multiplet.

The ^{92}Mo(d, α) case, which we also briefly discussed, illustrates the difficulty that will unavoidably arise when the dominant nuclear configurations do not make the dominant contributions to the observed cross sections. Inclusion of the successive pickup mechanism, of course, will not permit one to elude the horns of this dilemma, but it does give one additional confidence that the origin of the dilemma is indeed understood. The specific consequences of configuration mixing in such cases must be calculated in detail[28] with the help of realistic shell-model state functions, when available. This is not to say that inclusion of configuration mixing is a cure-all; examples of sum rules that give some guidance with regard to the effects of configuration mixing on the successive single-nucleon-transfer amplitudes are given by Coker, Udagawa, and Wolter.[19]

Finally, it should be noted that the CRC calculations reported here do not include contributions from the inelastic scattering channels. The collective 2^+ and 3^- states in ^{98}Mo have $B(El)$ factors of 20–30 single-particle units.[29] Maximum inelastic scattering cross sections to these states are a few mb/sr for 15 MeV deuterons[30] and around 10 mb/sr for 30 MeV ^{4}He.[31] Since the (d, α) cross sections are relatively small, it is not altogether safe to neglect multistep inelastic contributions.[32] However, the recent experience of one of us (T.U.) with the modified-radius Born approximation for inclusion of inelastic effects in direct reactions[33] sheds a good deal of light on this question. For strongly absorbed particles, such as we have here in all channels, the effect of inclusion of inelastic contributions is generally a slight adjustment in over-all magnitude of the angular distributions, which in the case of ^{98}Mo(d, α) would lie well within the experimental errors of the absolute cross sections.[33] Thus inelastic contributions do not affect the present results and conclusions significantly.

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