Coupled-channel Born approximation and $l=2$ j dependence in $^{28}Si(d,p)^{29}Si$ from 10 to 18 MeV†

W. R. Coker, Takeshi Udagawa, and G. W. Hoffmann
Center for Nuclear Studies, University of Texas, Austin, Texas 78712
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We discuss the general problem of j dependence in nuclear reactions, and evidence that $l=2$ j dependence seen in (d, p) reactions is, at least in many cases, connected with the collective character of the target and residual nuclei in the reaction. To test this idea, we present analyses of three sets of data for $^{28}Si(d, p)^{29}Si$, at 10, 13, and 18 MeV incident deuteron energy. These analyses are performed in terms of the coupled channel Born approximation (CCBA), and include inelastic excitations of vibrational character both in entrance and exit channels. It is shown that the observed $l=2$ j dependence, particularly for the 1.28 MeV $\frac{3}{2}^+$ and 2.03 MeV $\frac{5}{2}^+$ states in ^{29}Si, can be well explained by CCBA. Evidence is also presented that the 2.03 MeV $\frac{5}{2}^+$ and 2.43 MeV $\frac{3}{2}^+$ states have to a large extent the character $[^{28}Si(2_1^+)\times(s_{1/2})_n]$.

[NUCLEAR REACTIONS $^{28}Si(d,p)$, $E=10.0$, 13.0, 18.0 MeV; calculated $\sigma(\theta)$ with coupled channel Born approximation. $l=2$ j dependence of $\sigma(\theta)$ accounted for.]

I. INTRODUCTION

The dependence of the angular distributions of direct light-ion nuclear reaction cross sections on the transferred orbital angular momentum l has been exploited for more than twenty years by experimental nuclear physicists.[1] It is also well known that direct nuclear reaction cross sections show a sensitivity to the transferred total angular momentum j, much less clear-cut than the orbital sensitivity, but nevertheless quite striking in many cases.[2–9]

The classic case of j dependence occurs in the (d,p) reaction.[2,3,10] A reading of the original papers, with a degree of hindsight, shows that the j dependence originally reported probably arises from a complex of factors. It is the purpose of the present work to shed some light on one of these factors

Lee and Schiffer[2] originally reported three classes of examples of j dependence in (d,p) cross sections at EN tandem accelerator energies. The first class is $l=1$ j dependence, which has been exhibited for many spherical target nuclei (e.g., ^{40}Ca, ^{48}Ti, ^{52}Cr, ^{54}Fe). It was later shown[11,12] that this kind of $l=1$ j dependence is beautifully explained by ordinary distorted wave Born approximation (DWBA) calculations with a spin-orbit interaction in entrance and exit channels, and using optical potentials which fit *both* the elastic scattering cross section *and* the polarization at the appropriate energy (see also Sen *et al.*[13]). The j dependence observed in (p, α) and (α, p) is incidentally also well explained when realistic proton-nucleus spin-orbit potentials are used.[8,9]

The second class of j dependence reported[2] is $l=2$, which is *not* very successfully explained to date. The realistic potentials which account for $l=1$ j dependence fail in many of the observed cases to explain the observed $l=2$ dependence. However, it is instructive that the outstanding failures occur for targets (^{12}C, ^{24}Mg, ^{28}Si, ^{32}S) which are either deformed or strongly collective.[3] As a matter of fact, the most striking $l=1$ j dependence is also found in $^{12}C(d,p)$.[13,14] This already suggests that inelastic effects are likely to play an important role in the explanation of the standard examples of $l=2$ j dependence. A test of this hypothesis is the principal concern of the present work. Our example is $^{28}Si(d,p)$, for which there are copious data in the literature.[3,15,16]

There is a third class of j dependence, observed for $l=3$ transitions, which is quite mysterious. For (p,d) reactions at 20–50 MeV incident energy on targets in the $A\simeq 60$ mass region, there is a very remarkable $\frac{5}{2}^-$, $\frac{7}{2}^-$ j dependence[17,18] which despite extensive efforts remains unexplained. However, these effects are much vaguer in (d,p).[2,3,10,13] Perhaps this is due to the fact that, like the $l=1$ and 2 dependences, the presumed $l=3$ j dependence "washes out" quickly as the incident deuteron energy exceeds 10–12 MeV.[10]

In a recent paper by the present authors,[19] new data for $^{30}Si(d,p)^{31}Si$ at 10 MeV incident deuteron energy were presented, along with an analysis making use of the coupled-channel Born approximation (CCBA) to include properly the strong inelastic excitations in incident and outgoing reaction channels. The $\frac{3}{2}^+$ state at 2.32 MeV and the $\frac{5}{2}^+$ state at 2.79 MeV in ^{31}Si show a very dramatic difference in their angular distributions, the difference at extreme forward angles being most striking. CCBA calculations with no adjustable parameters, and including inelastic excitation for the residual $l=2$ states by proton scattering, gave a beautiful explanation in both shape and magnitude for the angular distributions observed for these two states,[19] while preserving consistency with the detailed features of the earlier DWBA spectroscopy of these and neighboring states.[20] The success of this analysis is so impressive that a more extensive test seems warranted. That test is described in what follows.

It would perhaps be more descriptive, throughout our subsequent discussion, to speak of a "state dependence" of the angular distributions, rather than a j dependence. For instance, at the lower incident energies considered, 10–13 MeV, the various $\frac{3}{2}^+$ angular distributions differ as much among themselves as they differ from the $\frac{5}{2}^+$ transitions. In short, there is a strong excitation-energy effect. As the expression "state dependence" is subject to obvious ambiguities, we will continue to speak of j dependence. However, it should be understood that all the observed differences, of whatever nature, among the angular distributions for different nuclear states are treated on an equal basis in our CCBA calculations. We will now describe these calculations and their results.

II. CCBA ANALYSIS

From the literature we have chosen three sets of data for $^{28}Si(d,p)^{29}Si$ to the $\frac{1}{2}^+$ ground state, and the 1.28 MeV $\frac{3}{2}^+$, 2.03 MeV $\frac{5}{2}^+$, 2.43 MeV $\frac{3}{2}^+$, and 3.07 MeV $\frac{5}{2}^+$ states. The data are obtained at 10,[15] 13,[3] and 18 [16] MeV. The states in ^{28}Si which we consider are the 0^+ ground state and 1.78 MeV 2^+ state

There are a number of studies of deuteron and proton inelastic scattering on $^{28,30}Si$, at a variety of incident energies, using both coupled channels (CC)[21,22] and DWBA[23,24] analyses. Results of CC and DWBA analyses yield very similar values of β_2, about 0.40 for ^{28}Si [21,23,24] and 0.30 for ^{30}Si.[22,24] We are led to adopt a value for ^{29}Si intermediate between those for $^{28,30}Si$, based upon the systematic study of mass-number dependence of β_2 presented by Fitz *et al.*[24] In all our calculations we have, therefore, fixed β_2 at 0.40 for ^{28}Si and 0.35 for ^{29}Si. A similar interpolation has worked well for $^{30}Si(d,p)^{31}Si$.[19]

The CCBA calculations were performed using the program MARS.[25] The optical model potentials were obtained from the literature, being selected from DWBA or coupled-channels analyses of elastic plus inelastic scattering data where available, and are set forth in Table I. The specific formulation of the CCBA which we have used is that given by Abdallah, Udagawa, and Tamura.[26] We have ignored the spin-orbit potentials, since by so doing we speed up the very slow calculations by more than an order of magnitude. Preliminary DWBA calculations showed that the spin-orbit potentials play little or no role in explaining the $l=2$ j dependence, and that neglect of the spin-orbit terms did not significantly affect the fits (or the lack thereof) to the available $^{28}Si(d,p)$ data. The calculations of Abdallah *et al.*,[26] for $^{24}Mg(d,p)$ and $^{26}Mg(p,d)$ show further that the same insensitivity to the spin-orbit terms for $l=2$ transitions is preserved in CCBA. Finally, in the CCBA calculations reported earlier[19] by the present authors for $^{30}Si(d,p)$ at 10 MeV, spin-orbit coupling was found to have a negligible effect on the shapes of the predicted $l=2$ angular distributions. Our only approximations in the present calculations are this neglect of spin-orbit forces, and the usual zero-range approximation, which is known to be excellent for (d,p); the coupled equations are

TABLE I. Optical model parameters used in the calculations. For all calculations $r_{so}=r$, $a_{so}=a$, if spin orbit coupling was used.

E_d (MeV)	Type	V	W (MeV)	W_D	V_{so}	r	a	r' (fm)	a'	r_c	Ref.
10	d	102.7	···	22.6	6.0	1.07	0.903	1.59	0.489	1.3	a
10	p	55.2	2.19	5.78	5.92	1.108	0.705	1.407	0.521	1.1	b
13	d	93.1	···	22.4	···	1.13	0.904	1.58	0.523	1.25	c
13	p	45.57	···	7.91	4.08	1.20	0.65	1.44	0.41	1.20	d
18	d	124.7	···	22.4	6.0	0.92	0.943	1.42	0.54	1.3	e
18	p	44.0	···	9.6	8.5	1.25	0.65	1.25	0.47	1.25	f

[a] W. Fitz, J. Heger, R. Santo, and S. Wenneis, Nucl. Phys. A143, 113 (1970).
[b] S. A. Fulling and G. R. Satchler, Nucl. Phys. A111, 81 (1968).
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[f] F. G. Perey, Phys. Rev. 131, 745 (1963).

solved exactly, to all orders. Vibrational coupling is assumed.[27]

The CCBA calculations for each transition involve three single-nucleon-transfer spectroscopic amplitudes A_{jls}: the amplitude $A^{(1)}_{1/2,0,1/2}$ for the transition from the 0^+ ground state of ^{28}Si to the $\frac{1}{2}^+$ ground state of ^{29}Si; the amplitude $A^{(2)}_{1/2,0,1/2}$ for the transition from the 2^+ first excited state of ^{28}Si to the particular residual $l=2$ state of ^{29}Si; and the amplitude $A^{(3)}_{j,2,1/2}$ for the direct transition from the ground state of ^{28}Si to the particular residual $l=2$ state of ^{29}Si. Amplitudes $A^{1,3}$ were obtained empirically, using the 18 MeV analysis of Mermaz *et al.*[16] Except for the 2.03 and 3.07 MeV states, we have taken the direct $A_{jls}=[S(d,p)]^{1/2}$, where $S(d,p)$ is the usual single-particle spectroscopic factor obtained by Mermaz *et al.* Table II summarizes the amplitudes adopted. In the case of the 2.03 and 3.07 MeV states, the direct term is so weak that a DWBA fit to the data somewhat overestimates the direct spectroscopic amplitude. Therefore the direct amplitudes for these states have been reduced by about 20% as discussed later. The amplitudes of Table II were used for the calculations at all three energies, and were not adjusted. Thus, the calculations make an absolute prediction of the magnitudes of the observed angular distributions.

Results of the calculations are compared with the data in Figs. 1 through 3. In the figures the amplitudes are included for fast reference, in the format $(A^{(1)}, A^{(2)}, A^{(3)})$.

We first discuss the fits to the 18 MeV data of Mermaz *et al.*,[16] shown in Fig. 1, since it is from this data that we obtained the majority of our spectroscopic information, as indicated in Table II. The CCBA calculations are seen to provide excellent fits for the $\frac{1}{2}^+$ ground state and the $\frac{3}{2}^+$ state at 1.27 MeV, as one might expect since these are rather good single-particle states.

TABLE II. Spectroscopic amplitudes for single-neutron transfer in ^{28}Si$(d,p)^{29}$Si.

Transition		lj	$S(d,p)$ [a]	A_{jls}
Initial	Final			
0^+g.s.	– $\frac{1}{2}^+$g.s.	$s_{1/2}$	0.53	0.73
0^+g.s.	– $\frac{3}{2}^+$ 1.27 MeV	$d_{3/2}$	0.74	0.86
0^+g.s.	– $\frac{5}{2}^+$ 2.03 MeV	$d_{5/2}$	0.12	0.34–0.27 [b]
0^+g.s.	– $\frac{3}{2}^+$ 2.43 MeV	$d_{3/2}$	<0.01	0.0
0^+g.s.	– $\frac{5}{2}^+$ 3.07 MeV	$d_{5/2}$	0.06	0.22 [b]
2^+ 1.78 MeV	– $\frac{5}{2}^+$ 2.03 MeV	$s_{1/2}$	···	0.73
2^+ 1.78 MeV	– $\frac{3}{2}^+$ 2.43 MeV	$s_{1/2}$	···	0.73

[a] Reference 16.
[b] See text.

Perhaps the most interesting states are the $\frac{5}{2}^+$ at 2.03 MeV and the $\frac{3}{2}^+$ at 2.43 MeV in excitation. The $\frac{5}{2}^+$ looks very different from the $\frac{3}{2}^+$ at 1.27 MeV—the classic example of $l=2$ j dependence—and the $\frac{3}{2}^+$ at 2.43 MeV does not appear to be populated by a direct process, showing no forward peak and a cross section more than an order of magnitude smaller than the neighboring $l=2$ states. It is tempting to assume that the 2.03 and 2.43 MeV states have a substantial weak vibrational coupling component of the form $[^{28}\mathrm{Si}(2_1^+)\times(s_{1/2})_n]_{3/2^+,5/2^+}$. The CCBA formalism allows one to include such coupling readily. We therefore performed CCBA calculations in which we set $A^{(2)}_{1/2,0,1/2}=A^{(1)}_{1/2,0,1/2}$, as one would expect in the weak coupling picture. Results of these calculations for the 2.03 and 2.43 MeV states are shown as solid lines in Fig. 1—for all other states, the solid lines are results of CCBA calculations with $A^{(2)}_{1/2,0,1/2}=0$, as indicated in Table II. For purposes of comparison, for the 2.03 and 2.43 MeV states only, the calculations with $A^{(2)}_{1/2,0,1/2}=0$ are shown as dashed lines.

One sees from Fig. 1 that the shape of the 2.03 MeV $\frac{5}{2}^+$ angular distribution is best fitted assuming such vibrational coupling, and that its magnitude is well fitted if the direct spectroscopic amplitude $A^{(3)}_{5/2,2,1/2}$ is reduced from 0.34 to 0.27, corresponding to a spectroscopic factor of 0.07.

The situation with regard to the 2.43 MeV state is less straightforward. The observed magnitude of the cross section is well accounted for by a pure multistep calculation, assuming the state cannot be reached directly, but only via entrance or exit channel inelastic excitation. However, the shape fit is not impressive. Compound nuclear contributions are also very likely to be important for this state, as it is so weakly excited. We discuss this possiblility in more detail later.

Finally, the 3.07 MeV state, which is also $\frac{5}{2}^+$, is fairly well fitted in shape, although the fit is by no means as good as that obtained for the 1.27 MeV $\frac{3}{2}^+$ or the 2.03 MeV $\frac{5}{2}^+$. The direct spectroscopic amplitude for this state was taken to be 0.22 for reasons discussed above. A value of about 0.27 would have resulted from using the average of the spectroscopic factors obtained by Mermaz *et al.*[16] and Betigeri *et al.*[15] The decrease of about 20% is in line with the decrease of 20% in the direct amplitude for population of the 2.03 MeV $\frac{5}{2}^+$ state, as shown in Table II. These changes should not be taken too seriously, since they are probably within the experimental errors of the (d,p) spectroscopic factors, especially for the 3.07 MeV state, and are of no particular significance in producing the fits shown in the figures—that is, the results shown are relatively insensitive to 10% changes in the spectroscopic amplitudes.

In summary, the $l=2$ j dependence manifested upon comparison of the 1.27 and 2.03 MeV angular distributions is clearly rather well accounted for. Such j dependence is *not* explained by ordinary DWBA calculations including spin-orbit coupling.[15,16]

We turn now to the 13 MeV data of Schiffer *et al.*,[3] which has not been previously analyzed. The data and the CCBA predictions are shown in Fig. 2, with all spectroscopic amplitudes the same as for the calculations shown in Fig. 1. The fits in shape and magnitude are again excellent, excepting the nondirect 2.43 MeV transition. The data for the 2.43 MeV state are here complete enough that one can see how the calculation with $A^{(2)}=A^{(1)}$ accounts for the observed magnitude, while the calculation with $A^{(2)}=A^{(3)}=0$ accounts far better for the observed shape. For such weak transitions, with no direct term and a nearly isotropic angular distribution, the inclusion of spin-orbit coupling in the CCBA calculations in some cases shifts the maxima and minima by 20° or so—see for example, Fig. 2(b) of Abdallah *et al.*[26] However, this effect has previously been observed only for permanently deformed nuclei. To test the possibility in our case, we performed CCBA calculations including spin-orbit coupling for the 2.43 MeV state. The

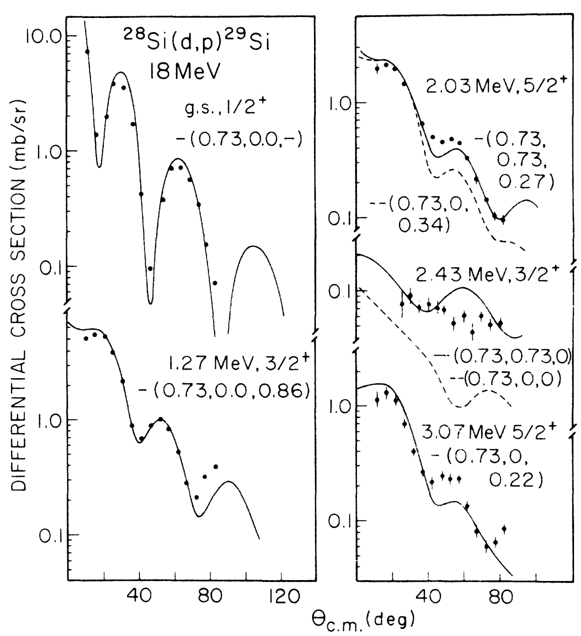

FIG. 1. The ^{28}Si$(d,p)^{29}$Si cross sections at 18 MeV incident deuteron energy for all states below 3.1 MeV in excitation, from Mermaz *et al.* Errors shown are statistical, and are smaller than the size of the data point where not indicated. The solid and dashed curves are results of CCBA calculations as discussed in the text. The set of three numbers given for each curve is ($A^{(1)}$, $A^{(2)}$, $A^{(3)}$)—see the text and Table II.

calculations with spin-orbit coupling are indistinguishable from the calculations shown in Fig. 2 except past 120° and cannot explain the discrepancy. This confirms further our previous findings concerning the insensitivity of the $l=2$ angular distributions to spin-orbit coupling.[19] An alternate explanation for the 2.43 MeV state's angular distribution is discussed in the next paragraph. At any rate, we would have to conclude that in fact $A^{(2)}$ is somewhat less than $A^{(1)}$ for the 2.43 MeV transition.

Again, a comparison of the angular distribution for the 1.27 MeV $\frac{3}{2}^+$ state with that of the 2.03 MeV $\frac{5}{2}^+$ state shows clearly how well the $l=2$ j dependence is accounted for. The 3.07 MeV state is also rather well described, except at backward angles, where an additional compound nuclear contribution which is isotropic at 0.09 mb/sr would largely account for the discrepancy, and is not so unlikely. For that matter, a substantial part of the 2.43 MeV cross section referred to in the last paragraph might also be compound in character. Adding an isotropic 0.09 mb/sr cross section to the CCBA cross section for $A^{(2)}=A^{(3)}=0$ gives a surprisingly good fit to the data, for example.

Finally, in Fig. 3, we show the 10 MeV data of Betigeri *et al.*[15] At these low energies, one would expect the most trouble. Indeed, we were not able to find sets of optical potentials completely suitable for these energies. The deuteron potential we use,

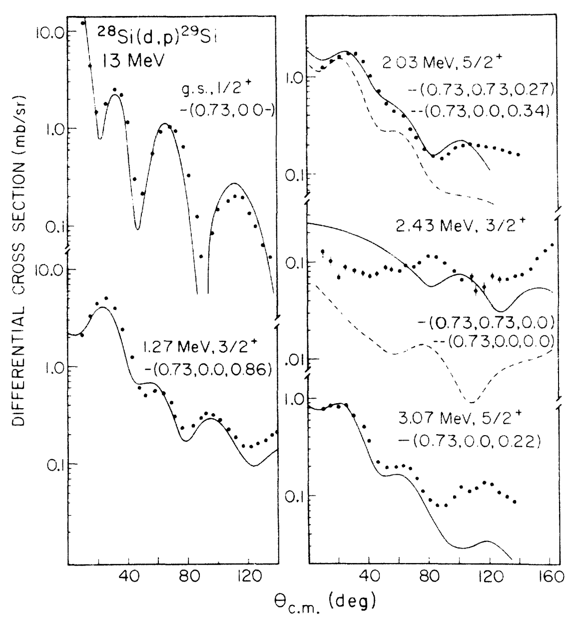

FIG. 2. The ^{28}Si$(d,p)^{29}$Si cross sections at 13 MeV incident deuteron energy for all states below 3.1 MeV in excitation, from Schiffer *et al.* The conventions are identical to those of Fig. 1.

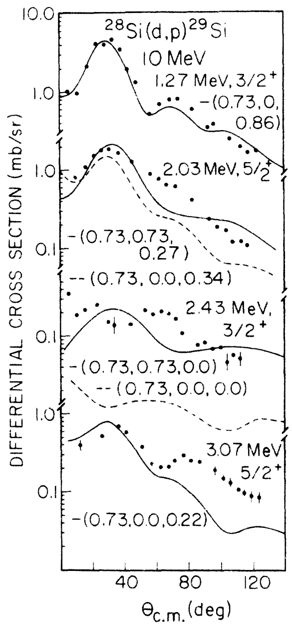

FIG. 3. The ^{28}Si$(d,p)^{29}$Si cross sections at 10 MeV incident deuteron energy for all states below 3.1 MeV in excitation, except the $\frac{1}{2}^+$ ground state which was not measured, from Betigeri *et al*. The conventions are identical to those of Figs. 1 and 2.

from Table I, was measured at 11.8 MeV while the proton potential was measured at 15 MeV. However, in fact the CCBA calculations still provide good descriptions of the data, both in shape and magnitude. The difference between the 1.28 MeV $\frac{3}{2}^+$ and 2.03 MeV $\frac{5}{2}^+$ states is quite well explained, and the fit to the angular distribution of the 3.07 MeV $\frac{5}{2}^+$ state is not too much worse than before—again, it could use an isotropic compound nuclear contribution of perhaps 0.1 mb/sr. The magnitude, if not the shape, of the nonstripping 2.43 MeV state angular distribution is also quite well explained.

III. CONCLUSIONS

In terms of the CCBA description of nuclear reactions[25,26,28] we have calculated the ^{28}Si$(d,p)^{29}$Si cross sections at 10, 13, and 18 MeV for all $l=2$ states below 3.1 MeV in excitation. We have previously shown that the strong $l=2$ j dependence observed in ^{30}Si$(d,p)^{31}$Si at 10 MeV for the 2.32 MeV $\frac{3}{2}^+$ and 2.76 MeV $\frac{5}{2}^+$ states is explained very well by CCBA calculations including inelastic excitations in the outgoing proton channels.[19] We show here that the observed $l=2$ j dependence, particularly that for the 1.28 MeV $\frac{3}{2}^+$ and the 2.03 MeV $\frac{5}{2}^+$ states in ^{29}Si, is also explained well by CCBA, if a further inelastic excitation, in the incident deuteron channel, is allowed to contribute through a ^{28}Si$(2_1^+)\times(s_{1/2})_n$ configuration for the 2.03 MeV $\frac{5}{2}^+$ and 2.43 MeV $\frac{3}{2}^+$ states.

In support of our conclusions, and to indicate the general validity of our results, we stress again that the other examples of strong $l=2$ j dependence in (d,p) extant in the literature also generally involve either deformed or highly collective target and residual nuclei—other targets, in particular, are ^{12}C$(\beta_2=0.6)$, ^{24}Mg$(\beta_2=0.65)$, and ^{32}S$(\beta_2=0.37)$.[3,29] The clear implication is that such j dependence in general will have the same explanation in terms of inelastic excitation in entrance and exit channels as that given here for ^{28}Si(d,p) and by Hoffmann *et al.*, for ^{30}Si(d,p).[19]

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