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Reexamination of the ^{24}Mg(d, p)^{25}Mg reaction for $E_d = 10$–15 MeV

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Complete angular distributions (18–165° c.m.) have been measured for the first six proton groups from the ^{24}Mg(d, p)^{25}Mg reaction and for the reaction ^{24}Mg(d, $d_{0,1}$)^{24}Mg at $E_d = 14$ and 15 MeV to provide data to study multistep contributions to the transfer reactions with emphasis on the "j-forbidden" transition to the $\frac{7}{2}^+$ (1.611 MeV) state of ^{25}Mg. To assess compound nuclear contributions, excitation functions were taken with $E_d = 10$–14 MeV for the first six proton groups from the ^{24}Mg(d, p)^{25}Mg reaction. The excitation functions indicate significant amounts of nondirect structure for $E_d < 13$ MeV in all the reaction channels. Optical model, Hauser-Feshbach, standard distorted wave Born approximation (DWBA), and perturbative multistep calculations of the data have been performed. Comparison of the Hauser-Feshbach calculations with the 14 and 15 MeV data imply that compound contributions are negligible for all of the reaction channels except the "j-forbidden" channel. The multistep calculations give somewhat better agreement with the experimental results than do the DWBA calculations; however, the multistep calculations must be renormalized for each state and each bombarding energy, indicating an incomplete description of the data.

NUCLEAR REACTIONS ^{24}Mg(d,p), measured $\sigma(E)$ at 60, 80, 100, 120° for $E = 10$–14 MeV. Measured $\sigma(\theta)$ at 14 and 15 MeV; $\theta = 18$–165°, $\Delta\theta = 5°$. DWBA and multistep DWBA analysis, deduced S. ^{24}Mg(d, $d_{0,1}$) measured $\sigma(\theta)$ at 14 and 15 MeV; $\theta = 18$–165°, $\Delta\theta = 5°$.

I. INTRODUCTION

Experimental studies of the reaction ^{24}Mg(d, p)^{25}Mg have been carried out during the last decade with two principal objectives. The earlier works[1-3] had as their primary objective the determination of the properties of the states in ^{25}Mg, while the later works[4-6] were undertaken to study the "j-forbidden" reaction to the $\frac{7}{2}^+$ (1.61 MeV) state of ^{25}Mg. The present work falls in the latter class, with the emphasis placed on providing data over the angular range and energies that theoretical calculations[7,8] have indicated are necessary for studying the contributions from multistep processes in the (d, p) reaction. The data to be reported here consists of complete ^{24}Mg(d, p)^{25}Mg angular distributions (18–165° c.m.) for the first six states in ^{25}Mg taken at the deuteron bombarding energies of 14 and 15 MeV as well as elastic and inelastic deuteron scattering data taken also at the same two energies. In addition, excitation functions for the (d, p) reaction have been taken in 50–100 keV steps over the incident deuteron energy range of 10–14 MeV at the four laboratory angles of 60, 80, 100, and 120° to assist in determining the nondirect contribution present in the reaction.

The analyses to be reported in the present work consist of optical model studies of the elastic scattering data and standard distorted-wave-Born-approximation (DWBA) calculations of the deuteron inelastic and allowed (d, p) data. Hauser-Feshbach (HF) type calculations for all of the states studied were done to assess the importance of compound nucleus contributions. The (d, p) data were also analyzed by a perturbation method,[7] which is computationally quicker than the presumably more accurate coupled-channel Born approximation, to more fully evaluate the validity of the Bindal-Koshel perturbation technique.

II. EXPERIMENTAL METHOD

The accelerated deuteron beam used in the present experiment was produced with the Florida State University FN tandem Van de Graaff accelerator. The calibration of the 90° analyzing magnet was not checked during the run but previous experience shows the energies quoted in the current work to be accurate to within ±20 keV. The target consisted of a self-supporting rolled foil enriched to 99.99% in ^{24}Mg and of thickness 530 μg/cm^2. The thickness of the foil was determined by weighing and also by measuring the energy loss in the foil by 5.48 MeV α particles from a ^{241}Am source. The reproducibility of the two results yields an

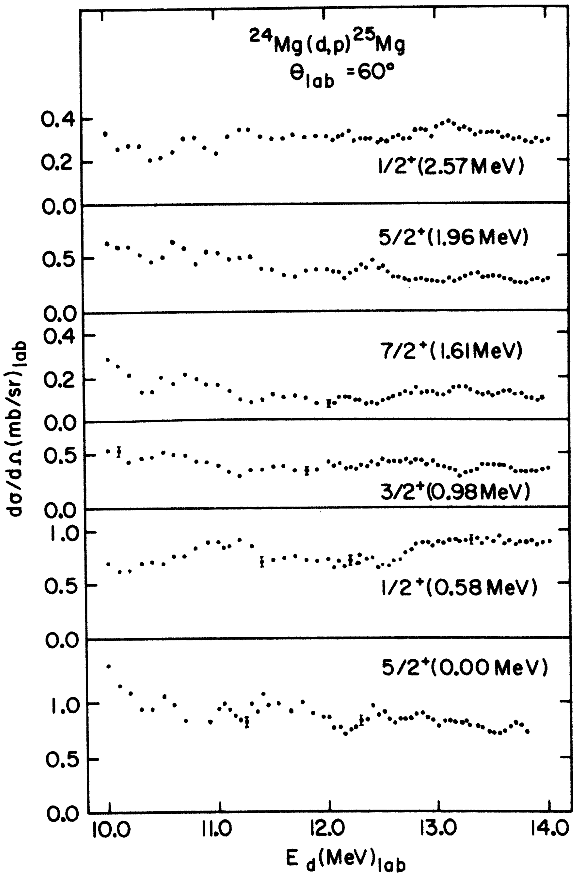

FIG. 1. Excitation functions for the reaction ^{24}Mg(d,p)^{25}Mg at $\theta_{lab}=60°$.

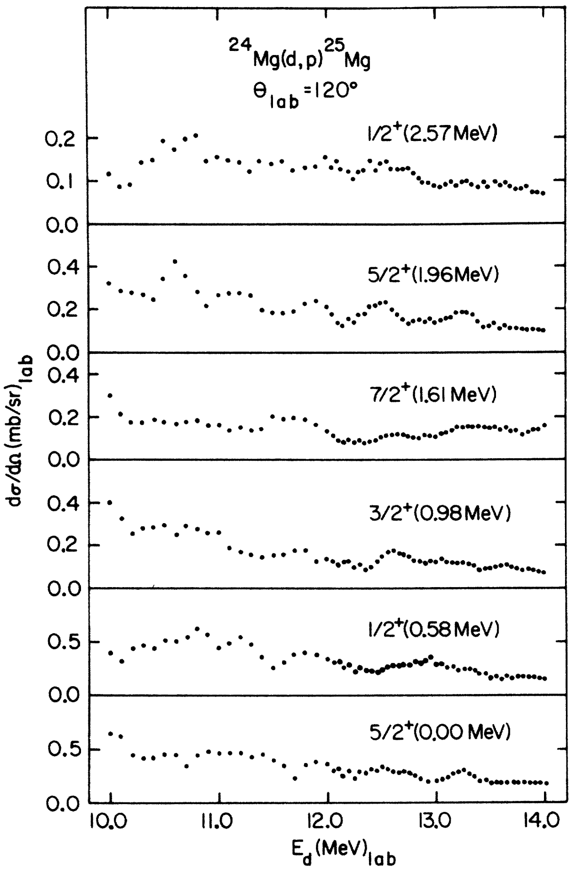

FIG. 2. Excitation functions for the reaction ^{24}Mg(d,p)^{25}Mg at $\theta_{lab}=120°$.

error of 3% in the determination of the target thickness.

To detect the reaction protons and deuterons, Si surface barrier and Si(Li) detectors cooled to −10°C were used. For the deuteron scattering, the particle identification technique of Goulding *et al.*[9] was used, while no particle identification was necessary to distinguish the proton reaction products. The detector solid angles were determined by measuring the defining slits directly and are known to 3%. An EMR-6130 computer was used on line with a TMC-4096 channel analyzer to assimilate and analyze the data. The experimental error in the data from the uncertainties in the target thickness, beam integration, detector solid angles, and analyzer dead time is 5%. The

TABLE I. Optical model parameters from elastic scattering analysis.

	E_d (MeV)	V (MeV)	v_r (fm)	a_r (fm)	W (MeV)	W_D (MeV)	r_i (fm)	a_i (fm)	r_c (fm)
Set 1	14.0	44.0	1.5	0.63	20.3		1.63	0.59	1.5
	15.0	48.0	1.5	0.63	19.7		1.63	0.59	1.5
Set 2	14.0	80.3	1.0	1.0		26.0	1.44	0.50	1.30
	15.0	89.7	1.0	1.0		24.8	1.44	0.50	1.30
Set 3	14.0	74.5	1.05	0.84		25.3	1.27	0.70	1.30
	15.0	81.2	1.05	0.84		20.9	1.31	0.70	1.30

$$U(r)=V_c(r)-Vf(r,r_r,a_r)+i4a_iW_D\frac{df(r,r_i,a_i)}{dr}-iWf(r,r_i,a_i)$$

$$f(r,r_ra_r)=\{1+\exp[(r-r_rA^{1/3})/a_r]\}^{-1}$$

statistical error in the data varied between 1 and 10% depending on the angle and particle group considered and was typically 3%.

III. EXPERIMENTAL RESULTS

The excitation functions for the reaction ^{24}Mg(d, p)^{25}Mg were measured at the laboratory angles 60, 80, 100, and 120° in the deuteron range 10–14 MeV. Representative results for 60 and 120° are shown in Figs. 1 and 2. Error bars are shown for those states where the experimental errors are larger than the data points. Energy increments of 100 keV were taken in the energy range 10–12 MeV and increments of 50 keV were taken in the range 12–14 MeV. Pronounced structure is present below 13.5 MeV for all of the proton groups and at all angles, but except for the region around 10.6 MeV no correlations in the structure are obvious. Confirmation of the presence of structure in the excitation functions is given by the unpublished work of Mayer-Böricke and Siemssen[5] who measured (d, p) excitation functions in the deuteron energy range 6–12 MeV at 90 and 150°.

In the extensive analyses of Bindal and Koshel[7] and Mackintosh,[8] the degree of success of the analysis is different depending on whether data taken at 10.1 MeV,[2] 12.3 MeV,[4] or 15 MeV[3] are used. The excitation functions in Figs. 1 and 2 show that nondirect contributions to the cross section are present throughout this energy range, and these contributions can be responsible for the poor reproduction of the data by the multistep calculations at the lower bombarding energies.

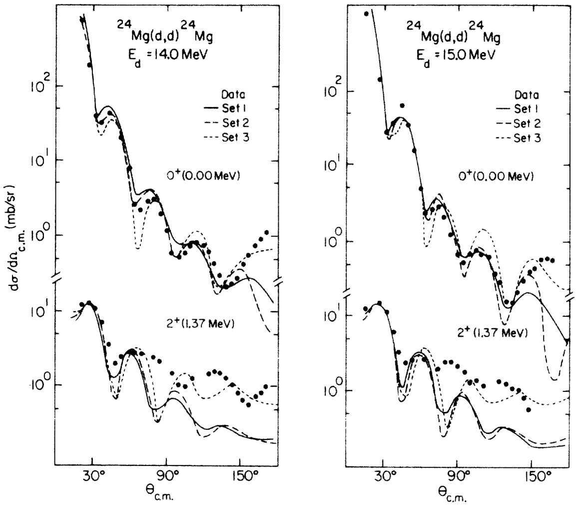

FIG. 3. Angular distributions for the elastic and inelastic scattering of deuterons from ^{24}Mg at $E_d = 14$ and 15 MeV. Also shown are optical model calculations for the elastic data and DWBA calculations for the inelastic data.

For the inelastic deuteron scattering, shown in Fig. 3, the two existing works[10,11] at 15 MeV are in sharp disagreement especially in the region of 30° which is critical for obtaining the quadrupole deformation. The current work exhibits the same angular distribution shape as Blair and Hamburger[11] while having a cross section magnitude consistently 10% larger although well within the combined 25% absolute errors. The work of Haffner[10] is apparently too large by as much as a factor of 2 at 20° c.m.

IV. ANALYSIS

The first step in the analysis of the data was to obtain optical model parameters for use in the subsequent reaction analysis. Since the reproduction of the energy dependence of the data often[12] decreases the ambiguities produced in an optical model analysis, both the 14 and 15 MeV elastic scattering data were included in the analysis. The code OPTIX1[13] which includes a spin-orbit potential for spin 1 particles was used to perform the calculations. The three sets of optical model parameters existing in the literature[14,15] were used as starting values for the parameter searches, which consisted of varying the real potential V, the real diffuseness a_r, the imaginary potential W, and the imaginary radius r_I. As can be seen in Fig. 3, all three sets of the final potentials given in Table I yield equally acceptable fits to the data at 14 MeV, but at 15 MeV Set 3 seems to reproduce the over-all shape of the data better than the two other sets. A parameter search was carried out with the spin-orbit potential included, but no improvement in the fits was found, and a complete lack of sensitivity to the value of the spin-orbit potential was found.

To obtain the magnitude of the quadrupole deformation $|\beta_2|$ of the nucleus ^{24}Mg for use in the subsequent perturbative two-step calculations, DWBA calculations with the computer code DWUCK,[16] were performed. The deformation parameter was obtained by normalizing the calculated cross section to the data at 25° c.m. for each of the parameter sets. The extracted $|\beta_2|$ values are given in Table II, and the data along with the calculations are shown in Fig. 3. The most serious failure of all of the DWBA calculations presented here is in the description of the inelastic scattering to the 2⁺ state of ^{24}Mg. Searches on the optical parameters have shown that a decrease in the absorption will increase the calculated cross section at larger angles indicating that part of the deficiency in the inelastic calculations can be attributed to the uncertainty in

TABLE II. Deformation parameters extracted from the DWBA analysis of ^{24}Mg(d,d')^{24}Mg* (2^+, 1.37 MeV).

Optical model set	E_d (MeV)	$\|\beta_2\|$	$\|\beta_2 R\|$
1	14.0	0.42	1.82
	15.0	0.42	1.82
2	14.0	0.52	1.50
	15.0	0.52	1.50
3	14.0	0.55	1.66
	15.0	0.56	1.70

the choice of optical parameters for the inelastic channel. However, much of the failure of these calculations must be dependent on the inherent properties of the deuteron since proton inelastic scattering is well described by the DWBA for ^{24}Mg.[17] Other possible reasons for the failure of the DWBA for deuteron scattering on deformed nuclei are given by Mackintosh.[8] The extracted deformation length $|\beta_2 r_r A^{1/3}|$ is shown in Table II. The values found from the present work fall well within the range of values found by several coupled channels calculations which were reported in the compilation of Rebel *et al.*[18]

For the (d, p) reaction calculations, optical potential set 3 of Table I was chosen since this type of potential is able to fit the elastic scattering data over the deuteron bombarding energy range of 7 to 15 MeV,[15] while the other two potential sets do not. All of the optical parameters used in the analysis of the ^{24}Mg(d, p)^{25}Mg data are given in Table III along with the parameters describing the spherical Woods-Saxon potential well used to generate the form factor of the transferred neutron. The proton parameters were taken from the work of Blair *et al.*[19] Again, the computer code DWUCK [16] was used to perform the DWBA calculations, and the Nilsson expansion coefficients $C_{Nlj}{}^2$ were obtained by normalizing the calculated cross section to the most forward angle data. A description of the necessary equations can be found in Ref. 3. The zero-range constant which multiplies the calculated cross section was taken to be 1.53. The extracted coefficients are shown in Table IV and the fits to the data can be seen in Figs. 4 and 5.

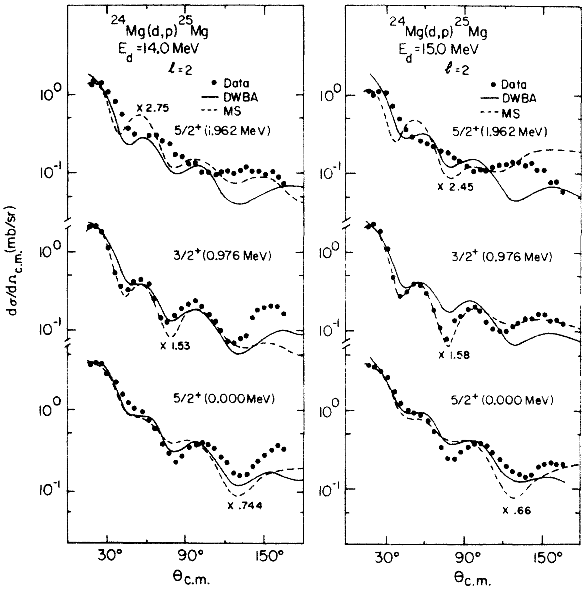

FIG. 4. Angular distributions for the reaction ^{24}Mg(d,p)^{25}Mg. The curves shown are the results of both DWBA and multistep calculations. The multiplication factors shown are the normalization factors for the multistep calculations.

To estimate the magnitude of the compound nucleus contribution present at a deuteron bombarding energy of 14 MeV, Hauser-Feshbach (HF) type calculations[20] have been carried out for both the (d, d') and (d, p) transitions. Expression (19) given by Eberhard *et al.*[20] was incorporated into the analysis of the elastic scattering data with two variable parameters, the spin-cut-off parameter σ and level density parameter ρ. Initial estimates of $\rho = 173$ and $\sigma = 2.6$ were obtained by assuming Fermi-gas expressions.[20] Fitting the 14 MeV elastic scattering data yielded $\rho = 397$ and $\sigma = 2.6$, with the fit to the data improved for angles greater than 150°. With these parameters, the calculated compound nucleus contribution to the deuteron in-

TABLE III. Optical model parameters used in the DWBA analysis.

		V (MeV)	r_r (fm)	a_r (fm)	W_D (MeV)	r_i (fm)	a_i (fm)	r_C (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
$d + ^{24}$Mg [a]	$E_d = 14$ MeV	81.2	1.05	0.84	25.9	1.28	0.70	1.30			
	$E_d = 15$ MeV	81.2	1.05	0.84	24.9	1.28	0.70	1.30			
$p + ^{25}$Mg [b]		46.7	1.24	0.65	8.3	1.28	0.50	1.25	5.5	0.92	0.50
Bound state		c	1.25	0.65					$\lambda = 25$		

[a] From the present work.

[b] From Blair *et al.* (Ref. 19).

[c] Adjusted to give the correct binding energy $B_n = [2.225 + Q(d,p)]$ MeV.

duced reactions is overestimated by about a factor of 3. However, Vogt[21] has pointed out that the compound nucleus contribution calculated for deuteron induced reactions should be multiplied by a reduction factor, since the deuteron interacts with only the surface nucleons because of the strong absorption present. In the current work the reduction in cross section was carried out by treating the level density parameter ρ as the parameter which normalizes the HF calculations to the data. The transmission coefficients necessary for the HF calculations were obtained from the optical model code OPTIX1. The data and the HF calculation for the deuteron inelastic scattering to the 2^+ (1.37 MeV) state of ^{24}Mg are shown in Fig. 6. The extracted level density parameter was $\rho = 1260$. The largest increase in the level density parameter for the allowed (d, p) reactions is necessary for the HF calculations that describe the (d, p) reaction to the $\frac{1}{2}^+$ (0.58 MeV) state and the normalization of the calculation shown for this state in Fig. 6 yields a value for ρ of 2060. For the $\frac{7}{2}^+$ (1.61 MeV) state, a much larger reduction factor is needed, and normalization of the calculation to the data, shown in Fig. 7 yields $\rho = 3050$. The calculations were also performed for $E_d = 15$ MeV with $\sigma = 2.65$ and similar reduction factors were found. Assuming the value of $\rho = 3050$, then the compound contributions to the (d, d) and allowed (d, p) cross sections are negligible. This conclusion is reinforced by noticing, for example, that the cross section data for the $\frac{1}{2}^+$ (0.58 MeV) state possesses a well defined, decreasing diffraction pattern even at the angles around 165°, in contrast to the expectation of Hauser-Feshbach theory. For the $\frac{7}{2}^+$ (1.61 MeV) state it is more difficult to assess the importance of a compound contribution as Fig. 7 shows. The extreme forward angle data of Hamburger and Blair[1] show a definite decrease in the cross section for angles less than 20° c.m. Combining this data with the back angle data reported here shows that the symmetry of the cross section about 90° necessary in the conventional HF theory is lacking, indicating a small compound contribution in the "j-forbidden" $\frac{7}{2}^+$ cross section at least in the mid-angle region. However, the present work does not rule out the possibility of large compound contributions over the whole an-

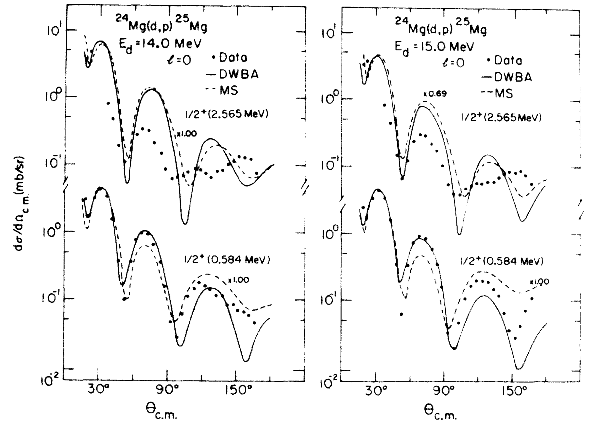

FIG. 5. Angular distributions for the reaction ^{24}Mg$(d,p)^{25}$Mg. The curves shown are the results of both DWBA and multistep calculations. The multiplication factors shown are the normalization factors for the multistep calculations.

TABLE IV. Nilsson coefficients used in the multistep calculations.

State	E_d (MeV)	C_{lj}^2 A[a]	B[b]
$\frac{5}{2}^+$ (0.00 MeV)	14.0	0.87	0.99
	15.0	0.81	
$\frac{1}{2}^+$ (0.58 MeV)	14.0	0.42	0.30
	15.0	0.39	
$\frac{3}{2}^+$ (0.98 MeV)	14.0	0.47	0.51
	15.0	0.48	
$\frac{7}{2}^+$ (1.611 MeV)	...		0.0018
$\frac{5}{2}^+$ (1.96 MeV)	14.0	0.17	0.18
	15.0	0.16	
$\frac{9}{2}^+$ (3.40 MeV)	...		0.013
$\frac{3}{2}^-$ (3.40 MeV)	14.0	0.6	
	15.0	0.6	

[a] Extracted from the data.
[b] From Ref. 22.

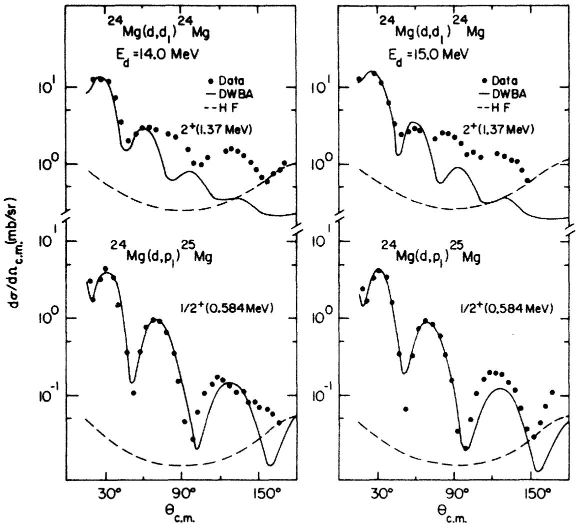

FIG. 6. Angular distributions for the inelastic deuteron scattering from ^{24}Mg as well as the (d,p) transition to the $\frac{1}{2}^+$, 0.58 MeV state in ^{25}Mg. Shown are the results of DWBA calculations and Hauser-Frshbach calculations.

gular range studied even at a bombarding energy of 15 MeV.

The data for the transfer reactions at 14 and 15 MeV were then analyzed using the perturbation approach to multistep reactions developed by Bindal and Koshel.[7] The computer code DUET developed from this formulation was used to perform the calculations. The optical model parameters used in the analysis were the same as those used in the DWBA analysis. In order to perform the calculations, spectroscopic amplitudes, essentially the C_{Nij} coefficients given in Table IV, were needed. In Table IV, case A denotes the coefficients which were extracted in the present DWBA analysis and case B denotes a set of calculated coefficients obtained in the work of Dehnhard and Yntema[22] in their study of neutron pickup on ^{26}Mg. The agreement between the two sets of coefficients is quite good, giving some indication that multistep contributions to the allowed transitions are not appreciable.

The results of the multistep calculations using the calculated C_{Nij} coefficients given in Table IV are shown in Figs. 4, 5, 7, and 8. No multistep calculations were performed for the $\frac{3}{2}^-$ state at 3.40 MeV because the exact nature of this state is not known.

In all the multistep calculations performed, inelastic scattering was included for both the en-

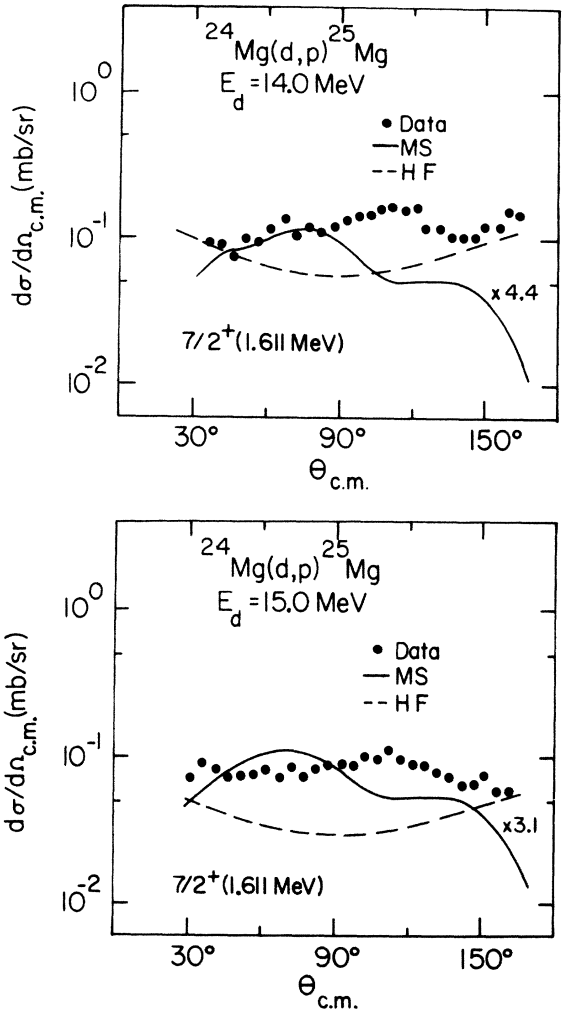

FIG. 7. Angular distributions for the "j-forbidden" ^{24}Mg(d,p) transition to the $\frac{7}{2}^+$, 1.61 MeV state in ^{25}Mg. Multistep and Hauser-Feshbach calculations are also shown. The multiplication factors shown are the normalization factors for the multistep calculation.

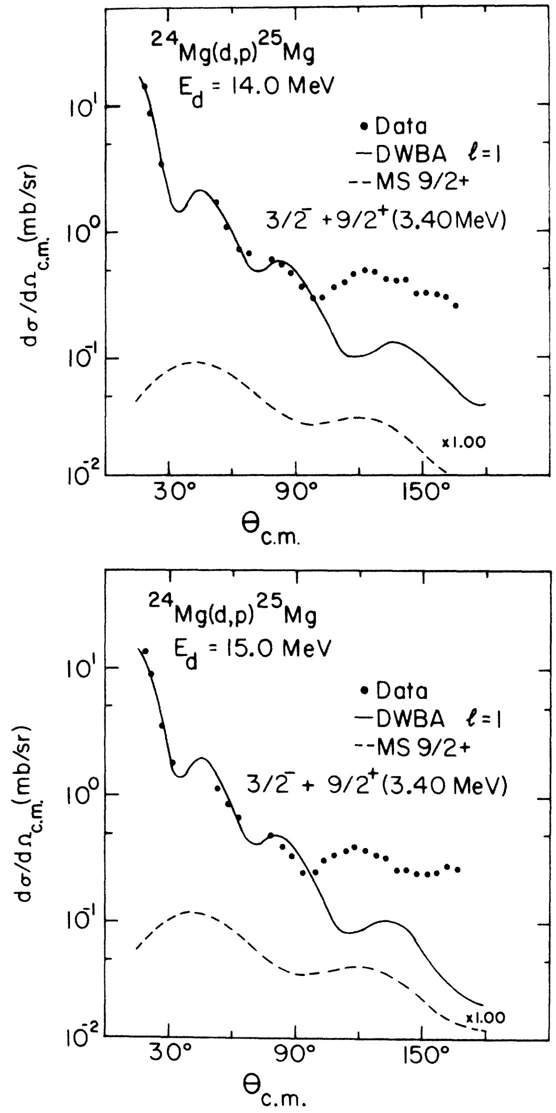

FIG. 8. ^{24}Mg(d,p) angular distributions for the combined transitions to the $\frac{3}{2}^-$ and $\frac{9}{2}^+$ state at 3.4 MeV in ^{25}Mg. The DWBA curves are for the transfer of a $2p_{3/2}$ neutron. The multistep calculations for the $\frac{9}{2}^+$ state are also shown.

trance and exit channels. In all cases, the inelastic scattering in the exit channel was small, only a few percent of the cross section, and could have been neglected. In the entrance channel, only the inelastic scattering to the 2^+ state was included. All possible transitions allowed within the formalism were included.

The most noticeable result of the multistep calculations is the renormalization necessary for each state as well as for each bombarding energy. In order to see if the normalization problem were due to the choice of the deuteron optical parameters, a thorough analysis was made of the deuteron elastic data at 14 MeV. A detailed parameter search was made which explored the Vr^n ambiguity. It became immediately apparent that the difficulty in obtaining good agreement with the 14 MeV data was due to the increase in the cross section at large angle. A separate study was then made which excluded the large angle data (≥110° c.m.). The essential difference between the two sets of optical model parameters obtained was the depth of the imaginary potential. Larger values of this parameter were found. However, agreement between DWBA calculations and the data for inelastic scattering to the 2^+ state was poor. The conclusion could be drawn that this is due to the use of the DWBA to describe inelastic scattering in a highly deformed nucleus; however, Nelson and Roberson[23] performed a coupled-channel calculation for the elastic and inelastic scattering in ^{24}Mg for deuterons of 21.1 MeV energy and also obtained a poorer fit to the inelastic cross section data than the elastic data. While their coupled-channel calculation agrees better with the data than do the DWBA calculations for the inelastic scattering given here, the coupled-channel approach does not yet seem to be the complete answer.

The optical model parameters found in these two studies were then used to repeat the calculations for the transfer reactions. With the use of optical model parameters found in the analysis when large angle data points were excluded, it was possible to obtain good agreement in magnitude and shape with the "j-forbidden" transition to the $\frac{7}{2}^+$ state in ^{25}Mg. However, many of the other calculated transitions did not at all agree with the data. It was determined that the good agreement with the $\frac{7}{2}^+$ transition was due to the magnitude of the absorption used. As the absorption was increased, the magnitude of the calculated cross section rapidly decreased. In fact, the difference between the normalizations obtained in the two-step calculations to this state at 14 and 15 MeV is primarily due to the fact that the absorption potential in the 15 MeV case is 1 MeV smaller than that used in the 14 MeV calculation. This sensitivity to the depth of the imaginary potential was observed in all of the two-step calculations. Thus, it was impossible to obtain a normalization of unity for all of the data by means of optical model changes. Because of this fact, calculations done in other works for only one or two levels in the residual nucleus should be suspect.

V. DISCUSSION OF RESULTS AND CONCLUSIONS

The extensive renormalizations found necessary in the present work to get agreement with the experimental data is certainly disturbing, even though the multistep calculations did seem to give a somewhat better fit to the shape of the angular distributions. It was the hope of nuclear physicists that the multistep approach to nuclear reactions would give a better understanding of the reaction mechanism; however, as has been shown here, this does not seem to be the case. It might be argued that this disagreement is due to the use of a perturbation method; however, as was demonstrated in Ref. 7, the agreement with regard to normalization in the perturbation and the coupled-channel Born-approximation (CCBA) methods is quite good. Also, the CCBA calculations of Nelson and Roberson have[23] this difficulty of normailization as well as the work of Obst and Kemper[24] on the ^{19}F(^{3}He, d)^{20}Ne reaction at 20–23 MeV.

Obviously, much better structure information would be useful in calculations of the type described here. This may solve the problem of normalization. In particular, a multi-step calculation which uses good shell model amplitudes to describe the inelastic as well as transfer scattering would be of extreme interest and usefulness.

One other important point should be mentioned. In Refs. 23 and 24, as well as in the present work, it can be observed that some of the transfer cross sections are comparable in magnitude to the inelastic cross sections at some angles. It is a fundamental hypothesis that in the DWBA and CCBA approach to direct reactions, the transition amplitudes one calculates are a perturbation on the amplitudes corresponding to the wave functions used in the entrance and exit channels. This does not seem to be the case here. What is needed, and what may solve the problem of normalization, is a study of the coupled-channel approach to direct reactions which includes mass transfer.

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