Proton-γ angular correlations in the reaction $^{24}Mg(d, p\gamma)^{25}Mg$†

F. Vogler, M. Berg, A. Hofmann, and H. Wagner
Physikalisches Institut III der Universität Erlangen-Nürnberg, Erlangen, Germany
(Received 8 August 1973)

The reaction $^{24}Mg(d,p\gamma)^{25}Mg$ has been studied at a deuteron energy of 10 MeV up to an excitation energy in ^{25}Mg of 3.5 MeV. A multidetector arrangement consisting of eight silicon surface-barrier detectors has been used to measure the proton spectra. Particle-γ-coincidence measurements have been performed with a Ge(Li) detector in and perpendicular to the reaction plane. The angular distributions of the absolute double differential cross sections have been measured for particle angles between 30 and 150°. It turned out that the differential as well as the double differential cross section for transitions with an l transfer of 0 or 1 can be described well by the distorted-wave Born-approximation (DWBA) method. DWBA fails to describe the angular correlations of the $l=2$ transitions. The "j-forbidden" $l=4$ transitions leading to the $\frac{7}{2}^+$ state at 1.611 MeV and $\frac{9}{2}^+$ state at 3.399 MeV have been compared with Hauser-Feshbach predictions. While the differential cross section of the transition to the $\frac{7}{2}^+$ state is compatible with Hauser-Feshbach calculations, the double differential cross sections for both transitions cannot be described by Hauser-Feshbach theory. Potential ambiguities, arising from DWBA analyses of the differential cross sections could not be removed from the analyses of the double differential cross sections.

[NUCLEAR REACTIONS $^{24}Mg(d,p\gamma)$, $E=10$ MeV; measured double differential cross sections. DWBA analyses of $l=0$, 1, and 2 transitions and Hauser-Feshbach analyses of $l=4$ transitions; enriched target.]

1. INTRODUCTION

Measurements of angular correlations are frequently used for the assignment of spins and parities of excited nuclear levels and for the deduction of the mixing ratios of the emitted γ radiations. For this purpose, besides the usual $\gamma\gamma$ angular correlation measurements, particle-γ angular correlation measurements are performed in the "Ferguson-Litherland II" geometry.[1]

The reaction mechanism, however, cannot be deduced from the shape of this angular correlation. If one departs from the Ferguson-Litherland II geometry, information about the mechanism of the reaction can be obtained in addition to the properties of the γ radiations. Because mixed terms of the transition matrix elements enter, particle-γ angular correlations are generally more sensitive to the reaction mechanism than the measurements of the angular distributions of the particles. For the positions of the particle detector away from the beam axis, however, in general extensive computer programs are necessary for the analysis of the data. An additional difficulty for the experiment arises from the fact that the solid angles subtended by the particle detectors have to be smaller than that in Ferguson-Litherland II geometry, otherwise the structure in the particle differential cross sections is smeared out.

Until now, relatively few investigations of the reaction mechanism through particle-γ angular correlations existed. Most of these investigations deal with the analysis of particle-γ angular correlations through inelastic scattering. In Refs. 2 and 3 $(d, p\gamma)$ correlations have been studied for transitions with orbital angular momentum transfer of $l_n=0$ and 1. In these cases the theoretical interpretation of the results is relatively simple and extensive computer calculations can be avoided. The main result of these investigations was that the distorted-wave Born approximation (DWBA) was found to be in better agreement with the experiment than the plane-wave Born approximation (PWBA).

Probably the $l_n=2$ particle-γ correlations in (d, p) reactions which have been investigated in most detail are the transitions to the first and second excited state in the reaction $^{28}Si(d, p\gamma)$-^{29}Si.[4-7] In these measurements the correlations have been measured with a particle detector fixed at a particular angle and with a NaI detector used for γ-ray detection at a varied angle. Because the statistical tensors which are included in the angular correlation function depend strongly on the particle angle, it seems to be more reasonable to measure the correlation with a fixed γ detector, varying the angle of the particle detector, in order to investigate the reaction mechanism.

In the present work angular distributions of the double differential cross section $d^2\sigma/d\Omega_p d\Omega_\gamma$ in the reaction $^{24}Mg(d, p\gamma)^{25}Mg$ have been measured absolutely for positions of the γ detector in and out of the reaction plane, respectively. A comparison between the measured double differential cross sections (in general more sensitive than the differential cross section) with predictions of reaction theories can give information about the character of the reaction. Another purpose of this work was to study whether one of the different sets of potential parameters, which in DWBA describe equally well the (d, p) angular distribution, would yield distinct agreement with the experimental double differential cross sections.

For the reaction $^{24}Mg(d, p\gamma)^{25}Mg$ there exist a number of analyses of the (d, p) reaction cross section in the tandem energy range.[8-14] Moreover, the data of the γ decay in ^{25}Mg needed for the analysis of the correlation is well known from $(p, p'\gamma)$ measurements.[15] Using a Ge(Li) detector it is possible to study simultaneously several l_n =0, 1, 2, and 4 transitions in the $^{24}Mg(d, p\gamma)^{25}Mg$ reaction even in the lower excitation energy range.

2. EXPERIMENT

A. Experimental arrangement

The deuteron beam of the Erlangen University EN tandem at an energy of 10 MeV has been used to bombard a 99.84% enriched ^{24}Mg foil (from Atomic Energy Research Establishment, Harwell) having a thickness of 4 mg/cm^2. The beam, which was collimated to 3 mm diameter at the target, was stopped in a tantalum plate at a distance of about 3.5 m from the center of the reaction chamber. The maximum beam current was about 8 nA. The total charge was measured with a current integration system. For particle detection eight surface-barrier detectors of n-type silicon (resistivity 32 kΩ cm, depletion layer 1800 μm) were used with a solid angle of 3.6×10^{-3} sr for each detector. The γ radiations were detected with a Ge(Li) detector of 45 cm^3 volume, which was shielded suitably from background radiation.

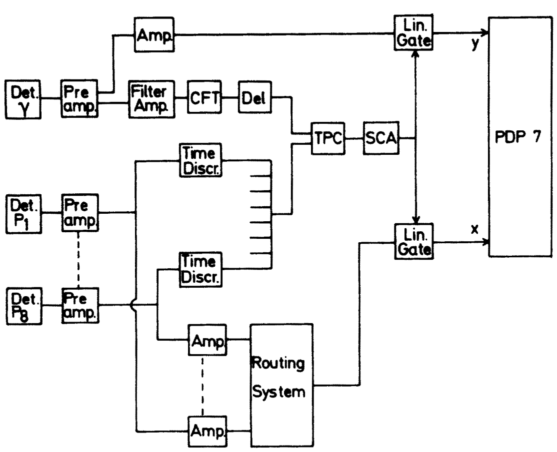

FIG. 1. Block diagram of the electronics.

The block diagram of the electronics used is shown in Fig. 1. In order to acquire the data simultaneously multichannel electronics was used. The time marking signals from the particle detectors were derived by the leading edge trigger method, while the γ pulses were fed into a constant fraction trigger with amplitude-rise-time compensation. Coincidences between particle and γ signals were obtained by a time-to-pulse-height converter. The triggered energy signals from the eight particle detectors were fed to a routing system. The rest of the electronics was conventional. Data acquisition was made two dimensionally with a ND161F double analog-to-digital converter (ADC) in conjunction with a PDP7 on-line computer. The channel configuration was 4096×1024 (8×512 channels for the particle detectors and 1024 channels for the γ-ray detector). The data were stored on magnetic tapes and analyzed using the two dimensional computer program COMBI DUAL.[16]

B. Measurement of absolute double differential cross sections

Double differential cross sections for the reaction $^{24}Mg(d, p\gamma)^{25}Mg$ have been measured absolutely for two positions of the γ detector placed at 90° to the deuteron beam in and perpendicular to the reaction plane. The in-plane correlation is expected to include more information about reaction mechanism than the out-of-plane correlation, because in the later case the correlation function is simplified for geometrical reasons. The coincidence counting rate between the γ detector and eight particle detectors was about 3 counts per sec.

In Fig. 2 a γ spectrum obtained in coincidence with eight particle detectors is shown. The transitions are marked by the level numbers (cf. Fig. 3). From the two-dimensional data matrix peak slices were cut from each coincident particle spectrum and these submatrices were projected on the γ axis for obtaining the coincident γ spectrum. The experimental double differential cross sections were obtained by integration of the photopeaks in the coincident γ spectra. Because of higher accuracy the photopeak efficiency ϵ_{ph} and the solid angle $d\Omega_\gamma$ of the γ detector have not been determined separately but as a product of ϵ_{ph} and $d\Omega_\gamma$ by using standard radioactive sources. The errors in the measured absolute double differential cross sections were in favorable cases [large (d, p) cross section, branching ratio of the γ transition nearly 100%] about 5%, in less favorable cases [(d, p) cross section small, multiple γ-transition branchings] up to 30%. These are due to uncertainties in the peak integration and statistical errors. The errors due to random coincidences were negligible, as could be seen by analyzing the "coincidence-γ spectra" of the ground-state (d, p) transition. Smearing out of the angular correlation function because of the finite solid angle of the γ detector has been taken into account in the analysis. In the present experiment corrections due to this were negligibly small.

3. THEORY

The theoretical basis for the present work has been described in detail by Rybicki, Tamura, and Satchler.[17] In the following we include some important details from Ref. 17.

Consider the reaction $A(a, b)B(\gamma)C$ with an unpolarized target A and an unpolarized projectile a, the excited state B has definite spin and parity and decays by γ emission to the state C. Particle-γ coincidences with the γ detector placed at a fixed angle and varying the particle angles allows one to measure a double differential cross section $d^2\sigma/d\Omega_b d\Omega_\gamma$. One has

$$\frac{d^2\sigma}{d\Omega_b d\Omega_\gamma}=\frac{1}{4\pi}\frac{\Gamma_\gamma^B}{\Gamma^B}W(\vartheta_\gamma, \varphi_\gamma, \vartheta_b, \varphi_b)\frac{d\sigma}{d\Omega_b} \quad (1)$$

with Γ_γ^B/Γ^B the branching ratio of the γ transition $B\to C$; $W(\vartheta_\gamma, \varphi_\gamma, \vartheta_b, \varphi_b)$ the angular correlation function; and $d\sigma/d\Omega_b$ the differential cross section.

The angular-correlation function W, which depends implicitly on the direction of emission of the particle b, has the form

$$W(\vartheta_\gamma, \varphi_\gamma, \vartheta_b, \varphi_b)=\sum_{KQ} A_{KQ}(k_a, k_b)\left(\frac{4\pi}{2K+1}\right)^{1/2} Y_K^Q(\vartheta_\gamma, \varphi_\gamma)\,. \quad (2)$$

In the axially symmetric case ($Q=0$), as in the geometry of Ferguson-Litherland II, the spherical harmonics Y_K^Q are replaced by Legendre polynomials. The correlation coefficients A_{KQ} can be written as a product of normalized statistical tensors which contain the mechanism of the reaction $A(a, b)B$, and the geometry coefficients, which are influenced by the spins J_B and J_C and the multipolarity of the γ radiation.

One can see from Eq. (8) of Ref. 17, that in contrast to the differential cross section the double differential cross section depends on a sum of off-diagonal density matrix elements.

There exist restrictions on the values of the summation index K of Eq. (2):

$$0 \leqslant K \leqslant 2J_B\,. \quad (3)$$

If only the direction but not the polarization of the γ radiation is observed, K has even values only. As a consequence of Eq. (3) the angular correlation function for reactions leading to a state $J_B=0$ or $\frac{1}{2}$ is constant, being independent of the reaction mechanism. In special cases it is also possible to have angular correlation functions that are constant for values of J_B other than 0 and $\frac{1}{2}$, namely

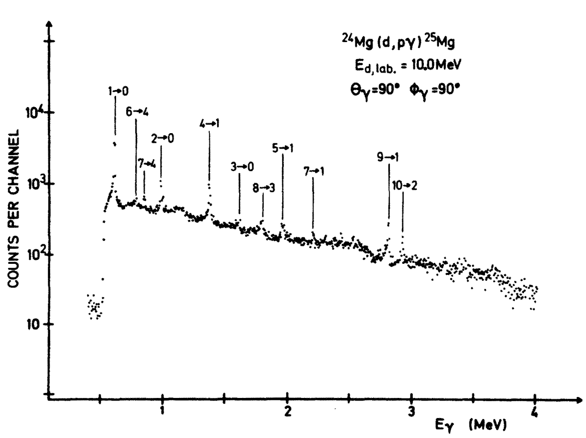

FIG. 2. γ spectrum of the reaction $^{24}Mg(d, p\gamma)^{25}Mg$ obtained in coincidence with eight particle detectors.

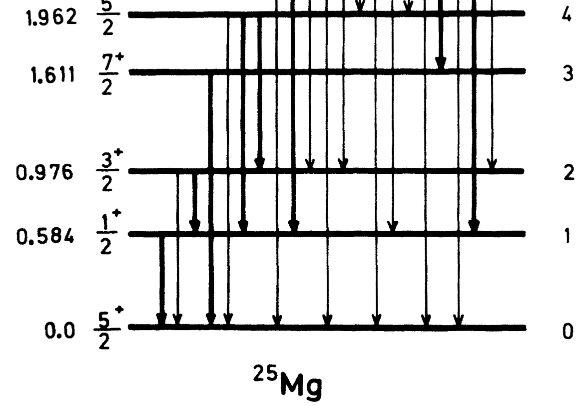

FIG. 3. Decay scheme of ^{25}Mg (from Ref. 15).

when the γ-ray multipole mixing has the appropriate value. However, nonconstant angular-correlation functions can never correspond to states with spin 0 or $\frac{1}{2}$. This can often be utilized to distinguish states with spin 0 or $\frac{1}{2}$ from other states. If, as in the present experiment, the branching ratios, multipolarities, and mixing ratios of the γ radiations and the spins J_B and J_C are known, the correlation function and, from this, the double differential cross section can be calculated by reaction theories. By comparison with the experimental data one can draw conclusions concerning the mechanism of the reaction.

4. RESULTS AND DISCUSSION

In the present work the double differential cross sections for the reaction ^{24}Mg$(d,p\gamma)^{25}$Mg for (d,p) transitions with orbital angular momentum $l=0$, 1, and 2 have been analyzed in the framework of DWBA. For the "j-forbidden" $l=4$ transitions the first-order DWBA is known to be unsuitable. Both the coupled-channel Born approximation (CCBA) and the Hauser-Feshbach theory have been suggested for describing these transitions. We discuss them below on the basis of Hauser-Feshbach calculations.

In our excitation energy range two $l=0$, one $l=1$, two $l=2$, and two $l=4$ transitions could be investigated. The decay scheme of ^{25}Mg is shown in Fig. 3 for the excitation energy range studied in this work. Only the γ transitions shown by thick lines could be used for evaluation. The branching and mixing ratios are taken from Ref. 15.

A. DWBA analysis of the $l=0$, 1, and 2 transitions

At first the angular distributions of the $l=0$, 1, and 2 transitions of the ^{24}Mg$(d,p)^{25}$Mg reaction have been analyzed by DWBA.[14] It turned out that the shape of the experimental angular distributions could be described equally well by different sets of potential parameters ("potential ambiguities"), whereas the spectroscopic factors obtained by comparison with the experiment were found to be very sensitive to the potential parameters,[14] especially to those of the transferred neutron.

The analysis of double differential cross sections has been made with the DWBA angular-correlation program VENUS.[18] For the distorted-wave calculation potentials of the Woods-Saxon type were used. The optical-model parameters in the entrance channel were taken from a detailed investigation of the deuteron scattering of ^{24}Mg.[19] The exit channel parameters and the parameters for the calculation of the form factors have been obtained by a DWBA analysis of the ^{24}Mg$(d,p)^{25}$Mg cross section. Systematic analyses for each (d,p) transition have been made to decide whether analyses of the double differential cross section can resolve the potential ambiguities. The influence of spin-orbit terms is of special interest, due to mixed terms of transition matrix elements included in particle-γ correlations.

At first no spin-orbit term either in the entrance channel or the exit channel (parameter set I) was included in the analysis. Later the spin-orbit interaction only in the exit channel (parameter set II) and then in both the channels (parameter set III) were taken into account. Set IV of parameters was obtained from set II by changing the real deuteron potential from 100 to 180 MeV.

l = 0 transitions

There are two $l=0$ transitions, which lead to $\frac{1}{2}^+$ states with $E_x=0.584$ and 2.565 MeV, respectively. Since the angular-correlation function W is con-

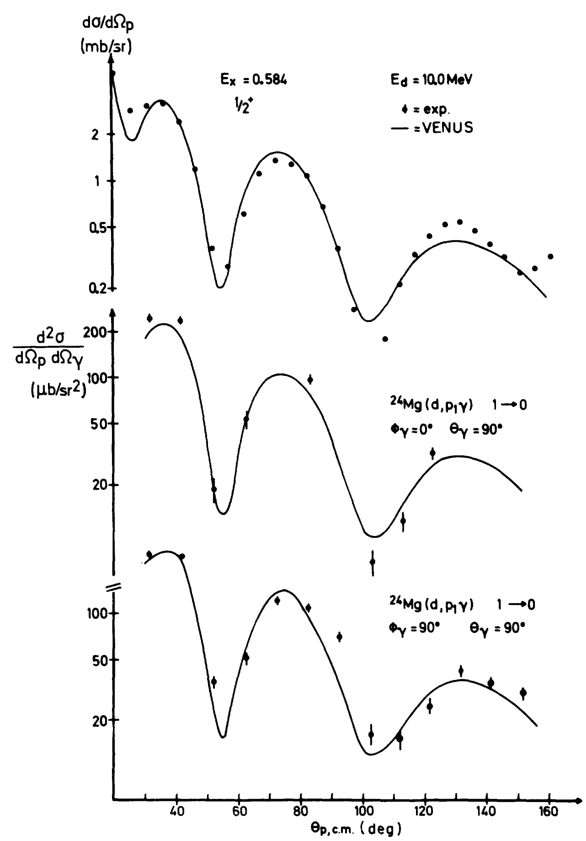

FIG. 4. Experimental differential and double differential cross sections of the reaction ^{24}Mg$(d,p_1\gamma)^{25}$Mg with DWBA calculations for two positions of the γ detector: in reaction plane ($\Phi_\gamma=0°$) and perpendicular to the reaction plane ($\Phi_\gamma=90°$), perpendicular to the incoming particle beam ($\theta_\gamma=90°$), respectively.

stant in these cases, the double differential cross section should have the same shape as that of the particle distribution for each position of the γ detector. Figure 4 shows the results for the $1\rightarrow 0$ correlation. [The symbol $1\rightarrow 0$ means the (d,p) reaction to the first excited state and γ decay to the ground state.] In the upper part of Fig. 4 the experimental angular distribution of the reaction $^{24}Mg(d,p_1)^{25}Mg$ is compared with a DWBA calculation. (The calculations with different sets of parameters agree within the drawn accuracy.) In the lower part of Fig. 4 the experimental double differential cross section for the reaction $^{24}Mg(d,p_1\gamma)^{25}Mg$ for the two positions of the γ detector is shown along with DWBA calculations. The agreement is excellent.

The results for the differential cross section for the reaction $^{24}Mg(d,p_5)^{25}Mg$ and double differential cross sections of the $5\rightarrow 1$ correlation are shown in Fig. 5. One can see that in this case also there is a good agreement between the measurements and the DWBA curves.

One should not at once conclude that these transitions are of one-step character. In Ref. 10 it is shown that CCBA gives also a good description for the cross sections of the $l=0$ transitions. This agreement holds for the correlations too because of the isotropic angular-correlation function in these cases. Therefore it is obvious that one should aim at a consistent description of several transitions with different l transfer.

$l=1$ transition

The $l=1$ transition to the ninth excited state in ^{25}Mg ($E_x=3.408$ MeV, $J^\pi=\frac{3}{2}^-$) cannot be resolved from the eighth excited state ($E_x=3.399$ MeV, $J^\pi=\frac{9}{2}^+$) in the measurements of the differential cross section.

In an earlier work (Ref. 3) a $(d,p\gamma)$ measurement of the $9\rightarrow 1$ correlation with a NaI detector

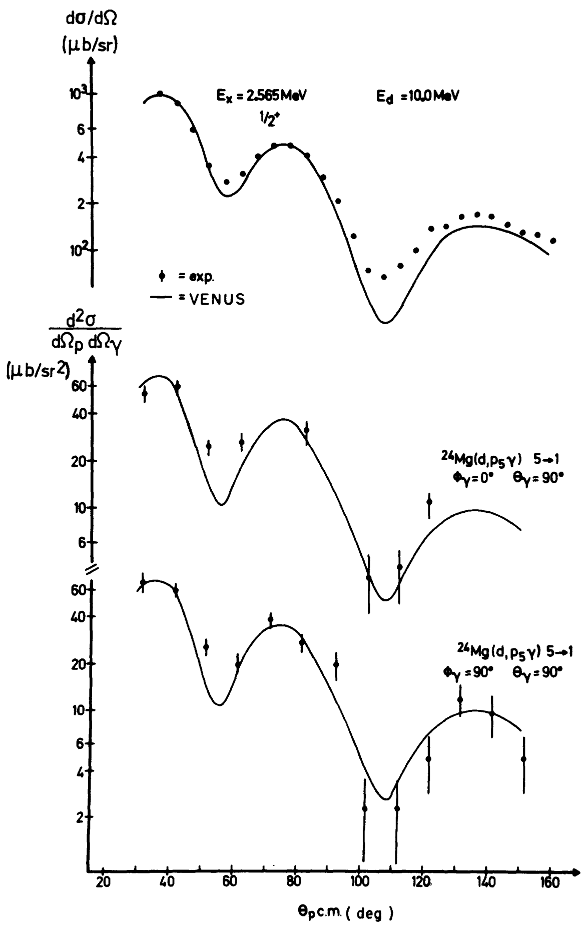

FIG. 5. Experimental differential and double differential cross section of the reaction $^{24}Mg(d,p_5\gamma)^{25}Mg$ with DWBA calculations.

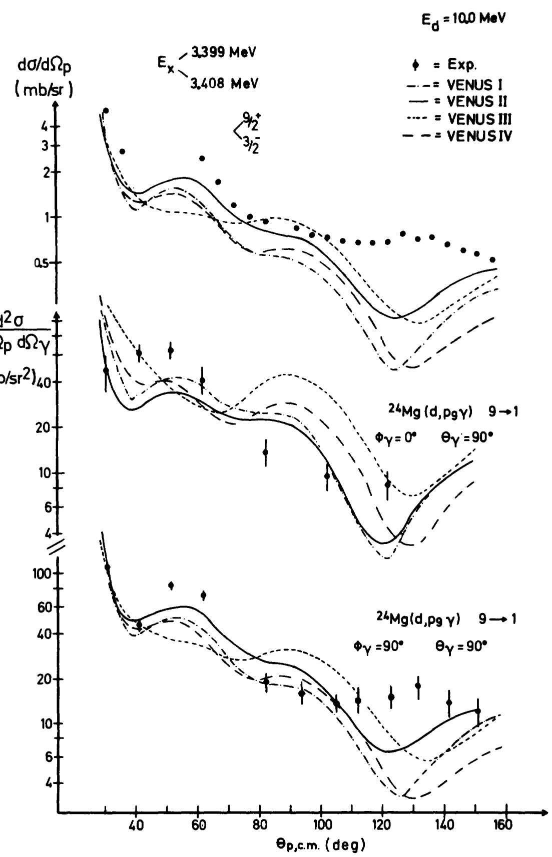

FIG. 6. Upper part: Experimental sum of the differential cross sections of the reaction $^{24}Mg(d,p_{8,9})^{25}Mg$ and DWBA cross section of the reaction $^{24}Mg(d,p_9)^{25}Mg$. Lower part: Experimental double differential cross sections of the reaction $^{24}Mg(d,p_9\gamma)^{25}Mg$ with DWBA calculations.

is reported. In this measurement only one particle detector was used, which was placed at the maximum of the stripping peak. The correlation was studied as a function of the angle of the γ detector. In order to study the reaction mechanism it seems to be more reasonable to measure the correlation as a function of the particle angle as done in the present work.

In contrast to the differential cross section the double differential cross section for the eighth and ninth excited state can be measured separately. The upper part of Fig. 6 shows a comparison of the experimental sum of the differential cross sections $(d, p_{8,9})$ with DWBA calculations for p_9. The agreement up to 90° is good. In the lower part of Fig. 6 the experimental double differential cross sections of the $9 \rightarrow 1$ correlation are shown together with various DWBA calculations. Parameter set III including a spin-orbit interaction in the entrance channel gives no maximum at 50°, while the other sets reproduce at least the position of the maximum.

In the case of the $l=1$ transition, DWBA calculations agree reasonably with the experimental data but not as well as for the $l=0$ transitions.

l = 2 transitions

Double differential cross sections have been measured for the $l=2$ transitions (d, p_2) and (d, p_4). The other $l=2$ transitions in the excitation energy range studied in this paper are very feebly excited via the (d, p) reaction and have small γ-branching ratios. They could, therefore, not be evaluated in the present work.

In Figs. 7–9 experimental differential and double differential cross sections for the $2 \rightarrow 0$, $4 \rightarrow 1$, and $4 \rightarrow 2$ correlations are shown. The experimental results of the $4 \rightarrow 1$ and $4 \rightarrow 2$ correlation differ from those of the $2 \rightarrow 0$ correlation because of the different transferred total angular momentum j in the (d, p) reaction and different properties of the γ radiation. Although the various DWBA calculations show differences none of them is able to reproduce the experimental results in a satisfactory way.

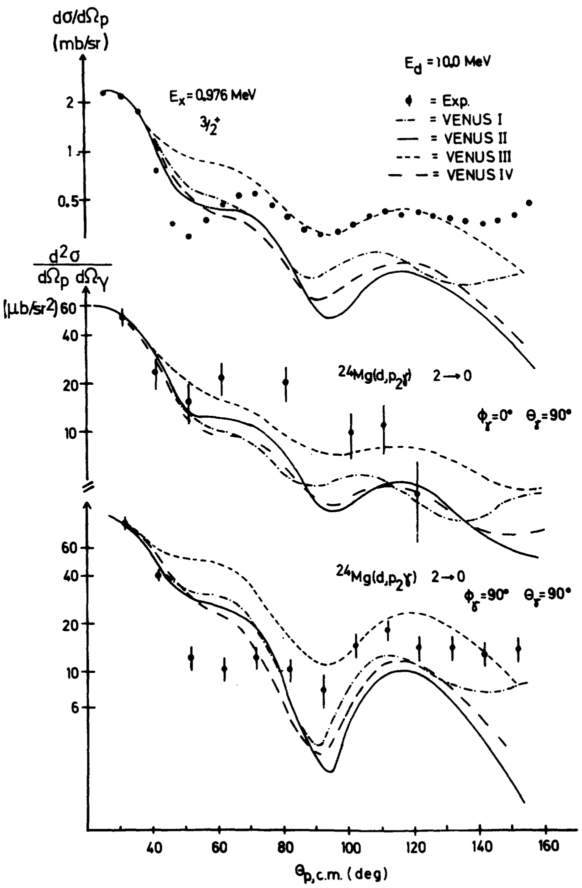

FIG. 7. Experimental differential and double differential cross sections of the reaction $^{24}Mg(d, p_2\gamma)^{25}Mg$ with DWBA calculations.

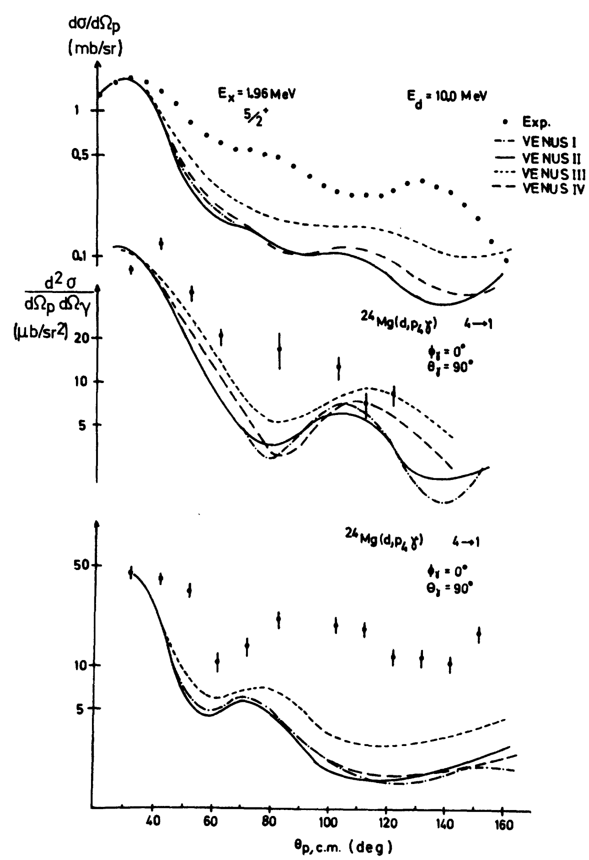

FIG. 8. Experimental differential and double differential cross sections of the reaction $^{24}Mg(d, p_4\gamma)^{25}Mg$ for the $4 \rightarrow 1$ correlation with DWBA calculations.

These results indicate that the $l=2$ transitions to ^{25}Mg do not take place via one-step processes, but other mechanisms like multistep processes may play a dominant role. This statement, which has been made already from the behavior of the cross section, is confirmed from our correlation analyses.

The DWBA analyses of the present data show that DWBA can reproduce the $l=0$ and, with some restriction, the $l=1$ differential and double differential cross sections. In contrast, DWBA is unable to describe the $l=2$ transitions in a satisfactory way. MacKintosh[10] was successful in describing differential cross sections to the low-lying states in ^{25}Mg by the method of CCBA. It will be interesting to examine, whether CCBA holds for the correlation data too.

The potential ambiguities, which appear in the DWBA analyses of differential cross sections could not be resolved by the analyses of double differential cross sections, although in some cases better agreement with the experiment was obtained by including spin-orbit interaction in the entrance channel.

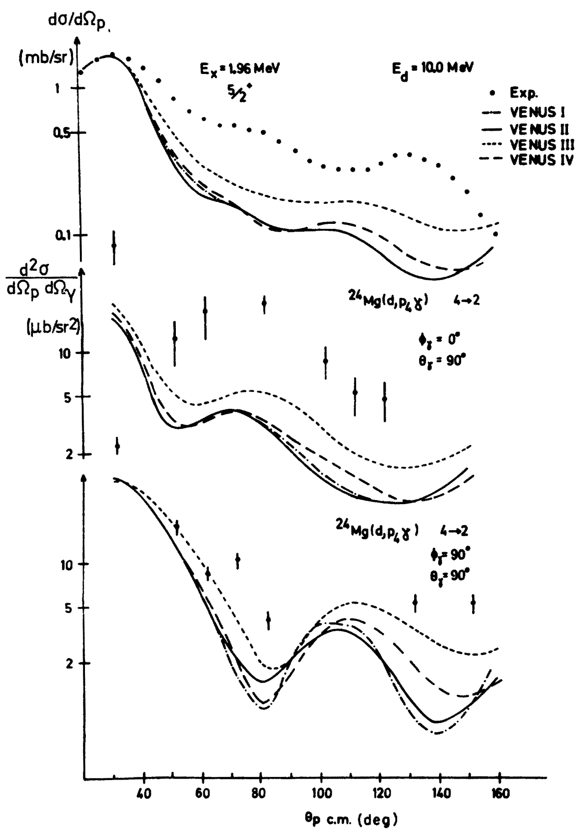

FIG. 9. Experimental differential and double differential cross sections of the reaction $^{24}Mg(d,p_4\gamma)^{25}Mg$ for the $4\rightarrow2$ correlation with DWBA calculations.

Generally one can conclude from the DWBA analyses that the inclusion of a spin-orbit interaction in entrance or exit channel leads to a smearing out of the structure of the angular-correlation function, without changing the position of the maxima and minima. On the other hand, the increase in the depth of the real deuteron potential causes a change of the phase of the correlation function. This behavior is shown for the $2\rightarrow0$ and $4\rightarrow1$ correlations in Figs. 10 and 11.

It seems desirable to investigate particle-γ correlations of reactions with target nuclei near closed nucleon shells. In these cases DWBA is known to give better agreement with the differential cross section. Then DWBA analyses of the double differential cross section with different sets of parameters can lead to a definite fixing of the potential parameters.

B. Discussion of the $l=4$ transitions

The DWBA is not suitable for the description of the $l=4$ transitions. These are the so called "j-forbidden" transitions, which in first order are not allowed by the shell or Nilsson model. Their occurrence can be understood for example by the assumption of inelastic processes in the entrance

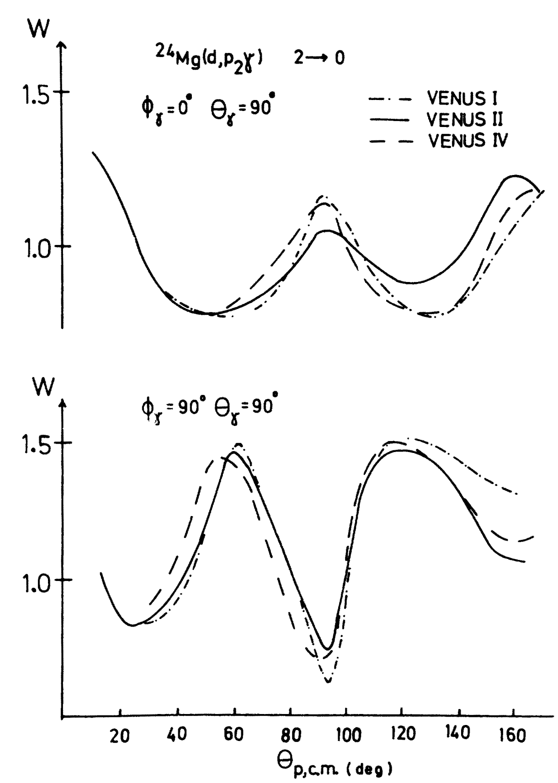

FIG. 10. Influence of the potential parameters on the $2\rightarrow0$ correlation.

and/or exit channel. The influence of inelastic processes is taken into account in CCBA calculations.

The $l=4$ transitions to the third excited state in ^{25}Mg ($E_x=1.611$ MeV, $J^\pi=\frac{7}{2}^+$) has been interpreted as a multistep process by different groups.[20-22, 11-13] Another indication of the multistep character of the reaction ^{24}Mg$(d,p_3)^{25}$Mg comes from the measurements of the vector analyzing power with polarized deuterons.[23]

The flat pattern of the differential cross section of the ^{24}Mg$(d,p_3)^{25}$Mg transition (Fig. 12) could also suggest the possibility of a compound nucleus reaction. This has already been mentioned in Ref. 24, where a Hauser-Feshbach analysis of this transition has been performed.

We have measured double differential cross sections for two $l=4$ transitions leading to excited states in ^{25}Mg with $E_x=1.611$ MeV and $E_x=3.408$ MeV. In order to get additional information about reaction mechanism we have analyzed our data, especially the double differential cross sections, with Hauser-Feshbach theory.

In the upper part of Fig. 12 the differential cross section of (d,p_3) transition is shown together with Hauser-Feshbach calculations with the computer program MANDYF.[25] While calculations with lower spin-cutoff parameter yield a minimum at 90°, the shape as well as the absolute value of the experimental angular distribution can be reproduced very well by the calculation with $2\sigma^2=20$. Using a simple level-density formula one estimates a value of $\Gamma/D=45$ starting from values of Refs. 26 and 27, which is in good agreement with the value of 44.2 obtained from the fitting of the experimental cross section to the Hauser-Feshbach calculations for $2\sigma^2=20$.

In the lower part of Fig. 12 double differential cross sections of the $3\to0$ correlation are shown. The double differential cross sections (especially of the measurement with $\Phi_\gamma=90°$, $\theta_\gamma=90°$) show a distinct structure in contrast to the differential angular-distribution cross section. The Hauser-Feshbach correlation calculations with the computer program BARBYF[25] with $2\sigma^2=20$ reproduce the correct absolute values, but are unable to describe the structure in the double differential cross section, even if one varies σ over a large range. The reason for this is that in our calculations the correlation function $W(\theta_p)$ is nearly 1 and almost independent of the Hauser-Feshbach parameters. Since CCBA calculations[10] are able to reproduce the differential cross section for (d,p_3) without taking compound contributions into account, an analysis of the $3\to0$ correlation with CCBA would be of interest. Using statistical tensors calculated with CCBA by Tamura[28] we have per-

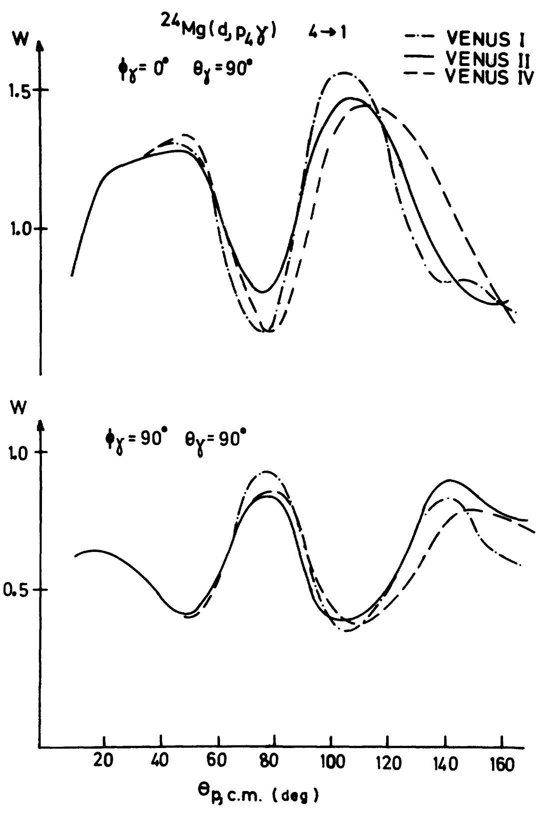

FIG. 11. Influence of the potential parameters on the $4\to1$ correlation.

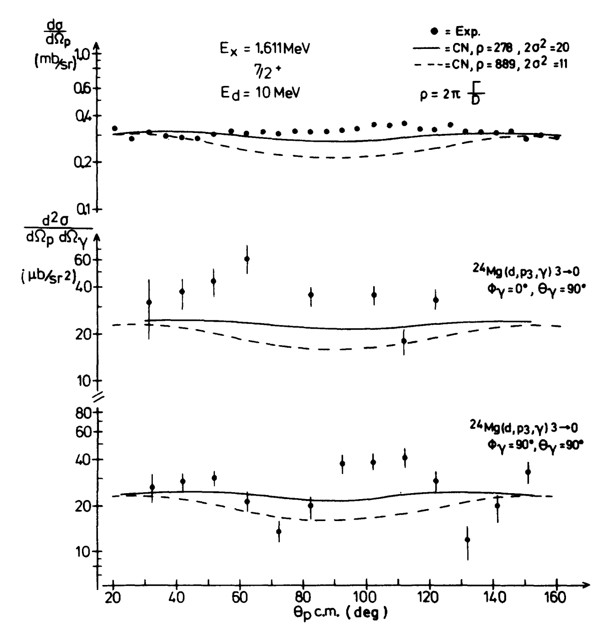

FIG. 12. Comparison of experimental differential and double differential cross sections of the reaction ^{24}Mg-$(d,p_3\gamma)^{25}$Mg with Hauser-Feshbach calculations.

formed preliminary analyses. Until now the analysis, however, has not proceeded so far as to reproduce the $3 \rightarrow 0$ correlations.

In the case of the $l=4$ transition to the eighth excited state in ^{25}Mg ($E_x = 3.399$ MeV, $J^\pi = \frac{9}{2}^+$) no absolute measurement of the differential cross section exists so far. To separate the (d, p_8) cross section from the (d, p_9) cross section is difficult for the following reasons: (i) This level is situated only 9 keV below a $\frac{3}{2}^-$ level, which is strongly excited by a direct $l=1$ process. (ii) The "j-forbidden" reaction leading to the $\frac{9}{2}^+$ state has a very small cross section, as it has been estimated by the shape of the sum line $(d, p_{8,9})$.[8] Separation is, however, possible with the aid of particle-γ angular correlations. In the present work it was possible to measure double differential cross sections of the $8 \rightarrow 3$ correlation with sufficient accuracy (Fig. 13). The drawn lines are Hauser-Feshbach calculations with the computer program BARBYF using a value of the spin-cutoff parameter of $2\sigma^2 = 20$ and $\Gamma/D = 44.2$ as in the case of the (d, p_3) reaction. Again the absolute value is reproduced by the calculations, but in this case also the calculations do not show any structure in contrast to the experiment.

We can conclude that the angular distribution for the $\frac{7}{2}^+$ state, but not the structure of double differential cross sections, of both the $\frac{7}{2}^+$ and the $\frac{9}{2}^+$ state can be described by the assumption of compound nucleus processes. Considering the $(d, p_3\gamma)$ results the double differential cross section seems to be a more sensitive test for investigating the reaction mechanism than the differential cross section alone. The question remains unanswered as to whether the assumption of multistep processes is suitable to reproduce the experimental results.

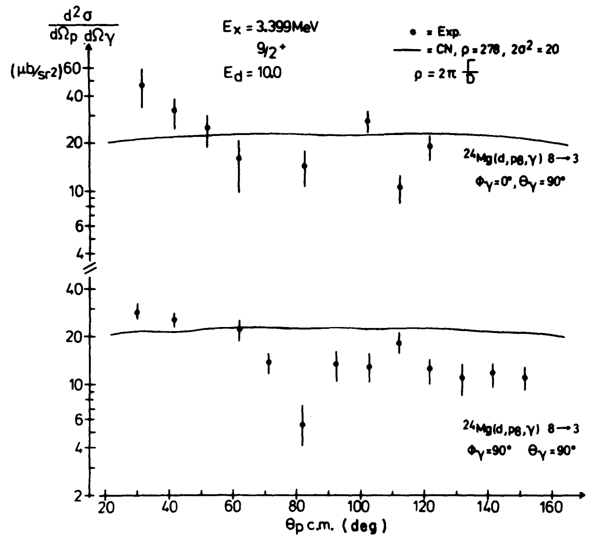

FIG. 13. Comparison of experimental double differential cross sections of the reaction $^{24}Mg(d, p_8\gamma)^{25}Mg$ with Hauser-Feshbach calculations.

We are very grateful to Ulrich Scheib, Dr. Klaus Thomas, and Dr. Gunther Philipp for their encouragement during the measurements and many discussions. Thanks are due Dr. R. Prasad for Hauser-Feshbach calculations and M. Mörike for computing facilities at a CDC 6600 computer.

†Work supported in part by Bundesministerium für Forschung und Technologie.

[1]A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).
[2]J. A. Kuehner, E. Almquist, and D. A. Bromley, Nucl. Phys. 19, 614 (1960).
[3]J. P. Martin, K. S. Quisenberry, and C. A. Low, Phys. Rev. 120, 492 (1960).
[4]K. W. Allen, B. Collinge, B. Hird, B. C. Maglic, and P. R. Orman, Proc. Phys. Soc. A69, 705 (1956).
[5]J. A. Kuehner, E. Almquist, and D. A. Bromley, Nucl. Phys. 19, 614 (1960).
[6]H. J. Hausman, W. E. Davis, C. V. Phillips, R. P. Sullivan, and G. R. Unrine, Phys. Rev. 148, 1136 (1966).
[7]A. Adams and J. M. Calvert, Nucl. Phys. A157, 273 (1970).
[8]R. Middleton and S. Hinds, Nucl. Phys. 34, 404 (1962).
[9]B. Cujec, Phys. Rev. 136, B1305 (1964).
[10]R. S. MacKintosh, Nucl. Phys. A170, 353 (1971).
[11]H. Schulz, H. J. Wiebicke, R. Fülle, D. Netzband, and K. Schlott, Nucl. Phys. A159, 324 (1970).
[12]P. J. Iano, S. K. Penny, and R. M. Drisko, Nucl. Phys. A127, 47 (1969).
[13]B. Braunschweig, T. Tamura, and T. Udagawa, Phys. Lett. 35B, 273 (1971).
[14]U. Scheib, A. Hofmann, G. Philipp, and F. Vogler, Nucl. Phys. A203, 177 (1973).
[15]J. F. Sharpey-Schafer, R. W. Ollerhead, A. J. Ferguson, and A. E. Litherland, Can. J. Phys. 46, 2039 (1968); G. J. McCallum and D. D. Sowerby, Phys. Lett. 25B, 109 (1967).
[16]P. Elzer, Diplomarbeit Erlangen, 1968 (unpublished).
[17]F. Rybicki, T. Tamura, and G. R. Satchler, Nucl. Phys. A167, 659 (1970).
[18]T. Tamura, W. R. Coker, and F. Rybicki, Comp. Phys. Comm. 2, 94 (1971).
[19]B. Schneck and A. Hofmann, Z. Physik 260, 35 (1973).
[20]K. Hosono, J. Phys. Soc. Jap. 25, 36 (1968).
[21]S. K. Penny and G. R. Satchler, Nucl. Phys. 53, 154 (1964).
[22]A. Hofmann and F. Vogler, Nuovo Cim. Lett. 2, 133 (1971).
[23]R. C. Brown, I. Govil, J. A. R. Griffith, G. Hudson,

O. Karban, and S. Roman, Nucl. Phys. A185, 49 (1972).
[24]G. Bassani, C. Levi. M. Mermaz, and L. Papineau, in Proceedings of the Symposium on Recent Progress in Nuclear Physics with Tandems, Heidelberg, 1966, edited by W. Hering (unpublished), p. 7 (available from Max Planck Institut für Kernphysik, Heidelberg).
[25]E. Sheldon, S. Mathur, and D. Donati, Comp. Phys. Comm. 2, 272 (1971).
[26]T. Ericson and T. Mayer-Kuckuk, Ann. Rev. Nucl. Sci. 16, 183 (1966).
[27]A. Bottega, W. R. McMurray, and W. J. Naudé, Nucl. Phys. A136, 265 (1969).
[28]T. Tamura, private communication.