d-γ Angular Correlations as a Test for the Importance of Multistep Processes in the Reaction ^{24}Mg(d,d')

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The in-plane ^{24}Mg$(d,d_1\gamma)$ angular correlation has been measured at an incident energy of 10 MeV. Analyses of the experimental data with distorted-wave and coupled-channel Born-approximation calculations show that multistep processes are important to describe this reaction although the distorted-wave Born approximation reproduces quite well the differential cross section.

To analyze cross-section data from nuclear reactions or scattering of light particles, often distorted-wave Born-approximation (DWBA) or coupled-channel Born-approximation (CCBA) calculations are used. While in the DWBA approach only the direct coupling of the final state to the target ground state is considered, the CCBA calculations also include multistep processes.[1] It is the purpose of the present Letter to show that the comparison of such calculations with particle-γ angular-correlation data gives more detailed information about the importance of multistep processes than analyses of differential cross sections alone.

As an example we have investigated the scattering of 10-MeV deuterons on ^{24}Mg. The deuterons scattered to the first excited state were measured absolutely in coincidence with the de-excitation γ rays. These correlation measurements were performed for six positions of the γ detector in the reaction plane. The scattered particles were observed between 25° and 90° in steps of 5° by means of a multidetector arrangement. To separate the interesting γ rays from background radiation peaks a Ge(Li) detector was used. The electronics and data handling were similar to those of Eyrich *et al.*[2] The self-supporting target, having a thickness of 2 mg/cm^2, was 99.84% enriched. The relatively high γ background limited the beam current to 10 nA, so that the measuring time for each of the six positions of the γ detector was about 12 h. In addition to the d-γ correlations, we also measured the differential cross sections of the elastic scattering and the inelastic scattering to the first excited state.

To present our results we adopt the notation of Rybicki, Tamura, and Satchler.[3] In this notation the "in-plane" angular-correlation function for the scattering to a 2^+ state of an even-even nucleus with subsequent γ de-excitation to a 0^+ state becomes

$$W(\varphi_\gamma) = A + B\sin^2(\varphi_\gamma - \varphi_1) + C\sin^2 2(\varphi_\gamma - \varphi_2).$$

φ_γ is the angle between beam direction and γ detector. If we choose the z axis perpendicular to the reaction plane, there is a simple relation between the parameters A, B, and C and the reaction amplitudes $X_{m_aM_Am_bM_B}$ which describe the transition from the magnetic substates m_a, M_A in the entrance channel to the magnetic substates m_b, M_B in the exit channel:

$$A = \tfrac{5}{4}[(|X_2| - |X_{-2}|)^2 + (|X_1| - |X_{-1}|)^2](d\sigma/d\Omega)^{-1},$$
$$B = 5|X_1||X_{-1}|(d\sigma/d\Omega)^{-1},$$
$$C = 5|X_2||X_{-2}|(d\sigma/d\Omega)^{-1},$$

with

$$|X_{M_B}| = \Big(\sum_{m_aM_Am_b} X_{m_aM_Am_bM_B} X_{m_aM_Am_bM_B}{}^*\Big)^{1/2}.$$

The phases φ_1 and φ_2 are given by

$$\exp(i2k\varphi_k) = \sum_{m_aM_Am_b} X_{m_aM_Am_bM_B=k} X_{m_aM_Am_bM_B=-k}{}^*(|X_k||X_{-k}|)^{-1}, \quad k=1,2.$$

Whereas the differential cross section is proportional to the sum of the absolute squares of all reaction amplitudes, the parameters B and C are the products of only two different $|X_{M_B}|$'s. For this reason structures of the individual $|X_{M_B}|$'s can be better seen in the parameters B and C than in the differential cross section.

As a consequence of Bohr's theorem, amplitudes with $M_B = \pm 1$ appear only if a deuteron spin

TABLE I. Optical-model parameters and deformation parameters β_2 for the DWBA calculations (potential depths in MeV; lengths in fm).

	V	r_V	a_V	W_D	r_W	a_W	$V_{s.o.}$	$r_{s.o.}$	$a_{s.o.}$	β_2
Entrance channel	114.8	1.32	0.53	18.5	1.06	0.89	6.0	1.32	0.53	
Exit channels										
Set 1	109.4	1.12	0.76	17.0	1.59	0.60	6.0	1.12	0.76	0.53
Set 2	109.4	1.12	0.76	19.3	1.59	0.60	6.0	1.12	0.76	0.45
Set 3	109.4	1.12	0.87	17.0	1.59	0.51	6.0	1.12	0.87	0.44

flip with $\Delta m = 1$ occurs. The χ^2 values of fits to the experimental points, neglecting the parameter B, were within the confidence limit. Therefore it should be reasonable to neglect amplitudes with $M_B = \pm 1$. Theoretical calculations also showed that these amplitudes are negligible in the considered angular region. Assuming that $X_{\pm 1} = 0$, the parameters A and C and the phase φ_2 have been extracted from the experimental points at each scattering angle and compared with model calculations.

The DWBA calculations were performed with the computer program DWUCK,[4] the CCBA calculations with the program INCH1.[5] These two routines were used in connection with the programs DWKS and CWKS,[6] respectively. The optical-model parameters are extracted from fits to the elastic-scattering data. Figure 1 shows the measured cross section of the first excited state compared with DWBA and CCBA calculations. The agreement with the experimental data is relatively good for all potential sets. In the case of DWBA the three potential sets (Table I) differ only in the exit channel. The sets of the CCBA calculations (Table II) are obtained by fitting the elastic and inelastic cross sections with distinct values of the depth of the real potential. The calculations were performed in the symmetric-rotator model in a 0^+-2^+ coupling scheme including spin-orbit interactions. By additional coupling of the 4^+ state using realistic β_4 values[7] the results are scarcely influenced.

To compare the calculations with our experimental data it seems not reasonable to consider

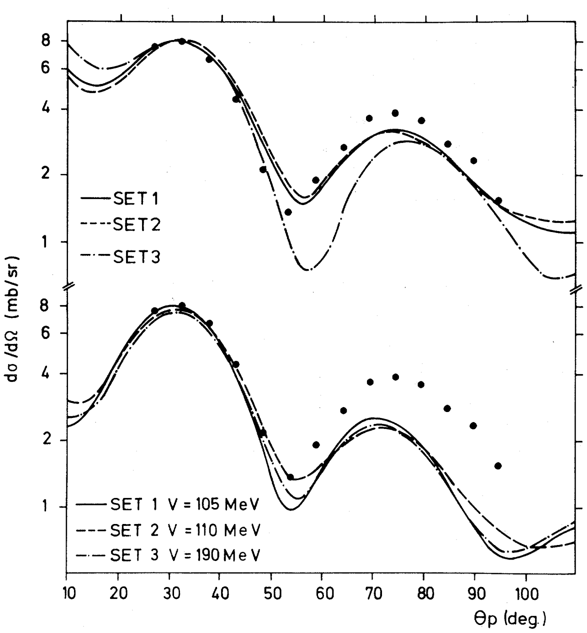

FIG. 1. Experimental differential cross sections are compared with different DWBA (upper part) and CCBA calculations (lower part).

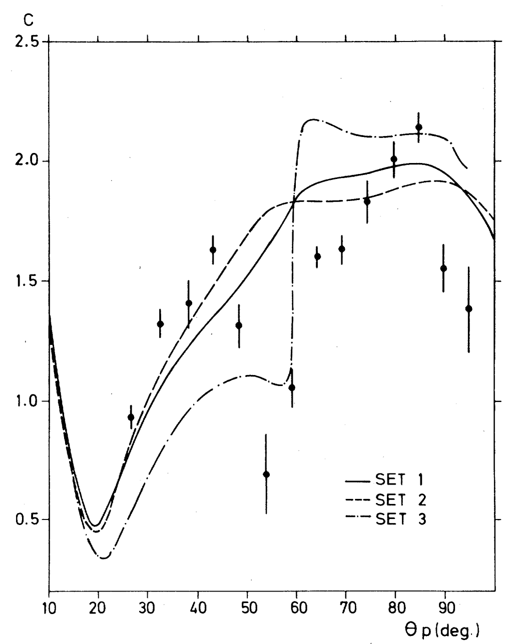

FIG. 2. Comparison of the parameter C with the DWBA calculations (same potential sets as in Fig. 1).

TABLE II. Optical-model parameters and deformation parameters β_2 for the CCBA calculations (potential depths in MeV; lengths in fm).

	V	r_V	a_V	W_D	r_W	a_W	$V_{s.o.}$	$r_{s.o.}$	$a_{s.o.}$	β_2
Set 1	105.0	1.54	0.50	16.0	1.13	0.83	6.0	1.54	0.50	0.42
Set 2	110.0	1.50	0.48	17.5	1.10	0.83	6.0	1.50	0.48	0.45
Set 3	190.0	1.00	0.65	14.0	1.37	0.75	6.0	1.00	0.65	0.50

the parameter A, because this parameter is very small except for a small maximum at 55°. Variations of the different calculations were found to be within the relatively large experimental errors. The phase φ_2, which can be extracted from the experimental with high accuracy, is in good agreement with all the different calculations.

As mentioned above we expect the parameter C to be of most interest. In Fig. 2 the experimental values of C are compared with the DWBA calculations. One can see that the agreement found for the cross-section data has disappeared. Especially the deep minimum at 55° cannot be reproduced by any of these calculations. Also Hauser-Feshbach calculations in addition to the DWBA results cannot reproduce this minimum, because of its sharp structure.

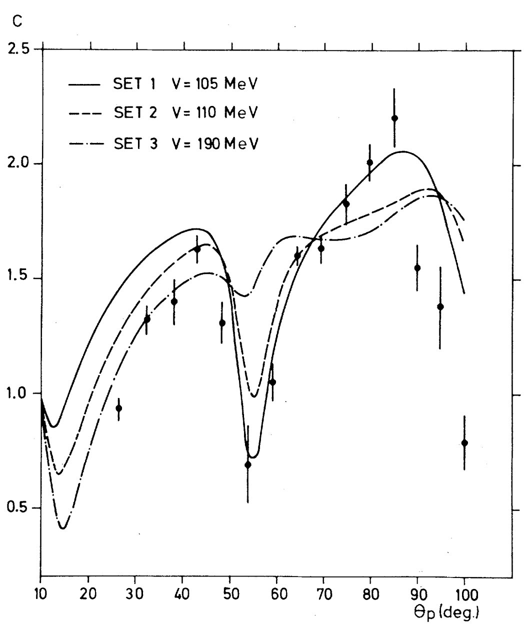

FIG. 3. Comparison of the parameter C with the CCBA calculations (same potential sets as in Fig. 1).

In Fig. 3 the parameter C is compared with the CCBA calculations. The pattern of C is well reproduced by potential sets with a depth of about 100 MeV, while the set with a depth of 190 MeV cannot describe the minimum at 55°. Also the absolute value of the calculations is in fairly good agreement with the experimental values of C. From these comparisons it can be seen that multistep processes as they are included in our CCBA calculations are important for this reaction.[8] The agreement of the DWBA calculations with the inelastic cross section is obviously accidental. An additional result is the possibility of resolving the ambiguities in the potential parameters. Even small variations in the potential parameters produce visible effects in C, whereas there is almost no effect in the differential cross section.

[1] T. Tamura, Rev. Mod. Phys. 37, 679 (1965).

[2] W. Eyrich, S. Schneider, A. Hofmann, U. Scheib, and F. Vogler, Phys. Rev. C 10, 2512 (1974).

[3] F. Rybicki, T. Tamura, and G. R. Satchler, Nucl. Phys. A146, 659 (1970).

[4] P. D. Kunz, University of Colorado Reports No. C00-535-613 and No. C00-535-606 (unpublished).

[5] A. Hill, computer code INCH1, Oxford, 1967 (unpublished).

[6] The programs DWKS and CWKS have been written to calculate the angular-correlation function from intermediate results of the program DWUCK and INCH1.

[7] H. Rebel, G. W. Schweimer, G. Schatz, J. Specht, R. Löhken, G. Hauser, D. Habs, and H. Klewe-Nebenius, Nucl. Phys. A182, 145 (1972).

[8] The inelastic scattering of ^{16}O on ^{56}Fe measuring particle-γ correlations has been investigated by S. G. Steadman, T. A. Belote, R. Goldstein, L. Grodzins, D. Cline, M. J. A. de Voigt, and F. Videbaek, Phys. Rev. Lett. 33, 499 (1974). They also conclude that the inclusion of coupled-channel effects proves to be important, but the dramatic effects seen in their measurements can be entirely understood in terms of Coulomb-nuclear interference.