# Inelastic two-step processes in (d,$^6$Li) reactions on $^{24}$Mg and $^{26}$Mg nuclei

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(Received 29 May 1984)

Evidence is given that two-step processes are largely involved in (d,$^6$Li) reaction on light deformed nuclei. Coupled reaction channels calculations can reproduce the experimental data in rather good agreement with the theoretical spectroscopic amplitudes.

The analysis and interpretation of transfer reaction measurements depend on the knowledge of the reaction mechanism. The (d,$^6$Li) reaction, which has been conventionally assumed to be a single-step (SS) cluster pickup process and treated within the one-channel distorted-wave Born approximation (DWBA) theory, has been used in various nuclear structure investigations. Its effectiveness has to be evaluated because of uncertainties in the reaction mechanism. In several investigations it has been found that the second-order processes in $\alpha$ transfer appear to make contributions that are comparable in importance to the SS processes where the latter are inhibited due to small spectroscopic factors or to selection rules.[1,2] There also is theoretical evidence that two-step transitions should contribute significantly to direct allowed transfer reactions. However, until recently little experimental evidence had been documented which convincingly demonstrated a significant two-step effect on the strong direct $\alpha$-transfer transitions. The assumption of a simple SS $\alpha$-transfer mechanism and the adequacy of the one-channel DWBA method to deduce the spectroscopic factors from experimental data has been recently brought into question by the results of the experimental investigation of the $^{24,26}$Mg(d, $^6$Li)$^{20,22}$Ne reactions[3] and also by the discrepancies present in the systematics of the ground state $\alpha$-particle spectroscopic strengths in the region of the *sd*-shell nuclei reported in Ref. 4. Indeed a comparison between experimental spectroscopic factors deduced by the SS-DWBA method and the theoretical ones arising from shell model (SM) calculations[5] and the significant difference between shapes of predicted and measured angular distributions for low lying collective states in the residual nuclei reveal the inadequacy of the SS calculations. The strong collective character of these states indicates the important role of the inelastic two-step processes (d, d')(d', $^6$Li) and (d, $^6$Li)($^6$Li, $^6$Li') even in cases where the direct transitions have significant strength, and suggests the necessity of applying the coupled reaction channels (CRC) formalism in the analysis. Moreover, a population of the lowest unnatural parity members of the $K^\pi = 2^-$ rotational band with substantial strengths was observed,[3] whereas such transitions are forbidden in a direct $\alpha$-transfer process in the usual zero-range DWBA theory. These observations offer an opportunity to try to determine the reaction mechanism.

The aim of this study is to show that the inelastic two-step processes could solve the difficulties encountered in SS-DWBA analysis of the (d, $^6$Li) reaction, independently of the critical choice of the optical potentials and of the spectroscopic amplitudes with sign included in the CRC calculation. Considering that the questions to be addressed in the present work are based on the comparison between experiment and DWBA predictions, namely, spectroscopic factors deduced by the DWBA method and theoretical predictions for the *sd*-shell nuclei, we preferred performing the CRC analysis in a framework "equivalent" to that used in the earlier DWBA calculations and leaving parameters unchanged over the nuclear range in question instead of improving fits to certain experimental angular distributions by varying one or the other of the parameters of the optical potentials or binding wells considered in CRC calculations.

The $^{24,26}$Mg(d, $^6$Li)$^{20,22}$Ne reactions leading to the low lying members of the ground state and $K^\pi = 2^-$ rotational bands at 80 MeV bombarding energy are interpreted in the framework of the CRC theory. In general, both one- and two-step processes feed coherently a state contributing to the reaction cross section. The inelastic scattering followed or preceded by the $\alpha$-transfer process was considered together with the direct transfer transitions. The CRC analysis of the transfer experiments can provide information about spectroscopic amplitudes relating also the excited states of both the target and final nucleus. The calculations, carried out using the code CHUCK[6] with the Legendre expansion of the deformed Woods-Saxon potentials, require solving a set of coupled equations. The inelastic transitions were computed using a symmetric rotational model and were checked by an equivalent calculation by using the code ECIS.[7] The inelastic transitions in the final nuclei [($^6$Li, $^6$Li')] were found to be stronger than those in the target nuclei [(d, d')]. For this reason the inelastic channels shown in the coupling schemes of Figs. 1 and 2 were included as the most important ones in CRC analysis. The deformation parameters were taken as averages of those given in various coupled channels (CC) scattering analyses,[8–12] applying corresponding $\beta R$ scaling and $\beta_4$ corrections ($^{20}$Ne: $\beta_2 = 0.28, \beta_4 = 0.15$; $^{22}$Ne: $\beta_2 = 0.31, \beta_4 = 0.02$; $^{24}$Mg: $\beta_2 = 0.33, \beta_4 = -0.015$, $^{26}$Mg: $\beta_2 = 0.29, \beta_4 = -0.02$). Optical potential and bound state parameters were the same as that used in equivalent DWBA calculations,[4] i.e., the potential for deuteron channels taken from Ref. 13 reproduces the data of the scattering experiments; for the $^6$Li potential the parameter set given in Ref. 14 was used except for the real and imaginary strengths, which were set 150 MeV and 12.4 MeV, respectively, and $r_0^b = 1.62$ fm according to Ref. 4. As the $^6$Li potentials are very little known, their absorption parts were not changed in CRC calculation, but a few reaction channels were treated explicitly. The inaccuracy introduced this way is believed to be smaller than the inaccuracy due to an accidental jump to a neighboring nonphysical po-

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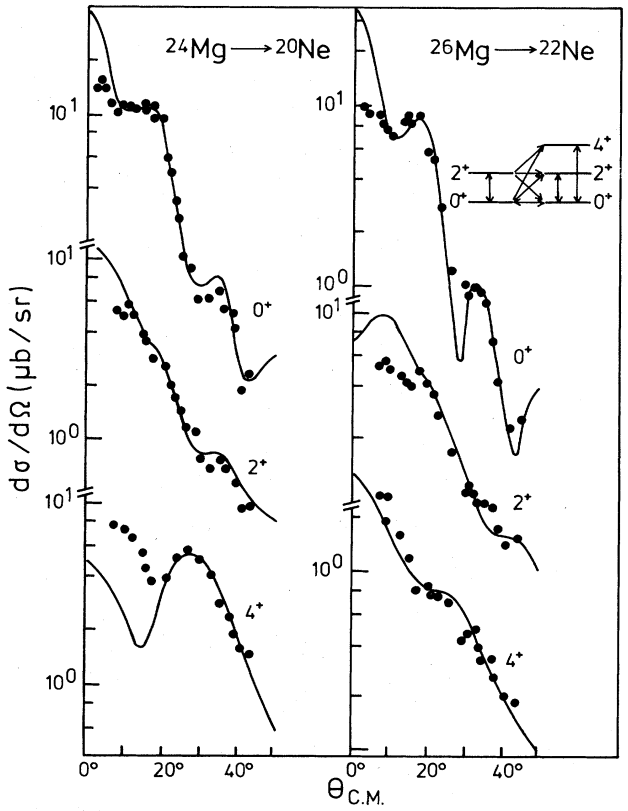


FIG. 1. Angular distributions for the ground state bands predicted by CRC calculations. The experimental data are taken from Ref. 3.

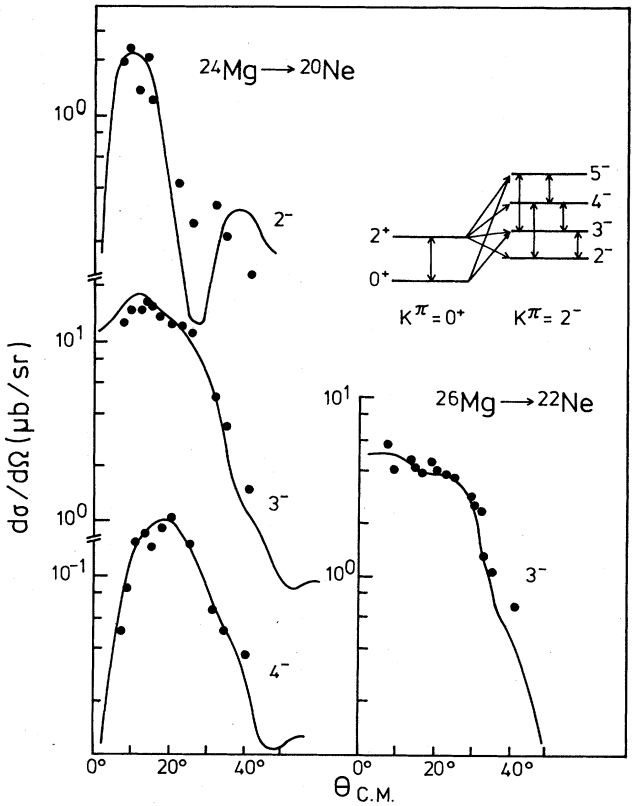


FIG. 2. Angular distributions for the $K^{\pi}=2^{-}$ bands predicted by CRC calculations. The experimental data are taken from Ref. 3.

tential family.

The transfer form factors were calculated in zero-range approximation applying finite-range correction contained in CHUCK. To obtain the correction parameter a finite-range calculation for g.s. → g.s. transitions was compared with the corresponding zero-range one performed by using CHUCK. The values of the correction parameters were found to be 0.56 and 0.65 (in case of Gauss-type correction) for the transitions from $^{24}$Mg and $^{26}$Mg, respectively. This correction has the effect of suppressing the contribution of the nuclear interior to the cross sections and therefore tends to make the oscillations in the angular distribution more pronounced. The zero-range normalization was done in similar way including the finite-range corrections.

The g.s. bands have predominantly a configuration $(sd)^n$. SM calculations[5] in a basis constructed with $(0d5/2)$, $(1s1/2)$ and $(0d3/2)$ orbitals provided the spectroscopic amplitudes included in CRC analysis. Some of their values

TABLE I. Spectroscopic amplitudes for the members of g.s. band (normalized to the unity for the g.s. → g.s. transition).

| Transitions | | $^{24}$Mg | | | $^{26}$Mg | | |
|---|---|---|---|---|---|---|---|
| | | CRC | | SM[a] | CRC | | SM[a] |
| $I_i \rightarrow I_j$ | $l_{tr}$ | $a_{ij}$ | $\hat{I}_i a_{ij}$ | $a_{ij}$ | $a_{ij}$ | $\hat{I}_i a_{ij}$ | $a_{ij}$ |
| $0^+ \rightarrow 0^+$ | 0 | −0.774[b] | −0.774 | −0.768[b] | −0.640[b] | −0.640 | −0.655 |
| $0^+ \rightarrow 2^+$ | 2 | −0.544 | −0.544 | −0.443 | 0.289 | 0.289 | 0.389 |
| $0^+ \rightarrow 4^+$ | 4 | −0.641 | −0.641 | −0.641 | −0.445 | −0.445 | −0.145 |
| $2^+ \rightarrow 0^+$ | 2 | −0.254 | −0.569 | −0.569 | −0.227 | −0.508 | −0.508 |
| $2^+ \rightarrow 2^+$ | 0 | 0.202 | 0.452 | 0.452 | −0.16 | −0.374 | −0.374 |
| $2^+ \rightarrow 2^+$ | 2 | −0.047 | −0.105 | −0.105 | 0.06 | 0.138 | 0.138 |
| $2^+ \rightarrow 2^+$ | 4 | 0.221 | 0.495 | 0.495 | −0.15 | −0.365 | −0.365 |
| $2^+ \rightarrow 4^+$ | 2 | 0.269 | 0.602 | 0.602 | −0.37 | −0.82 | −0.37 |
| $2^+ \rightarrow 4^+$ | 4 | −0.17 | −0.38 | −0.38 | 0.0 | 0.0 | 0.0 |
| $2^+ \rightarrow 4^+$ | 6 | 0.0 | 0.0 | 0.0 | −0.28 | −0.62 | −0.28 |

[a]Reference 5.
[b]Normalized to g.s. → g.s. transition in the $^{20}$Ne(d, $^6$Li)$^{16}$O reaction.

TABLE II. Spectroscopic amplitudes for the members of the $K^\pi = 2^-$ band (normalized to the unity for the g.s. → g.s. transition).

| Transitions | | $^{24}$Mg | | $^{26}$Mg | |
|---|---|---|---|---|---|
| | | CRC | SU(3)[a] | CRC | SU(3)[a] |
| $I_i \rightarrow I_j$ | $l_{tr}$ | $a_{ij}$ | $a_{ij}$ | $a_{ij}$ | $a_{ij}$ |
| $0^+ \rightarrow 3^-$ | 3 | 1.23 | 1.633 | 0.81 | 0.7 |
| $0^+ \rightarrow 5^-$ | 5 | −0.71 | 0.71 | −0.99 | 0.99 |
| $2^+ \rightarrow 2^-$ | 3 | 0.48 | · · · | −0.50 | · · · |
| $2^+ \rightarrow 3^-$ | 3 | −0.30 | · · · | 0.55 | · · · |
| $2^+ \rightarrow 4^-$ | 3 | −0.50 | · · · | · · · | · · · |
| $2^+ \rightarrow 4^-$ | 5 | 0.15 | · · · | · · · | · · · |
| $2^+ \rightarrow 5^-$ | 3 | 0.40 | · · · | 0.40 | · · · |

[a]Reference 16.

were changed to get agreement with the experiment. The angular distributions, the CRC results and experimental data for $0^+$, $2^+$, and $4^+$ states as well as the spectroscopic amplitudes, normalized to unity for the g.s. → g.s. transition, are presented in Fig. 1 and Table I. These spectroscopic amplitudes in most cases show a deviation of a factor $\hat{I}_i = (2I_i+1)^{1/2}$, where $I_i$ is the spin of the initial states (Table I, second part of column CRC). The source of this difference may be in the definition used either in SM or in CHUCK codes for the spectroscopic amplitude. The difference in shape between the experimental angular distributions for $4^+$ states of $^{20}$Ne and $^{22}$Ne nuclei is very striking. The latter is rather structureless, not characteristic of particular $l=4$ transfer, indicating the involvement of important contributions from other reaction paths than the direct one. This remarkably unlike interplay between one- and two-step contributions to the $4^+$ states of these neighboring nuclei has been well reproduced by CRC calculation. Moreover the g.s. → g.s. spectroscopic amplitudes, their values having been normalized to that for $^{20}\mathrm{Ne}_{g.s.}(d, {}^6\mathrm{Li})^{16}\mathrm{O}_{g.s.}$ transition, agree rather well to the SM predictions. The inelastic two-step processes seem to be responsible for the discrepancies which are present in the systematics of the ground state spectroscopic strengths,[4] at least in case of the $^{24,26}$Mg nuclei.

The $K^\pi = 2^-$ rotational bands with bandheads 4.97 MeV and 5.48 MeV in $^{20}$Ne and $^{22}$Ne nuclei, respectively, are predominantly $(sd)^n(0p)^{-1}$ in character. The fact that significant strength in population of the unnatural parity members $2^-$(4.96 MeV) and $4^-$(7.004 MeV) states in $^{20}$Ne was experimentally observed indicates non-negligible contributions from nondirect processes. In general for $s=0$ transfer the very forward angle behavior of the angular distribution is very important to distinguish whether a "forbidden" transition proceeds via inelastic two-step transition or successive particle transfer.[15] For the former a sharp fall to zero angle is expected. Where experimental data exist for small angles, they do show a forward angle decrease (Fig. 2). The population of the $K^\pi = 2^-$ band was analyzed separately since no strong inelastic couplings of $\lambda = 3, 5$ exist to the g.s. band members. The main mechanism for populating the $K^\pi = 2^-$ band is the direct $\alpha$ transfer to its normal parity states. The transitions to the $2^-$ and $4^-$ states include these transfers followed by inelastic scattering in the exit channels. In addition, an inelastic excitation of the $2^+$ member of the target g.s. band precedes the $\alpha$-transfer transition to $2^-$ and $4^-$ final states with angular momentum transfer $l = 3, 5$ ($l=1$ is forbidden due to $K$ selection rule). The deformation parameter of the excited rotational band was taken to be the same as that of the g.s. band. The spectroscopic amplitudes arising from SU(3) strong coupling model calculations[16] assuming a $(\lambda\mu)\kappa_L = (82)2$ configuration, were included, where available, in the CRC analysis. The values deduced by present calculation using a coupling scheme according to that shown in Fig. 2 and the predicted angular distributions in good agreement with the experimental data are shown in Table II and Fig. 2, respectively.

The transition to the $3^-$(5.91 MeV) member of the $K^\pi = 2^-$ band in $^{22}$Ne was observed with a strength a factor of 3 larger than the SU(3) prediction assuming a $(\lambda\mu)\kappa_L = (84)2$ configuration. The $2^-$(5.48 MeV) was found to be very weakly populated. The $5^-$(8.452 MeV) member of this band experimentally was not resolved. Its transition has significant strength according to SU(3) theory. Using the same coupling scheme as in case of $^{24}$Mg target (Fig. 2) except for the coupling to the $4^-$ state, the interpretation from the CRC calculation of the measured transition strength to the $3^-$ state is in agreement with the theoretical expectation as shown in Fig. 2 and Table II. The predicted population strength for $2^-$ state was found to be smaller a factor of 0.02 than the corresponding strength for $^{20}$Ne nucleus in accordance with the experiment. The success of the CRC analysis to interpret the observed population of the unnatural parity states of $^{20}$Ne and the unexpectedly large experimental strength found for the $3^-$ state in $^{22}$Ne with reasonable values of the spectroscopic amplitudes is remarkable.

Strong evidence has been given that inelastic two-step processes are largely involved in (d, $^6$Li) reactions on deformed *sd*-shell nuclei at 80 MeV bombarding energy. Coupled reaction channels calculations based on the strong-coupling collective model, using realistic optical model potential and deformation parameters give a good interpretation of the experimental data using spectroscopic amplitudes predicted by SM or SU(3) calculations even for low lying members of the ground state and $K^\pi = 2^-$ rotational bands, which are forbidden for direct $\alpha$ transfer. It is then clear that the coupled reaction channels method must be used for analysis of (d, $^6$Li) reaction on nuclei with strong collective nature.

We are indepted to Professor V. A. Madsen for the helpful discussion and critical reading of the manuscript. We thank E. Brökel for the technical assistance connected with the computation.

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