# Higher order effects in the $^{16}$O$(d,p)^{17}$O and $^{16}$O$(d,n)^{17}$F transfer reactions

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Full coupled channels calculations were performed for the $^{16}$O$(d,n)^{17}$F and $^{16}$O$(d,p)^{17}$O transfer reactions at several deuteron incident energies from $E_{lab}$=2.29 MeV up to 3.27 MeV. A strong polarization effect between the entrance channel and the transfer channels $^{16}$O$(d,n)^{17}$F$(1/2^+,0.495)$ and $^{16}$O$(d,p)^{17}$O$(1/2^+,0.87)$ was observed. This polarization effect had to be taken into account in order to obtain realistic spectroscopic factors from these reactions.

## I. INTRODUCTION

The interest in the experimental and theoretical study of few nucleon transfer reactions has been renewed in the past years mainly due to the possibility to obtain information of astrophysical relevance from these reactions [1–4]. Direct measurement of capture reactions at energies of astrophysical interest is, in some cases, nearly impossible due to the low reaction yield, especially if the capture involves exotic nuclei. Alternative indirect methods, such as the asymptotic normalization coefficient (ANC) method, based on the analysis of breakup [5] or transfer reactions [1], have been used as a tool to obtain astrophysical $S$-factors. The advantage of indirect approaches comes from the fact that transfer and breakup reactions can be measured at higher energies, where the cross sections are much larger. However, to obtain useful information from transfer reactions one needs to understand, as clearly as possible, the reaction mechanism involved.

Actually, by comparing the DWBA calculations with the experimental angular distributions it is possible to determine the spectroscopic factors of the transferred particles in the target and projectile system. However, as a first order theory, the DWBA method is based on the assumption that the transfer occurs in one single step from the ground state of the entrance channel directly to one specified state of the final nucleus in the outgoing channel. Within the DWBA, the transfer cross section is proportional to the product of the spectroscopic factors of the transferred particle in the projectile and target system. So, if one of the spectroscopic amplitudes is known, the other can be obtained by comparing the DWBA calculation with the experimental angular distribution. Spectroscopic factors extracted from transfer reaction analysis appear to be in some cases energy dependent, indicating that a simple DWBA analysis may not be applicable. Also, if one of the nuclei in the entrance channel is strongly excited during the collision, the one channel approach implicit in the DWBA scheme might be inappropriate. In this case, the coupled channels Born approximation (CCBA) approach is

more suitable [6]. In the CCBA formalism, the transfer is still considered as a one step process but the effect of the coupling to a set of selected excited states of the projectile or target are included explicitly. The spectroscopic amplitudes obtained in CCBA will be the result of the mixing of amplitudes for different excited states. Due to this mixing, the results of such calculation cannot be used to extract the asymptotic normalization coefficient for astrophysical calculations. In addition to the coupling to inelastic excitations, other effects, such as strong polarization between the entrance channel and the transfer channels, might be important to describe the data. In this case, multistep transfer going forward and backward between states of different partitions could give rise to a rearrangement of the flux of the specified channels and the coupled reaction channels (CRC) formalism should be used instead. Although in the CRC formalism the final cross section of the transfer channel will be affected by this polarization, it may be still possible to obtain the ANC and $S$-factor provided that the coupling with other intermediate excited states are negligible. In case of weak coupling between excited states and strong polarization, only one spectroscopic amplitude is involved and it can be reliably extracted for astrophysics purposes.

In this paper, we investigate the importance of considering channel couplings effects in the analysis of the $^{16}$O$(d,n)^{17}$F and $^{16}$O$(d,p)^{17}$O transfer reactions, at incident deuteron energies from $E_d$=2.279 MeV to $E_d$=3.155 MeV, for which experimental data exist [7]. By performing CRC calculations, we show that if realistic spectroscopic information is to be obtained from these reactions one has to go beyond the Born approximation.

The paper is organized as follows. In Sec. II, DWBA and CCBA calculations are presented for the reactions under study. In Sec. III, CRC calculations are performed for the same reactions. The results obtained with the different reaction formalisms are discussed in Sec. IV. Finally, in Sec. V we summarize the main conclusions achieved in this work.

TABLE I. Optical model parameters used in the DWBA calculations. All potentials have a Woods-Saxon derivative imaginary potential. Potential depths are in MeV, while nuclear radii and diffusiveness are in fm.

| System | $V_0$ | $r_0$ | $a_0$ | $W_d$ | $r_i$ | $a_i$ | $V_{so}$ | $r_{so}$ | $a_{so}$ | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| $d+^{16}$O (a) | 110.0 | 1.012 | 0.876 | 9.3 | 1.837 | 0.356 | 6.0 | 1.4 | 0.7 | [8] |
| $n+^{17}$F (b) | $-49.3+0.33E_{c.m.}$ | 1.25 | 0.65 | 5.75 | 1.25 | 0.70 | 5.5 | 1.25 | 0.65 | [9] |
| $p+^{17}$O (c) | $-53.8+0.33E_{c.m.}$ | 1.25 | 0.65 | 7.5 | 1.25 | 0.70 | 5.5 | 1.25 | 0.65 | [9] |
| $n+^{17}$F (d) | | | | 65 | 2.0 | 0.332 | | | | (DPP) |
| $p+^{17}$O (e) | $-11.1$ | 1.25 | 0.58 | 2.3 | 1.25 | 1.07 | | | | (DPP) |

## II. DWBA ANALYSIS

The $^{16}$O$(d,n)^{17}$F transfer reaction was analyzed in terms of the DWBA formalism which, in prior form, involves the transition operator $V_{[p\text{-}^{16}\text{O}]}+U_{[n\text{-}^{16}\text{O}]}-U_{[d\text{-}^{16}\text{O}]}$. The distorting potential for the entrance channel, $U_{[d\text{-}^{16}\text{O}]}$, was considered as a variation of the Satchler parametrization [8]. A slight modification of the parameters was introduced in order to improve the fit to the data. The exit channel optical potential, $U_{[n\text{-}^{17}\text{F}]}$, was determined from the survey of Rosen [9]. This global parametrization was also used for the core-core interaction, $U_{[n\text{-}^{16}\text{O}]}$, although only the real part of the potential was retained. These potentials are listed in Table I. For the binding potential of the $^{17}$F nucleus a Woods-Saxon form with the standard parameters $r_0=1.25$ fm and $a_0=0.65$ fm was considered. The valence proton in the ground state of $^{17}$F is assumed to occupy the $1d_{5/2}$ orbit, with a spectroscopic factor adjusted to reproduce the experimental angular distribution data. For the $p$-$n$ binding potential, $V_{pn}$, a Gaussian form $V_{pn}(r)=-v_0\exp(r^2/a^2)$ with $a=1.484$ fm and $v_0=72.15$ MeV was used. These parameters were chosen to reproduce the rms and binding energy of the deuteron. A pictorial representation of this reaction is shown in Fig. 1. The DWBA transitions considered in our calculations are indicated by solid arrows.

In Fig. 2, we present the DWBA-prior calculations for $^{16}$O$(d,n)^{17}$F$_{gs}$ reaction, at two different scattering energies, along with the experimental angular distribution from Ref. [7]. To separate the direct cross section from the compound nucleus component we have considered energy averaged angular distributions. The average compound nucleus (CN) contributions for this reaction, estimated by Dietzsch *et al.*
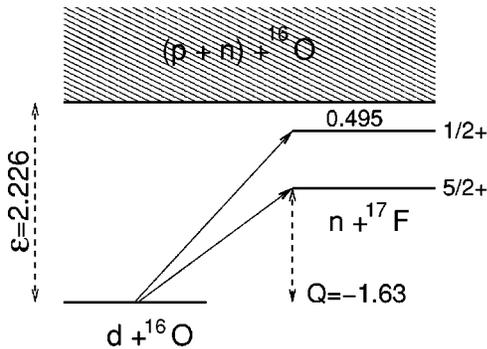
[7] are 1.5 mb/sr for $E_d=2.56$ MeV and 2.0 mb/sr for $E_d=2.85$ MeV. Since this contribution is roughly angular independent, we just added these values to the calculated angular distributions. The spectroscopic factors $S=0.85$, for the $\langle^{17}$F$|^{16}$O$\rangle$ vertex, and $S=1$, for $\langle d|n\rangle$, were used at both incident energies. The overall agreement between the calculated and experimental angular distributions, in both shape and normalization, is good, although the calculations underestimate the experimental data at the larger angles for $E_d=2.85$ MeV. Similar DWBA calculations were performed for the proton transfer to the first excited state in $^{17}$F at $E_x=0.495$ MeV. This state has $J^{\pi}=1/2^+$ assignment, which corresponds mainly to a $2s_{1/2}$ valence proton coupled to a zero-spin $^{16}$O core. In Fig. 3, the DWBA calculations (dashed lines) for the $^{16}$O$(d,n)^{17}$F$^*(0.495)$ reaction, are compared with the experimental angular distributions obtained at four different incident energies. As can be seen in the figure, the calculations overestimate the data for all energies considered. A spectroscopic factor of the order of $S\approx0.7$ for the $\langle^{17}$F$^*|^{16}$O$\rangle$ overlap would be required to reproduce the data. This small value is in clear disagreement with shell model calculations and with previous measurements at higher energies (8–12 MeV) [10–12], which give spectroscopic factor close to 1 for this overlap.
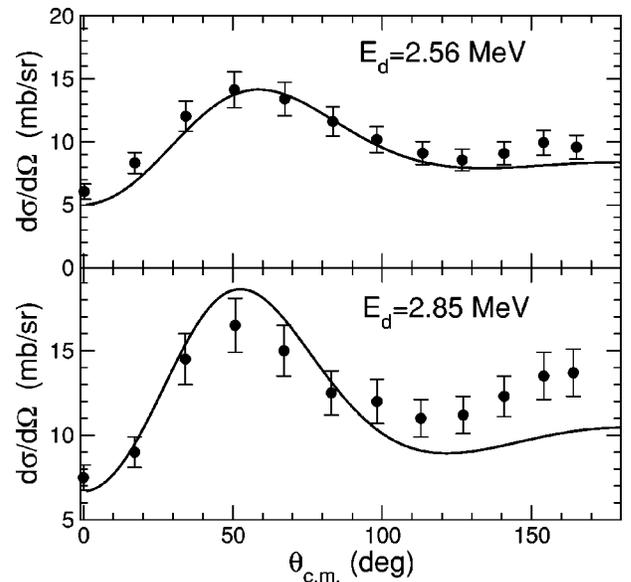


FIG. 2. DWBA calculations for the proton transfer reaction $^{16}$O$(d,n)^{17}$F$_{gs}$ at $E_d=2.56$ MeV and $E_d=2.85$ MeV. In both cases, a spectroscopic factor of 0.85 is used for the $\langle^{17}$F$|^{16}$O$\rangle$ overlap.
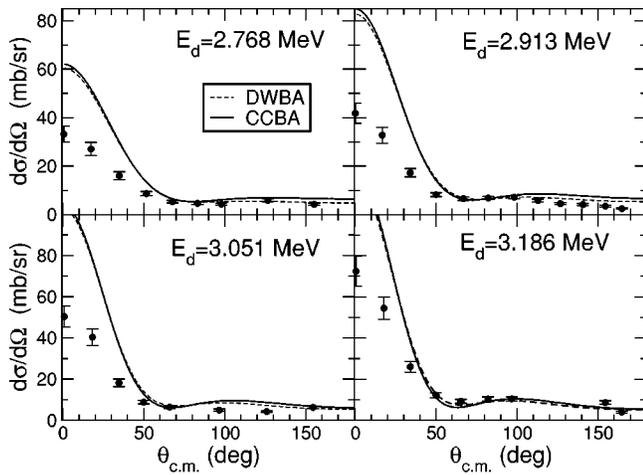


FIG. 1. Coupling scheme for the $^{16}$O$(d,n)^{17}$F reaction. Solid arrows indicate transitions considered in the DWBA calculations.

FIG. 3. DWBA and CCBA (prior form) calculations for the proton transfer reaction $^{16}$O$(d,n)^{17}$F*(0.495) at four different scattering energies. A spectroscopic factor of 1 was used for the $\langle^{17}$F$|^{16}$O$\rangle$ overlap.

Similar calculations were performed for the neutron transfer reaction $^{16}$O$(d,p)^{17}$O. The potentials used in this case are the same as those used in the analysis of the proton transfer reaction, except for Rosen potential, which predict slightly different potentials for protons and neutrons [see potential (c) in Table I]. The ground $(5/2^+)$ and first excited $(1/2^+, E_x = 0.871$ MeV) states in $^{17}$O were considered in the analysis (see scheme in Fig. 4). Pure single-particle configurations for the valence neutron, with spectroscopic factors 0.85 and 1, for the ground and excited states, respectively, were assumed. The calculated angular distributions for the deuteron incident energy $E_d = 2.85$ MeV are presented in Fig. 5. As in the case of the $(d,n)$ reaction, there is a good agreement between the calculated and experimental angular distribution for the $(d,p_0)$ reaction at forward angles, while a clear overestimation for the $(d,p_1)$ data is observed. A spectroscopic factor of about 0.6 would be required to fit the forward angle data which, as in the $^{17}$F case, is not consistent with the marked single-particle character expected for this state.

### CCBA calculations

One of the main sources of ambiguity in the DWBA calculations presented above is the optical potential for the exit
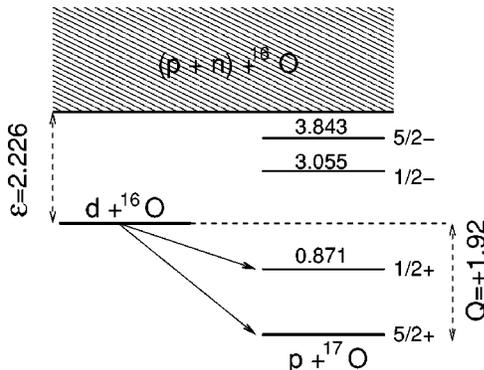


FIG. 4. Coupling scheme for the $^{16}$O$(d,p)^{17}$O reaction.



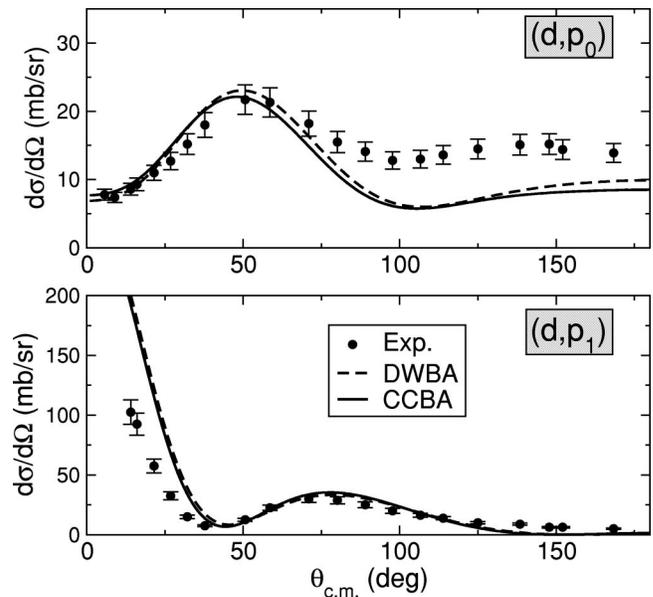FIG. 5. DWBA and CCBA (prior) calculations for the neutron transfer reaction $^{16}$O$(d,p)^{17}$F at $E_d = 2.85$ MeV.

channel $(n+^{17}$F or $p+^{17}$O). In the former case, the weakly bound nature of the $^{17}$F$(1/2^+, 0.495)$ state produces a long tail in the bound state wave function, making the system more diffuse than the ground state. For instance, the rms, calculated in a Woods-Saxon well with standard parameters, are 3.75 fm and 5.40 fm for the ground and excited state, respectively. Therefore, the different character of these two states might cast doubt on the validity of the global (Rosen [9]) parametrization used to describe the $n+^{17}$F* elastic scattering. In addition, couplings between the ground and excited states of $^{17}$F are neglected in the DWBA calculations. These effects can be properly taken into account within the CCBA formalism [13], where the final state wave function is obtained as a solution of the set of coupled equations, where diagonal as well as nondiagonal couplings between a set of selected projectile or target states are considered. In the case under consideration, these couplings can be naturally generated by assuming that the $^{16}$O behaves as an inert core and folding the $p$-$n$ and $n$-$^{16}$O interactions, i.e.,

$$U_{ij} = \langle \phi_i | V_{p\text{-}n} + U_{n\text{-}^{16}\text{O}} | \phi_j \rangle, \tag{1}$$

where $i$ and $j$ refer to either the ground or the excited state. In our calculation, only the ground and first excited states in $^{17}$F were considered in the model space (see Fig. 1). Note that the effect of the weak binding energy of this excited state is implicitly included in the intercluster wave function $\phi_i$. The resulting diagonal potentials for both states are shown in Fig. 6. The weakly bound nature of the excited state produces a slightly more diffuse real potential. Note that the imaginary potentials are almost identical. The small difference between these two folded potentials indicates that the halo effect does not show up in the folded potential. This conclusion is confirmed in Fig. 3, where CCBA calculations (solid lines) are compared with DWBA calculations (dashed lines) for the $(d,n)$ channel. As one can see, the calculated
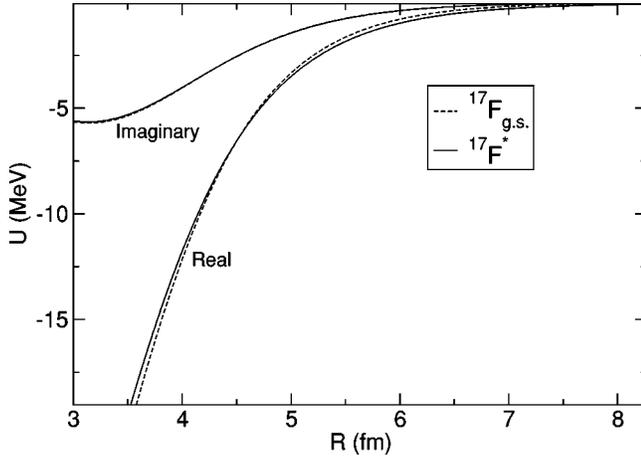
FIG. 6. Diagonal part of the cluster-folded potential for $n$ $+^{17}F_{gs}$ and $n+^{17}F^*$.

angular distributions are very similar in both approaches, indicating that final state interactions arising from target excitation play a negligible role in this reaction.

## III. CRC CALCULATIONS

In the previous sections we have shown that both DWBA and CCBA calculations do not reproduce adequately the transfer cross section for the $^{16}O(d,n)^{17}F^*$ and $^{16}O(d,p)^{17}O^*$ reactions, unless very small spectroscopic factors are used for the $\langle^{17}F^*|^{16}O\rangle$ and $\langle^{17}O^*|^{16}O\rangle$ overlap wave functions. The accuracy of these two approaches relies on the validity of the Born approximation (BA). In this section we assess the accuracy of the BA for the present reaction by performing coupled reaction channels (CRC) calculations.

In the CRC approach [13], the optical potentials for the entrance and exit channels must be understood as *bare* potentials. Once the transfer couplings are set in both directions, the bare potentials are defined as to reproduce the elastic channel on their respective channels. In principle, all the parameters of the potentials involved in this treatment could be considered as free parameters. These parameters could be simultaneously determined in the optimization of the overall agreement between the calculated cross section and the experimental angular distributions for the $(d,d)$, $(d,p)$ and $(d,n)$ channels. In addition, the spectroscopic factors can also be treated as adjustable parameters. However, adjusting all optical potentials and spectroscopic factors simultaneously would turn the searching procedure very lengthy. Moreover, the lack of experimental data for the proton and neutron elastic scattering for the exit channels makes it hard to determine realistic OP for these systems. Consequently, the OP parameters for these exit channels were kept fixed to the values given by the Rosen parametrization. We verified nevertheless that slight changes in these parameters, within physically reasonable constraints, did not affect significantly the agreement between the calculation and the data nor the extracted spectroscopic factors. We found also that, in order to obtain a good description of the elastic cross section of the entrance channel, the spin-orbit term in the deuteron optical

TABLE II. Deuteron optical potential parameters and spectroscopic amplitudes resulting from CRC calculations performed for the $^{16}O(d,n)^{17}F^*$ and $^{16}O(d,p)^{*17}O$ angular distribution at $E_d$ $=2.85$ MeV. The parameters not listed in the table are those of potential (a) from Table I.

| | $V_0$ (MeV) | $W_d$ (MeV) | $a_i$ (fm) | Spectroscopic amplitude | |
| | | | | $\langle^{17}F^*|^{16}O\rangle$ | $\langle^{17}O^*|^{16}O\rangle$ |
|---|---|---|---|---|---|
| Set I | 102 | 20.2 | 0.232 | $1.00^a$ | $1.00^a$ |
| Set II | 104 | 24.9 | 0.233 | $0.89\pm0.02$ | $0.95\pm0.01$ |

[a]These values were kept fixed in this search.

potential had to be eliminated. The initial parameters of these potentials were the same as those used in the DWBA calculations described in the previous sections. The nonorthogonality correction [14] was also included in the CRC calculations, since this effect was found to be important in all cases considered. All calculations were performed with the search routine of the computer code FRESCO [15], version frxy.

The estimates of the CN contributions obtained in Ref. [7] rely to some extent on DWBA calculations which, as we have shown, do not account properly for the measured data. Consequently, the experimental data for $(d,p_0)$ and $(d,n_0)$ reactions were not included in our searching procedure, and the spectroscopic factors involved in these transitions were set to unity.

The best fit parameters corresponding to different searches are presented in Table II. For the set I, only the depths and the diffuseness of the imaginary part of the deuteron central potential were considered as free parameters. These parameters were adjusted as to minimize the $\chi^2$ for the $(d,d)$ angular distribution. The radii and the real part diffuseness are the same as in Table I. All spectroscopic amplitudes were set to one.

As one can see, the imaginary part of the $d+^{16}O$ optical potential, which comes out from the CRC analysis, is much deeper and less diffuse than the deuteron optical potential (a) listed in Table I.

The CRC calculations for the $(d,p)$ and $(d,n)$ angular distributions, using the set I of parameters, are presented in Figs. 7–9, respectively. For comparison purposes, the DWBA prediction, assuming unit spectroscopic factor, is also included in the figure. The CRC $(d,d)$ distribution (thick dashed line in Fig. 7) is in perfect agreement with the data. Also, these calculations preserve the agreement with the $(d,n_0)$ and $(d,p_0)$ distributions, as compared with the DWBA calculations. Furthermore, the CRC calculations produce a reduction in the cross section at forward angles for the $(d,p_1)$ and $(d,n_1)$ reactions, improving significantly the agreement with the experimental with spectroscopic factors close to one.

In a second search, set II in the Table II, $V_0$, $W_d$, $a_i$ and the spectroscopic amplitudes for the overlaps $\langle^{17}O^*|^{16}O\rangle$ and $\langle^{17}F^*|^{16}O\rangle$ were set as free parameters. As a result of the $\chi^2$ minimization, the real and imaginary depths were slightly modified with respect to the values of the previous search, while the imaginary diffuseness results also on a small value.
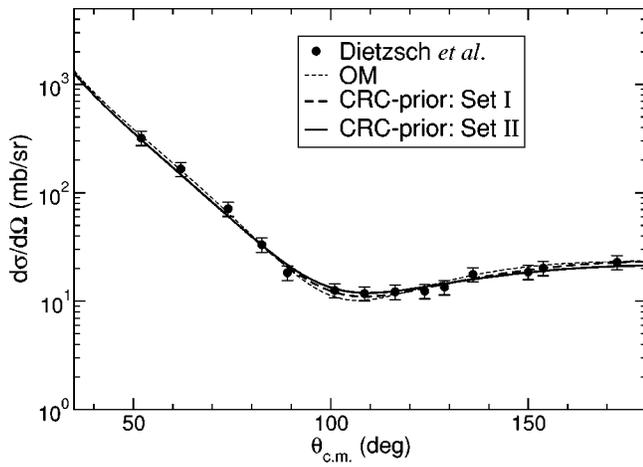
FIG. 7. Experimental and calculated elastic angular distributions for $d+^{16}$O at $E_d$=2.85 MeV.

Interestingly, the extracted spectroscopic factors are very close to 1. The results of this search, which are presented in Figs. 7, 10, and 11, are very similar to those obtained in the previous fit, the main difference being a slight improvement in the fit for the $(d,n_1)$ distribution at forward angles. The calculated angular distributions for the $(d,n_0)$ and $(d,p_0)$ reactions agree very well with the data, although the backward angular region is still underestimated. The calculation, also, overestimates the $(d,p_1)$ distribution.

As it has been said before, the extracted deuteron potential is less diffuse than the OP(a). This suggests that the imaginary part of this bare potential comes from a short-
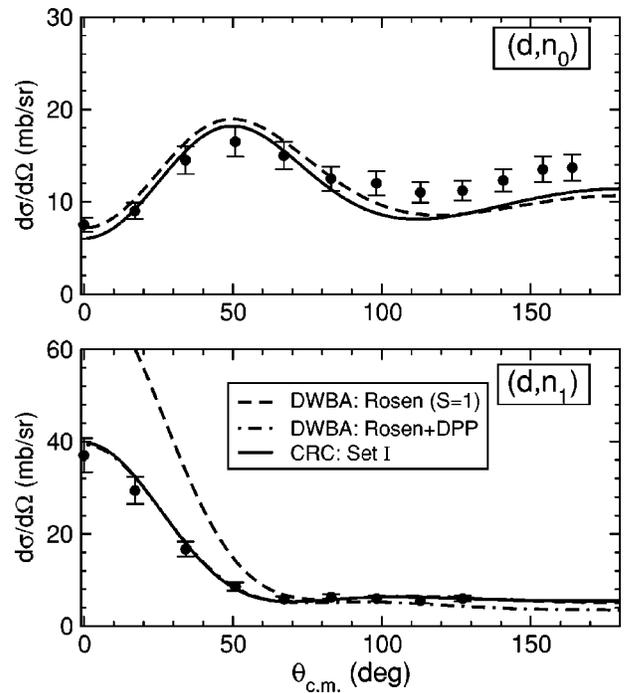


FIG. 9. CRC calculations for the $^{16}$O$(d,n)^{17}$F reaction at $E_d$ =2.85 MeV, using the set I of parameters (see Table II). The $(d,n_0)$ includes a contribution of 2.0 mb/sr, coming from CN formation.

range process, such as compound nucleus formation. This interpretation is consistent with the fact that, in our CRC calculations, all the relevant direct couplings are explicitly
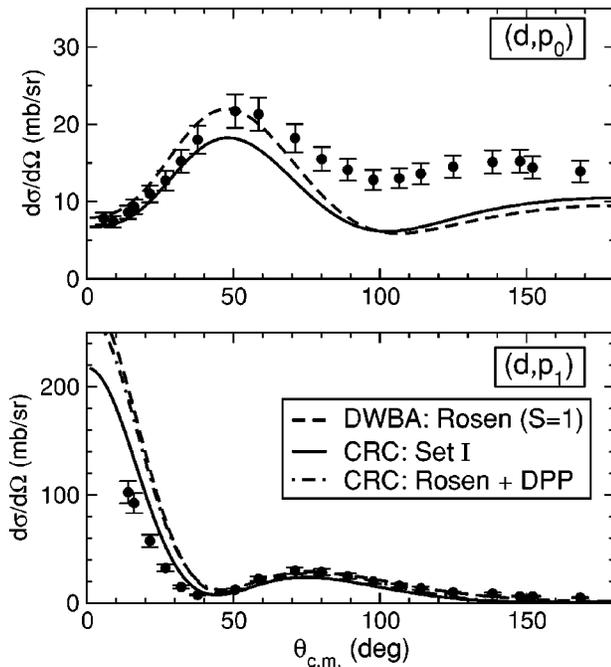


FIG. 8. CRC calculations for the $^{16}$O$(d,p)^{17}$O reaction at $E_d$ =2.85 MeV, using the set I of parameters (see Table II). The contributions of 2.95 mb/sr and 1.14 mb/sr, coming from CN formation, have been added to the $(d,p_0)$ and $(d,p_1)$ distributions, respectively.
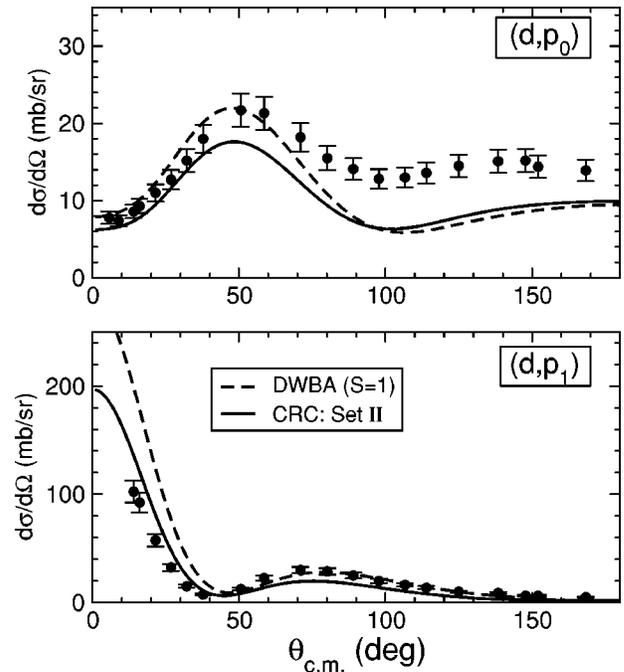


FIG. 10. CRC calculations for the $(d,p_0)$ and $(d,p_1)$ channels in the $d+^{16}$O reaction at $E_d$=2.85 MeV, using the set II of parameters (see Table II), for the incoming distorted potential. The $(d,p_0)$ and $(d,p_1)$ include the contributions of 2.95 and 1.14 mb/sr, respectively, coming from CN formation.
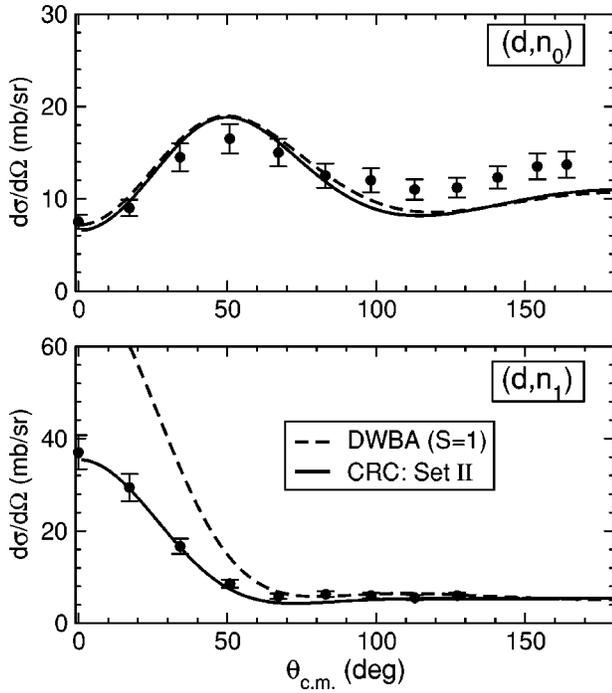
FIG. 11. CRC calculations for the $(d,n)$ channels in the $d + {}^{16}O$ reaction at $E_d = 2.85$ MeV, using the set II of parameters (see Table II).

included. Note that at these scattering energies, target excitation is forbidden by energy conservation, and projectile breakup is expected to be very small due to the restricted phase space available. Therefore, the only channels that could contribute to the absorption of the $d + {}^{16}O$ potential, besides those already included, are those leading to compound nucleus formation and, possibly, a small direct contribution coming from the $(d,\alpha)$ process. In this respect we note that the experimental excitation functions for the transfer reactions, in this energy region, exhibit structures which, in principle, could be due to a reminiscent effect of the resonances in the compound nucleus (see, for instance, Ref. [7]). Near these resonances, the meaning and usefulness of the optical model is questionable and all the conclusions reached above can be attributed to an inadequacy of the DWBA calculation.

To rule this possibility out, we have extended our analysis to other energies, ranging from $E_d = 2.29$ to $E_d = 3.186$ MeV for $(d,n)$ reaction and from $E_d = 2.279$ to $E_d = 3.155$ MeV for the $(d,p)$ reaction. The average spectroscopic factors obtained from the CRC analysis are summarized in Table III for two different sets of the incoming channel optical potential. The standard deviation specified as the error of the spectroscopic factors were obtained from the average of the four energies analyzed. Except for the $(d,p_1)$ channel, all spectroscopic factors are close to one. The small value found for the $\langle {}^{17}O^* | {}^{16}O \rangle$ spectroscopic factor should be considered an open problem in our analysis.

## IV. DISCUSSION

The large discrepancy between the CRC and DWBA calculations presented above suggests that the Born approxima-

TABLE III. Extracted values for the spectroscopic factors derived from CRC calculations.

| | Average spectroscopic factor | | | |
| | $(d,p_0)$ | $(d,p_1)$ | $(d,n_0)$ | $(d,n_1)$ |
| --- | --- | --- | --- | --- |
| Set I | 1.14(7) | 0.70(16) | 0.97(11) | 1.00(12) |
| Set II | 1.19(5) | 0.69(17) | 0.93(11) | 0.96(12) |

tion may not be valid to describe the angular distribution of the studied transfer reactions. This conclusion might depend, nevertheless, on how the potentials in the DWBA amplitude are defined. In the standard DWBA, the entrance and exit distorting potentials are defined as to reproduce the elastic scattering in their respective channels. In our case, the entrance optical potential could be determined accurately, since experimental data for the elastic channel was measured in the experiment of Dietzsch *et al.* [7]. However, for the $n + {}^{17}F$ exit channel, no elastic data exist due to the exotic nature of the ${}^{17}F$ nucleus. For the $p + {}^{17}O$ system, the only low energy data available in the literature, up to our knowledge, consist on excitation functions for elastic scattering in the energy range $E_p = 0.5 - 1.33$ MeV [16] and $E_p = 1.4 - 3$ MeV [17] for a few scattering angles. Thus, to generate the distorted waves for the exit channel in our analysis of the $(d,p_0)$ reaction, we rely on the Rosen parametrization, which reproduces reasonably well the data of Ref. [17]. However, there is no guarantee that this OP describes properly the (hypothetical) elastic scattering for $p + {}^{17}O^*$ system, where the target is in the first excited state. Actually, the CRC calculations, presented throughout this work, clearly indicate that the $d \rightarrow p_0$ and $d \rightarrow p_1$ couplings have very different strengths, the latter being much stronger. Thus, as shown below, different optical potentials were required for $p + {}^{17}O_{gs}$ and $p + {}^{17}O^*$. A similar argument and conclusion holds for the OP for $n + {}^{17}F_{gs}$ and $n + {}^{17}F^*$ system.

To get further insight into this problem, OM elastic scattering calculations obtained with the Rosen parametrization were compared with the result of the CRC calculation for $n + {}^{17}F_{gs}$ and $n + {}^{17}F^*$ at the neutron energy appropriate for the $(d,n)$ reaction at $E_d = 2.85$ MeV. These calculations are shown in Fig. 12. The dashed lines are the OM calculations with the Rosen parametrization and the solid lines are the CRC calculation using the parameters from set I (see Table II). As it can be seen, both $n + {}^{17}F_{gs}$ and $n + {}^{17}F^*$ angular distributions are clearly modified when coupling to the transfer channels are included. Interestingly, the ${}^{17}F_{gs}(n,n){}^{17}F_{gs}$ elastic scattering remains basically unchanged at small angles. This result might explain why the DWBA calculation reproduces the angular distribution for the ${}^{16}O(d,n){}^{17}F_{gs}$ transfer and not the ${}^{16}O(d,n){}^{17}F^*$ channel. On the other hand, the ${}^{17}F^*(n,n){}^{17}F^*$ scattering is strongly enhanced at forward angles due to the coupling to the transfer channels. It becomes apparent that an OP that fits the $(n_0,n_0)$ elastic scattering will not reproduce the $(n_1,n_1)$ scattering. Consequently, this OP will not be suitable as distorted potential for the DWBA amplitude of the $(d,n_1)$ process.

One could go further and ask whether an optical potential that fits the $(n_1,n_1)$ elastic scattering angular distribution,
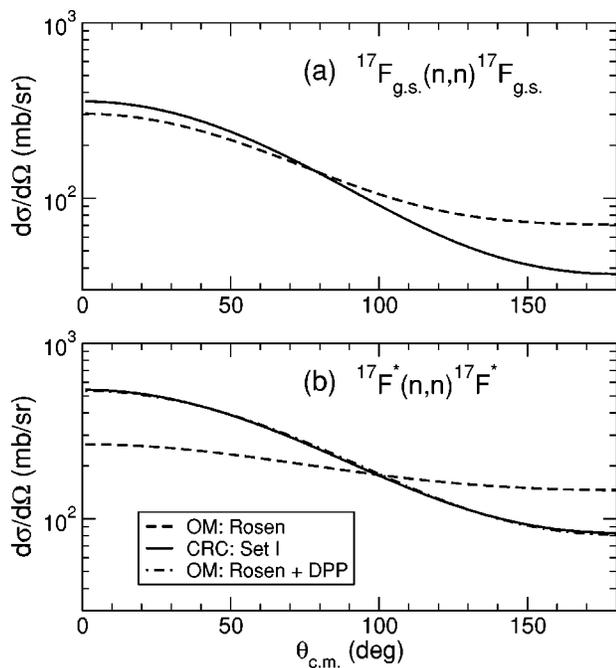
FIG. 12. Elastic scattering for $n+^{17}$F, at $E_n=0.9$ MeV and $E_n=0.4$ MeV, with $^{17}$F initially in the ground (upper panel) or excited (lower panel) state, respectively.



FIG. 13. Elastic scattering for $p+^{17}$O, at $E_p=4.7$ MeV and $E_n=3.8$ MeV, with $^{17}$O initially in the ground (upper panel) or excited (lower panel) state, respectively.

given by the CRC calculation, could be used as distorting potential in the DWBA amplitude to improve the agreement of the DWBA calculations for the $(d,n_1)$ angular distribution with the data. To answer this question, a phenomenological OP has been added to the one obtained with the Rosen parametrization in a such way that the combined potential reproduces the $(n_1,n_1)$ angular distribution given by the CRC calculation.

Obviously, the choice of this extra potential is not unique and, for simplicity, just the imaginary part, with a surface Woods-Saxon shape, has been considered. The extracted parameters are listed in Table I, set (d). The corresponding calculated angular distribution is shown in Fig. 12(b) indicated by the dotted-dashed line. As it can be seen, the CRC effects are perfectly accounted for by using this phenomenological OP. Furthermore, by using this potential as a distorting potential for the exit channel in the $(d,n_1)$ reaction, the DWBA calculated angular distribution is in excellent agreement with the CRC calculation and, hence, with the experimental data. The result of this calculation is shown in the bottom panel of Fig. 9, indicated by the dotted-dashed line (Rosen+DPP). This result suggests that the additional potential can be regarded as a *dynamic polarization potential* (DPP) that accounts for the coupling effect of the $(d,n_1)$ channel in the $^{17}$F$^*(n,n)^{17}$F$^*$ elastic scattering.

A similar analysis was carried out for the proton channel. The calculated angular distributions for the $p+^{17}$O elastic scattering, at the outgoing proton energy for the reaction $^{16}$O$(d,p)^{17}$O at $E_d=2.85$ MeV, are shown in Fig. 13. Again, the difference between the pure optical model calculation (dashed lines) and the CRC calculation (solid lines) is more pronounced in the $(p_1,p_1)$ than in the $(p_0,p_0)$ case. This is a clear indication that the $d\rightarrow p_1$ coupling is stronger than the
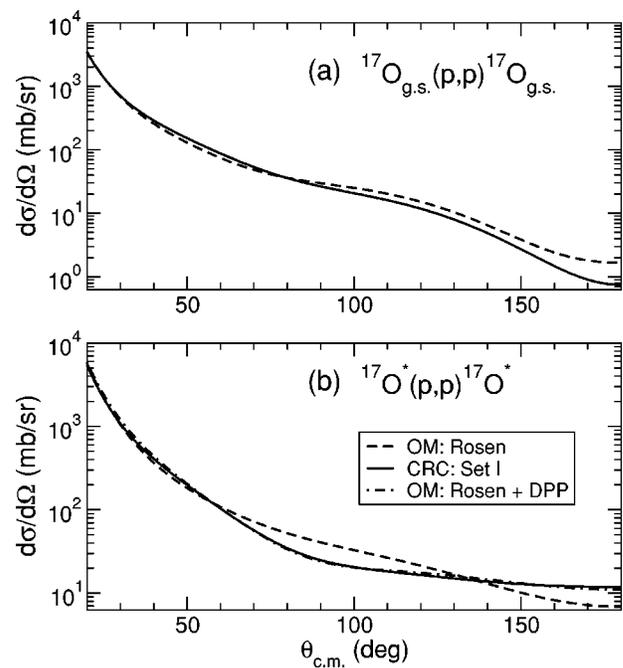
$d\rightarrow p_0$ one. In analogy with the neutron case, a DPP potential has also been added to the $p+^{17}$O potential to reproduce the CRC elastic scattering distribution for $(p_1,p_1)$. In this case, a complex potential, comprising a real volume term and an imaginary surface part, has been used. The parameters for this potential are listed in Table I, set (e). As it can be seen, in this case the polarization potential is repulsive and has a diffuse and shallow absorptive component.

Unlike the neutron case, using this extra polarization potential together with the potential (c) as distorting potential in the DWBA calculation did not reproduce the CRC result for the $^{16}$O$(d,p)^{17}$O$^*$ reaction. The result of the DWBA calculation with this extra DPP, shown in Fig. 8 by the dotted-dashed line, is very similar to the DWBA calculation with the bare potential alone. Of course, since the extra DPP potential is not unique, there is always the possibility that another more appropriate DPP would improve the agreement with the experimental angular distribution for the $^{16}$O$(d,p)^{17}$O$^*$ reaction. Unfortunately, we have not been able to find such a potential. Notwithstanding these considerations, we would like to stress that it is not obvious that the (nonlocal) transfer coupling can be described in general by a simple local potential. To support this conclusion, we have calculated the trivially local equivalent polarization potential [18] for the $p+^{17}$O$^*$ and $n+^{17}$F$^*$ elastic scattering, using the solution provided by our CRC calculations. The polarization potential so obtained was found to be very oscillatory, and strongly $L$ dependent, supporting the idea that transfer couplings are not easily representable by simple Woods-Saxon forms. A similar analysis was performed by Coulter and Satchler [18], reaching similar conclusions.

It has been argued by several authors [19,20] that in some cases the appropriate incoming (exit) distorting potential to

be used in the DWBA amplitude does not necessarily fit the experimental elastic scattering in the entrance (exit) channel. Instead, these authors suggest the use of an alternative prescription in which the distorted potential is replaced by the bare potential, as obtained from a CC or CRC calculation. Ichimura and Kawai [21], for instance, have investigated the validity of the conventional and alternative expressions of the DWBA amplitude for the $^{16}O(d,p)^{17}O^*$ transfer reaction. However, they found that both DWBA prescriptions fail to reproduce the CRC result. Our calculations seem to support this conclusion.

## V. SUMMARY AND CONCLUSIONS

In this work we have studied the $^{16}O(d,p)^{17}O$ and $^{16}O(d,n)^{17}F$ transfer reactions at sub-Coulomb energies ($E_d \approx 2-3$ MeV). We have shown that standard DWBA calculations, that satisfactorily reproduce the $(d,n_0)$ and $(d,p_0)$ forward angular distributions, do not quite reproduce the $(d,n_1)$ and $(d,p_1)$ data, unless anomalously small spectroscopic factors are used for the $\langle ^{17}F^*|^{16}O\rangle$ and $\langle ^{17}O^*|^{16}O\rangle$ overlaps. This discrepancy remains even when couplings between excited states of the final nucleus are included through the CCBA formalism. A full coupled reaction channels (CRC) calculation, which treats the transfer couplings beyond the Born approximation, greatly improves the agreement with the data. In particular, the polarization between the entrance

$(d,d)$ channel and the $(d,p_1)$ and $(d,n_1)$ reaction channels reduces the cross sections at forward angles, resulting in a very good agreement with the data, while maintaining spectroscopic factors close to one, particularly in the case of the $(d,n_1)$ reaction. In that case, we have found that these higher order effects can be accounted for within the DWBA formalism by adding an effective optical local potential to the exit channel distorting potential for $n+F^*$. This polarization potential is chosen in such a way that the total (bare+DPP) potential reproduces the elastic data on the exit channel. Therefore, in this particular case, one can still use the DWBA formalism, provided that different distorting potentials are used for the $(d,n_0)$ and $(d,n_1)$ channels. Unfortunately, such a DPP could not be found for the $(d,p_1)$ channel. Other authors [21] were also not able to find such DPP for the same reaction at higher energies. With the present analysis we aim to call the attention to some of the limitations in the DWBA formalism as a tool to extract spectroscopic information from reactions of astrophysical interest.

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