Astrophysical S-factors for the p+^{16}O and n+^{16}O captures from the analysis of $^{16}O(d,n)^{17}F$ and $^{16}O(d,p)^{17}O$ transfer reactions

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Astrophysical S-factors for the $p+^{16}O$ and $n+^{16}O$ captures from the analysis of ^{16}O(d,n)^{17}F and ^{16}O(d,p)^{17}O transfer reactions

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Abstract. Coupled reaction channels calculations were performed for the ^{16}O(d,n)^{17}F and ^{16}O(d,p)^{17}O transfer reactions for the ground and first excited states at several energies from E_{lab}=2.29 MeV up to 3.27 MeV. A strong polarization effect between the entrance channel and the transfer, ^{16}O(d,n)^{17}F ($1/2^+$,0.495) and ^{16}O(d,n)^{17}O ($1/2^+$,0.87), channels was observed. This polarization effect had to be taken into account to all orders for obtaining realistic spectroscopic factors from these reactions. The ^{16}O(p,γ)^{17}F and ^{16}O(n,γ)^{17}O direct captures were calculated using the Asymptotic Normalization Coefficients (ANC) values from these transfer reactions analysis. The astrophysical S-factors were compared to measurements. The Maxwellian-averaged neutron capture cross section at kT=30 keV was 22(3)μbarn.

Keywords: direct reaction, coupled-channel, distorted-wave model, capture cross section, astrophysical S-factor
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INTRODUCTION

The interest in the experimental and theoretical study of few nucleon transfer reactions has been renewed in the last years mainly due to the possibility of obtaining astrophysical relevant information from these reactions [1, 2, 3, 4, 5]. The direct measurements of capture reactions at energies of astrophysical interest are, in some cases, nearly impossible due to low reaction yield, especialy if the capture involves exotic nuclei. Alternative indirect methods such as the asymptotic normalization coefficient (ANC) method, based on the analysis of breakup [6] or transfer reaction [1] have been used as a tool for obtaining astrophysical S-factors. The advantage of the indirect approach comes from the fact that the transfer and breakup reactions can be measured at higher energies, where the cross sections are much larger. However, in order to obtain useful information from transfer reactions one needs to understand, as clear as possible, the reaction mechanism therein involved.

In this paper, we investigate the importance of considering the CRC (coupled reaction channel) calculation 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 and comparing to DWBA

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(distorted wave Born approximation) and CCBA (coupled channel Born approximation) results, we show that if realistic spectroscopic information is to be obtained from these reactions one has to go beyond the Born approximation. We use the spectroscopic factors obtained from a full CRC calculation to evaluate the $p+^{16}O$ and $n+^{16}O$ capture cross sections. In particular, the large ^{16}O(n,γ)^{17}O cross section obtained has implications for nucleosyntesis theories, especially in metal-defficient massive stars as an important neutron poison [8].

DWBA AND CCBA ANALYSIS

Firstly, the transfer reactions were analyzed in terms of the DWBA approach. The distorting potential for the entrance channel was considered as a variation of the Satchler parametrization [9] slightly modified to improve the fit to the $d+^{16}O$ angular distribution. The optical potentials in the exit channels were obtained from parametrization of Rosen [10]. These potentials are listed in Table 1 and the spin-orbit contributions are V_{so}=6.0 MeV, r_{so}=1.4 fm and a_{so}=0.7 fm for the d+^{16}O system. Both n+^{17}F and p+^{17}O systems have been considered the values of V_{so}=5.5 MeV, r_{so}=1.25 fm and a_{so}=0.65 fm.

TABLE 1. Optical potential parameters used in DWBA and CCBA analysis.

System	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_d (MeV)	r_i (fm)	a_i (fm)
d+^{16}O	110.0	1.012	0.876	9.3	1.837	0.356
n+^{17}F	-49.3+0.33Ec.m.	1.25	0.65	5.75	1.25	0.70
p+^{17}O	-53.8+0.33Ec.m.	1.25	0.65	7.5	1.25	0.70
Set(CRC)	104	1.25	0.65	24.9	1.25	0.233

The DWBA calculation is in good agreement with the ground state for (d,n_0) and (d,p_0) reactions at forward angles, while a clear overestimation for the first excited state for (d,n_1) and $(d,p_1)$is observed in lower pannels of Figure 1.(a) and 1.(b). In these cases, the spectroscopic factor of about 0.6 would be required to fit the data what is not consistent with the single-particle character expected for the ^{17}F and ^{17}O nuclei. In all calculations, a compound nucleus contributions obtained by Dietzch et al. [7] were subtracted from experimental data. One of the main sources of ambiguity in the DWBA calculations presented above is the optical potential for the exit channels ($n+^{17}F$ or $p+^{17}O$) for which no experimental data exists. 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. Therefore, the different character of these two states might cast doubt on the validity of the global parametrization [10] 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 by using the CCBA formalism. By performing the CCBA calculations, we noted that the results are very similar to the DWBA results, indicating that the final state interaction arising from target excitation plays a negligible role in this reaction [11].

CRC CALCULATIONS

Previous section has shown that both DWBA and CCBA calculations do not quite reproduce the transfer cross section for the ^{16}O(d,n)$^{17}F^*$ and ^{16}O(d,p)$^{17}O^*$ reactions, unless unreasonably small spectroscopic factors are used for the $\langle ^{17}F^*|^{16}O\rangle$ and $\langle ^{17}O^*|^{16}O\rangle$ overlaping wave functions. The accuracy of both, the DWBA and CCBA approaches, rely on the validity of the Born approximation.

In the CRC approach, the optical potentials for the entrance and exit channels could be understood as *bare potentials*. Once the transfer couplings are set in both directions, the bare potentials is defined as to reproduce the elastic scattering of the respective channel. We used the search version SFRESCO [12] code to determine the bare potential in the entrance channel by varying V_0, W_d, a_i and the spectrosopic amplitude in order to fit simultaneously the elastic $(d+^{16}O)$ data and transfer channels at 2.85 MeV. The obtained values of V_0, W_d and a_i are listed in the Table 1. The optical potentials in the exit channels were kept fixed to the Rosen parametrization. The best fit for Set(CRC) is listed in Table 1. Results using this set of parameters, are presented in Figure 1.(a), 1.(b) and 1.(c). For comparison purposes, The DWBA prediction, assuming unit spectroscopic factor, is also included in the figure. The CRC (d,d) (solid lines in Figure 1.(c)) is in very good agreement with the data. Futhermore, the CRC calculation produces a reduction of the cross section at forward angles for the (d,n_1) and (d,p_1)reactions, improving significantly the agreement with the experimental data using spectroscopic factors close to one.

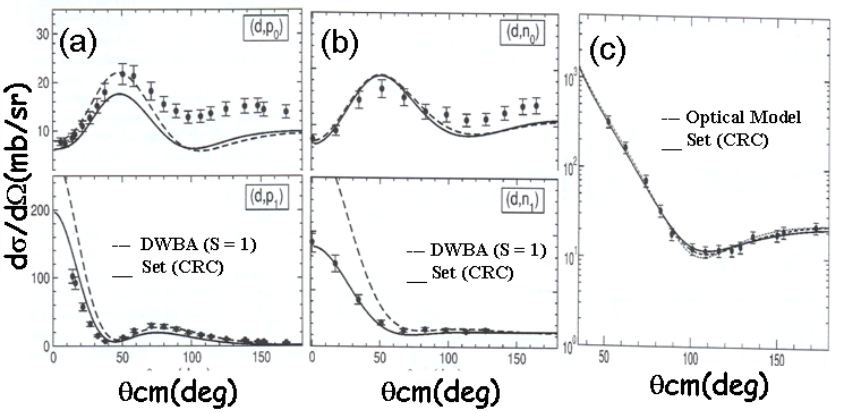

FIGURE 1. (a) CRC calculations (solid line) for the ^{16}O(d,n)^{17}F and (b) ^{16}O(d,p)^{17}O reactions for the ground (upper pannels) and first excited (lower pannels) states at 2.85 MeV, using the Set(CRC) of parameters (see Table 1). (c) Experimental and calculated elastic angular distributions for $d+^{16}O$ at E_d=2.85 MeV. The experimental data were obtained by Diezsch et al. and CN contributions [7] are included.

We have extended the CRC analysis to other energies, i.e., from E_d= 2.29 to E_d= 3.186 MeV for the (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 this analysis are summarized in Table 2. The standart deviation specified as the error of the spectroscopic factors were

obtained from the average of four analyzed energies. Except for the (d,p_1) channel, all spectroscopic factors are close to one. The small value for the $\langle {}^{17}O^*|{}^{16}O\rangle$ spectroscopic factor should be considered as an open problem in our analysis.

TABLE 2. Average spectroscopic factors and ANC values from CRC calculations.

	(d,p_0)	(d,p_1)	(d,n_0)	(d,n_1)
Spectroscopic Factor	1.19(5)	0.69(17)	0.93(11)	0.96(12)
ANC Values (fm^{-1})	0.88(3)	6(1)	0.85(7)	6017(493)

PROTON AND NEUTRON CAPTURE CROSS SECTIONS

In order to get reliable ANC values from the spectroscopic factors it is necessary to assure that the transfer reactions are peripheral. For this purpose we performed tests in our previous DWBA calculations by varying the lower cut in the DWBA integrals and observing the sensitivity to the calculations. The results of these tests indicated that one calculations were practically insensitive to cuts until $r_{cut} \sim 5$ fm and become very sentive above r_{cut}=6 fm showing that the transfer reactions are quite peripheral [13]. The obtained ANC values for $p+{}^{16}O$ and $n+{}^{16}O$ are shown in Table 2.

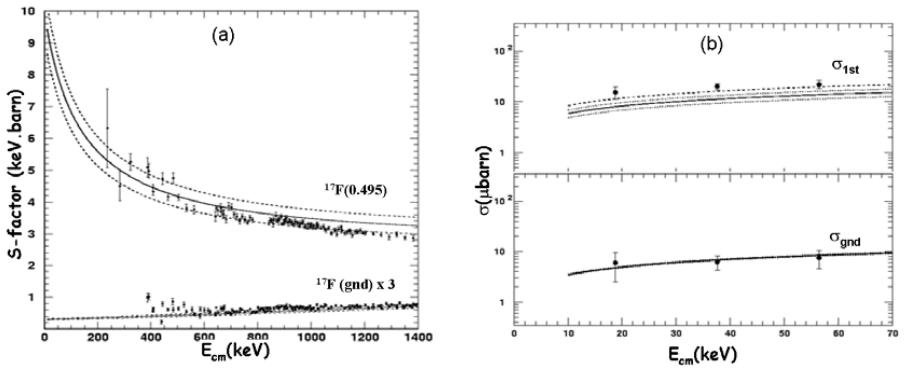

FIGURE 2. (a) Astrophysical S- factor from ^{16}O(d,n)^{17}F transfer reaction and (b) neutron capture cross section from ^{16}O(d,p)^{17}O transfer reaction performed by CRC analysis. The solid lines are our results and the dashed lines are error bands. The dotted line in (b) was obtained using the spectroscopic factor equal to one. The experimental data were obtained by Morlock et al. [15] and by Igashira et al.[8] (resonance effect are included), respectively.

The astrophysical S-factors for the ^{16}O(p,γ)^{17}F and ^{16}O(n,γ)^{17}O capture cross sections were determined using the program Radcap [14]. The results are shown in Figure 2 (a) and (b) compared to experimental data of Morlock et al. [15] and Igashira et al. [8], respectively. The zero energy S-factor for the first excited state ^{16}O(p,γ)$^{17}F^*$ was obtained as 9.6 ± 0.8 keVbarn and it is in agreement with the value of Gagliardi et al [4]. For the ground state in both S-factor calculations underestimate the experimental data,

however, Morlock et al. [15] suggest that the ground experimental data could have been contaminated by the background [15].

The neutron captures to the ground and first excited states of the ^{17}O nucleus are shown in Figure 2.(b). The Maxwellian-averaged direct cross section at kT=30 keV was calculated as 22 ± 3 μbarn from our transfer reaction analysis. Igashira et al. [8] reported a 34 ± 4 μbarn from experimental data with the resonance effect subtracted. This large cross section result could have implications for nucleosynthesis theories and inhomogeneous models [8].

CONCLUSIONS

We investigated in detail the mechanism of the ^{16}O(d,n)^{17}F and ^{16}O(d,p)^{17}O transfer reactions at very low energies. We have shown that standard DWBA and CCBA calculations do not reproduce the (d,n_1) and (d,p_1) reactions unless very small spectroscopic factors are used, while the CRC calculations greatly improve the agreement with the (d,n_1) and (d,p_1) channels. The spectroscopic factor obtained from the CRC analysis is close to unit in agreement with theoretical predictions. The obtained astrophysical S-factors for the ^{16}O(p,γ)$^{17}F^*$ and ^{16}O(n,γ)$^{17}O_{gs}$ capture reactions are in good agreement with the experimental measurements. The ^{16}O(p,γ)$^{17}F_{gs}$ and ^{16}O(n,γ)$^{17}O^*$ cross sections obtained in this work underestimate the experimental data. The Maxwellian-averaged cross section at kT=30keV for the total (gs+1^{st}_{exc}) ^{16}O(n,γ)^{17}O capture, has been determined to be 22(3)μb. The present results demonstrate the possibility of determining astrophysical S-factors from transfer reaction measurements.

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