Test of Determination of (p,γ) Astrophysical S-Factors Using the Asymptotic Normalization Coefficients from Neutron Transfer Reactions *

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The asymptotic normalization coefficients (ANCs) for the virtual decay $^{17}O\rightarrow^{16}O+n$ are derived from the angular distributions of the $^{16}O(d,p)^{17}O$ reaction leading to the ground and first excited states of ^{17}O, respectively, using the distorted wave Born approximation and the adiabatic wave approximation. The ANCs of ^{17}F are then extracted according to charge symmetry of mirror nuclei and used to calculate the astrophysical S-factors of $^{16}O(p,\gamma)^{17}F$ leading to the first two states of ^{17}F. The present results are in good agreement with those from the direct measurement. This provides a test of this indirect method to determine direct astrophysical S-factors of (p,γ) reaction. In addition, the S-factors at zero energy for the direct captures to the ground and first excited states of ^{17}F are presented, without the uncertainty associated with the extrapolation from higher energies in direct measurement.

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Nuclear capture reactions, such as (p,γ), play an important role in the evolution of stars. Determination of the reaction cross sections of short-lived nuclear species is one of the major challenges for nuclear physics and nuclear astrophysics. Many of these reactions are difficult to measure directly with currently available experimental techniques because these species are too short-lived to serve as targets and the intensities of their ion beams are very low. In addition, one has to extrapolate the results at higher energies to the energies of astrophysical interest. It is therefore important to explore alternative indirect methods for determining reaction cross sections of unstable nuclei.

In recent years, the asymptotic normalization coefficient (ANC) approach has been developed[1,2] and utilized to determine the direct capture cross sections and S-factors of (p,γ) reaction at astrophysical energies using proton transfer reactions.[3−5] This technique has been respectively tested using the ANC from (^{3}He,d) and (d,n) proton transfer reactions.[6,7] Recently, the relationship of the neutron and proton ANCs for mirror pairs has been established[8,9] and utilized to study the astrophysical ^{8}B$(p,\gamma)^9$C, ^{26}Si$(p,\gamma)^{27}$P, ^{13}N$(p,\gamma)^{14}$O and ^{11}C$(p,\gamma)^{12}$N reactions.[10−13] In this Letter, we verify the technique to determine astrophysical S-factors of (p,γ) reaction using the ANC from (d,p) neutron transfer reaction.

For a peripheral transfer reaction, such as ^{16}O$(d,p)^{17}$O, the ANC can be extracted by comparing the experimental angular distribution with the theoretical calculation,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp}=\sum_{j_ij_f}(C^{d}_{l_ij_i})^2(C^{^{17}\rm O}_{l_fj_f})^2\frac{\sigma^{th}_{l_ij_il_fj_f}}{(b^{d}_{l_ij_i})^2(b^{^{17}\rm O}_{l_fj_f})^2},\quad(1)$$

where $\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp}$ and $\sigma^{th}_{l_ij_il_fj_f}$ are the measured and theoretical differential cross sections. $C^{^{17}\rm O}_{l_fj_f}$, $C^{d}_{l_ij_i}$ and $b^{^{17}\rm O}_{l_fj_f}$, $b^{d}_{l_ij_i}$ represent the nuclear and corresponding single particle ANCs for virtual decays ^{17}O $\rightarrow$ ^{16}O + n and $d\rightarrow p+n$, respectively. Here l_i,j_i and l_f,j_f denote the orbital and total angular momenta of the transferred neutron in initial and final nuclei d and ^{17}O, respectively.

In the present calculation, the code PTOLEMY[14] is employed to calculate the angular distributions. The optical potentials of d+^{16}O are obtained by two ways. Firstly, the optical potential of entrance channel is obtained by fitting the elastic scattering data.[15] We refer to the results as the distorted wave Born approximation (DWBA). In addition, the adiabatic deuteron potential is calculated with the parametrization in Ref. [16] to include the breakup effects of deuteron. We refer to the results as the adiabatic wave approximation (ADWA). The adiabatic distorting potential governing the c.m. motion of the deuteron is well described by the sum of the neutron- and proton-target optical potentials.[16] In the present calculation, the optical potentials of nucleon-target are taken from Refs. [17,18], respectively. All the optical potential parameters are listed in Table 1. Figures 1 and 2 show the normalized angular distributions of the ^{16}O$(d,p)^{17}$O reaction leading to the ground and first excited states of ^{17}O, respectively, together with the experimental data.[19] In the present calculation, three data around the peak are used to derive the ANCs. C^2_d is taken to be 0.76 fm^{-1} from Ref. [2]. Each set of the optical potential corresponds to one ANC, as listed in Table 2. Their averaged values are taken as the ANCs of ^{17}O virtual decays. The squared ANCs

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of the ground and first excited states of ^{17}O are then extracted to be $0.82 \pm 0.11\,\mathrm{fm}^{-1}$ and $8.4 \pm 1.3\,\mathrm{fm}^{-1}$, respectively. The errors result from the uncertainty of experimental data and the deviation of optical potentials.

Table 1. Optical potential parameters used in the calculation, where V and W are in MeV, r and a in fm. D and P denote the entrance and exit channels, respectively. $P1$ and $P2$ represent the potentials for the ground state of ^{17}O, $P3$ and $P4$ represent the potentials for the first excited state of ^{17}O.

Set	$D1$[15]	$D2$[16]	$P1$[17]	$P2$[18]	$P3$[17]	$P4$[18]
V_r	115.9	91.47	49.0	50.09	47.7	50.37
r_{0r}	1.017	1.161	1.25	1.162	1.25	1.162
a_r	0.846	0.722	0.61	0.69	0.62	0.69
V_I		3.02		1.49	4.0	1.426
r_{0I}		1.615		1.167	1.25	1.167
a_I		0.442		0.69	0.966	0.69
W_s	11.257	12.9	4.5	7.26	0.4	7.33
r_{0s}	1.073	1.16	1.25	1.17	1.25	1.17
a_s	0.584	0.69	1.2	0.69	1.4	0.69
V_{so}	11.6	5.9	6.8	5.9	4.8	5.9
r_{0so}	0.578	0.864	1.25	0.87	1.25	0.873
a_{so}	0.343	0.63	0.61	0.63	0.62	0.63
r_{0c}	1.3	1.3	1.25	1.29	1.25	1.29

To verify if the transfer reaction is peripheral, the ANCs and spectroscopic factors for the first two states in ^{17}O are computed by changing the geometry parameters of Woods–Saxon potential for single particle bound state, using two sets of the optical potentials ($D2$–$P2$ for the ground state, $D1$–$P3$ for the first excited state), as shown in Figs. 3 and 4. One can see that the spectroscopic factors vary significantly, while the ANCs are nearly a constant, indicating that the ^{16}O$(d,p)^{17}$O reactions are dominated by peripheral process at the present energy.

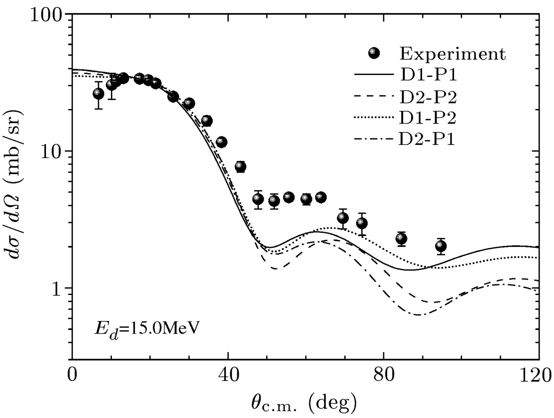

Fig. 1. Angular distributions of ^{16}O$(d,p)^{17}$O$_{\mathrm{g.s.}}$. The experimental data are taken from Ref. [19].

Table 2. Neutron ANCs for virtual decays of the ground and first excited states (0.871 MeV) of ^{17}O.

ANC^2 (fm^{-1})	$D1$-$P1/P3$	$D2$-$P2/P4$	$D1$-$P2/P4$	$D2$-$P1/P3$	Average
^{17}O$_{\mathrm{g.s.}}$	0.85 ± 0.03	0.75 ± 0.02	0.73 ± 0.02	0.95 ± 0.03	0.82 ± 0.11
^{17}O$_{0.871}$	9.6 ± 1.0	7.2 ± 0.7	8.3 ± 0.8	8.4 ± 0.8	8.4 ± 1.3

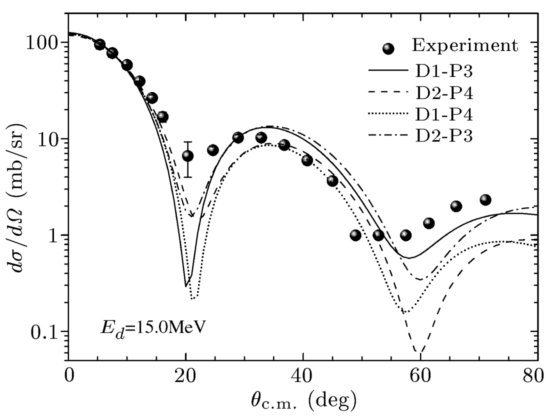

Fig. 2. Angular distributions of ^{16}O$(d,p)^{17}$O$_{0.871}$. The experimental data are from taken Ref. [19].

The ground and first excited states of ^{17}F and ^{17}O are mirror pairs, thus the ANCs of ^{17}F can be related to the ANCs of ^{17}O by $(C^{^{17}\mathrm{F}}_{l_f j_f})^2 = R(C^{^{17}\mathrm{O}}_{l_f j_f})^2$, where R can be computed with[8,9]

$$R = \left|\frac{F_l(ik_pR_N)}{k_pR_Nj_l(ik_nR_N)}\right|^2, \tag{2}$$

where F_l and j_l are the regular Coulomb wave function and the spherical Bessel function, and R_N is the radius of nuclear interior. The wave number k_p (k_n) can be determined by the proton (neutron) separation energy.

On the other hand, if we assume that the single particle spectroscopic factors S_p and S_n are equal for mirror pair, the ANC ratio R can also be obtained based on the relationship of $C_{p(n)} = \sqrt{S_{p(n)}}b_{p(n)}$.

$$R = (b^{^{17}\mathrm{F}}_{l_f j_f})^2/(b^{^{17}\mathrm{O}}_{l_f j_f})^2. \tag{3}$$

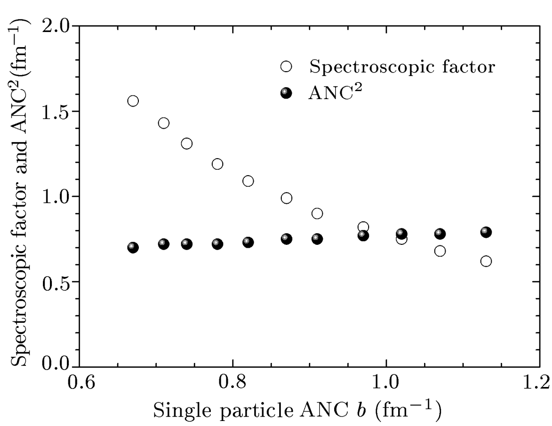

Fig. 3. Dependence of the spectroscopic factor and the square of ANC (ANC^2) on the single particle ANC (b) for the ground state of ^{17}O.

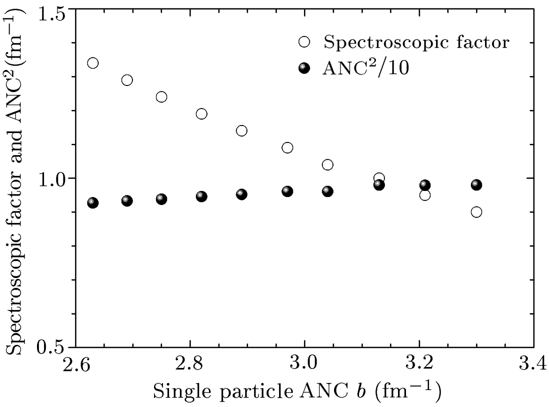

Fig. 4. Dependence of the spectroscopic factor and the square of ANC (ANC^2) on the single particle ANC (b) for the first excited state of ^{17}O.

The ANC ratios R are extracted for both the states according to Eqs. (2) and (3) and listed in Table 3, respectively. Their averaged values are then used to derive the proton ANCs of the ground and first excited states in ^{17}F. All these results are listed in Table 3. The errors of proton ANC arise from those of the neutron ANC and R.

Table 3. Proton ANCs of the ground and first excited states (0.495 MeV) in ^{17}F.

	J^π	R		ANC^2 (fm^{-1})
^{17}F$_{\rm g.s.}$	$5/2^+$	1.23	1.17	0.98 ± 0.14
^{17}F$_{0.495}$	$1/2^+$	820	786	6720 ± 990

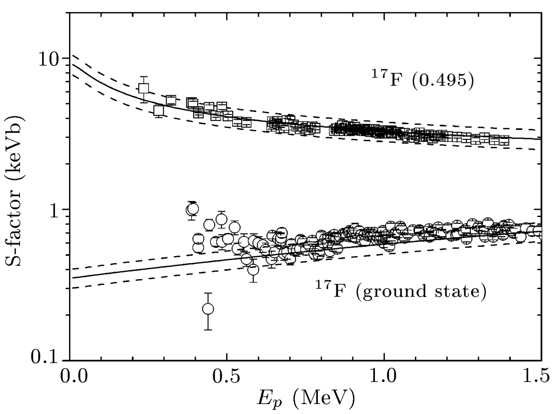

Fig. 5. Astrophysical S-factors of ^{16}O$(p,\gamma)^{17}$F leading to the ground and first excited states of ^{17}F. The squares and circles are taken from Ref. [20]. The solid lines represent our calculated S-factors, and the dashed lines denote the $\pm 1\sigma$ error bands. Note that the ground state S-factors in Ref. [20] may be contaminated by background at energies below 500 keV.[6]

The direct capture cross sections and S-factors of ^{16}O$(p,\gamma)^{17}$F can be calculated with the proton ANCs of ^{17}F using the formulae in Ref. [13]. According to the present ANCs (0.98 ± 0.14 fm^{-1}, 6720 ± 990 fm^{-1}), the energy dependences of S-factors for the direct captures to the ground and first excited states of ^{17}F are extracted, as shown in Fig. 5, together with the data from direct measurement.[20] One can see that the present results for both the states are in good agreement with those from the direct measurement experiment within the uncertainties except the ground state S-factors at energies below 500 keV. This inconsistency mainly arises from the contaminated experimental data of the ground state at energies below 500 keV.[6,20] The direct capture S-factor for the first excited state of ^{17}F at zero energy is found to be 0.35 $\pm$ 0.05 keV b and it is in agreement with those (0.40 $\pm$ 0.04 keV b, 0.28 $\pm$ 0.03 keV b) in Refs. [6,7]. The direct capture S-factor for the ground state of ^{17}F at zero energy is derived to be 9.3 $\pm$ 1.4 keV b, which is in agreement with those (9.8 $\pm$ 1.0 keV b, 9.6 $\pm$ keV b) in Refs. [6,7].

In summary, we have reanalysed the existing angular distributions of the ^{16}O$(d,p)^{17}$O reaction leading to the ground and first excited states of ^{17}O, respectively, using the DWBA and ADWA approaches. The neutron ANCs for virtual decays of both the states of ^{17}O are then extracted. Based on charge symmetry, the proton ANCs of the ground and first excited states of ^{17}F are derived and utilized to calculate the astrophysical S-factors for ^{16}O$(p,\gamma)^{17}$F leading to the first two states of ^{17}F. The calculated results are found to be in good agreement with those from direct experiment. Therefore, the results from ANC method using neutron transfer reaction can provide an experimental constraint to astrophysical S-factors and rates of radiative capture reactions in the case that the data from direct measurement are not available. In addition, the S-factors at zero energy for the direct captures to the first two states in ^{17}F are given in the present work, without the uncertainty associated with the extrapolation from higher energies in direct measurement.

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