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Nuclear Physics A 986 (2019) 26–33

NUCLEAR PHYSICS A

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Precision measurement of the angular distribution for the ^{16}O(d, p)^{17}O transfer reaction to the ground state of ^{17}O

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Received 21 January 2019; received in revised form 10 March 2019; accepted 11 March 2019
Available online 29 March 2019

Abstract

The mechanism of the (d, p) reaction, which has been proven a powerful spectroscopic tool, is believed to be reasonably well understood. However, the ^{16}O(d, p)^{17}O reaction leading to the ground state in ^{17}O seems to be a possible exception. It was found in the previous experiments that the ^{16}O(d, p)^{17}O angular distribution exhibits a rapid decline below the peak at the angle of 15 degrees. To date this abnormal behavior has not been reproduced by theoretical models. In this work we present a re-measurement of the ^{16}O(d, p)^{17}O$_{g.s.}$ angular distribution by using a high-precision magnetic spectrograph. Our new angular distribution shows a slower decline than the previous data do. A comparative analysis with the distorted Born approximation (DWBA), the adiabatic distorted wave approximation (ADWA) and the continuum discretized coupled channels (CDCC) method suggests that the drop of the differential cross sections at the forward angles is due to the deuteron breakup coupling effects. In addition, we extracted the spectroscopic factor (SF) and the asymptotic normalization coefficient (ANC) for the ^{17}O ground state.

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https://doi.org/10.1016/j.nuclphysa.2019.03.004
0375-9474/

Keywords: Transfer reaction ^{16}O(d, p), $E_{lab} = 15$ MeV; Angular distribution; Asymptotic normalization coefficient; Spectroscopic factors; Adiabatic distorted wave approximation; Continuum discretized coupled channel

1. Introduction

Present and future radioactive ion beam facilities offer opportunities to probe the structure of unstable nuclei beyond the limits of beta stability. Spectroscopic information on unstable nuclei could unveil novel structural feature [1], and is important for astrophysical applications [2]. (d, p) reaction has proven to be a powerful tool for exploring the spectroscopic overlaps of a valence neutron added to a core. To date (d, p) reactions have been used extensively to extract the spectroscopic information of single neutron orbitals in nuclei [3–10], and it is also at the frontier of the experimental investigation of shell evolution and new magic numbers in neutron-rich regions [11–15], and of astrophysical reactions relevant to the *s*-process and the *r*-process nucleosynthesis [16,17].

Direct reactions have been studied and understood for a much longer time, starting with the pioneering experiments on deuteron-induced reactions [18] and the reaction models [19] in 1950. To date the mechanism of (d, p) reaction, required for extracting spectroscopic information, has been believed to be reasonably well understood. Many (d, p) reactions have been successfully described by the distorted wave Born approximation (DWBA) model in the framework of the direct one-step transfer [2,5,7–9]. It is also known that the deuteron breakup could have an effect on the transfer cross sections, especially at higher energies. Such effect can be effectively dealt with using the adiabatic distorted wave approximation (ADWA) method, which was developed by Johnson and Soper [20] and has been successfully used to describe the (d, p) reactions [4,6, 10]. However, the ^{16}O(d, p)^{17}O reaction seems to be a possible exception. In 1961, Keller measured the angular distribution of the ^{16}O(d, p)^{17}O reaction populating the ground state of ^{17}O with 15 MeV deuterons [21]. It was found in his work that the angular distribution peaks at the angle of 15 degrees and exhibits a rapid decline below that peak. This behavior was also found in the ^{16}O(d, p)^{17}O reaction at higher energy of 25.4 MeV [22]. The abnormal rapid decline attracted theoretical interests. In 2007, Pang et al. investigated this reaction at energy of 15 MeV by considering the DWBA and ADWA methods, as well as other higher order effects which include multiple transfer couplings within the coupled reaction channel (CRC) and multistep excitations of the target within the coupled channel Born approximation (CCBA) approaches [23]. Recently, Timofeyuk and Johnson developed a new method for the analysis of the (d, p) reactions, in which the nonlocality of the nucleon optical potential was included in a consistent way together with the deuteron breakup [24–26]. Surprisingly, all these models cannot well reproduce the rapid decline of the ^{16}O(d, p)^{17}O$_{g.s.}$ angular distribution at the forward angles. We note that there are large uncertainties of the experimental data of Keller et al. at the most forward angles [21,23]. Thus a precise measurement of the ^{16}O(d, p)^{17}O$_{g.s.}$ angular distribution is highly desirable.

In this article a new measurement of the ^{16}O(d, p)^{17}O angular distribution populating the ground state in ^{17}O was performed with the high-precision Q3D magnetic spectrograph. The DWBA, ADWA and CDCC models were used to analyze our new experimental data. The spectroscopic factor (SF) and the asymptotic normalization coefficient (ANC) for the ^{17}O ground state were then derived by normalization of the theoretical calculations to the present experimental data.

2. Experiment

The experiment was performed at the HI-13 tandem accelerator of China Institute of Atomic Energy (CIAE), Beijing. The experimental setup and procedures were similar to those previously reported [27–31]. The deuterium beam with an energy of 15 MeV was delivered and utilized to measure the angular distribution of the ^{16}O(d, p)^{17}O reaction. The $^{94}ZrO_2$ material was deposited on a self-supporting ^{12}C foil as the target. Target thickness was determined to be 57.9 μg/cm^2 (with the ^{16}O material of 14.7 μg/cm^2) by using an analytical balance with a precision of 1 μg. The beam current was measured by a Faraday cup. Three pieces of two-dimensional position sensitive silicon detectors (X1), each with a length of 50 mm, were fixed at the focal plane of the Q3D magnetic spectrograph. The solid angle was measured to be 0.34 msr by a micrometer. The detector dead regions only accounts for 3.3% of total area. The typical dead time of data acquisition is less than 0.4%. We used the Rutherford scattering cross section on the Au target to evaluate the systematic uncertainty except for the ^{16}O target thickness. Furthermore, we used the well-known differential cross sections of the d + ^{16}O elastic scattering [32,33] to evaluate the beam charge collection efficiency and the transport efficiency through the spectrometer, and the systematic uncertainty including the present ^{16}O target thickness. Overall, based on both the uncertainty of the individually determined quantities and the error of the cross sections for the d + ^{16}O elastic scattering, an uncertainty of 5.0% was assigned for the present systematic uncertainty.

The two-dimensional position information from X1 enabled the products emitted into the acceptable solid angle to be completely recorded, and the energy information was used to remove the impurities with the same magnetic rigidity. As an example, Fig. 1 displays the focal-plane position spectrum of proton at $\theta_{lab} = 18.05°$ from the ^{16}O(d, p)^{17}O reaction. The energy resolution is approximately 10 keV. The proton events corresponding to $^{17}O_{g.s.}$ are well separated from the contaminants and clearly identified. Since the proton events corresponding to the first excited state (0.87 MeV) of ^{17}O are about 300 mm away from the protons corresponding to the ground state, these events cannot be recorded together with those related to the ground state in one run. Fig. 2 shows our experimental ^{16}O(d, p)$^{17}O_{g.s.}$ angular distribution, together with the previous result in Ref. [21]. The uncertainty of the present differential cross sections below the peak at the angle of 15 degrees was reduced from the previous 22% [21] to 5.3%. In addition, our new angular distribution shows a slower decline than the previous data do.

3. Results

In the present work we used three methods of DWBA, ADWA and CDCC to analyze the experimental angular distribution. Deuteron breakup effect was not treated explicitly in DWBA. On the other hand, it is treated approximately in ADWA and more rigorously in CDCC calculations. All these calculations were made with the computer code FRESCO [34]. The DWBA calculation requires the optical potentials for the entrance channel (d + ^{16}O), exit channel (p + ^{17}O), and the core-core (p + ^{16}O) interactions. A Gaussian form of interaction $V_{np}(r) = -V_0 \exp(-r^2/r_0^2)$ was used for the n-p system with parameters $V_0 = 72.15$ MeV and $r_0 = 1.484$ fm [35]. The single particle wave function of the neutron in the ground state of ^{17}O (in the orbital $1d_{5/2}$) was obtained with a Woods-Saxon potential whose radius and diffuseness parameters r_0 and a are 1.25 fm and 0.65 fm, respectively. The depths of this potential was adjusted to give the experimental neutron separation energy of 4.143 MeV. The effective local potential for d + ^{16}O was obtained by us-

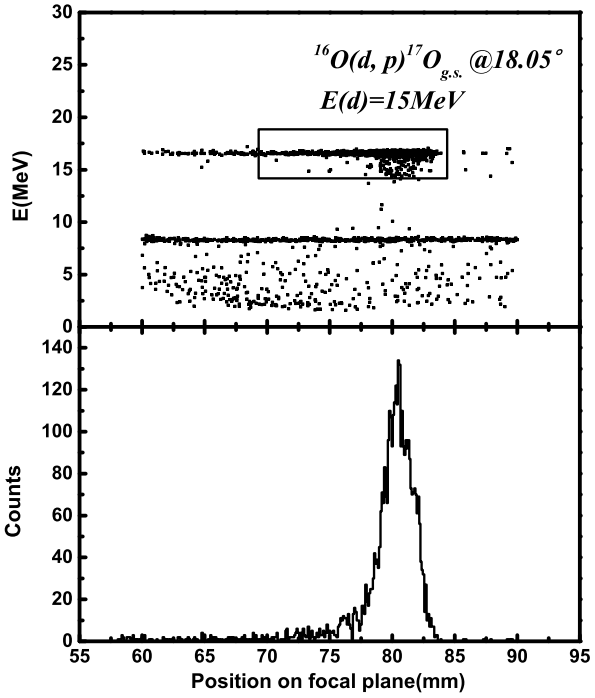

Fig. 1. Focal-plane position spectrum of proton; at $\theta_{lab} = 18.05°$ from the $^{16}O(d, p)^{17}O_{g.s.}$ reaction. (a) Two dimensional spectrum of energy vs. focal-plane position. (b) Spectrum gated by the proton events in the window of (a).

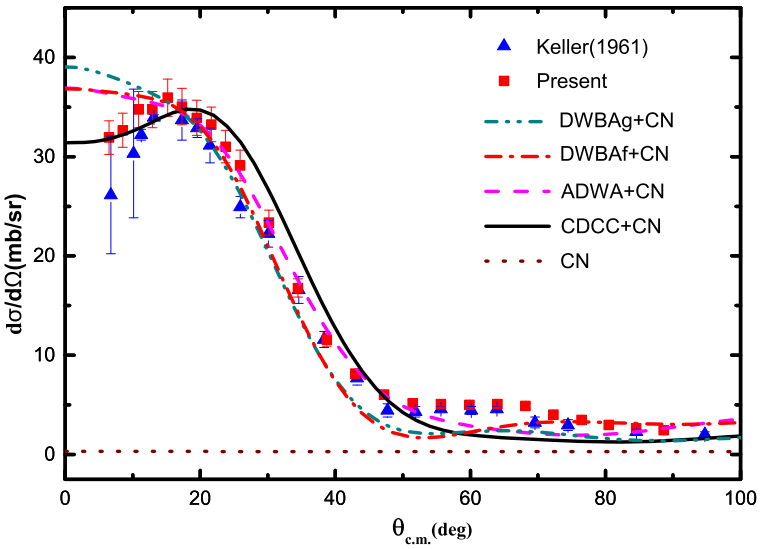

Fig. 2. Present experimental angular distribution of the $^{16}O(d, p)^{17}O_{g.s.}$ reaction, together with the previous result [21], the results calculated with DWBA, ADWA and CDCC methods and the compound-nucleus (CN) contribution. DWBAg refers to the global potential from [36]; DWBAf refers to the potential from the fitting to the corresponding elastic scattering data at 15 MeV [23].

Table 1
Optical potential parameters used in the DWBA, ADWA and CDCC calculations where V and W are in MeV, r and a in fm. We use the same potential parameters in ADWA and CDCC calculations.

Set No.	DWBAg		DWBAf		ADWA/CDCC		
Channel	Entrance	Exit	Entrance	Exit	p	n	Exit
V_r (MeV)	90.179	58.26	115.911	58.26	59.152	59.152	58.26
r_r (fm)	1.149	1.135	1.017	1.135	1.143	1.143	1.135
a_r (fm)	0.751	0.57	0.846	0.57	0.57	0.57	0.57
W_i (MeV)	2.037	0	11.257	0	0	0	0
r_i (fm)	1.345	1.135	1.073	1.135	1.143	1.143	1.135
a_i (fm)	0.603	0.5	0.584	0.5	0.5	0.5	0.5
W_s (MeV)	10.371	10.344	–	10.344	4.518	4.518	10.344
r_s (fm)	1.394	1.135	–	1.135	1.143	1.143	1.135
a_s (fm)	0.687	0.5	–	0.5	0.5	0.5	0.5
V_{so} (MeV)	3.557	5.5	11.6	5.5	5.5	5.5	5.5
r_{so} (fm)	0.972	1.135	0.578	1.135	1.143	1.143	1.135
a_{so} (fm)	1.011	0.57	0.343	0.57	0.57	0.57	0.57
r_{c0} (fm)	1.303	1.135	1.25	1.135	1.143	1.143	1.135

ing the energy-dependent global optical potential from An et al. [36], which was designated as DWBAg. We also used optical potentials fitted specially to the experimental data of the d + ^{16}O elastic scattering at 15 MeV [23], which was indicated as DWBAf. With the ADWA for a (d,p) reaction, the distorting potential governing the centre-of-mass motion of the deuteron is well described by the sum of the neutron- and proton-target optical potentials. In the present calculation, the optical potentials of nucleon target was taken from Ref. [37], which is a systematic potential specially fitted for nucleon elastic scattering from 1p-shell nuclei. The result of which is marked as ADWA. The same potentials were used in CDCC calculations. Throughout this work we always used the global parametrization by Watson et al. [37] for the outgoing distorted waves. In most recent work, Chen et al. also found that with the Watson's potential the CDCC calculations can simultaneously reproduce both the differential cross sections of elastic scattering and total reaction cross sections of the loosely-bound deuteron projectile impinging on 1p-shell nuclei [38]. All the optical potential parameters are displayed in Table 1. In the CDCC calculation, the same Gaussian interaction for neutron and proton was used. Nuclear and Coulomb breakups were included. The maximum multipole order in the expansion of the coupling potentials was $q = 4$. The continuum states were discretized in momentum space with a maximum k value of $k_{max} = 1$ fm^{-1}, with an interval of $\Delta k = 0.01$ fm^{-1}. Only s and d waves of the n-p system were included in the calculations. The p-wave components in the n-p continuum occur via a dipole excitation. For (d,p) reactions with light targets, such as ^{16}O studied in this work, the dipole effect is very small and the contribution from the p-wave components to the transfer cross sections is negligible. In addition, we evaluated the compound-nucleus (CN) contribution in the ^{16}O(d, p)^{17}O$_{g.s.}$ reaction using the UNF code [39], and then found that the CN differential cross sections are order of 0.3 mb/sr, as shown in Fig. 2. One sees that the ^{16}O(d, p)^{17}O$_{g.s.}$ angular distribution at the very forward angles can be reasonably well reproduced only by the CDCC method, suggesting that such a decrease of differential cross sections at these forward angels is caused by the coupling effects from the n-p continuum states.

In order to verify if the ^{16}O(d, p)^{17}O$_{g.s.}$ reaction at present energy is dominated by the peripheral process, the spectroscopic factors and the ANC for different geometric parameters of

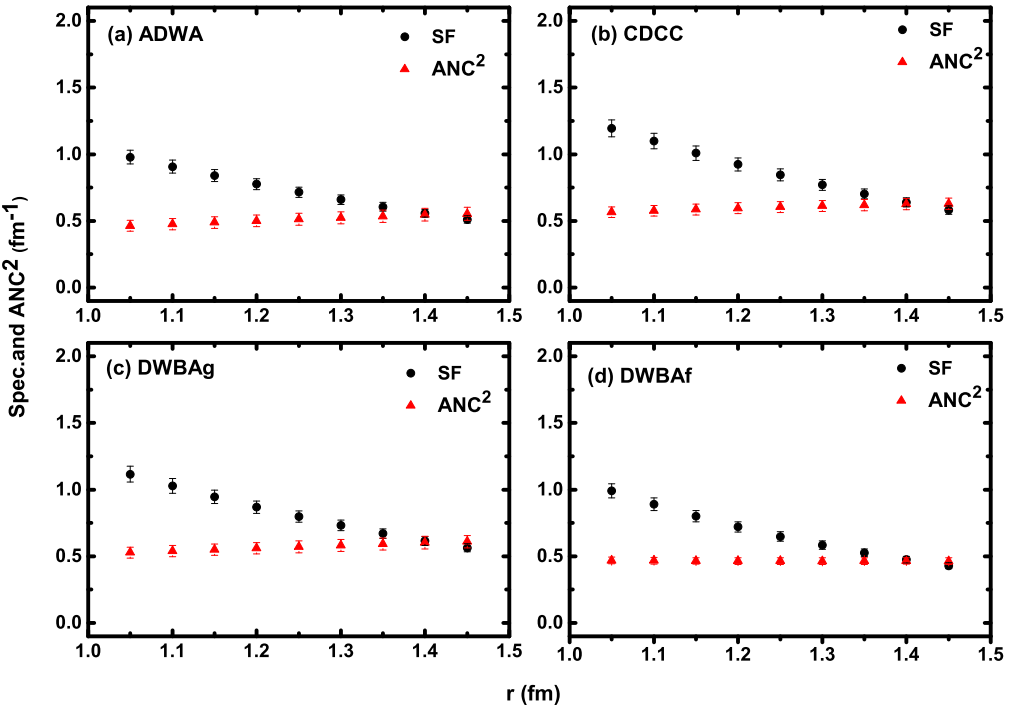

Fig. 3. Dependence of the spectroscopic factor (SF) and the square of ANC (ANC^2) on the geometric parameter of Woods-Saxon potential (radius).

Woods-Saxon potential that binds the valence neutron to the ^{16}O core were calculated using four sets of potential parameters mentioned above. The results are shown in Fig. 3. One can see that in the four calculations the spectroscopic factors vary ±34% of the average value, while the ANCs vary from ±3.1% to ±8.4% (see Table 3), indicating that this process is peripheral.

Since the CDCC method well reproduces the ^{16}O(d, p)$^{17}O_{g.s.}$ angular distribution, we chose to extract the spectroscopic factors and the ANCs by normalization of the CDCC calculation to the experimental data after substracting the CN component. The spectroscopic factor was calculated using the standard geometrical parameters r = 1.25 fm and a = 0.65 fm, which have been extensively utilized to study the ground state neutron spectroscopic factors for 80 nuclei of Z = 3-24 [4] and 565 excited state neutron spectroscopic factors for Z = 8-28 nuclei [6]. The present spectroscopic factors and ANCs are summarized in Table 2, together with the results from the previous experiments [4,23] and the shell model calculations [4,40]. The uncertainty of the spectroscopic factor mainly comes from the statistics (1.8%) and the systematic error (5.0%). The error of the ANC mainly comes from the uncertainty of the spectroscopic factors and the geometrical parameters. All the detailed uncertainties are summarized in Table 3. We then determined the neutron spectroscopic factor and ANC for the ^{16}O(d, p)$^{17}O_{g.s.}$ reaction to be 0.84 ± 0.04 and 0.60 ± 0.04 fm^{-1} respectively. The new SF is in good agreement with the one from the previous analysis of the (d,p) data ($SF = 0.94 \pm 0.13$) [4] and the ones from shell model calculations [4,40]. The new ANC is reasonably consistent with the one (0.67 ± 0.05 fm^{-1}) from a reanalysis [23] of the previous heavy ion transfer data [41,42].

Table 2
Neutron SF and ANC for the ground state in ^{17}O.

	DWBAf	DWBAg	ADWA	CDCC
SF	0.65 ± 0.03	0.80 ± 0.04	0.72 ± 0.04	0.84 ± 0.04
ANC^2 (fm^{-1})	0.47 ± 0.02	0.57 ± 0.04	0.51 ± 0.04	0.60 ± 0.04
			Shell model calculation	
	Heavy ion transfer [23]	(d, p) [4]	[4]	[40]
SF		0.94 ± 0.13	1	0.95
ANC^2 (fm^{-1})	0.67 ± 0.05			

Table 3
Source of the uncertainties in the SF and ANC^2 of the ^{17}O ground states in the DWBA, ADWA and CDCC calculations.

Uncertainty source	DWBAf		DWBAg		ADWA		CDCC	
	SF	ANC^2	SF	ANC^2	SF	ANC^2	SF	ANC^2
Systematic	5%	5%	5%	5%	5%	5%	5%	5%
Statistics	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%
Geometrical parameters		3.1%		6.0%		8.4%		5.6%
Total	5.3%	6.2%	5.3%	8.0%	5.3%	9.9%	5.3%	7.7%

4. Summary and discussion

In this work we present a precision measurement of the angular distribution for the ^{16}O(d, p)^{17}O reaction populating the ground state in ^{17}O by using a high-precision magnetic spectrograph. The uncertainty of the present differential cross sections below the peak at the angle of 15 degrees was reduced from the previous 22% [21] to 5.3%. Our new angular distribution exhibits a slower decline below the peak than the previous one does. Furthermore, we carried out the DWBA, ADWA and CDCC calculations, and then found the CDCC method better reproduces the present angular distribution at most forward angles where the data are important for extracting spectroscopic information, suggesting that such a decrease of differential cross sections at these forward angels is caused by the coupling effects from the n-p continuum states. This work shed some light on the existing discrepancies in the angular distribution between the theories and the previous experiment.

It should be noted that all the DWBA, ADWA and CDCC calculations did not well reproduce the second maximum which locates between 50 to 70 degrees in the experimental angular distribution. Therefore, we evaluated the compound-nucleus (CN) contribution in the ^{16}O(d, p)^{17}O$_{g.s.}$ reaction. However, the CN differential cross sections were found to be only at order of 0.3 mb/sr. Although the results can describe the experimental data a bit better than that without CN contribution, it seems that this did not give a perfect description of the second maximum yet. It is highly desirable to understand it in the near future.

Acknowledgements

The authors thank the staff of the HI-13 tandem accelerator for the smooth operation of the machine. This work was supported by the National Key Research and Development Project under Grant No. 2016YFA0400502, the National Natural Science Foundation of China under Grants

No. 11490561, No. 11475264, No. 11475265, and No. 11575292, and the 973 program of China under Grant No. 2013CB834406.

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