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The ^{16}O(d,p)^{17}O reaction to the unbound 5.09-MeV state of ^{17}O

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New measurements of the ^{16}O(d,p) reaction cross sections to the ground-, 0.87-, and 5.09-MeV states in ^{17}O have been performed for eleven angles from 17.5° to 150° at a bombarding energy of 12 MeV. The results are compared with earlier measurements at the same energy. The new measurements are shown to resolve a discrepancy observed for the comparison of the neutron strength of the unbound 5.09-MeV state extracted from earlier (d,p) studies with that from neutron scattering experiments. These results indicate that the method of Vincent and Fortune for distorted-wave analysis of stripping to unbound states yields a reliable value for the neutron width for this important test case. Measurements of ^{16}O(d,d) elastic scattering cross sections performed simultaneously are reported.

[NUCLEAR REACTIONS ^{16}O(d,d) elastic scattering and ^{16}O(d,p)^{17}O (0.0, 0.87, 5.09 MeV), E=12 MeV; measured $\sigma(\theta)$; θ=17.5°–150°, eleven angles; deduced neutron width from the (d,p) reaction to 5.09-MeV state.]

I. INTRODUCTION

The 5.09-MeV $\frac{3}{2}^+$ state of ^{17}O has been used[1-4] as a "test case" for methods of analyzing data on stripping reactions leading to unbound final states. It is considered[5] to be a good single-particle state so that the spectroscopic factor obtained from a direct-reaction model analysis is expected to be near unity. Stripping reactions to unbound states have the advantage that the nucleon width, rather than the spectroscopic factor, is measured by the absolute magnitude of the cross section. This extracted width can be compared with experimental measurements of the elastic-scattering width when available. The neutron width of the 5.09-MeV state has been accurately measured to be $\Gamma_n = 96 \pm 5$ keV.[6] Fortune and Vincent[3,4] have used a contour-integration technique[3] within the framework of the distorted-wave Born approximation (DWBA) to extract a neutron width from the ^{16}O(d,p) reaction cross section measurements of Alty *et al.*[2] at a deuteron energy of 12 MeV. Their analysis[4] yields a neutron width of 65 keV, which is 30% smaller than the neutron width measured by neutron scattering. Fortune and Vincent[4] show that the neutron width extracted from the (d,p) analysis implies a spectroscopic factor of about 0.7. Since the DWBA contour-integration technique has provided[7-10] good agreement between nucleon widths obtained from analyses of stripping data and those obtained from resonant-scattering data for a number of other cases, this difference for the 5.09-MeV state of ^{17}O has been difficult to understand. The discrepancy for the 5.09-MeV state of ^{17}O has been supported by the separate measurements of the ^{16}O(d,p) reaction cross sections by Cooper *et al.*[11] at deuteron energies of 25.4, 36.0, and 63.2 MeV. They extracted neutron widths with the contour-integration technique of Vincent and Fortune which were consistently about 20% smaller than the neutron width from the neutron-scattering measurements, apparently in essential agreement with the analysis of Fortune and Vincent of the (d,p) data at 12 MeV.

Because the ^{16}O(d,p) cross section measurements of Alty *et al.* were renormalized by a factor of 1.75 for a target thickness correction in a separate paper by Naqib and Green,[12] and because Alty *et al.*[2] did not indicate in adequate detail how the cross section of the unbound 5.09-MeV state was extracted, there has existed some uncertainty regarding the accuracy of the 12-MeV data adopted by Fortune and Vincent for their analysis. Since this case should provide a good test of the DWBA calculations to unbound states, we decided to remeasure the ^{16}O(d,p) reaction cross section to the 5.09-MeV state of ^{17}O at a deuteron energy of 12 MeV in order to provide reliable data for the theoretical analysis. In contrast to the earlier measurements by Alty *et al.*, these measurements were performed specifically to study the transition to the 5.09-MeV state. In addition to providing new experimental data, it was recognized that our study would also provide an opportunity to reexamine the analysis procedure for extracting the cross section of the 5.09-MeV unbound state.

Because there exist other known states in ^{17}O that are difficult to resolve from the 5.09-MeV state, and because it is necessary to properly account for the Breit-Wigner line shape of unbound states, it is important that the extraction of the peak area for the 5.09-MeV state be performed carefully, using as many fixed parameters for known states from the literature as possible. Our new measurements and analysis of the data are described below. Data for the ^{12}C$(d,p)^{13}$C* reaction to unbound states were also taken but will not be analyzed until a theoretical calculation for this case is available.

II. EXPERIMENTAL PROCEDURE

The experimental apparatus used has been described in detail by Jarmie *et al.*[13] and Detch.[14] A deuteron beam from the Los Alamos tandem Van de Graaff accelerator passed through an oxygen gas target with thin (0.1 mil) Havar foil windows placed at the center of a 30 in. scattering chamber. The scattered deuterons and protons were detected by a single E-ΔE detector telescope using solid-state counters. Amplified pulses gated by the E-ΔE coincidence were digitized and sent to an SDS-930 on-line computer for mass analysis and storage. The resulting proton and deuteron spectra were analyzed later for yields.

The energy of the incident beam is 12.00 MeV known to ±15 keV with a full width at half-maximum spread of 10 keV. The beam was collected in a tantalum-backed, water cooled Faraday cup placed behind the target. The Faraday cup was carefully designed to collect all of the beam, eliminate δ rays from the target, and contain all secondary electrons from the beam dump. The purity of the oxygen gas was determined from a careful analysis of the deuteron elastic-scattering spectrum and from a mass spectrographic analysis. The purity of the oxygen gas was determined to be $98.35 \pm 0.71\%$, with the major contaminants being carbon (1.3%), nitrogen (0.1%), and argon (0.25%). The temperature of the gas target was measured with a chromel-alumel thermocouple attached to the brass target assembly. The pressure of the gas target was measured with a diaphragm capacitance-bridge-type pressure transducer. The voltage output from this transducer was measured with digital voltmeters. As a cross check, a mechanical diaphragm-type pressure gauge was included in the gas manifold system. Temperature and pressure readings were taken at the beginning and end of each run (which were typically 40 minutes long), and the average readings were obtained for analysis.

A particle telescope comprised of two silicon surface-barrier detectors of approximate thicknesses of 75 and 2000 μm and areas of 100 and 150 mm^2, respectively, provided energy measurement and mass identification of the scattered protons and deuterons. The full width at half maximum (FWHM) of the scattering angles accepted by the detectors was defined by a collimator comprised of a pair of nickel slits. The collimator-detector assembly was positioned in a precisely machined radial slot in the rotating turntable, which served as the floor of the scattering chamber. The scattering angle had a width defined mostly by the collimating system of 1.1° FWHM. This width included contributions from foil multiple scattering, 0.9° acceptance of the detector slits, and incident beam divergence. Measurements were performed at both left and right angles for each angle reported. The angular accuracy was ±0.03°. The silicon surface-barrier detectors were cooled by a simple Peltier refrigerator and provided an intrinsic energy resolution of about 45 keV. The overall energy resolution was observed to be about 65 keV and included the energy spread of the beam (~10 keV), beam straggling in the target gas and foils (~35 keV), and intrinsic resolution of the detectors.

Detector pulses were input to charge-sensitive preamplifiers. The preamplifier signals then went into linear amplifiers which provided dual outputs, one for energy information and the other for coincidence circuits. The E and ΔE signals were summed, digitized by analog-to-digital converters (ADC), and interfaced to the SDS-930 computer. The ADC's were gated open when the signals from both detectors in the telescope were in coincidence. Crossover timing was used in the coincidence circuit which had a resolving time of 1 μsec.

III. DATA REDUCTION

The spectra for each run were analyzed for the number of counts in the ground, 0.87- and 5.09-MeV states of ^{17}O, and in the deuteron elastic-scattering peak. The number of counts for the ground and 0.87-MeV states of ^{17}O and for the deuteron elastic-scattering peak was obtained by summing across the peak and subtracting a linear background. The ratio of the peak to background was usually larger than 100 to 1 and the uncertainty in the background was approximately 0.1% of the peak total.

In order to obtain the number of counts for the 5.09-MeV unbound state, it was found to be necessary to fit six or seven peaks simultaneously in the excitation region around the 5.09-MeV state.

The fitting was performed with an improved version of the computer program GRASP[15] modified to use Breit-Wigner line shapes plus an arbitrary resolution function. The use of Breit-Wigner line shapes is absolutely essential to accurately describe nuclear resonances, and the resolution function was taken to be the shape of the bound ^{17}O ground-state peak. A quadratic or cubic polynomial background was also fitted simultaneously by the computer program. The method of fitting the region of interest in the proton energy spectrum was found to be of great importance. All peaks fitted corresponded to nuclear states of ^{17}O as reported in the compilation of Ajzenberg-Selove,[5] and the width of the Breit-Wigner peak for each state was taken from that compilation and held fixed.

In our first attempts to extract the number of counts under the 5.09-MeV state, we followed the example of Cooper *et al.*[11] and tried to fit only the 5.09-, 5.22-, and 5.38-MeV states simultaneously. We eventually concluded that fitting only these three peaks caused the background to be made too large and the contribution of the large Breit-Wigner tails to be significantly underestimated. In fact, since the background between the low-lying bound states was observed to be very small, it was realized that most of the "background" under the 5.09-, 5.22-, and 5.38-MeV states complex is actually the overlapping tails of all of the nearby unbound states. The method adopted by Cooper *et al.* seems to us to be inaccurate because of this "background" question. They extract the number of counts for the 5.09-MeV state by first fitting a background from below the 5.09-MeV state to above the 5.38-MeV state and then fitting the three peaks after the fitted background had been subtracted. This procedure does not allow for some of the observed "background" below the 5.09-MeV state or above the 5.38-MeV state to be due to the tail contributions of the 5.09-MeV state. This error would be largest at the most forward angles where the 5.09-MeV state dominates this region of the proton energy spectrum, and we estimate it could cause the extracted number of counts to be 10–20% too small. Since the theoretical calculations are normalized to the forward-angle results to obtain the neutron width, this error could explain the observed discrepancy of the results of Cooper *et al.* with the neutron width obtained from neutron-scattering experiments.

In order to properly account for the contributions of the Breit-Wigner tails of nearby peaks to the background under the 5.09-MeV peak, we decided to fit six peaks simultaneously at forward angles and seven peaks simultaneously at backward angles. Furthermore, the polynomial background was fitted simultaneously with the Breit-Wigner peaks and not separately as a first step. Note that even this procedure is somewhat of an approximation, since, for example, the Breit-

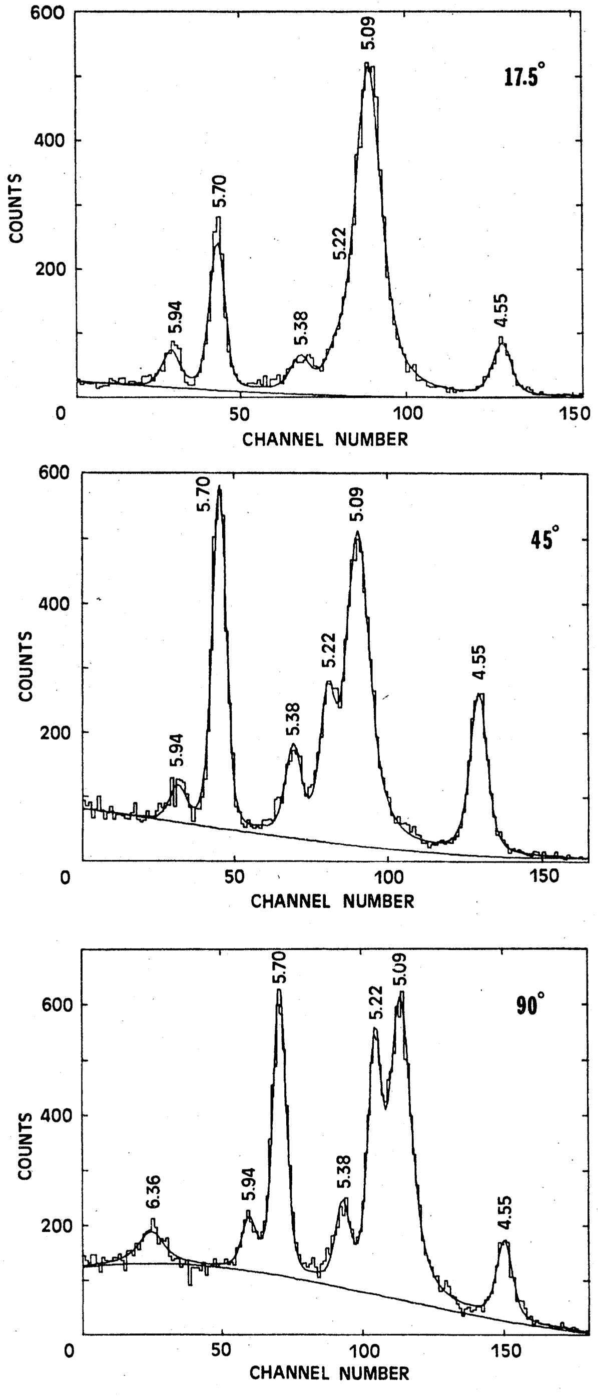

FIG. 1. Computer fits to the proton spectra in the region of the 5.09-MeV state of ^{17}O at (a) 17.5°, (b) 45°, and (c) 90°. The fitted backgrounds are also shown.

Wigner tails of the $\frac{3}{2}^-$ states at 4.55 and 5.38 MeV could interfere with each other. Our spectra and fitted curves at 17.5°, 45°, and 90° are presented in Fig. 1. The peaks fitted (with their fixed widths in keV) were the 4.55 (40)-, 5.09 (95)-, 5.22 (0)-, 5.38 (28)-, 5.70 (3.4)-, and 5.94 (32)-MeV states and at backward angles only the 6.36 (124)-MeV state. The narrow peaks reported to be at 5.73 and 5.87 MeV were unresolved from the wider peaks at 5.70 and 5.94 MeV, respectively. The fitted backgrounds are shown in Fig. 1 and are seen to always be below the level of the data below the 5.09-MeV state and above the 5.38-MeV state. The fitted background is especially small at the most forward angles and now represents actual experimental background and the remaining effect of tails from unbound states even farther away from the region of the 5.09-MeV state. The locations of all the fitted peaks were checked to be sure that they were located to within 1 channel of the correct kinematic location. At 17.5° and 30° the narrow peak at 5.22 MeV appears as a shoulder on the 5.09-MeV peak and is not clearly resolved. Since the width and location of this peak are known, the fitting seems to be unambiguous. The number of counts under the 5.22-MeV peak was determined to be only 2 and 4% of the number of counts under the 5.09-MeV at 17.5° and 30°, respectively, and the extracted angular distribution for the small peak shows no peculiar behavior for the forward angles. The uncertainty in the number of counts under the 5.09-MeV peak due to any difficulty in knowing the number of counts for the 5.22-MeV state is believed to be less than ±2%. The overall uncertainty in extracting the number of counts for the 5.09-MeV state by the fitting procedure is estimated to be ±5% and is limited by the remaining uncertainty in determining the background.

The target gas density was computed from the pressure and temperature measurements made for each run and corrected for the impurities in the gas. The number of scattering centers per cubic centimeter was known to ±0.25%. The solid angle or "*G* factor" for the detector system was determined by measuring the slit dimensions and using the formula of Silverstein.[16] The uncertainty was ±0.2%, and only the lowest-order term of the Silverstein relation was needed as the higher-order corrections have been calculated[14] to be negligible. The beam current in the Faraday cup was measured with a current integrator calibrated with a precision current source so that the beam current was known to ±0.2%, including the effects of multiple scattering, δ rays, and secondary electrons.

Cross sections were calculated for each run, and then the corresponding left- and right-angle runs were averaged. This reduced the uncertainty in the knowledge of the zero angle, since the included angles were known to ±0.03°. A summary of the uncertainties is contained in Table I. They have been separated according to whether they contribute to the relative or scale uncertainty. The total uncertainty may be found by combining the relative and scale uncertainties in quadrature. The 5% for the fitting of the 5.09-MeV state is listed as the background uncertainty for that state.

IV. RESULTS

The cross sections and uncertainties are listed in Table II for the ^{16}O(d, d) elastic-scattering reaction and for the ^{16}O(d,p) reaction to the ground, 0.87-, and 5.09-MeV states of ^{17}O at a bombarding energy of 12.00 MeV. Listed are the lab angle (known to ±0.03°), the lab cross section in mb/sr, and the c.m. angle and cross section along with the relative uncertainty given in percent. For all the reactions except the (d,p) reaction to the 5.09-MeV state of ^{17}O, the primary

TABLE I. Uncertainties.

Scale		Relative	
Source	% uncertainty	Source	% uncertainty
Pressure	0.1	Yield	$1/\sqrt{N}$
Temperature	0.1	Background	
Purity	0.71	0.0- and 0.87-MeV states	~0.2
G factor	0.2	5.09-MeV state	~5.0
N_{beam}	0.2	Dead time	<0.04
Total scale	0.78		

contribution to the relative uncertainties is the counting statistics. The other sources of relative uncertainties contribute less than 0.2% in quadrature. For the 5.09-MeV state, the relative uncertainty is the reduced chi square of the fit times the statistics for that datum, combined in quadrature with a 5% uncertainty for the peak fitting procedure. The beam energy was known to ±15 keV with a spread of 10 keV FWHM.

The cross sections for the $^{16}O(d,p)^{17}O$ (5.09-MeV) reaction are compared to the earlier measurements of Alty *et al.*[2] in Fig. 2. Our new results show good agreement with the earlier measurements at the middle angles but have significantly larger cross sections for the forward angles and somewhat smaller cross sections at the very backward angles. Similar comparisons for the ground and 0.87-MeV state reactions show the same disagreement at very backward angles and that our measurements are slightly higher at the very forward angles, but not as much higher as for the 5.09-MeV state reaction. Our measurements of the ground- and 0.87-MeV state reaction cross sections are 15% (±5%) higher than those of Alty *et al.* (with the renormalization

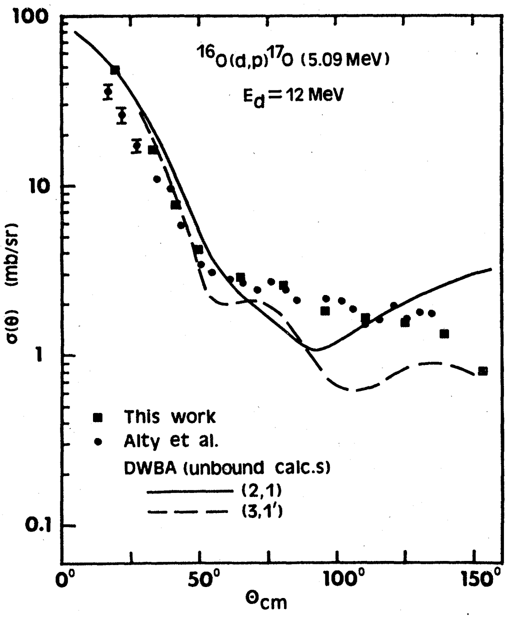

FIG. 2. The new measurements of the $^{16}O(d,p)$ reaction to the 5.09-MeV state of ^{17}O at 12 MeV compared with the earlier measurements of Alty *et al.* (Ref. 2) and DWBA calculations for this unbound state by Fortune and Vincent (Ref. 4). The numbers inside the parentheses refer to different optical-model parameter sets for the incident deuteron and outgoing proton wave functions and are labeled identically to the calculations in Fig. 1 of Ref. 4.

TABLE II. $^{16}O(d,d)$ and $^{16}O(d,p)$ differential cross sections at E_d = 12.00 MeV.

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	$\theta_{\text{c.m.}}$ (deg)	$\sigma(\theta)_{\text{c.m.}}$ (mb/sr)	Relative uncertainty (%)
$^{16}O(d,d)^{16}O$ elastic scattering				
17.50	1478	19.68	1178	0.5
30.00	66.93	33.63	64.44	0.7
37.50	19.58	41.92	16.21	0.6
45.00	49.85	50.14	42.14	0.3
60.00	21.96	66.29	19.53	0.3
75.00	1.991	82.02	1.880	1.0
90.00	2.386	97.27	2.406	0.8
105.00	3.327	112.02	3.585	0.6
120.00	4.220	126.29	4.842	0.7
135.00	3.575	140.13	4.333	0.7
150.00	3.511	153.63	4.439	0.6
$^{16}O(d,p)\,^{17}O^*$ (0.0 MeV)				
17.50	36.62	18.89	31.60	1.0
30.00	28.30	32.31	24.75	0.7
37.50	15.55	40.30	13.76	0.6
45.00	8.896	48.26	7.976	0.7
60.00	5.909	63.99	5.474	0.6
75.00	3.873	79.45	3.728	0.7
90.00	2.212	94.61	2.219	0.8
105.00	2.509	109.45	2.625	0.8
120.00	2.909	123.99	3.166	0.8
135.00	2.767	138.26	3.116	0.8
150.00	2.556	152.30	2.955	0.7
$^{16}O(d,p)\,^{17}O^*$ (0.87 MeV)				
17.50	22.20	18.93	19.06	1.3
30.00	11.14	32.39	9.698	1.2
37.50	11.22	40.40	9.885	0.7
45.00	6.090	48.38	5.440	0.8
60.00	1.130	64.14	1.044	1.3
75.00	3.282	79.61	3.155	0.8
90.00	2.104	94.78	2.112	0.8
105.00	0.622	109.61	0.652	1.6
120.00	0.546	124.13	0.596	1.9
135.00	0.702	138.37	0.794	1.5
150.00	0.814	152.38	0.947	1.2
$^{16}O(d,p)\,^{17}O^*$ (5.09 MeV)				
17.50	56.66	19.28	46.93	5.1
30.00	19.34	32.97	16.30	5.1
37.50	9.000	41.12	7.697	5.1
45.00	4.844	49.21	4.214	5.1
60.00	3.126	65.16	2.836	5.1
75.00	2.648	80.75	2.524	5.1
90.00	1.780	95.95	1.789	5.1
105.00	1.522	110.75	1.616	5.2
120.00	1.374	125.15	1.536	5.3
135.00	1.122	139.20	1.310	5.3
150.00	0.665	152.97	0.804	5.5

of Naqib and Green[12]) at our most forward angle of 17.5° (lab). Our measurement of the 5.09-MeV state reaction cross section at 17.5° (lab) is 50% (±5%) higher than the measurements reported by Alty *et al.* (by linear interpolation between their two most forward-angle points). Our measurement of the $^{16}O(d, d)$ elastic-scattering cross section at $\theta_{lab} = 45°$ agrees to within 2.1% of the earlier published result of Jarmie[17] of 48.80 (±2.4%) mb/sr (lab). Since our experimental apparatus has been used to measure various accurate charged-particle cross sections over this angular range in previous experiments[13,17,18] for which there has been no indication of difficulty at angles larger than about 12° (lab), we believe that the stated uncertainties for these new measurements are reasonable and that the possibility of a systematic error is small.

V. DISCUSSION

The deduced neutron width changes linearly with the cross section values at the most forward angles. Since our cross sections for the 5.09-MeV state are 50% larger at 17.5° (lab) than those of Alty *et al.*,[2] the result of the analysis by Fortune and Vincent[4] can simply be scaled to yield a neutron width for the 5.09-MeV state of 1.5×65 keV = 97 keV. Since our cross sections are accurate to about ±5%, the uncertainty in the extracted neutron width is now dominated by the uncertainty of the DWBA analysis. This new result is now in excellent agreement with the neutron width of this state as measured by neutron scattering to be 96 ± 5 keV.[6] Note that this new determination of the neutron width from our (d,p) measurements is simply a renormalization of the theoretical analysis of Fortune and Vincent[4] based on the ratio of our new measurements to the earlier measurements of Alty *et al.* [near 20° (c.m.)]. If we adopt also the relationship between the extracted neutron width and the spectroscopic factor used by Fortune and Vincent, our new measurements imply a spectroscopic factor of $1.5 \times 0.7 = 1.05$.

The DWBA calculations of Fortune and Vincent (from Ref. 4) for this unbound state using the contour-integration technique are shown in Fig. 2 multiplied by the factor 1.5. The two theoretical calculations agree at very forward angles, and the calculation with optical-model parameter sets labled (3, 1′) agrees well with our new measurements out to about 50° (c.m.). The poorer fits at backward angles are normal, especially for reactions in light nuclei.

The improved agreement between the neutron width of the 5.09-MeV state of ^{17}O obtained from these new measurements of the $^{16}O(d,p)$ reaction and the neutron width obtained from neutron scattering is due to the larger cross sections we measure at 17.5° and 30°. Part of the increase in the cross section appears to be due to a systematic difference in forward-angle cross sections measured by us compared to the earlier measurements of Alty *et al.* However, most of the increase is due to our improved procedure for including the strength of the tails of the Breit-Wigner line shapes for unbound states while extracting the number of counts for the 5.09-MeV state from the experimental spectra. These new results remove the discrepancy seen in the comparison of the neutron width extracted from the (d,p) data of Alty *et al.*[2] by Fortune and Vincent[3,4] to that extracted from neutron scattering by Johnson.[6] Because Cooper *et al.*[11] did not properly allow for part of the observed background under the 5.09-MeV state complex to be due to the tails of Breit-Wigner line shape for that peak, we estimate that their earlier cross sections are 10 to 20% too small for this transition, so that the discrepancy they report would also be largely removed. We conclude that there no longer appears to be any substantial disagreement between the neutron width for the 5.09-MeV state extracted from $^{16}O(d,p)$ data with a DWBA analysis using the contour integration technique of Vincent and Fortune and the neutron width available from neutron scattering measurements.

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