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Publication Date

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THE STRUCTURE OF ^{16}O AND THE $^{17}\text{O}(\text{p},\text{d})^{16}\text{O}$ REACTION*

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July 1969

The reaction $^{17}\text{O}(\text{p},\text{d})^{16}\text{O}$ at $E_p = 31$ MeV has been used to test recent "exact" shell-model calculations which considered active particles in the $1p_{1/2}$, $2s_{1/2}$, and $1d_{5/2}$ orbitals. Little $1p_{3/2}$ strength appeared below 18 MeV excitation in agreement with the model, but the 4^+ level at 10.36 MeV was produced with <5% of its predicted intensity. This is the first significant failure of these calculations. It is attributed to matrix-element values rather than the neglect of additional orbitals.

- - -

Recent shell model calculations¹ have enjoyed considerable success in describing experimental properties of the oxygen isotopes ^{15}O , ^{16}O , and ^{17}O . Unlike previous structure calculations (for example, Refs. 2-5), both "collective" and "spherical" states were described in a unified, microscopic picture. Using a spherical basis of $1d_{5/2}$, $1p_{1/2}$, and $2s_{1/2}$ orbitals, wave functions were calculated which reproduced the energy level schemes¹, gave satisfactory values for electromagnetic transition rates⁶ and gave agreement with experimental single-nucleon stripping amplitudes.^{7,8,9} Qualitatively similar wave functions were obtained using matrix elements previously derived from both nucleon-nucleon scattering (using G-matrix methods), and from least-squares fitting of experimental energy levels. Thus the model seems to show great promise for giving an extended many-body description of nuclear structure.

In this letter we present a test of these wave functions using the pick-up reaction $^{17}\text{O}(\text{p},\text{d})^{16}\text{O}$. This reaction provides information which is, in a sense, complimentary to that obtained^{7,8,9} from the single nucleon stripping reactions $^{15}\text{N}(^3\text{He},\text{d})^{16}\text{O}$ and $^{15}\text{N}(\text{d},\text{n})^{16}\text{O}$. In these stripping reactions, $\text{lp}_{1/2}$ proton transfer allows population of only 0^+ and 1^+ states while $2\text{s}_{1/2}$ and $\text{ld}_{5/2}$ transfer populates 0^- , 1^- , 2^- , and 3^- states. By contrast, the $^{17}\text{O}(\text{p},\text{d})^{16}\text{O}$ reaction can populate all even-parity states from 0^+ to 5^+ through $\text{ld}_{5/2}$ pick-up, while $\text{lp}_{1/2}$ pick-up allows only population of 2^- and 3^- states.

Even parity levels with $J > 0$ were predicted to be populated through the overlaps of strong $3\text{p}-2\text{h}$ (3 particle-2 hole) and weaker $5\text{p}-4\text{h}$ admixtures in the ^{17}O ground state with mixed $2\text{p}-2\text{h}$ and $4\text{p}-4\text{h}$ components in the "rotational" states in ^{16}O . For $J^\pi = 0^+$, population was predicted to be through "spherical" ($0\text{p}-0\text{h}$) admixtures in addition to the above. Unlike the 2^- and 3^- states which are expected to be produced primarily from the large $[(\text{lp}_{1/2})^4(\text{ld}_{5/2})]$ component in the ^{17}O ground state wave function, the 1^- and 4^- states can only be populated through $\text{p}_{3/2}$ admixtures. Thus the population of 1^- and 4^- states provides a measure of the $\text{lp}_{3/2}$ pick-up strength. This strength should be zero if the approximation of an inert $\text{lp}_{3/2}$ shell which was used in the shell-model calculation is correct. An examination of total $\ell = 1$ strength serves as an additional test since this value would be increased by considering pick-up from $\text{lp}_{3/2}$ orbitals.

A 31 MeV proton beam from the Berkeley 88-inch cyclotron was used to bombard oxygen gas contained at 20 cm pressure in a 6.4 cm diameter cell. The target was enriched in ^{17}O to give an isotopic composition of 72.85% ^{17}O , 9.55% ^{16}O , and 17.60% ^{18}O . Contaminant peaks were identified by also studying the reaction $^{18}\text{O}(\text{p},\text{d})^{17}\text{O}$; for this purpose a 98% enriched ^{18}O gas target was

used. Particles were detected using two (dE/dX) -E counter telescopes which fed Goulding-Landis identifiers. The (dE/dX) detectors consisted of 250 μ phosphorus-diffused silicon counters, while the E detectors were 3 mm lithium-drifted silicon. The accuracy with which absolute cross-sections could be measured was checked by observing proton scattering from hydrogen at $\theta_{cm} = 90^\circ$ and comparing yields with accurately known cross-sections.¹⁰ The agreement obtained was within 10%. A detailed discussion of the experimental equipment has been presented elsewhere.¹¹

Figure 1 shows a typical (p,d) spectrum. The resolution (FWHM) was 100 keV. Prominent features of the spectrum are the strong population of the ground and $(T = 0 \text{ and } T = 1) J = 2^-, 3^-$ states. The (6.05-6.13) MeV doublet was determined at all angles to be dominated (i.e., >70%) by the 6.13 MeV state; this followed from consideration of the centroid positions and peak widths. The 6.92 MeV state could not be resolved from a contaminant peak arising from population of the 3.08 MeV state in ^{17}O . Subtraction of the contaminant, using $^{18}\text{O}(p,d)^{17}\text{O}$ data, showed only that the 6.92 MeV state could be no stronger than the 7.12 MeV state. An unambiguous measure of the yields of the very weak 9.85 MeV state could not be obtained at forward angles because of possible interference from tritons that fell within the deuteron window; hence, only an upper limit could be set on its cross-section. The peak attributed to the doublet at (12.44-12.53) MeV appeared to be dominated by the 12.53 MeV state. No evidence of significant population of the 2^+ , $T = 0$, 13.01 MeV or 1^- , $T = 1$, 13.08 MeV states was seen. Possible population of the 3^- , $T = 0$ state at 13.12 ± 0.010 MeV ($\Gamma = 128$ keV) was observed through the broadening of the high energy side of the 13.26 MeV state. Using the previously measured properties of the state,¹² an upper limit was placed on its cross-section. An unresolved

group labeled 15.42 MeV in Fig. 1, presumably contained the 2^- , 15.22 MeV state, the 2^+ , 15.26 MeV state and the (3^-) , 15.42 MeV state. At forward angles the broad 15.26 MeV state ($\Gamma = 720$ keV) was weak and the 15.42 and 15.22 states were clearly resolved allowing accurate determination of their yields.

The (p,d) angular distributions were fitted with the distorted wave Born approximation (DWBA) code DWUCK¹³ using finite range correction and no cutoff on the radial integration.¹⁴ Proton optical model parameters¹⁵ from scattering of 30.3 MeV protons by ^{16}O were used as none were available for ^{17}O . The shape of the predicted angular distributions was found to be sensitive to the deuteron parameters so that parameter sets from several sources were used to obtain fits. A set of parameters (Set I) which varied smoothly with energy was used initially (dash-dot-dot line in Fig. 2).¹⁶ These parameters gave rather poor fits to the data and it was found that improvements could be realized only by using deeper surface-imaginary well depths. Parameters obtained at 34.4 MeV¹⁷ (solid line in Fig. 2) with the imaginary well depth arbitrarily increased by a factor of two to $W_D = 18$ MeV (Set II) and 15.8 MeV parameters¹⁸ with $W_D = 15$ MeV (Set III) (dashed line in Fig. 2) both gave improved fits. Similar behavior has been encountered previously in fitting (p,d) reactions with DWBA in light nuclei and is discussed elsewhere.^{19,20} In any case, the peak cross-sections obtained with all sets of deuteron parameters did not vary by more than 30% for $\ell = 1$ transitions nor by more than a factor of two for $\ell = 2$ transitions; so that it is believed that spectroscopic factors assigned from peak cross-sections are reliable to this extent.

A summary of our experimental spectroscopic factors (C^2S) and theoretical predictions using the complete shell-model wave functions obtained in Ref. 1 are presented in Table I.²¹ Spectroscopic factors obtained using Set II parameters

have not been included as they give results very similar to those from Set III. Two prescriptions were used in calculating the form factors required in the DWBA calculations: 1) the effective binding energy method (EBM), in which the bound state well depth was determined by the binding energy of the $T_{<}$ state (for both $T_{<}$ and $T_{>}$ states) and 2) the separation energy method (SEM) in which the well depth was dependent only on the binding energy of the final state. The experimental spectroscopic factors calculated by the EBM are shown in parentheses; all others were calculated using the SEM. Experimental errors are shown where they are significant. Where peaks could not be resolved it was only possible to set limits on their intensity; for these cases ranges of C^2S are shown in the table.

A prominent feature of transitions to even parity states is the large discrepancy between theory and experiment for the population of the 10.36 MeV state. The spectroscopic strength of this state is calculated to be 30% of that of the ground state but is observed to be at least a factor of twenty too weak. Since this is far outside the error attributable to the reaction theory this represents a significant failure of the model. The theoretical spectroscopic strength for this "rotational" state is contributed to approximately equally by 2p-2h and 4p-4h terms which overlap with a large 3p-2h and a smaller 5p-4h term (in ^{17}O), respectively. Since the 3p-2h and 5p-4h terms comprise approximately 50%, by intensity, of the ^{17}O ground state wave function, the transition should take place through major components in both initial and final wave functions. The disagreement with our results thus indicates a gross inadequacy in the description of either or both wave functions.

Other than the 10.36 MeV state the only even parity states which could be clearly resolved were the ground state and the 2^+ , 9.85 MeV state. The

theory assigns a value of $C^2S = 0.09$ to a 2^+ state near 10 MeV excitation; the observed state is at least a factor of ten weaker. However, due to the weak population of the 9.85 MeV state in the $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$ reaction²² and its strong population in the $^{20}\text{Ne}(d, ^6\text{Li})^{16}\text{O}$ reaction²³ it is believed that this state resembles an alpha particle coupled to the 2^+ , 4.43 MeV state in ^{12}C .²⁴ The negligible population of this state here ($C^2S < 0.008$) would be in agreement with this picture but would require another 2^+ state at about this energy to be produced quite strongly. Unfortunately, the ^{15}O ground state contaminant peak prevented resolution of the 2^+ , 11.53 MeV state which is relatively more strongly populated in the $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$ reaction.

The agreement with theory is seen to be fair for the negative parity states. The EBM results are included for the $T_>$ states as they give an indication of what strength is expected if one were to properly account for the isospin-dependent term in the optical potential.²⁵ Thus the fact that the $T_>$ sum rule $C^2 \sum_i (S_{>})_i = 1$ is exceeded in the SEM does not necessarily indicate $lp_{3/2}$ admixtures are significant for $T = 1$ states.

The 2^- and (3^-) states at 15.22 and 15.42 MeV respectively were not seen in the $^{15}\text{N}(^3\text{He}, d)^{16}\text{O}$ and $^{14}\text{N}(\alpha, d)^{16}\text{O}$ reactions^{7,26} indicating that they do not contain significant $(lp_{1/2}^{-1} ld_{5/2})$ amplitude. Their excitation energies relative to the $T = 1$ quadruplet at 13 MeV indicates they can only be $T = 0$ states. We believe that these two odd parity states contain some of the $(lp_{3/2}^{-1} ld_{5/2})$, $T = 0$ amplitude. Unfortunately, the similarity of $\ell = 1$ and $\ell = 2$ angular distributions means that an even parity assignment to the 15.42 MeV state could not be ruled out. The maximum²⁷ strength for $lp_{1/2}$ pick-up is 1.0 for $T_<$ states (and $T_>$ states). If we allow $lp_{1/2}$ and $lp_{3/2}$ pick-up the total theoretical sum rule is 3.0 for $T_<$ states (and $T_>$ states). The maximum experimentally observed strength for $\ell = 1$, $T = 0$ states is equal to 1.6, of which

0.5 comes from the presumed $lp_{3/2}$ strength. It thus appears that little of the total $lp_{3/2}$, $T = 0$ strength is expended below 18 MeV. The weak population of the 1^- , $T = 0$ state at 7.12 MeV is of particular interest.

Although the major components in the 2^- , 8.88 MeV and 3^- , 6.13 MeV states must be different from those in the 1^- , 7.12 MeV state, it is not expected that the 2^- and 3^- states should have significantly more $lp_{3/2}$ strength. Thus the population of the 7.12 MeV state sets a value of $(lp_{3/2}^{-1} ld_{5/2})$ admixtures of $C^2S \approx 0.1$ for each state. Similar arguments may be made for the $T_>$ sum rule but, as discussed above, ambiguities are introduced from uncertainties in the reaction theory.

The 2^- , 12.53 MeV state, strongly formed in the $(^3\text{He}, d)$ reaction, exhausts 90% of the sum rule for $d_{3/2}$ stripping.⁷ We observe a very weak population of this state in agreement with this result. Thus it appears that since the $T = 0$, $(lp_{1/2}^{-1} ld_{3/2})$ strength resides primarily in one state, $ld_{3/2}$ orbitals are not likely to be important in a discussion of other low-lying states in ^{16}O .

Thus, the weakness of $lp_{3/2}$ admixture, with its attendant high-lying strength, and the apparent high degree of concentration of the $ld_{3/2}$ strength indicates that the neglect of these orbitals in the shell model calculation may not be responsible for the serious discrepancy found in the yield of the 4^+ , 10.36 MeV state. In fact the source of discrepancy may lie in the values of the matrix elements rather than in the approximations used. Since both "effective interaction" type matrix elements and "realistic" matrix elements do yield similar wave functions, and the two sets of matrix elements have many significant differences, it appears that a reexamination of those matrix elements for which Ref. 1 kept the same values in both sets may remove the discrepancy.

The authors would like to thank Drs. Andres Zuker, Brian Buck, Joseph McGrory and Charles Glashausser for many helpful discussions and useful suggestions. One of us (J.C.H.) gratefully acknowledges a fellowship from the Miller Institute for Basic Research in Science.

FOOTNOTES AND REFERENCES

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

Fig. 1. A typical $^{17}\text{O}(\text{p,d})^{16}\text{O}$ spectrum. Peaks due to ^{16}O and ^{18}O target contaminants are shown in parentheses.

Fig. 2. Angular distributions and typical $\ell = 1$ and $\ell = 2$ DWBA fits using the separation energy method (SEM). The dash-dot-dot line refers to Set I deuteron parameters, the solid line refers to Set II parameters and the dashed line refers to Set III parameters. These are discussed in the text.

Table 1. Spectroscopic factors (C^2S)
for major levels of interest in O^{16} .

State (MeV)	J,T	Set I ^a	Set III ^b	Theory: ZBMC ^c
0.00	$0^+,0$	0.985	1.00	0.88
6.05	$0^+,0$	<0.16	<0.24	0.00014
6.13	$3^-,0$	0.38-0.48	0.30-0.43	0.40
6.92	$2^+,0$	<0.08	<0.07	0.028
7.12	$1^-,0$	0.08	0.07	-
8.88	$2^-,0$	0.36	0.27	0.26
9.85	$2^+,0$	<0.004	<0.008	0.09 ^d
10.36	$4^+,0$	0.006 ± 0.003	0.012 ± 0.006	0.25
12.53	$2^-,0$	<0.06	<0.04	-
12.97	$2^-,1$	0.60-0.91 (0.20-0.32)	0.40-0.61 (0.13-0.20)	0.29
13.08	$1^-,1$	<0.23 (<0.08)	<0.15 (<0.05)	-
13.12	$3^-,0$	<0.36	<0.27	-
13.26	$3^-,1$	0.54-0.90 (0.19-0.32)	0.37-0.64 (0.12-0.20)	0.39
15.22	$1^-,0$	0.08 ± 0.03	0.13 ± 0.04	-
15.42	$(3^-),0$	0.19 ± 0.06	0.31 ± 0.10	-

^aSee Ref. 16.

^bSee Ref. 18.

^cSee Ref. 1.

^dThis spectroscopic strength may actually refer to the 2^+ ,
11.53 MeV state. See discussion in text.

XBL695-2761

Fig. 1

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Fig. 2

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