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$O^{17}(d,p)O^{18}$ Reaction and Nuclear Structure of O^{18}†

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A target enriched to 40% in O^{17} was bombarded with 10-MeV deuterons, and the emitted protons were analyzed with a broad-range magnetic spectrograph. Angular distributions of the groups corresponding to the ground and 12 excited states of O^{18} were measured and analyzed using plane-wave theory. The predicted 3^+ state arising from the $(d_{5/2}s_{1/2})$ configuration was found to be at 5.37-MeV excitation. Relative reduced widths and spectroscopic factors were determined from the stripping analysis, and were found to be in good agreement with recent theoretically predicted wave-function amplitudes. This implies that several states of O^{18} have an appreciable collective component.

INTRODUCTION

DURING the past few years, considerable interest has been shown in the mass-18 nuclei, and many authors[1–9] have made detailed shell-model calculations on the positions of the low-lying positive parity states of O^{18}. Usually, states are considered as arising from the coupling of two neutrons in the $1d_{5/2}$ and $2s_{1/2}$ orbitals outside a closed O^{16} core. Six positive parity states can be formed in this way, viz., 0^+, 2^+, and 4^+, arising from the $(d_{5/2})^2$ configuration, 0^+ from the $(s_{1/2})^2$, and 2^+ and 3^+ from the $(d_{5/2}s_{1/2})$ configurations. Some configuration mixing between the two 0^+ and two 2^+ states is expected, while the 3^+ and 4^+ states should be relatively pure.

The $d_{3/2}$ single-particle level is known to occur at 5.08-MeV excitation in O^{17}, and, hence, states in O^{18} arising from the $(d_{3/2})^2$ configuration are not expected much below 10-MeV excitation. The lowest state arising from the $(d_{5/2}d_{3/2})$ configuration is expected to have a spin and parity of 4^+ and to have an excitation energy of about 7 MeV. For these reasons, the effects of the $d_{3/2}$ orbital have usually been neglected in the calculations on the low-lying, positive parity states.

More recently, the effects of positive parity states arising from excitation of the O^{16} core have been investigated by Brown[10] and by Federman and Talmi.[11] They considered that a state could be formed by lifting two protons from the $p_{1/2}$ orbital into the $d_{5/2}$ or $s_{1/2}$ orbitals. A state formed in this way would resemble the Ne^{20} ground state, and might, therefore, be expected to exhibit similar collective properties. The introduction of such a state not only accounts for the new experimental data on O^{18}, as will be discussed later, but also accounts for the enhanced gamma-ray transition between the 3.63- and 1.98-MeV levels. The latter transition probability has long been known to be some 60 times the largest value that could be reasonably predicted by a simple two-particle model.[10]

Experimental studies of O^{18} have been made by Jaffe *et al.*[12] and by Middleton and Pullen,[13] using the $O^{16}(t,p)O^{18}$ reaction. Several spins and parities were assigned, but, because the double-stripping selection rules forbid the excitation of unnatural parity states, the 3^+ state arising from the $(d_{5/2}s_{1/2})$ configuration could not be located. Both authors report the existence of several weakly excited states, one of which might arise from this configuration. No positive identification could be made, however, since any or all of these weakly excited states might have negative parity and arise from configurations such as $(p_{1/2})^{-1}(d_{5/2})^3$.

The $O^{17}(d,p)O^{18}$ reaction has been previously studied by Bilaniuk and Hough,[14] but because of poor target enrichment, only angular distributions of proton groups corresponding to the ground and first two excited states were measured. The present work was undertaken to extend these measurements to higher excitation energies, and in particular to look for the predicted 3^+ state arising from the $(d_{5/2}s_{1/2})$ configuration. Such a state is predicted to lie between 4.5- and 6.0-MeV excitation,[1–9] and should be strongly excited by an $l=0$ transition. A preliminary account of this work has been published elsewhere.[15]

EXPERIMENTAL PROCEDURE

A tungsten oxide target, 40% enriched in O^{17}, was bombarded with 10-MeV deuterons from the Univer-

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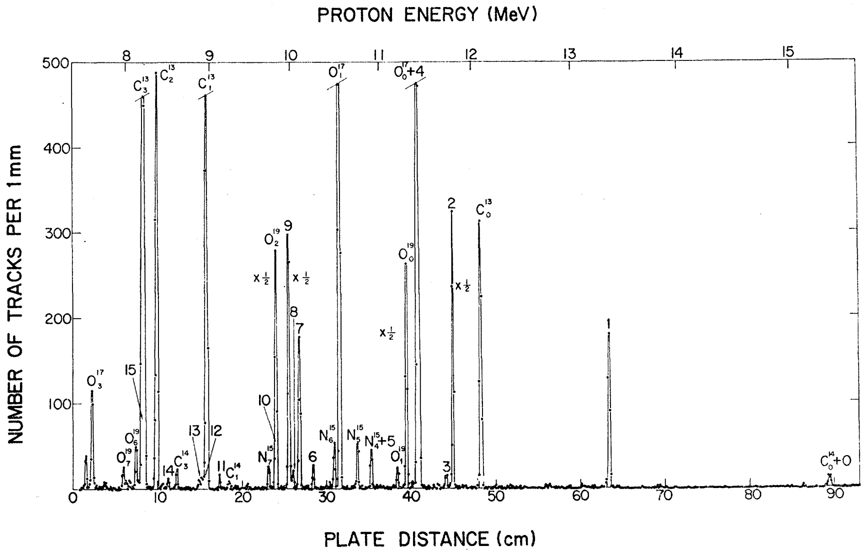

FIG. 1. A typical proton energy spectrum for the $O^{17}(d,p)O^{18}$ reaction measured at an incident energy of 10.0 MeV and at an angle of 40°. Groups corresponding to states in O^{18} are labelled numerically with 0 referring to the ground state.

sity of Pennsylvania Tandem accelerator, and the emitted protons were analyzed with a 65-cm-radius broad-range magnetic spectrograph. The tungsten oxide target was about 70 μg cm^{-2} and was supported on a 20 μg cm^{-2} carbon backing foil. Proton energy spectra were recorded at eight angles in the range 7° to 70° on 25-μ nuclear emulsion plates. A thin Mylar strip, directly in front of the emulsion surface, served to absorb all but the reaction protons. Exposure strengths were measured by integrating the beam current passing through the target and into a Faraday cup. Since no independent monitor was used, target deterioration was checked by repeating the 22° and 30° exposures at the end of the measurements. Within statistical accuracy, losses were found to be negligible.

RESULTS

A typical proton energy spectrum, measured at an angle of 40°, is shown in Fig. 1. Groups corresponding to states in O^{18} were identified by their characteristic change of energy with angle, and are labelled numerically, with 0 referring to the ground state. Those arising from target impurities are labelled with the symbol of the final nucleus, and a subscript to denote the appropriate excited state. The principal target impurities were O^{16} and C^{12}, with lesser amounts of O^{18}, N^{14}, and C^{13}. The excitation energies of the O^{18} levels, up to the fifteenth excited state, were found to be consistent with those reported by Hinds, Marchant, and Middleton[16] and, therefore, no independent determinations were made.

Angular distributions of the groups corresponding to all but the levels at 5.52, 6.39, and 6.86 MeV are shown in Figs. 2 and 3. These three states were weakly excited and reliable intensity measurements could only be made at one or two angles. The angular distributions showing stripping characteristics were fitted with plane-wave theory using the Lubitz tables.[17] An interaction radius of 5.25 fm was used throughout.

Values of l, the orbital angular momentum of the captured neutron, were deduced, as were relative values of $(2J+1)\Theta^2$, where J is the spin of the final state and Θ^2 is the reduced width for the transition. These results and the relative peak differential cross sections are shown in Table I. Also included are the L-value de-

TABLE I. The orbital angular momentum transfers l, the relative reduced widths $(2J+1)\Theta^2$, and the peak differential cross sections determined from the $O^{17}(d,p)O^{18}$ reaction. Also included are the orbital angular momentum transfers L determined by Middleton and Pullen[a] from the $O^{16}(t,p)O^{18}$ reaction.

		$O^{17}(d,p)O^{18}$ Present work				
Group No.	Level energy (MeV)	l	$(2J+1)\Theta^2$ relative	σ_p arbitrary units	$O^{16}(t,p)O^{18}$ L	J^Π
0	0	2	5.66	0.8	0	0^+
1	1.98	0	8.82	20.0	2	2^+
		2	25.4	4.0		
2	3.55	2	77.6	15.0	4	4^+
3	3.63	(2)	1.54	0.3	0	0^+
4	3.92	0	28.1	50.0	2	2^+
5	4.45	...	...	0.25	...	...
6	5.09	...	...	0.4	...	...
7	5.25	0	26.5	35.0	2	2^+
8	5.33	...	...	0.25	0	0^+
9	5.37	0	123.1	160.0	...	3^+
10	5.52	...	...	<0.2	...	...
11	6.19	...	...	0.4	...	...
12	6.34	...	...	0.5	...	...
13	6.39	...	...	<0.2	...	...
14	6.86	...	...	<0.2	...	...
15	7.10	(2)	12.1	5.75	...	4^+

[a] See Ref. 13.

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[16] S. Hinds, H. Marchant, and R. Middleton, Nucl. Phys. 38, 81 (1962).

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terminations of Middleton and Pullen[13] from the $O^{16}(t,p)O^{18}$ reaction along with the most probable spin and parity assignments.

DISCUSSION

The ground and first two excited states of O^{18} are known to have spins and parities of 0^+, 2^+, and 4^+ respectively, from the results of the (t,p) investigations. In the (d,p) reaction, the ground and second excited states are both excited by $l=2$ transitions, indicating that they contain appreciable components of $(d_{5/2})^2$. The first excited state at 1.98 MeV is populated by a combination $l=0$ and $l=2$ transition, which indicates the presence of some $(d_{5/2}s_{1/2})$ in addition to the expected $(d_{5/2})^2$ component. Similar results have been obtained by Bilaniuk and Hough[14] at a bombarding energy of 7.77 MeV.

The 0^+ state at 3.63 MeV has long been thought to arise from the $(s_{1/2})^2$ configuration, and therefore was expected to be strongly excited by an $L=0$ transition in the $O^{16}(t,p)O^{18}$ reaction. Although both Jaffe *et al.* and Middleton and Pullen observed $L=0$, the transition amplutides were surprisingly weak, and the latter authors observed a pronounced backward peak. In the present work, the 3.63-MeV level was seen to be weakly excited but with some evidence for $l=2$ stripping. This suggests the presence of an admixture of $(d_{5/2})^2$.

Middleton and Pullen assigned 2^+ to the 3.92-MeV level and assumed it to contain a large component of $(d_{5/2}s_{1/2})$. This assumption was confirmed in the present study by the observation of a strong $l=0$ transition to this state. It may be noted that at small angles of emission, the protons corresponding to this level have almost the same energy as those corresponding to the O^{17} ground state. The groups could not be clearly resolved, and a combined angular distribution was measured. This was well fitted by a combination of $l=0$ and $l=2$, the latter component arising from the $O^{16}(d,p)O^{17}$ ground-state transition.

The 4.45-MeV level was very weakly excited by the (t,p) reaction, and since it is also observed to be very weakly excited by the $O^{17}(d,p)O^{18}$ reaction, it is thought to be a negative parity state arising from the lifting of a nucleon from the p shell into the d-s shells. Angular-correlation studies made by Gobi *et al.*[18] using the $O^{18}(p,p'\gamma)$ reaction, indicate the spin of this state to be 1. Recently, Zeidman and Braid[19] observed the 4.45-MeV level to be strongly excited by the $F^{19}(d,He^3)O^{18}$ reaction, and their angular distribution measurements were consistent with $l=1$. It is notable that Hinds *et al.*[16] also observed this level to be very strongly excited by the $F^{19}(t,\alpha)O^{18}$ proton pickup reaction, but no angular distribution was measured. Thus it appears most likely that the 4.45-MeV level is 1^- and does arise from the removal of a proton from the p shell. These conclusions are in complete disagreement with those of Yagi *et al.*,[20] who report this level to be strongly excited in the $O^{17}(d,p)O^{18}$ reaction, and assign $l=1$ to the transition. Since these authors used a target containing only 1% O^{17}, it appears very likely that they incorrectly assigned an impurity group as corresponding to the 4.45-MeV level.

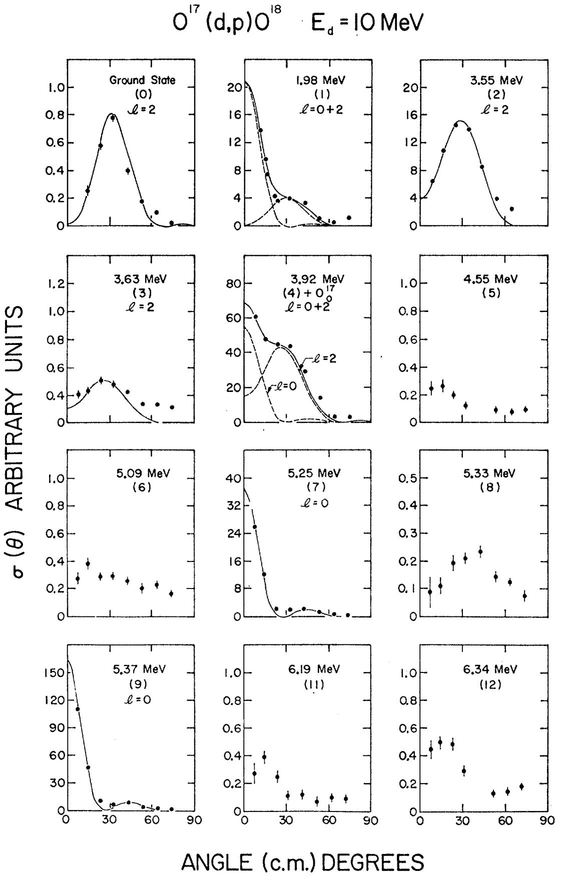

FIG. 2. Angular distribution of the ground- and eleven excited-state groups from the $O^{17}(d,p)O^{18}$ reaction. The full-line curves were calculated from plane-wave stripping theory using a radius of interaction of 5.25 fm.

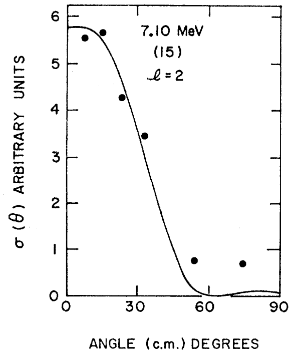

FIG. 3. Angular distribution of the proton group corresponding to the 7.10-MeV level of O^{18}. The arbitrary units of intensity are the same as those used in Fig. 2.

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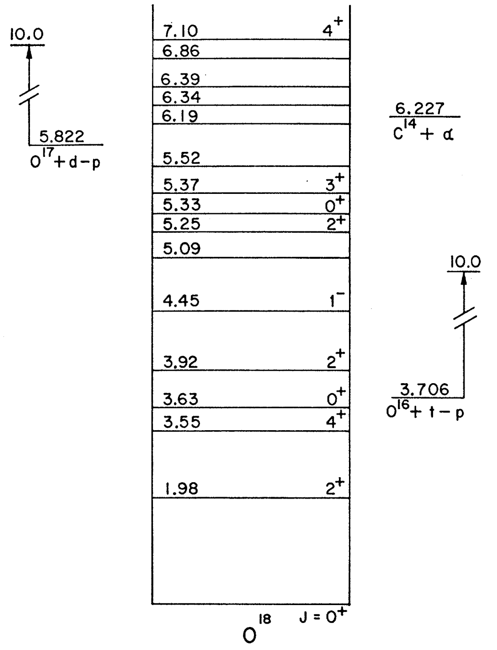

FIG. 4. Energy-level diagram of O^{18} indicating the most probable spin and parity assignments.

The 5.09-MeV level is also weakly excited by both the single- and double-stripping reactions, and possibly is a negative parity state arising in a way similar to the 4.45-MeV level. However, since this state is not particularly strongly excited by the $F^{19}(t,\alpha)O^{18}$ reaction,[16] this possibility is less certain.

Middleton and Pullen[13] were able to make a fairly definite assignment of 2^+ to the 5.25-MeV level from their study of the $O^{16}(t,p)O^{18}$ reaction. In the present work, this level was observed to be strongly excited by $l=0$, suggesting that, like the 2^+ states at 1.98 and 3.92 MeV, it contains an appreciable component of the $(d_{5/2}s_{1/2})$ configuration.

The (t,p) work of Middleton and Pullen also definitely assigns 0^+ to the level at 5.33 MeV, while the present work shows this to be only weakly excited by the $O^{17}(d,p)O^{18}$ reaction. A possible explanation is that this state has the configuration $(d_{3/2})^2$; however, as was mentioned earlier, this configuration is not expected to occur much below 10-MeV excitation. A more probable explanation is that this state shares a large part of the $(s_{1/2})^2$ configuration, as will be discussed in more detail later.

The 5.37-MeV level is weakly excited by the (t,p) reaction, and proceeds very strongly by $l=0$ in the $O^{17}(d,p)O^{18}$ reaction. Thus, it seems highly probable that this is the 3^+ state arising from the $(d_{5/2}s_{1/2})$ configuration. Similar results and conclusions have recently been reported by Moreh *et al.*[21] who also studied the $O^{17}(d,p)O^{18}$ reaction, but at a lower bombarding energy.

The levels at 5.52, 6.19, 6.34, 6.39, and 6.86 MeV are all very weakly excited by the (d,p) reaction and no definite conclusion could be reached as to their spins, parities, or possible configurations. The only other level which was observed to be significantly excited in the present work was at 7.10-MeV excitation. An angular distribution of this transition is shown in Fig. 3, where the full-line curve was calculated using plane-wave theory, assuming $l=2$ and an interaction radius of 5.25 F. Since this level is bound with respect to neutron emission by only about 1 MeV, the assignment of $l=2$ is not totally unambiguous. The 7.10-MeV level is known to be 4^+ from the gamma-ray angular distributions arising from the $C^{14}(\alpha,\gamma)O^{18}$ reaction.[22] This assignment precludes the possibility of the level being populated by a (d,p) transition of odd l, and since $l=0$ is not allowed by the requirements of angular momentum conservation, the assignment of $l=2$ seems quite likely. Thus, it is possible that the 7.10-MeV level might have a large component of $(d_{5/2}d_{3/2})$, and as was mentioned earlier, the lowest state of this configuration is expected to be 4^+ and to occur at around 7-MeV excitation.

The most probable spins and parities of the states of O^{18} are summarized in Fig. 4.

Relative values of $(2J+1)\Theta^2$ are listed in Table I. Spectroscopic factors were deduced from these following the method described by Glendenning,[23] and using the estimate of MacFarlane and French[24] for the ratio of the single-particle reduced widths, i.e., $\Theta_0^2(2s_{1/2})/\Theta_0^2(1d_{5/2})=2.5\pm0.5$. These values were normalized assuming a spectroscopic factor of 1 for the 3^+ state. This latter assumption was considered reasonable in view of the expected purity of this state. Coefficients of fractional parentage (CFP) deduced from these are presented in Table II. It may be worth noting that the effects of admixtures arising from the $d_{3/2}$ orbital were neglected in these calculations.

TABLE II. Comparison of the coefficients of fractional parentage (CFP) determined from the present study of the $O^{17}(d,p)O^{18}$ reaction with those predicted by Federman and Talmi.[a]

O^{18} level energy (MeV)	$J\Pi$	CFP (Experimental)		Theoretical CFP (Federman and Talmi)			
		$d_{5/2}^2$	$d_{5/2}s_{1/2}$	$d_{5/2}^2$	$d_{5/2}s_{1/2}$	$s_{1/2}^2$	Col.
0	0^+	0.64	···	0.84	···	0.38	0.39
1.98	2^+	0.60	0.32	0.95	0.30	···	0.13
3.55	4^+	0.80	···	···	···	···	···
3.63	0^+	0.33	···	0.50	···	0.81	0.29
3.92	2^+	···	0.56	0.16	0.78	···	0.61
5.25	2^+	···	0.55	0.28	0.55	···	0.78
5.33	0^+	<0.33	···	0.21	···	0.44	0.87
5.37	3^+	···	1.00	···	···	···	···

[a] See Ref. 11.

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The present results for the ground and first two excited states were found to be in good agreement with those reported by Bilaniuk and Hough.[14] From Table II, the ratio of the $(d_{5/2})^2$ amplitude to that of the $(d_{5/2}s_{1/2})$, for the first excited state, is seen to be 1.9±10% as compared to their value of 1.8±10%.

CONCLUSIONS

It was mentioned earlier that a simple two-particle model of O^{18} predicts the existence of six positive parity states below 6-MeV excitation. These states arise from the $(d_{5/2})^2$ configuration, which produces 0^+, 2^+, and 4^+ states, $(s_{1/2})^2$, which can produce only a 0^+ state, and $(d_{5/2}s_{1/2})$, which produces a 2^+ and a 3^+ state. Configuration mixing between the two 0^+ and between the two 2^+ states is expected, but the 3^+ and 4^+ states should be relatively pure.

The present results from the $O^{17}(d,p)O^{18}$ reaction, in conjunction with those of Middleton and Pullen[13] from the $O^{16}(t,p)O^{18}$ reaction, strongly indicate that the 3^+ and 4^+ states arising from the above configurations are the 5.37- and 3.55-MeV levels, respectively. However, whereas the two-particle model predicts two 0^+ and two 2^+ states below 6-MeV excitation, three 0^+ and three 2^+ states are observed. This difficulty of the simple shell model was first removed by Brown[10] and more recently by Federman and Talmi[11] by the introduction of a collective state arising from the removal of two nucleons from the O^{16} core. Thus, because of configuration mixing, three 0^+ states are generated, of the form $a(d_{5/2})^2+b(\text{col.})+c(s_{1/2})^2$ and three 2^+ states of the form $a'(d_{5/2})^2+b'(\text{col.})+c'(d_{5/2}s_{1/2})$, as is observed experimentally.

Since the calculations of Federman and Talmi are somewhat more recent and extensive than those of Brown, we compare our results to the predictions of these authors. The measured and predicted amplitudes are presented in Table II, where agreement is generally good. It should be noted that only the magnitudes are listed since the phases could not be obtained from the reduced widths measured in the (d,p) reaction. The phases, however, profoundly affect the (t,p) double-stripping cross sections, and it is gratifying that the amplitudes of the $(d_{5/2})^2$ and $(s_{1/2})^2$ components of the second 0^+ state are predicted to be of comparable magnitude and opposite sign, thus explaining the weak $L=0$ transition to this state.

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