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Study of O^{19} by the $O^{17}(tp)O^{19}$ and $O^{18}(d,p)O^{19}$ Reactions*

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A tungsten oxide target enriched to 30% in O^{17} was bombarded with 12.0-MeV tritons and a similar target enriched to 50% in O^{18} was bombarded with 12.0-MeV deuterons. In both cases, emitted protons were analyzed using a broad-range multiangle spectrograph. The $O^{18}(d,p)O^{19}$ reaction was also studied at a bombarding energy of 11 MeV using a gas target and magnetic analysis. Energy levels up to 6.3-MeV excitation in O^{19} were determined and no evidence was found for the recently reported levels at 0.348 and 2.617 MeV. Angular distributions were measured and several new spin and parity assignments were made.

I. INTRODUCTION

OXYGEN-19 is a particularly difficult nucleus to study since there are only two convenient reactions by which it can be formed. These are the $O^{18}(d,p)O^{19}$ and $O^{17}(t,p)O^{19}$ reactions having ground-state Q values of 1.732 and 3.521 MeV, respectively.

Several authors[1–6] have studied the $O^{18}(d,p)O^{19}$ reaction at various bombarding energies, but often have reported conflicting energy-level determinations. These discrepancies are in some cases attributable to low-energy resolution, but more often arise from the fact that the (d,p) reaction can strongly excite only three or four levels below about 6-MeV excitation. Most of the low-lying states are expected to arise from the coupling of three neutrons in the $1d$ and $2s$ orbitals but only those states having configurations similar to the O^{17} single-particle levels can readily be formed by the addition of a single neutron to O^{18}.

Since the $O^{17}(t,p)O^{19}$ reaction involves the transfer of two neutrons, it is expected that this reaction will directly excite a wider variety of states. For example, whereas the (d,p) reaction can only directly excite the $\frac{5}{2}^+$ level arising from the $(d_{5/2})^3$ configuration, the (t,p) reaction should excite strongly the $\frac{3}{2}^+$ and $\frac{9}{2}^+$ components in addition to the $\frac{5}{2}^+$. However, the experimental investigation of the (t,p) reaction has been impaired by the lack of highly enriched O^{17} gas, and by the difficulties associated with the acceleration of tritium. Previous to the present work, a study of the $O^{17}(t,p)O^{19}$ reaction was reported by Moreh and Jaffe[7] who used a beam of 5.55-MeV tritons.

The present investigation of the $O^{17}(t,p)O^{19}$ and $O^{18}(d,p)O^{19}$ reactions was undertaken to establish a reliable energy-level scheme for O^{19}. In addition, since both reactions were studied at a bombarding energy of 12 MeV, it was hoped that the angular distributions would be amenable to analysis by direct reaction theory, enabling certain spin, parity, and configuration assignments to be made.

II. EXPERIMENTAL PROCEDURE

A tungsten oxide target, enriched in O^{17}, was bombarded by 12.0-MeV tritons from the Aldermaston Tandem accelerator, and the emitted protons were analyzed with a multiangle spectrograph.[8] The target consisted of about 70 μg cm^{-2} of tungsten oxide enriched to approximately 30% in O^{17} and was supported by a 10 μg cm^{-2} carbon foil. Proton energy spectra were recorded at 24 angles in the range 5° to 175° using 50-micron nuclear-emulsion plates. Thin polyethylene strips were placed immediately in front of the emulsion surfaces to absorb all but the reaction protons. The exposure strength was 1000 μC.

The same procedure was used to study the $O^{18}(d,p)$ O^{19} reaction at a bombarding energy of 12.0 MeV. In this case, a similar tungsten oxide target was used, but was enriched to about 50% in O^{18}. Since it was anticipated that the proton groups from this reaction would vary considerably in intensity, two exposures of 400 and 1300-μC duration were made.

Since the analysis of the (d,p) energy spectra was complicated by the presence of several target impurities, additional studies were made using the University of Pennsylvania 65-cm-radius broad-range magnetic spectrograph and a gas target. The latter was of the type described by Hoogenboom[9] and was filled to a pressure of 2 cm Hg with 95% enriched O^{18} gas. A thin layer of gold was evaporated onto the Formvar window of the gas cell in order to inhibit rapid oxidation and subsequent rupture. Since the gold could not be conveniently evaporated onto the inner surface of the window, 10 turns of Formvar were wound on the cell, gold was then evaporated, and then a final 20 turns were added.

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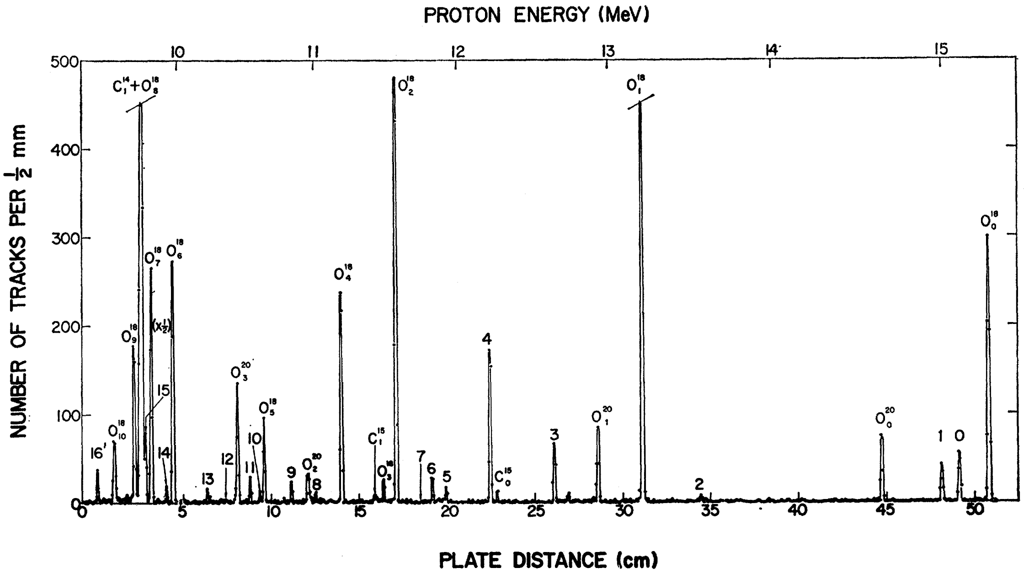

FIG. 1. A typical proton energy spectrum for the $O^{17}(t,p)O^{19}$ reaction measured at an incident energy of 12.0 MeV and at an angle of 20°. Groups corresponding to states of O^{19} are labeled numerically with 0 referring to the ground state.

Several exposures were made using both O^{18} and O^{16} gas at angles in the range 12° to 30°, and at a bombarding energy of 11.0 MeV.

III. RESULTS

A. Energy Levels of O^{19}

A typical proton energy spectrum from the $O^{17}(t,p)O^{19}$ reaction, measured at 20°, is shown in Fig. 1. Groups corresponding to levels in O^{19} were identified by their characteristic variation of energy with angle, and are labeled numerically. Groups arising from target impurities are labeled according to the residual nucleus with a subscript to denote the particular excited state. The principal target impurities were C^{12} and O^{16} with lesser amounts of O^{18} and C^{13}.

Proton energy spectra arising from the $O^{18}(d,p)O^{19}$ reaction measured at $12\frac{1}{2}°$ using the tungsten oxide target, and at 12° using the gas cell, are shown in Figs. 2 and 3, respectively. Groups corresponding to states in O^{19} were identified and labeled in the manner described for the (t,p) reaction. In both spectra, impurity groups arising from C^{12} and O^{16} can be observed, although it may be noted that the intensities of these groups are considerably less for the case of the gas target. Additional impurity groups arising from C^{13} and N^{14} were

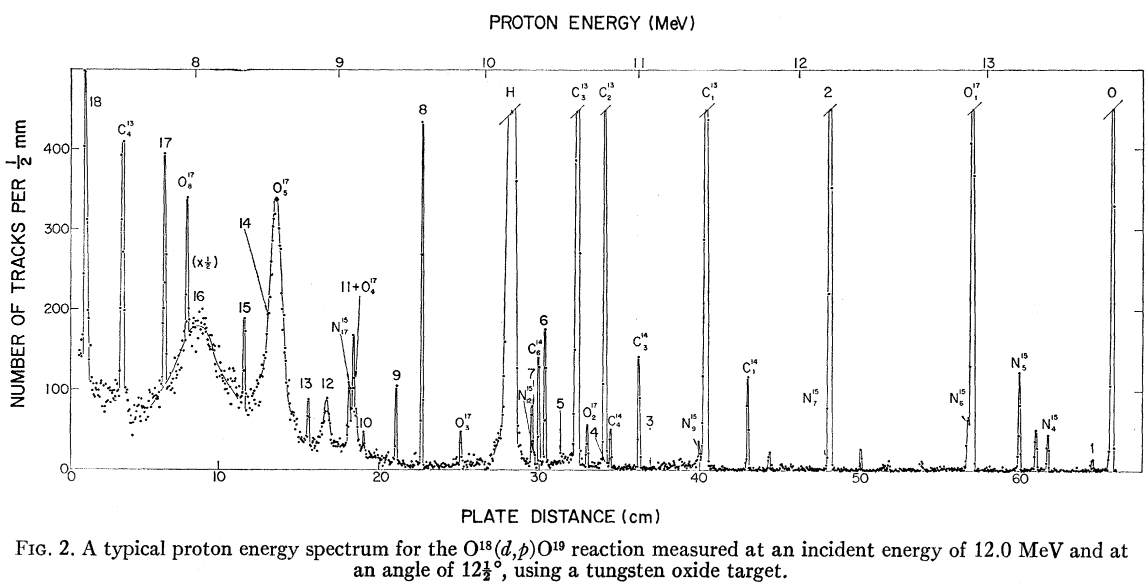

FIG. 2. A typical proton energy spectrum for the $O^{18}(d,p)O^{19}$ reaction measured at an incident energy of 12.0 MeV and at an angle of $12\frac{1}{2}°$, using a tungsten oxide target.

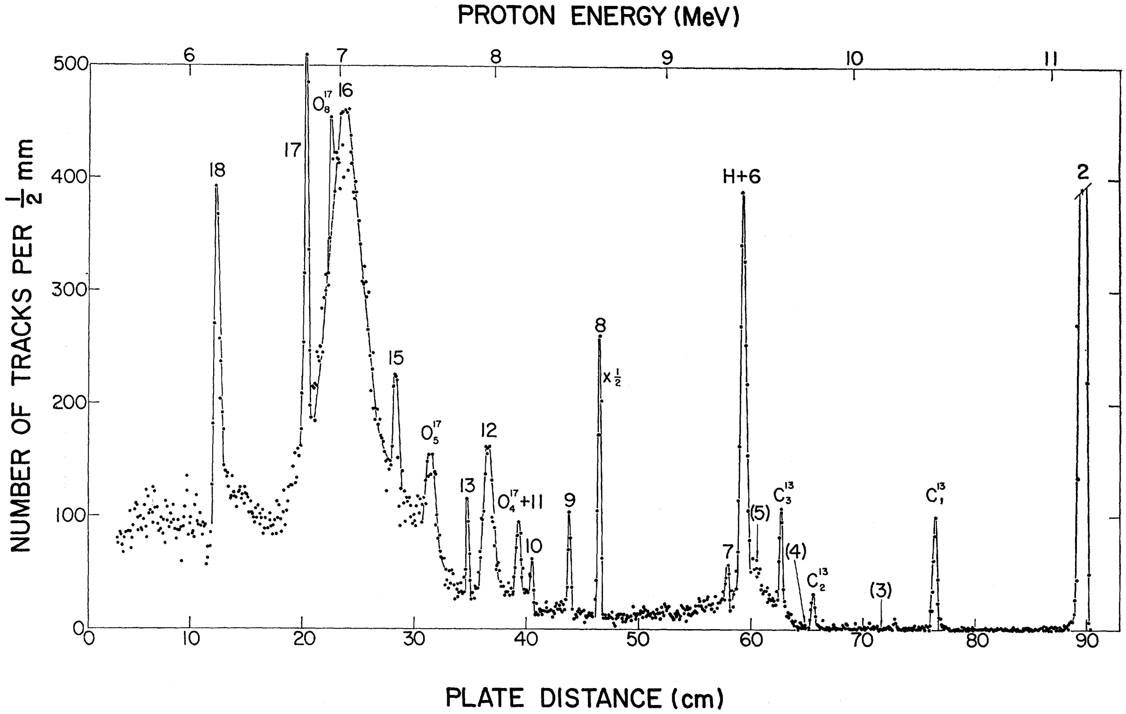

FIG. 3. A typical proton energy spectrum for the $O^{18}(d,p)O^{19}$ reaction, measured at an incident energy of 11.0 MeV and at an angle of 12°, using a rotating gas target.

also observed in the case of the solid target. The former impurity presumably is due to the 1.1% of C^{13} present in natural carbon, while the latter may be due to the formation of a tungsten nitrogen compound. The presence of C^{12} in the gas-cell spectra was surprising, and it is surmised that this results from the oxidation of the Formvar window with the possible liberation of carbon monoxide or dioxide.

TABLE I. Excitation energies obtained from the $O^{17}(t,p)O^{19}$ and $O^{18}(d,p)O^{19}$ reactions. Mean values are certain to ±12 keV. Also included are width measurements for groups corresponding to states above the neutron separation energy in O^{19}.

Group No.	Level energy $O^{18}(d,p)O^{19}$ Gas tgt. (MeV)	Solid tgt. (MeV)	Level energy $O^{17}(t,p)O^{19}$ (MeV)	Level energy mean (MeV)	Γ (keV)
0	···	0	0	0	···
1	···	0.096	0.096	0.096	···
2	1.464	1.468	1.471	1.467	···
3	···	···	2.373	2.373	···
4	···	(2.783)	2.779	2.779	···
5	···	(3.059)	3.070	3.070	···
6	3.156	3.156	3.157	3.156	···
7	3.229	3.229	···	3.229	···
8	3.943	3.945	3.946	3.945	···
9	4.112	4.109	4.111	4.111	<15
10	4.336	4.329	(4.337)	4.333	<15
11	(4.409)	(4.400)	4.402	4.402	<15
12	4.586	4.582	···	4.584	75
13	4.715	4.702	4.706	4.707	<15
14	···	(4.990)	4.998	4.998	<15
15	5.141	5.149	5.154	5.148	<15
16	5.471	5.457	···	5.460	310
16′	···	···	(5.502)	5.502	<15
17	5.723	5.704	···	5.714	<15
18	6.282	6.278	···	6.280	<15

A summary of the energy levels determined from the present work is presented in Table I. The excitation energies determined using the gas cell are the mean values of measurements made at two angles. Since the magnetic field strength was chosen not to include the ground and first excited states, the excitation energies were normalized assuming a value of 3.156 MeV for the sixth excited state which was obtained using the solid target. The values of excitation energy obtained with the solid target are the averages of measurements made at four angles and those from the $O^{17}(t,p)O^{19}$ reaction are the averages of three determinations.

Several levels were observed to be strongly excited in one reaction but extremely weakly in the other. For example, the excited states at 2.373, 2.779, and 3.070 MeV were very weakly excited by the (d,p) reaction but were clearly observed in the (t,p) study. Conversely, the well established broad state at 5.460 MeV was observed to be very strongly excited by the (d,p) reaction, but was not observed at all in the (t,p) reaction. However, a narrow level was observed in the (t,p) reaction at close to this excitation energy, and is designated by 16′ in Table I. It may be noted that this level was relatively weakly excited, and the possibility that this arises from a target impurity cannot be excluded. Where levels are strongly excited by both reactions, agreement between the excitation energies is quite good and within the experimental uncertainty of about ±12 keV. Weighted

TABLE II. Comparison of the present energy-level determinations with those reported by previous authors.

O^{19} level number	Present work ±12 keV	Excitation energy (MeV) $O^{18}(d,p)O^{19}$ El Bedewi *et al.*[a] ±10 keV	Yagi *et al.*[b] ±15 keV	Armstrong and Quisenberry[c] ±35 keV	Sjögren *et al.*[d] ±30 keV	$O^{17}(t,p)O^{19}$ Moreh and Jaffe[e] ±12 keV
0	0	0	0	0	0	0
1	0.096	0.095	...	...	0.098	0.093
	...	0.348	...	...	...	...
	...	...	...	...	(1.257)	...
2	1.467	1.467	1.468	1.469	1.469	1.468
3	2.373	2.371	...	...	2.353	2.367
	...	2.617	2.612	...	...	...
4	2.779	2.794	...	...	2.765	2.775
5	3.070	...	...	...	(3.047)	3.061
6	3.156	3.161	3.171	3.164	3.144	3.153
7	3.229	3.243	...	...	...	3.223
	...	...	...	...	3.796	...
8	3.945	3.953	3.942	3.948	3.942	3.946
9	4.111	4.116	4.111	(4.123)	4.109	4.107
10	4.333	...	...	...	...	(4.328)
11	4.402	4.421	...	...	...	4.396
12	4.584	4.599	...	(4.586)	...	...
13	4.707	4.725	...	(4.706)	...	...
14	4.998	4.954	...	...	...	...
	...	5.107	...	...	...	...
15	5.148	5.172	5.153	(5.165)	...	...
16	5.460	...	5.447	5.45	...	...
16′	(5.502)	...	...	...	...	...
	...	5.582	...	...	...	...
17	5.714	...	5.708	5.707	...	...
18	6.280	...	6.282	6.279	...	...

[a] See Ref. 6. [b] See Ref. 5. [c] See Ref. 2. [d] See Ref. 3. [e] See Ref. 7.

mean values from the three independent determinations are presented in the next to the last column of Table I.

O^{19} is known to be unstable with respect to neutron emission above 3.957 MeV, and groups corresponding to levels above this energy were examined for natural width. Only two levels were observed to be appreciably broader than the instrumental width of about 15 keV. These are the levels at 4.584 and 5.460 MeV, and their measured widths are 75±15 and 310±30 keV, respectively. The present value for the 5.460-MeV level is considerably larger than the determination of about 200 keV reported by Armstrong and Quisenberry.[2] A previous determination of 70 keV has been made of the width of the 4.584-MeV level from the neutron-elastic-scattering studies of Donoghue *et al.*[10]

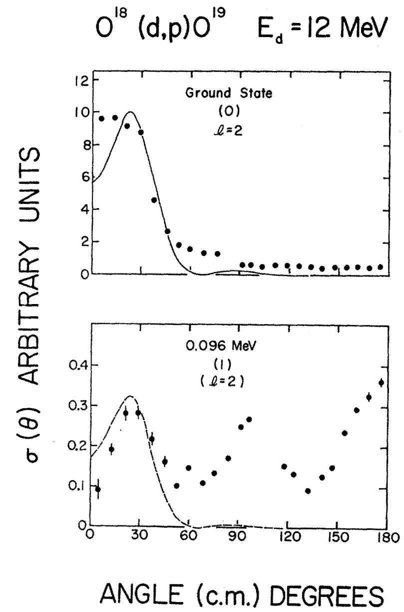

FIG. 4. Angular distributions of the ground and first excited state groups from the $O^{18}(d,p)O^{19}$ reaction. The curves were calculated from plane-wave stripping theory using an interaction radius of 5.0 F.

In Table II, the present energy-level determinations are compared with values reported by several authors.[2–7] Agreement between the present values and those reported by Moreh and Jaffe[7] is well within the experimental error and confirms the suspected level reported by the latter authors at 4.328 MeV. No evidence was found for the low lying states at 0.348 and 2.617 MeV reported by Bedewi *et al.*,[6] and at 1.257 MeV reported by Sjögren *et al.*[3]

B. $O^{18}(d,p)O^{19}$ Angular Distributions

Angular distributions of the seven most intense proton groups corresponding to states below 4.2-MeV excitation are presented in Figs. 4 and 5, where the arbitrary units of differential cross section are the

[10] T. R. Donoghue, A. F. Behof, and S. E. Darden, Nucl. Phys. **54**, 33 (1964).

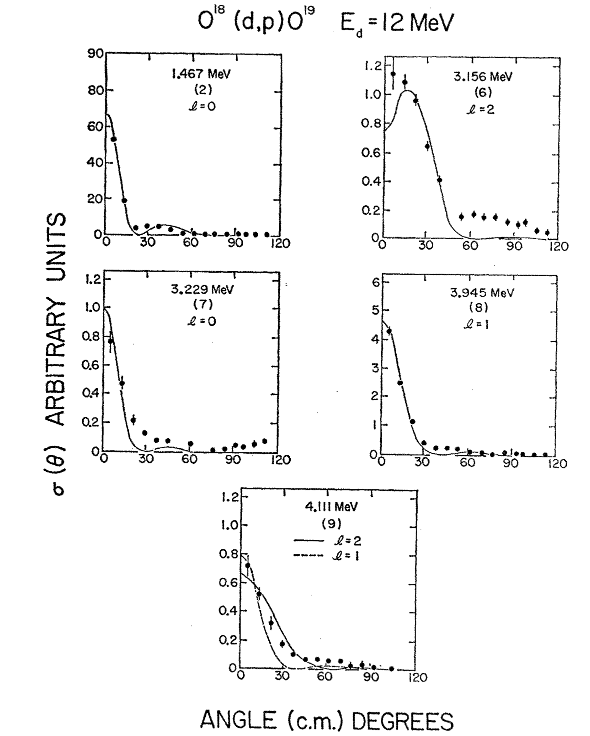

FIG. 5. Angular distributions of five excited state groups from the $O^{18}(d,p)O^{19}$ reaction. The curves were calculated from plane-wave stripping theory using an interaction radius of 5.0 F. The arbitrary units of intensity are the same as those used in Fig. 4.

same in both figures. The curves were calculated from plane wave stripping theory using the Lubitz Tables[11] and an interaction radius of 5.0 F. In most cases unambiguous l-value assignments could be made and these are listed in Table III. Also included in the table are the relative reduced widths $(2J+1)\Theta^2$ and the peak differential cross sections σ_p.

The ground and first excited states of O^{19} are known to have spins and parities of $\frac{5}{2}+$ and $\frac{3}{2}+$, respectively. If these states have configurations which can be formed by the simple addition of a neutron, both transitions can only proceed by $l=2$. This was observed to be the case for the ground-state transition, but the first excited state was weakly excited and the angular distribution exhibits a pronounced backward peak. A similar angular distribution was observed for this state by Bedewi *et al.*[6] at 10-MeV bombarding energy. It is interesting that although the general shape of the angular distribution is not characteristic of a stripping process, best agreement at forward angles is had by $l=2$ (see broken line curve in Fig. 4).

An unambiguous l-value assignment could not be made for the virtual state at 4.111 MeV, since equally good agreement could be had for $l=1$ or 2 by making slight adjustments to the interaction radius. If a radius of 5.0 F is used, as was found satisfactory for the other

[11] C. R. Lubitz, Numerical Tables of Butler-Born Stripping Cross Sections, University of Michigan, 1957 (unpublished).

TABLE III. The orbital angular-momenta transfers l, relative reduced widths $(2J+1)\Theta^2$ and peak differential cross sections determined from the $O^{18}(d,p)O^{19}$ reaction. Also included are the orbital angular momenta transfers L and the peak differential cross sections determined from the $O^{17}(t,p)O^{19}$ reaction.

		$O^{18}(d,p)O^{19}$			$O^{17}(t,p)O^{19}$		
Group No.	Level energy (MeV)	l	$(2J+1)\Theta^2$ (relative)	σ_p (arbitrary units)	L	σ_p (arbitrary units)	J^Π
0	0	2	0.57	9.1	0	10.5	$\frac{5}{2}+$
1	0.096	(2)	(0.014)	0.28	2	1.75	$\frac{3}{2}+$
2	1.467	0	1.0	66.0	···	0.42	$\frac{1}{2}+$
3	2.373	···	···	<0.02	···	1.5	···
4	2.779	···	···	<0.1	2	4.4	$\frac{9}{2}+$
5	3.070	···	···	<0.06	···	0.5	···
6	3.156	2	0.035	1.02	0	4.2	$\frac{5}{2}+$
7	3.229	0	0.084	1.00	···	<0.04	$\frac{1}{2}+$
8	3.945	1	0.055	4.6	···	0.31	$(\frac{1}{2}-)$
9	4.111	2	0.048	0.7	2	0.49	$(\frac{3}{2}+$ or
		1	0.036				$\frac{5}{2}+)$
10	4.333	···	···	<0.12	···	<0.17	···
11	4.402	···	···	···	···	0.45	···
12	4.584	···	···	2.8	···	<0.21	···
13	4.707	···	···	<0.4	0	1.0	$\frac{5}{2}+$
14	4.998	···	···	···	···	0.55	···
15	5.148	···	···	1.0	0	9.0	$\frac{5}{2}+$
16	5.460	···	(0.24)	28.0	···	···	$(\frac{3}{2}+)$
16′	(5.502)	···	···	···	···	0.8	···
17	5.714	···	···	1.8	···	···	···
18	6.280	···	···	4.0	···	···	$(\frac{7}{2}-)$

states, neither $l=1$ nor $l=2$ is favored, as is evident from Fig. 5. The assignment of $l=2$ is favored however, if one considers the fact that the (t,p) angular distribution corresponding to this state suggests even parity.

No attempt was made to measure the angular distributions corresponding to states above 4.2-MeV excitation because of the complexity of the energy spectra and because of the well-known inadequacies of stripping theory as applied to highly virtual states. Since the transition to the 5.460-MeV level was particularly intense however, and since there is evidence that this is the analog of the $d_{3/2}$ single-particle level in O^{17} an estimate of its reduced width was made assuming $l=2$.

C. $O^{17}(t,p)O^{19}$ Angular Distributions

Angular distributions of 13 proton groups from the $O^{17}(t,p)O^{19}$ reaction were measured, and are shown in Fig. 6. Several of these were characteristic of a double stripping reaction mechanism and have been fitted with the results of plane-wave calculations using the theory of Newns.[12] Although it was attempted to fit all the angular distributions using a constant radius of interaction of about 5.5 F, it was found necessary to use substantially smaller values for some of the higher excited states. This anomalous behavior of plane-wave theory for negative Q values is well established and has been discussed previously by Middleton.[13] Values of the

[12] H. C. Newns, Proc. Phys. Soc. (London) 76, 489 (1960).

[13] R. Middleton, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962,* edited by E. Clementel and C. Villi (Gordon & Breach Science Publishers, Inc., New York, 1963), p. 435.

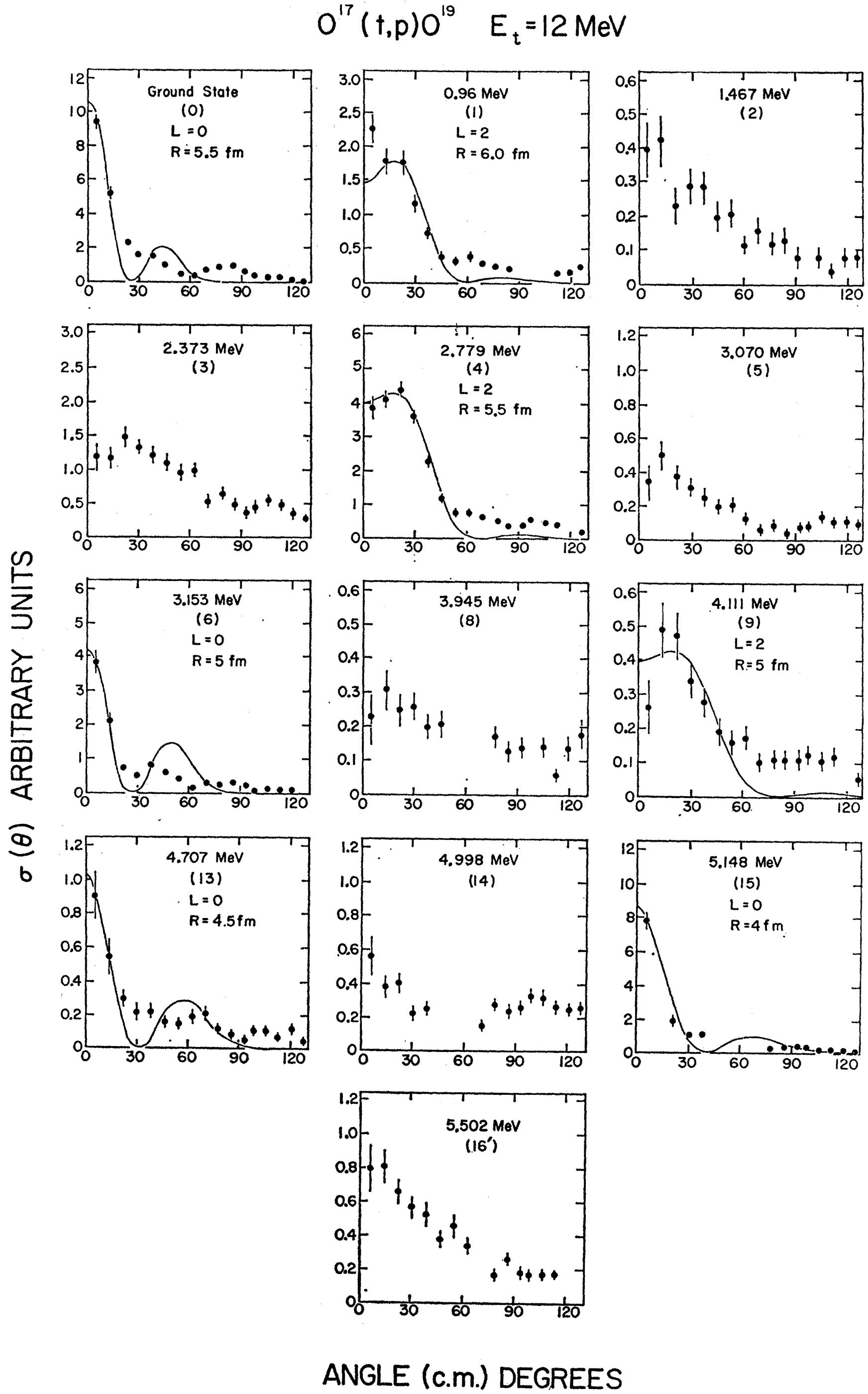

FIG. 6. Angular distributions of the ground and 12 excited-state groups from the $O^{17}(t,p)O^{19}$ reaction. The full-line curves were calculated from plane-wave double-stripping theory.

transferred orbital angular momenta L and the relative peak differential cross sections σ_p are listed in Table III.

IV. DISCUSSION

Several authors[14–19] have made shell-model-type calculations on the low-lying even-parity states of O^{19}. It is usually assumed that these arise from the coupling of three neutrons in the $1d$ and $2s$ orbitals outside an inert O^{16} core.

Three states are expected to arise from the $(d_{5/2})^3$

[14] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) 229, 536 (1955).

[15] M. G. Redlich, Phys. Rev. 99, 1427 (1955).

[16] I. Talmi and I. Unna, Nucl. Phys. 30, 280 (1962).

[17] S. P. Pandya, Nucl. Phys. 43, 636 (1963).

[18] S. Cohen, R. D. Lawson, M. H. MacFarlane and M. Soga, Phys. Letters 9, 180 (1964).

[19] T. Inque, T. Sebe, H. Hogiwara, and A. Arima, Nucl. Phys. 59, 1 (1964).

configuration having spins and parities of $\frac{5}{2}+$, $\frac{3}{2}+$, and $\frac{9}{2}+$, respectively. Only the $\frac{5}{2}+$ state can be formed directly by (d,p) stripping, whereas all three states are expected to be excited by the (t,p) double stripping reaction. The present results are consistent with the ground state being the $\frac{5}{2}+$, the first excited state being the $\frac{3}{2}+$, and the 2.779-MeV level being the $\frac{9}{2}+$ state arising from the $(d_{5/2})^3$ configuration. The latter assignment is in agreement with the results of Moreh and Jaffe[7] and confirms the prediction of Talmi and Unna[16] that the $\frac{9}{2}+$ state lies between 2.6- and 3.1-MeV excitation.

A low-lying $\frac{1}{2}+$ state is expected to arise from the $(d_{5/2})^2{}_0s_{1/2}$ configuration, and this has long been identified with the 1.467-MeV level. The strong $l=0$ transition observed in the present (d,p) study confirms this conclusion. In the (t,p) reaction this state should be formed by the transfer of s- and d-wave neutrons, and, hence, with $L=2$. Surprisingly, it is observed to be only weakly excited, and the angular distribution is not characteristic of double stripping. It may be noted that the shell model predicts no other low-lying $\frac{1}{2}+$ states. However, a probable $l=0$ assignment has been made from the (d,p) study to the 3.229-MeV level, suggesting an additional $\frac{1}{2}+$ state. Two $\frac{1}{2}+$ states containing $(d_{5/2})^2{}_0s_{1/2}$ components could arise from the admixture of a collective component similar to that known to occur in O^{18}.[20]

Two $\frac{5}{2}+$ states are predicted by Talmi and Unna[16] to occur around 4-MeV excitation, having the configurations $(d_{5/2})^2{}_2s_{1/2}$ and $d_{5/2}(s_{1/2})^2$. In the present work, $L=0$ (t,p) transitions to the 3.156-, 4.707-, and 5.148-MeV levels were observed, indicating a spin and parity of $\frac{5}{2}+$ for each. These three states may possibly arise from the admixture of $(d_{5/2})^2{}_2s_{1/2}$ and $d_{5/2}(s_{1/2})^2$ with a collective component.

By analogy with O^{17}, it might be expected that four states of O^{19} should be strongly excited by the O^{18}-$(d,p)O^{19}$ reaction. These are essentially the single-particle states formed by the addition of a neutron to the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ orbitals. In the present study, five states are observed to be strongly excited by the (d,p) reaction and to have peak differential cross sections in excess of 4.0 arbitrary units of intensity. These are the ground 1.467-, 3.945-, 5.460-, and 6.280-MeV states. Although the ground and 1.467-MeV levels clearly correspond to the $1d_{5/2}$ and $2s_{1/2}$ single-particle states, the identification of the $1d_{3/2}$ and $1f_{7/2}$ single-particle states is considerably more difficult. Since these latter states are known to lie at 5.08 and 5.697 MeV, respectively, in O^{17}, the most likely counterparts in O^{19} are the 5.460- and 6.280-MeV levels. Angular distributions arising from (d,p) transitions to these states have been measured by Yagi *et al.*[5] and by Armstrong and Quisenberry.[2] Although stripping analysis is complicated by the fact that both states are virtual, the results are not inconsistent with these conclusions. Also, Donoghue *et al.*[10] observe a broad d-wave resonance corresponding to the 5.460-MeV level in their study of the neutron elastic scattering from O^{18}.

The strong transition leading to the 3.945-MeV state appears to be most consistent with $l=1$. It would be surprising if this were a single-particle state formed by adding a neutron to the $2p_{3/2}$ orbital. A more probable explanation is that this state is based on an appreciable admixture of $(1p_{1/2})^{-2}$ $(d_{5/2})^4$ in the O^{18} ground state as has been suggested recently by Federman and Talmi.[21] Thus, the most likely configuration of the 3.945-MeV state is $(p_{1/2})^{-1}$ $(d_{5/2})^4$, implying a spin and parity of $\frac{1}{2}-$.

A summary of the present energy-level determinations and most probable spin and parity assignments to the states of O^{19} is presented in Fig. 7.

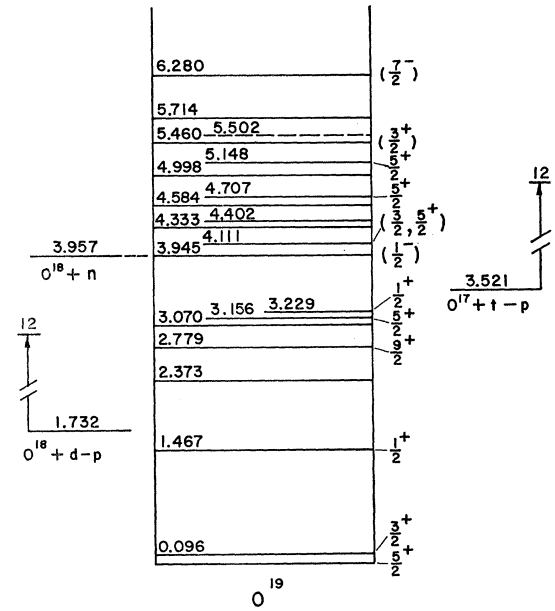

FIG. 7. Energy-level diagram of O^{19} indicating the most probable spin and parity assignments.

ACKNOWLEDGMENTS

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