Study of the ^{26}Mg(^{3}He, p)^{28}Al reaction*

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An analysis of the ^{26}Mg(^{3}He,p)^{28}Al reaction at a bombarding energy of 18 MeV has enabled the identification of 80 levels in ^{28}Al below E_x = 8.65 MeV. A distorted-wave analysis of the angular distributions of these transitions has led to unique spin-parity assignments for 8 levels. Limits have been set on the spins and parities of 17 states.

[NUCLEAR REACTIONS ^{26}Mg(^{3}He,p), E = 18 MeV; measured $\sigma(E_p, \theta)$, enriched target. ^{28}Al deduced levels L, J, π.]

I. INTRODUCTION

This experiment forms part of a continuing study of the (^{3}He,p) reaction on s-d shell nuclei which is being carried out at the University of Pennsylvania.[1] Results of the ^{20}Ne(^{3}He,p)^{22}Na and ^{24}Mg(^{3}He,p)^{26}Al reactions[2,3] have already appeared. In the previous papers it has been shown that the (^{3}He,p) reaction is a valuable spectroscopic tool and that the distorted-wave theory can provide at least qualitative agreement with the experimental results. In the present paper, L values assigned from the results of distorted-wave (DW) calculations, together with the results of previous studies,[4-15] are used to make several new spin-parity assignments.

Considerable experimental information exists on the low-lying levels of ^{28}Al. Information prior to 1965 is summarized in the compilation of Endt and Van der Leun.[4] More recently, results of studies of the ^{27}Al(d,p)^{28}Al reaction[5-7] have been published. These results are particularly useful since, in many cases, a combination of the l_n value in (d,p) and the L value in (^{3}He,p) enables an unambiguous spin-parity assignment to be made, whereas the individual results do not. Further studies of ^{28}Al include measurements of neutron capture γ rays[8-10] and measurements of branching ratios using the ^{27}Al($d,p\gamma$)^{28}Al reaction.[11]

Angular-correlation techniques have also been used to assign spins of states populated in the ^{26}Mg(^{3}He,$p\gamma$)^{28}Al and ^{30}Si($d,\alpha\gamma$)^{28}Al reactions.[12] Lifetimes of states below E_x = 2.7 MeV have been measured by Maher *et al.*[13] using the Doppler shift attenuation method. Additionally, properties of some ^{28}Al levels have been deduced from a study of the β^- decay of ^{28}Mg.[14,15]

The results of recently published shell-model calculations for A = 28 nuclei[16,17] show reasonable agreement with single-particle transfer strengths and the electromagnetic properties of these nuclei, although the results for ^{28}Al are in poorer agreement with observation.

II. EXPERIMENTAL PROCEDURE

A beam of 18-MeV ^{3}He^{++} ions from the University of Pennsylvania tandem Van de Graaff was used to bombard a 30-μg/cm^2 ^{26}Mg (99.70% enrichment) target mounted on a 100-μg/cm^2 gold foil. The reaction protons were detected in Kodak NTB nuclear emulsions after being momentum analyzed in a multiangle spectrograph. Mylar foil of 0.04-cm thickness was used to prevent charged particles other than protons from striking the emulsions. Spectra were recorded in 7.5° intervals from 7.5 to 67.5°.

III. RESULTS AND ANALYSIS

A spectrum obtained at a laboratory angle of 7.5° is shown in Fig. 1. Groups identified as belonging to ^{28}Al were identified by their kinematic shift with angle and are labeled with their excitation energies. Contaminant groups are shown shaded and are labeled by the final nucleus and excitation energy. The excitation energies of the ^{28}Al groups were calculated at four of the most forward angles using the beam energy calculated from the positions of the strong contaminant groups. These excitation energies are listed in Table I along with values of the excitation energies taken from the literature.[4,5,11] The over-all

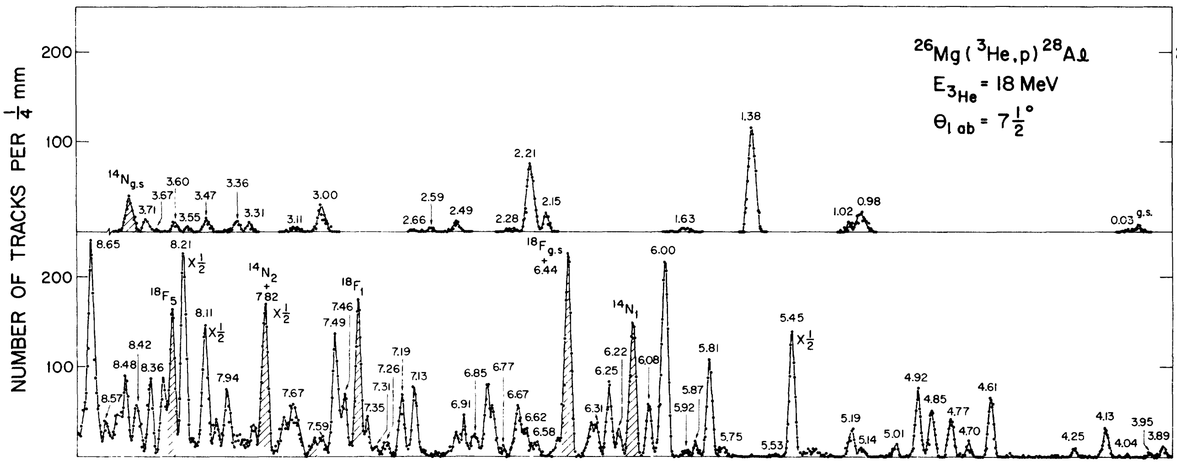

FIG. 1. Spectrum of the $^{26}Mg(^{3}He,p)^{28}Al$ reaction measured at a bombarding energy of 18 MeV and a laboratory angle of 7.5°.

agreement with the present values is excellent. The present work yields a value of 8.285 MeV ±5 keV for the Q_0 value of the $^{26}Mg(^{3}He,p)^{28}Al$ reaction—in good agreement with the value of 8.284 MeV ± 4 keV from the Mass Tables.[18]

Angular distributions were extracted for all transitions up to 6.25 MeV in excitation and for clearly resolved levels up to 8.65 MeV excitation. These are shown in Figs. 2–5. The absolute cross-section scale was determined from the nominal target thickness, measured by direct weighing, and is believed accurate to ±25%.

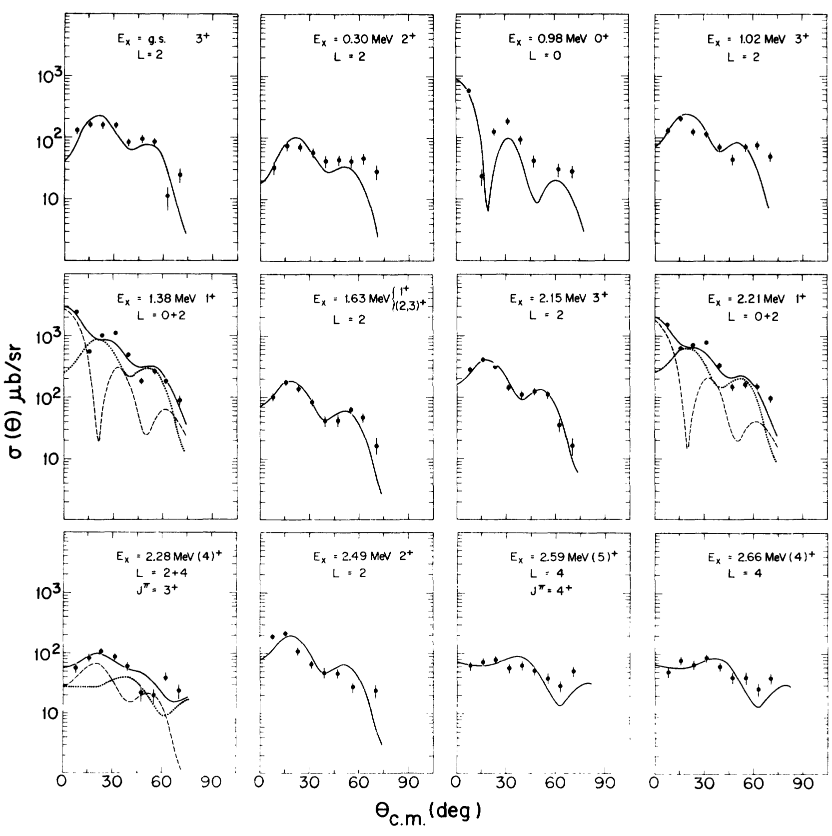

FIG. 2. Angular distributions of $^{26}Mg(^{3}He,p)^{28}Al$ transitions. The curves are the results of distorted-wave calculations.

TABLE I. Results of the $^{26}Mg(^{3}He,p)^{28}Al$ reaction.

E_x (MeV) Present[a]	E_x (MeV) Literature[b]	J^π Literature	l_n (d,p)[c]	L $(^3He,p)$	J^π Assigned	Remarks
0	0	3^+	0+2	2		
0.030	0.031	2^+	0+2	2		
0.976	0.972	(0^+)	(2)	0	0^+	
1.021	1.013	3^+	0+2	2		
1.378	1.373	1^+	2	0+2		
1.625	{1.620 1.623	1^+ $(2,3)^+$ }	(0)+2	2		
2.145	2.139	$(2,3)^+$	0+2	2		
2.209	2.200	1^+	2	0+2		
2.275	2.271	$(3)^+, 4^+$	2	2+4	3^+	
2.494	2.486	2^+	0+2	2		
2.586	2.581	$(5)^+$	...	4	4^+	
2.664	2.655	$(4)^+$	2	4		
2.999	{2.9887 3.011	$(0-5)^+$ $(0-5)^+$	(2) 2 }	0+2	$(0,1)^+$	
3.112	3.105	$(0-5)^+$	2	2	$(1-3)^+$	
3.305	3.295	$(2,3)^+$	0+2	2		
3.355	3.346	$(2,3)^+$	0+2	2		
3.473	3.465	4^-	1+3	2+4	3^+	(Doublet?)
3.548	3.537		(2)			
3.601	3.591	$4^-(2)^-$	1+3			
3.669	3.669	$(2,3)^+$	0+2			
3.709	3.702	$(2,3)^+$	0+2	2		
3.891	{3.875 3.900	$(1-4)^-$ $(0-5)^+$	1 (2)			
3.948	3.935	$(2,3)^+$	0+2			
4.044	4.033	$(0-6)^-$	3	3	$(2-4)^-$	
4.127	4.115	$(0-5)^+$	2	0+2	1^+	
4.254	4.243	$(2,3)^+$	0+2	2		
	4.315	$(0-5)^+$	2			
	4.383	$(0-5)^+$	2			
	4.466	$(0-5)^+$	2			
	4.518	$((2,3)^+)$	(0)			
4.608	4.598	$((2,3)^+)$	(0)	2	$(2,3)^+$	
4.699	4.691	$2^-, (3^-)$	1	(2)		Inconsistent
	4.739					
4.768	4.766	$(2,3)^-$	1+3	1	2^-	
4.854	4.835	$(0-5)^+$	(0)+2	0+2	1^+	
4.915	4.905	$(2,4)^-$	1+3	1+3	2^-	
	4.928					
5.010	{4.999 5.019	$(0-5)^+$ $(2,3)^+$	2 0+2			
5.143	5.138			2	$(1-3)^+$	
	5.168					
5.186	5.179					
	5.191					
	5.289					
	5.331					
	5.346					
	5.377					
	5.405					
5.452	5.445			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
5.530	5.525					
	5.596					

TABLE I *(Continued)*

E_x (MeV) Present[a]	Literature[b]	J^π Literature	l_n (d,p)[c]	L (^{3}He,p)	J^π Assigned	Remarks
5.752	5.746					
	5.766					
5.810	5.802			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
5.869	5.867			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
5.915	5.909			2	$(1-3)^+$	
	5.931					
	5.960					
6.002	5.989	$0^+, T=2$		0		
	6.012					
	6.027					
	6.067					
6.075	6.073			0+(2)	$(0, 1)^+$	
	6.163					
6.215	6.201					
6.253	6.247			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
6.313	6.322					
	6.424					
6.441	6.446					
	6.485					
6.577	6.569					
	6.591					
6.617	6.626					
6.666	6.657					
	6.719					
6.773	6.760					
	6.835					
6.852	6.856					
6.911	{6.896					
	{6.934					
	6.970					
	7.025					
	7.090					
7.133	{7.121			2	$(1-3)^+$	
	{7.149					
7.194	7.180			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
7.258	7.247					
	7.274					
7.318						
7.354	7.345					
	7.408					
	7.444					
7.462	7.460					
7.493	7.505			1 or 0+2	$(0^-, 1^\pm, 2^-)$	
7.593	7.596					
	7.655					
7.673	7.669					
	7.700					
	7.731					
7.818	many levels					
7.941						
8.105				1 or 0+2	$(0^-, 1^\pm, 2^-)$	
8.206				1 or 0+2	$(0^-, 1^\pm, 2^-)$	

TABLE I (*Continued*)

E_x (MeV) Present [a]	Literature [b]	J^{π} Literature	l_n (d,p) [c]	L (^{3}He,p)	J^{π} Assigned	Remarks
8.364						
8.422						
8.478						
8.571						
8.649				3	$(2-4)^-$	

[a] ±8 keV.
[b] Excitation energies up to 3.9 MeV from Ref. 11; 3.9–5.1 MeV, Ref. 5; 5.1 MeV up, Ref. 4.
[c] References 5, 6, and 7.

IV. DW ANALYSIS AND L ASSIGNMENTS

As in our previous studies of the (^{3}He,p) reaction in this mass region,[2,3] transitions to states of known spin-parity were used to establish the characteristic shapes of the different L transfers. Having established that the DW calculations give a satisfactory account of these shapes, the calculated shapes were then used to assign L values to other transitions.

There are, however, cases in which the data are not sufficient to distinguish between various possible L values. The most striking example of this effect is the close similarity between the predicted shapes of $L=1$ and *strongly* mixed $L=0+2$ transitions. Those angular distributions falling into this category are shown in Fig. 5 and are discussed in more detail in the next section. Simple shell-model configurations were used to generate the form factors used in the distorted-wave calculations, since it has previously been shown that, for the same L value, the shape of the predicted angular distribution has only a slight dependence on the configuration of the transferred nucleons.

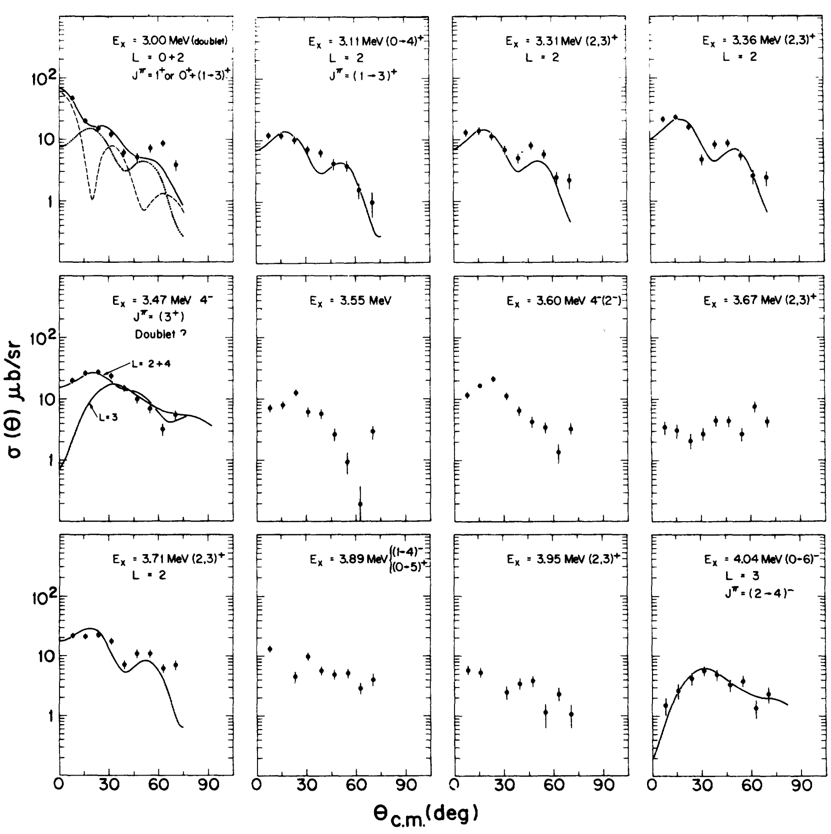

FIG. 3. Angular distributions of ^{26}Mg(^{3}He,p)^{28}Al transitions. The curves are the results of distorted-wave calculations.

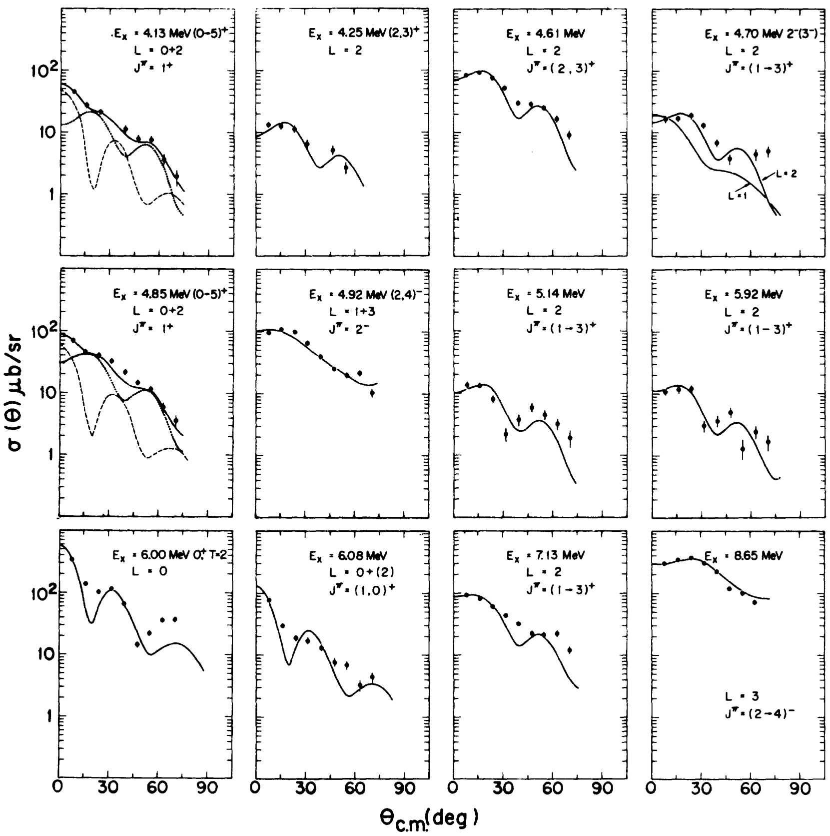

FIG. 4. Angular distributions of ^{26}Mg(^{3}He,p)^{28}Al transitions. The curves are the results of distorted-wave calculations.

The optical-model parameters were taken from other work in this mass region.[19–21] In order to reproduce the forward angle minimum of the observed $L=2$ shapes it was necessary to reduce the depth of the real well in the entrance channel while simultaneously increasing the radius of the real well, according to the relation $V_0 r^2=\text{const}$. All other parameters are standard and are listed in Table II.

Results of the calculations are shown superimposed on the data in Figs. 2–5 and the L values are listed in Table I. Whenever ambiguities in L value exist, more than one curve is shown—these transitions are discussed in detail in Sec. IV. The over-all qualitative agreement between the data and the calculated curves is excellent—better than has been achieved previously in this mass region.[2,3] At the present time it is not possible to make a quantitative comparison between our results and the distorted-wave calculations. It is well known that the predicted magnitudes depend extremely sensitively on the details of the initial- and final-state wave functions, and such a comparison must await the availability of two-particle spectroscopic amplitudes calculated from detailed wave functions.

V. SPIN-PARITY ASSIGNMENTS

In this section we discuss the individual transitions in some detail. In several cases we are able to make new spin-parity assignments. There are, however, some inconsistencies with previous results and they are also discussed here.

As expected from the simplest shell-model picture of ^{28}Al, the lowest-lying states are characterized by a 2^+, 3^+ doublet formed by the coupling of the odd neutron in the $2s_{1/2}$ orbit and the odd proton in the $1d_{5/2}$ orbit. The ground state and 0.030-MeV level of ^{28}Al have been known for some time[22] to have spin-parity 3^+ and 2^+, respectively. The present data show pure $L=2$ shapes for both transitions. The absence of any observable $L=4$ component in the ground-state transition is significant. Although an $L=4$ component is allowed by the macroscopic selection rules for the (^{3}He,p) reaction on a spin-zero target proceeding to a 3^+ final state, this would require the transfer of either a $(1d_{5/2})(1d_{3/2})$, $(1d_{3/2})(1d_{3/2})$, or $(1d_{5/2})(1d_{5/2})$ neutron-proton pair. The absence of such an allowed $L=4$ component indicates the weakness of such components in the wave function, although

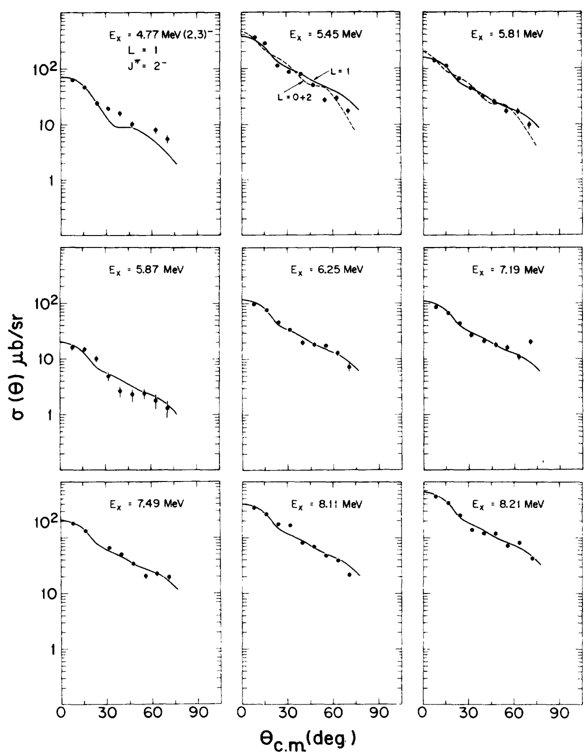

FIG. 5. Angular distributions of $^{26}Mg(^{3}He,p)^{28}Al$ transitions characteristic of either $L=0+2$ or $L=1$ transfer.

the possibility of accidental cancellations suppressing the $L=4$ component cannot be ruled out. It is worth noting that the relative magnitudes of the ground-state and 0.030-MeV transitions are reasonably well reproduced by assuming pure $[(1d_{5/2})(2s_{1/2})]_{3^+,\,2^+}$ transfer of the neutron-proton pair. These conclusions are borne out by an inspection of the wave functions of Ref. 17, in which the ground state and first excited state are dominated by this particular configuration.

The 0.976-MeV level has been thought to have spin-parity 0^+ for some time,[12] but until recently direct evidence has been lacking. The pure $L=0$ transition observed in the present work indicates a definite 0^+ assignment for this level. This result from the present data has been reported previously.[1]

The 1.021-MeV level is thought to have $J^\pi=(2,3)^+$ with the $^{30}Si(d,\alpha\gamma)^{28}Al$ data of Boerma and Smith[12] favoring $J^\pi=3^+$. The present $L=2$ $(^{3}He,p)$ transition is consistent with either possibility.

An assignment of $J^\pi=1^+$ has been made to the 1.378-MeV state on the basis of an allowed β^- branch in the decay of ^{28}Mg.[14] The strong $L=0+2$ $(^{3}He,p)$ transition confirms this assignment.

In the present work the level observed at 1.625 MeV corresponds to an unresolved doublet with 3 keV separation at excitation energies[11] of 1.620 and 1.623 MeV, respectively. The lower member has previously[14] been assigned $J^\pi=1^+$, and the upper member $J^\pi=(2,3)^+$ on the basis of an $l_p=0$ transition in the $^{27}Al(d,p)^{28}Al$ reaction.[6] The present data indicate a pure $L=2$ $(^{3}He,p)$ transition which, although consistent with the previous spin-parity assignments, is rather surprising. A $0^+\to 1^+(^{3}He,p)$ transition is allowed to proceed by both $L=0$ and 2. In nearly all cases studied so far[1-3] the $L=0$ component dominates, due primarily to the kinematic favoring of this L transfer. The absence of any $L=0$ component in the present data for the 1.62-MeV doublet indicates either that the 1^+ member is only weakly excited or that it is populated by pure $L=2$.

Spin-parity of either 2^+ or 3^+ has been suggested[12] for the 2.145-MeV level. The present data, which show pure $L=2$, are consistent with either possibility. The strong $L=0+2$ transition to the 2.209-MeV level indicates a spin-parity of 1^+ in agreement with the suggestion of Ref. 12.

TABLE II. Optical-model parameters used in the distorted-wave analysis of the $^{26}Mg(^{3}He,p)^{28}Al$ reaction.

Channel	V_0 (MeV)	$r_0=r_{so}$ (fm)	$a=a_{so}$ (fm)	W (MeV)	$W'=4W_D$ (MeV)	r_0' (fm)	a' (fm)	r_{0c} (fm)	V_{so} (MeV)
$^{26}Mg+^{3}He$ [a]	150.	1.24	0.72	12	⋯	1.60	0.77	1.29	5
$^{28}Al+p$ [b]	58.02	1.13	0.57	⋯	39.76	1.13	0.50	1.13	5.5
Bound state [c]	d	1.26	0.60	⋯	⋯	⋯	⋯	1.26	$\lambda=25$

[a] Reference 20. The $V_0r_0^2=$const.: Continuous ambiguity was used to derive the present values of V_0 and r_0 from the quoted values of $V_0=177$ MeV and $r_0=1.14$ fm.

[b] Reference 21. The set shown is for the ground state, and the energy dependence is as given in the reference.

[c] Reference 22.

[d] Adjusted to give the correct binding energy as determined by the separation-energy method.

Maher *et al.* have suggested[13] that the 2.275-MeV level has spin-parity of 4^+, although 3^+ could not be ruled out. The present data show an admixed $L=2+4$ angular distribution which requires $J^\pi=3^+$. With the assumption of 4^+ for the 2.275-MeV level, Maher *et al.* assigned $J^\pi=5^+$ to the 2.586-MeV level,[13] since the γ branch from this state to the 2.275-MeV level requires that the spins differ by no more than 1. If, in fact, the 2.275-MeV state has $J^\pi=3^+$—as suggested by the present data—then the 2.586-MeV level must be 3^- or 4^+ [the (d,α) data of Ref. 12 require $J^\pi=3^-, 4^+$, or 5^+]. The angular distribution of the $(^3He,p)$ transition to the 2.586-MeV level is well fitted by a pure $L=4$ calculation, thus indicating $J^\pi=3^+$, 4^+, or 5^+. The only spin-parity consistent with all the available information for the 2.586-MeV level is therefore $J^\pi=4^+$.

The level at 2.664 MeV is observed to be populated with an apparently pure $L=4$ angular distribution. This result is consistent with the spin-parity of 4^+ suggested by Maher *et al.*[13] On the basis of all the existing information, however, it is not possible to exclude $J^\pi=5^+$.

The group observed in the present work at 2.999 MeV excitation corresponds to two unresolved levels at 2.988 and 3.011 MeV. Both of these levels are observed to be populated with $l_n=2$ in the $^{27}Al(d,p)^{28}Al$ reaction, leading to spins of 0 to 5 and positive parity for both. The present data show an admixed $L=0+2$ transition which, if this corresponded to a single group, would lead to an unambiguous $J^\pi=1^+$ assignment. However, on the basis of our data it is not possible to make any definite statement except that one member of the doublet has $J^\pi=0^+$ or 1^+. If one member has $J^\pi=0^+$ then the other must have $J^\pi=(1,2,3)^+$. The shell-model calculations[17] of deVoigt and Wildenthal predict a 0^+ state at 3.75 MeV and all the predicted 1^+ states have experimental counterparts which would suggest that this doublet contains the second 0^+ state in ^{28}Al.

It has previously been suggested[5] that the 3.112-MeV level has $J^\pi=(0-5)^+$. The $L=2$ $(^3He,p)$ transition observed in the present work restricts the possible spins to $(1,2,3)^+$.

Measurements of the circular polarization of neutron capture γ rays from ^{28}Al have led to an assignment of $J^\pi=4^-$ for the 3.473-MeV level.[9] The $(^3He,p)$ selection rules require that such a level be populated with $L=3$ or 5. The $(^3He,p)$ angular distribution is not characteristic of either of these possibilities but is well fitted with a mixture of $L=2+4$—indicating a 3^+ assignment. However, this level was seen to be populated with $l_n=3$ in the $^{27}Al(d,p)^{28}Al$ reaction, in agreement with a 4^- assignment. A possible solution to the discrepancy would be the existence of a 3^+, 4^- doublet at this energy, with only the 3^+ member being populated in the $^{26}Mg(^3He,p)^{28}Al$ reaction. Alternatively, the difficulty may lie in the failure of the distorted-wave calculations to reproduce the shapes of $L=3$ transitions. Such a possibility seems to be negated by the excellent agreement between the data for the 4.044-MeV level and an $L=3$ distorted-wave calculation. This state has previously been assigned $J^\pi=(0-6)^-$ on the basis of an $l_n=3$ $^{27}Al(d,p)^{28}Al$ transition.[5] The observed $L=3$ $^{26}Mg(^3He,p)^{28}Al$ transition confirms negative parity and further restricts the spin possibility to $J=2$, 3, or 4.

A definite assignment of $J^\pi=1^+$ is possible for the 4.127-MeV state on the basis of the $L=0+2$ transition observed. An $L=2$ transition to the 4.608-MeV level indicates $J^\pi=1, 2$, or 3 and positive parity. Similarly, the transition to the 4.699-MeV level is fairly well fitted by $L=2$, giving spin-parity $J^\pi=(1-3)^+$. However, the $l_n=1+3$ $^{27}Al(d,p)^{28}Al$ transition is in conflict with these possibilities.[5]

For the 4.854-MeV state, $J^\pi=1^+$ is assigned on the basis of an observed $L=0+2$ transition. The $l_n=2$ (d,p) transition[5] previously established positive parity for this level.

Both the 5.143- and 5.915-MeV transitions are characteristic of $L=2$, leading to $J^\pi=(1,2,3)^+$ assignments for both these levels.

The level observed at 6.002 MeV in the present study corresponds to a state observed at 5.989 MeV by Clark *et al.*, who identified this level as the 0^+, $T=2$ analog of the ^{28}Mg and ^{28}P ground states.[23] This assignment has recently been substantiated by a study of its γ decays.[24] The pure $L=0$ transition in the present work is consistent with the 0^+ assignment. Another relatively strong $L=0$ transition is observed to the level at 6.075 MeV. On the basis of the present data we can assign $J^\pi=(0,1)^+$ to this level. The absence of a minimum near 50° strongly suggests a 1^+ assignment.

An $L=2$ transition to the 7.133-MeV doublet requires $J^\pi=(1-3)^+$ for one or both members.

The 8.649-MeV transition is characteristic of $L=3$, giving $J^\pi=(2-4)^-$. This transition is very strong but at the present time it is not possible to make any definite statement about the possible configuration of this level.

As mentioned in Sec. III, one of the ambiguities that exists in the identification of L values in the $(^3He,p)$ reaction originates from the difficulty in distinguishing between strongly mixed $L=0+2$ transitions and $L=1$ transitions. Several transitions observed in the present study fall into this category. If the parity of the level is known from other sources, the ambiguity is removed, and all $L=0+2$ or $L=1$ assignments quoted thus far correspond to states with previously known parities. An example is shown in Fig. 5. The transition to the 4.768-MeV level can be equally well fitted by $L=1$ (solid line) or $L=0+2$ (dashed line). However, the $l_n=1+3$ transition observed in the $^{27}Al(d,p)^{28}Al$ reaction[5] established negative parity for this level, thus eliminating the $L=0+2$ possibility and therefore leading to a $J^\pi=1^-$, 2^- assignment. If the 3^- or 2^- restriction of Ref. 5 is correct, then our results require $J^\pi=2^-$. The parities of the 5.452-, 5.810-, 5.869-, 6.253-, 7.194-, 7.493-, 8.105-, and 8.206-MeV levels are, however, not known. Nevertheless, the identification of the L values of these transitions as either $L=0+2$ *or* $L=1$ requires $J^\pi=0^-$, $1^\pm$ or 2^-. All these angular distributions are shown in Fig. 5.

VI. CONCLUSIONS

This study of the $^{26}Mg(^3He,p)^{28}Al$ reaction has enabled the identification of 80 ^{28}Al levels up to 8.65 MeV in excitation. The excitation energies from the present study are in good agreement with previously published values. A comparison of the angular distributions with the predictions of the distorted-wave theory allows the assignment of L values for many transitions. These L values, when combined with previous results, have resulted in the following spin-parity assignments: 0.976 MeV, 0^+; 2.275 MeV, 3^+; 2.586 MeV, 4^+; 3.473 MeV, probable 3^+, 4^- doublet; 4.127 MeV, 1^+; 4.768 MeV, 2^-; 4.854 MeV, 1^+; and 4.915 MeV, 2^-. New limits have also been set on the spin-parity of 17 additional states.

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